SOME PROBLEMS OF THE DIMENSIONING OF ELECTRICAL INSULATION IN INHOMOGENEOUS FIELDS

By

J. Eisler

Institute for Electric Power Plants, Polytechnical University, Budapest

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1. Introduction

In the practice of electrical insulations very frequently we have to do with more or less inhomogeneous fields. The exact calculation of the field strength or electrical stress in such inhomogeneous fields is more or less complicated in most cases, consequently the common practice is to calculate the stress for the nearly homogeneous parts of the field and then to make corrections for the strongly inhomogeneous parts (edges, voids, etc). It seems worth while to investigate a few such cases, whether it would be possible to reverse this procedure and to start with the dimensioning on these strongly inhomogeneous parts of the insulation. In the following we will try to investigate the possibilities for such a procedure for the embedded electrode type insulation. The problem of the dimensioning of the bushing type insulation has been dealt with in a former paper [1].

We shall consider an insulation to be of the embedded electrode type if one electrode is in contact with only one kind of insulating material. Fig. 1 shows this type and also the two other types of insulations : the supporting and the bushing type.

It is obvious that practically all fields are inhomogeneous, with exception of the field of two infinite parallel planes in a homogeneous material. It seems, however, useful to divide this wide variety of inhomogeneous fields in two groups. We propose to consider a field inhomogeneous in the first degree if a partial breakdown is not possible in it ; therefore in this respect the field is more similar to the homogeneous field in which a partial breakdown is also impossible.

These inhomogeneous fields in which a partial breakdown is possible, which are therefore "more inhomogeneous" belong, according to our proposal, to the second group : they are inhomogeneous in the second degree.

It seems that insulations in air, in oil, etc. in which a partial breakdown could be tolerated for a short time, e. g. due to testing or to overvoltages, are in certain cases to be dimensioned differently from those in which a partial breakdown could not be allowed at all.

It is obvious that we cannot tolerate partial breakdown in a solid material, but this is not always the case in gas-filled voids of a solid material. If a partial breakdown could be tolerated, then it were possible to carry out the dimensioning in such a way, that at normal operating voltage no partial breakdowns should occur, but at testing or at overvoltages we allow such partial breakdowns in the form of glow discharges.

After all these preparatory considerations we shall now try to investigate our problem in detail. It must be pointed out that we do not propose entirely new principles — the impossibility of such a task is quite obvious. We will only try to demonstrate in a few examples that the known principles could perhaps be used for dimensioning from a somewhat different point of view.

We shall start with the embedded electrode type with only one insulating material.

2. Embedded electrode type in homogeneous material

This type of insulation is very frequently applied in gases, less frequently in oil and seldom in solid material.

2.1. *Air and other gases*

Obviously the breakdown voltage of an insulation is always determined by the parts where the stress is maximum. In most cases this occurs on the edges of the electrodes. It is known from the work of Schwaiger [2] and others, that

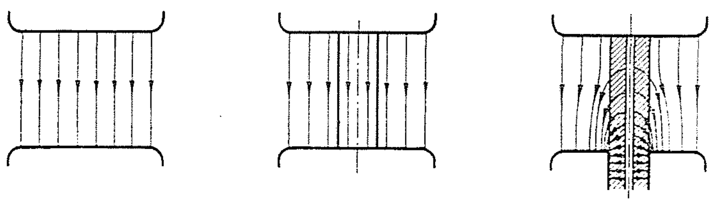

Fig. 1

a) Embedded electrode type, *b)* Supporting type, *c)* Bushing type

the edges can be considered in most important practical cases as parts of cylinders. Dreyfus [3] showed by using conformal transformation how the field of the "cylindrically rounded-off edge-plane" electrode arrangement can be calculated. The ratio $\frac{E_{\max}}{E}$ as a function of $\frac{a}{r}$ is shown on Fig. 2. This field is less inhomogeneous than the "cylinder-plane" field (Fig. 3) with the same cylinder radius r and electrode distance a. The ratio of $E_{\max}$ to $E_{average} = \frac{U}{a}$ is shown for both cases in Fig. 4. Both these electrode arrangements may be inhomogenous in the first or in the second degree, depending on the ratio $\frac{a}{r}$ and on r.

