THE EFFECT OF THE NUMBER OF SPACER INSULATORS ON THE BREAKDOWN VOLTAGE OF VACUUM INSULATION

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ABSTRACT

It was shown that when extended high voltage vacuum insulation is being considered, the effect of the number of spacer insulators on the breakdown voltage of the system has to be taken into account. Two cylindrical electrode systems with a variable number of spacers were investigated. A very distinct decrease of the breakdown voltage with the increase in the number of insulators was noted. This effect was much greater than could be predicted when the normal distribution of the flashover voltages of a single insulator was assumed. A much better approximation was obtained when the Weibull distribution was used.

INTRODUCTION

Investigations of vacuum from the point of view of its future use as a high voltage insulation concentrate on the quantitative and qualitative assessing of parameters determining the optimal design of the spacers. Much research [1] has been devoted to the problem of choosing the best material and shape of the spacers, and to the solution of their contact area with the electrodes. As a rule these tests were made on single models of insulators which is a significant limitation in the application of the results obtained in the design of real insulation systems. The validity of these results is limited to simple insulation systems with only a few insulators. In more complicated cases when the number of the insulators must be great because of constructional reasons as, for instance, in the high voltage vacuum insulation for cryocables, one has to take into consideration the possible influence of the number of insulators on the breakdown voltage of the system. Each additional insulator may be here considered as a new weak point of the insulation. Flashover across one of the insulators is equivalent to the breakdown of the whole insulation system.

If the flashover probability of an insulator at a voltage U is $P_i(U)$ and n is the number of insulators working in parallel then the breakdown probability of the system at the same voltage is

$$P_s(U) = 1 - \prod_{i=1}^{i=n} \left[1 - P_i(U)\right]$$

Assuming $P_i(U)$ to be the same for all the insulators

$$P_s(U) = 1 - \left[1 - P_i(U)\right]^n$$

and when $P_i(U) \ll \frac{1}{n}$, then $P_s(U) = n \cdot P_i(U)$.

With the increase in the number of insulators, the probability of breakdown of the system increases at a constant voltage, or for the same probability, the breakdown voltage of the system is decreased. The rate of this decrease depends not only on the number of the insulators but also on the distribution of breakdown voltages of single insulators.

For the evaluation of insulation systems depending on the properties of air, e.g. the insulation of overhead transmission lines, the normal distribution of $P_i(U)$ is generally assumed. For this distribution, the mean breakdown voltage of the system may be expressed in terms of the mean flashover voltage of a single insulator as follows:

$$U_{s50} = U_{i50} - a_n \sigma_i \tag{1}$$

where: σ_i - standard deviation of a single insulator,

a_n - tabulated value depending on the number of insulators.

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For solid and compressed SF_6 insulation systems such as cables, when the effect of length or weak points is under consideration, the Weibull distribution is generally used [2,3]. In this case the dependence of the breakdown voltage of the system on the breakdown voltage of a single insulator at the same probability may be expressed as

$$U_s^b \cdot n = U_i^b, \text{ or } U_s = n^{-1/b} \cdot U_i \qquad (2)$$

where b is the shape parameter of Weibull distribution.

Also in vacuum, each spacer insulator is known to have some distribution of its flashover voltages, There is no question therefore that, in this insulation also, the number of spacers must influence the breakdown voltage of the system. However, the question is how significant this decrease will be and what kind of distribution gives the best approximation to the experimental data. As no data on this subject were known to the authors, a special research program was started. The main aim of this program was to determine the severity of this effect and to determine whether this effect should be taken into consideration when designing extended high voltage vacuum insulation.

EXPERIMENTAL

These investigations constituted a part of a wider research program dedicated to the prospects of vacuum as high voltage insulation for cryocables. Hence coaxial cylindrical electrodes were used. In order to exclude the possible electrode area effect [4] the tests were made by varying the number of spacer insulators at constant electrode area.

Two electrode arrangements were tested. The first one consisted of two coaxial electrodes 0.865 m long, made of duraluminium. The inner diameter of the outer electrode was equal 0.057 m, the outer diameter of the inner electrode amounted 0.040 m. A special arrangement of aligning grips allowed the variation in the number of spacers from 6 to 21 in steps of 3. The total electrode area was equal 0.13 m^2. The electrodes were placed in a special vacuum vessel made of stainless steel, provided with bushing insulators as shown in Fig. 1. The second electrode system consisted of a 1.56 m long model of cryoresistive cable. The diameters of the electrodes were 0.09 and 0.04 m with the total electrode area of 0.32 m^2. The number of spacer insulators could be changed from 1 to 8. As the model was provided with bushing insulators, no special vacuum vessel was needed as shown in Fig. 2. The tested spacer insulators were in the form of cylinders with diameters 0.008 m for the first electrode arrangement, and 0.021 for the second, made of special ceramics selected in preliminary tests as the most stable material from the point of view of voltage endurance [5]. Much care was taken to ensure good contact between the spacer insulators and the electrodes. Fig. 3 shows the configuration of the electrode - insulator junction used in the first system.

