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Diagnostic of vacuum on the basis of the dielectric strength

***Abstract**. The proposed method of diagnosing the state of the vacuum based on the assumption that for a given type of chamber are known characteristics of the reference voltage as a function of the pressure and the distance between contacts. We will present this kind of characteristics which plotted the selected data cited in the literature with the Paschen curve, and similar characteristics obtained in own tests.*

***Streszczenie.** Proponowana metoda diagnozowania stanu próżni opiera się na założeniu, że dla danego rodzaju komory znane są charakterystyki referencyjne napięcia przeskoku w funkcji ciśnienia i odległości międzystykowej. Zaprezentowane zostaną tego rodzaju charakterystyki, gdzie wykreślono wybrane dane cytowane w literaturze wraz z krzywą Paschena oraz podobne charakterystyki otrzymane w badaniach własnych. (**Diagnozowanie stanu próżni na podstawie wytrzymałości elektrycznej**).*

Keywords: vacuum circuit breaker, diagnosing the state of vacuum.
Słowa kluczowe: wyłącznik próżniowy, diagnozowanie stanu próżni.

Introduction

The vacuum of vacuum circuit breakers has two functions: provides insulation between contacts and creates conditions for the formation of specific, very easy to extinguish arc. Treating the vacuum - after all, always imperfect as a special condition of the gas in terms of insulation is characterized by the fact that shifts the operating point on the Paschen curve (fig. 1) far to the left of the minimum, to the point where the strength of the system determined by the properties of electrodes - mainly the material and surface condition.

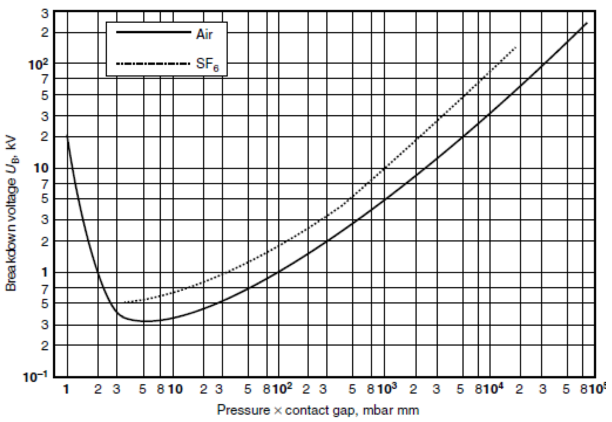


Fig. 1. Paschen curve [1]

From Paschen curve, it appears that the strength of the gas will grow to infinity with decreasing pressure to zero. However, even in theory, the residual gas effect ends when the pressure at which the free path of electrons exceeds the distance between contacts. In the air, for a distance of $d = 1$ cm, the pressure is approximately 15 Pa (0,15 mbar). At the lower pressures (product value pd) when the avalanche mechanism practically does not occur, reveal a variety of processes related with emission of charge carriers from the electrodes, their movement and exchange. These processes [2] bring into the space between contacts free charge carriers and neutral particles, cause the avalanche build-up of charge carriers as a result of the collision ionization of neutral particles by free electrons, and (to a lesser extent) ions are accelerated in an electric field. In the monograph [3] based on the analysis of literature from the years 1930 to 2008 different possible mechanisms of initiation and development of the discharge in a vacuum were classified in four groups: 1- exchange between contacts electrons and ions resulting from secondary emission, increasing avalanche until the arc discharge, 2- points field emission of electrons from the cathode, causing heating of the cathode and anode (concentrated electron stream bombardment) to the boiling point of the electrodes material , pairs of this material are gas, in which the discharge develops, 3- initial discharge developing in the residual gases released from the adsorbed gas in a layer on the electrode surface and condensing screen, 4- electrode surface bombardment by microparticles of the material electrodes (nuggets) released and accelerated by an electrostatic field; discharge develops in the metal vapours generated from heating energy of collision and/or an increase in field emission of electrons on the edges of microparticles settled on the electrodes