Table I

Voltages and maximum dielectric stresses of partial (U_g ; E_{gm}) and total breakdown (U_b ; E_{bm}) for cylinder-plane arrangement. (See Fig. 3 and Fig. 5.)

$r = 0,4$ mm (2r = 0,8 mm)

a cm	0,2	0,37	0,45	0,6	0,65	0,75	0,9
U_g kV	—	—	—	—	7,4	7,8	8,3
E_{gmax} kV/cm	—	—	—	—	54,5	55	55,5
U_b kV	4,0	5,5	6,2	7,1	7,8	0,0	10,8
E_{bmax} kV/cm	50	52	55	56	57,2	62	71

$r = 1$ mm (2r = 2 mm)

a cm	0,3	0,4	0,625	0,67	0,77	1,08	1,3	1,96
U_g kV	—	—	—	—	11,1	12,3	13,2	15,6
E_{gmax} kV/cm	—	—	—	—	46	44	44	44
U_b kV	6,0	7,3	8,4	10,1	11,2	12,8	14,8	24,8
E_{bmax} kV/cm	40	40,5	42	43,5	46,5	48	49	69

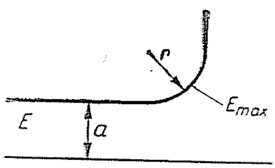

Fig. 2/a
Electrode arrangement

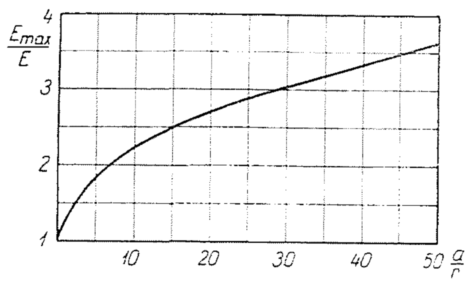

Fig. 2/b
$\frac{E_{\max}}{E}$ as function of a/r

Table I shows for the "cylinder-plane" arrangement that for the value of $r = 0,04$ cm the field is inhomogeneous in the first degree for distances a smaller than 0,6 cm, and for $r = 0,1$ cm for distances smaller than 0,7 cm. If the distances are greater than these values, a partial breakdown will occur, the field is inhomogeneous in the second degree.

It should be here mentioned, that especially if r is small, of the order of 10^{-1} cm, it is worth while taking into consideration, that the breakdown strength of gases (and also of liquids) depends on r. This can be expressed e. g. for air by the Peek formula (also see our values given in Table I and Fig. 5).

$$E_b = 21 + \frac{7}{\sqrt{r}} \text{ kV/cm} . \tag{1}$$

We shall demonstrate our statement on a few examples.

As is well-known, the maximum field strength for the "cylinder-plane" arrangement can be expressed by

$$E_{\max} = \frac{U}{r \ln \dfrac{\sqrt{a^2 + 2ar} + a}{\sqrt{a^2 + 2ar} - a}} \sqrt{\frac{a + 2r}{a}} \tag{2}$$

or if $r \ll a$, by

$$E_{\max} \approx \frac{U}{r \ln \dfrac{2(a+r)}{r}} \cong \frac{U}{r \ln \dfrac{2a}{r}} . \tag{3}$$

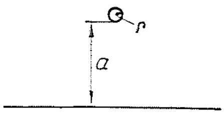

Fig. 3
Cylinder plane electrode arrangement

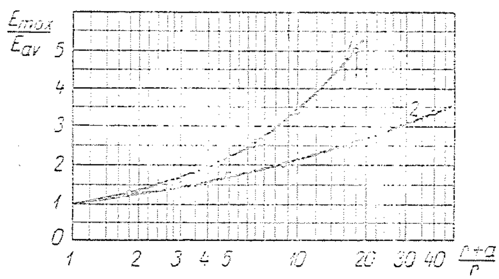

Fig. 4

curve 1 $\frac{E_{\max}}{E_{av}}$ for the electrode arrangement cylinder-plane

curve 2 the same for the electrode arrangement cylindrically rounded off edge-plane

