DIELECTRIC HYSTERESIS AT RADIO FREQUENCIES.*

By

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The investigation of dielectric hysteresis at high frequency, which I have taken as a subject for this paper, has been carried out in order to get data of value to the electrical industry, but the phenomena involved have a still more intimate bearing on the construction of apparatus used in radio telegraphy.†

TRANSFORMER DESIGN.

The design of the high tension transformer, which has been used in the dielectric tests, involved a number of unexpected difficulties, and several models were discarded before one which could be satisfactorily operated was produced. The use of an iron core transformer was not seriously considered for high voltages, because the insulation difficulties, which are great enough without any iron core, would obviously be increased. It is not implied that an iron core transformer may not be found valuable for certain purposes. For instance it may be desired to design a transformer for moderate voltages with substantially the same characteristics as an ordinary low frequency transformer that has a constant transformation ratio regardless of the frequency. However, for the present purpose, where high voltages were desired, no attempts were made to realize such conditions, inasmuch as constant potential characteristics would not be of great value in the measurements of losses. On the other hand it was important to use an apparatus the inherent losses of which were as low as possible, in order to attain great accuracy in the measurements of small quantities of dissipated energy.

In designing the transformer, the feasible alternatives of construction were either the open air type or the oil type. Of these, the open air type was found to be the more practical, partly on account of an inherently greater facility in re-arranging the various coils in order to adapt the transformer for use at dif-

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†With reference to the measurements of dielectric hysteresis, the author wishes to acknowledge the assistance of Mr. S. P. Nixdorff.

ferent voltages and frequencies, and partly because of dielectric losses in the oil itself which would have been so considerable at high voltages that the accuracy of the energy measurements would have been much impaired.

The first transformer which was made consisted of a number of coils designed so as to have minimum internal capacity between the layers of the windings and between the various coils. The insulation losses to be expected are naturally reduced if the internal capacity is kept down to a minimum. Altho the proportioning of the coils was carried as far as could reasonably be expected in this direction, it was found that the insulation losses were excessive. The insulation between the layers of the winding was varnished cambric, and each coil was supported on a frame of fiber. The greatest losses seemed to occur in the fiber spool. It was found that the transformer could be operated only for a short time at a maximum permissible frequency of 40,000 cycles and at about 25,000 volts before it became so hot that it was necessary to interrupt the test. Consequently a new set of coils was made of the same general type, but without the fiber frame and simply taped with cotton. These coils were used in a number of tests at frequencies up to 30,000 cycles. However, it was found that even the varnished cambric insulation between the layers of the winding caused excessive losses. Considerable trouble was experienced from damage caused by corona discharge at high voltages. It was then attempted again to make a fireproof coil, but of somewhat different proportions, by covering the coils with asbestos tape. This proved to be an entire failure, because the heating of the asbestos was excessive even at moderate voltages, and the energy consumption was so great that high voltages could not be obtained at all.

The type of transformer that finally proved successful consists of a considerable number of thin, flat coils wound with wire having a braided cotton covering, but without any further insulation or spacing between layers. The average diameter of the coils is about one foot (30 cm.) and there are 84 turns per coil, each consisting of four wires side by side, the wires being arranged in 21 layers. A voltage ot 100,000 can be generated by 18 of these coils in series. Furthermore, it appears that the insulation losses have been entirely eliminated, at least as far as it has been possible to determine them by measurement, and that the losses of the transformer, outside of the I^2R losses, seem to be only the dielectric losses in the air. The coils are insulated as described by nothing but dry cotton, and they are naturally

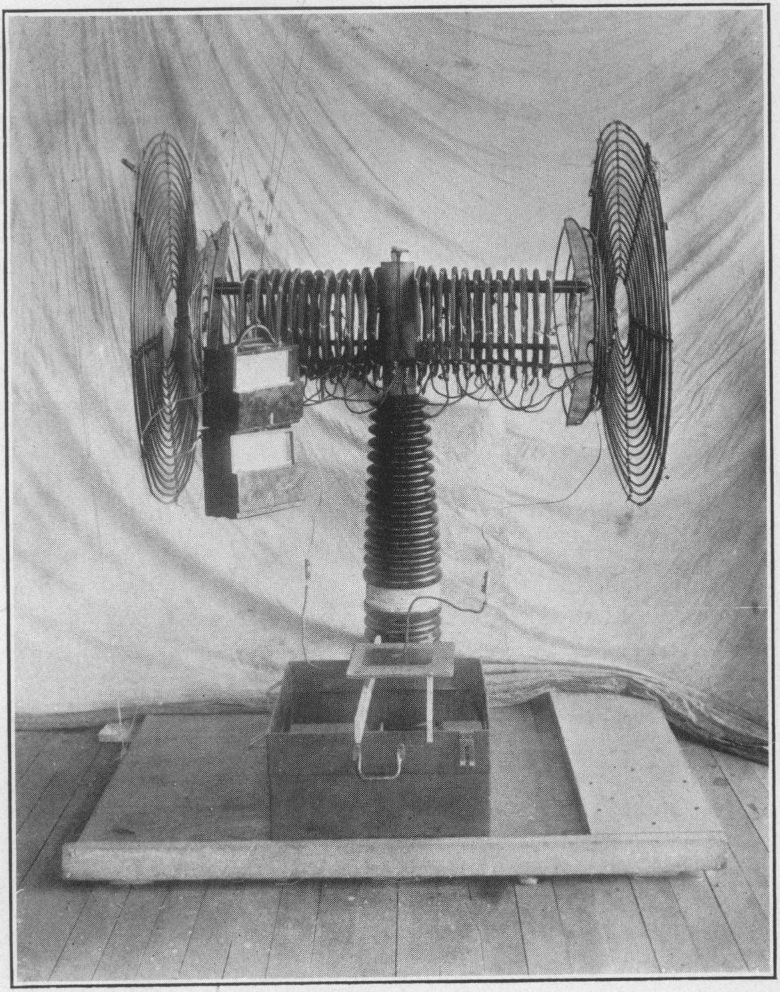

FIGURE 1—Transformer for 100,000 Volts at 100,000 Cycles, Used in Measurements.

