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Marx Generator Model for Corona Discharge in Air

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Abstract—To calculate the parameters of the Marx generator, such as the voltage at the generator output, the values of the circuit elements and, if necessary, the number of generator cascades, an electrical model was created with a load represented as a negative corona discharge in a cylindrical electrode system at atmospheric pressure.

When creating the model, its input parameters were defined, the influence of the current-voltage characteristic of the corona discharge on the generator operation was investigated, and the impact of deionization processes on the output parameters of the model (output voltage on the generator, nominal values of circuit elements, etc.) was analyzed. For more effective modeling of processes in the Marx generator, its general equivalent circuit was divided into two parts, in which the charging and discharging processes of the Marx generator stages were studied separately.

The model will be useful in the design of relatively simple systems based on a Marx generator that use a corona discharge, such as ionisers, electric filters, surface modification devices, etc.

Keywords — corona discharge; Marx generator; high voltage; ionization.

I. Introduction

Corona discharge today has many applications: smoke and dust electrofiltration [1], gas conversion [2]–[4], etc.). Today, the use of corona discharge for ozone generation is becoming widespread. Corona discharge is excellently suited for this purpose as it is a source of low-temperature plasma [5].

To generate this type of discharge, a high electric field intensity is required.

Pulsed sources for corona generation can have various designs. For example, in the work [1], a device based on inductive energy storage is used for methane conversion, while in [2], a Marx generator is also used for gas conversion.

The existence of corona discharge is characterized by the presence of a highly non-uniform electric field in a gas with pressure close to atmospheric. The electrode system must have an electrode with a small radius of curvature, around which the corona will be generated. One of the most common electrode systems for corona discharge is the wire-tube system [6]. When sufficient voltage is applied to the electrodes, a corona discharge occurs around the wire, which manifests as a glow around the electrode with a small radius.

In the literature sources [1], [6], [16], [17], [8]–[15], the parameters of corona discharge such as current-voltage characteristics, discharge inception voltage, the influence of pressure and radius of curvature on the critical electric field strength, as well as deionization processes in corona discharge, its time, and other factors have been studied. These parameters need to be taken into account when creating the model.

To generate corona discharge, a high voltage source is required. This article examines the Marx generator circuit, which operates based on parallel charging and series discharging of capacitances into a load. This circuit was chosen due to its relatively simple design and ability to produce sufficiently high voltage [7][8].

The operating principle of the Marx generator is described by two phases: charging and discharging. When calculating the model for each phase, a separate equivalent circuit is introduced, within which calculations are performed that relate only to the specific phase. The circuit used in this article is shown in Fig. 1.

The operation of the Marx generator is described in [7], [8], [18], [19]. These works describe the processes that occur during the discharge and charging of stages, and outline the main parameters of the Marx generator. These include the input and output voltage of the cascade, generator charging time, output pulse duration,

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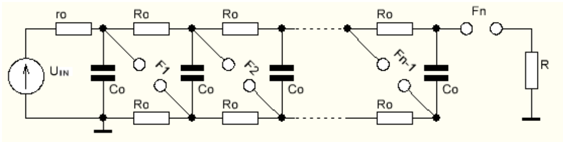

Fig. 1 Marx generator [18]

stage utilization coefficient, and the coefficient of charging circuit influence on the discharge circuit.

The developed model is based on the classical Marx generator model for active resistance, which is described in the work [18]. However, corona discharge has a much more complex behavior. Therefore, changes were made to the model to account for the influence of corona discharge on the circuit operation.

II. Methods and Materials

To construct a Marx generator model with corona discharge operating at atmospheric pressure in the load, it is necessary to:

- determine the initial parameters of the system to create the model;
- investigate the influence of the current-voltage characteristics of the corona discharge on the generator operation;
- determine the impact of deionization processes on the output parameters of the model;
- To effectively study the charging and discharging processes in a Marx generator, divide its overall circuit into two independent equivalent circuits, where the charging and discharging processes of the stages will be examined separately;
- Derive formulas for determining the parameters of the Marx generator circuit, taking into account the parameters of the corona discharge.

III. Corona Discharge

A. Electric field strength distribution

In Fig. 2a, a schematic view of a cylindrical electrode system is shown, while Fig. 2b illustrates the electric field strength distribution within it. The inner corona electrode-cathode is a thin wire with a small radius r_1, positioned along the axis inside a tube with a larger radius r_2, which is a second external electrode-anode.

