THE INFLUENCE OF IONIZING α AND γ RADIATION ON THE STATISTICS OF THE RANDOM VARIABLE ELECTRICAL BREAKDOWN OF ELECTRONEGATIVE GASES

by

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Scientific paper
https://doi.org/10.2298/NTRP2404261B

The paper examined the stochasticity of the random variable electrical breakdown of electronegative gases (SF_6 gas) in homogeneous, inhomogeneous, and highly inhomogeneous electric fields. These tests indirectly allowed for the assessment of the homogeneity of the insulating properties of the electronegative gas within the inter-electrode space. Tests were conducted at pressures ranging from 10^{-3} bar to 5 bar and an inter-electrode distance from 0.1 mm to 5 mm. During the test, it was established that the insulation with electronegative gas is inhomogeneous in the inter-electrode space. This inhomogeneity is explained by the high affinity of SF_6 gas for forming negative ions. To prevent the occurrence of inhomogeneity in the insulation with electronegative gas, α and γ radiation were applied. The increase in the number of free, potentially initial electrons contributed to homogenization of the insulation with the electronegative gas.

Key words: homogeneity of insulation, electronegative gas, stochastic approach, ionizing radiation

INTRODUCTION

Electrical breakdown of gases occurs due to the collision of electrons with gas molecules. These collisions create positive ions and free electrons, which can result in the establishment of a maintenance mechanism. The established, self-sustaining discharge is controlled by collisional processes involving charged particles and their transport properties. The development of the breakdown process is highly dependent on the relative efficiency of the mechanisms of the creation and loss of free electrons [1-3].

Electron ionization is the basic elementary process of all electrical phenomena in gases. In the case of electronegative gases (SF_6 gas), the ionization process is associated with the dissipation of molecules. This results in the creation of new free electrons, as well as negative and positive ions. The presence of negative ions complicates the mathematical modeling of electric discharge in SF_6 gas. For this reason, the first primary Townsend ionization coefficient α is replaced by the net ionization coefficient α-η, where η is the attachment coefficient (the number of electrons attached to electronegative atoms or molecules per unit path in the direction of the electric field) [4, 5]. The secondary townsend coefficient γ plays a crucial role in the self-maintenance of the electric discharge. This coefficient is determined by the number of secondary electrons generated per primary avalanche [6].

Since the ionization process depends on the presence of free electrons, which are scarce in SF_6 gas, the aim of this work is to establish the influence of ionizing radiation on the statistical behavior of the random variable electric breakdown in SF_6 gas.

ELECTRICAL BREAKDOWN OF ELECTRONEGATIVE GASES

The self-sustainability of electric discharge in gases is achieved by positive feedback which is determined by the value and nature of the secondary Townsend coefficient. If secondary effects on the electrodes (ion burst, photoemission, metastable burst) are dominant, the breakdown occurs via the townsend mechanism. Conversely, if secondary effects in the gas (ionization by positive ions, photoionization, and ionization by metastable states) dominate, the breakdown

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follows via the streamer mechanism [6, 7]. There are analytical expressions that enable the calculation of the minimum value of the electrical breakdown by the Townsend and streamer mechanism. Such a calculation requires knowledge of the dependence of the primary Townsend coefficients on the ratio of electric field values to gas pressure. It is also necessary to know the value of the electric field at each point of the inter-electrode space. The minimum values of the electrical breakdown obtained by such calculations correspond to the value of the electrical dc breakdown [8, 9].

The electrical breakdown of the SF_6 gas occurs when a plasma cloud composed of electrons and negative ions moves toward the anode. This plasma cloud is followed by successive clouds initiated by secondary Townsend processes. As this series of plasma clouds progresses through the inter-electrode space, a breakdown occurs [10]. Figure 1 illustrates the time-dependent increase in voltage that enables the breakthrough. Here U_{DC} is the minimum value of the breakdown voltage, t_S – the static time (the time that elapses from the moment when the rising voltage reaches the moment when the first initial electron appears), t_L – the time of avalanche formation (the time that elapses from the appearance of the initial electron of the first avalanche to the main discharge), and t_F – the formation time (the time that elapses from the bridging of the inter-electrode distance by the conducting channel to its thermal ionization).

STOCHASTICITY OF A RANDOM VARIABLE ELECTRICAL BREAKDOWN OF AN ELECTRONEGATIVE GAS

Based on fig. 1 it is clear that the source of the stochasticity of the gas breakdown value lies in the stochasticity of the statistical time t_S. This is particularly pronounced in SF_6 gas, where the number of free electrons is minimal due to the affinity of gas molecules for forming negative ions. Therefore, for the initial electron (the electron that initiates the avalanche process) to be generated, a free electron must be positioned to trigger the ionization avalanche. This means that the free electron should be located in a part of the inter-electrode space where it can gain energy from the electric field that is higher than the bond energy of the electron in the gas molecule over one mean free path length. That part of the inter-electrode space is called the critical volume [11, 12]. Based on this, it can be concluded that the stochastic nature of the random variable electrical breakdown of gas, particularly in SF_6 gas, depends on the degree of inhomogeneity of the electric field in the inter-electrode space. The avalanche construction time t_L and formation time t_F can conditionally be considered deterministic quantities.