susceptible to damage by corona (brush) discharges. It was, therefore, particularly important to construct the transformer in such a way as to protect the coils from exposure to excessive dielectric strains. This has been done by mounting the coils between two end terminals, each sufficiently large entirely to shield the coils from excessive electric strains and to create an electric field of uniform gradient within which the coils are supported. Inasmuch as these terminals or shields are cut by the magnetic field of the transformer, they could not be constructed of solid plates in which eddy currents would be induced, thereby causing serious losses. A convenient structure designed to avoid such losses was made up in the form of a spiral of heavy copper wire with free ends, wound on a wooden frame support. The profile of the frame had an outline with rounded corners, thus avoiding localized dielectric strains in the air. The electrostatic capacity effects produced by these terminal shields is considerable at the high voltages and frequencies used; and it was found, both by calculation and by test, that the capacity of the air circuit would absorb about 200 kilovolt-amperes (K.V.A.) at 100,000 cycles and 100,000 volts. The electrostatic capacity of the terminals was therefore of great importance in connection with the tuning which is absolutely necessary to build up high voltages.

Consequently the number of turns in the coils was so selected as to give inductances fulfilling the requirements for tuning without the addition of an additional external capacity. Any object connected to this apparatus, even a piece of wire attached to the terminals, adds to the electrostatic capacity, and whenever any measurements were made, the added capacity was compensated for by reducing the number of coils in the circuit so as to tune properly at the new voltage and frequency. The assembled apparatus is shown in Figure 1. The transformer coils are mounted on the horizontal supports, which are attached to the top of the large vertical corrugated insulator. The rounded end shield, together with the larger supplementary shields, are clearly seen. The ammeters are suspended by insulating cords in the foreground. In the lower portion of the illustration, a sample under test, between the terminal electrodes, is resting on the top of the oil tank.

If the input (in watts) supplied to the apparatus be measured with the transformers, connecting wire, and necessary instruments in circuit as well as with the sample dielectric properly placed and then if the sample be removed and the input again measured at the same voltage and frequency as before, the difference between the two inputs is the dielectric loss in the sample. In order that these measurements should be accurate, it is evidently important that the losses in the transformer and its accessories should be kept as small as possible compared with those in the sample. This was actually the case in the measurements that have been made, the total losses in the apparatus being only a small fraction of the total energy that was measured.

ENERGY MEASUREMENTS.

The method used for measuring the energy in the radio frequency circuit is in principle, the same as the one described in a paper by the author, delivered before the American Institute of Electrical Engineers on "CORE LOSS IN IRON AT HIGH FREQUENCY." The method is based on the use of both voltmeters and ammeters, because accurate wattmeters for such high frequencies have not been developed. The method depends further on a well-known characteristic of alternating current circuits in which sinusoidal currents are flowing. The impedance can be resolved into an "energy component" and a "wattless component," and the wattless component can be completely neutralized by a suitable choice of inductance and capacity. If the impedance of such a circuit is measured, and the ratio of inductance to capacity varied, various values of the impedance can be obtained and plotted as a curve. This curve passes thru a point of minimum impedance for which the inductance and capacity neutralize each other. At that point, the product of volts and amperes represent the energy component or the equivalent resistance of the circuit. This is the condition of unity power factor.

The apparatus which is used for these measurements is adjusted so as to determine this minimum point in the simplest way, without the necessity of plotting the whole curve. Thus, it is possible to make measurements of energy wherein the watts are obtained directly from the product from the volts and amperes, which latter quantities are being observed. The adjustment which is needed to find this minimum point is made by selecting an inductance which is nearly right, and then finding the exact point of minimum impedance by a slight variation of the frequency. The measurement requires simultaneous observation of a voltmeter and an ammeter; and the condition to be looked for is that at which the ratio between the voltmeter reading and the ammeter reading is a minimum. In order to facilitate this observation without recourse to calculation, the

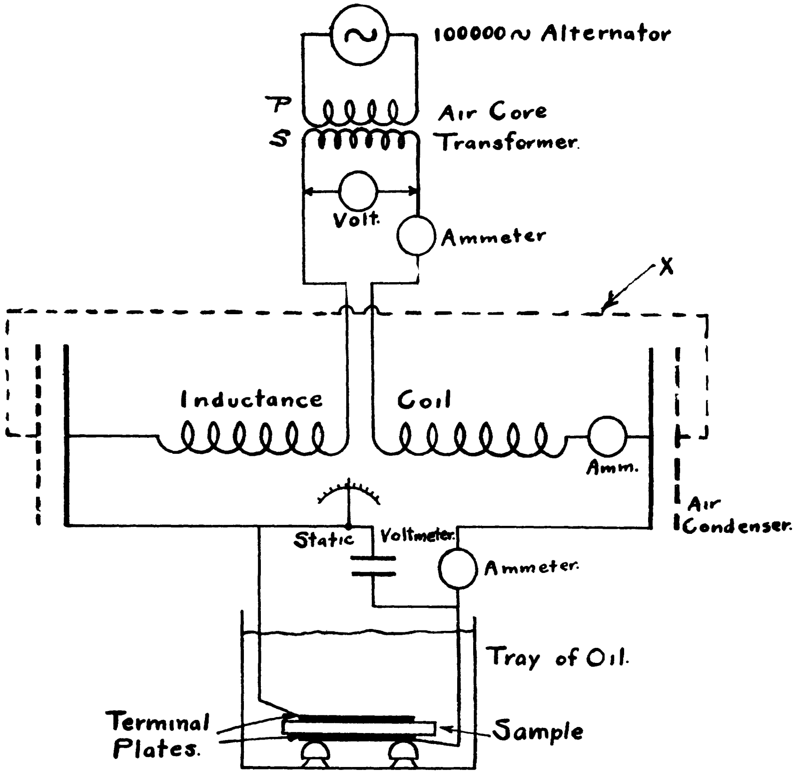

FIGURE 2—Diagram of Connections of Transformer for 100,000 Volts at 100,000 Cycles.

circuit is so adjusted that the voltage remains practically constant while the current goes thru a sharp maximum. It is also possible to arrange the circuits so as to keep the current practically constant while the voltage goes thru a sharp minimum. In other words, the measurements can be made conveniently either on constant potential or on a constant current.

