ELECTRIC STRENGTH

When a dielectric material is subjected to electric voltage, two different types of currents are induced. Applied voltage exerts force on the bound charges that give rise to displacement current. On the other hand, free charge carriers move under the influence of this force, which constitutes the conduction current. There are no free charge carriers in an ideal dielectric material. If the applied voltage is constant with time (dc), then the displacement current shows up only as a transient phenomenon that results in the polarization charge at steady-state condition. Displacement current will be nonzero at the steady state if applied voltage is time-dependent, and it is also known as the capacitive current or the polarization current. Conduction current (or leakage current) produces heat as a result of I^2R loss while the displacement current represents the energy stored. The two currents increase with a rise in applied voltage. This is true as long as the applied voltage is not sufficiently significant to introduce sharp or irreversible changes in the material.

In the foregoing description, it is assumed that the applied voltage remains below a certain limit such that the properties of dielectric material are preserved. However, if the applied voltage is high enough to exert a large force on bound charge carriers, then the material may break down. This change in characteristics of material may be irreversible. In this case, the electric resistance of the dielectric material decreases sharply; this gives rise to a large conduction current flowing through certain channels formed between the electrodes, practically producing a short-circuit. Maximum voltage V_{bd} applied at the moment of breakdown is known as the breakdown voltage of that material. The point of breakdown generates a spark or an electric arc that can fuse, burn or crack the material and the electrodes. When the applied voltage is removed, the solid dielectric may exhibit a trace of breakdown in the form of a punctured, fused or burnt-through hole, generally speaking, of an irregular shape. If this sample is again subjected to electric voltage, then the breakdown occurs in most cases at the already punctured spot even at a rather low voltage. Thus, a breakdown of solid insulation is a failure that puts the device out of operation and requires serious repairs. The liquid as well as gaseous dielectrics generally recover after the breakdown voltage is removed because of the mobility of constituent particles. However, if the power and duration of the electric arc are large, then the entire volume may change and the material may not recover.

Experiments indicate that the breakdown voltage of a material depends on the thickness between the two electrodes. The thicker the material, the more it withstands higher voltages; V_{bd} grows nonlinearly when thickness increases. On the other hand, layers of the same thickness but made of different dielectric material exhibit different breakdown voltage. This indicates that every insulating material has the unique ability to resist breakdown. This parameter is an electric field intensity value known as the electric strength E_{bs}.

For the simplest case of a uniform electric field produced by voltage V_{bd} in a dielectric of thickness d, one can write

$$E_{bs} = \frac{V_{bd}}{d} \tag{1}$$

Dielectric (or electric) strength may be regarded as the electric field intensity at a given point in a dielectric material that causes the breakdown at that location. Generally, the electric strength of an electrical insulating material is understood to mean average breakdown intensity. In Eq. (1), V_{bd} is in volts, d is in meters, and E_{bs} is in V/m. Other commonly used units of electric strength are kilovolts/millimeter, kilovolts/centimeter, and volts/micrometer. Another unit—volt/mil—is frequently used in the United States. Since a mil is one thousandth of an inch, 1 V/mil is equal to 39.37 kV/m. Alternately, 1 MV/m is equal to 25.4 V/mil.

The electric strength depends on various factors including temperature, humidity, frequency, and duration of the applied voltage. Its value varies over a broad range and therefore it is important to include the conditions under which a given datum is measured. For example, the electric strength for mica ranges from 100 to 300 MV/m, from 15 to 25 MV/m for transformer oil, while it is only 2 to 5 MV/m for air under normal conditions of pressure and temperature. Table 1 shows typical electric strength and the dielectric constant of selected materials. The table also shows that high-quality solid dielectrics possess higher electric strength, in general, in comparison with those of liquid and gaseous dielectrics. Therefore, the electric strength of the medium surrounding a specimen needs to be taken into account. For example, consider a comparatively thick solid test sample that is placed in

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Table 1. Dielectric Constant and Electric Strength of Certain Materials (5)

Material	Dielectric Constant	Electric Strength (kV/m)
Air	1	30
Barium titanate	1200	75
Oil	2.3	150
Paper	3	200
Porcelain	7	200
Glass	6	300
Paraffin	2	300
Quartz (fused)	4	400
Polystyrene	2.6	500
Mica	6	2000

air, as shown in Fig. 1. In this case, an increase in the applied voltage may cause first not a breakdown through the specimen, but a surface discharge or flashover through the surrounding medium.

