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Correlation and regression between the breakdown voltage and pre-breakdown parameters of vacuum switching elements

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ABSTRACT

This paper considers the influence of switching operations on the characteristics of vacuum switching elements. The following operations, all with circuit-making without current, have been taken into account: circuit-breaking without current, circuit-breaking with nominal current and circuit-breaking with short-circuit current. The influence of switching operations is examined for the random variables breakdown voltage (ac and pulse) and the pre-breakdown parameters V_{-4}, V_{-5}, and V_{-6}. Parameters V_{-4}, V_{-5}, and V_{-6} represent the dc voltage at which the pre-breakdown current takes values of 10^{-4}, 10^{-5}, and 10^{-6} A, respectively. Switching element characteristics after the switching operations are compared with the corresponding results obtained for switching element with conditioned contacts. The main result is an examination of the correlation and regression between the experimentally obtained breakdown voltage (ac and pulse) random variable and its corresponding pre-breakdown parameters V_{-4}, V_{-5}, and V_{-6}, respectively. Statistical samples created by using this method do not require the repetition of switching operations and therefore the dielectric strength of the vacuum insulation is kept in its initial state. The examination is carried out on commercial vacuum switching elements with CuCr and CuBi contacts.

1. Introduction

Examining the vacuum switching elements by repeating the measurements of breakdown voltage is an irreversible procedure. Namely, an electric vacuum breakdown is possible if the vacuum, as an insulating medium, is part of the insulating system which comprises the insulating medium and electrode system. In the vacuum, the mean free path length of a particle is larger than the characteristic dimension of the system, i.e. the interelectrode distance, and then an ionization avalanche cannot occur [1–4]. The vacuum breakdown is carried out in two steps: (1) by introducing thermal instability of one of the electrodes; and (2) by gas breakdown in electrical evaporation of electrode material through the Townsend avalanche mechanism [5–7]. The introduction of thermal instability of a single electrode may occur in various ways, according to which the vacuum breakdown mechanisms are divided into the following: (1) the cathode emission mechanism; (2) the anode emission mechanism, and (3) the micro-particle mechanism [8,9]. Regardless of the mechanism that leads to vacuum breakdown, a change of the electrode surface topography occurs as a consequence. Since the electrode surface topography has the main role in causing thermal instability of the electrodes, it is clear that the breakdown of the vacuum insulating system is an irreversible process. Namely, the high temperature of the spark channel (~5000 K) and the corresponding pressure within it (~20 bar) lead to melting of the electrode material and its dispersion into the interelectrode space. In the case of the vacuum switching element, the rate of irreversible characteristics of the insulating system increases due to the effects of switching operations [10]. To be exact, in the course of switching operations, contact welding occurs as well as the breaking of these welding points, and sometimes an electric arc effect may even occur, since vacuum switches cannot break the current if it does not equal zero [11–14]. All of these factors lead to the impossibility of forming a representative statistical sample of the random variable of the breakdown voltage of the vacuum switching element with the type of previous switching operation as a parameter.

The aim of this paper is to examine the possibility of forming a

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representative sample of the random variable breakdown voltage of the vacuum switching element by measuring the pre-breakdown current without repetition of switching operation.

2. Correlation and regression

If several statistical samples of different random variables are measured for the same examined samples, then the mathematical values of correlation and regression measure their interrelationship [15,16]. In that case, the examination of the correlation between two experimentally determined statistical samples of random values x and y provides an answer to the question of whether there is a linear dependence between the determined random values. The quantitative indicator of this linear dependence is expressed by the correlation coefficient r:

$$r = \frac{\sum_{i=1}^{n} x_i y_i - n\bar{x}\cdot\bar{y}}{\sqrt{\left(\sum_{i=1}^{n} x_i^2 - n\bar{x}^2\right)\left(\sum_{i=1}^{n} y_i^2 - n\bar{y}^2\right)}} \tag{1}$$

The sample taken consists of n pairs of values (x_i, y_i) characterized by the arithmetic means $\bar{x}$ and $\bar{y}$.

