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TECHNICAL MEMORANDUM 1998

AN ENGINEERING STUDY COMPARING INSULATION RESISTANCE TO DIELECTRIC STRENGTH TESTING

RICHARD J. MEMICE

SAFEGUARD QUALITY ASSURANCE DIVISION

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PICATINNY ARSENAL
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TECHNICAL MEMORANDUM 1998

AN ENGINEERING STUDY COMPARING INSULATION RESISTANCE TO DIELECTRIC STRENGTH TESTING

BY
RICHARD J. MEMICE

AMCMS CODE NO. 4270.15.9000.6

MAY 1971

PICATINNY ARSENAL
DOVER NEW JERSEY

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ABSTRACT

This study investigates the differences, simulations, and interrelationships between insulation resistance and dielectric strength testing to determine if either can be eliminated to effect economy in testing.

SUMMARY

The object of this study is to determine the most economical test method for insulation resistance and dielectric strength testing. It is common practice in some industries to test by elevating the insulation resistance DC testing voltage by some multiplying factor which has been determined as equivalent to the dielectric strength AC test; and thus eliminate the dielectric strength test altogether, resulting in economies generated by the savings in testing time, data reduction and analysis, and test hardware. This analysis will investigate the differences, similarities, and interrelationships between insulation resistance and dielectric strength testing to determine if there is an overlap or equivalent duplication of testing that could be eliminated, resulting in the above mentioned economies. This study is also extended to include the theoretical analysis of the various types of failures and breakdowns that can occur in insulation resistance and dielectric strength testing. This type of knowledge is necessary before anyone can competently establish specification test requirements and test methods.

CONCLUSIONS

Aircraft equipment testing found dielectric strength testing of 28-volt equipment at 500 volts rms and 60 hertz not sufficient in detecting flaws in insulation thicker than one mil, therefore this test will not offer more significant data than an insulation resistance test of 500 volts DC and it will not provide quantitative leakage data.

I. REASONS FOR INSULATION RESISTANCE AND DIELECTRIC STRENGTH TESTING

Purpose of Insulation Resistance Testing

The primary purpose of insulation resistance (direct current) testing is to determine if the leakage currents in an insulator are low enough to ensure safe and reliable operation with a minimum of maintenance and repair. Insulation resistance testing checks insulation condition with respect to dryness and contamination with dirt, oil, and chemicals. Low insulation resistance can form unwanted paths for current which can disrupt and cause failure in the component, serve as false signals, or dissipate electrical signals. When leakage currents are excessive, insulation deterioration is accelerated because of internal heating or through electrolysis. Cold flow of the insulation may cause the insulation resistance to be lowered to the point where large leakage currents may be formed. Insulation resistance testing can assure adequacy of insulation thickness, proper clearance of parts, and lack of mechanical defects which can cause electrical breakdown. Insulation resistance tests indicate not only the immediate condition, but can be used to estimate the probable future life of the insulation by observing the value of the leakage current as the voltage is increased. If the leakage current rises linearly to the final value of the test voltage, the life expectancy of the tested item can be expected to be good. If the leakage current changes exponentially to the final value of the test voltage, the life expectancy of the item will probably be short.

Insulation resistance testing is affected by the temperature, time and rate of application, level of applied voltage, moisture, contour of the specimen, environment, contamination, aging, and previous history of the insulation. Insulation resistance testing is mainly used as a nondestructive test made on high capacitive items, motors, generators, cable runs, components, assemblies, or completed equipment to determine whether the insulation level is satisfactorily high to assure reliable operation. Insulation resistance testing can minimize the possibility of expensive service failures, can show up cases of inadequate design, and can lead to a more efficient product.

Purpose of Dielectric Strength Testing

The primary purpose of dielectric strength (alternating current) testing is to determine if the dielectric can operate safely and reliably at its rated voltage and if it can withstand high voltage surges and transients. Switching transients and high operating voltage have emphasized the need for high quality dielectrics and dielectric strength tests to prevent breakdown. Transients caused by capacitive discharges are infrequent because they must be charged above line voltage. Transients caused by inductive discharges are very common and usually occur in motors, solenoids, relays, or with any interruption in any inductive circuit. The maximum instantaneous voltage will be equal to $\sqrt{L/C}$ I volts

where L = inductance

C = capacitance

I = current

A circuit with a 10 mh inductor, a 100 pf capacitor and a current of 100 ma can have a transient of 1,000 volts. Dielectric strength testing can determine which materials are extremely susceptible to corona damage, carbonization, and puncture by high voltage surges. Insulation should withstand dielectric strength testing without rupture, in addition to preventing excessive current flow between two circuits. Solid electrical insulation materials are generally nonhomogeneous and may contain dielectric defects of various kinds. Weak spots within the material usually determine if the test results will be good or bad.

Dielectric strength testing is affected by temperature, pressure, time, rate and level of application, moisture or humidity, frequency, thickness of specimen, electrode configuration, environment, contamination, waveshape, aging and previous test history. Dielectric strength tests can be conducted either with AC or DC, but AC is generally used to determine if large capacitive currents are present in addition to leakage currents. As a rule, dielectric strength tests are used for production testing of small capacitive items, for materials testing and anywhere go-no-go information is desired. Defective equipment caught early can prevent extensive and costly repairs and ensure reliability, quality, and safety.

II. COMPARISON OF ALTERNATING CURRENT TO DIRECT CURRENT

The Dielectric Circuit

The following differences between insulation resistance and dielectric strength testing were found to exist:

a. Dielectric strength tests are usually conducted with alternating current and are mostly used for go-no-go testing of small, low capacitance equipment, for production testing, and materials tests.

b. Insulation resistance tests are conducted with direct current and are made on components, assemblies, or completed equipment items to determine whether the insulation level is high enough to assure reliable operation. They are generally employed where quantitative, rather than qualitative results, are necessary or when large equipment or cable runs having high capacitance must be tested.

c. Because direct current voltage distribution is inversely proportional to conductivity and alternating current voltage distribution is determined by permittivity, thermal and disruptive breakdown will usually occur first with AC, while intrinsic breakdown will usually occur first with DC for a given voltage and time.

The following similarities between insulation resistance and dielectric strength testing were found to exist:

a. As a dielectric material or component is repetively tested, a lower test voltage will give the same results as did the initial test voltage due to deterioration caused by voltage fatigue.

b. Because dielectric strength factors are not significant at low frequencies if capacitance is low, a graph (based on capacitive power factor) was generated to indicate when to use insulation resistance and/or dielectric strength testing. By neglecting the leakage current or the capacitive current when it is 10 percent or less of the total current, the related test may be omitted.

