J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

IMPULSE TESTING

All electrical equipment is subjected to voltage surges (impulses) during operation. These surges vary in magnitude and duration depending on their origin and the system parameters in which the equipment is installed. Impulse voltages generated in a piece of equipment or a system are termed overvoltages because they usually exceed the normal operating voltage.

In designing electrical equipment, two main factors are taken into consideration. The first is the insulation, which depends not only on the operating voltage but also on the voltage surges that it may be subjected to during operation. Consequently, the insulation of a piece of electrical equipment should provide complete isolation between electrically live parts and other parts, either live or dead, for the safety of the equipment and personnel. The second factor is the equipment current. It should not produce excessive heating, which may shorten the life of the equipment or damage its conducting and insulating materials.

Overvoltages in a piece of electrical equipment installed in a power system are generated either from external or internal sources. Lightning is an external source of overvoltage to power systems, which is usually characterized by large magnitudes and a short duration. Switching operations in power systems are internal sources of overvoltages and are characterized by lower magnitudes and a longer duration.

Electrical equipment is subjected to impulse testing to verify its ability to withstand surge voltages or currents to which it may be subjected during operation.

Lightning Overvoltages

Upward humid air drafts from the earth's surface reaching high altitudes are subjected to relatively low temperatures where their moisture content condenses into large water drops. These drops disintegrate into smaller ones. The process of disintegration produces electrification where the small drops carry positive charges and the negative charges are carried by the ambient air. The head of a cloud is positively charged, whereas its lower part is negatively charged (1). The process of water drops disintegration may be repeated, thus creating many charges. These charges produce potentials on the order of millions of volts within the cloud and voltage gradients on the earth surface on the order of a few tens or even hundreds of kilovolts per centimeter, depending on the amount of charge contained in the cloud and its height from ground surface. Under some favorable conditions, a direct lightning stroke may occur between the cloud and the earth's surface, buildings, or electrical installations including power transmission lines. The process of lightning strokes are rather complicated in their growth, and numerous theories are found in the literature (2,3). Direct lightning strokes are characterized by large and fast rising discharge currents. The amplitude of discharge current is on the order of few tens of kiloamperes and in severe cases may reach 200 kA. Its rise time is few microseconds with an average steepness of few kiloamperes per microsecond. The process of developing of lightning stroke is illustrated in Fig. 1. Direct lightning strokes may cause severe damage to buildings and power systems if they are not properly protected. Protection of buildings and similar structures is usually carried out by means

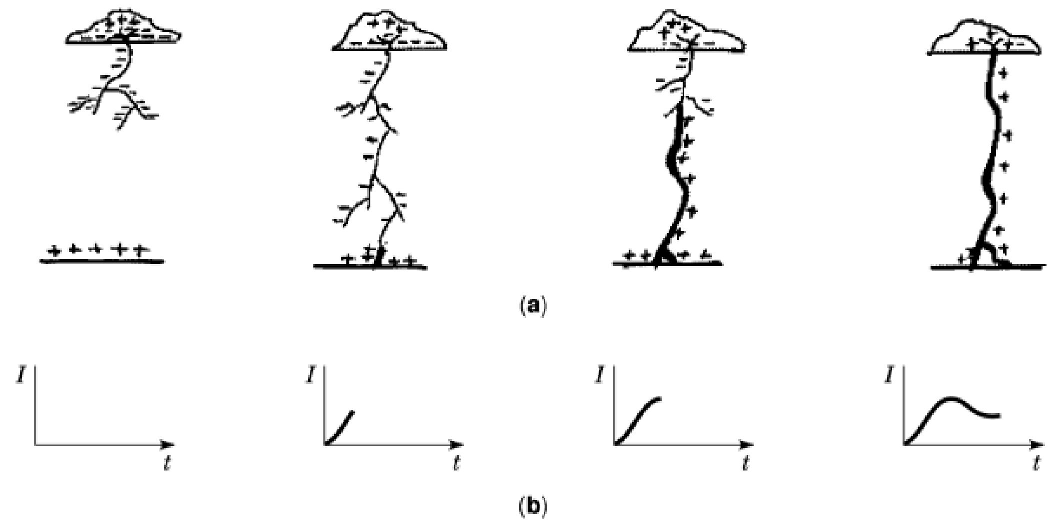

Fig. 1. Direct lightning strokes. (a) Development of a lightning stroke. (b) Accompanied discharge current.

Table 1. Switching Overvoltages

Temporary Overvoltages	Switching Overvoltages
Load rejections	Short circuit currents
Energization of unloaded lines	Inductive currents
Earth faults	Capacitive currents
Resonance effects	Short lines

of metal masts (Franklin rods). Power transmission lines are protected by earth wires strung between towers above the line conductors.

Switching Overvoltages

Power systems are subjected to switching overvoltages during their operation. These voltages are classified into two main categories, according to the switching operation and the switched current. Table 1 shows the main switching operations in power systems.

Compared to lightning surges (impulses), switching surges are characterized by their long duration and lower magnitudes. Figure 2 shows the duration of lightning and switching overvoltages as well as their magnitudes per unit of system working voltage.

Generation of Impulse Voltages

For test purposes, impulse voltages, simulating voltage surges from lightning or switching, are generated in high-voltage test laboratories.

