Power Losses in Insulating Materials

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SYNOPSIS: It is shown that a satisfactory measure of power loss in a dielectric is the product of phase angle and dielectric constant. Although the dielectric constant need not be explicitly considered in the design of condensers, it is important in such cases as the design of apparatus panels, and vacuum tube bases. The method used in measuring phase angle and dielectric constant is discussed.—*Editor.*

IN working with electrical circuits operating at very high frequencies and moderately high voltages, such as radio transmitting circuits, it is found that failure in the insulation is seldom due to puncture or flashover as is usually the case at power frequencies, but is generally due to excessive heating which, in turn, causes both mechanical and chemical disintegration. As this heating is due almost entirely to the energy losses occurring in the dielectric itself, it is essential that the factors involved in the calculation of these losses be well understood.

In the past, various indices have been used as a measure of power losses for the purpose of comparing different dielectrics. Of these, power-factor, phase difference and watts per cubic centimeter probably are the most common. None of these, however, is very satisfactory for this purpose since the first two give only part of the desired information, and the last is not in any sense a property of the material, as it is dependent on both the voltage gradient and the frequency.

However, it can be shown that the product of the phase difference and the dielectric constant of a material is to a sufficient approximation an index of its power losses. Let us consider for a moment the complete expression for dielectric loss. In any condenser the capacity

$$C = a\,K$$

where a is a constant depending on the geometrical dimensions, and K is the dielectric constant. If a voltage, E, is applied to the condenser the power loss

$$P = E\,I\,sin\,\Psi,$$

where I is the current through the condenser and Ψ is the phase difference of the dielectric; $sin\ \Psi$ being the power factor. (Plate resistance assumed negligible.) For small angles this may be written

$$P = E\,I\,\Psi,^1$$
$$= 2\pi f\,E^2\,a\,K\,\Psi,$$

since $I = 2\,\pi f\,E\,C$, f being the frequency.

In the particular case of a condenser of two parallel plates

$$a = m\frac{A}{d},$$

where m is a constant depending on the units used, A the area of one plate, and d the thickness of the dielectric.

Hence $$P = 2\pi f\,E^2\,m\frac{A}{d}\,K\,\Psi.$$

But the volume of dielectric $V = A\,d$, and the voltage gradient $E_g = \frac{E}{d}$. Therefore the power loss per unit volume is

$$\frac{P}{V} = m'\,E_g^2 f\,K\,\Psi, \qquad (1)$$

where $m' = 2\,\pi\,m$, and $m'\,K\,\Psi$ = loss per unit volume at unit frequency and potential gradiant.

Thus it is seen that while no single factor of the expression can be used to represent the losses, the product of phase difference and dielectric constant [2] can be used in this way. Furthermore, for most good insulators, this product remains fairly constant throughout a considerable range of voltage and frequency. For example, we have found that for such materials as wood, phenol fibre, and hard rubber, the change of this product with frequency is of the order of 20 per cent from 200,000 cycles to 1,000,000 cycles. Hence it is possible to compare directly the losses in different materials even though the measurements were not made at exactly the same frequency.

If Ψ is taken in degrees, E_g in volts per centimeter, and f in cycles per second, the constant m' reduces to $0.97\times10.^{-14}$. Hence, for a frequency of 1,000,000 cycles per second and a potential gradient of 10,000 volts per centimeter, the product of K and Ψ (in degrees) is within 3 per cent of being numerically equal to the dielectric loss in watts per cubic centimeter.

[1] The substitution of the angle for its sine is correct to better than 5 per cent for angles as large as 30°.

[2] This relation has been brought to the attention of the Committee on Electrical Insulating Materials of the American Society for Testing Materials and is included in their "Tentative Method of Test for Phase Difference (Power Factor) and Dielectric Constant of Molded Electrical Insulating Materials at Radio Frequencies."

Data showing the variations with frequency and temperature of the phase difference, dielectric constant, and their product, for several materials are given in Tables I. and II. below.

TABLE I.