The following interrelationships between insulation resistance and dielectric strength testing were found to exist:

a. In the early days of the electrical industry, DC high potentials were unobtainable and with the development of transformers, alternating current generators and motors, most insulation testing was done with AC. Today, with great advances in the field of selenium and silicon solid-state rectifiers, the DC test set is being used in areas where AC once predominated.

b. There can be no general agreement on an AC rms to DC conversion factor because materials will differ in leakage, and electrolytic action.

The quivalent circuit of a dielectric may be represented by a capacitor, C, and resistance Ra and Rb in parallel as shown in Figure 1 (a) when an AC current is used.

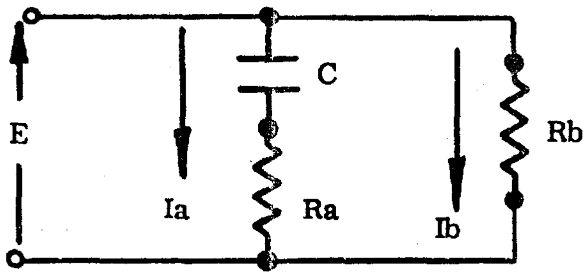

Figure 1 (a) AC Dielectric Circuit

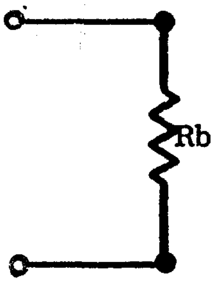

Figure 1 (b) DC Dielectric Circuit

The capacitance represented by C is between the two metallic circuits, the resistance Ra represents the absorption losses and Rb represents the leakage paths through and over the insulation. Figure 1 (b) represents the equivalent circuit of a dielectric when DC is used and capacitive and absorption currents are small enough to be neglected.

AC Components

When an alternating current is applied across the circuit, the total current would consist of an out-of-phase capacitive current, Ia, and an in-phase or leakage current, Ib. The AC test set must supply the vector sum of these two currents. When the item under test is low in capacitance, the capacitve current may be small compared to the leakage current and may be neglected. When the item under test is high in capacitance, the capacitive current may be many times the leakage current.

This statement can be illustrated with the aid of the following example. In Figure 1 (a) the impedance of the first branch, Za, can be represented by the following equation:

$$Za = Ra + jwC = \sqrt{(Ra)^2 + (1/WC)^2} \tan^{-1} 1/wRaC$$

where W = 2 π times the frequency

C = capacitance of item under test

Ra = resistance due to absorption losses

The impedance of the second branch, Zb, can be represented by the following equation:

$$Zb = Rb$$

where Rb = resistance due to leakage paths.

The current, I, can be found by dividing the voltage, V, by the total impedance, Z.

If we let Ra = 10^7 ohms

Rb = 10^8 ohms

$w = 2\pi f = 2\pi (60)$

Currents and impedances can be calculated and are listed in Table 1, page 12 for several values of capacitance with other parameters held constant.

TABLE 1 - CURRENT AND IMPEDENCE
FOR
SEVERAL VALUES OF CAPACITANCE

V	C	Z_a	Z_b	I_a	I_b
$500\angle 0°$	10^{-12} f.	$2.66 X 10^{9} \angle -90°$	$10^{8} \angle 0$	$0.188 \angle 90°$ ua	5ua
$500\angle 0°$	10^{-11}	$2.66 X 10^{8} \angle -88°$	$10^{8} \angle 0$	$1.88 \angle 88°$	5
$500\angle 0°$	10^{-10}	$2.84 X 10^{7} \angle -70°$	$10^{8} \angle 0$	$17.6 \angle 70°$	5
$500\angle 0°$	10^{-9}	$1.035 X 10^{7} \angle -15°$	$10^{8} \angle 0$	$48.2 \angle 15°$	5
$500\angle 0°$	10^{-8}	$10^{7} \angle -20$	$10^{8} \angle 0$	$50\angle 2°$	5

As shown in Figure 2 the magnitude of the capacitive current, Ia, increases as capacitance increases. When the capacitance is 10^{-12}f the leakage current is over 25 times the capacitive current and the capacitive current may be neglected. As capacitance increases to 10^{-8}f the capacitive current is 10 times the leakage current and in most cases the leakage current can be neglected. The ITT Reference Data for Radio Engineers shows the capacitance per foot for most single and double braided cables to be about 30 pf (10^{-12}) per foot, but some low capacitance cables can get below 10 pf/ft. Depending upon the distance between conducting paths and the length of the path, the capacitance increases the magnitude of the capacitive current will also increase.

DC Components

When a direct potential is applied across the circuit, the total current flow would be the sum of (1) capacitive current, (2) absorption current, and (3) leakage current. The capacitive current decays at an exponential rate according to the equation:

$$I_c = \frac{E}{R} \exp(-t/RC)$$

where

I_c = capacitive current

E = applied voltage

R = internal resistance

t = time after voltage application

C = capacitance of item under test

The absorption current is caused by polarization of electric charges which take place in an imperfect dielectric under the stress of an applied voltage. The absorption current also decays exponentially according to the equation