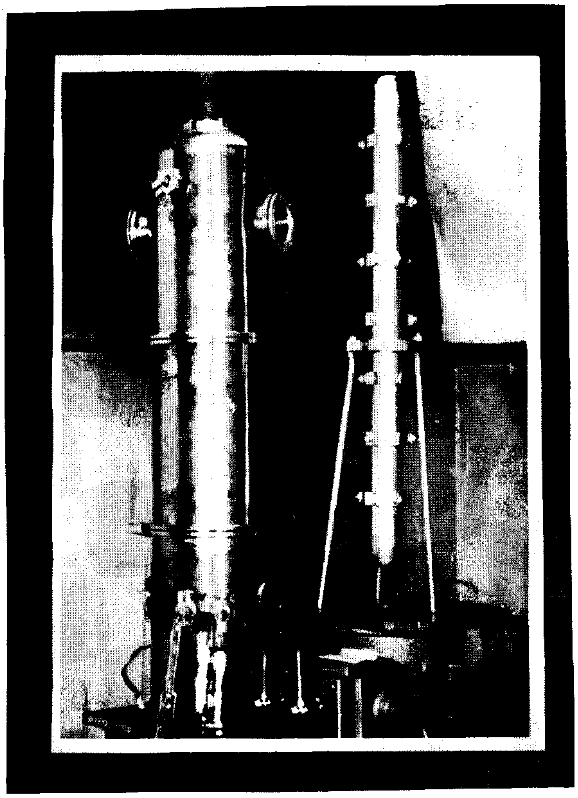

Fig. 1: Vacuum vessel and electrode arrangement allowing from 6 to 21 spacer insulators.

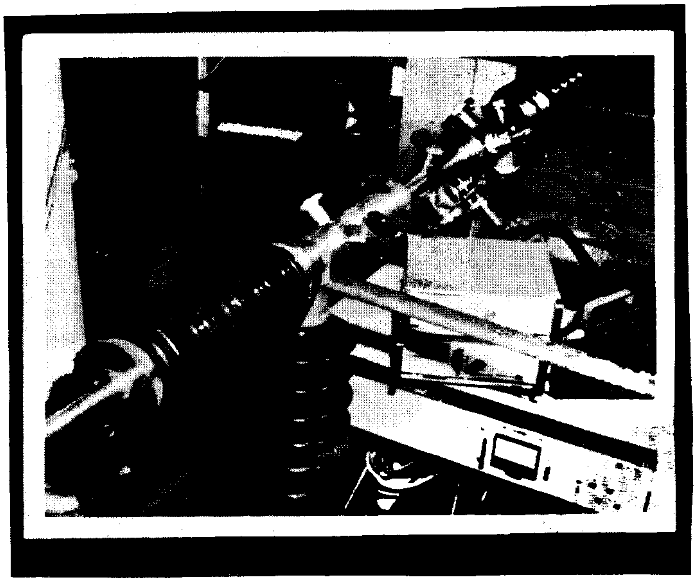

Fig. 2: A short model of cryoresistive cable with vacuum insulation. The number of spacer insulators can be changed from 1 to 8.

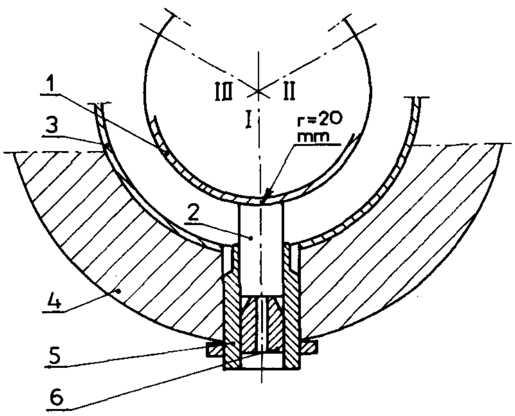

Fig. 3: Configuration of the electrode - insulator junction used in the system shown in Fig. 1.

1 - inner electrode,

2 - spacer insulator with the surface contacting the inner electrode polished to its radius,

3 - outer electrode,

4 - aligning grip with mountings for 3 spacers, distributed at an angle of 120°,

5 - centering unit,

6 - tightening unit.

Measurements were made at pressures lower than $8 \cdot 10^{-3}$ Pa, checked continually during the tests.