The diagram of connection for a typical arrangement is shown in Figure 2.* The shields or terminals which are used to protect the windings from electrostatic strains are at the same time used as the plates of an air condenser which is needed to create

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*The apparatus used is practically a long coil having distributed capacity and inductance thruout its length, and added end capacities. A stationary wave is produced on this coil by exciting it inductively at its central point from a radio frequency Alexanderson alternator. The coil in question is the long horizontal row of flat coils, and the added end capacities referred to are the terminal circular shields.

The stationary wave produced has maxima of potential at the outer ends of the terminal shields and zero potential at the center of the coil S resonance. If a measurement is made wherein the sample is subjected to a difference of potential, it is convenient to connect the apparatus so as to produce a positive and negative difference of potential at the ends of the transformer secondary with a grounded neutral point. In this case, the energy is introduced at the middle of the high tension coil of the transformer by introducing the energy thru a low tension transformer arranged with a variable ratio of transformation. The energy measurements are made at the point at which the current is led into the high tension coil. The only instruments needed are a hot wire voltmeter and ammeter. It is sometimes convenient to have a static voltmeter connected across the high tension terminals to indicate the voltage impressed on the sample, but it is to be noted that the indications of a static voltmeter sometimes are unreliable, because at high frequencies corona and brush discharges appear at comparatively low voltages. The use of the static voltmeter is not necessary if the inductance of the high tension coil is known, because the voltage can be obtained by multiplying the current by the reactance due to the inductance. It was actually found necessary to use this method in the measurements at the higher potentials. The inductance of the coil was found by calculation, and also by measurement at the lower potentials. This was necessary because at higher potentials the static meters that were available broke down and arced over.

DIELECTRIC STRENGTH OF AIR.

The phenomena which were observed when the high tension oscillation transformer was operated at a high potential were such as to suggest the immediate conclusion that the dielectric constants of the air differ entirely at radio frequencies from those that have been observed at ordinary frequencies. A further analysis has led to a modification of those conclusions, at least in part; and there are several indications that all the abnormal phenomena at very high frequencies can be explained as secondary effects. A theoretically ideal condition may be supposed for which air would have exactly the same characteristics at radio frequencies as it has at audio frequencies. Whether this is the

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whereby it is inductively coupled to coil P and the alternator. In order to produce this stationary wave, it is necessary that the inductance of the long coil, together with its distributed and end capacities, shall cause resonance at the given frequency.

The distributed capacity of the long coil and of the end shields is indicated by the dotted line (X) of Figure 2. This capacity is, of course, only present in effect; and is not actually definitely connected in setting up the apparatus.—(EDITOR'S NOTE.)

case or not, the fact remains that for all practical purposes the phenomena at very high frequencies are radically novel, and any apparatus which is to be subjected to such high frequencies must be quite specially designed. Constants obtained by observation must be known for the materials used, as well as the proper proportioning of parts that are to be used in the radio frequency circuit. For instance, at 100,000 cycles, a small wire is surrounded by so much corona discharge even at a potential difference relative to ground of 15,000 volts, that such potentials can be handled without excessive loss only when observing great precautions. Thus, we must use a cable of at least the thickness of a lead pencil and protect all projecting corners by shields of tin foil. On the other hand, we find practically the same constants for the dielectric strength of air as have been found for ordinary frequencies if the measurements are based on the arc-over distance between spheres of polished brass. The arc-over distance for a pair of spheres of 5 inches (12.9 cm.) diameter was found to be 3 inches at 100,000 volts and 100,000 cycles, and no corona was noticed on the spheres before the arc took place. The difficulty in arranging these measurements consisted in producing this potential difference and conducting it to the spheres without excessive static discharge from the terminals and leads. This could be accomplished only by placing the spheres within the uniform electrostatic field that is created between the transformer terminals or end shields which are used to protect the coils on which the potential is generated. This is obviously an artificial condition and it is safe to say that, for practical purposes, it is not possible to conduct a current, even for short distances, at a potential difference approaching 100,000 volts at such radio frequencies.

DIELECTRIC LOSSES IN INSULATION.

In measuring the losses in solid dielectrics, it was necessary for the reasons given above to immerse the sample under test in oil. The attempts to make measurements in air failed because the air space between the terminals and the sample gave rise to such an excessive loss of energy from corona discharge that the sample would crack or burn, because of the heating, at a much lower potential than that corresponding to the true dielectric strength of the material. Commercial insulation, which successfully resisted 100,000 volts at any ordinary frequency, cracked after being subjected for about a minute to 15,000 volts at 100,000 cycles, because of the heat of the corona produced at the metallic terminals. Tho immersion of the sample in oil makes it possible to measure the losses in the material itself without interference by secondary phenomena, it must be remembered that in practice insulators of existing designs have no such protection, and may be subjected to the local heating caused by corona. A test of commercial insulators under oil will, therefore, not give fair indications of their values, even tho the dielectric characteristics of the material itself might, as determined by such a test, be apparently quite satisfactory.