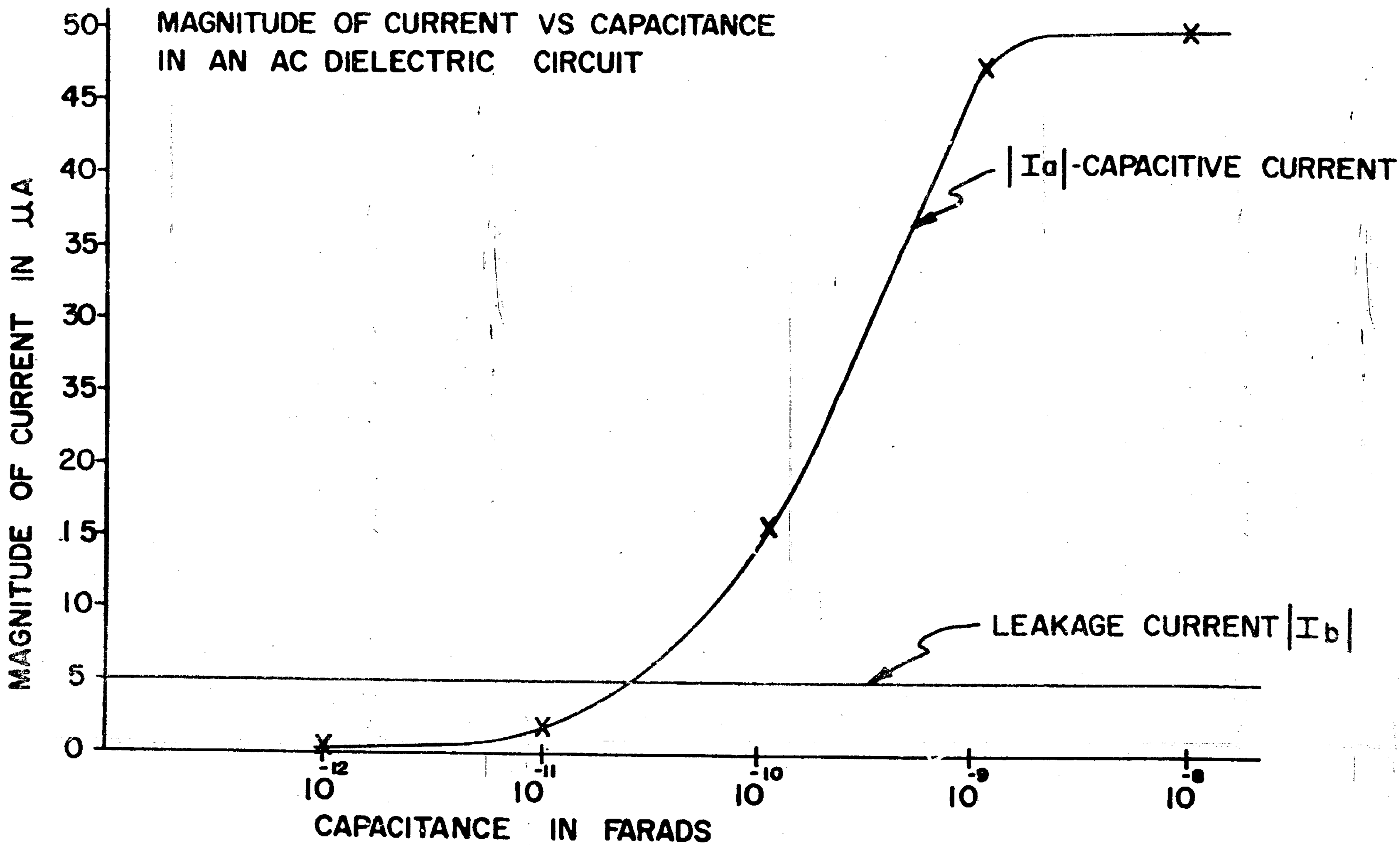
MAGNITUDE OF CURRENT VS CAPACITANCE
IN AN AC DIELECTRIC CIRCUIT
|Ia|-CAPACITIVE CURRENT
LEAKAGE CURRENT |Ib|
MAGNITUDE OF CURRENT IN μA
50
45
40
35
30
35
20
15
10
5
0
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
CAPACITANCE IN FARADS

FIGURE 2

$$I_a = AVct \exp(-B)$$

where I_a = absorption current

A, B = constants depending upon the material

V = incremental change in voltage

t = time after change in voltage

C = capacitance of item under test

The leakage current depends on the total series resistance of the circuit and is given by the equation:

$$I_b = \frac{E}{R_s}$$

where: I_b = leakage current

E = applied voltage

R_s = total series resistance

Because the first two components decay with time, the current measured after sufficient time has elapsed for conditions to stabilize is the true leakage current.

Advantages of the AC Test Set

Alternating current is primarily used in the field of materials testing where breakdown tests are made on samples of insulating materials and where samples are small enough for capacitive currents to be neglected. Alternating current stresses the dielectric in proportion to the dielectric constant of the material, rather than in proportion to the leakage resistance as is the case with DC testing. If the dielectric constant is to be stressed or mechanical vibration produced by alternating current, an AC test set would be required.

Alternating current test sets are primarily go-no-go testers. As the voltage is raised to a specific level, the item under test may or may not break down. Indication of pass or failure is usually given by a light. The degree to which an item passed or failed is not known. This test will indicate only if the item is good or bad. An AC test set may be inconveniently large when equipment or cables of high capacitance are being tested. The capacitive current could mask abnormally high leakage currents when high capacitance is present. In production testing, alternating current permits the use of a small high-resistance transformer which is safe and easy for the operator to use.

Advantages of the DC Test Set

A direct current test set can give more than a good or bad indication. It can indicate the degree to which an item passed or failed. Direct current is used when information regarding the comparative condition of the items tested is needed. The AC test set requires a circuit breaker for go-no-go failure indication, while with a DC unit, leakage current is measured and may be compared with a limiting value. Catastrophic failure is indicated by detection of avalanche breakdown. The acceptable value of leakage current is usually determined by comparison testing. In a DC test set, the capacitance will have little or no effect on the steady-state value of the leakage current, but a considerable length of time may be needed for the current to decay to the steady-state value. The charging currents can be kept within reasonable limits by gradually raising the voltage so that the incremental voltage divided by the series resistance yields an initial current within the rating of the test set. If the voltage is raised slowly enough, even a highly capacitive item may be tested with a unit capable of delivering only a few milliamps. Direct current test sets are usually used when the capacitive current of the item to be tested is so high that a very large AC unit would be needed to perform the same test.

AC to DC Conversion Factor

When direct current is used in place of alternating current, a conversion factor is generally used. Aerospace industry has been using values between 1.8 and 2.0. Many manufacturers have been using the value of 1.7. The cable manufacturers have used 2.3 and even higher numbers. In the American Institute of Electrical Engineers (AIEE), Transactions Paper No. 58-845, the value 1.414 times the 60 hz rms sine wave AC test voltage is suggested. The value of 1.7 has appeared the most, but it is not the accepted standard. The reason that there is no universal factor is because the dielectric constant varies from material to material and alternating current stresses a nonhomogeneous material in proportion to its dielectric constant. Other factors including different mechanisms for breakdown, transport of charges, surface leakage effects, electrolytic action, etc., which differ from material to material make it virtually impossible to establish a universal factor. The test voltage to be used in any given situation depends on the results of an experimental approach, and the judgment of the test engineer in general agreement with the R&D engineer and other concerned parties.

III. THEORY OF BREAKDOWN

Thermal Breakdown

The thermal theory of breakdown is based on the assumption that all solid dielectrics are heterogeneous. Because of this quality some parts or areas have a lower resistance than other parts of an apparently uniform material. When a current is passed through a sample, it will not be uniformly distributed. Parts lower in resistance will carry more current and will be heated quicker than parts with lower currents. If the adjacent electrodes or insulation can conduct the heat away as fast as it is generated, the temperature remains stable and no failure will result. However, if the heat is not removed as rapidly as it is generated in any part of the dielectric, parts with higher currents grow hotter, thereby lowering the resistance still further. As the voltage is increased, the temperature rises until thermal instability occurs. Therefore, the dielectric will breakdown at its weakest point.