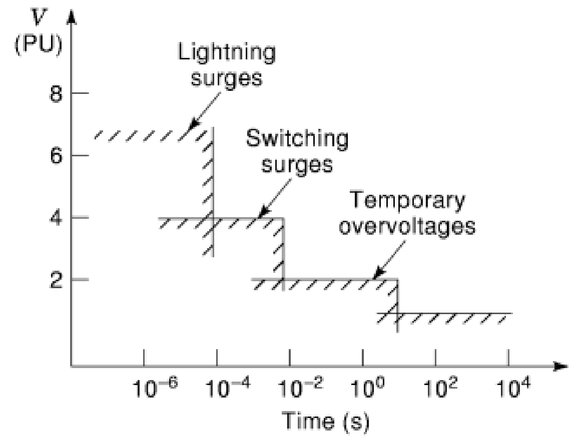

Fig. 2. Magnitudes and duration of lightning and switching voltage surges.

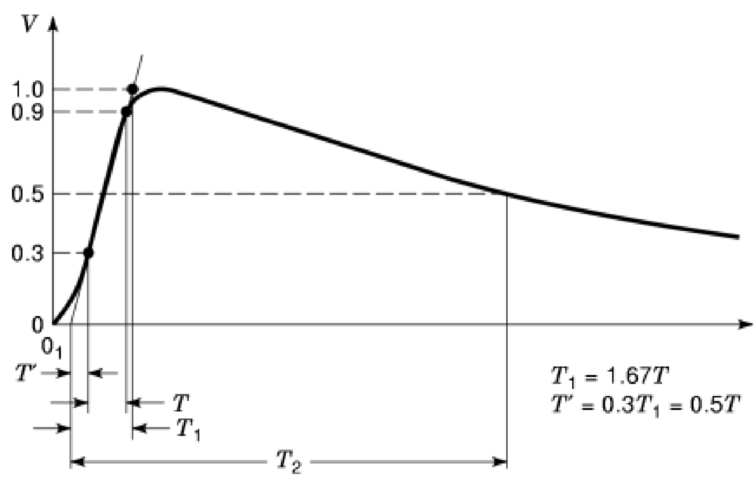

Fig. 3. Lightning impulse voltage wave. Exact evaluation of wave front and tail times are shown.

An impulse voltage is a unidirectional voltage that rises to peak value in a short time and decays slowly to zero value. For the purpose of standardizing high-voltage tests, the impulse voltage shape should be precisely defined. Figure 3 shows an impulse voltage wave simulating a lightning surge. The wave shape, in general, is defined by its time to crest (wave front T_1) and its decay time to 50% of crest value (wave tail T_2).

Usually generated impulse voltages have a low rate of rise at their initial and final stages of buildup. On the other hand, a considerable percentage of the peak value builds up in a relatively short time compared to the total front time. To overcome this, the wave front and tail times are evaluated, as shown in Fig. 3. Impulse voltage waveshapes are defined by the values T_1 and T_2 in microseconds (T_1/T_2).

Impulse voltage in the range of 100 kV are generated by single-stage impulse generators and higher voltages, up to about 6 MV, are generated by multistage generators.

Single-Stage Impulse Generators. Impulse voltages are simply generated by charging a condenser from a dc source and suddenly discharging it through a resistor by closing a fast-acting switch. In actual impulse generators, this switch is in the form of a sphere gap, controlled to close the circuit and start operation when required. Figure 4 shows a single-stage impulse generator. Construction of the impulse generator's control

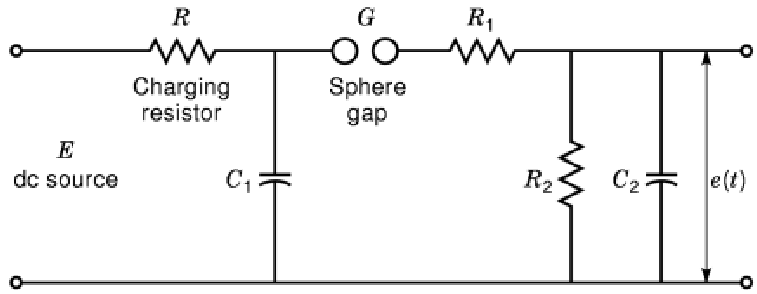

Fig. 4. Single-stage impulse generator circuit.

circuit (trigatron) is not shown; more details are given in Refs. 4 and 5. The voltage E is the input dc voltage usually obtained from a variable step-up high-voltage transformer with full-wave rectifier and smoothing circuit. The resistor R is for charging the stage capacitor C_1; R_1 and R_2 control the wave front and tail times, respectively; and C_2 is the test object capacitance. The output voltage $e(t)$ can be obtained by Laplace transform and simple circuit equations, which is in the form

$$e(t) = \frac{E}{R_1 C_2(\alpha_2 - \alpha_1)}[\exp(-\alpha_1 t) - \exp(-\alpha_2 t)] \qquad (1)$$

where

$$\begin{aligned} \alpha_1, \alpha_2 &= \frac{a}{2} \mp \sqrt{\left(\frac{a}{2}\right)^2 - b} \\ a &= \left(\frac{1}{R_1 C_1} + \frac{1}{R_1 C_2} + \frac{1}{R_2 C_1}\right) \\ b &= \frac{1}{R_1 R_2 C_1 C_2} \end{aligned} \qquad (2)$$

Equation (1) is the difference between two exponential voltage waves decreasing with time. The first one decays slowly with time, *and* the second decays relatively faster. Examination of the two constants α_1 and α_2 in Eq. (2) shows that the values of R_1 and R_2 control the wave front and tail times. Complete details of other circuits arrangements, calculation of the wave front and tail times, and efficiency of the generator are fully given in Ref. 5.