The behaviour at ac voltage is most crucial for the evaluation of high voltage insulation. Therefore 50 Hz ac voltage was selected as the test voltage. A conventional high voltage ac test circuit with a series resistance of about 1 MΩ was used. The voltage was raised at the rate of about 2 kV per second. Before the proper measurements, a given arrangement of spacers was conditioned until a further increase in the number of breakdowns in the system did not give any rise in the breakdown voltage. After conditioning, not less than 20 measurements of the breakdown voltage were taken at a particular condition. Then the tested system was dismantled, the spacers exchanged and the test procedure repeated. Three sets of not less than 20 results each provided the base for further statistical evaluation of one spacer arrangement.

The test results for the first electrode system are summarized in Fig. 4. The measured dependence of the breakdown voltage and standard deviation on the increase of the number of spacers from 6 to 21 is shown as a full line. The value for one spacer was obtained by extrapolation. As predicted, the breakdown voltage decreases with the number of spacers.

Although the distribution of the test results satisfied the normal distribution, this decrease is much sharper than could be calculated from the Eq. (1) shown by the dashed line in Fig. 4, and the difference between the measured and calculated values increased with the number of spacers.

Validity of the Weibull distribution was then checked with positive results. The breakdown voltages plotted on Weibull probability paper showed good linearity for all numbers of spacers, the distribution lines running almost parallel to each other. The shape parameter was 3.7. The dependence of breakdown voltages on the number of spacer insulators calculated according to Eq. (2) is shown in Fig. 4 by the crosses. This calculated curve lies quite close to the measured one: the differences are within 10%.

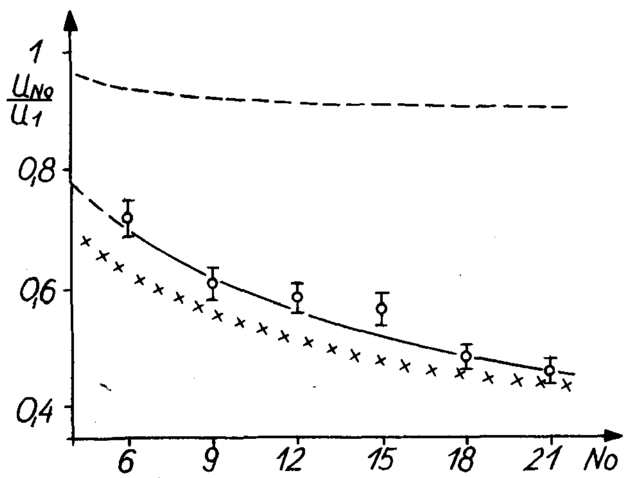

Fig. 4: The dependence of the relative breakdown voltage on the number of spacer insulators for the electrode system shown in Fig. 1.

——— *- measured values and their standard deviation,*

----- *- calculated values using normal distribution,*

xxxxx *- calculated values using Weibull distribution.*

Similar results were obtained for the second electrode system and are plotted in Fig. 5. A very distinct effect of the number of spacer insulators was noted, with the Weibull distribution giving a much better approximation to the measured values than the normal distribution.

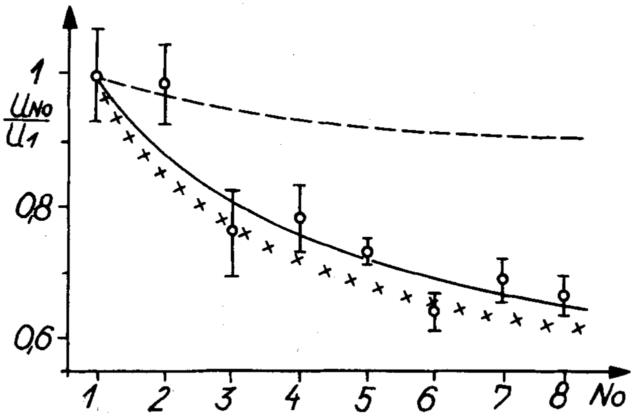

Fig. 5: The dependence of the relative breakdown voltage on the number of spacer insulators for the electrode system shown in Fig. 2.

——— - *measured values and their standard deviation,*

----- - *calculated values using normal distribution,*

××××× - *calculated values using Weibull distribution.*

CONCLUSIONS

As anticipated, a very distinct effect of the number of spacers on the breakdown voltage of high voltage vacuum insulation was observed. The increase in the number of insulators to 21 gave a 50% decrease in the breakdown voltage. This decrease is much greater than could be predicted when a normal distribution of the flashover voltages was assumed. When the Weibull distribution was considered, the calculated values compared well with the measured ones.

Each additional spacer insulator must here be regarded as a new weak point introduced into the insulation system, whose distribution of flashover voltages deviates from the normal distribution in the direction of the extreme distributions. Therefore, the significant influence of this effect on the breakdown voltage must be taken into consideration when designing extended high voltage vacuum insulation.

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