Even when measurements are made under oil, the insulator is apt to break down because of deterioration caused by the heat generated in dielectric hysteresis, rather than because of dielectric strain. The same effect is found to occur when oil is used and the arc-over occurs at much lower voltages than those corresponding to ordinary frequencies. This is another instance where the apparently different characteristics are dependent for their difference on secondary phenomena. It is probable that under theoretically perfect conditions the same dielectric strength would be found at high frequencies as at low frequencies, and in oil and solid dielectrics as well as in air. This would be the case if the incidental phenomena of corona and heating could be eliminated. In order to be able to apply systematic and scientific methods to the design of radio frequency circuits, the author has made a series of measurements of dielectric losses for different insulation materials. These results are presented on the curve sheets in order to give the designers data for calculating the insulation losses in each part of a complete structure designed for use at such very high frequencies.

All the measurements have been made on samples 0.6 cm. (0.25 inch) thick, and with an area of 200 sq. cm. (30 square inches). The samples were in every case immersed in oil for reasons that have been explained. The insulation materials which were investigated are mica, glass, paper, varnished cambric, and asbestos. A general comparison between the characteristics of these materials is given by the curves of Figure 3 to Figure 7 inclusive. Figure 3 gives a comparison between the dielectric permittivities of the materials that were measured. This information is given by plotting the amperes of displacement current that would flow through a centimeter cube under a potential difference of 10,000 volts against the frequency. Figure 4 gives the watts loss in a centimeter cube for 10,000 volts at different frequencies. For the sake of comparison the losses of each of the materials, among which mica gives the lowest values and

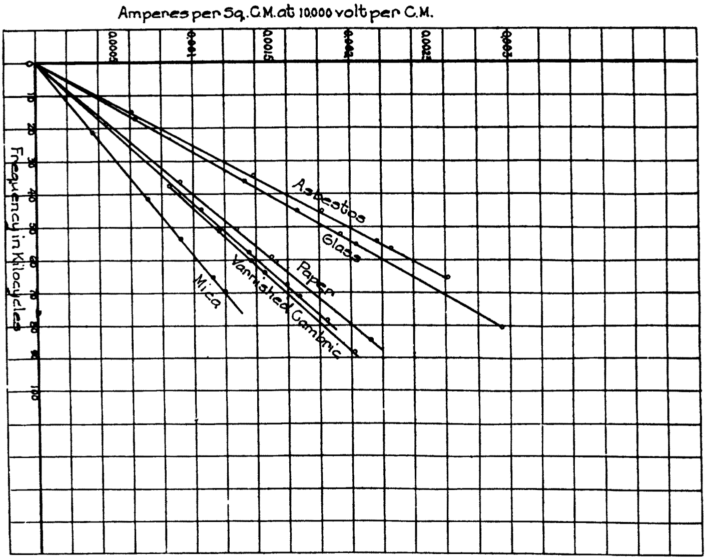


Fig. 3
Dielectric Permittivity

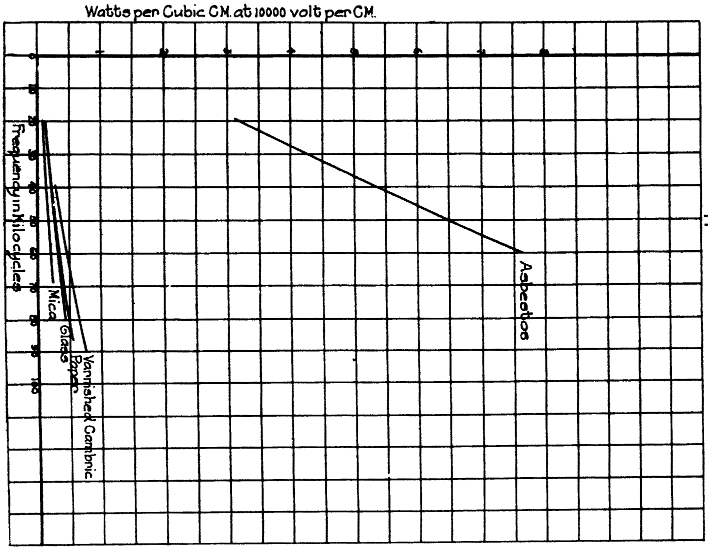


Fig. 4
Comparison of Dielectric Losses in Different Materials

asbestos the highest, are plotted on the same curve sheet. It is noticeable from this comparison that asbestos has a loss which is so far the greatest as to make it appear to be in a different class. For a closer comparison of the ordinary insulation materials; namely, mica, glass, paper, and varnished cambric, the losses per centimeter cube are shown on Figure 5. On Figure 5 is also given the power factor of each of these materials at the different frequencies. The power factor is the ratio between the watts loss and the volt-amperes absorbed.

It was found, in examining this data, that the figure for the power factor gives the most important and characteristic information of the insulation materials so far as dielectric losses are concerned. As seen from the curves the power factor is substantially constant at all frequencies and all voltages. This fact naturally leads to some interesting speculations as to the real nature of the dielectric losses. The dielectric losses are usually called dielectric hysteresis, but the question has been raised whether this is an appropriate name; and the data for dielectric losses has, by several investigators, been given in a form that would indicate that the nature of the losses is such as would be presented by a resistance in series with the capacity, while others have indicated it as a shunt resistance. A series resistance would give a power factor increasing in proportion to the frequency and a shunt resistance a power factor decreasing with the frequency.

The data obtained shows a power factor that increased slightly with the frequency for glass, mica, and paper; whereas the power factor for asbestos decreases. If we assume that the losses consist of a true dielectric hysteresis as well as series resistance and shunt resistance, it appears that that dielectric hysteresis, which is characterized by a constant loss per cycle, and consequently a constant power factor, is by far the predominant portion. In addition to this, it would appear that mica, glass, and paper have a slight series resistance and that asbestos has a shunt resistance, which is large enough to be slightly predominant over the series resistance. The losses in all the insulation materials are dependent upon the temperature; and a variation in losses due to this cause is apt to introduce differences considerably greater than the actual changes in power factor due to a series resistance or a shunt resistance. It can therefore be said that for practical purposes, the losses may be considered as if they were due to a true hysteresis, at a constant power factor, at all frequencies and all voltages. After the general data has been obtained for each sample, the test was carried further to the point of break-