The aforementioned characteristics lead to the conclusion that solid dense dielectrics should have higher electric strengths in comparison with those porous dielectrics containing many gaseous inclusions. The electric strength of porous dielectrics can be increased appreciably by impregnating it with high-quality liquid or solidifying insulating materials. The operating voltage V_{op} of insulating material in an electrical device (machine, cable, etc.) should be less than the breakdown voltage of that material. The ratio of the breakdown voltage to the operating voltage (V_{bd}/V_{op}) is generally called the safety factor of electric strength of insulation.

Two main kinds of breakdown occur largely in solid dielectrics: the electric and electrothermal breakdown. Electric breakdown represents the destruction of a dielectric material due to the force of an applied electric field. It occurs either because accelerating free charged particles (electrons, ions) interact with the material structure or because of inelastic displacement of bound charges in a dielectric under the action of an external electric field. The secondary processes (heating, chemical reactions, and so forth), which may occur in a dielectric under the action of an electric field, never take place in this intrinsic electric breakdown.

Theoretical analysis of electric breakdown is extremely complex. Experimental results frequently differ from those calculated on the basis of the structure and various parameters of materials. Estimated values of intrinsic electric strength are generally higher than the experimental results. This discrepancy is sometimes attributed to minute cracks and other defects present in the material.

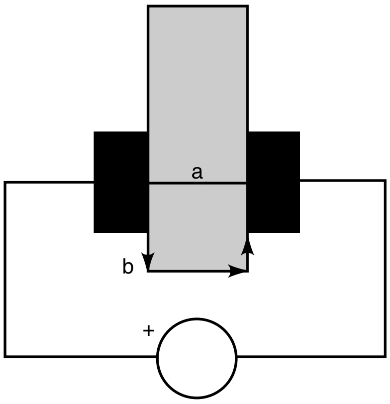

Figure 1. An arrangement of the electrodes with flashover path.

Electrothermal breakdown occurs due to loss of electrical energy in a material. The energy loss raises the temperature of insulating material and that, in turn, increases the energy loss even further. This process continues up to the point when the dielectric is fused, burnt, ruptured, or develops cracks.

BREAKDOWN IN LIQUIDS

Petroleum oils are important liquid dielectrics because of their frequent use in transformers, capacitors and cables that operate at high voltage. These are mixtures of various hydrocarbons and serve as neutral or weakly polarized dielectrics. In order to be employed in electrical insulation they must be free of water, oxidation products, aging and other contaminants. Even a small amount of water can influence the electric strength of petroleum oils significantly. This may be attributed to the fact that the dielectric constant of water (around 80) is much higher than that of oil (in the range of 2.2 to 2.4). Water droplets present in oil as emulsion, become elongated by the applied electric force and are broken into still finer droplets. These fine droplets form chains and are drawn into the sites where field intensity is especially high (i.e., towards the edges of the electrodes). It is precisely these sites that form the foci for the development of oil breakdown. The fibrous impurities reduce the electric strength of oil even more sharply.

Electric strength of the liquid dielectric material is found to increase noticeably when its thickness d between the electrodes is reduced. The following empirical relation can be used to estimate the electric strength of petroleum oil with d ranging from 0.01 to 1.0 mm (1):

$$E_{bd} = 31.3\, d^{-0.2085} \tag{2}$$

In Eq. (2), E_{bd} is in MV/m (acting value) and d is in millimeters.

BREAKDOWN IN GASEOUS DIELECTRIC MATERIAL

Besides chemical composition, pressure, and temperature of the gas, the design of electrodes and their separation affect the breakdown voltage and its pattern. In case of a comparatively uniform field, a gradual increase in applied voltage produces a breakdown of the entire gap between the electrodes. Generally, a spark is produced instantaneously and becomes an electric arc if the source of current has sufficient power.