In calculating the parameters of the impulse wave, no consideration was taken for the inherent inductance of the circuit elements and connecting leads. However, the value of this inductance has a great effect on its shape.

For the purpose of impulse voltage testing, standard impulse waves are recommended by different national and international standards. The most common impulse waves are 1.2/50 in Europe and 1/40 in North America.

Multistage Impulse Generators. For technical reasons, the dc charging voltage is usually limited to voltages around 200 kV. To obtain impulse voltages in the range of 6 MV multistage impulse generators are constructed. The basic idea of these generators is to charge several condensers in parallel from a moderate voltage dc source (say 200 kV) and then simultaneously discharging them in series through resistors. Figure 5 shows the circuit of a multistage generator in which an impulse voltage of approximately ten times the charging voltage is obtained. Full details of multistage impulse generators circuit, operation, and control are given in several high-voltage engineering textbooks (4,5,6).

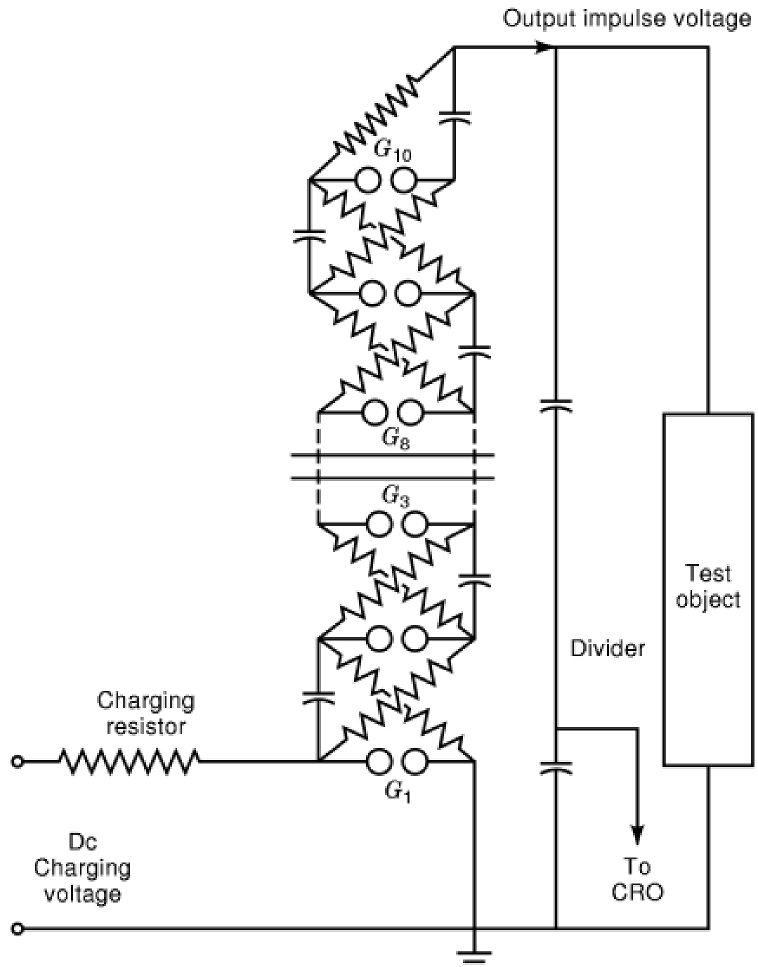

Fig. 5. Multistage impulse generator circuit. Charging voltage = 200 kV, number of stages = 10, output impulse voltage ≈ 2 MV.

Generation of Switching Surges

Switching voltage surges are characterized by their long front and tail times and high energy. The definition of the wave front and tail times is more or less similar to that of lightning impulse voltages (7). Switching impulse voltage wave shapes in common use for testing purposes have wave front and tail times on the order of several hundred microseconds (250/2500 and 500/2500 μs). These voltages can be generated from normal impulse generators with some modifications in their circuit elements to control the wave front and tail times to the required values. Alternative methods for generating such voltages are by producing voltage oscillations in the low-voltage winding of a step-up transformer or coil (Tesla coil). These oscillations are then transferred to the high-voltage side. Adjustment of the low- and high-voltage side parameters (inductance and capacitance) of the transformer or coil circuit and the instant of switching operation on the low-voltage side control the generated voltage shape. Figure 6 shows the well-known circuit of a Tesla coil. Interested readers may refer to Refs. 4 and 5 for more details on circuit construction, operation, and merits and demerits of different systems.