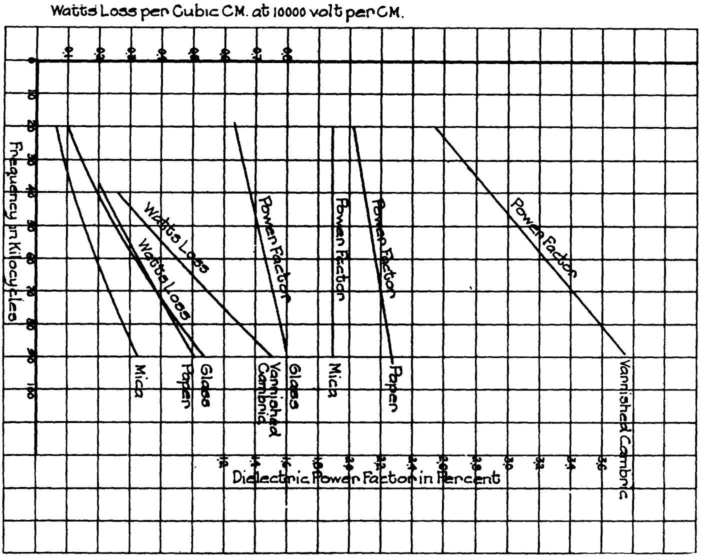


Fig. 5
Losses per Unit Volume and Dielectric Power Factor

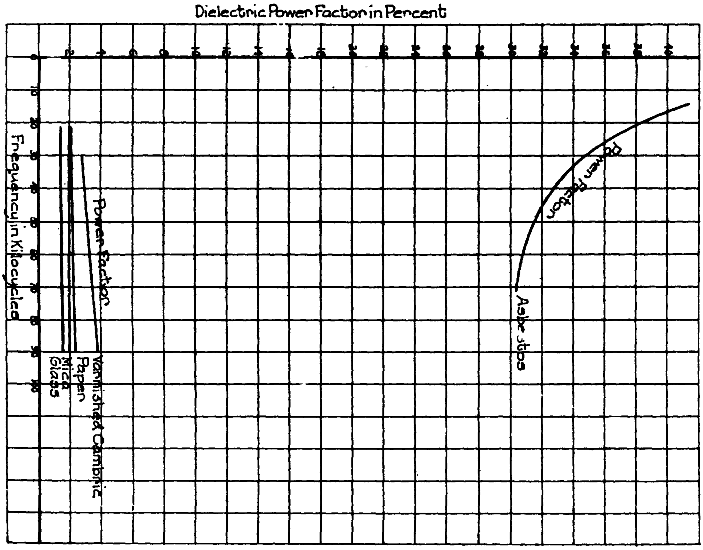


Fig. 6
Comparison of Dielectric Power Factor in Different Materials

down of the insulation. It is found that in each case, before the actual breakdown, a certain rise occurs in the power factor, and a slight decrease in the dielectric capacity. This rise of power factor is due to the increased heating, which becomes cumulative when the temperature has reached a certain limit. A set of average curves for the increase of power factor before the breakdown is shown in Figure 7 for the different materials. These curves show that the different materials, regardless of their inherent power factor, break down after the power factor has reached substantially the same value. The limits of power factor, given by the curves of Figure 7, therefore depend more upon the method of cooling of the particular samples that were used than on any inherent characteristic of the material. To illustrate the change in the power factor, the curves are plotted for the actual volts applied to a sample 0.6 cm. thick. The results can be duplicated only if the sample under test is cooled in the same way.

Figures 8 to 12 inclusive give the results of the measurements from which the above conclusions are drawn. The curves are plotted for each set of measurements, so that the reader will have the opportunity to form an opinion of the magnitude of the variations, which are due to voltage and frequency values, and also of those variations that were incidental to the experimental procedure which were due to rise of temperature. The shape of the power factor curve for each set of measurements is not sufficiently continuous to allow any definite conclusions to be drawn as to the law of variation of power factor with the frequency; nevertheless the assembled set of data indicate a general shape of the curves quite clearly.

With regard to the losses in mica, it should be noted that the samples used were of commercial built-up mica. Tests have since been made of clear mica for condensers and it was found that there is a wide variation of losses depending upon the grade of material. Measurements of power factor in various grades of mica used commercially for insulation have shown variations from 0.5 per cent. power factor to 7 per cent. power factor. Most commercial grades of mica fall between 1 per cent. power factor and 3.5 per cent. power factor, and it may be assumed that such mica as might be selected for condensers should have a loss of not more than that corresponding to 1 per cent. power factor.

Fig. 7
Rise of Dielectric Power Factor
Before Break Down

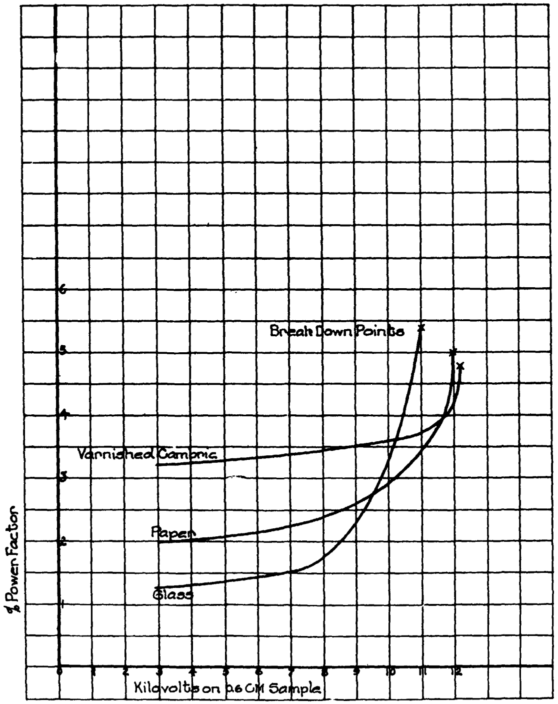
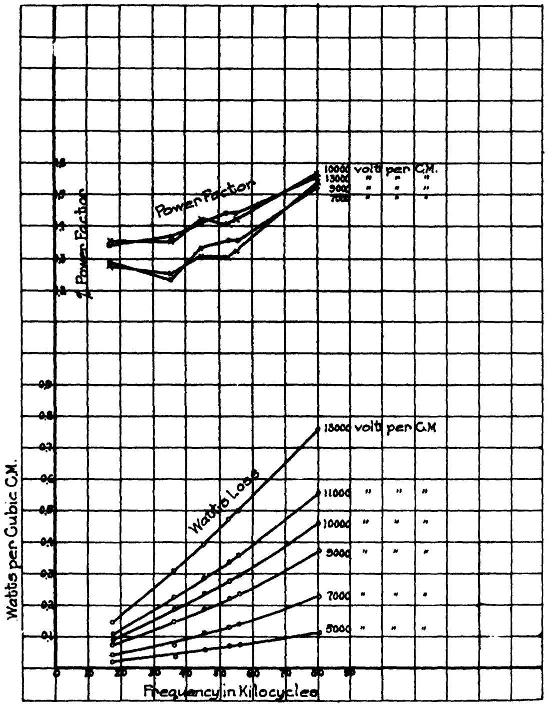