If the field distribution is inhomogeneous, then an increase in voltage may first result in a discharge in the gas that appears only at the points where electric field intensity is strongest (for example, at sharp spots) without expanding over the entire gap between the electrodes. This discharge is commonly known as corona discharge (or for the sake of brevity, simply as corona) and it has a bluish luminescence. It is associated with a characteristic sound, that is, buzzing or crackling. The corona appears mainly because of chemical transformation of gas in that volume and the rapid growth of energy expenditure as voltage is increased. Peek's law may be used to estimate the latter as follows:

$$P_c = Af(V - V_c)^2 \quad \text{for } V \geq V_c \tag{3}$$

where P_c is power expressed in watts that is liberated in corona, and A is a constant that depends on the electrode geometry, gas composition, pressure and temperature. For example, it will be smaller if the electrode surface is made smoother; A has unit of watts/square volt, f represents frequency in hertz; V in volts is the voltage between electrodes, and V_c is voltage at which the corona appears initially.

As voltage is increased further, the corona occupies more and more space, causing a spark or an arc discharge between the electrodes puncturing the gas gap. Ordinarily, it develops during a very short time—of the order of several microseconds or less. In view of this, the breakdown voltage is practically the same for a direct current as well as for alternating current with a frequency up to a few kilohertz. If the breakdown occurs due to voltage pulses of very short duration, then the magnitude of breakdown voltage becomes larger than that of a low-frequency alternating voltage. The ratio of breakdown voltage with a pulse of given duration and form to breakdown voltage under alternating current of low frequency is known as the pulse coefficient β. When an electric field has a fairly high frequency (of the order of 100 MHz or so) the value of β reaches 1.5 to 2.

The influence of pressure and temperature of a gas on its electric strength is of great importance. The electric strength of air rises with increase in pressure above the normal atmospheric value. When it drops below the normal atmospheric pressure, the electric strength of the gas passes through a minimum and then increases appreciably in the region of reduced pressure. This is why gases are employed as an insulating medium at a high or markedly reduced pressure. This phenomenon can be explained via the theory of collision ionization as a cause of gas puncture. A gas always contains some electrically charged particles (electrons, negative and positive ions) generated by cosmic rays, radiation of radioactive matter, ultraviolet rays and other factors. Similar to the molecules of a gas, these particles are in a state of chaotic thermal motion. These charged particles are accelerated by the applied electric field. Hence, they acquire a velocity that results in higher kinetic energy until they collide with a molecule. If λ denotes the mean distance traversed by a charged particle before colliding with a molecule and the charge on that particle is q, then its kinetic energy in a uniform field with an intensity E at the moment of collision will be given as follows:

$$W = Eq\lambda \tag{4}$$

If this energy is sufficient to ionize the molecule, that is, to separate it into a positive ion and an electron, then the gas may be punctured. This occurs because the new particles generated upon collision ionization will, in turn, be accelerated by the electric field and ionize the other molecules. This process will continue until a complete breakdown occurs in the gap. A rise in pressure (with temperature remaining the same) increases the density of gas, and, in turn, reduces the mean molecular distance and diminishes the value of λ. It is true that λ increases in the region of high vacuum, but there is much less probability of collision between the charged particles and the molecules of rarefied gas. The latter effect dominates the former (the effect of increase in λ). At high vacuum, the value of λ can even exceed the dimensions of the container.

In practical calculations, the effect on the electric strength of air to slight deviations in normal pressure p and temperature T (p = 760 mm Hg, T = 293 K) is estimated as follows. Assume that V_{bdo} represents the breakdown voltage at normal condition and V_{bd} is its new value. Then

$$v_{bd} = V_{bdo}d \tag{5}$$

where d is the relative density of air. It is the ratio of the density of air at a pressure of p and a temperature T to the density of air in normal condition, and given by

$$d = 0.385526\frac{p}{T} \tag{6}$$

In this equation p is measured in mm Hg and T in kelvin.