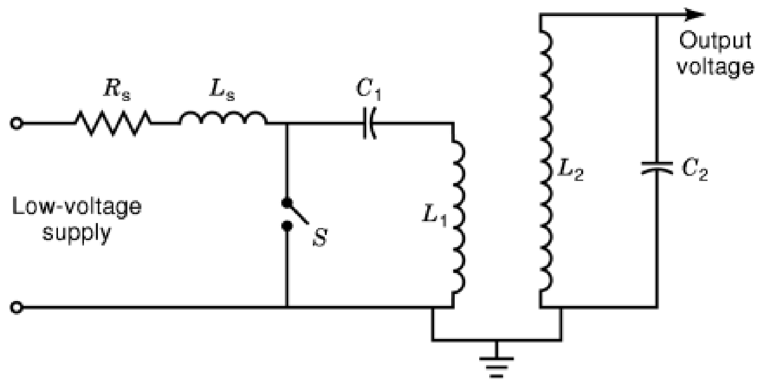

Fig. 6. Switching impulse voltage generation by Tesla coil.

Impulse Voltage Measurement

Impulse voltage measurement needs special measuring equipment and techniques to give true measure of the peak value and wave shape. When measuring high-impulse voltages on the order of megavolts and high rising rates, the measuring process becomes rather complicated, and the accuracy is highly reduced. Whatever the method used to measure impulse voltages, tedious precautions should be taken to reduce measuring errors. These errors are mainly introduced by external interference and response of the measuring system to such single-event voltages.

The main measuring methods used in impulse testing and research work are (1) sphere gaps and (2) resistive or capacitive voltage dividers.

Sphere Gaps. Measurement of the peak value of impulse voltages by means of sphere gaps, especially at extra high voltages, is very common in impulse testing. They consist of two identical metallic spheres separated by an air gap. The basic principle of measurement by sphere gaps is that the air in the separating gap breaks down in response to the peak value of the applied voltage, provided that its rise time is not less than 1 μs. To obtain accurate measurement by sphere gaps, several precautions should be taken. These precautions include sphere diameter selection, separation, and mounting; surface conditions; and connection to the measured voltage and nearby objects. Standard sphere diameters in common use range between 6.25 cm and 200 cm.

Measurement of impulse voltages by sphere gaps is the simplest method, with an accuracy of $\pm 3\%$, provided all recommendations given by IEC (8) are strictly followed. In laboratory testing work, it is difficult to control the temperature and pressure to standard values (20°C and 101 kPa) because of the large space and size of equipment. A correction factor k is used to obtain actual values corresponding to ambient conditions. This factor depends on the relative air density δ, which is given by

$$\delta = \frac{P}{760}\frac{(273+20)}{(273+t)} = \frac{0.386P}{273+t} \tag{3}$$

where t and P are the ambient temperature and pressure in degrees Celsius and millimeters of mercury, respectively. If V_s is the breakdown voltage at standard conditions given in IEC (8), then the actual voltage measured is kV_s. The values of δ and k are very close to each other (8).

Resistive Dividers. Resistive voltage dividers are commonly used in measuring ac and dc high voltages, and their construction is relatively simple. When measuring high-impulse voltages on the order of megavolts having short rise time, these dividers need special construction to give a true picture of the measured signal in magnitude and shape. Theoretically, resistive dividers consist of a high resistance in series with a low-value resistor. The combination is connected directly on the test object with the low-voltage terminal earthed. The division of voltage between the high- and low-resistance sections of the divider is not simply in the ratio of their values. In ac and dc measurement by resistive dividers, the error is usually much less than when measuring impulse voltages. The difficulty with impulse voltage dividers is that their transfer characteristics introduce large errors in both magnitude and shape if they are not properly constructed and sized. More details on the transfer characteristics of voltage dividers will be presented later. The sample voltage signal on the low-voltage section of the divider can be measured and recorded by oscilloscopes, analog/digital conversion circuits, attenuators, or high-voltage probes. The accuracy of voltage measurement, of course, depends on the divider construction, electromagnetic interference from test equipment, connection leads, and effectiveness of the grounding system.

Capacitive Dividers. Similar to resistive dividers, capacitive dividers are constructed from a single capacitor unit or several units in series and connected across the test object. Construction of high-voltage capacitors needs high technical measures and experience. However, compressed gas (sulfur hexafloride, SF_6) capacitors are now available with good performance characteristics. Again, the main difficulty with capacitive dividers is their transfer characteristics and electromagnetic interference. It is obvious that the measured voltage signal across the low-voltage section of the divider is not simply proportional to the inverse ratio of the divider capacitances. This is true because the equivalent circuit of the divider involves stray capacitances, inherent inductances, and resistors either actual or representing losses in the capacitors dielectric.

Impulse Currents. Lightning and voltage surges (impulses) are often accompanied by current surges that flow in a piece of equipment or a system subjected to such surges. Thus, impulse currents are generated in high-voltage laboratories for testing purposes. Surge arresters, used for protecting high-voltage equipment, are tested with impulse currents to verify their performance characteristics.

Similar to lightning and switching voltage impulses, two current wave shapes are used for testing electrical equipments. Figure 7(a) shows the wave shape recommended by IEC for testing under lightning impulse currents. Again, the wave shape is defined by the wave front and tail times in microseconds (T_1/T_2). The standard lightning impulse currents used in testing purposes are 1/20, 4/10, 8/20, and 30/80. Figure 7(b) shows the wave shape, recommended by IEC, for testing under switching impulse current. The wave shape is nearly rectangular in shape. The two time parameters defining the current wave T_d and T_t are shown in Fig. 7(b). Standard rectangular impulse currents have a time duration T_d of 500, 1000, or 2000 μs.

