Box 1: Calculation Technique for High-Voltage Equipment in Gas

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Introduction

The analysis of an electrostatic field and the calculation of breakdown voltage are demonstrated here. A reasonably good prediction can be obtained by a technique developed in Obninsk [1, 2]. The high accuracy (errors within $\pm$(2–3)%) is a consequence of the physical model used. This model is called "asymptotic breakdown gradient" (ABG) or "the method of base". The high accuracy is also a consequence of the calculation of the electrostatic field on curvilinear electrode boundaries with correction for the systematic errors in computing a potential gradient [3].

Elementary Phenomenon

When we solve the problem of the electric strength of a gas, the failure of insulation is considered in the form of a spark breakdown or the beginning of a corona discharge. Electric strength is expressed in terms of a statistical average breakdown voltage $\overline{U}$ and the standard deviation of the breakdown voltage σ. The elementary phenomenon is defined exactly.

Elementary Structure

An element of an insulation structure is unambiguously formed by the electrostatic field on the surfaces of the electrodes, and it is characterized by four parameters. An element of the insulation system represents a part of the surface of the electrodes adjoining a point where the potential gradient is equal to its maximum value E_{max} and where the radius of average curvature of the surface has the value R_{av}. The area of an element is limited to the "effective" surface S_{eff}, where the strength of the field, that is, the gradient of potential with the sign reversed, is given by $E \geq 0.8\, E_{max}$ [2]. Each element has a value of the breakdown voltage U_{br}. It is also necessary to define two important parameters: the breakdown voltage of the insulation system and the relative strength of its element [1].

The Theoretical Model

A theoretical model of electric breakdown in a gas needs to be based on some sort of affirmation. The "law of similarity of gaseous discharge" (Paschen's law, in a uniform field) could be such a fundamental and conclusive statement [4]. In a nonuniform field, the law of similarity can have the form

$$E_{br} = E_{uni} \left(1 + a_{uni}/(p_{20} R_{av})^{m_{uni}}\right) , \quad \text{(B1.1)}$$

where E_{br} and E_{uni} (both in MV/m) are the breakdown gradients in nonuniform and uniform fields, respectively. $a_{uni} = 0.061$ and $m_{uni} = 0.38$ are constants valid for air and N_2/CO_2 gas, and $a_{uni} = 0.0045$ and $m_{uni} = 0.54$ are constants valid for SF_6 gas. p_{20} is the gas pressure adjusted to its value at 20°C, and R_{av} is the radius (in m) of the average curvature of the electrode surface,

$$R_{av} = 2/(1/R_{k1} + 1/R_{k2}) , \quad \text{(B1.2)}$$

where R_{k1} and R_{k2} are the principal radii of surface curvature at a point where $E = E_{max.}$. Below, the theoretical model of electric breakdown in a gas is outlined:

– Electric strengths of a system and of its elements are estimated from an end result, breakdown voltages. The breakdown voltage is a linear function of the breakdown gradient E_{br}:

$$U_{br} = E_{br}(U_{calc}/E_{max}) , \quad \text{(B1.3)}$$

where E_{max} denotes the maximum gradient of the potential on an electrode surface at a potential difference of U_{calc} in the calculation between the electrodes.

– For increasing distance between the electrodes in a uniform field, the breakdown gradient of the potential approaches asymptotically the value E_{asm}.

– This asymptotic breakdown gradient can be calculated from the data of the preliminary base experiment, if two conditions are fulfilled. Firstly, the chemical composition of the gas and the way of conditioning the gaseous insulation and also the electrode material, the finishing of the surface, and the way of preparation of the electrodes to be tested should be identical in the base structure and in the designed structure. Secondly, the maximal gradients of potential in both the structures may not differ by more than

$$0.1 \leq (E_{max}/U_{calc})/(E_{max.base}/U_{calc}) \leq 10 . \quad \text{(B1.4)}$$

– As the criterion for the electric strength in the calculations, the parameter "breakdown voltage of a base gap" $U_{br.base}(p_{20})$ is used instead of conditions for self-maintenance of a discharge obtained for some abstract gaps with a uniform field or nonuniform field [5].

The Calculation Procedure and its Verification

The technique has been tested with experimental results obtained for a 3 MV Pelletron tandem with pure SF_6 [6]. For this accelerator, the following value is valid at 0.6 MPa: $U_{exp}(0.6) = 3.673\,\mathrm{MV}$, as

$$U_{exp} = 5.085(p_{20})^{0.637}\,\mathrm{MV}, \quad \sigma = 2.9\%, \quad p_{20} = 0.21 - 0.6\,\mathrm{MPa}\,. \quad \text{(B1.5)}$$

The starting point of the calculation is the computation of the breakdown voltage value obtained from the base experiment on MP tandems [7], $U_{br.base}(0.6) = 13.663\,\mathrm{MV}$, as

$$U_{br.base} = 19.757(p_{20})^{0.722}\,\mathrm{MV}, \quad \sigma = 2.9\%, \quad p_{20} = 0.3{-}0.85\,\mathrm{MPa}\,. \quad \text{(B1.6)}$$