Fig. 8
Results of Measurements
2 Sheets of Glass - Total Thickness 0.59 CM.



DIELECTRIC HYSTERESIS OF AIR.

It has usually been assumed that air has no dielectric hysteresis whatever. While this may be so in a theoretical sense, the measurements made by the author for the purpose of determining the dielectric losses in air indicate that even the most perfect air condensers which it has been possible to establish, have losses which are easily measurable, and within the range of the apparatus used for this purpose. The losses that have been measured in different air condensers vary considerably in magnitude, and they depend principally on the sharpness of the corners and edges. For instance, if sheets of tinfoil about 6-inch square (15 cm.) are suspended at about 2-inch (5 cm.) distance, they show a loss as high as 1 per cent. Round copper plates of about $\frac{1}{32}$ inch (0.8 mm.) thickness and 2 feet (60 cm.) in diameter suspended at 6-foot (1.8 m.) distance from each other show a loss of about 0.4 per cent. The end shields of the high tension transformer, which are shaped so as to avoid, as far as possible, any local dielectric strains, show a loss of 0.2 per cent.; and a pair of brass spheres suspended at 0.5 inch (1.3 cm.) distance also show 0.2 per cent. [A part of this measured loss may be due to incipient corona which cannot be detected, and a part of it may be due to actual dielectric hysteresis in the air space. However, it is certain that a part of it is due to radiation into space. This was proven conclusively by some measurements on the end shields of a transformer when in one case for which these losses appeared to be unusually high. This was found to be due to a fine wire which was suspended about 5 feet (1.5 m.) above the apparatus, but entirely disconnected. It may be possible to design an apparatus so as to separate and measure these losses. The radiation losses could be eliminated by enclosing the whole apparatus in which the high voltages are generated in a metal cage constructed so that no losses could occur due to the short circuits cut by the varying magnetic flux; and the losses due to incipient corona could probably be eliminated by comparing the losses in air circuits of different lengths but with the same voltage gradient at the terminals.

A demonstration which is both unexpected and striking to the effect that the fundamental loss which has been found at low frequency remains applicable at extremely high frequencies, is found in the measurements of energy loss due to corona around a small wire. The measurements were made on two wires, each 40 inches (1 m.) long, suspended free in air at a distance apart of 2 feet (60 cm.). The wires were 0.01 inch (0.4 mm.) in diam-

Fig. 9
Results of Measurements
4 Sheets of Mica – Total Thickness 0.55

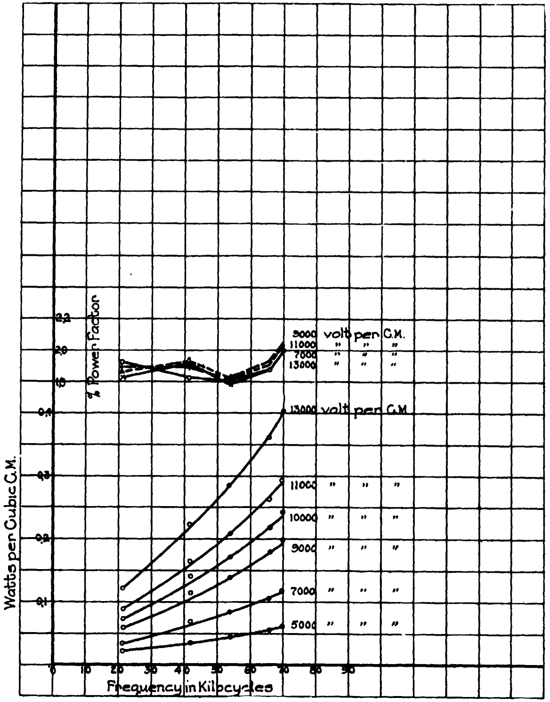
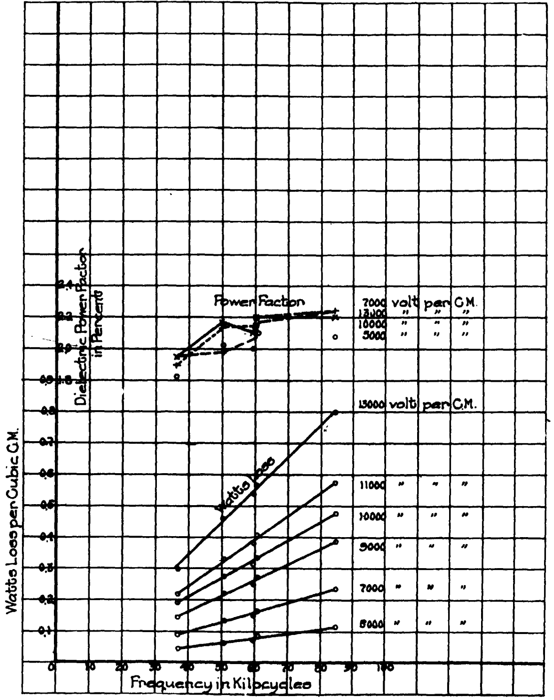