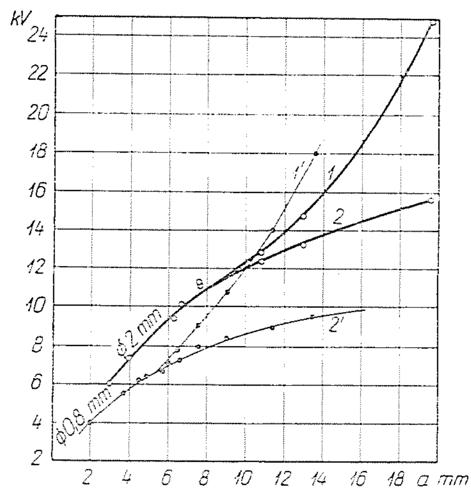

Fig. 5
Voltages for partial (2; 2′) and total breakdown (1; 1′) as function of a with $2r = \varnothing$ as parameter in cylinder-plane arrangement

Obviously, we must dimension in such a way, that $E_{\max}$ will be smaller then E_b. If $E_{\max} = kE_b$, where $0 < k < 1$, then the distance needed is

$$a = \frac{r}{2} e^{\frac{U}{kE_b r}} . \tag{4}$$

From this formula one sees that we get a smaller distance a if we take into account that E_b is not constant and depends on r as given in the Peek formula.

A numerical example gives, if $U = 86$ kV (test voltage for 35 kV operating line voltage), $r = 0{,}3$ cm

$$a_1 = 10^5 \text{ cm with } E_{\max} = E_b = \text{const} = 21 \text{ kV/cm.}$$

$$a_1' = 8{,}9 \cdot 10^2 \text{ cm with } E_{\max} = E_b = 21 + \frac{7}{\sqrt{r}} = 33{,}9 \text{kV/cm.}$$

These results prove that if we will not permit a partial breakdown even at the test voltage of 86 kV, we cannot use electrodes with so small a radius.

The distances needed for the normal operating voltage to earth $\frac{35}{\sqrt{3}} \cong$ $\cong 20$ kV are only

$$a = 3{,}6 \text{ cm (with } E_b = \text{const} = 21 \text{ kV/cm)}$$

$$a' = 1{,}1 \text{ cm (with } E_b = 21 + \frac{7}{\sqrt{r}} = 33{,}9 \text{ kV/cm).}$$

If on the contrary we allow partial breakdown at the test voltage, the distance needed (which is much greater than 1,1 cm, but much smaller than 8,9. 10^2 cm) can be experimentally determined. If this should not be known from experiments, we may calculate the *maximum* distance needed from the formula giving the experimental values for the electrode arrangement „point-plane" which is certainly more inhomogeneous than our electrode arrangement "cylinder-plane".

The distance needed will be according to the formula

$$U_b = 3{,}5\, a + 10 \text{ kV [4]}$$

$$a \geq \frac{U_b - 10}{3{,}5}\,. \tag{5}$$

This gives us in our particular case

$$a = 21{,}2 \text{ cm}.$$

If we make the distance $a \geqq 21{,}2$ cm, it is certain that we will have no discharges at the normal operating voltage and no total breakdown at the test voltage.

We see that by permitting partial breakdown above the operating voltage we may also get reasonable dimensions for so small a radius as $r = 0{,}3$ cm.

We may calculate the voltage by which the partial breakdown occurs from formula (3):

$$U = r E_b \ln \frac{2\,a}{r} = 0{,}3 \cdot 33{,}9 \ln \frac{2 \cdot 21{,}2}{0{,}3} = 51 \text{ kV.}$$

We have seen that if we substitute the electrode with edges of a radius r by a cylinder of the same radius, we can get the dimensions needed from the known formulae of electrostatics and from the experimental results for the function $E_b = f(r)$. We will see, however, that by this substitution we have introduced too severe conditions, consequently we get too great distances.