Measurement of Impulse Current. Fast-rising high-impulse currents up to few hundreds kiloamperes (200 kA) are usually encountered in testing surge arresters and lightning discharges. The main requirements from the measuring system are: (1) accuracy, (2) fast response, (3) simple construction, and (4) size.

Measurement of impulse currents relies on its basic effects; voltage drops when passing in a resistive element, associated magnetic field, and optical phenomenon. Resistive shunts are commonly used for high-impulse current measurement having ohmic resistance on the order of few milliohms. The voltage drop across the shunt (a few hundred volts) is measured by any voltage-measuring device such as a cathode-ray oscilloscope (*CRO*). The difficulties in designing resistive shunts are their inherent inductance, which should be minimal; the voltage across the shunts, which should be on the order of few hundreds volts; and their volume, which should be capable of absorbing the energy associated with the measured current without the temperature exceeding a permissible rise (20°C). Different designs and performance characteristics are given in Refs. 9 and 10. Methods based on the magnetic effect of electric currents use a single-turn coil placed perpendicular to the magnetic field. The induced voltage in the coil is a function of the measured current in magnitude and shape.

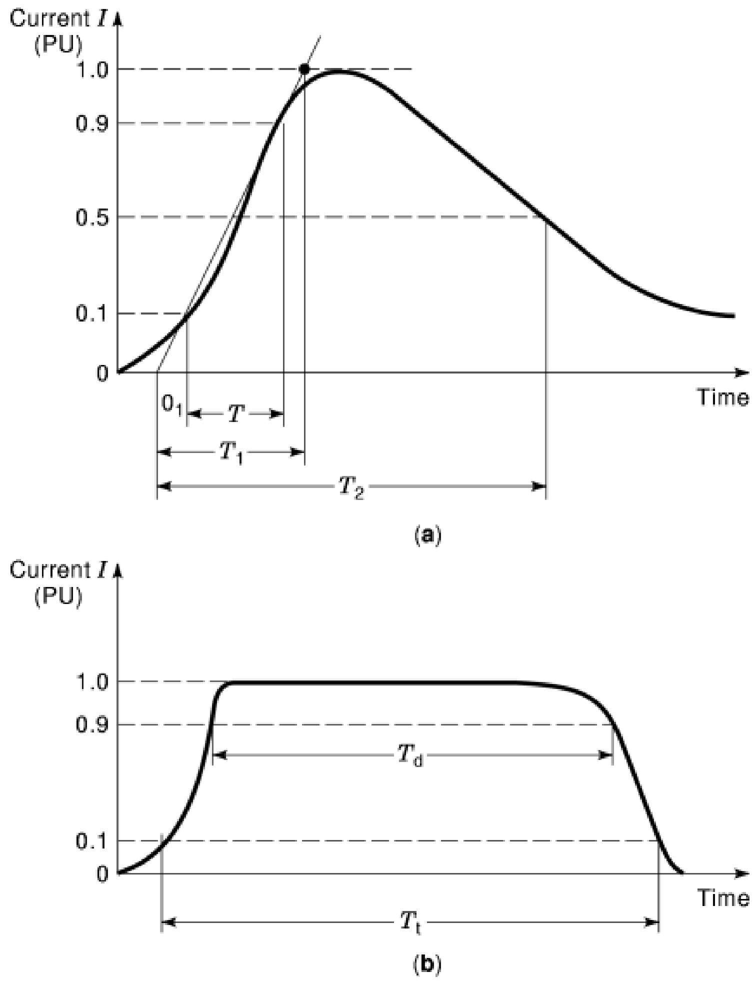

Fig. 7. Impulse current wave shapes: (a) exponential and (b) rectangular.

The basic equations governing the measured current and induced voltage in the coil are

$$\oint_c H dl = I \tag{4}$$

$$\int\int B ds = \phi \tag{5}$$

$$e = -\frac{d\phi}{dt} \tag{6}$$

$$e = -\mu \frac{r^2}{R_o} \frac{di(t)}{dt} \tag{7}$$

where H is the magnetic field, ϕ is the flux linking the coil, r is the radius of the coil, and R_0 is the distance between the coil center and the current-carrying conductor.

Pulse current transformers are sometimes used to measure impulse currents. However, their accuracy, lowpass band (a few kilohertz), and saturation problems limited their applications.

Optical methods used to measure impulse currents are based on two facts. The first is that, when a current flows through a light emitting diode, it generates light that depends on the current shape and magnitude. This light can be detected and transformed by photodetectors to an electrical signal, which is taken as a measure of the current (11). The second is that light beams show rotation when subjected to magnetic fields. Again, photodetectors are used to transfer this rotation to an electrical signal (12) proportional to the measured current.