Since the statistical time depends on the number of free electrons and the size of the critical volume, the influence of these two parameters on the stochasticity of the random variable electrical breakdown was examined. The test was conducted using an experimental procedure, and experimentally obtained results were analyzed using statistical methods.

In addition to standard statistical methods, the volt-secondary characteristic (impulse characteristic) is useful for examining the stochasticity of the electrical breakdown of gases [13-15]. The volt-secondary characteristic can be expressed analytically based on the assumption that the ionized gas in the inter-electrode space moves at a speed proportional to the value of the electric field

$$v(x,t) = k[E(x,t) - E_{DC}] \tag{1}$$

where, k is a constant that depends on the mechanism of electrical discharge and voltage polarity and E_{DC} – the minimum value of the breakdown voltage.

On the condition that the space charge in the inter-electrode space is neglected, it can be written

$$E(x,t) = u(t)g(x) \tag{2}$$

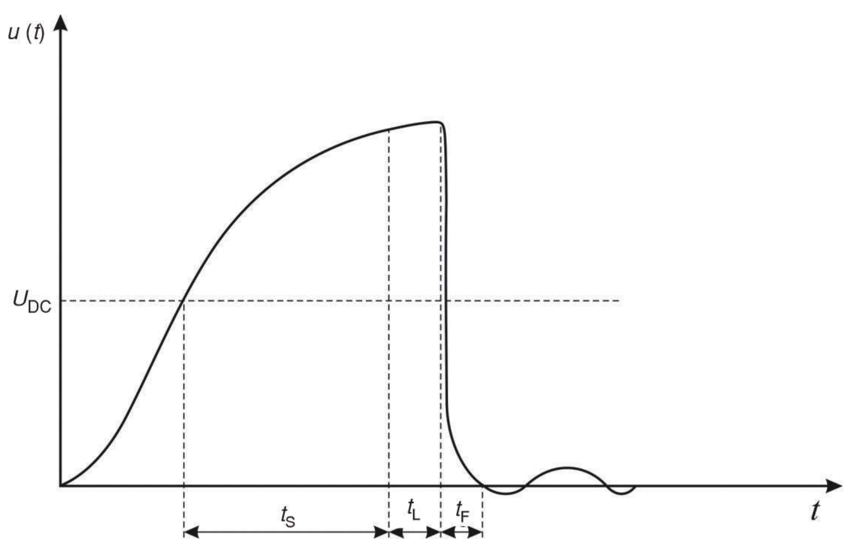

Figure 1. The time course of the rising voltage *u*(*t*) that caused the breakdown

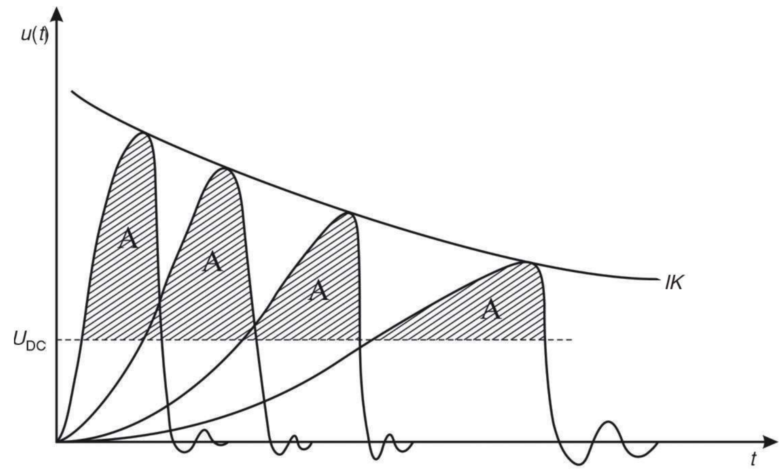

Figure 2. Illustration of the law of surface constancy in the voltage-time plane

where $u(t)$ is the time dependence of the applied voltage and $g(x)$ – the spatial dependence of the electric field (depending on the electrode configuration. The moment when the Townsend electric discharge mechanism changes to the streamer mechanism [16, 17], we get

$$\frac{1}{k}\int_0^{x_k}\frac{dx}{g(x)}=\int_{t_1}^{t_1+t_k}(u(t)-U_{DC})\mathrm{d}t \tag{3}$$

where x_k is the point in space where the Townsend mechanism turns into the streamer mechanism and $t_k + t_1$ – the corresponding moment, with t_1 indicating the time when the voltage $u(t)$ reaches the minimum value of the breakdown voltage U_{DC}.