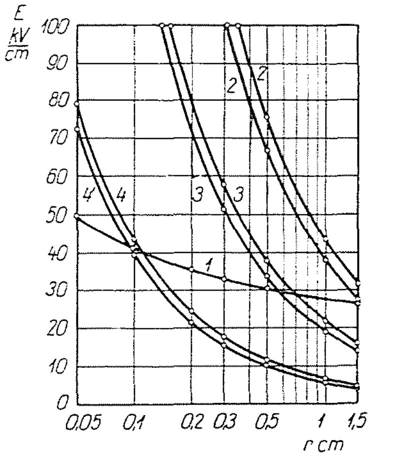

Fig. 6

1. Breakdown dielectric stress as function of r for air in cylinder-plane arrangement on the surface of the cylinder electrodes
2, 3, and 4. E_{max} for $U = 30$, 100 and 200 kV, $a = 50$ cm 2', 3' and 4' E_{max} for $U = 30$, 100 and 200 kV, $a = 100$ cm

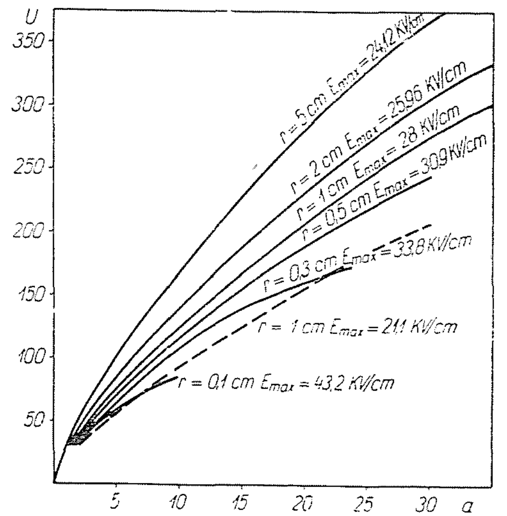

Fig. 7

Breakdown voltages as function of a with r as parameter

Now let us consider the electrode arrangement "cylindrically rounded-off edge-plane". We find from Fig. 2*b* graphically for 86 kV, $r = 0,3$ cm

$$a_2 = 14,5 \text{ cm for } E_b = \text{const} = 21 \text{ kV/cm}$$

$$a_2' = 7,3 \text{ cm for } E_b = 21 + \frac{7}{\sqrt{r}} = 33,9 \text{ kV/cm}\,.$$

It can be seen that for this electrode arrangement we do not even get a partial breakdown at a test voltage of 86 kV and a distance of 7,3 cm.

It must be mentioned, however, that the plane parts of the electrodes should not be too small, because the diagram given is exactly valid only if the plane parts are infinite.

The dimensioning may be facilitated with graphs of various kinds. We will show only two, as examples. On Fig. 6, curve *1* shows E_b as a function of r, curves *2*, *3* and *4* E_{max} as a function of r with a and U as parameters. The intersection of the curves *2*, *3* and *4* with *1* determines the minimum permissible r for the given conditions. On Fig. 7 we show curves $U = f(a)$ with r as parameter for the electrode arrangement "rounded-off edge-plane".

Both kinds of graphs give the initial discharge voltages or initial field strengths. If we do not permit partial breakdown, we may carry out the dimensioning with such graphs, taking the test voltage as a basis.

If the distances we get in such a way are too great, we have two alternatives.

1. We may choose a greater value of r
2. we may permit partial breakdown above the normal operating voltage.

In the latter case we must have experimental values which give the total

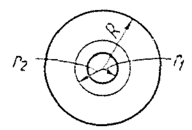

Fig. 8
Electrode arrangement two concentric cylinders with two dielectrics

breakdown voltage for the given conditions. As we have already seen, the maximum of the distance needed to avoid total breakdown may be calculated from the formula for the "point-plane" arrangement.

2.2. *Oils and other liquids*

The methods may be used in the same way as for gases, but one must consider that the function $E_b = f(r)$ is not always as well-known as in the case of air. Another difficulty is that in liquids the distances are much smaller, therefore, it cannot always be supposed that E_b is only a function of r.

2.3. *Solid materials*

The methods of calculation may be the same, but it must be taken into account that in solid materials a partial breakdown could not be permitted even at the highest voltage which may occur.

A practical difficulty further lies in the fact that we have comparatively few reliable results of the function $E_b = f(r)$ for solid materials. Therefore it seems to be, for the time being, the best procedure to calculate with a value of E_b valid for nearly homogeneous fields. If we proceed in this way, the error will lie in the direction of safety.

The distance needed for a given r and U may be determined by calculation or by graphical methods. In most cases we may consider the edges as "cylinder-plane" or as "cylindrically rounded-off edge-plane" and we always have to take for basis the *highest possible* voltage, because a partial breakdown cannot be tolerated.

