Chapter 16

Basic testing techniques

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16.1 Introduction

Tests are generally necessary to demonstrate that the equipment under test fulfils the specified requirements and quality standards. The tests may have different purposes, a type test as check and quality assurance for the design of the equipment and a routine test as check and quality assurance for the manufacturing processes. Above all a routine test should show that the equipment is able to withstand the test conditions, which are selected according to the stress during the whole time period of service. That means that the test stress should be high enough concerning the sensitivity but low enough to prevent an initiation of undetected defects during the test procedure, which may lead to damage after a certain period of service. Therefore the test requirements are based on experiences concerning the stress and the behaviour of the tested material during normal operation conditions. Furthermore the following parameters have to be taken into account for the type and/or routine tests:

- regulations by law
- requirements
- recommendations
- mutual agreements on technical specifications
- economy.

The following sections are only related to high voltage testing requirements and recommendations for type and routine tests, without any consideration of regulations by law, mutual agreement on technical specifications and economic factors.

16.2 Recommendations and definitions

IEC Publ. 60071 [1] describes the relationship between the different test voltages:

- AC voltage at power frequency
- lightning impulse voltage
- switching impulse voltage.

IEC Publ. 60060 [2] gives the general definitions and requirements on the voltage shape, the tolerances and the measuring uncertainty.

For some high voltage apparatus specific IEC publications exist due to the strong influence of the test object on the generally defined test voltages and due to the specific test conditions. The IEC Publ. 60076 describes, for example, a switching impulse shape for transformer tests, which is related to the behaviour of the transformer and the strong influence on the waveshape by the transformer as test object. This recommendation has to be taken into account during the transformer test in addition to the general recommendations given in IEC Publ. 60060. Also, for high voltage cables an additional recommendation concerning impulse voltages exists. IEC Publ. 60230 [3] allows for high voltage cable tests with lightning impulses a front time up to 5 μs, because the capacitance of the cable under test is normally so high that a standard front time of 1.2 μs cannot be reached without oscillations. Therefore the technical compromise, defined in the recommendations, is to enlarge the front time in order to have a double exponential waveshape without any oscillations but also without any influence on the test result. Furthermore a clear definition of all the relevant parameters regarding the test technique and procedure is necessary to ensure comparable and reproducible test results.

The most important definitions, given in [1], should be named and explained here for understanding of the following chapters.

Insulation co-ordination: the selection of the dielectric strength of equipment in relation to the voltages which appear on the system for which the equipment is intended and taking into account the service environment and the characteristics of the available protective devices (note that the dielectric strength means the rated or standard insulation level).

External insulation: the distances in atmospheric air, and the surface in contact with atmospheric air of solid insulation of the equipment which are subject to dielectric stresses and to the effects of atmospheric and other external conditions, such as pollution, humidity, etc.

Internal insulation: the internal solid, liquid or gaseous parts of the insulation of equipment which are protected from the effects of atmospheric and other external conditions.

Self-restoring insulation: insulation which completely recovers its insulating properties after a disruptive discharge.

Non-self-restoring insulation: insulation which loses its insulating properties or does not recover them completely after a disruptive discharge.

Nominal voltage of a system: a suitable approximate value of voltage used to designate or identify a system.

Highest voltage of a system: the highest value of operating voltage which occurs under normal operating conditions at any time and at any point in the system.

Highest voltage for equipment (U_m): the highest RMS value of phase-to-phase voltage for which the equipment is designed in respect of its insulation as well as other characteristics which relate to this voltage in the relevant equipment Standards.

Overvoltage: any voltage between one phase conductor and earth or between phase conductors having a peak value exceeding the corresponding peak of the highest voltage for equipment. It is expressed unless otherwise clearly indicated, such as for surge arresters, in pu referred to $U_m \sqrt{2}/\sqrt{3}$.

Classification of voltages:

- continuous power frequency voltage
- temporary overvoltage (power frequency)
- transient overvoltage (short duration overvoltage of ms or μs)
  slow front overvoltage, 20 μs $\leq T_p \leq$ 5000 μs, $T_2 \leq$ 20 ms
  fast-front overvoltage, 0.1 μs $\leq T_1 \leq$ 20 μs, $T_2 <$ 300 μs
  very-fast-front overvoltage, time to peak $\leq$ 0.1 μs, total duration < 3 ms, superimposed oscillations 30 kHz $< f <$ 100 MHz.