Detailed study of the breakdown in gases with various pressure p and the electrode separation t indicates that the magnitude of breakdown voltage in a comparatively homogeneous field depends not on the value of p and t taken separately, but a product of these two parameters; this is known as Paschen's law. A definite minimum breakdown voltage V_{bdm} describes each gas. When the voltage is less than this value, the gas-filled gap of any length and under any pressure can not be punctured. The value of V_{bdm} is 326 V for air for $p \cdot t$ = 5.67 mm Hg · mm. In the case of inert gases, V_{bdm} also

Table 2. Comparative Values of Electric Strength of Gaseous Dielectrics (1)

Gas	Chemical Composition	Molecular Mass	Electric Strength Relative to Air
Helium	He	4	0.06
Hydrogen	H_2	2	0.6
Carbon dioxide	CO_2	44	0.9
Nitrogen	N_2	28	1.0
Freon-12	CCl_2F_2	120	2.6
Perfluoromethylcyclohexane (vapor)	C_7F_{14}	350	6.0
Perfluorodibutylether (vapor)	$C_8F_{18}O$	454	7.5
Perfluorodimethylcyclohexane (vapor)	C_8F_{16}	400	8.5
Perfluorophenatrene (vapor)	$C_{14}F_{24}$	624	10.0

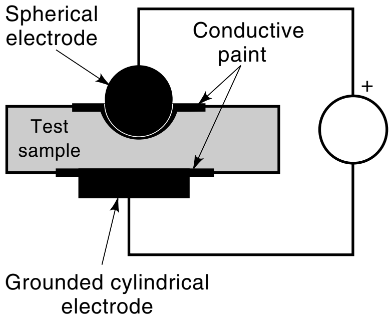

Figure 2. An assembly of spherical and cylindrical electrode geometry.

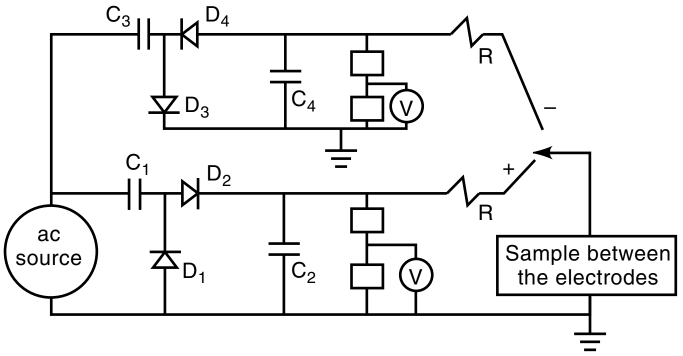

Figure 4. A direct voltage test arrangement for specimen.

depends on the material of the electrode (cathode). If the cathode is made of an alkali or alkaline-earth metal that possesses a low work function of electrons (or is at least coated with such metal) then V_{bdm} is reduced. This fact is utilized to make gas-discharge devices.

It may be inferred that gases varying in their chemical composition have different electric strength under the same conditions. Thus, the electric strengths of hydrogen and inert gases, such as argon, neon, and helium, are lower compared with air. There are also gases that possess an electric strength appreciably larger than that of air. The gases with high electric strengths that can be employed as electrical insulation in high-voltage devices (especially at high pressure) have rather high molecular mass and density. These are primarily the gases containing strongly electronegative elements—fluorine, chlorine, and so forth. The electronegativity is an arithmetic sum of the energies of ionization and affinity to electron. The metalloid properties in a given element with higher electronegativity are more pronounced, while the metallic properties manifest themselves more at a lower electronegativity. The high electric strength of electronegative gases is due to the ability of the molecules of these gases to combine easily with free electrons or to absorb part of the energy of the electrons colliding with them. Table 2 illustrates some of these properties.