3. Embedded electrode type insulation with two or more insulating materials

3.1. *Electrode coverings*

It is a well-known fact that we can considerably diminish the distances needed in air or in oil if we use on the edges of the electrodes a covering of solid insulating material. One might think that the insulating material used as a covering ought to have a great permittivity. However, this supposition is wrong if we apply the covering in order to diminish the electrical stress (field strength) in our gaseous or liquid insulating material. It is not diffcult to demonstrate our statement if we substitute, e. g., our electrode arrangement "cylinder-plane" by the electrode arrangement "two concentric cylinders" (Fig. 8), which gives, as is well-known, a somewhat greater stress than the "cylinder-plane" arrangement of same distance R-r_1 and same voltage U.

The maximum stresses are in both cases

$$E_{\max} \frac{U}{r_1 \ln \frac{R}{r_1}} \tag{7}$$

and

$$E'_{\max} = \frac{U}{r_1 \ln \frac{2\,(a + r_1)}{r_1}} = \frac{U}{r_1 \ln \frac{2R}{r_1}} \approx \frac{U}{r_1 \left(\ln \frac{R}{r_1} + \ln 2 \right)} < E_{\max}\,. \tag{8}$$

Then, taken from a well-known formula of elementary electrostatics, the maximum stresses on the surface of the inner electrode of radius r_1 and on the surface of the covering of radius r_2 and permittivity ε_1 are :

$$E_{1\max} = \frac{U}{r_1} \frac{\varepsilon_2}{\varepsilon_2 \ln \frac{r_2}{r_1} + \varepsilon_1 \ln \frac{R}{r_2}} \tag{9}$$

and

$$E_{2\max} = \frac{U}{r_2} \frac{\varepsilon_1}{\varepsilon_2 \ln \frac{r_2}{r_1} + \varepsilon_1 \ln \frac{R}{r_2}}\,. \tag{10}$$

or

$$E_{2\max} = \frac{U}{r_2} \frac{1}{\frac{\varepsilon_2}{\varepsilon_1} \ln \frac{r_2}{r_1} + \ln \frac{R}{r_2}}\,. \tag{10}$$

Obviously, $E_{2\max}$ diminishes if ε_1 diminishes. Therefore, we should use for the covering a material with as small a permittivity ε_1 (and as great a breakdown strength) as possible.

We will now consider a numerical example. Let r_1 be 0,3 cm as in a previous example (page 5),

$$U = 86 \text{ kV}, \; E_b = E_{\max} = 21 + \frac{7}{\sqrt{r}} \text{ kV/cm}.$$

Then we get for R, if we use no covering

$$R = 1470 \text{ cm}. \tag{12}$$

With a covering of 0,3 cm thickness and $\varepsilon_1 = 2$

$$R = 45{,}7 \text{ cm} \tag{13}$$

and with a covering of 0,7 cm thickness and $\varepsilon_1 = 2$

$$R = 11{,}8 \text{ cm}. \tag{14}$$

If the permittivity of the solid insulating material is $\varepsilon_1 = 4$, then we get for R the values

$$R'_{0,3} = 54{,}3 \text{ cm} \tag{15}$$

and

$$R'_{0,7} = 16 \quad \text{cm}. \tag{16}$$

It is to be seen that R will be greater if the permittivity E_1 increases.

The calculation for, e. g., the "rounded-off edge-plane" electrode arrangement is somewhat involved, so that we will not consider it here. It is obvious, however, that for such arrangements it will also be advantageous to use a covering with as small a permittivity as possible.

3.2. *Gas-filled voids*

Now we will consider another problem, that of the voids in a solid insulating material. The field in a solid insulating material with gas- or oil-filled voids is also inhomogeneous between parallel plate electrodes. If the thickness of the void is comparatively small, then we can take for the field strength in the void

$$E_v = \frac{U}{a_v + \dfrac{\varepsilon_v}{\varepsilon_s} a_s} \tag{17}$$

where a_v and a_s are the thicknesses of the voids resp. of the solid insulating material, ε_v and ε_s the relative permittivities, U the voltage. $a = a_v + a_s$ is the total distance of the electrodes. It is obvious that in nearly homogeneous fields E_v remains the same, if instead of one void with a thickness a_v we have n voids with thicknesses $a'_v = \frac{a_v}{n}$, (Figs. 9, 10)

$$E_v = \frac{U}{n\, a'_v + \frac{\varepsilon_v}{\varepsilon_s} a_s} \,. \tag{18}$$