Thermal Effect on Insulation Resistance and Dielectric Strength

Electrical conductivity rises with increasing temperature, therefore the hottest part of the solid insulation is relieved of some of its electrical stress with DC where the voltage distribution is inversely proportional to the conductivity. This relief is not inherent in AC testing where the field distribution is determined by the permittivity of the material which is usually independent of temperature. Therefore, an insulation resistance test conducted under the influence of DC may tolerate high ambient temperature where breakdown may occur on a dielectric strength test conducted under the influence of AC.

Intrinsic or Ionic Breakdown

If thermal instability does not cause breakdown of the dielectric, failure may result when the field intensity becomes sufficiently high to accelerate electrons through the material. The critical field intensity is known as the intrinsic dielectric strength. Ionization will occur from either collision or chemical action under the influence of field voltage. As the voltage is increased, ions will dissipate energy and produce other ions. By increasing the voltage a higher field intensity is formed, ions are produced at a faster rate until instability occurs and insulation failure results.

Intrinsic Effect on Insulation Resistance and Dielectric Strength

When direct current voltage is increased, electrons leaving the cathode will move toward the anode with greater velocity and fewer of them will return to the cathode. When sufficient energy is attained, collisions between electrons can free additional electrons from molecules in the process known as ionization. With direct current, acceleration of electrons will be constant and ionization can occur at a maximum rate. Alternating current may cause reversal in the field in less time than ionization can get started. Therefore, an insulation resistance test using DC will probably cause intrinsic breakdown before a dielectric strength test using AC for any given voltage.

Disruptive or Electric Discharge Breakdown

Electrical breakdown is caused by physical rupture of the dielectric resulting in the destruction of molecular and other bonds. This rupture is caused by electrical charges which are produced by high local fields. If solid materials are tested, the discharges usually occur in the surrounding medium which increases the test area and produces failure at or beyond the electrode edges. Discharges usually occur in internal voids or bubbles that are present or may develop. They are caused by local erosion or chemical decomposition. This process usually continues until a complete failure path is formed between electrodes.

Discharge Effect on Insulation Resistance and Dielectric Strength

A discharge across a void is similar to discharging a capacitor. After discharge, the voltage drop across the void itself is lowered and the discharge may stop. Depending on the time constant of the material, further discharges may take place with DC. When alternating current is used, the internal discharges can occur during each half cycle. Alternating current will subject the insulation to a vibrating mechanical force which results from the alternating field and this effect cannot be obtained with steady direct current. Therefore, an AC test will probably cause disruptive breakdown before a DC test.

IV. THE IMPORTANCE OF 60 HERTZ DIELECTRIC STRENGTH TESTING

In a report titled "High-Potential Testing of Aircraft Equipment Electrical Insulation", failure analysis of 28-volt equipment showed that 500-volt rms, 60-hz, tests were not detecting insulation flaws which subsequently caused service failures. The purpose of the 500-volt, test was to detect flaws in the insulation. In operation, inductive circuit interruption transients are very likely to discharge through these flaws or puncture marginally thin insulation and cause insulation failure by tracking. Circuit transient voltages discharged across voids in the material were not being detected by this test.

An investigation was made to determine the reason for insulation failure. The investigation indicated four factors caused insulation breakdown. They are:

a. Voltage gradients in the gap area caused by the change in dielectric constant from air to material.

b. Limited dissipation of heat caused by loss of convection cooling.

c. Contamination of the air gap area with products of the discharge.

d. Air gap pressure changes caused by confining the discharges in small holes.

Under highly controlled conditions, tests were made on materials 1, 5, 3, 7, and 9 mils thick. Results showed 500 volts rms, 60 hz, tests would not detect a flaw reliably in insulation thicker than one mil. One thousand volts rms would probably be needed to detect a flaw in 3 mil insulation. The investigation also showed that the larger the diameter of the hole the lower the breakdown voltage.

Governmental Dielectric Withstanding Voltage Tests

The purpose of the Dielectric Withstanding Voltage Test in MIL-STD-202D, Method 301, is "to determine whether insulating materials and spacings in the component part are adequate". In governmental tests, Dielectric Withstanding Voltage Tests are usually conducted at 500 volts rms, 60 hz, and according to the previous report on dielectric strength testing of aircraft equipment, only a one mil flaw can be detected reliably at 500 volts rms and 60 hz. To detect a 3 mil flaw, 1,000 volts rms at 60 hz would be needed. The aircraft equipment report and various other sources indicate there is little advantage to equipment testing using 500 volts rms AC when 500 volts DC testing is preferred. "Failure analysis of 28-volt equipment repeatedly demonstrated that 500-volt, 60-cycle AC tests were not detecting insulation flaws which subsequently caused service failures."[5] Other sources can support the aircraft equipment report's findings. American Society for Testing and Materials (ASTM) maintains that "dielectric strength is not significantly influenced by frequency variations in the range of commercial power frequencies (50-60 hz)." "The effects of capacitance are discernable at 60 hz."[2] It is a known fact that an AC current can cause field reversal in less time than avalanche breakdown can get started.

History of High Potential Testing

The importance of sound electrical insulation has been recognized from the early days of electricity. The need for improved testing and insulation was emphasized by damage caused by flashover, lightening, transients, and problems caused by continued use.

Most early testing was done with DC potentials of up to 500 volts. Higher DC potentials were not feasible. Later, with the development of transformers, AC generators and motors much insulation of testing turned to AC. As the years passed and the electrical industry expanded, rotating machinery, transformers and cables became larger. AC test equipment became larger and more costly to keep pace with the insulation to be tested. The phase-to-phase or phase-to-ground capacitance of some cables became so large that the capacitive current was as high as 2-3 amperes.

It was not until the 1930's that the invention of the Kenetron rectifier tube led to the development of direct current high voltage supplies. Because of new designs available with the Kenetron tube, DC voltage supplies were a great improvement when compared to size, weight, and cost of the AC units. But still, AC test sets predominated in the 1930's and 1940's because of its longer history and the considerable data that had been accumulated correlating test results. Most testing was done with AC also because of the lack of general familiarity with the newer, more sophisticated DC test equipment, and the availability of AC equipment, rather than because the AC test per se is better.

As time progressed, tremendous advances in the electronic industry, increasing use of high voltages, and the increasing complexity of equipment, the demand for more sophisticated, more sensitive, and safer test equipment increased. The high reactance transformer made small portable units for AC testing fast, convenient to use, and safe to operate. It was not until the 1940's that the advent of the high vacuum rectifiers reduced the size, weight, and cost of the DC set that DC testing became popular. Today, with the great advances in the field of selenium and silicon solid-state rectifiers, the DC test set is high in quality and reasonably priced.