ELECTRODE GEOMETRY USED FOR MEASUREMENTS

The value of electric strength is, in general, influenced by the shape of the electrode. If the measurement conditions are unknown, the specified value of electric strength will have very little practical importance. In that case, the designer must measure it before proceeding with the design. A commonly used electrode system is depicted in Fig. 2. Here, a cylindrical electrode is used as ground while the high voltage is applied through a spherical electrode that is placed over a recessed section of the sample-under-test. Conducting paint or an evaporated metallic film that extends over the normal thickness facilitates the contacts between the electrode and the specimen. Depending on the chemical compatibility, mineral or synthetic oils are used as the immersing medium to control the flashover and corona discharge along an external path. The spherical electrode can be rotated after each breakdown to avoid subsequent breakdown originating from the previously pitted electrode surface. If both electrodes are spherical, then their alignment may become a problem. This can be circumvented by the use of a translucent polymethyl methacrylate (PMMA) disk that has a cylindrical hole with a diameter equal to that of the spherical electrodes, as shown in Fig. 3. The sample-under-test is in the form of a disk without recessed surfaces. It is in contact with the spherical electrodes that together with the specimen are embedded in epoxy resin. This kind of system is preferred for precise measurement of

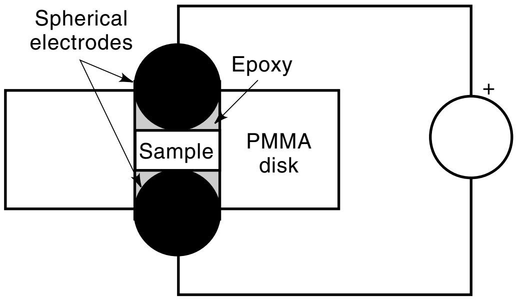

Figure 3. A two-spherical electrode assembly.

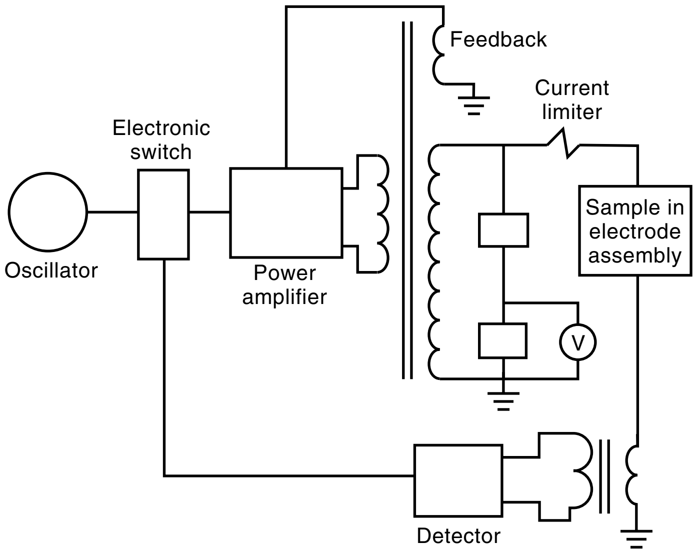

Figure 5. An alternating voltage test arrangement.

electric strength. Various kinds of cylindrical disk electrodes have also been used for routine measurement (2,3). However, those are not described here for the sake of brevity.

TEST APPARATUS

The test circuit requires a means to generate a controlled high voltage. In case of a direct voltage testing, the polarity of applied voltage may be another parameter that needs to be taken into account. Figure 4 shows a test circuit that employs the voltage multiplication to generate high dc from an ac source. A voltmeter connected via a voltage divider circuit monitors the voltage applied to electrodes. The purpose of resistor R is to limit the current at breakdown. It should not have too large a value that can produce large voltage drop. Separate circuits generate the positive and negative voltages.

A low-frequency (up to a few kilohertz) alternating voltage test circuit is illustrated in Fig. 5. An oscillator that feeds the primary side of a transformer via the power amplifier generates the desired frequency signal. A feedback from the transformer is used to regulate the power amplifier. The transformer output is applied to electrodes via a resistor that limits the current and protects the circuit. The detector block senses the breakdown of specimen and signals the electronic switch to interrupt the input.

When the alternating voltage has a fairly high frequency (in microwave range), the power capacity is a more significant specification than the breakdown voltage (4). However, in case of dielectric materials it is perhaps useful to convert the results to a corresponding voltage to permit correlation with data available at the lower frequency. The specimen of a specific geometry is placed inside the microwave cavity and the breakdown power is monitored.

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