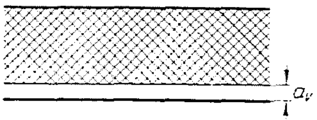

Fig. 9
Solid material and one void between parallel-plate electrodes

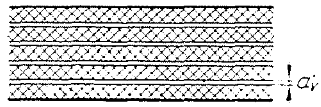

Fig. 10
Solid material and four voids, with the same resultant thickness as in Fig. 9.

The maximum value of E_v is certainly less than

$$E'_v = \frac{U}{\frac{\varepsilon_v}{\varepsilon_s} a} \tag{19}$$

because we get this value if the total thickness of the voids tends towards zero. Taking without great error $\varepsilon_v \approx 1$, we get

$$E_{v\,\max} \leqq E'_v = \frac{\varepsilon_s U}{a} \tag{20}$$

that is ε_s-times as much as if the gap were filled with gas or solid material alone.

At first sight therefore it seems that thin voids are very dangerous, because the stress is very high in them. If, e. g., $\varepsilon_s = 4$ (bakelite plate or pressboard), $a = 1$ cm, $U = 40$ kV, then

$$E'_v = \frac{4 \cdot 40}{1} = 160 \text{ kV/cm},$$

a field strength which surpasses the 21 kV/cm commonly used as breakdown strength for air nearly 8 times.

This problem is very important for all insulations where laminated materials are used. It is very interesting, however, that the experiences arrived at with such kinds of insulation are not as bad as might be expected from previous considerations.

We can explain this, if we take into account that the breakdown strength of air in very thin layers is, as is well-known, much higher than 21 kV/cm, according to Paschen's law (see Fig. 11) ≈ 300 V is minimum voltage which can cause a breakdown in air. Fig. 11 shows that this minimum lies at 0,57

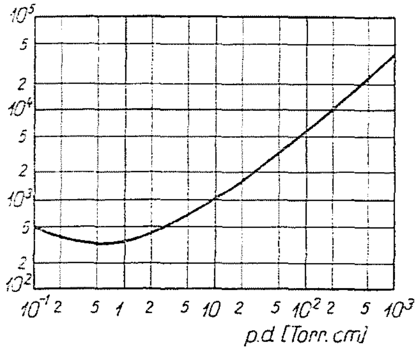

Fig. 11

Paschen's Law. Breakdown voltage for air as a function of $p \cdot d$

Torr cm, which for 1 at = 760 Torr gives $0{,}75 \cdot 10^{-3}$ cm. E_b under such conditions is

$$E_b = \frac{0{,}3\ \text{kV}}{0{,}75 \cdot 10^{-3}\ \text{cm}} \approx 400\ \text{kV/cm!} \tag{21}$$

We may express this result as follows :

The condition for a breakdown in air is

$$E_v a_v' \geq 0{,}3\ \text{kV}. \tag{22}$$

If $E_v a_v' < 0{,}3$ kV, a breakdown in the void is impossible. According to formula (18),

$$E_v = \frac{U}{n\, a_v' + \frac{\varepsilon_v}{\varepsilon_s} a_s}, \tag{23}$$

or

$$E_v\, a_v' = \frac{U}{n\, a_v' + \frac{\varepsilon_v}{\varepsilon_s} a_s} a_v' \leqq 0{,}3\ \text{kV}. \tag{24}$$