It has been assumed that the random variables x and y belong to the normal distribution. According to the absolute value, the correlation coefficient must be less than or equal to 1. There is no correlation between the random variables x and y if $r = 0$. In the case when the correlation coefficient is close to 1, there is a strong correlation, i.e. linear dependence, between the observed random variables. If the correlation coefficient r is greater than zero, then the random variables x and y will increase simultaneously. This case is better known as a positive correlation. A negative correlation occurs when one of the random variables x and y increases while the other decreases. In that case, the correlation coefficient is smaller than zero. The correlation coefficient is determined on the basis of empirical evidence.

In the case of linear regression, and under the assumption that random variables belong to a normal distribution, the random variables are mostly related by the linear dependence. Such a linear dependence is called a regression curve and represents the corresponding mathematical expectation.

The regression curve parameters are determined by the empirical expressions [15,16]. A clear-cut distinction ought to be drawn between a dependent variable and an independent one. The empirical regression curve used in estimating from y to x is obtained by the following equation:

$$y = a_{yx} + b_{yx}\cdot x \tag{2}$$

where

$$b_{yx} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(x_i - \bar{x})^2} \quad \text{and} \quad a_{yx} = \bar{y} - b_{yx}\cdot\bar{x} \tag{3}$$

In the reverse case, from x to y, the regression curve is obtained as the following:

$$x = a_{xy} + b_{xy}\cdot y \tag{4}$$

where

$$b_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \quad \text{and} \quad a_{xy} = \bar{x} - b_{xy}\cdot\bar{y}. \tag{5}$$

Regression curves, in the simplest case, are obtained graphically by using the least squares method. If the realizations (x_i, y_i) are greatly scattered around the regression curve, and if the regression coefficient, b_{yx} or b_{xy} in equations (2) and (4), is consequently small, there is a weak linear relationship between variables x and y. On the other hand, if the scatter is slight and regression coefficient is large, then the strong correlation is indicated. Therefore, the angle of intersection of regression curves given with equations (2) and (4) is the measure of correlation between the x and y order sets. If this angle is equal to zero, the correlation coefficient is 1. As the angle increase the correlation coefficient decrease, so in the case that the angle of intersection of regression curves is 90° the correlation coefficient equals zero.

3. The experiment and experimental data processing

3.1. The used vacuum chambers

The investigation was conducted on four types of commercial vacuum switching elements designated A, B, C and D hereinafter. The insulating cover of cylindrical shape was made of Al_2O_3 ceramic for all switching elements. The contacts placed within the switching element were not visible. According to the manufacturer's specification, the contacts of elements A and B were made of sintered CuCr, and those of C and D were made of sintered CuBi. Elements of type A and B were with transverse magnetic field contacts, while C and D were with axial magnetic field contacts. The parameters of the examined switching elements are given in Table 1, in regard to manufacturer specifications.

The pneumatic cylinder was used as a drive for a movable contact of vacuum switching element. This device converted the rotation of its movable part into a translation of the movable contact (1 mm = 360°). The zero distance of the contact is determined by measuring the ohmic resistance between their carriers.

Outside flashovers were prevented by putting the switching element into a vessel filled with SF_6 gas under a pressure of 2 bar. The vacuum chambers were located behind a lead shield with a thickness of 4 mm with the goal of providing protection from X-rays. Radiation measurement performed behind the shield was in accordance with the level of the natural background radiation.

Dielectric examination was carried out by ac and pulse voltages for all types of vacuum switching chambers. The applied pulse voltage had negative polarity, with a shape of 1.2/50 μs, while the amplitude was 250 kV. The applied ac voltage had a rise rate of 20 kV/s.

3.2. Experimental equipment

A four stage Marx generator with capacitors of 70 kV/200 nF per degree was used as a source of pulse voltage. The generator was adjusted to provide a voltage shape of 1.2/50 μs. The amplitude of the breakdown voltage was adjusted so that the breakdown occurred always at the wave front [18,19].

Fig. 1 shows an outline of the circuit for dielectric investigation through the ac and dc voltage. During ac measurements CND1 and

Table 1
The tested vacuum circuit breakers' parameters.

Type of switching element	A	B	C	D
Rated line voltage [kV]	12	12	12	12
Rated continuous current [kA]	2	1.6	2	1.6
Rated short-circuit breaking current [kA]	20	20	20	20
DC percentage [%]	50	50	50	50
Rated short-circuit making current [kA]	50	50	50	50
The contact gap [mm]	8	8	8	8
Average opening speed [m/s]	1	1.2	1	1