Electrical Discharge

Insulation media in electrical equipments may be a liquid, solid, gas, or combination of them. Gases are used to insulate electrical equipments such as circuit breakers, high-voltage capacitors, and other equipment. Gases, when compressed, are excellent insulants and superior to other media. Under natural conditions, a gas constitutes neutral molecules and few free electrons (negative charge carriers) produced by natural sources such as cosmic rays. When this gas is subjected to a uniform electric field between two electrodes, the free electrons gain energy and move toward the positive electrode (anode). On their way to the anode, they collide randomly with the neutral gas molecules. If they have enough energy, they may ionize these molecules, thus producing new electrons and positive ions. The new electrons and the initiatory ones in their way to the anode may produce additional electrons. This process is a cumulative one, and a large number of electrons form an "electron avalanche" heading toward the anode. In the mean time, positive ions travel slowly (because of their relative large mass) toward the cathode. This process of ionization is called the Townsend primary ionization process. The flow of electrons between the electrodes is a flow of charge or a current. This current increases with the increase of electric field between the electrodes. Many other ionization and de-ionization processes are involved in gaseous discharge. How these processes occur, the factors governing their contribution to the electrical discharge, and the equations quantifying their contribution is a very broad subject, which is covered in a huge number of articles and reference books (2,4,5,13). The basic equation for current growth is

$$i = i_0 \frac{e^{\alpha d}}{1 - \beta(e^{\alpha d} - 1)} \tag{8}$$

where i is the current flowing between the electrodes, i_0 is the initiatory primary current, α is Townsend first ionization coefficient, β is Townsend secondary ionization coefficient, and d is the electrode spacing. Equation (8) does not take into consideration all secondary ionization and deionization processes such as photoionization in the gas and at the cathode surface, ionization by metastable atoms, thermal ionization, diffusion, and attachment. However, Eq. (8) was modified to be in the form

$$i = i_0 \frac{\dfrac{\alpha}{(\alpha - \eta)} e^{(\alpha - \eta)d} - \dfrac{\eta}{\alpha - \eta}}{1 - \dfrac{\gamma\alpha}{(\alpha - \eta)}[e^{(\alpha - \eta)d} - 1]} \tag{9}$$

where γ is the secondary ionization coefficient and may involve more than one secondary process and η is the attachment coefficient.

The coefficients α, η, and γ in Eq. (9) are functions of more than one of the parameters evolved in gaseous discharges (electric field, gas, electrode geometry, cathode material, and gas pressure and temperature).

The condition of breakdown in the gas is assumed when the current flowing between the electrodes is theoretically equal to infinity. This occurs when

$$\frac{\gamma\alpha}{\alpha-\eta}\{\exp[(\alpha-\eta)\,d_s]-1\}=1 \tag{10}$$

where d_s is the electrode separation at breakdown.

Electric discharge leading to breakdown as given by Townsend's equations has many limitations in explaining how breakdown occurs in long gaps and nonuniform field gaps resulting from the very short time observed during their breakdown. The streamer theory was then developed to account for such limitations. In brief, the streamer theory is based on the fact that for breakdown to occur in a time on the order of 10^{-6} s to 10^{-8} s, there must be a buildup of a high electric field in the gap to accelerate the breakdown process. This field was attributed to the accumulation of the slow moving positive ions in the gap, thus leading to an external space charge field. Photoionization in the gas was also considered as an additional accelerating factor for breakdown. Several explanations and equations have been developed by Meek, Loeb, and Raether on the theory of streamer breakdown (2,3).

In nonuniform field electrode geometries (e.g., point to plane, parallel wires, and coaxial wire-cylinder), the electric field is highly localized at the point or the wires while it is relatively low at other places. This high field may start discharge at and around these electrodes while the rest of the gap is not. This phenomenon is known as Corona discharge, and it is characterized by its pale violet light, smell of ozone, and hissing noise. Corona represent continuous power losses on transmission lines, and its presence in electrical equipment should be avoided because it may lead to their failure.

Impulse Breakdown

Breakdown under impulse voltages is different from those under ac and dc because of their short duration time. For breakdown to start, at least one electron should exist in the gap at a favorable location and time. Alternating (60 Hz or 50 Hz) and direct voltages can be considered constant during the buildup of the breakdown process. The probability of the appearance of an electron or electrons in the gap is high, and that explains the small scatter in the breakdown voltages under ac and dc. On the other hand, the appearance of an electron away from the peak of the impulse voltage has very low probability to initiate breakdown. Figure 8 shows how breakdown occurs under impulse voltages. If an electron appears at time t_1 or t_4 corresponding to voltages V_1 and V_4 on the wave front and tail, respectively, no breakdown can occur because the voltages at these instants are less than the static breakdown voltage V_s. For discharge to start and develop to breakdown, the initiatory electron should appear within a time between t_2 and t_3, where the impulse voltage exceed V_s. The time interval between t_2 and t_b is divided into two time intervals:

(1) Statistical time lag T_s, which is defined as the time that elapses from the instant the impulse voltage reaches the static breakdown value until an initiatory electron appears at a suitable location in the gap to start discharge.
(2) Formative time lag T_f, which is defined as the time that elapses between discharge initiation until breakdown develops.

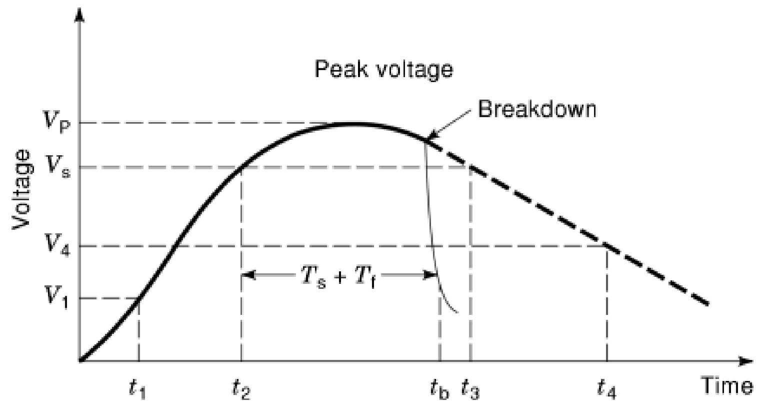

Fig. 8. Breakdown under impulse voltage.