Standard voltage shapes:

- power frequency voltage between 48 Hz and 62 Hz, duration of 60 s
- standard switching impulse voltage with T_p/T_2 = 250/2500 μs
- standard lightning impulse voltage with T_1/T_2 = 1.2/50 μs.

Withstand voltage: the value of test voltage to be applied under specified conditions in a withstand test, during which a specified number of disruptive discharges is tolerated:

- conventional assumed withstand voltage with a withstand probability P_w of 100%
- statistical withstand voltage with a withstand probability P_w of 90%.

For non-self-restoring insulation conventional assumed withstand voltage, for self-restoring insulation statistical withstand voltages are specified in [1].

Co-ordination withstand voltage (U_{cw}): the value of the withstand voltage of the insulation configuration that meets the performance criterion in the actual service conditions.

Standard withstand voltage (U_w): the standard value of the test voltage applied in a standard withstand test. It is a rated value of the insulation and proves that the insulation complies with one or more required withstand voltages.

Rated insulation level: a set of standard withstand voltages which characterise the dielectric strength of the insulation.

Standard withstand voltage tests: a dielectric test performed in specified conditions to prove that the insulation complies with a standard withstand voltage. These tests are:

- short duration power frequency voltage tests
- switching impulse voltage tests
- lightning impulse voltage tests
- combined voltage tests.

More details are given in IEC Publ. 60060 [2]. Very fast impulse standard withstand tests should be specified by the relevant Apparatus Committee.

16.3 Test voltages

A test voltage is defined by its amplitude, frequency and/or shape within specified tolerances. In [2] the standard and preferred test voltages are described, but as already mentioned, it may sometimes be necessary depending on the test object or test circuit to modify the frequency or shape of the test voltage in order to enable the tests.

16.3.1 DC voltage

A direct voltage (DC) is defined as the mean value between the highest and lowest level within a time period. The duration of the period depends on the generating system. Figure 16.1 shows a typical example of a DC voltage, generated by rectification of an AC voltage.

The DC voltage U_{DC} is the arithmetic mean value of the voltage $u(t)$. The voltage drop ΔU is the difference between the peak voltage of the AC power supply and the DC voltage, which is given by the so-called 'internal impedance' of a multiple stage rectifier. The difference between the highest and lowest value of $u(t)$ is called ripple, and represents the charging of the capacitors by the AC source during the conductive period of the diodes and the discharging of the capacitors by the load during the nonconductive period of the diodes. It is obvious that the charging time is much shorter than the discharging time and this should be taken into account for the design of the diodes, because the charging current is much higher than the discharge current. According to the IEC Publ. 60060 the value of the ripple should be less than ± 3% of U_{DC}. The main parameters influencing the ripple are the frequency of the AC supply voltage, the value of the smoothing capacitance and the load current. For small load currents the ripple can be calculated by the following equation:

$$\delta U = \frac{I}{fC}\frac{N}{4}(N+1) \tag{16.1}$$

with the load current I, the frequency of the AC power supply f, the smoothing capacitance C and the number of stages of a multiple stage rectifier N. From eqn (16.1) it is clear that the ripple increases linearly with increasing load current and quadratically with the number of stages, and decreases with increasing frequency and smoothing capacitance. The voltage drop ΔU influences only the mean value U_{DC} of a DC generator and depends also on the design of the generator. For a multiple stage generator the voltage drop can be calculated according to the equation

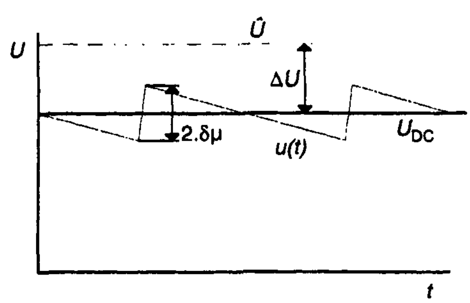

Figure 16.1 *Parameter of a DC voltage*
$\hat{U}$ = peak value of the AC supply voltage, U_{DC} = arithmetic mean value of the voltage $u(t)$, ΔU = difference between peak voltage and DC voltage, $2.\delta\mu$ = difference between highest and lowest value of $u(t)$

$$\Delta U = \frac{I}{fC}\frac{N}{3}(2\,N^2 + 1) \tag{16.2}$$

with the same parameters as in eqn (16.1).