The right side of the expression represents the area under the time dependence of the applied voltage and the minimum value of the breakdown voltage, fig. 2. The left side is the spatial integral that has a constant value. Since the left side of the expression does not depend on the applied voltage but only on the insulation parameters, it can be concluded that the value of the area represented by the right side of the expression is constant for a given gas-insulated electrode configuration at constant pressure

$$\int_{t_1}^{t_1+t_k}(u(t)-U_{DC})\,\mathrm{d}t = A = \text{constant} \tag{4}$$

The expression makes it possible to determine the volt-secondary characteristic of a gas-insulated electrode configuration based on a statistical sample of the random variable electrical breakdown, obtained through a voltage with a precisely determined time dependence.

EXPERIMENTAL SET-UP

The experimental results were processed through the following steps: (1) formation of statistical samples based on 100 consecutive measurements of the random variable, (2) testing all statistical samples for belonging to a unique statistical distribution, (3) using graphical methods, $\chi 2$ test, and Kolmogorov test to examine the adherence of the statistical sample to normal, Weibull double-exponential, and logarithmic distribution, (4) determining the statistical distribution with the smallest statistical uncertainty for the examined statistical sample by applying the methods of central moments and maximum reliability, and (5) determining impulse characteristics for 0.1 % and 99.9 % quantile probability based on the adopted statistical distribution.

In the previous chapter, it was stated that the stochastic nature of the random variable electrical breakdown is determined by the stochasticity of the statistical time. This stochasticity is influenced by the appearance of a free electron that meets the conditions to become an initial electron, which is determined by the ratio of the voltage rise time to the characteristic time of the electronic processes involved in the elementary processes of electric discharge in gases. Moreover, the stochastic nature of electrical breakdown as a random variable depends on the concentration of free electrons in the gas, and the ratio of the critical volume to the total volume of the inter-electrode space. For this reason, the parameters of the experimental procedure included the voltage rise time, ionizing radiation of the inter-electrode space, and the shape of the electric field.

The voltage rise time was altered by changing the parameters of the output circuit of the Max's type pulse generator. A simplified scheme of the output circuit for forming pulses is shown in fig. 3 and an integral high voltage source in fig. 4.

Figure 5 shows the chamber used for the experiments. The chamber was flexible, allowing for adjustments to the gas pressure (electronegative SF_6 gas), the electrode sheet, and the inter-electrode distance. Also, it was possible to change the sheet and the direction of the ionizing radiation. The changes in gas pressure, type of electrodes and inter-electrode distance were performed according to the standard procedure [18, 19]. The manipulation with ionizing radiation was based on the ionizing radiation carrier, as depicted in fig. 5(b) [20]. During this