The statistical time lag is relatively long and is in the range of 10 s to 10^{-3} s. Short formative time lags in the 10^{-9} s range were recorded (5).

Impulse Breakdown Strength

When testing an insulation system under impulse voltage, large scatter in the results is usually observed. The probability of breakdown under impulse voltage depends on its peak value and duration time. a probability breakdown curve is usually drawn to define the impulse breakdown. Figure 9 shows the breakdown probability characteristics of a test object (e.g., an insulator string). This curve can be obtained by applying a certain number of shots for each voltage level and determining the ratio between the number of breakdowns and the total shots. This ratio is the probability of breakdown for a specified impulse voltage. It is clear that the breakdown probability increases with the increase of the applied voltage relative to the static breakdown voltage of the test object. To obtain representative values of the breakdown probability, large number of voltage shots (say 100 shots) at each voltage level are applied. In practical testing, this number is limited to 15 or 20 shots. Figure 9 shows two distinct voltages V_0 and V_{100} corresponding to zero and 100% breakdown probability. The question now arises which value is taken to represent the impulse breakdown voltage? The answer to this question is that it is the voltage corresponding to 50% breakdown probability and it is termed critical flash over voltage (*CFO*). The value of V_0 and V_{100} are of importance to the insulation design and insulation coordination, respectively. Exact determination of V_0 and V_{100} from Fig. 9 needs the application of large number of shots, which is time-consuming. In practice, more realistic procedures are used. These procedures depend on the fact that the breakdown probability function is Gaussian; interested readers may refer to Refs. 4 and 5.

Transfer Characteristics

In measuring and recording impulse voltages by means of voltage dividers and CRO, errors as high as 10% or even higher are usually observed. The errors are not only in magnitude but also in phase. Whatever the equivalent circuit of voltage dividers is, they can be represented by a four-terminal network, and their transfer characteristics (output voltage/input voltage, v_o/v_i) can be evaluated. Practical impulse voltage shapes are the difference between two exponential voltages. The mathematical analysis for such waves is very lengthy and tedious. Checking the response of voltage dividers by applying a unit step function is recommended by IEC (14).

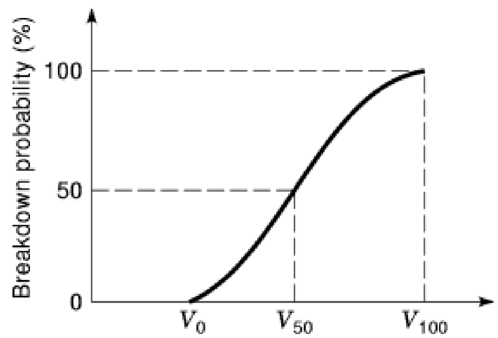

Fig. 9. Impulse voltage breakdown probability.

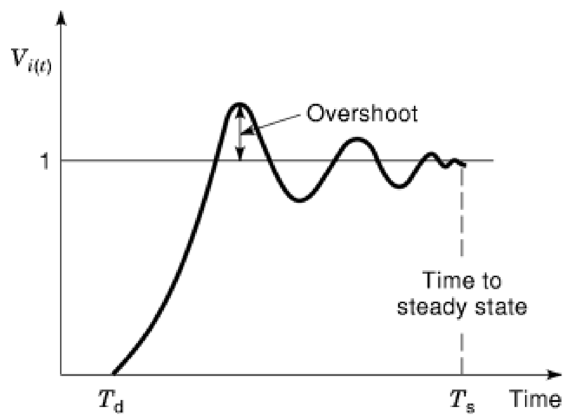

Fig. 10. Response of voltage dividers to unit step function voltage.

If a unit step function in the form

$$v_i(t) = \begin{cases} 0 & t < 0 \\ 1 & t > 0 \end{cases} \tag{11}$$

is applied to a voltage divider, the output response will be $v_o(t)$. The response to another input voltage can be derived by Laplace transform, and hence the output in the time domain is obtained (4). Figure 10 illustrates how the output voltage of a divider can differ from the input in magnitude and shape. Good design of voltage dividers should provide (1) short delay time T_d, (2) low overshoot, and (3) short time to steady state.

In recording impulse voltage waves, the output of the divider is taken via coaxial cables to a CRO. Unless proper matching is provided, errors resulting from voltage reflections are introduced.

Measurement Standards

All standard specifications for impulse voltage and current limit measurement accuracy. Table 2 shows the standard accuracy limits for impulse voltage and current measurement as well as acceptable tolerances in their generation (7).

Table 2. Standard Impulse Voltage and Current Tolerances and Measurement Accuracy

Quantity	Lightning Voltage (%)		Switching Voltage (%)		Impulse Current (%)	
	Tol.	Accu.	Tol.	Accu.	Tol.	Accu.
Peak value (full impulse)	±3	±3	±3	±3	±10	±3
Peak value (chopped)						
on front		≤±5				
on tail		≤±3				
Front time	±30	±10	±20	±10	±10	±10
Tail time	±20	±10	±60	±10	±10	±10

Calibration

Regular calibration of the measuring system against a standard measuring device is a common practice in impulse testing and research work. The sphere gap is an acceptable standard measuring device for measuring the peak value of an impulse voltage with an accuracy of ±3%. When recording an impulse wave, the recording system should be calibrated against a reference measuring system. The accuracy of the reference system ranges between ±1 and ±3% for measuring the peak voltage or current and ±5% for measuring the time parameters (14).