The so-called vacuum arc is therefore a discharge in pairs of metal electrodes. Pressure those vapour reaches in certain zones of the arc of many atmospheres. As long as the vapour pressure dominates over the residual gas pressure the vacuum state has indirect influence on the extinguishing, because it determines the diffusion of particles from the post-arc canal to the surroundings in a much later period of the critical off a few microseconds after current zero. Reasonable approximation of the maximum allowable pressure may be taken as the pressure at which the electron mean free path exceeds the distance between contacts. Determination of this distance as a function of pressure encountered difficulties arising from the difficulty estimates of the gas composition (pairs of metals and ions) collide with electrons. Manufacturers of vacuum chambers empirically determine the maximum pressure of 10^{-2} Pa. At the same time, however, from the new chambers required pressure $<10^{-7}$Pa. This drastic difference in the requirements dictated by the leakage of chambers, the effects for the same data is assessed on the increase in pressure 10^{-11} Pa / s This gives the lifetime of the chamber (transition from 10^{-7} to 10^{-2} Pa) close to 40 years

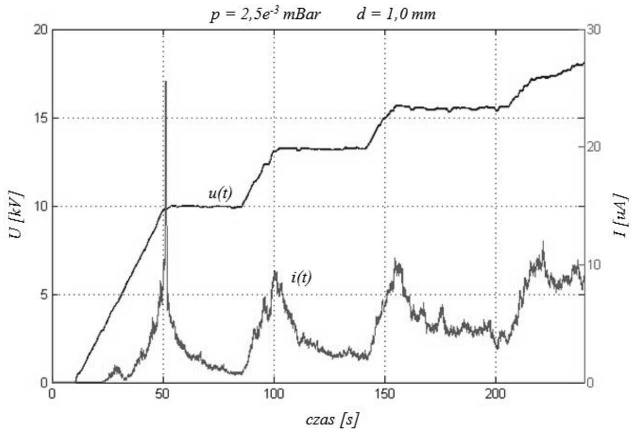
The dielectric strength of vacuum

At pressures below 10^{-2} Pa vacuum electric strength is high and its level as a function of pressure changes relatively stable, which is extremely important for the insulation systems. If we look at the vacuum as a limiting condition of a gas insulation system, then by the reduction of gas pressure below atmospheric pressure, decrease of electrical strength according to the Paschen law, and then rises to reach local maximum at pressure about 10^{-1}-10^{2} Pa. For pressures lower than 10^{-1} Pa the breakdown voltage is lower than the theoretically determined using the Townsend mechanism, because somewhere round this pressure take place change in the mechanism initiating discharge to the mechanism of electrical skip in vacuum. Only at pressures below about 10^{-2} Pa breakdown voltage for alternating current is practically independent of changes in pressure. Therefore, this range of pressures - 10^{-2}-10^{-4} Pa is the most interesting from the viewpoint of vacuum insulation systems (considering the pressure of not less than 10^{-4} Pa). With increasing pressure to values in the range 10^{-2}-10^{-1} Pa generates growth of electric strength while reducing amplification factor of the electric field at micro different of electrodes and increasing the departure work of electrons from the electrode surface. The observed increase in breakdown voltage apparent significantly for systems with greater distance between contacts (about a few millimeters) and is almost completely invisible to the system with a one milimeter break. The phenomenon of increasing breakdown voltage only for greater distances between electrodes can be explained by a higher average speed of positive ions colliding with the cathode, which bombarding the surface leads to greater atomization mikronidles peaks which are good electron emitters and a reduction in their surface electric field amplification factor. Increasing the electron departure work is explained by the increase of gas adsorption on the electrode surface during increasing pressure. These facts limit the field-emission electron current, which helps to increase the breakdown voltage. In addition to the distance between electrodes , the impact of these phenomena are, of course, the diameters of electrodes and electrodes material. Despite the variation in electrical resistance at different vacuum pressure ranges should strive to ensure that the switching phenomena occurred for pressures at which this variability is the lowest. Plateau electric strength from the the pressure corresponding to pressures below 1 Pa.

Collected from various sources the breakdown voltage depending on the pressure for flat electrodes at different distances [1,2,3] indicate that at a pressure decreases from the conventional of vacuum boundary breakdown voltage of about 100 Pa to 5 – 0,5 Pa, the breakdown voltage increases, and after that at small distances between contacts stabilizes at the level depending on the distance, but at larger distances the strength increases to a peak value and then stabilizes at a slightly lower level, also dependent on the contact distance. The dependency of the breakdown voltage from the pressure above all can see that in the pressure range 5 – 0,5 Pa (depending on contact distance) come to move from the breakdown conditioned of the kinetics of gas to the breakdown initiated in any of the mechanisms of the vacuum. The occurrence of 'optimal' in terms of strength show [2] the role of residual gases in the initiation of ignition and can be interpreted as meaning that in the correctly conditioned system ignition is initiated by field emission of concentrated electron stream bombardment, whose intensity is enhanced by ionization of residual gas. More cathode gap make that the breakdown occurs at higher currents. Emission of charge carriers from the electrodes amplified the aforementioned ionization of residual gas, so it can be followed by spraying of peaks of inequality on the electrodes and the reduction of local extremes of the electric field.

