Preparation of high-voltage vacuum gap surfaces by the glowing discharge

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Abstract. The paper presents a method for processing parts and components of high-voltage vacuum gap gas-discharge device (GDD), operating on the basis of the Penning discharge, at the stage of their preparation for manufacturing. This method includes the irradiation of the part surfaces by the flow of inert gas ions obtained from gas discharge plasma. The purpose of treatment is to increase the electrical strength and GDD stability. The results of research are presented.

1. Introduction
Currently, when a certain number of GDD are operating, there are failures associated with a decrease of the high-voltage vacuum gap dielectric strength. As shown in [1], one of the reasons is the appearance of an emission electron current in it, which is determined by mechanical defects (microtip, cracks, etc.) and the presence of oxide films and adsorbed molecular gases on the negative electrode surfaces.

The result of the emission current action on vacuum gap positive electrode is a secondary electron current and X-ray radiation occurs. In turn, the X-ray radiation and electron fluxes effect on the GDD vacuum gap insulator leads to the formation of bound charges in its near-surface layer, which are the main cause of surface damage and breakdowns of the GDD. It leads to loss of tightness of the device [2].

The effect of residual and working gases adsorbed by the GDD internal surfaces is also manifested in the form of sorption and desorption processes under the influence of corpuscular fluxes and thermal loads [3]. In this case, during the operation of the device, gas exchange between the working surfaces of the parts is observed, which contributes to the appearance of pressure surges when the GDD is turned on after long interruptions.

The literature analysis shows that today, in the preparation process of GDD to remove oxides and sorbed gases, along with traditional methods of cleaning parts and assemblies in preparation for assembly (chemical etching, high-temperature annealing), additional methods are applied. These methods are based on the GDD structural elements treatment in plasma glow discharge in inert gases [4, 5]. However, the sequence and processing modes described in the literature are largely determined by the GDD parts geometrical and physical features and are individual for a particular type of instrument. Thus, in particular, it is indicated that the current density during surface treatment may be in the range from 0.1 to 10 mA·cm\(^{-2}\), the discharge voltage from hundreds of volts to tens of kilovolts and the pressure of inert gas from 0.01 to 100 Pa [4–9]. Therefore, in the present work, in order to...
increase the electrical strength and stability of GDD, containing the Penning ion source and accelerating system, the ion-plasma treatment (IPT) method of the vacuum gap electrodes and high-voltage insulator at the stage of their preparation for product assembly was developed.

2. The ion-plasma treatment installation description

Figure 1 shows the appearance of the installation, which is held IPT of the vacuum high-voltage gap insulator and electrodes.

![Figure 1. The IPT installation appearance: 1 – vacuum chamber, 2 – docked vacuum volume for IPO tool placement, 3 – gas supply valves, 4 – personal computer (PC).](image1)

A docked with the vacuum chamber sealed volume is a metal-glass insulator with a diameter of 110 mm. Inside of the sealed volume there is a threaded rod for accommodating the IPT electrodes equipment, and it is an integral part of the vacuum chamber (figure 2).

![Figure 2. A docked vacuum volume with the IPT electrodes equipment (explanations are presented in the text).](image2)

The electrodes IPT equipment consists of collet 3 и 7, tight fixing insulator 5, intended for their galvanic isolation. Inside each collet mounted bushings. A flat anode 4 is placed in the bushing of the collet 3, and on the bushing of the collet 7 there is a GDD processed electrode 6. The assembled equipment is mounted inside the vacuum volume 2 by threaded connection of the collet 7 with the flange 8. In this form, the vacuum volume is docked to the vacuum chamber 1 through standard ISO flanges. The collet 3, and accordingly, the anode 4 is grounded, and the collet 7, and accordingly, the electrode 6 is at a negative bias potential relative to the anode 4. In the anode 4 system, the electrode 6 (cathode) ignites the discharge plasma and the IPT electrode 6 is processed.

Figure 3 shows the placement inside the external metal-glass insulator equipment for the IPT of high-voltage vacuum gap insulator. It is a glass cylinder with metal cuffs sealed on both sides.
In this construction, the cuff of the insulator 3, directed to the pumping system, is grounded, and the negative polarity voltage from the high-voltage power supply is applied to the other.

The management of the IPT process and its control is performed using a PC with software written in the LabVIEW environment. In this case, in automatic mode, such parameters as discharge current and voltage, gas pressure and process duration are recorded.