Fig. 3 shows the voltage-current characteristic of the corona in a cylindrical electrode system. The A-B region corresponds to the saturation process, while with a further increase in voltage (region B-C), a noticeable rise in current occurs from the corona onset voltage U_{cr}. If the voltage continues to increase, a spark breakdown occurs at U_{br} (region C and beyond) [9].

The corona discharge voltage is determined from the expression

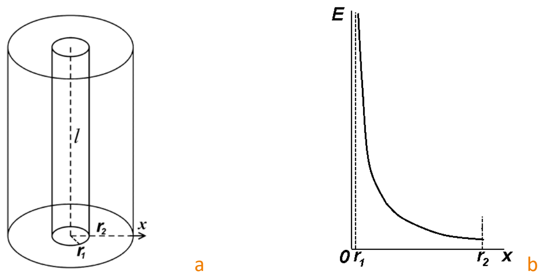

Fig. 2 Cylindrical electrode system (wire–tube). a) geometrical parameters, b) electric field distribution [1]

$$U_{cr} = E_{\mathrm{cr}} r_1 \ln \frac{r_2}{r_1}, \qquad (1)$$

where r_1 and r_2 are electrode radii [m], E_{cr} is the critical field strength [V/m] at which corona discharge occurs. Its value is determined by Peek's empirical formula, which is calculated for air in a cylindrical electrode system. For negative corona, it takes the form

$$E_{\mathrm{cr}} = 3,04\left(\beta + 0,0311\sqrt{\frac{\beta}{r_1}}\right)10^6, \qquad (2)$$

where β is the ratio of gas density under normal conditions (T_0 = 293 K, p_0 = 101.3 kPa) to density under working conditions:

$$\beta = \frac{pT_0}{p_0 T}, \qquad (3)$$

where p is gas pressure, Pa; T is gas temperature, K [1].

Let's determine the system's limiting voltage at which the transition from corona to spark discharge occurs:

$$U_{\mathrm{br}} = E_{\mathrm{br}} d = E_{br}(r_2 - r_1). \qquad (4)$$

The ratio of electrode radii is important, since incorrectly selected values can result in spark breakdown instead of corona discharge.

Therefore, the following condition must be met, [10]

$$\frac{r_2}{r_1} > \frac{E_{\mathrm{cr}}}{E_{\mathrm{br}}}. \qquad (5)$$

B. Current-voltage characteristic

At voltages lower than U_{cr} (Fig. 3 region *A-B*), the current in the discharge gap is negligibly small. Therefore, the beginning of the corona current-voltage characteristic is considered to be the moment of its inception, when the applied voltage has a value between U_{cr} and U_{br} (Fig. 3 region *B-C*).

The corona current dependence in a cylindrical electrode system is described in [11]. From this, the current-voltage characteristic formula is derived, which is approximated by a parabolic function [1], [12], [13]

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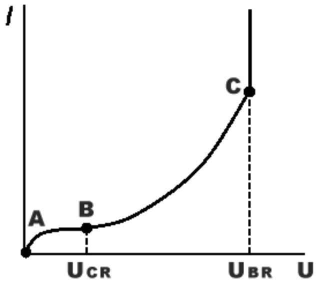

Fig. 3 Current-voltage characteristic of the corona discharge [1]

$$I = AU(U - U_{cr}), \quad (6)$$

$$A = \frac{8\pi\varepsilon\varepsilon_0 k}{r_2^2 \cdot \ln\left(\frac{r_2}{r_1}\right)}, \quad (7)$$

where A is the current-voltage characteristic parameter, k is the electron mobility coefficient, which depends on the system's geometric parameters and gas type, and for air is determined as [11]

$$k = \frac{1}{p}\left(0,027 + \frac{0,14}{\left(1 + \frac{E}{p}\cdot 10^{-5}\right)^{0,53}}\right). \quad (8)$$

C. Deionization of the discharge gap

After voltage removal from the discharge gap, charges remain there for some time [14]. The equation describing the change in charge concentration has the form

$$n_e(t) = \frac{n_{e0}}{1 + n_{e0}\beta_e t}, \quad (9)$$

where n_e is the concentration of recombining charges, n_{e0} is the initial concentration at the moment of voltage removal, β_e is the volume recombination coefficient (for air at atmospheric pressure $\beta_e = 1.4 \cdot 10^{-10}$ m^3/s) [15], [20].