Fig. 10
Results of Measurements
25 Sheets of Paper – Total Thickness 0.6 C.M.



eter. The measurable corona loss was first evident at 15,000 volts difference of potential; and increased very rapidly so that at 27,000 volts, the energy absorption was nearly 0.5 kilowatt. It is the quantitative magnitude which is surprising in this case; and it is difficult to imagine that this large amount of energy is radiated from such fine wires without bringing them to incandescence. However, there appeared to be no evidence of heating on the wire itself, and the wires were surrounded by the blue flame of the corona, which was well visible even in bright daylight. The most interesting feature of these results is the fact that they agree remarkably well with the laws of the corona as developed theoretically by Mr. F. W. Peek, Jr., and given in a paper* for the American Institute of Electrical Engineers in 1911. Both the point at which the corona begins, and the shape of the sharply rising curve of losses at increased voltages are in agreement with calculations. An agreement has thus been found between phenomena occurring at low frequencies and at radio frequencies, not only as to arc-over distances between spheres of polished metal but also for the measurement of corona loss on wires. This justifies confidence in such theoretical assumptions as may be necessary in order to determine by calculation the losses under various conditions that are not conveniently subjected to laboratory measurements. In view of this, I believe that calculations for a number of phenomena, which are at present uncertain in nature, can be made on a semi-theoretical basis, thereby furnishing practical data for the design of insulators and conductors which are to be subjected to very high frequencies.

In the first attempts to make measurements of corona losses on wires, as was previously mentioned, some difficulty was found in suspending the wires. If a cotton string was used, it soon caught fire and burnt off because of the heating caused by the corona flame. It was then attempted to use a small porcelain insulator suspended by a cotton string. In this case, there appears to be an excessive corona discharge between the wire and the insulator at voltages lower than that of the appearance of corona on the wire itself, and the insulator eventually heats up sufficiently to break it into loose pieces. The heating of the insulator itself would, of course, interfere with the accuracy of the measurements that were to be made. As a practical method of suspending the wires without introducing extra losses, they

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*The Law of Corona and the Dielectric Strength of Air," F. W. Peek, Jr., Proc. A. I. E. E., Vol. XXX, Part 1, Page 1485.

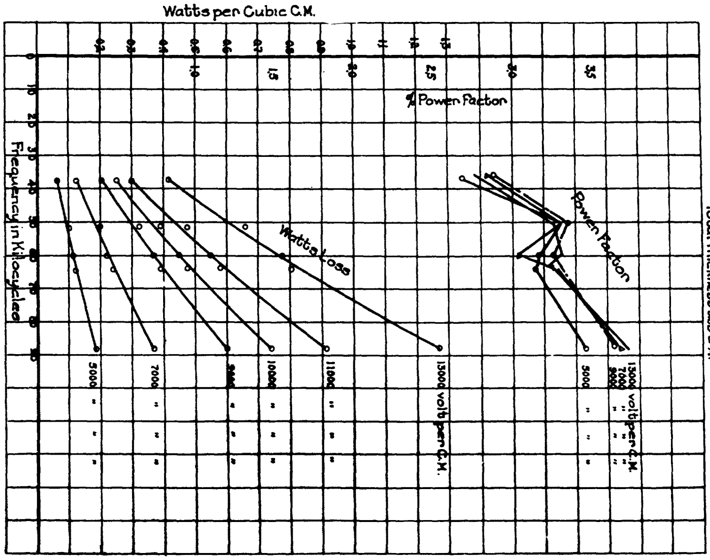


Fig. 11
Results of Measurements
21 Sheets of Varnished Cambric
Total Thickness 0.33 C.M.

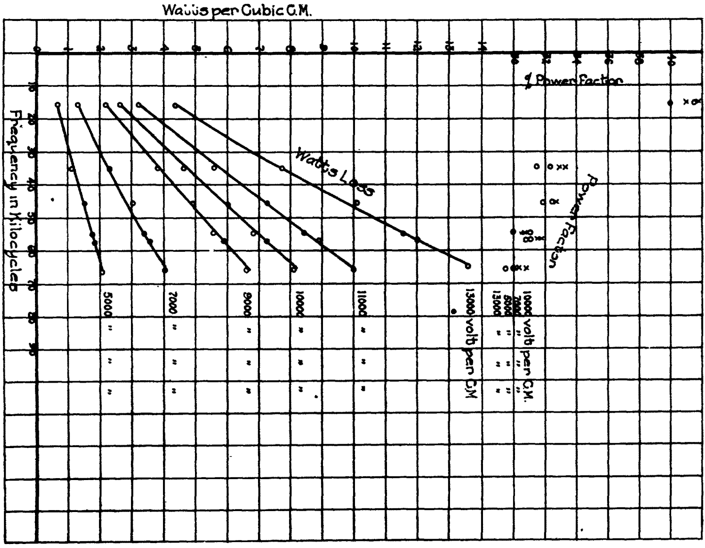
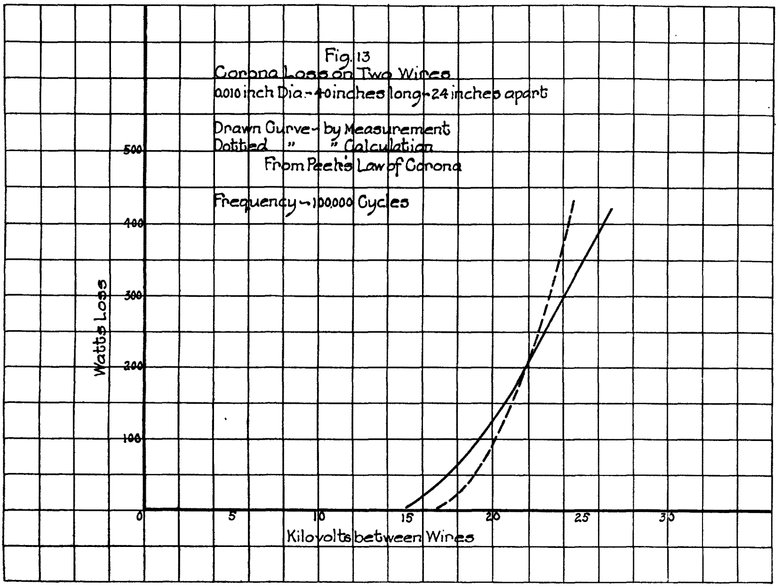