In spite of the early head start AC test sets had, DC test units are being used in areas where AC predominated. DC test sets are preferred to test items of high capacitance or when quantitative rather than qualitative measurements must be made.

V. FACTORS AFFECTING INSULATION RESISTANCE AND DIELECTRIC STRENGTH TESTING

Temperature

Dielectric Strength

The temperature of the test specimen and its surrounding medium influence the dielectric strength, but for most materials small variations of ambient temperature may have a negligible effect. Dielectric strength will decrease with increasing temperature, but the extent to which this is true depends upon the material tested. Raising the temperature reduces the number of molecules per unit volume causing the electrons to travel farther and farther between collisions with molecules of the gas, thereby permitting them to pick up sufficient energy to cause ionization with every collision, lowering the breakdown voltage.

Insulation Resistance

Insulation resistance is also affected by temperature as dielectric strength and the degree of difference will depend on the type of insulation, the moisture content, and the condition of the insulation surfaces. Experimental work has shown that insulation resistance will be reduced by a fixed ratio for each specific temperature increment. Most insulators have multipliers of 40 percent to 75 percent for each 10° C increase in temperature, with the multiplier for each kind and condition of insulation remaining approximately constant over the operating range.

Pressure

In general, as pressure is increased, the dielectric strength of the material is increased. This is due to the fact that as pressure is increased molecules in the gas are packed closer together with the distance between collisions being less and not permitting them to pick up sufficient energy to cause ionization with every collision, thereby increasing the breakdown voltage. However, this rule is not applicable to all pressures. As the gas pressure is lowered collisions become less frequent, thus permitting the electrons to pick up sufficient energy to cause ionization and lower the break down voltage. As the gas pressure is lowered still further, there is a point where there are so few molecules that the electrons have a very good chance of reaching the anode without many collisions. The chance of breakdown becomes less and additional voltage is needed to cause breakdown as shown in Figure 3. It can be restated that as pressure decreases, the breakdown voltage decreases to a minimum at a critical pressure and then it increases until the value of breakdown in a perfect vacuum is reached. Because of poorer ionization efficiency at very low pressures a long gap may break down at a lower voltage than a shorter gap.

The dielectric strength of air at normal atmospheric temperature and pressure is 22,000 volts (rms) per inch, breakdown can occur at 341 volts at the critical pressure. Breakdown voltage decreases by approximately 15 percent for every 20 percent decrease in pressure. The decrease in breakdown voltage of air with an increase in altitude makes the testing of airborne or missileborne equipment of greater importance because spacings which were more than adequate at normal atmospheric pressure may become inadequate at high altitudes.

Time and Rate of Applied Voltage

Dielectric Strength

Test results are influenced by the time and rate of voltage application. In most cases, the breakdown voltage will tend to increase with increasing rate of voltage application. This results from the fact that both thermal breakdown mechanism and the discharge mechanism are time-dependent, although in some cases the discharge mechanism may cause rapid failure by producing critically high local field intensities. Also, the slower the application of voltage, the more likely failure will occur at a lower voltage. Generally, voltage is increased slowly from zero to the required value, unless breakdown occurs first, or the voltage is raised in discrete steps. To be meaningful, a statement concerning dielectric strength about a particular material should specify or imply the time of voltage application just prior to breakdown. Studies indicate breakdown voltage will tend to decrease if the duration of the test is extended. Breakdown by ionization is not instantaneous, therefore a definite interval of time is required for breakdown to occur. Because of this fact, it is very possible for a sharp, high voltage pulse not to have enough time to cause breakdown while a smaller pulse of longer duration could.