Since plasma conductivity in the discharge gap depends on the charge carrier concentration, after voltage removal it gradually decreases similarly (9) [16].

The initial corona discharge parameters required for modeling are shown in Table 1.

IV. Model

Before starting the modeling, it is necessary to set initial parameters within the ranges specified in Table 1.

The generator is powered by input voltage U_{in}, producing pulsed output voltage U_{out}, whose value strongly depends on the number of stages. The value of U_{in} is determined by the working voltage of capacitors used in the generator. Usually, it's 5 – 30 kV. Taking lower values is not recommended since the output voltage may be insufficient for corona discharge generation. Voltage U_{out}

Table 1 Input parameters of the model

Parameter	Limits	Description.
U_{in}, [V]	5 – 30 kV	Input voltage
U_{out}, [V]	$U_{cr} – U_{br}$	Output voltage
t_{ch}, [s]	0,1 – 10 s	Generator charge time
t_i, [s]	0,05 – 50 ms	Output pulse duration
α	0,01 – 0,06	The coefficient of influence of the charging circuit on the discharge circuit
η	0,5 – 0,95	Degree utilisation rate
r_1, [m]	< 5 mm	Internal electrode radius
r_2, [m]	5 – 50 cm	Outer electrode radius
l, [m]	0,05 – 1 m	Electrode system length
p, [Pa]	≥ 100 kPa	Pressure range of the environment
T, [K]	—	Operating temperature of the environment

should have a value between U_{cr} and U_{br}, as these are the limits within which corona can exist. Stages are charged to voltage U_0, which for stable circuit operation is taken slightly lower than the input voltage. For this purpose, a stage utilization coefficient η is introduced, which determines its voltage:

$$U_{0п} = \eta U_{in}. \quad (10)$$

The lower the coefficient, the more stable the stage switches will operate, but the lower the output voltage will be.

Charging time t_{ch} determines the charging speed of stage capacitances to the required voltage, and consequently the frequency of generator output pulses. It is chosen based on generator speed. In theory, the circuit shown in Fig. 1 can produce up to several dozen pulses per second. In this work, we'll limit ourselves to ten pulses, as at this frequency the real circuit will guaranteed work stably. Choosing charging time more than 10 s is also not recommended, as in this case charging resistors will start approaching the values of capacitor leakage resistances, which will lead to excessive stage discharge and the generator may not reach the required stage breakdown voltage.

The output pulse duration should not be taken too small, as such values require very small stage capacitances. Too large values, conversely, lead to large capacitances which will be difficult to charge.

The length of the electrode system should not be too large, as this will lead to increased discharge capacitance, which will significantly reduce the generator output voltage. Too small length may cause incorrect corona discharge formation due to possible low curvature in other places of the electrode system.

Pressure and temperature are recommended to be taken close to normal conditions. The pressure value should not be too low, as this will complicate corona appearance.

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The arresters in this system are conventional globular ones that operate at atmospheric pressure. For their calculation, the breakdown gradient of air E_{br} is taken, which under normal conditions is 3 MV/m. In this model, for calculation simplification, their transient processes are not considered, meaning operation occurs instantaneously.

Although both phases of generator operation are considered independently, the parameters determined in the discharge phase will determine the parameters related to the charging phase [8], [18].

A. Discharge Circuit Model

For analyzing the generator discharge process, its equivalent circuit is introduced (Fig. 4), consisting of charging (surge) capacitance C_k, spark gap breakdown resistance R_i, equivalent total resistance of charging resistors R'_0, discharge resistance R, discharge capacitance C, and electrode system. Components C and R are constituent parameters of the electrode system that depend on the medium and construction. The model neglects the influence of parasitic capacitances between the circuit and the ground. The parasitic inductance of the discharge circuit with conductor lengths ranging from tens of centimeters to several meters will have a magnitude of order $n \cdot 10^{-8}$ H. Combined with the discharge capacitance, they will constitute an oscillatory LC circuit with a resonant frequency that exceeds the operating frequency of the Marx generator by 8 orders of magnitude, which allows it to be neglected.