Dielectric Constant, Phase Difference and Their Product for Several Commercial Insulating Materials [3]

Material	Frequency C. P. S.	Dielectric Constant	Phase Difference Degrees	Product
Phenol Fibre A	295,000	5.9	2.9	17.1
	500,000	5.8	2.9	16.8
	670,000	5.7	2.9	16.5
	1,040,000	5.6	3.3	18.5
Phenol Fibre B	190,000	5.8	2.2	12.7
	500,000	5.6	2.5	14.0
	675,000	5.6	2.6	14.6
	975,000	5.6	2.8	15.7
Phenol Fibre C	200,000	5.4	2.1	11.3
	395,000	5.4	2.2	11.8
	685,000	5.3	2.3	12.2
	975,000	5.2	2.4	12.5
Phenol Fibre D	194,000	5.4	4.2	22.7
	500,000	5.2	3.9	20.3
	695,000	5.2	3.9	20.3
	1,000,000	5.1	3.8	19.4
Wood (Oak)	300,000	3.2	2.1	6.7
	425,000	3.3	2.0	6.6
	635,000	3.3	2.2	7.3
	1,060,000	3.3	2.4	7.9
Wood (Maple)	500,000	4.4	1.9	8.4
Wood (Birch)	500,000	5.2	3.7	19.2
Hard Rubber	210,000	3.0	.5	1.5
	440,000	3.0	.5	1.5
	710,000	3.0	.5	1.5
	1,126,000	3.0	.6	1.8
Flint Glass	500,000	7.0	.24	1.68
	720,000	7.0	.24	1.68
	890,000	7.0	.23	1.61
Plate Glass	500,000	6.8	.4	2.7
Cobalt Glass	500,000	7.3	.4	2.9
Pyrex Glass	500,000	4.9	.24	1.18

[3] All of the samples had been in the laboratory for some time during summer weather without artificial drying or other special preparation.

TABLE II.

Variation with Temperature of Dielectric Constant, Phase Difference and Their Product for Some Commercial Insulating Materials (Frequency 500,000 C. P. S.) [4]

Material	Temperature Degrees C	Dielectric Constant	Phase Difference Degrees	Product
Molded Phenol Product A......	21	5.6	3.1	17.4
	71	6.9	6.5	45.0
	120	10.4	22.0	230.0
	21	5.5	2.9	16.0
Molded Phenol Product B......	21	5.2	2.3	12.0
	71	6.1	3.7	22.5
	120	7.6	8.9	68.0
	21	5.2	2.3	12.0
Molded Phenol Product C......	21	5.3	2.8	14.8
	71	6.1	3.6	22.0
	120	6.7	9.6	64.0
	21	5.0	2.5	12.5
Phenol Fibre B..............	21	5.6	2.5	14.0
	71	6.6	3.1	20.5
	120	6.5	4.6	30.0
	21	5.4	2.4	13.0
Phenol Fibre C..............	21	5.4	2.3	12.4
	71	6.0	3.9	23.5
	120	5.3	4.9	26.5
	21	4.9	2.4	11.8
Phenol Fibre D..............	21	5.2	3.9	20.3
	71	6.6	6.9	46.0
	120	6.3	13.5	85.5
	21	5.1	3.1	15.8
Hard Rubber.................	21	3.	.5	1.5
	71	3.1	1.2	3.7
	120	3.2	3.7	11.8
Pyrex Glass..................	20	4.9	.24	1.18
	74	5.0	.4	2.0
	125	5.0	.7	3.5
	19	4.9	.25	1.22

The above data were obtained by the resistance variation method,[5] Fig. 1. Each value of phase difference and of dielectric constant represents the average of at least five readings on a single sample using not less than three different values of the known resistance R. A condenser, the dielectric of which consists of the material to be tested, is connected in series with a suitable inductance, a known re-

[4] The measurements on each sample were made in the order in which they are given in the table.

[5] Bureau of Standard Circular No. 74, p. 180.

sistance which can be varied, and a radio frequency ammeter. An oscillator is coupled loosely to the inductance and its frequency varied until resonance is obtained as indicated by maximum current through the meter. Without changing the tuning, the resistance is changed

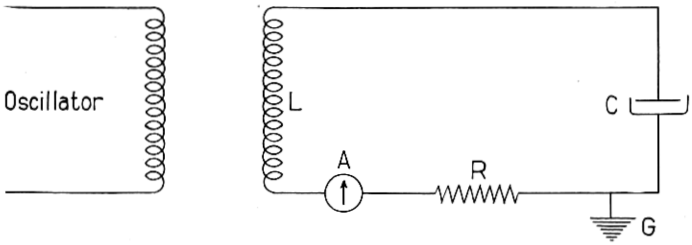

Fig. 1

and a second reading of current is obtained. Then, since the e.m.f. induced in the measuring circuit is the same in both cases, if R_1 and R_2 are the known resistances, I_1 and I_2 the corresponding currents, and r the resistance of the remainder of the circuit,

$$I_1 (r + R_1) = I_2 (r + R_2),$$

$$r = \frac{R_2 I_2 - R_1 I_1}{I_1 - I_2},$$

or, if R_1 be made zero

$$r = \frac{R_2}{\frac{I_1}{I_2} - 1}.$$

A standardized variable air condenser having negligible resistance is then substituted for the condenser under test and the process repeated except that the circuit is tuned to resonance by varying the capacity instead of the frequency. In this way the resistance of the circuit exclusive of the test condenser may be determined. The difference between these two circuit resistances is the resistance of the test condenser from which the phase difference may be computed. The capacity of the test condenser is equal to the capacity of the standard condenser which produces resonance. From this and the dimensions of the sample, its dielectric constant may be computed.