The most important point is the increasing of the voltage drop by the cubic power of the number of stages, but this can be taken into account by choosing the adequate no load voltage of the generator and a fast voltage regulating system. The strongest requirements are necessary for DC pollution tests, where the load current can change very rapidly within a large range from some mA up to some A. For these cases the voltage should be kept stable within given limits, and that requires a strong AC power source, a large smoothing capacitance and a fast regulation system.

Figure 16.2 shows the diagram of a multiple stage rectifier with its main components. The measures to reduce the ripple δU can be deduced from eqn (16.1) depending on the requirements and conditions. The voltage drop ΔU is normally no problem for the test generator, because it can be taken into account by the performance of the generator. For DC voltage tests on polluted insulators the voltage drop may influence the test results due to fast change of the load. For these particular tests the transient behaviour of the voltage regulator should be taken into account, because in case of high load current the energy supply should be regulated very fast by feeding the current from the smoothing capacitor or from the main power supply or from both, which is normally the most economic solution. Figure 16.3 shows the relationship between the number of stages, the maximum load current and the output voltage for a multiple stage rectifier with a no load voltage of 400 kV per stage.

Figure 16.4 shows a DC test system with a rated output DC voltage of 1500 kV and a rated current of 20 mA.

16.3.2 AC voltage

The alternating voltage is defined by its RMS value and/or by its peak value depending on the purpose. For a pure sinusoidal waveform the relation between the peak value and the RMS value is given by the square root of 2. This relation is also used in the recommendations [2] to define the tolerance of the sinusoidal waveshape by the following equation:

$$\frac{\hat{U}}{U} = \sqrt{2} \pm 5\% \tag{16.3}$$

The flashover or breakdown behaviour of insulating material is determined by the peak value of the supplied voltage for short stress time. At

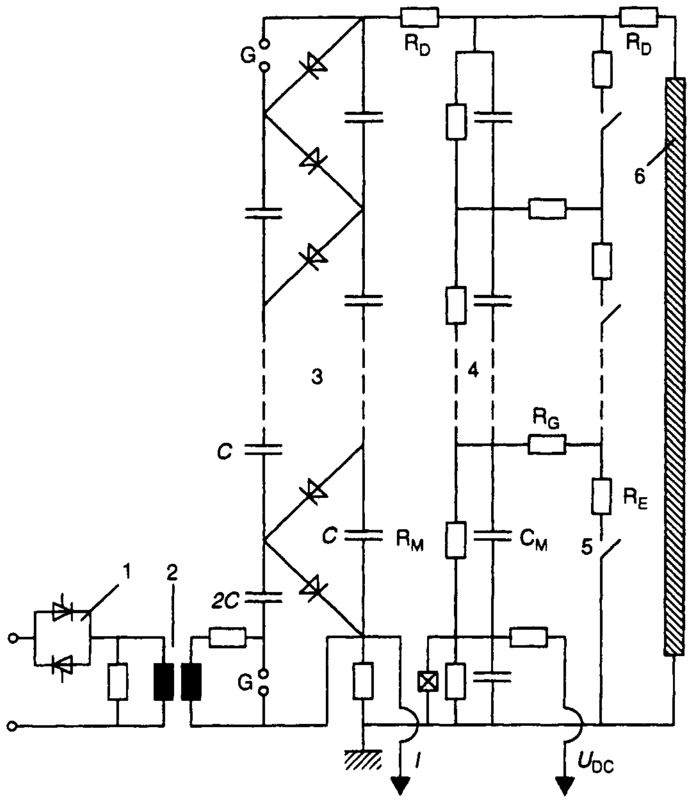

Figure 16.2 *Equivalent diagram of a multiple stage rectifier*
1 *Thyristor controlled voltage regulation*
2 *High voltage transformer*
3 *Rectifier with diodes, charging and smoothing capacitors*
4 *Voltage divider with grading capacitors*
5 *Discharging and grounding device*
6 *Test object*
C *smoothing capacitor*
C_M *grading capacitor of the measuring resistor*
R_M *measuring resistor*
R_D *damping resistor*
R_E *earthing resistor*
R_G *grading resistor of the earthing switch*

longer stress time or under service stress, very often the RMS value is the most important parameter for the breakdown depending on the loss characteristic and the thermal behaviour of the insulating material.