We assume that during discharge, all spark gaps operated simultaneously. Stage capacitances C_0 are connected in parallel. Therefore, the impact capacity is

$$C_k = nC_0, \tag{11}$$

where n is the number of generator stages. It is found using output voltage U_{out} and intermediate stage voltage U_{0inter} expressed in (10)

$$n = \mathrm{ceil}\left(\frac{U_{out}}{U_{0inter}}\right), \tag{12}$$

where ceil() is the function of rounding up to the nearest integer.

Having the number n, we can find the stage voltage.

$$U_0 = \frac{U_{out}}{n}. \tag{13}$$

Spark gaps operate in air at atmospheric pressure. For them, the discharge gap is calculated considering the field strength value E_{br} = 3 MV/m and known stage voltage in (13):

$$l_F = \frac{U_0}{E_{br}}. \tag{14}$$

During system discharge, capacitances are shunted by two charging resistors R_0. The discharge of capacitances C_0 to charging resistors can be accounted for by introducing resistance R'_0 parallel to discharge resistance R:

$$R'_0 = \frac{n}{2} R_0. \tag{15}$$

Since the recommended value of coefficient α is $0.01 \le \alpha \le 0.06$, the charging resistance can be determined by it

$$R_0 \ge \frac{2R_{\min}}{\alpha n}. \tag{16}$$

With too large values of R_0, the charging time and non-uniformity of stage charging increase, while with small values, spark gap operation deteriorates [18].

The discharge resistance R value is found from the voltage-current characteristic of the electrode system. This value depends on the applied voltage, which imposes additional complications in calculations. If using Ohm's law, then from equation (6) we can express the dependence of the resistance R on the applied voltage U [1].

$$R = \frac{U}{I} = \frac{U}{AU(U - U_{cr})} = \frac{1}{A(U - U_{\mathrm{cr}})}. \tag{17}$$

If conductivity б is expressed through resistance, we get the formula [16].

$$\sigma = \frac{1}{R} = A(U - U_{cr}). \tag{18}$$

To simplify the determination of the resistance R, which is used to calculate the time-independent constant parameters, it can be taken as the minimum value obtained from (17) at the maximum voltage equal to the generator output voltage U_{out}:

$$R_{\min} = \frac{1}{A(U_{out} - U_{br})}. \tag{19}$$

When applying voltage pulse to electrodes, first the discharge capacitance C between electrodes is charged, which is found as:

$$C = \frac{2\pi\varepsilon\varepsilon_0 l r_1}{\ln\left(\frac{r_2}{r_1}\right)}, \tag{20}$$

where dielectric permittivity in case of air ε ≈ 1 [17]. During this process, charge flows from surge capacitance C_k to discharge capacitance C through total

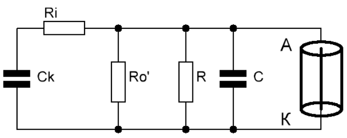

Fig. 4 Equivalent discharge circuit

resistance of the discharge channels of the spherical discharge arrester R_i. It is found using Toepler's formula:

$$R_i = \frac{nk_\text{T} d}{q} = \frac{nk_\text{T}(r_2 - r_1)}{U_0 C_0}, \quad (21)$$

where k_T = 1.5·10^{-2} V·s/m, q is the stage capacitor charge [3]

The voltage dependence on time on capacitors C_k and C, denoted as $u_k(t)$ and $u(t)$, respectively, is described by the following formulas

$$u_{k1}(t) = (U_{out} - U_{cr})\exp\left(\frac{-t}{\tau_{\text{p1}}}\right) + U_{cr}, \quad (22)$$

$$u_1(t) = u_{k1}(t)\frac{R'_0}{R'_0 + R_i}\left(1 - \exp\left[\frac{-t}{\tau_{\text{p1}}}\right]\right), \quad (23)$$

$$U_{cr} = \frac{C_k U_{out}}{C_k + C}, \quad (24)$$

$$\tau_{\text{p1}} = R_i \frac{C_k C}{C_k + C}, \quad (25)$$

where $u_{k1}(t)$ and $u_1(t)$ are the impact voltage at the generator output and the voltage on the electrode system respectively during charge flow, τ_{p1} is the flow time constant, U_{cr} is the equilibrium voltage of both capacitors.

In addition to the flow of capacitor charges, their discharge also occurs through resistance R'_0:

$$u_{k2}(t) = U_{out}\exp\left(\frac{-t}{\tau_{\text{p2}}}\right), \quad (26)$$

$$\tau_{\text{p2}} = C_k(R_i + R'_0), \quad (27)$$

where τ_{p2} is the discharge time constant of capacitance C_k.