In addition to the general precautions mentioned in the Bureau of Standards Bulletin, two others should be observed in the measurement of dielectrics. First, the electrodes must be in intimate contact at all points with the surface of the sample, as a very small air space will cause a large error in the values of phase difference and dielectric constant obtained for the sample. For this reason only mercury electrodes have been found suitable, the sample being floated on a pool of mercury forming the lower electrode and the upper electrode being formed by pouring a pool of mercury inside a metal ring on the upper surface of the sample. This introduces the second difficulty. The lower electrode being, of necessity, larger than the upper one, the electric field spreads out considerably beyond the edges of the upper electrode and increases the effective area by an unknown amount.

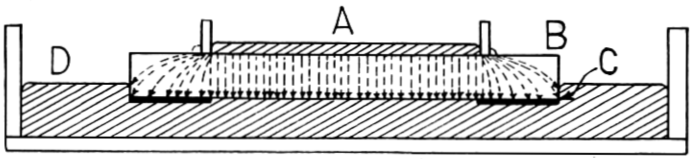

Fig. 2

To determine the magnitude of this error, measurements were made on samples prepared as shown in Fig. 2 *A* is the upper electrode, *B* is the sample under test and *C* is a tinfoil guard ring shellaced to the lower surface of the sample but separated from the lower electrode *D* by a sheet of paper shellaced over the guard ring. The guard ring covers all of the lower surface of the sample except the area equal to the upper electrode and directly under it. The direct capacity[6] between *A* and *D* is measured using the guard ring as a shield to intercept the flux which spreads out around the upper electrode, diverting it away from the measuring circuit. This measurement is made at audio frequency on a completely shielded substitution bridge. The difference between this capacity and the capacity of *A* to *D* without the guard ring is approximately the correction due to this edge effect. Using samples 6 inches square with an upper electrode 5 inches square, this correction was found to be about 7 per cent for samples 1/8 inch thick and 14 per cent for samples 1/4 inch thick. All values of dielectric constant given above have been corrected. The phase difference is not affected appreciably since it is dependent only on the ratio of resistance to reactance and does not involve the area of the sample.

The radio frequency generator used consists of a vacuum tube oscillator having a maximum output of 250 watts. The coupling between the generator and the measuring circuit was very loose and

[6] Direct Capacity Measurement, George A. Campbell, *The Bell System Technical Journal*, July, 1922.

care was taken to avoid capacity couplings. The measuring circuit was shielded from the observer by a metal screen. In spite of these precautions the results obtained on the same sample at different times do not agree as well as might be desired although the individual readings taken at the same time agree in most cases to within 5 per cent. Other observers have found that measurements made on the same sample at intervals of a few hours often differ by more than the apparent error of the measurements and have attributed it to actual changes in the properties of the material.[7] Hence it is possible that at least part of the apparent variation with frequency shown above is due to unknown errors in the measurements or unknown changes in the samples or both.

As an illustration of the error involved in taking only phase difference as a measure of power loss, suppose we wish to compare hard rubber having a phase difference of about 0.5 degree and a dielectric constant of 3., with a certain grade of glass having a phase difference of about 0.3 degree and a dielectric constant of 7. On the basis of phase difference alone the hard rubber appears very much worse than the glass, but when the dielectric constant is taken into account, the glass is found to give a 40 per cent higher power loss. Similarly, some untreated woods were found to have considerably lower losses than the phenol fibres although their phase differences are nearly the same.

Conclusion

In the case of ordinary insulation where the object is to provide a mechanical separator or support, the product of phase difference and dielectric constant is a true measure of the energy loss per unit volume as shown by the equation (1). In the case of a *condenser* where the object is to obtain a given *capacity*, the phase difference alone determines the power loss since in this case the effect of the increased dielectric constant is exactly balanced by the smaller volume of dielectric required.

[7] R. Mesing—*L'Onde Electrique*, April, 1922, p. 235 and Augustin Frigon—*Comptes Rendus*, May 22, 1922, p. 1339.