DIELECTRIC STRENGTH VS PRESSURE AND ALTITUDE

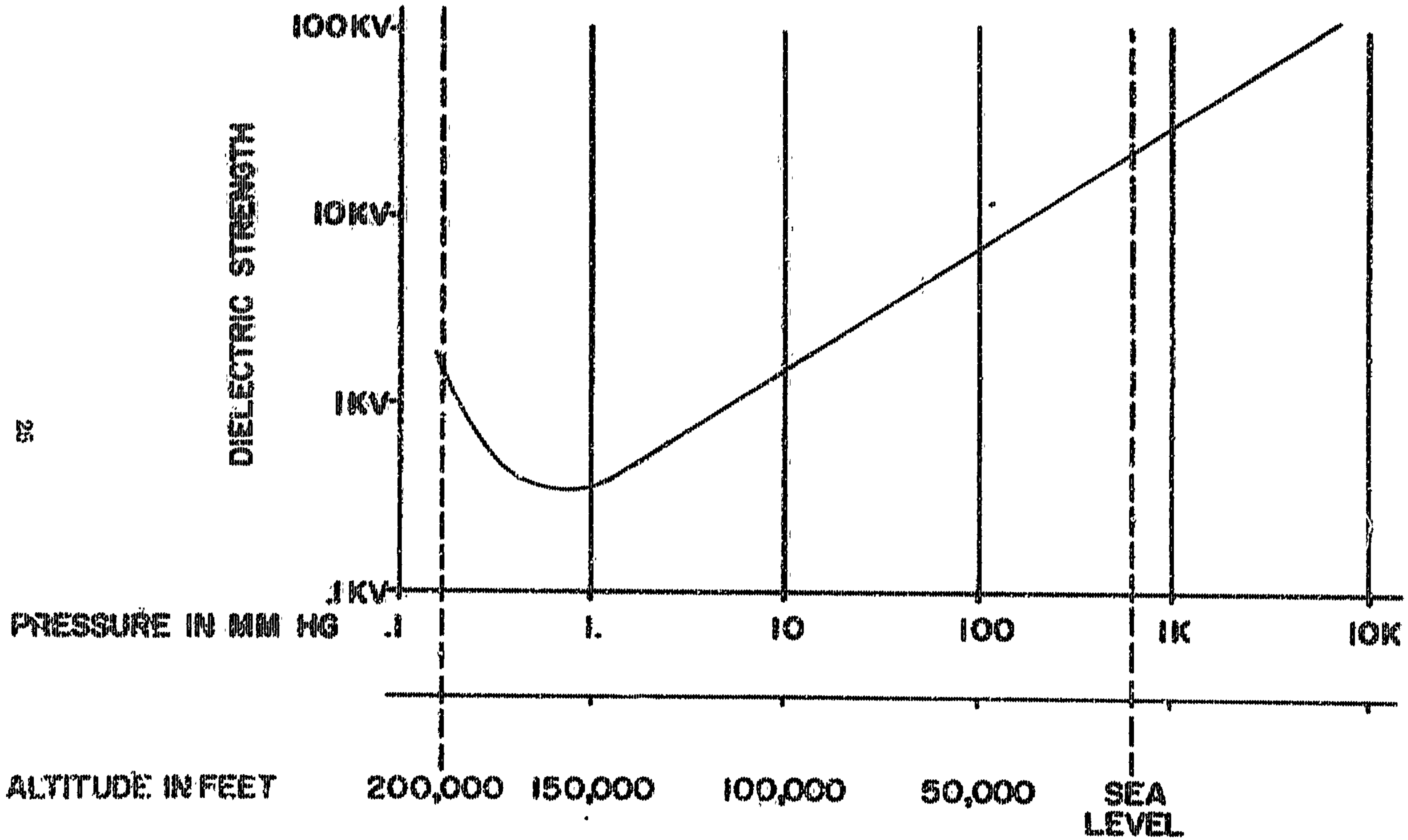

FIGURE 3

Insulation Resistance

Measurement of insulation resistance is complicated by the time of electrification. Time of electrification means that as a potential difference is applied to a specimen, the current through it generally decreases asymptotically toward a limiting value which may be less than 1 percent of the current observed at the end of the first minute. The decrease of current is attributed to dielectric absorption, changing capacitance, and the sweep of mobile ions to the electrode. The conventional arbitrary time of electrification has been specified as one minute.

Level of Applied Voltage

Dielectric Strength

Dielectric strength tests which are nondestructive are called "proof tests". They are made to detect design deficiencies, flaws, damage in manufacture, or any significant variation in dielectric strength. The level of voltage applied should give consideration to both the inherent dielectric breakdown strength and the spacing breakdown for the insulating wall thickness. By spacing breakdown voltage is meant the equivalent voltage at which air spacings will breakdown. Dielectric testing should be greater than the gas spacing breakdown level and lower than the dielectric breakdown voltage.

Insulation Resistance

In many cases both volume and surface resistance or conductance of the specimen may be voltage sensitive. In such a case the same voltage gradient must be used if results are to be consistent. A tolerance of 5 percent is generally given between applied and specified voltage. Insulation resistance tests are generally performed at 500 volts DC with special test sets. Generally, insulation resistance will decrease with an increase of applied voltage. The variation in resistance is usually due to moisture or voids in the insulation wall. A sudden change in resistance can be a forewarning of an impending failure.

Humidity

Dielectric Strength

The relative humidity can greatly influence dielectric strength. When moisture is absorbed by or on the surface of the material tested the dielectric loss and surface conductivity is increased. The extent to which dielectric loss and surface conductivity are increased is dependent upon the nature of the material being tested. However, some materials that absorb little or no moisture may be affected because of the greatly increased chemical effects of discharge in the presence of moisture. Moisture lowers dielectric strength because water's dielectric properties are dominated by a polarization consisting of the orientation of the molecules by the action of the applied field, the molecule having two hydrogen atoms with their +1 charges unsymmetrically disposed with respect to the oxygen atom with its -2 charge, thereby giving it a permanent electric moment. This polarization accounts for the very high dielectric constant of water at ordinary temperatures ($\epsilon_r = 80$). The effects of relative humidity can be limited by standard conditioning procedures.

Insulation Resistance

When moisture is absorbed into the pores of the insulation, the resistance becomes lower while the power factor is increased. Volume resistivity is very sensitive to temperature changes, while surface resistance will change rapidly with changes in humidity. The change is always exponential. If relative humidity is changed from 25 percent to 90 percent, resistance can be changed by a factor of one million. When an insulating surface gets wet, a thin film of water may be formed making the surface highly conductive.

Frequency

It has been shown in Section III that dielectric strength is not severely affected at power frequencies (50-60 hz). At higher frequencies the converse may be true. Capacitance may increase making the insulator a relatively good conductor where it can give or ground out electrical signals.

Thickness

The dielectric strength of electrical insulating material is dependent on specimen thickness. The dielectric strength for most materials varies inversely as a fractional power of the specimen thickness. For some materials the dielectric strength varies as the reciprocal of the square root of the thickness. As a result, dielectric strength of an insulating material is equal to the breakdown voltage divided by the thickness and is usually expressed in volts per mil.

Electrode Configuration

Dielectric Strength

In general, breakdown voltage tends to decrease with increasing electrode area and this effect is more pronounced on thinner specimens. Results are also affected by electrode material since the thermal and discharge mechanisms may be influenced by the thermal conductivity and work function of the electrode material. The air breakdown voltage increases as spacing between the electrodes increases, but as spacing approaches zero distance the curve differs because of Paschen's Law. After the critical gap spacing is reached the breakdown voltage of air varies inversely proportional to the electrode spacing. According to Paschen's Law, the minimum voltage required to breakdown air at any separation is equal to 335 volts DC or AC peak. This is a significant point to be considered in insulation design and testing. For lower voltages, any separation between two wires is adequate as long as it is clean and dry.

Contour of Specimen

The measured value of the insulation resistance of a specimen results from both its volume and surface resistances. Because of the different properties in different materials, there is no assurance that, if material A has a higher insulation resistance than material B, it will also have a higher resistance than B in the application for which it is intended. The contour of the specimen can change the insulation resistance significantly.

Environment

The environment can affect the heat transfer rate, external discharges, and field uniformity, thereby influencing test results. Results from one medium will differ when compared to those obtained from a different medium. Most of today's equipment is subject to a wide range of environmental conditions and exceeding high reliability requirements. Most equipment used in aircraft or missiles may be subjected to temperatures ranging from -70° F to several hundred degrees Fahrenheit under normal operating conditions. Vehicular vibration due to movement over roads or acceleration in the air may cause considerable stress on equipment. Handling subjects equipment to various degrees of wear and tear.

Contamination

Dielectric Strength

Contamination of the surface of the insulation with airborne chemicals, dust, moisture, etc., can severely reduce the dielectric strength of a material. When impurities are present the amount and nature of the impurity, the material, size, shape and spacing of electrodes will all have a considerable affect upon the final dielectric strength. Other contaminants such as grease and oil picked up during handling of the material may lower the dielectric strength.

Insulation Resistance

The resistance of clean, dry insulation will tend to increase for hours when measured at a fixed voltage. On contaminated insulation, the steady value of resistance will be reached quicker and usually at a much lower level. Dirt or dust on an insulating surface will increase the tendency for the formation of moisture films. A very thin moisture film may have such a high conductivity as to reduce the insulation resistance by a factor of several thousand to one.