The waveform of an AC voltage can be defined by the ratio of the basic frequency and the harmonics of different order. The harmonics should be taken into account for the measuring devices, which may be not able to measure the true RMS value due to its frequency behaviour.

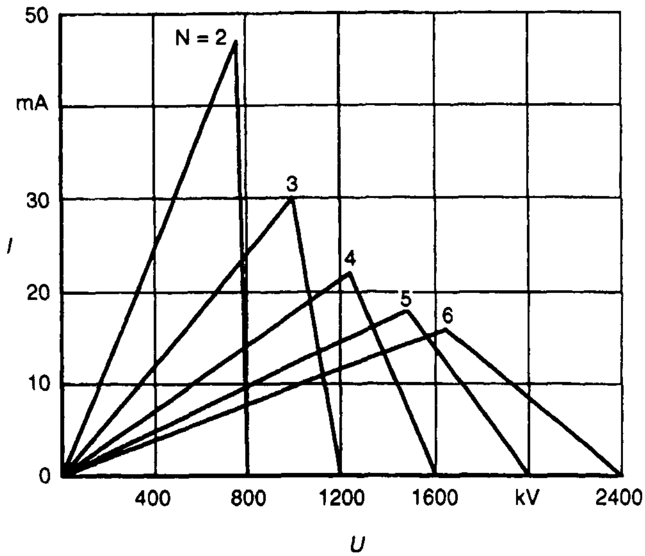

Figure 16.3 *Output current as function of the output voltage at 3% ripple N = number of stages (400 kV rated voltage)*

Very often RMS measuring systems use the relation between the peak value and the RMS value, and they are in reality peak value measuring systems. With modern digital measuring devices a Fourier Analysis of the measured AC voltage is possible and the harmonics can be simply determined.

The generation of an AC voltage is much simpler than a DC voltage, because the voltage can be transformed by a very simple circuit. Figure 16.5 shows a simplified equivalent diagram of a voltage transformer.

The ratio between the two voltages U_1 and U_2 is given by the ratio of the number of windings, and therefore theoretically every voltage ratio can be reached by a single stage transformer. Because of the nonlinear behaviour of the insulating material it is very often useful to generate high AC voltage by means of a transformer cascade to reduce the cost for the insulating material and to have a flexible combination of a number of single transformer units. Figure 16.6 shows a typical three-stage cascade arrangement with identical units. Each unit needs only the insulation for a single-stage transformer.

Important parameters for an AC voltage generator are the short-circuit impedance and the content of harmonics as a function of the load. The short-circuit impedance, given normally in percentage, represents the voltage drop under full load conditions assuming the resistive part is negligible in comparison to the inductive part. For a cascade the short-circuit impedance is more than the sum of the short-circuit