High-purity argon (99.998%) is used as the working gas. Adjustment of pressure in the system is ensured by a needle valve – leak with the pump gate closed. The gas pressure measurement is carried out using a wide-range vacuum gauge FRG-702.

3. The ion-plasma treatment of high voltage vacuum gap electrodes and insulator

3.1 High-voltage vacuum gap electrodes treatment

3.1.1 Discharge mode depending on argon pressure

With this processing, the processed electrode 6 (figure 2) is supplied with a negative polarity of 1.5 kV from the high-voltage power source Spellman SL 1200 relative to the grounded anode 4. At the same time, to stabilize the gas discharge, the power source operates in the current stabilization mode, which is an adjustable parameter in the IPT process.

It was found that, depending on the argon pressure, there are two discharge modes in the system: either between the anode and the edges of the electrode being processed (figures 4a and 4b), or in its cavity (figure 4c).

From figure 4a it can be seen that the discharge plasma cathode glow is localized on the edges and the electrode outer surface at a distance from the edges of approximately 5 mm. In turn, from figure 4b it can be seen that the plasma column does not penetrate the electrode cavity. So the treatment of internal surfaces in this type of discharge is minimized. Thus, the total surface area around which glow is observed and which is subject to IPT is approximately 3.9 cm², which, with a processing current of 8 mA, makes it possible to achieve an IPT current density of 2.1 mA cm⁻².

Another situation is observed when the discharge predominantly in the cavity of the electrode being processed. From figure 4c it can be seen that in this case there is practically no cathode glow on the external surfaces and electrode edges, and the discharge is localized mainly in the cavity of the electrode being processed. The surface area is already 10 cm², so the current density drops to 0.8 mA cm⁻².

Adjusting the argon pressure in the system allows the processing of these surfaces in turn. For explanation, refer to figure 5.
Figure 4. Photo of the discharge between the edges of the electrode being processed and the anode of the system (front view (a), side view (b)) and of the discharge in the cavity of the electrode being processed (c): 1 – system anode, 2 – processed electrode (cathode).

Figure 5. Discharge voltage variation depending on gas pressure in the system.

At the initial moment the system is pumped out to a pressure of the order of $10^{-6}$ Torr, a voltage of minus 1.5 kV is applied to the electrode being processed. A gradual increase in argon pressure leads at time $t_1$ to ignition of a high-voltage discharge mainly along the surface of insulator 5 shown in figure 2. Then at time $t_2$ a discharge is initiated between the edges of the input aperture of the electrode being processed and the anode and continues to burn there until time point $t_3$. In this case, as the pressure increases, the discharge voltage drops evenly, then it sharply decreases by almost half, and at
time \( t_a \) a discharge is ignited in the cavity of the processed electrode (discharge with a hollow cathode).

### 3.1.2 Stages of electrode processing and experimental results discussion

The testing of the IPT process was included the determination of the optimal time with the existing discharge current of 8 mA. During the experiments, a discharge was initiated first between the edges of the electrode being processed and the anode of the system, and then inside the electrode. When processing both the edges and the inner surface of the electrode, the pressure change in the system and the discharge voltage as a function of time were monitored (figure 6). In each case, at least two measurement cycles were carried out, between each of which pumping of the desorbed gases and the change of the working gas were performed.

![Figure 6. The change of discharge voltage and pressure in the system with the IPT of the GDD vacuum gap electrodes: □ and ■ – I cycle, △ and ▲ – II cycle, ○ and ● – III cycle, opaque figures – pressure, transparent – discharge voltage.](image)

It can be seen from the figure that in each processing cycle there is an increase in the system pressure, apparently due to the removal of contaminants from the surface of the electrode processed by the glow discharge. The discharge voltage drop can be explained by at least two reasons. The first of these is related to the fact that at such pressures and a fixed distance between the anode and cathode (30 mm) the discharge voltage takes on the value in accordance with the left (decreasing) branch of the Paschen curve for argon [10]. The second explanation is based on the fact that when processing an electrode as a result of removing dielectric oxide films from its surfaces, the resistance of the discharge gap decreases, and, as a result, the discharge voltage. It is also seen from the figure that when the pressure in the system reaches 0.1 Torr, the sensor readings change significantly slower than before reaching the specified value, although the discharge voltage continues to fall, which indicates the continuation of gas evolution processes. The slow change in pressure readings is due to the low sensitivity of the FRG-702 vacuum gauge in the studied range.