Waveshape

Dielectric strength is influenced by the waveshape of the applied voltage. The peak value of a sine wave should be 1.414 times the rms voltage. Undersized or overloaded input circuits and excessive leakage current (low resistance) can cause waveshape distortion. Most distortion consists of flattened, sharp, or jagged peaks higher than those found in undistorted waveshapes. The maximum stress on a material being tested is due to the rms value when heating is most significant or peak value of the voltage when highest voltage stress is most significant. The scale of a voltmeter is usually calibrated in terms of rms, but yields the true rms value only if the output is a good sinusoidal wave. If the waveshape is irregular, the peak reading obtained may not be 1.414 times the true rms voltage.

Aging

Aging is defined as any slow deterioration that has not been satisfactorily explained. Mineral insulating materials like mica and quartz are slightly affected by aging, but most dielectrics are organic compounds and are liable to undergo changes. Aging consists of an oxidation of the material, reaction with the water molecules that penetrate its structure, the liberation of free ions, the breaking up of long chain molecules into shorter ones, the linking up of chain into a three-dimensional network or the breaking up of crystalline aggregates. Aging is accelerated by electrical use, chemical corrosion in the atmosphere, temperature changes, and exposure to light or ionized air. Aging is liable to be accompanied by critical changes in dielectric properties which may lead to trouble where suitable insulation once existed.

Previous Test History

Dielectric Strength

Every application of voltage to a dielectric material deteriorates the insulation and lowers the dielectric strength. Deterioration can change the electrical parameters and physical characteristics. It is generally accepted that if a piece of material can safely withstand a given voltage for one minute, it can withstand 80 percent of that voltage for hours. A one-minute test at a given voltage is considered equivalent to a five-second test at 120 percent of that voltage.[1] As a dielectric material is continually retested, a lower test voltage can give the same results as did the initial test voltage.

Insulation Resistance

As with dielectric strength, each application of voltage to an insulator deteriorates the insulation and lowers the insulation resistance. An example of previous test history affect on insulation resistance would be aging. The longer a piece of electrical equipment is used, the more liable to breakdown it becomes.

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GLOSSARY

Dielectric

A nonconducting sub... ice or material through which, however, induction, magnetic lines of force, or electrostatic lines of force may pass. A dielectric is a medium in which it is possible to produce and maintain an electric field with little or no supply of energy from outside sources. The energy required to produce the electric field is recoverable, in whole or in part, when the field is removed. In general, all insulating materials are dielectrics.

Dielectric Absorption

A phenomenan that occurs in imperfect dielectrics, whereby positive and negative charges are separated and then accumulated at certain regions within the volume of the dielectric. This phenomenon usually manifests itself as a gradually decreasing current after the application of a fixed DC voltage.

Dielectric Polarization

The dipole moment per unit volume in a dielectric. It is a vector in the direction of the electric field and related to it by the following relationship:

$$P = D - \epsilon_0 E = (X_e \epsilon_0 \; E) = (\epsilon - \epsilon_0)\,E$$

where P = Dielectric Polarization

D = Electric Displacement

ϵ = Permittivity of the Dielectric

ϵ_0 = Permittivity of Free Space

Xe = Susceptibility = $(\epsilon/\epsilon_0 - 1)$

Dielectric Strength

The dielectric strength of a material is the potential gradient at which electrical failure or breakdown occurs. To obtain the true dielectric strength, the actual maximum gradient must be considered, or the test piece and electrodes must be designed so that uniform gradient is obtained. The value obtained for the dielectric strength in practical tests will usually depend on the thickness of the material and on the method and conditions of test.

Electret

An electret is a dielectric body possessing separate electric poles of opposite sign and of a permanent or semipermanent nature. It is an electrical analog of a permanent magnet.

Imperfect Dielectric

A dielectric in which a part of the energy required to establish an electric field in the dielectric is not returned to the electric system when the field is removed. The energy which is not returned is converted into heat in the dielectric. (AIEE)

Insulator

A material of such low conductivity that the flow of current through it under specific conditions can usually, but not always, be neglected.

Insulator Strength

The loading in pounds at which the insulator fails to perform its function either electrically or mechanically, voltage and mechanical stress being applied simultaneously. (AIEE)

Permittivity

The permittivity (ϵ) of an isotropic medium, for which the directions of the electric displacement and the electric field intensity are the same at any point in the medium, is the magnitude of the electric displacement density (D) at that point divided by the electric field intensity there. The permittivity of a material is the value of the constant ϵ appearing in the denominator of the Coulomb force equation which expresses the force between two charges immersed or imbedded in the material. The permittivity is the relative permittivity multiplied by the permittivity of free space,

$$\epsilon = Ke\epsilon_o$$

where: ϵ = permittivity

Ke = relative permittivity (dielectric constant)

ϵ = permittivity of free space.

Power Factor, Dielectric

In electric power systems, the cosine of the dielectric phase angle or sine of the dielectric loss angle.

FORMULAS

$$X_C = 1/wC = 1/2\pi fC$$

$$Z_{AC} = R_{DC} + j X_C = \sqrt{(R_{DC})^2 + (X_C)^2}$$

where: X_C = Capacitive Reactance

Z_{AC} = Impedance to Alternatic Current

R_{DC} = Resistance to Direct Current

Let R_{DC} = 100 MEGOHMS

C = 10 pf = 10^{-11}

APPENDIX

The dielectric constant of a material is the ratio of the capacitance, Cx, of a given configuration of electrodes with a material as the dielectric, to the capacitance, Cv, dielectric: Ke = Cx/Cv. When absorption losses are neglected, a dielectric material can be represented by the following schematic:

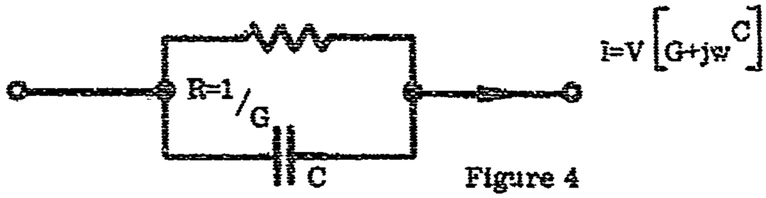

Figure 4

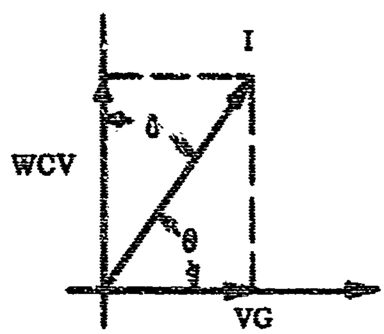

Figure 5

Dielectric Phase Angle, θ, is the angular difference between the sinusoidal alternating potential difference applied to a dielectric and the component of the resulting alternating current having the same period as the potential difference.