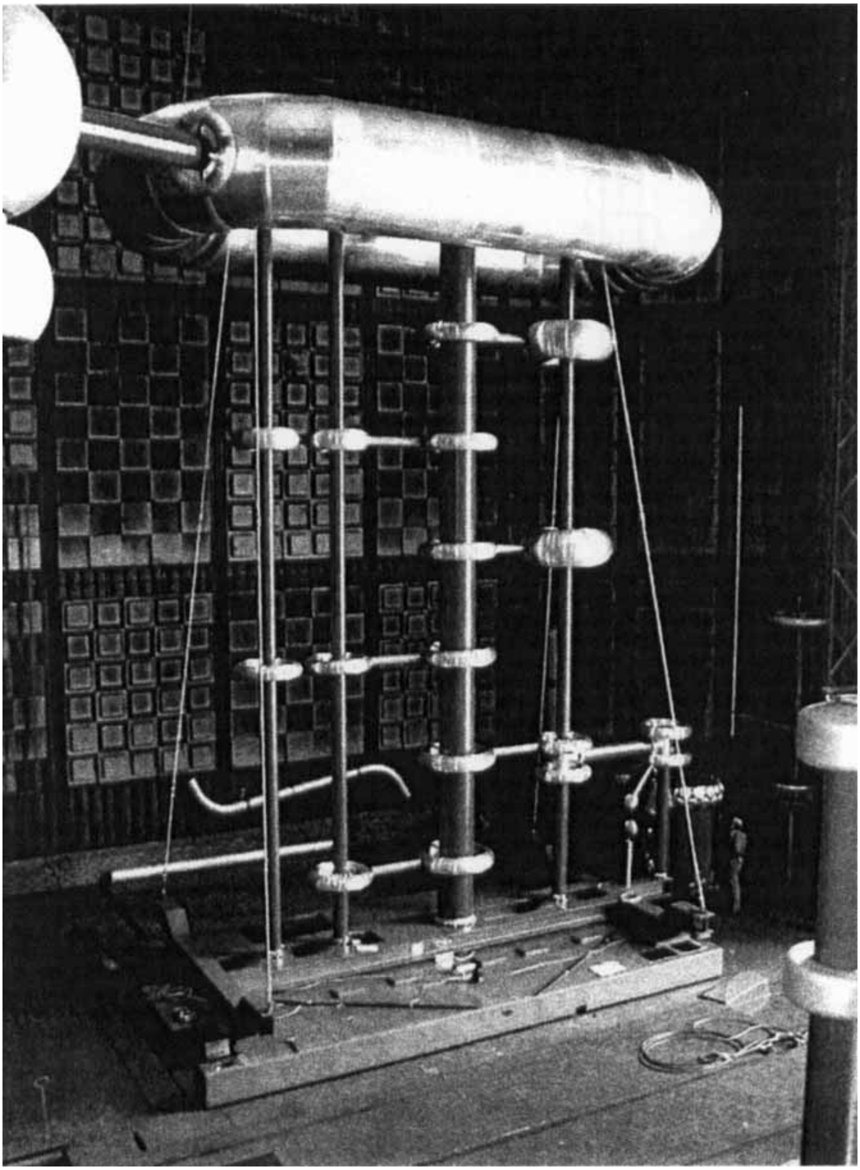

Figure 16.4. *DC test system 1500 kV/20 mA*
(Courtesy of High Volt Prüftechnik, Dresden)

impedance of the single units and increases more than linearly with the number of stages. The combination shown in Figure 16.6 can also be used with two transformers at the bottom stage and one transformer in the second stage to get a higher output current, but at a lower output voltage. Therefore the use of each unit as a single transformer or the combination

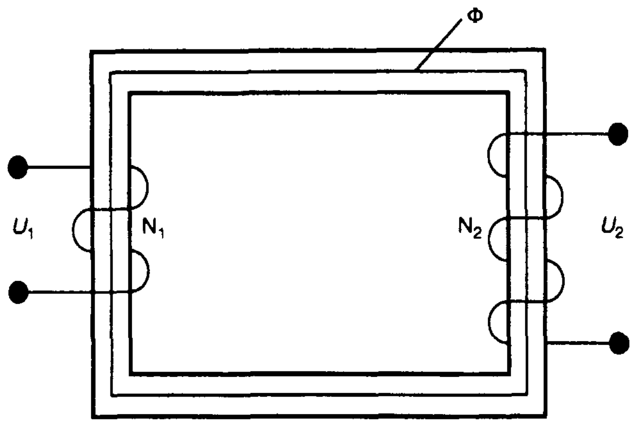

Figure 16.5 *Equivalent diagram of a voltage transformer*
N = number of windings, Φ = magnetic flux