We may now calculate the maximum of void thickness which is permissible if we want to avoid breakdown in the void. If we neglect na'_v with respect to $\frac{\varepsilon_v}{\varepsilon_s} a_s$, then $a_s \approx a$, $\frac{U}{a} \approx E_s$, the field strength in the solid material for the case of $\varepsilon_v \approx 1$

$$\frac{\varepsilon_s U}{a} a'_v \leqq 0{,}3 \text{ kV}, \tag{25}$$

or

$$\varepsilon_s E_s a'_v \leqq 0{,}3 \text{ kV}, \tag{26}$$

or

$$E_s a'_v \leqq \frac{0{,}3}{\varepsilon_s} . \tag{27}$$

The maximum permissible value of a'_v is then

$$a'_v \leqq \frac{0{,}3}{E_s \varepsilon_s} . \tag{28}$$

Thus a'_v diminishes if E_s and ε_s increase. That means that we can avoid breakdown in the voids if we choose a low value for E_s. This result is well-known, but from formula (28) we may calculate the maximum permissible value of E_s as being

$$E_{s\,\max} = \frac{0{,}3}{a'_v \varepsilon_s} . \tag{29}$$

As an example we may consider an impregnated paper insulation with $\varepsilon_s = 4$. a'_v is the thickness of one single paper layer.

In this particular case $E_{s\,\max} = \frac{0{,}075}{a'_v}$.

If $a'_v = 10^{-3}$ cm then

$$E_{s\,\max} = 75 \text{ kV/cm} .$$

It is interesting to note that the *number* of the voids seems to be irrelevant, only the *thickness* of the individual void is essential.

One might think that from this we can draw the paradox conclusion that an insulation in which there are practically *only* voids would be very advantageous, because the breakdown strength would then be the value calculated from Paschen's law.

However, it is not difficult to show that this conclusion is erroneous. The field strength in the solid material is

$$E_s = \frac{U}{\frac{\varepsilon_s}{\varepsilon_v} n a'_v + a_s} \tag{30}$$

or, with $\varepsilon_v = 1$,

$$E_s = \frac{U}{\varepsilon_s n a_v' + a_s}. \tag{31}$$

Let the overall thickness of the solid material decrease towards zero (which is naturally only an approximation, a_s may be very small but not zero), then with $na_v' = a$ we get

$$E_s' = \frac{U}{\varepsilon_s a} \tag{32}$$

because now $na_v' \approx a$ and obviously $E_s' \leqq E_{bs}$, where E_{bs} is the breakdown strength of the solid insulating material.

Thence

$$\frac{U}{\varepsilon_s a} \leqq E_{bs} \tag{33}$$

or with $\frac{U}{a} = E$, the overall permissible field strength of the whole arrangement will be

$$E \leqq E_{bs} \varepsilon_s \tag{34}$$

In the present paper we have not considered the bushing type insulation, but we wish to remark that its efficiency, as already shown in a previous paper, is very poor indeed. E. g. for a distance of 80 mm and the electrode arrangement "rounded-off edge-plane" with $r = 0{,}3$ cm, we experimentally got a breakdown voltage of 83 kV in air. If the gap between the electrodes was filled with bakelite plates ($\varepsilon = 4{,}5$) of an overall thickness of 80 mm, then we got partial breakdown (glow discharges) at $\approx 10{,}5$ kV, according to the formula

$$U_b = 8{,}1 \left(\frac{a}{\varepsilon}\right)^{0{,}45} \text{ (Kappeler).}$$

4. Conclusions

We have seen that it seems advantageous to start the dimensioning calculations by evaluating the dimensions needed on the edges of the electrodes, by using the pioneer works of Schwaiger and of Dreyfus. The electrodes may be substituted by electrode arrangements "cylinder-plane" of "cylindrically rounded-off edge-plane". It is worth taking into account the dependence of E_b on the radius r. It seems very useful to determine the function $E_b = f(r)$ for the liquid and solid insulating materials most frequently used, and it also seems that voids, if thin enough, are not as dangerous as one might suppose. The permissible stress in the solid material, as a function of void thickness, may be easily calculated. With coverings of solid insulating material we are able to diminish the distances needed considerably, if the permittivity of the solid insulating material is small enough and if it has a sufficiently great electric strength.

Summary

It is proposed in the paper to start by the dimensioning already with the calculation on the most inhomogeneous parts of the field (on the edges) on the voids etc. As it is known, the edges can be regarded in most cases as cylindrical electrodes. The principles are demonstrated on the most frequently occuring practical cases (calculation of the distances needed, the permissible dimensions of voids, dimensions of coverings). It is shown, that it is worth while to take into consideration that the dielectric strength of air and oil depends on the electrode radius, and that it may be useful to use for coverings materials with as low a permittivity as possible.

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Prof. Dr. J. EISLER, Budapest Budafoki út 8.