From equations (22), (23), and (26), we obtain the dependence of voltage on time for these capacitors during their simultaneous charging and discharging:

$$u_{k12}(t) = u_{k1}(t)\cdot u_{k2}(t) = \\ = \left(\left[U_{out} - U_{\text{cr}}\right]\exp\left[\frac{-t}{\tau_{\text{p1}}}\right] + U_{\text{cr}}\right)\exp\left(\frac{-t}{\tau_{\text{p2}}}\right), \quad (28)$$

$$u_{12}(t) = u_{k12}(t)\frac{R'_0}{R'_0 + R_i}\left(1 - \exp\left[\frac{-t}{\tau_{\text{p1}}}\right]\right), \quad (29)$$

The voltages described in will change in this way until corona occurs at $u(t) < U_{\text{cr}}$ or $t < t_{\text{cr}}$, where t_{cr} is the time of corona occurrence

$$u(t_{\text{cr}}) = U_{\text{cr}}. \quad (30)$$

The corona discharge changes the output signal form, and in the system this is reflected as the appearance of corona resistance $R(u)$, which depends on the applied voltage and is connected in parallel to resistance R'_0.

$R(u)$ can be calculated using iterative approximation, making the formula for corona resistance recursive, where the voltage value $u(t)_m$ at step m is taken from the previous $u(t)_{m-1}$. In the first step, resistance $R(u)$ is absent, so the ordinary voltage functions (28) and (29) are used here.

In all subsequent steps, resistance R must be taken into account, so we transform the existing formulas (17), (27) – (29) into a recurrent form:

$$R(u)_m = \frac{1}{A(u(t)_{m-1} - U_{cr})}, \quad (31)$$

$$(\text{при } u(t)_{m-1} \le U_{\text{cr}}, R = \infty);$$

$$\tau_{pm} = C_k\left(R_i + \frac{R'_0 R(u)_m}{R'_0 + R(u)_m}\right); \quad (32)$$

$$u_k(t)_m = \\ = \left(\left[U_{out} - U_{sr}\right]\exp\left[\frac{-t}{\tau_{\text{p1}}}\right] + U_{\text{cr}}\right)\exp\left(\frac{-t}{\tau_{pm}}\right); \quad (33)$$

$$u(t)_m = u_k(t)_m \frac{R'_0}{R'_0 + R_i}\left(1 - \exp\left[\frac{-t}{\tau_{\text{p1}}}\right]\right); \quad (34)$$

where m is the step number. The resulting voltages can be expressed by the average values of the voltages of each step:

$$u_{k\text{p}}(t) = \frac{u_{k12}(t) + \sum_{m=1}^{K} u_k(t)_m}{K+1}, \quad (35)$$

$$u_{\text{p}}(t) = \frac{u_{12}(t) + \sum_{m=1}^{K} u(t)_m}{K+1}, \quad (36)$$

where K is the number of steps.

In the case of $u(t) \le U_{\text{cr}}$, resistance $R(u)$ is ignored since it becomes very large (theoretically infinite), therefore

$$\tau_{pm} = C_k\left(R_i + \frac{R'_0 R(u)_m}{R'_0 + R(u)_m}\right) = \\ = C_k\left(R_i + R'_0\right) = \tau_{\text{p2}}, \ (\text{при } u(t)_m \le U_{cr}). \quad (37)$$

After the voltage $u(t)$ has reached its maximum and began to decrease, deionization processes in the electrode system come into effect. As stated in Section III, when voltage is removed from the discharge gap, its conductivity does not decrease instantly. This is characterized by the appearance of a certain current, which depends on the concentration of carriers, and thereby slows down the decrease of the output voltage.