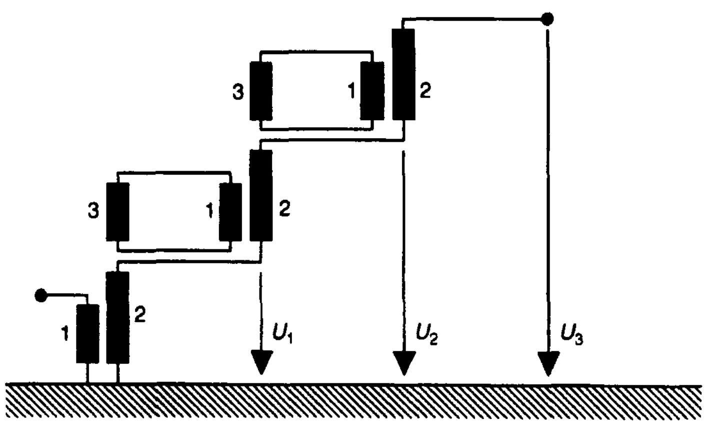

Figure 16.6 *Equivalent diagram of a three-stage transformer cascade*
1 primary winding, 2 secondary winding, 3 tertiary winding

of the units offers a number of possibilities. Concerning the power distribution within a cascade it is important that the primary winding of the first stage should be designed to carry the full output power of the cascade. The secondary windings in all stages are loaded with the same power, given by the output power divided by the number of stages assuming that all transformers are identical. The tertiary winding of the first stage is loaded with two-thirds of the output power. The windings in all other stages are loaded with the relevant load distribution within the transformer. Figure 16.7 shows a three stage transformer cascade with voltage divider.