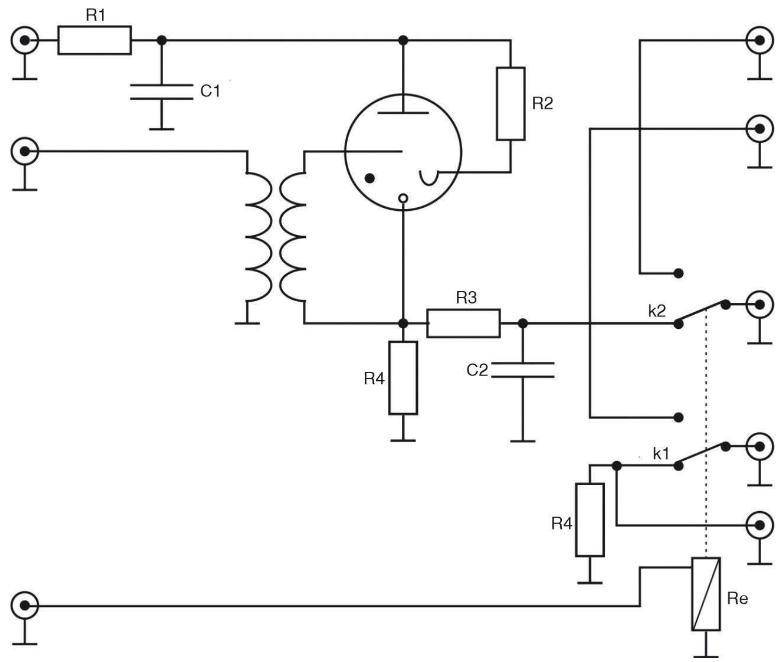

Figure 3. Simplified scheme of the output circuit for forming pulses

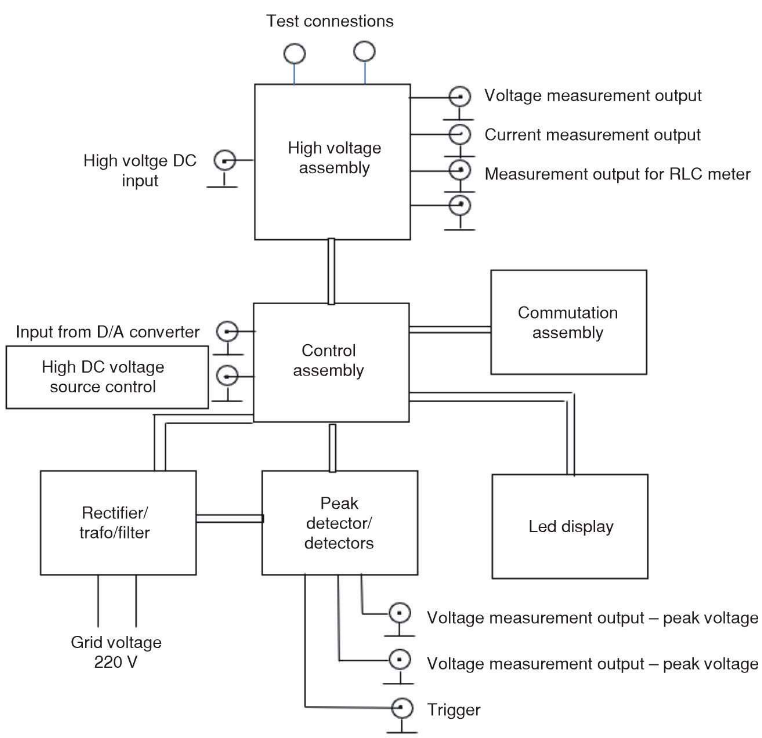

Figure 4. Integral scheme of the high voltage source

process, sources of α radiation (^{241}Am; 2012, 1.11 GBq) and γ radiation (^{60}Co; 2015. 37.8 GBq) were used. The chamber shown in fig. 5 was used to determine the geometric distance from the source to the electrode. This measurement was carried out using the setup shown in fig. 5(d), where a Ge detector, cooled by liquid nitrogen, was placed under the same He pressure instead of the cathode.

The shape of the electric field was altered by changing the electrodes and the inter-electrode distance. By combining the electrodes shown in figs. 6(a) and 6(b), it is possible to shift from a homogeneous to an inhomogeneous and a pronounced inhomogeneous electric field, as depicted in figs. 6(c) and 6(d). The inter-electrode distances were adjusted from 0.1 mm to 5 mm. The SF_6 gas pressure varied from 10^{-3} bar to 5 bar. During the adjustments of the inter-electrode distance and the gas pressure, the type B measurement uncertainty remained below 1 %.

The experimental procedure was conducted under maximally controlled laboratory conditions. Modern, certified measuring equipment with known measure-