Applications

Electrical equipment is subjected to voltage and current surges during operation, and impulse testing is one of the main tests specified by all standard specifications. Circuit breakers, cables, transformers, high-voltage capacitors, switchboards, transmission line insulators, surge arresters, and other kinds of equipment are tested under impulse voltages and/or current. The main purpose of impulse tests is to validate the performance characteristics, proper design, and manufacture quality. Impulse voltages and currents have several applications other than for testing. They can be used for triggering electronic circuits and components. Electrostatic precipitators, used to collect dust particles from the exhaust of chimneys, use high-impulse voltages in their operation. The basic construction of such devices consists of a thin wire concentric with a metallic cylinder. When a high voltage is applied between the wire and the cylinder, corona discharge starts at and around the wire. The flow of charges between the wire and cylinder charges the particles, and they move toward the cylinder wall where they are collected. It is claimed that using impulse voltages instead of dc is more effective in collecting dust particles. In cars, an inductive electric circuit, supplied from a 12 V battery, is regularly switched off and on to produce impulse voltages of several kilovolts. This voltage is applied to the car's plugs to produce sparks, thus igniting the fuel.

Low-voltage impulse signals are used for fault detection and location in underground cables. This is based on the fact that when a voltage surge is applied at one end of a long conductor in air it travels to the other end with light velocity ($c = 3 \times 10^8$ m/s). In the case of underground cables, it travels with velocity where ϵ_r is the relative permittivity of the cable insulating material. If there is a fault in the cable, between its ends, the voltage signal is reflected at the fault. The reflected signal is received at the voltage source on a recording device, such as a CRO. Knowing the velocity of the voltage signal and the time taken to reach the fault and return back to the source, one can then estimate distance. The reflected voltage signal may be positive or negative depending on whether the fault resides in an open cable's conductor or insulation. By this method fault location is determined with high accuracy and the type of fault is known, thus reducing the effort and time of digging and repairing the fault. Cable's fault detectors are now available in the marketplace and can detect and locate faults without any human calculations.

Fast-rising impulse voltages of a few tens of kilovolts are used to generate ozone for water treatment. Ozone generators are similar to electrostatic precipitators in their basic construction. Corona discharge is initiated by applying a repetitive voltage pulse to a thin wire in a duct where air flows axially or radially. Corona discharge starts at and around the wire surface, due to the high electric field therein, and consequently ozone is formed. The amount of generated ozone depends on the magnitude of the applied impulse voltage, its repetition rate, duration, wire diameter, and rate of air flow.

Lightning protection from thunderstorms is usually carried out by means of metallic rods (Franklin rods) installed on or around the protected objects. These rods have a protection zone where they are highly effective, and beyond it the degree of protection is reduced. To increase the protection zone and degree of protection and to decrease the height of the rod, the electric field at the tip of the protecting rod should be increased to help direct the lightning stroke to it. The field at the tip of the rod can be increased by applying to it a repetitive impulse voltage of a few tens of kilovolts from an external source.

BIBLIOGRAPHY

1. J. D. Cobine, *Gaseous Conductors*, 2nd ed., New York: Dover, 1958.
2. J. M. Meek, J. D. C. Craggs, *Electrical Breakdown of Gases*, Oxford: Clarendon Press, 1953.
3. R. H. Golde (ed.), *Physics of Lightning*, London: Academic Press, 1977.
4. E. M. Khalifa (ed.), *High-Voltage Engineering: Theory and Practice*, New York: Marcel Dekker, 1990.
5. E. Kuffel, W. S. Zaengl, *High Voltage Engineering: Fundamentals*, New York: Pergamon, 1984.
6. W. Hawley, *Impulse-Voltage Testing*, London: Chapman & Hall, 1959.
7. IEC Publication 60-1, *High-Voltage Test Techniques*, 2nd ed., Geneva: International Electrotechnical Commission, 1989.
8. IEC Publication 52, *Recommendations for Voltage Measurement by Means of Sphere-Gaps*, Geneva: International Electrotechnical Commission, 1960.
9. R. Malewski, Wirewound shunts for measurement of fast current impulses, *IEEE Trans. Power Appar. Syst.*, **PAS 103**: 2927–2933, 1984.
10. O. B. Oliveira, M. T. Silva, F. A. Chagas, Design, construction, and response evaluation of shunts for the measurements of high impulse current, *7th Int. Symp. High-Voltage Eng.*, Dresden, 1991.
11. E. A. Ulmer, A high-accuracy optical current transducer for electric power systems, *IEEE Trans. Power Deliv.*, **5**: 892–898, 1990.
12. A. J. Schwab, *High-Voltage Measurement Techniques*, Cambridge, MA: MIT Press, 1972.
13. E. Nasser, *Fundamentals of Gaseous Ionization and Plasma Electronics*, New York: Wiley, 1971.
14. IEC Publication 60-2, *High-Voltage Test Techniques*, 2nd ed., Geneva: International Electrotechnical Commission, 1994.

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