Conditioning and deconditioning

Conditioning is a process that affects the increase in electric strength of vacuum insulation systems for removing pollution from the surface of electrodes, adsorbed gases, leads to the detachment of microparticles weakly bound of the electrodes material, and helps to align the microasperities, which increases the gain of the electric field. There are three basic methods of conditioning the surface of contact: 1- conditioning by multiple hops 2- conditioning by ion of gases bombardment of the electrode surface 3- conditioning by field emission electron current and micro discharges. The third method consists in slowly raise the test voltage until the flow by conditioned insulation system a small current (few μA). After stabilizing the value of the current the voltage is rising again and again, waiting for the stabilization of the current. This pattern is repeated several times until it detects the first skip. This process leads to the field and thermal desorption of gases from the contact material of residual gas. Remaining ions and the field-emitted electrons bombarding the surface of the electrodes. This leads to the removing of impurities, the "blind spots" on the electrode surface and smoothing those surface, which results in a reduction amplification factor electric field and reducing the amount of adsorbed gas on contact surfaces. This method leads to greater electrical strength than the method of hops. The electron current conditioning shown figure 2.



Rys.2. Current and voltage waveforms of the vacuum chamber during field emission electron current conditioning

Due to the complexity of processes and complexity of the interdependence between these processes in the initiation of breakdown in vacuum systems, insulation, electrical strength of these systems is not stable and may undergo a process of deconditioning. As a result of residual gas adsorption and surface migration the electric strength of previously conditioned system can be reduced even to pre-conditioning. Especially if circuit breaker remains de-energized. Similarly, the dielectric strength of the vacuum system can be significantly weakened by the bombarding of electron and settling on the cover of a porcelain chamber. It was also observed that after the no-load switching operations, which is typical to test a mechanism of circuit breaker, may also be weakening the dielectric strength. Especially in the case after turning on a large current and off without load.

A high voltage system to study emission current

Emission currents those occur between the contacts of the vacuum chamber preceding the jump. With the increase of voltage and distance between contacts currents are rising, but their value is negligible compared to the current breakdown. Measuring such a small current (<1mA) requires a high shunt resistance and added protection against high voltage that appears on recorder to bypass the breakdown. Both the breakdown voltage and current emission are strongly dependent on the state of contact surface and the pressure in the chamber. The presented system (fig. 3) consist of regulated voltage source in the form of high-voltage transformer *HVT* and diode rectifier circuit *D* as well as an oscillating circuit *LCR*. *LC* resonant circuit is used to generate the impulse discharge inside the chamber with frequency of several kHz with the current limited by resistor R. This made the puncture between the contacts is not fully breakdown which can change condition of the contacts and is extinguished by the chamber. The gap between contacts recovers its strength. Test system for testing AC voltage is similar to that shown in Figure 3, with the exception that works without elements of D, C and L.

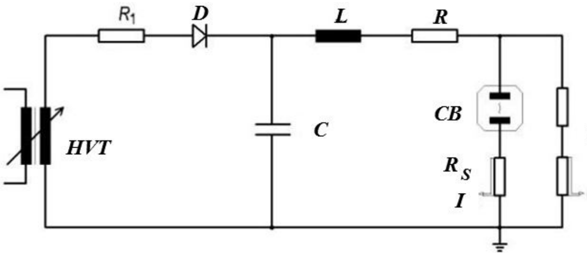


Fig. 3. Diagram of the test circuit to study emission currents

Example of rejected field emission current as function of voltage between contact and pressure are shown accordingly on figures 4 and 5.