To calculate it, it is first necessary to determine the time t_0 when deionization begins. It is found at the peak of the output voltage $u_\text{p}(t)$ as the extremum point of this function within the range from 0 to τ_{p1} [4]:

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$$\frac{du(t_0)}{dt}=0;\ (0<t_0<\tau_{p1}). \tag{38}$$

To find the initial concentration of charge carriers n_{e0} at point t_0, we use the formula

$$n_{e0}=\frac{\sigma_0 \nu_m}{2{,}82\cdot 10^{-10}}=\frac{A(U_{e0}-U_{cr})\nu_m}{2{,}82\cdot 10^{-10}}, \tag{39}$$

where б$_0$, U_{e0} – conductivity and voltage of the gap at moment t_0

$$U_{e0}=u_{\text{p}}(t_0), \tag{40}$$

e – electron charge, ν_m – collision frequency [s^{-1}] [16]:

$$\nu_m=2{,}92\cdot 10^7\, p. \tag{41}$$

During deionization, the discharge gap will generate some current, which will reduce the rate of decrease in the output pulse amplitude. The voltage can be shown as changing proportionally to the concentration of charges [5][19]:

$$\begin{aligned} &\frac{n_e}{n_{e0}}=\frac{u_e}{U_{e0}};\\ &u_e(t)=\frac{n_e(t-t_0)U_{e0}}{n_{e0}}. \end{aligned} \tag{42}$$

Therefore, the output voltage *u(t)* will be described as

$$u(t)=\begin{cases} u_{12}(t),\ 0<t\le t_{cr}\\ u_{\text{p}}(t),\ t_{cr}<t\le t_0\\ u_e(t),\ t_0<t. \end{cases} \tag{43}$$

The duration t_{i} of the discharge pulse at the system output is measured from its beginning to half the amplitude during voltage drop [18]:

$$u(t_{\text{i}})=\frac{U_{e0}}{2}. \tag{44}$$

The impact capacitance C_k can be approximately found using the formula (22). Let the output voltage of the system be given only by this formula. By substituting the pulse duration t_{i}, we can find the time constant τ_k, which determines the voltage decay during this process. Since the duration is defined on the interval from the beginning to half-height, the resulting voltage must fall to half

$$\exp\left(\frac{-t_{\text{i}}}{\tau_k}\right)=0{,}5. \tag{45}$$

Expressing τ_k from (45) we get

$$\tau_k=-\frac{t_{\text{i}}}{\ln(0{,}5)}=\frac{t_{\text{i}}}{0{,}69}. \tag{46}$$

Therefore, the impact capacitance C_k is found as

$$C_k\approx\frac{t_{\text{i}}}{0{,}69\dfrac{R'_0 R_{\min}}{R'_0+R_{\min}}}. \tag{47}$$

Having the value of the impact capacitance, we can find the value of the stage capacitance C_0:

$$C_0=nC_k. \tag{48}$$

After the discharge process is complete, the generator transitions to the capacitor charging phase [18].

B. Charging Circuit Analysis

During charging, the capacitances of all stages are considered discharged and connected in parallel. The capacitors charge unevenly due to the increase in charging resistance as the stage number increases [8], [18].

Since the voltage delay at each stage is approximately the same, we can use the average voltage of all stages, the change of which can be approximately characterized by a first-order inertial circuit.

The increase in r_0 leads to a decrease in the voltage drop between capacitive stages and to a greater approximation of all transient characteristics to an exponential graph.

The approximation of the dynamic parameters of the charging circuit of a multi-stage generator for the average voltage $\bar{u}_3$ to the dynamic parameters of a first-order inertial circuit makes it possible to introduce an equivalent charging circuit (Fig. 5) for a single-stage generator with the following parameters:

$$\tau_{\text{e}}=R_{\text{e}}C_{\text{e}}, \tag{49}$$

$$R_{\text{e}}\approx r_0+R_0\left(\frac{n}{3}-1\right), \tag{50}$$

$$C_{\text{e}}=nC_0. \tag{51}$$

This scheme shows the equivalent charging capacitance C_e, which is charged from a constant voltage source U_{in} through an equivalent charging resistance R_e.

Using the equivalent circuit allows analyzing a multi-stage generator using formulas for a single-stage one. Therefore, when charging the circuit with constant voltage, the voltage on the stage capacitance, which in calculations is taken as the average voltage on all stage capacitors, is found as:

$$\bar{u}_0(t)=k_{\text{в}}U_{in}\left[1-\exp\left(\frac{-t}{\tau_{\text{e}}}\right)\right]. \tag{52}$$

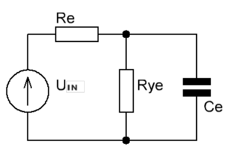

Fig. 5 Equivalent charging circuit diagram

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By substituting the charging time t_{ch} into (52), we find the equivalent charging resistance:

$$R_e = -\frac{t_3}{C_e \ln\left(1-\frac{U_0}{U_{in}}\right)}. \tag{53}$$

By comparing (50) and (53), we obtain the formula for the charging resistance r_0:

$$r_0 = -\frac{t_3}{C_e \ln\left(1-\frac{U_0}{U_{\text{BX}}}\right)} - R_0\left(\frac{n}{3}-1\right). \tag{54}$$

The charging time t_{ch} corresponds to the interval from the beginning of the voltage rise on the capacitances during charging to the triggering of spark gaps. This parameter directly sets the frequency of the output pulses [18].