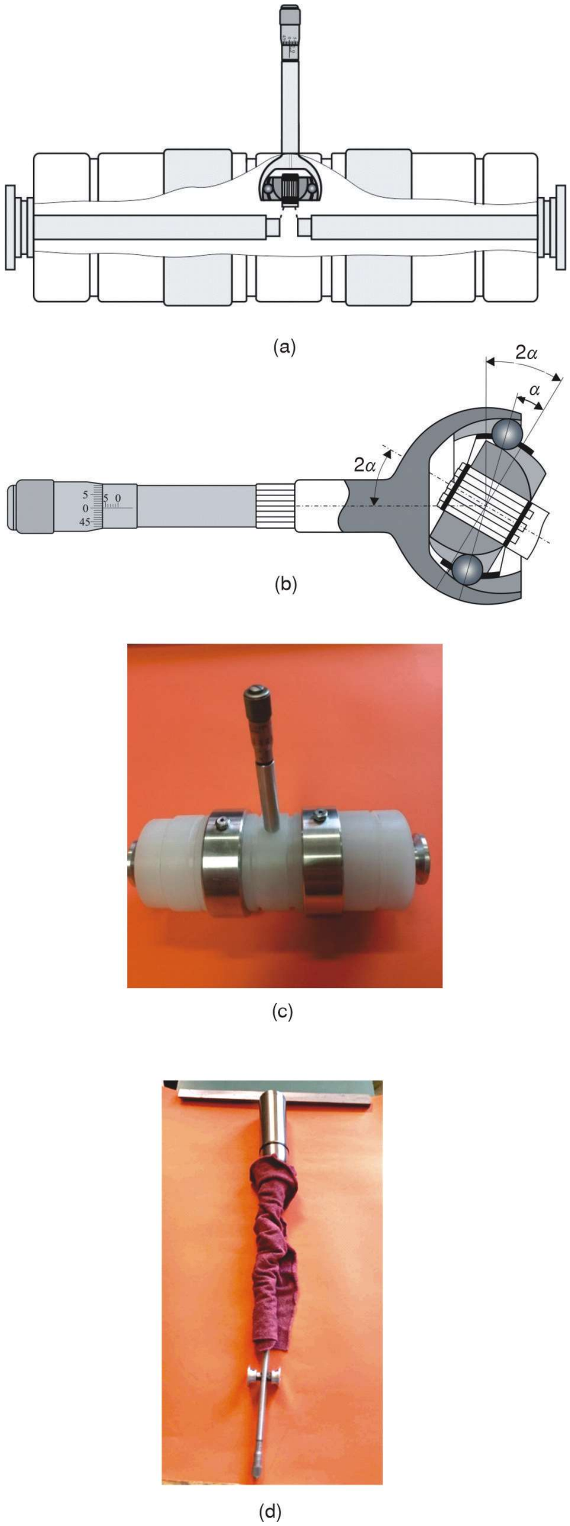

Figure 5. Chamber and carrier of ionizing radiation; (a) – scheme of the chamber, (b) – scheme of the carrier of ionizing radiation, (c) – photograph of the chamber, and (d) – chamber for determining the trajectory and neutron spectrum of the AmBe source in He (together with the Ge detector cooling system)

ment uncertainty was used. All external influences on the measurement results were eliminated during the measurements [21, 22]. The combined measurement uncertainty of the experimental procedure was less than 5 %.

RESULTS

Figure 7 illustrates the dependence of the ratio of the statistical deviation to the mean value of the statistical sample of the random variable electrical breakdown on the voltage rise rate. The parameters of the experiment included the shape of the electric field and the pressure of the SF_6 gas.

Based on the results shown in fig. 7, it can be concluded that at low rates of voltage rise, the random variable electrical breakdown exhibits little (or no) dispersion for a homogeneous electric field. For an inhomogeneous electric field, there is a statistical deviation in the random variable electrical breakdown. For all investigated electric fields, both the statistical dispersion and the mean value of the random variable for electrical breakdown increase as the rate of voltage rise increases. In a homogeneous field, this relationship takes the form of a parabola, whereas in inhomogeneous and highly inhomogeneous field, the observed dependence is linear. All observed dependencies are more pronounced at lower pressures and lower overpressure values compared to higher overpressure values.

The results shown in fig. 7 can be explained by the ratio of the rate of voltage change to the rate of elementary processes of electric discharge in gases. Specifically, for low voltage rise rates, all elementary electric discharge processes in gases occur at a constant voltage value. Therefore, the statistical time shown in fig. 7, is negligible. This means that breakdown occurs at the minimum value of the random magnitude of the breakdown voltage. This is true for a homogeneous field. However, this is not the case for an inhomogeneous field. In an inhomogeneous electric field (especially a highly inhomogeneous one), the critical volume is small, so the appearance of a free electron in critical volumes is a stochastic quantity. This phenomenon is more pronounced at low pressure of SF_6 gas, due to the fact that low pressure implies low density and, consequently, a low concentration of free electrons.

Based on the results shown in fig. 7, it was decided to examine the statistical nature of the observed stochasticity of the random variable electrical breakdown at a voltage rise rate of 10^{11} V/s (100 kV/μs). Statistical samples of the random variable electrical breakdown obtained by voltages with a rate of increase of 100 kV/μs were examined for belonging to the normal distribution, the Weibull three-parameter distribution, the double-exponential distribution, and the logarithmic distribution. The obtained results with the smallest statistical uncertainty were adopted as representative distributions for the observed random variable.

Table 1 shows the obtained statistical distributions with the corresponding minimum value of the statistical uncertainty for quantities, typically represented by the three-parameter Weibull distribution. Statistical uncertainty was determined using the modi-