The analysis of the dependences presented in figure 6 allows us to conclude that at the beginning of the first treatment cycle, there is a rapid gas release with a further gradual slowdown. In cycles II and III, there is a significant slowdown in the growth of pressure and a drop in discharge voltage as compared with cycle I. In each cycle, the dependence of the discharge voltage on time is approximated (the correlation coefficient \( R^2 = 0.98 \)) an exponential function of the form:

\[
U_{\text{dis}}(t) = U_f + U_0 e^{-t/\tau}
\]

where \( U_0 \) – constant (kV), \( U_f \) – voltage at \( t = \tau \) (kV), \( \tau \) – voltage drop constant (s). The parameter \( \tau \) shows in this case the moment of time at which there is a sharp change in the angle of the discharge voltage inclination as a function of time. This means that the rate of gas emission is slowing down, and further continuation of the processing cycle is impractical. In the particular case presented above, the
following expressions are obtained $U_{\text{dis I}}(t) = 0.831 + 0.298 \cdot e^{-t/97}$, $U_{\text{dis II}}(t) = 0.656 + 0.346 \cdot e^{-t/241}$, those the required duration of the IPT electrode at stage I is $\tau_1 = 97$ seconds, at stage II – $\tau_{\text{II}} = 241$ seconds and at stage III – $\tau_{\text{III}} = 236$ seconds. According to the results of at least 10 experiments, it was established that the average duration of each cycle of the electrode processing should be about 2 minutes. The criterion for the cycle termination is the slowdown of the discharge voltage drop during processing, which is observed in real time on the PC screen.

3.2 High-voltage vacuum gap insulator treatment
At this stage, the IPT of insulator 3, shown in figure 3, was tested. The peculiarity of this electrode system is that it is a gap, when a discharge is ignited in which the power source stabilizes in voltage, i.e. maintains its value, forcibly set on the device by adjusting the current depending on the discharge gap resistance. It is not possible to perform current stabilization in such a system, since any set voltage value is eventually reset by the device to a value of 520 V.

At smaller values the discharge does not ignite and at large values it begins to burn along the surface of an insulator with a diameter of 110 mm. Figure 7 shows a photo of the discharge in the IPT of the GDD vacuum high-voltage gap insulator.

![Figure 7. Photo of the discharge in the IPT of the GDD vacuum high-voltage gap: 1 – grounded insulator cuff, 2 – high-voltage insulator cuff.](image)

The testing of the IPT insulator process as in the case of electrodes was included the determination of the optimal processing time. With the current discharge voltage of 520 V the change in pressure in the system and discharge current with time was monitored (figure 8). In each case, at least two measurement cycles were carried out, between each of which pumping of the desorbed gases and the change of the working gas were performed.

![Figure 8. The change of discharge current and pressure in the system with the IPT of the GDD vacuum gap insulator: □ and ■ – I cycle, △ and ▲ – II cycle, ○ and ● – III cycle, opaque figures – pressure, transparent – discharge current.](image)
It can be seen from the figure that in each processing cycle, the change in pressure readings in the system does not occur synchronously with the readings of current changes, which, like in the case of processing electrodes, is explained by the low sensitivity of the FRG-702 vacuum sensor in the pressure range under study. For this reason, the graphs of the discharge current versus processing time are indicative and most informative. The increase in the discharge current in the system is apparently due to an increase in the intensity of gas evolution from the surface of the insulator being processed, which is confirmed by an increase in pressure in the system.

Analysis of the discharge current dependences allows us to conclude that in the first processing cycle there is a rapid gas evolution with a further gradual slowing down. In the second cycle, there is a significant slowdown in the growth of the current and its termination at a value that is half as much as at the end of the first cycle. In the III cycle, the graph of the current change becomes even more gentle than in the II cycle and much earlier reaches the plateau. In each cycle, the dependence of the discharge current change on time is approximated (correlation coefficient $R^2 = 0.98$) by an exponential function:

$$I_{dis}(t) = I_f + I_0 e^{-t/\tau} \quad (2)$$

where $I_0$ – constant (mA), $I_f$ – current at $t = \tau$ (mA), $\tau$ – current growth constant (s). By analogy with the IPT of the GDD vacuum gap electrodes the parameter $\tau$ shows the time point at which there is a sharp change in the angle of inclination of the discharge current versus time. This means that the rate of gassing is slowing down, and further continuation of the processing cycle is impractical. In the particular case presented above, the following expressions are obtained $I_{dis \ I}(t) = 2.5 + 2.1 e^{-t/676}$, $I_{dis \ II}(t) = 1.2 + 0.76 e^{-t/581}$, $I_{dis \ III}(t) = 0.95 + 0.5 e^{-t/309}$ those the required duration of the IPT insulator at stage I is $\tau_I = 676$ seconds, at stage II $\tau_{II} = 581$ seconds and at stage III $\tau_{III} = 309$ seconds The total time of the IPT was thus 26 minutes. Similar values were obtained for at least 8 insulators participating in the experiment, which indicates the same effect of the IPT effect on this GDD vacuum gap insulator type.

4. The results of GDD studies, complete with IPT parts and components

To study the IPT effectiveness regarding the increase GDD electrical strength, 4 groups of devices were manufactured: group No. 1 – three products without additional treatments, group No. 2 – three products with IPO of the GDD vacuum gap electrodes, group No. 3 – two products with IPO of the GDD vacuum gap insulator and group No. 4 – two products with IPO of both GDD vacuum gap electrodes and insulators.

Studies were carried out in two stages. At the first stage, the current-voltage characteristic (CVC) of the GDD high-voltage vacuum gap was recorded. In the case of emission processes in it, the CVC has a characteristic kink (figure 9a). In this case, the voltage $U_{breakdown}$, corresponding to a sharp increase in the CVC inclination angle, in accordance with [11], is taken as the beginning of the emission breakdown currents appearance and characterizes the high-voltage gap electrical strength.

The emission current is a stream of electrons, which interacting with the surfaces of the vacuum gap grounded elements, generates X-rays. Since the magnitude of the radiation dose rate $D$ is proportional to the emission current [11], the shape of the curve $D = f(U)$ (figure 9b) is similar to the shape of the curve $I = g(U)$ (figure 9a). Therefore, the electric strength can be estimated from the magnitude of the accelerating voltage corresponding to the beginning of the increase in the X-ray dose rate. It is believed that the value of the emission current is determined by the presence of field emission centers (microtip, organic and oxide films) on the surface of the GDD vacuum gap electrode under negative potential, as well as the amount of adsorbed gases [12]. So the decrease in the dose rate of X-ray radiation in GDD with IPO parts and assemblies testified to the effectiveness of this operation.

At the second stage, the degree GDD structural element surfaces gas saturation was determined. For this purpose a thermo desorption curve was taken for a linear rise in temperature from 20 to
150°C. Based on the observed value of pressure, we judged the possibility of GDD stable operation at elevated ambient temperatures.

Figure 9. CVC of the GDD high-voltage gap (a) and the corresponding dependence of the X-ray dose rate (b).

Figure 10 shows the GDD groups study results according to the effectiveness IPT criteria: the X-ray dose rate $D$ and the pressure at the maximum of the gas release curve $P_{\text{max}}$.

It can be seen from the figure 10 the use of GDD high-voltage vacuum gap electrodes and an insulator IPT, both individually and jointly, can significantly reduce the X-ray dose rate, and therefore suppress the flow of undesired field emission processes. Also from figure 10 it can be concluded that the use of IPO makes it possible to reduce the level of residual gas evolution in the GDD volume. Moreover, the best effect is achieved if the GDD is completed with electrodes and an insulator with an IPO by simultaneous. This suggests that at elevated ambient temperatures the emission of residual gases into the GDD volume will be minimal. It means that the GDD working stability will not be disturbed.

5. Conclusion
In the present work, in order to increase the electrical strength and stability of GDD, operating on the basis of the Penning discharge, a method of the high-voltage vacuum gap parts and assemblies processing is implemented at the stage of their preparation for product assembly. This method involves irradiating the surface of parts with a flow of inert gas ions obtained from gas discharge plasma. It is shown that by varying the pressure of the working gas in the system, treatment of both the external and internal surfaces of the GDD high-voltage vacuum gap electrode is achieved.
Criteria for the IPT operations effectiveness were proposed. On the basis of criteria judged about the GDD stability and change in the electrical strength. It has been established that the best effect of achieving the GDD electric strength and stability of the device operation is demonstrated by simultaneous IPT of both the vacuum high-voltage gap electrodes and the insulator.

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