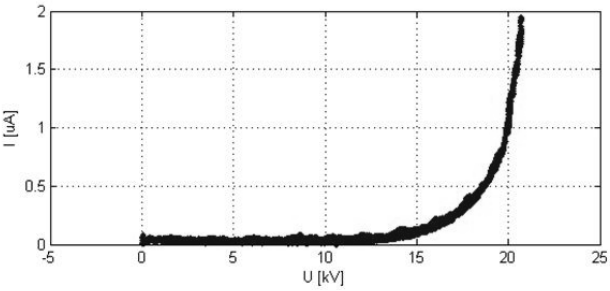


Fig. 4. Field emission current as a function of voltage between contacts

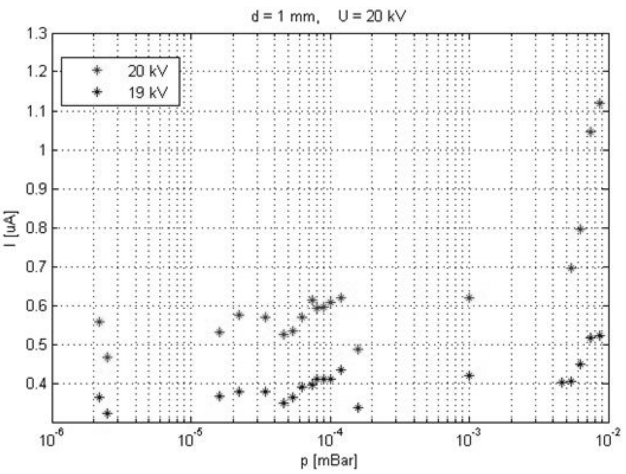


Fig. 5. Field emission current as a function of pressure

Model Vacuum Chamber

Examination of the vacuum are made on the model arising from untighten commercially manufactured chambers. The location of leaks have been soldered by flanges for connection to a set of vacuum pumps. This solution seems to be attractive due to the behavior of the real geometry of the circuit breaker. A set of vacuum pump is a device *HiCube Eco 40* of *Pfeiffer Vacuum* capable of providing a vacuum of up to 10^{-7} mbar, i.e., 10^{-5} Pa. A set of pumps consists of a membrane, an oil-free vacuum pump, turbomolecular pump, electronic control system, the pressure measuring transducer (mounted at the chamber) and a flexible connecting pipes and valves.

The distance between contacts in the test chamber is set by fall out of the driving mechanism and by pitch a nut with screw-thread of 1 mm. Theoretically, there is a direct ratio between the depth of pulling the tightening nut, and the distance between contacts and it would seem that this path can be precisely adjusted following the speed nut. The studies were performed at distances between contacts: 1 mm (1 turn of the nut from the loss of contact), 2, 5, 10 and 15 mm.

Diagnostic method of vacuum on the basis of the dielectric strength

The proposed method of diagnosing the state of vacuum based on the assumption that for a given type of chambers are known the reference characteristics as a function of the pressure breakdown and the distance between contacts. This kind of performance can have the form shown in figure 6, plotted with the selected data cited in the monograph [3] and the Paschen curve.

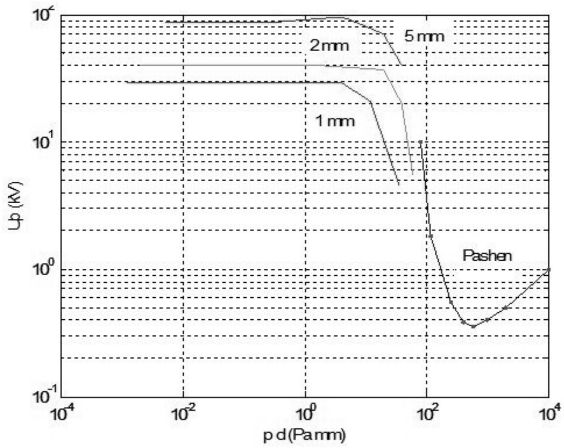


Fig.6. The characteristics of a flat dielectric strength of vacuum at different distances between contacts as a function of distance and pressure with the Paschen curve according to the literature data

Similar characteristics obtained in the present study are shown on figure 7. The characteristics shows typical for larger distance between electrodes higher breakdown voltage at the value of the product pd of about 1 Pa mm.