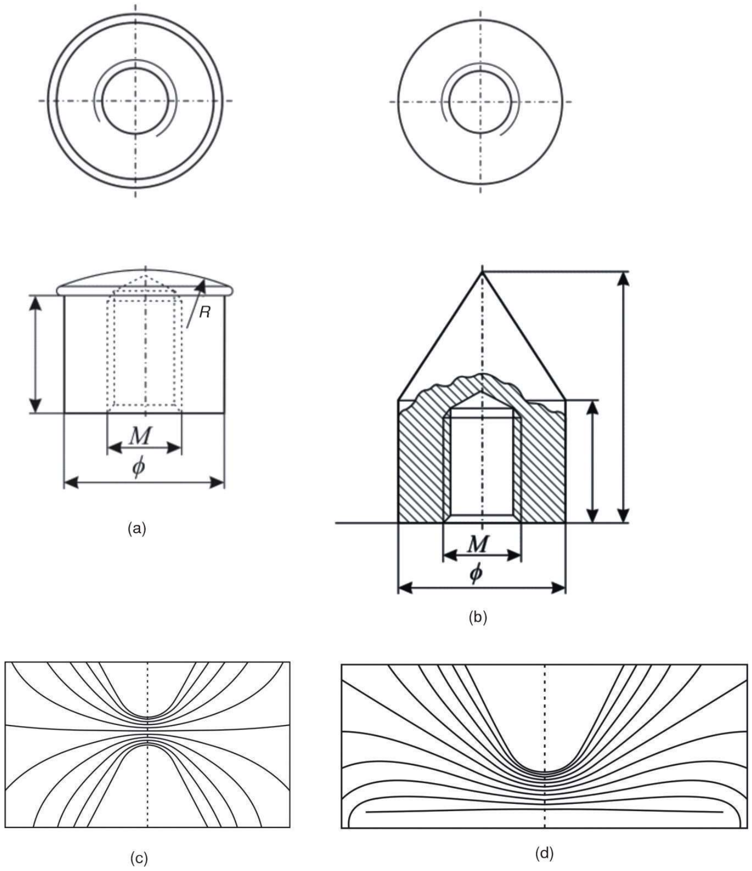

Figure 6. Drawings of electrodes used to form homogeneous (electrode a/electrode (a), inhomogeneous (electrode a/electrode (b), and strongly inhomogeneous electric field (electrode b/electrode (c); a – Electrode of the Rogowski shape, b – Spike-shaped electrode; c – Highly inhomogeneous field, and d – inhomogeneous field

fied Kolmogorov test. Calculations were based on the level of significance [21].

Confirmation of this interpretation is the statistical random variables electrical breakdown shown in figs. 8 and 9 and tab. 2.

Comparing the obtained results with similar findings for electropositive and noble gases [22-24], reveals that the insulating medium in SF_6 gas is not homogeneous. This conclusion is drawn from the observation that in SF_6 gas, the random variable electrical breakdown behaves according to the three-parameter Weibull distribution. Since inhomogeneity is not a desirable feature of insulation, applying ionizing radiation in the inter-electrode space has been shown to achieve homogeneity in insulation with an SF_6 gas. This effect is due to a significant increase in the number of free electrons in the inter-electrode space and the elimination of the ion absorption in electronegative gases. Such an effect would be beneficial for power plants insulated with SF_6 gas.

The findings, shown in tabs. 1 and 2 and fig. 8 best confirm the impulse characteristics determined based on expression 4 and illustrated in fig. 9.

CONCLUSION

Considering the stochastic nature of the random variable electrical breakdown of an SF_6 gas within homogeneous, inhomogeneous, and strongly inhomogeneous fields, it was revealed that the insulating gas behaves as inhomogeneous insulation. Such behavior of gas insulation violates the basic property of homogeneity. The inhomogeneity in the insulation characteristics of SF_6 gas is attributed to the small number of free electrons and the abundance of negative ions. This phenomenon results in a broader range of impulse characteristics between 0.1 % and 99.9 % probability quantiles, which is highly unfavorable for the application of SF_6 gas insulation. However, this negative effect can be mitigated by using α and γ radiation.

AUTHORS' CONTRIBUTIONS

Č. Belić, U. D. Kovačević and A. R. Jusić conceived the idea for the experiment. V. S. Malaš and G. B. Poparić conducted the experiment. All authors analyzed the results and contributed to the preparation of the final version of the manuscript. This research was supervised and guided by Č. Belić and U. D. Kovačević.

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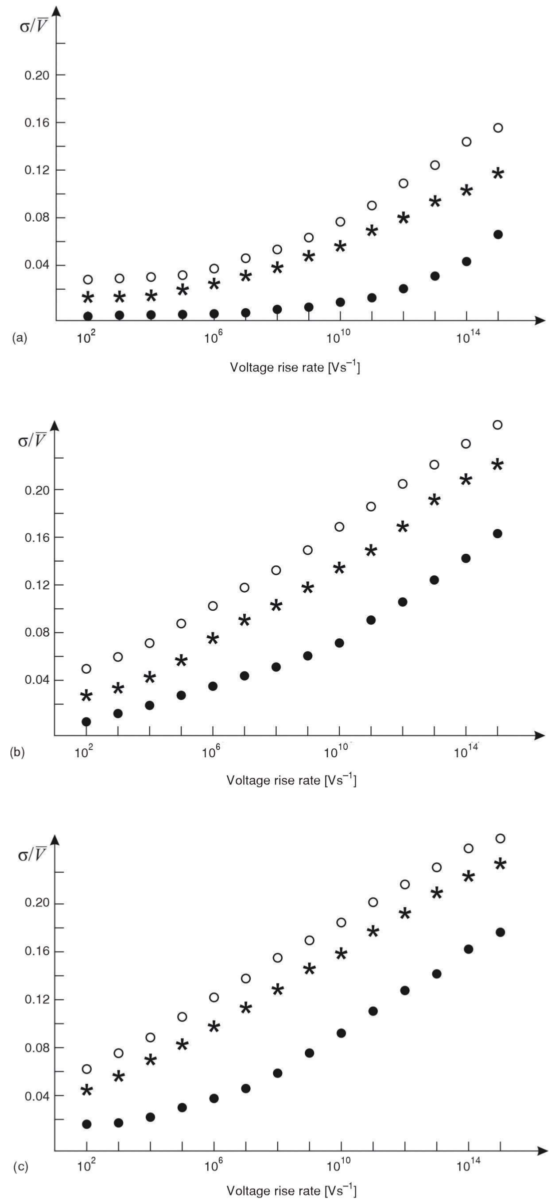