The accuracy of (B1.6) has been checked [2]. The inequality (B1.4) is fulfilled, and therefore the choice of base is valid (with $E_{max.base}/U_{calc} = 2.107\,\mathrm{MV/m}$, $E_{max}/U_{calc} = 7.47\,\mathrm{MV/m}$, according to Fig. B1.1). The normalized voltage [1] with 100% SF_6 gas, $k_{rel} = 1$, positive polarity, $k_{pol} = U_{br}/U_{br.pos} = 1$, and 100% of the conditioning, $k_{cdtn} = U_{br}/U_{br.stbl} = 1$, is given by

$$U_{norm.base} = U_{br.base}/(k_{rel}k_{pol}k_{cdtn}) = 13.663\,\mathrm{MV}\,. \quad \text{(B1.7)}$$

The breakdown gradient in the nonuniform field of the base insulation gap is, according to (B1.3) (with $E_{max.base}/U_{calc} = 2.107\,\mathrm{MV/m}$),

$$E_{br.base} = U_{norm.base}(E_{max.base}/U_{calc}) = 28.788\,\mathrm{MV/m}\,. \quad \text{(B1.8)}$$

The breakdown gradient in a uniform field, according to (B1.1) with $R_{av.base} = 0.0376\,\mathrm{m}$, is given by

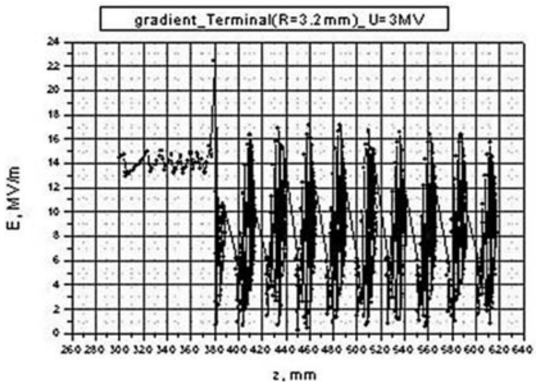

Fig. B1.1. The distribution of the potential gradient along the surfaces of the terminal ($R_{k1} = 3.2\,\mathrm{mm}$) and of the hoops of the column ($R_{k1} = 8\,\mathrm{mm}$) for a 3 MV Pelletron. The terminal potential is equal to 3.0 MV. The coordinate z is counted from the middle of the terminal

$$E_{uni.base} = E_{br.base}\left(1 + a_{uni}/(p_{20}R_{av.base})^{m_{uni}}\right)^{-1} = 27.818\,\mathrm{MV/m}\,. \tag{B1.9}$$

The asymptotic breakdown gradient in the base experiment, according to (B1.5) in [2] with $L_{base} = 1.8\,\mathrm{m}$, $a_{asm} = 0.000004$ and $m_{asm} = 1$, is given by

$$E_{asm.base} = E_{uni.base}\left(1 + a_{asm}/(p_{20}L_{base})^{m_{asm}}\right)^{-1} = 27.818\,\mathrm{MV/m}\,. \tag{B1.10}$$

The asymptotic breakdown gradient, according to (2) in [2] in the 3 MV Pelletron structure, is

$$E_{asm} = E_{asm.base}\left(1 - ((\sigma/\overline{U})/\sigma_N)\ln(S_{eff}/S_{eff.base})\right) = 31.791\,\mathrm{MV/m}\,, \tag{B1.11}$$

with $S_{eff} = 0.01\,\mathrm{m}^2$, $S_{eff.base} = 1.42\,\mathrm{m}^2$, $\sigma/\overline{U} = 0.0344$, $\sigma_N = 1.1938$ and $N = 80$. The breakdown gradient in a uniform field for the Pelletron, with $L = 0.416\,\mathrm{m}$, is given by

$$E_{uni} = E_{asm}\left(1 + a_{asm}/(p_{20}L)^{m_{asm}}\right) = 31.791\,\mathrm{MV/m}\,. \tag{B1.12}$$

The breakdown gradient in a nonuniform field, with $R_{av} = 0.00635\,\mathrm{m}$, is given by

$$E_{br} = E_{uni}\left(1 + a_{uni}/(p_{20}R_{av})^{m_{uni}}\right) = 34.677\,\mathrm{MV/m}\,. \tag{B1.13}$$

The breakdown normalized voltage, using $E_{max}/U_{calc} = 7.47\ \mathrm{m}^{-1}$, according to Fig. B1.1, is given by

$$U_{norm} = E_{br}/\left(E_{max}/U_{calc}\right) = 4.644\,\mathrm{MV}\,. \tag{B1.14}$$

For the breakdown voltage using $k_{rel} = 1$ and $k_{pol} = 1$, and considering two values for the coefficient of conditioning $k_{cdtn} = 1$ and $k_{cdtn} = 0.8$ as the real coefficient is unknown, we have

$$U_{br} = U_{norm}\left(k_{rel}k_{pol}k_{cdtn}\right) = 4.644 - 3.715\,\mathrm{MV}\,. \tag{B1.15}$$

Comparing the results from (B1.5) and (B1.15) gives

$$\delta U = U_{br}/U_{exp} = 1.26 - 1.01\,. \tag{B1.16}$$

The ratio of 1.26 between the calculated and experimental values is probably a result of an incomplete conditioning of the system. The tandem in Lund is always conditioned without sparks (defined in this calculation to be incomplete), leading to a coefficient of conditioning $k_{cdtn} = 0.8$ in SF_6. The results of the calculation show also that the column is not a weak element (as was supposed in our preliminarily calculations [1]) but that the terminal is. Hence the calculation technique has a satisfactory accuracy of the prediction of the breakdown voltage if a careful numerical calculation of the field is carried out.

References

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