V. Results

The model allows determining the resulting parameters such as the output voltage, the voltage on the generator stages, the voltage of corona occurrence and breakdown of the electrode system, the values of capacitances, resistances, and the number of generator stages, which largely depend on the parameters of the electrode system (radii and length of electrodes), the environment (pressure, temperature) and the specified initial parameters of the generator, which need to be taken into account when calculating the circuit (input and output voltage, charging time and duration of the output pulse, etc.).

Conclusions

Based on the analysis of literature sources, the physics of corona discharge and the operation of the Marx generator were studied. The obtained information was applied to build a model of the Marx generator for generating corona discharge in air, which was obtained by modifying an existing model with an active load.

The developed model does not take into account parasitic capacitance (between the system and ground) and the inductance of the discharge circuit. Therefore, when practically implementing this system, it is worth reducing factors of probable increase in the values of these parameters, for example, by additionally insulating the generator and using the shortest possible connection to the electrode system.

The data, which are the results of modeling, can be applied to build corona discharge generation systems. For example, in the design of electrostatic precipitators, gas converters, gas activators, ultraviolet radiation sources, etc.

Considering the relevance of research aimed at finding new applications for corona discharge, the work done can be considered useful for science, as the resulting model makes it possible to calculate and implement a corona discharge generation system with a simple design.

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Модель генератора Маркса для генерації коронного розряду у повітрі

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Анотація—У статті розглянуто роботу генератора Маркса з навантаженням у вигляді від'ємного коронного розряду в повітрі за атмосферного тиску та побудовано його електричну модель. Досліджено вплив вольт-амперної характеристики коронного розряду на вихідну напругу генератора та вплив процесів деіонізації на параметри генератора Маркса.

Було обрано циліндричну електродну систему, що складається з трубки (анод), в середині якої вздовж осі натягнуто тонкий дріт (катод), навколо поверхні якого формується корона. Схема генератора Маркса, що моделювався, була обрана класична, яка складається з конденсаторів, резисторів і газових проміжків. Вона має ряд переваг перед іншими існуючими джерелами високої напруги. Це можливість генерувати високі напруги до 10 МВ і має високу електрична міцність, оскільки в схемі відсутні компоненти, які можуть легко вийти з ладу через пробій. Крім того, схема дуже проста і повторювана.

Для того, щоб виконати розрахунки системи, необхідно задати значення вхідних параметрів моделі. Серед них: геометричні розміри електродної системи (радіус внутрішнього і зовнішнього електродів та довжина циліндра), вхідна і вихідна напруга генератора, температура і тиск середовища. Результатом моделювання є вихідні параметри, а саме: кількість каскадів генератора, напруга одного каскаду генератора, напруга утворення корони та іскрового або дугового пробою електродної системи, значення конденсаторів та опорів генератора тощо. Крім того, модель дозволяє будувати графічні залежності процесів заряду і розряду системи.

Модель не враховує паразитні параметри, такі як ємність між пристроєм і землею та індуктивність розрядного контуру, які присутні в реальній схемі. Тому, щоб зменшити їх вплив, рекомендується внести деякі особливості в конструкцію. Для зменшення паразитної ємності контур генератора Маркса слід ізолювати від навколишнього середовища, помістивши його в товстостінний пластиковий корпус і, якщо розрядники розміщені в захисній колбі, залити всі компоненти трансформаторним маслом або епоксидною смолою. Для зменшення впливу паразитної індуктивності необхідно підключати електродну систему до генератора якомога коротшими проводами.

Результати розрахунків можуть бути використані для проектування пристроїв, робота яких базується на використанні коронного розряду. Це можуть бути пристрої для очищення газів (електрофільтри), переробки газу, генерації озону та ультрафіолету тощо.

Ключові слова — коронний розряд; генератор Маркса; висока напруга; іонізація.