Dielectric Loss Angle, δ, is the difference between 90 degrees and the dielectric phase angle. The y-component, wCV, is affected by frequency and capacitance, while the x-component is affected by conductance. If the capacitance is low (1pf) or frequency is low (50-60 hz), the y-component may be smaller than the x-component. If capacitance or frequency is high the opposite is true and is shown in Figure 5.

Table 2 contains the results of capacitive reactance, X_C, impedance to alternating current, Z_{AC}, and the ratio X_C/Z_{AC} with the DC resistance equal to 100 megohms and capacitance equal to 10 pf for 10, 60, 100, 1,000 and 2,000 hz and 100 pf for 5, 10, 60, 100 and 1,000 hz. The graph in Figure shows how X_C/Z_{AC} varies with frequency and capacitance. The coordinate is variable X_C/Z_{AC} and the abscissa is the variable frequency. Cutoff values for insulation resistance and dielectric strength were made at the points X_C/Z_{AC} equal to 10 percent and 90 percent. This value may be increased or decreased, but 10 percent change was used as an engineering approximation. In the area below 10 percent dielectric strength would probably be the only test. Above 90 percent insulation resistance would probably by the only test. The shaded areas show where both insulation resistance and dielectric strength might be applied.

At the point $X_c/Z_{AC} = 0.5$

$$X_C = 0.5\ Z_{AC} = 0.5\sqrt{(R_{DC})^2 + (X_c)^2}$$

$$X_C^{\ 2} = 1/4\ \left[(R_{DC})^2 + (X_C)^2\right]$$

$$3\ X_C^{\ 2} = (R_{DC})^2$$

$$R_{DC} = \sqrt{3}\ X_C$$

states the current through the capacitor is $\sqrt{3}$ times the leakage resistance current.

In conclusion, the graph in Figure 6 shows that when the leakage current is 10 times the capacitive current only insulation resistance testing would probably be used and if the capacitive current is 10 times the leakage current only dielectric strength testing would probably be used. All other times both test might be applied.

TABLE NO. 2

f_{HZ}	X_C	Z_{AC}	X_C/Z_{AC}
10	1.59×10^9	1.6×10^9	0.99
60	2.65×10^8	2.84×10^8	.93
100	1.59×10^8	1.89×10^8	.84
1000	1.59×10^7	1.03×10^8	.15
2000	8×10^6	10^8	.08
5*	3.2×10^8	3.35×10^8	.96
10*	1.59×10^8	1.89×10^8	.84
60*	2.65×10^7	1.03×10^8	.26
100*	1.59×10^7	1.01×10^8	.16
1000*	1.59×10^6	10^8	.02

*C = 100 pf = 10^{-10}

CAPACITIVE POWER FACTOR VS FREQUENCY

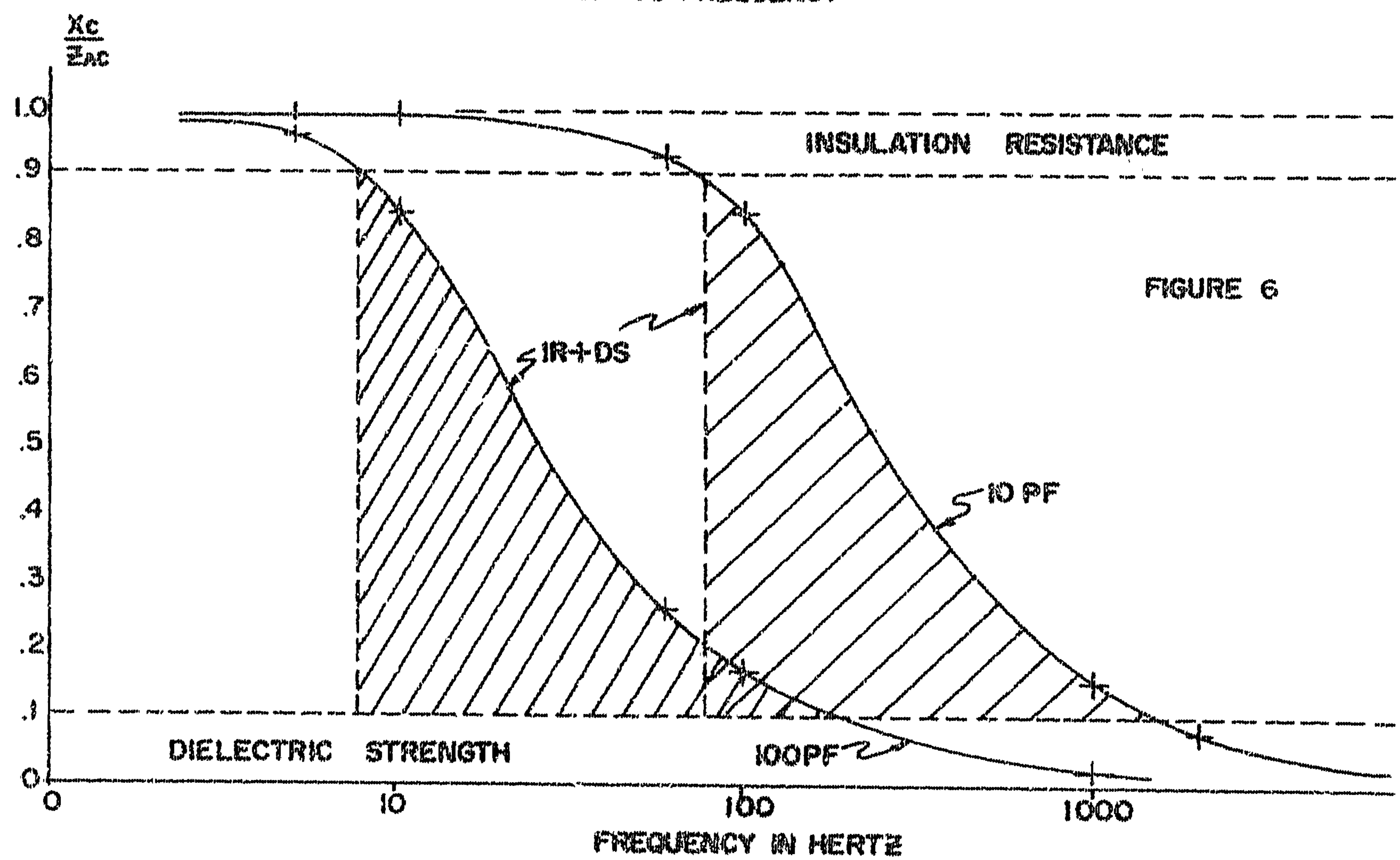

FIGURE 6