Fig. 12
Results of Measurements
8 Sheets of Asbestos-Total Thickness 0.6 C.M.

were tied to a cotton string, and the joint wrapped with tinfoil to a considerable thickness and in such a shape that the point where the wire touched the metal was surrounded by a bell shaped shield of tinfoil. In this way the corona discharge from the terminals was not only reduced but also kept away from the joint between the wire and the metal. While it is in practice necessary to use insulators in supporting wires there can be no doubt that the success of the apparatus depends greatly upon the design of the insulators and the effectiveness with which losses due to local heating are avoided. The excessive corona losses at the point where the metal touches the insulator can easily be explained from a consideration of the dielectric characteristics of the materials. We may, for instance, assume that the insulator has a dielectric constant five times as high as the air, and that the layer of air between the metal and the insulator is not of sufficient thickness to change the distribution of the electric field in the insulator. If the wire were totally embedded in the dielectric the higher permittivity of the insulator would cause five times as great a current to flow from the wire into the dielectric as would flow if the wire were suspended in air, but the distribution of potential in the insulator would be the same as the distribution of potential when the wire is totally sur-



rounded by air. If, however, there is a small layer of air between the wire and the insulator, the current flowing thru this layer of air is five times as great as it would have been if the insulator had not been present, and consequently the potential gradient in this layer of air becomes five times as great. In this case it is to be expected that corona would appear locally at a voltage only one-fifth as great as the voltage that would produce corona if the wire were suspended freely in air. The measurements of corona losses in a 10 mil (0.4 mm.) wire, as well as theoretical considerations, indicate that corona should commence at 15,000 volts between such wires suspended at a considerable distance. In other words, corona begins when each wire has a difference of potential of 7,500 between it and the surrounding air. If such a wire be brought close to a large insulator, which has a permittivity five times that of air, it is to be expected that corona would appear at a voltage one-fifth as great as before, that is at 3,000 volts potential difference (or 1,500 volts above ground potential, provided that one side of the insulator is grounded). This agrees substantially with the results of observation, and tho it may be desirable to collect more empirical data on this point, it should be possible to extend this line of reasoning to phenomena which cannot be subjected to measurements, thereby gaining a quantitative knowledge of many phenomena which have an important bearing on the proper functioning of the very high frequency circuit.

TABLE 1.

REPRESENTATIVE VALUES OF DIELECTRIC LOSSES.

	Power Factor per cent.	Watts Loss per cm. cube at 10,000 volts per cm.; per kilocycle.
Clear Mica for Condensers,	1.0	0.0016
Built-up Mica,	1.9	0.003
Mica,	1.9	0.003
Glass,	1.4	0.005
Paper,	2.2	0.0055
Varnished Cambric,	3.3	0.0080
Asbestos,	3.0	0.13

(September 14, 1914.)

SUMMARY: The development of a transformer for 100,000 volts at 100,000 cycles is described in detail. The successful construction is given. The necessary even potential gradient along the high tension secondary of the transformer is provided by special end shields. The dielectric strength of air is determined at radio frequencies, and the novel behavior of air at these frequencies is described. The methods of measurement of dielectric losses

of various materials are given. The materials tested show that the predominant loss is constant per cycle (i. e., it gives rise to a constant power factor). Mica, glass and paper show also a slight equivalent series resistance (corresponding to a power factor increasing with the frequency); asbestos a shunt resistance. The break-down conditions of the various dielectrics were studied. The dielectric hysteresis of air is measured, and it is found that radio frequency corona as well as arc-over distance are subject to the same laws as at audio frequencies.

DISCUSSION.

Robert H. Marriott (*Chairman*): On behalf of The Institute of Radio Engineers, I wish to thank Mr. Alexanderson for presenting this paper before us. It is of great value to workers in the radio field.

H. E. Hallborg: There are three recent papers; one by Fortescue read before the American Institute of Electrical Engineers, and those by Dr. Austin and Mr. Alexanderson read before the Institute of Radio Engineers, which mark three milestones in our emancipation from insulation difficulties. These papers should certainly be read by all radio engineers.

Our methods in the past have been empirical in the extreme. If we found that one foot of insulation would not withstand 100,000 volts, we simply added an additional foot of insulation. The effect might well be the opposite of that desired. It is very important in such problems to consider the stresses in the dielectric (that is, the electric field intensity). There is no doubt that these problems will eventually be worked out in the same systematic fashion as that in which problems involving the magnetic circuit containing iron are now handled.

The total dielectric field is represented by the product C times E (C, of course, is capacity and E voltage). Fortunately for most insulators, the value of C is small, so that in spite of the application of a high voltage the total dielectric field remains such that the dielectric flux per unit area is very low, and the danger of failure therefore remote. When, however, the value of C becomes appreciable, as in a condenser, then the application of even a moderate voltage sets up a dense field and the flux per unit area becomes high. Hence, it is readily seen that it is by no means a just test to compare insulation by voltage test alone since there may be a vast difference in field intensity, and the insulation that is found to be the poorer by this test may really be the better when densities are taken into account. We compare samples of transformer iron for losses at equal densities; why not dielectrics? I believe that the time is com-