Figure 7. Dependence of the ratio of the statistical deviation and the mean value of the statistical sample of the random variable electrical breakdown on the voltage rise rate for; (a) – homogeneous field, (b) – inhomogeneous field, and (c) – highly inhomogeneous field (• 10^{-3} bar, * 1 bar, °10^{4} bar) (1 bar = 100 kPa)

Table 1. Weibull three-parameter distributions of the random variable electrical breakdown and the corresponding minimum statistical uncertainty the rate of rise of the applied voltage 100 kV(μs)$^{-1}$

Electric field	Pressure [bar]	Statistical uncertainty [%]
Homogeneous	10^{-3}	6.22
Homogeneous	1	6.12
Homogeneous	4	5.12
Inhomogeneous	10^{-3}	7.21
Inhomogeneous	1	6.84
Inhomogeneous	4	6.40
Extremely inhomogeneous	10^{-3}	5.28
Extremely inhomogeneous	1	5.10
Extremely inhomogeneous	4	4.88

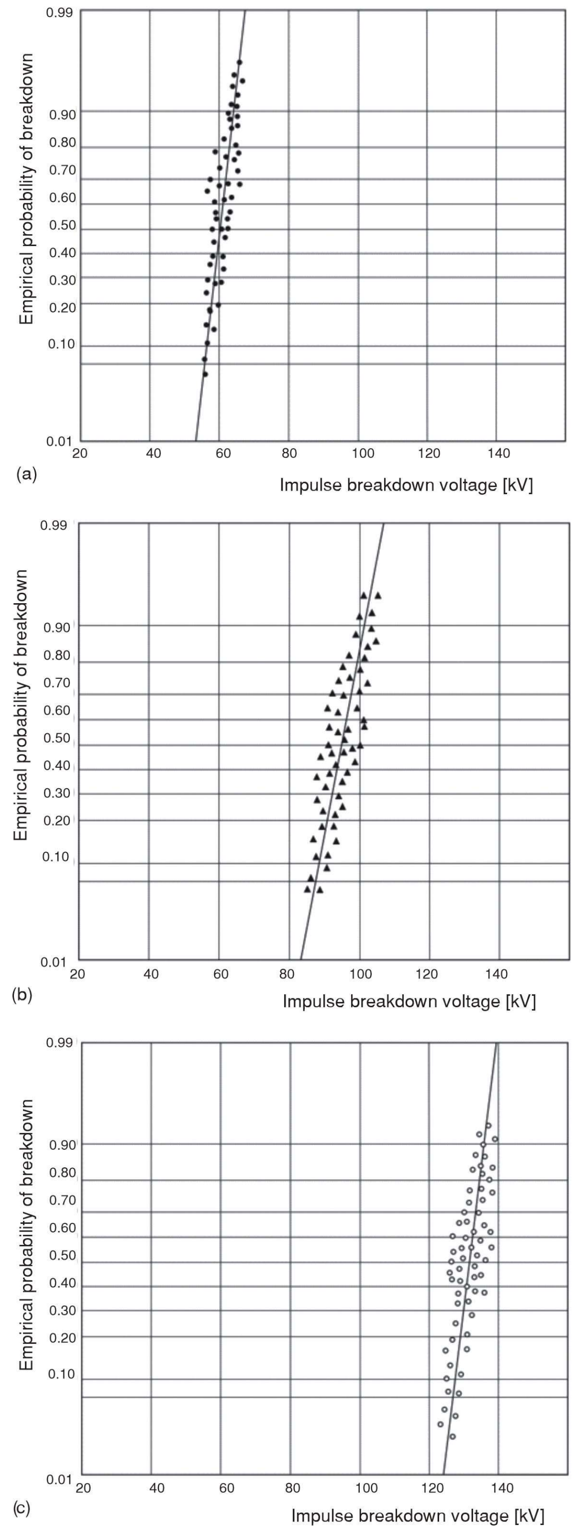

Figure 8. Electrical breakdown of random variables following normal distribution (a) – homogeneous electric field, pressure 10^{-3} bar, (b) – inhomogeneous electric field, pressure 1 bar, and (c) – highly inhomogeneous electric field, pressure 10^{4} bar, inter-electrode space in the field of α radiation, breakdown voltage rise rate 100 kV (μs)$^{-1}$