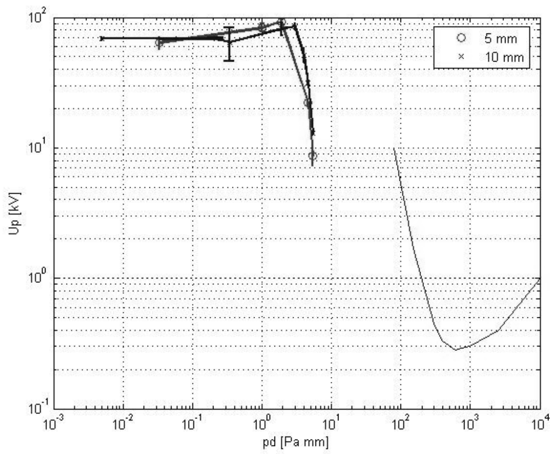


Fig.7. The characteristics of dielectric strength of vacuum measured by the authors on the actual circuit breaker compartment at different distances between contacts as a function of distance and pressure with the Paschen curve

In addition, you can see the discrepancy between the theoretical characteristics of the and the designated strength characteristics for vacuum. All this indicates a change in mechanism to initiate breakdown. Having defined breakdown voltage on one or several known distances vacuum level can be assessed vacuum level comparing the measurements with those of the reference. Structured and repeatable results can be expected at small distances between contacts and then only for a well-conditioned chambers.

In full conditioned chamber development of the discharge is a result of field emission mechanism, or the exchange of charged particles. The process of initiation can be observed by recording and analyzing the current prior to discharge (fig. 4 and 5). Application of the Fowler and Nordheim formula (1), and suitable for the approximation allows to determine which mechanism led to a breakdown [1] - see figure 8 and 9.

$$log_{10}\left(\frac{I_e}{U^2}\right) = log_{10}\left(\frac{A_e B_1 \beta^2}{\varphi d^2}\right) - \frac{B_2 \varphi^{1,5} d}{2,303\beta}\left(\frac{1}{U}\right) \tag{1}$$

where: I_e- emission current, U- voltage between contacts, A_e- emission area, β- enhancement factor, B_1, B_2- constans, d- distance between contacts, φ- work function

If the emission current I_e is measured as voltage U is varied and a plot of $log_{10}(I_e/U^2)$ versus U^{-1} is made, the resulting graph will give a straight line whose slope and intercept will allow β and A_e to be calculated.
The straight line indicates only the presence of electron emission current (fig. 8). Rapid increase in current (exactly its function) just before discharge (small argument, large voltage) testifies about the appearance of the avalanche of ionization of residual gas (fig.9).

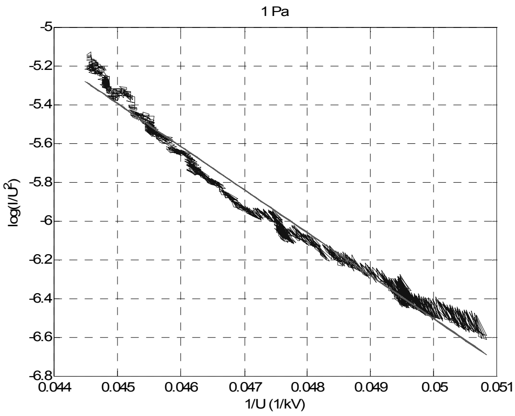


Fig.8. Fowler and Nordheim plots based on records of current and voltage waveforms for the pressure 1 Pa

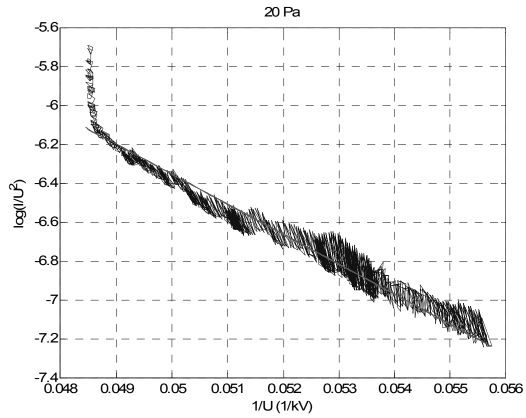


Fig.9. Fowler and Nordheim plots based on records of current and voltage waveforms for the pressure 20 Pa

Conclusion

The proposed method can be used if:
• The reference sheet will be available for diagnosed chambers
• efficient method will be developed and combined with diagnostic measurements of conditioning chambers built on the switch. In this respect, the best prospects gives conditioning and surge voltages diagnosis
• mastered the measurement of electron emission current at surge voltages.

Mastering these technical problems are not present unbreakable difficulties. While the broader perspective of the practical application of the proposed method depends on the economy against the background of the cost of diagnosing fault circuit breakers and the cost of preventive replacement of chambers.

This work was supported by the Ministry of education of funds for research in 2010-2013.

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