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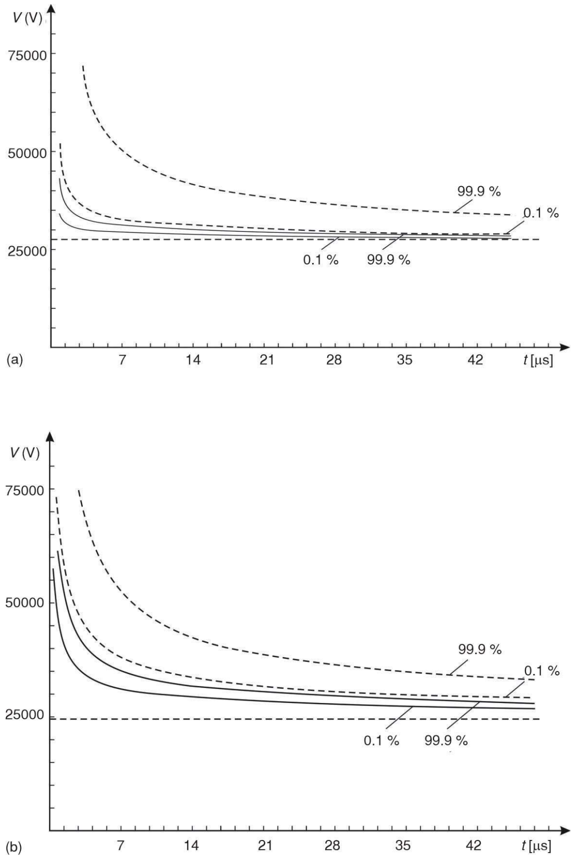

Figure 9. Impulse characteristics obtained by applying eq. (4) and measuring electrical breakdown in 100 random variables using an impulse voltage of 100 kV (μs)$^{-1}$ (a – homogeneous field, pressure 3.5 bar, inter-electrode distance 1 mm, b – homogeneous field, inter-electrode distance 1 mm, pressure 4 bar, a – without a source of ionizing radiation, with a source of α ionizing radiation, b – without a source of ionizing discharge,

Table 2. Statistical normal distributions of the random variable electrical breakdown and the corresponding minimum statistical uncertainty in the field of α and γ radiation, the rate of rise of the breakdown voltage 100 kV (μs)$^{-1}$, with the application of an α source and with the application of a γ source

Electric field	Pressure [bar]	Statistical uncertainty α field [%]	Statistical uncertainty γ field [%]
Homogeneous	10^{-3}	4.21	4.29
Homogeneous	1	3.95	4.02
Homogeneous	4	3.86	4.00
Inhomogeneous	10^{-3}	4.08	4.21
Inhomogeneous	1	3.88	4.08
Inhomogeneous	4	3.64	4.00
Extremely inhomogeneous	10^{-3}	4.01	4.95
Extremely inhomogeneous	1	3.75	4.90
Extremely inhomogeneous	4	3.60	4.89
Homogeneous	10^{-3}	3.94	4.12
Homogeneous	1	3.82	3.81
Homogeneous	4	3.54	3.72
Inhomogeneous	10^{-3}	3.88	3.41
Inhomogeneous	1	3.60	3.31
Inhomogeneous	4	3.21	3.12
Extremely inhomogeneous	10^{-3}	3.87	3.45
Extremely inhomogeneous	1	3.35	3.52
Extremely inhomogeneous	4	3.20	3.61

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Received on Novembar 19, 2024
Accepted on December 31, 2024

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УТИЦАЈ ЈОНИЗУЈУЋЕГ α И γ ЗРАЧЕЊА НА СТАТИСТИКУ СЛУЧАЈНО ПРОМЕНЉИВЕ ЕЛЕКТРИЧНОГ ПРОБОЈА ЕЛЕКТРОНЕГАТИВНИХ ГАСОВА

У раду је испитивана стохастичност случајне променљиве пробојног напона електронегативних гасова (SF_6 гас) у хомогеном, нехомогеном и изразито нехомогеном електричном пољу. То испитивање је посредно омогућило да се испита хомогеност изолационих особина електронегативног гаса у међуелектродном простору. Испитивања су вршена при притисцима од 10^{-3} бара до 5 бара и међуелектродном растојању од 0,1 mm до 5 mm. Током испитивања је установљено да је изолација електронегативним гасом нехомогена у међуелектродном простору. То је објашњено великим афинитетом за стварањем негативних јона SF_6 гаса. Да би се избегла појава нехомогености изолације електронегативним гасом, примењено је α и γ зрачење. Повећање броја слободних, потенцијално иницијалних, електрона је хомогенизовало изолацију електронегативним гасом.

Кључне речи: хомогеност изолације, електронегативан гас, стохастички приступ, јонизујуће зрачење