Another important factor for AC voltage generation by a transformer

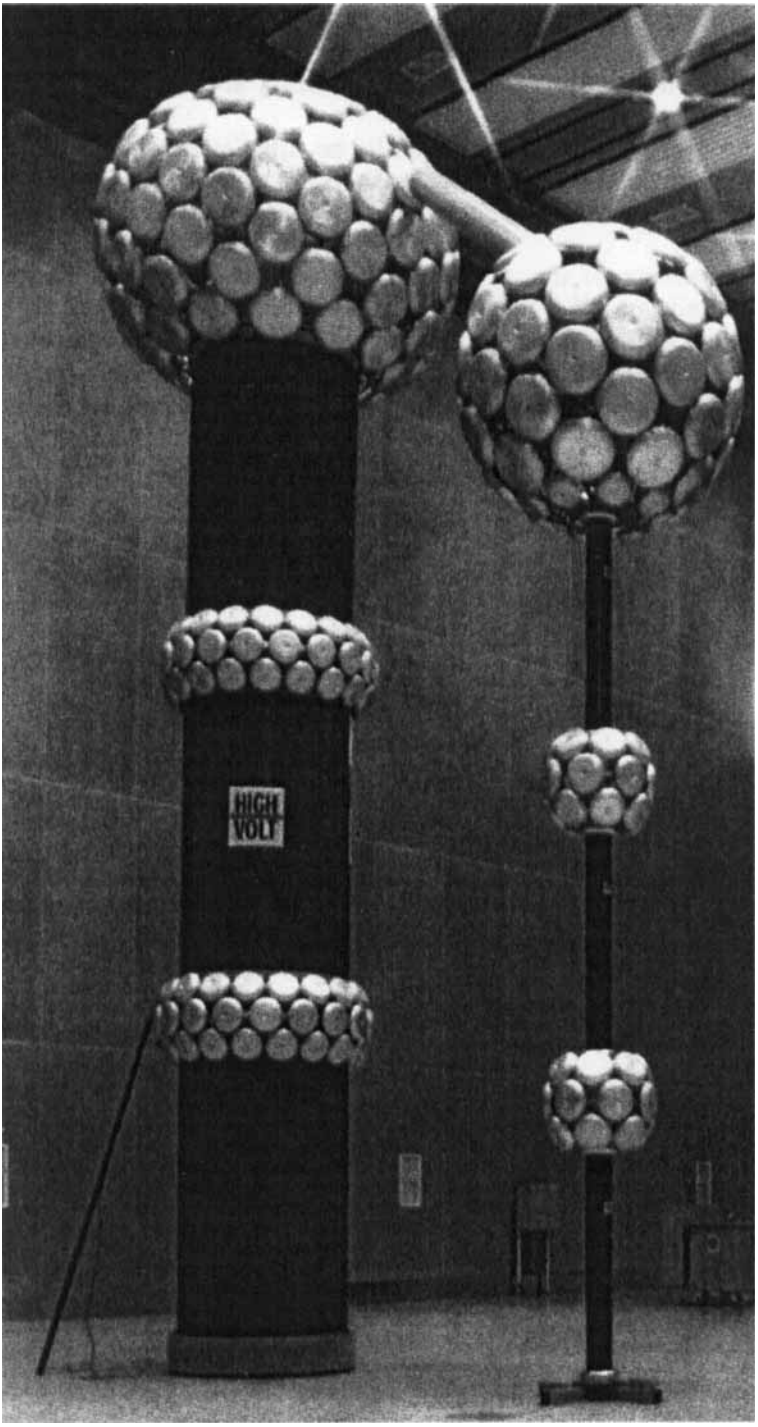

Figure 16.7 *AC test system 1000 kV/1A*
(Courtesy of High Volt Prüftechnik, Dresden)

is the voltage increase due to the capacitive load, which is normally the case for AC test objects. Figure 16.8 shows the vector diagram for a simplified transformer circuit, whereby all elements are referred to the high voltage side.

The output voltage U_2 can normally be calculated by the ratio of the windings, but due to the capacitive load the voltage U_2 is higher than calculated. This can be demonstrated by the vector diagram, shown in Figure 16.9.

The increasing of the output voltage due to the capacitive load is normally undesirable, but for AC tests the increasing voltage at the secondary side can be used to reduce the input voltage or the size of the test equipment. If the capacitance of the load including the transformer capacitance is equal to the reciprocal value of the inductance of the

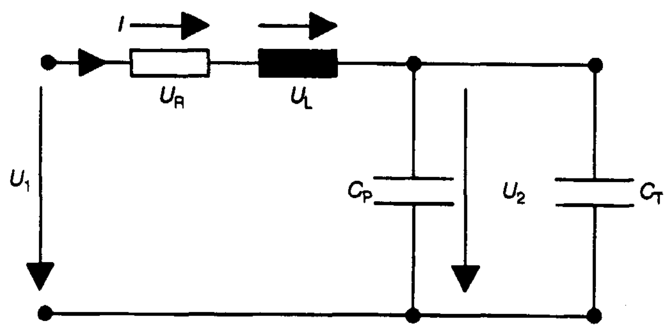

Figure 16.8 *Equivalent diagram of a transformer with capacitive load*
U_I = input voltage referred to the high voltage side, U_2 = output voltage across the capacitive load, I = transformer current, C_T = capacitor representing the transformer capacitance, C_P = capacitor representing the load capacitance

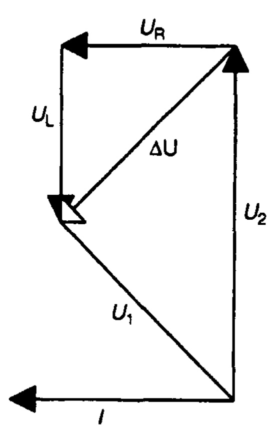

Figure 16.9 *Vector diagram of a transformer with capacitive load*

transformer including the circuit inductance, then the circuit is in resonance and theoretically the output increases up to infinity. Owing to the existing resistance in the circuit the voltage will be limited, but the ratio between input voltage and output voltage can be very high, up to 100, and the necessary reactive power is very low. The resonance conditions can be reached for voltage test purposes by changing the inductance of the circuit, resulting in resonance conditions at constant frequency or by changing the frequency, resulting in resonance conditions at different frequencies, depending on the circuit inductance and capacitance. With this type of test equipment test objects with very high capacitance can be tested with reasonable size and power of the test equipment. In all cases it should be taken into account that the regulation system of the test system should be adapted very carefully to the required voltage level to prevent an overshoot of the test voltage. Figure 16.10 shows a three stage resonant test system including a capacitive load.

16.3.3 Impulse voltage

An impulse voltage or current is defined by its peak value and its time parameter. To reproduce results at impulse voltage tests the waveshapes are defined in general recommendations [2] or apparatus related recommendations [3–5]. The standard lightning impulse voltage has a peak value $\hat{U}$ at the maximum and a front time T_1 and a time to half-value T_2 according to Figure 16.11.

The front time T_1 is given by the following equation:

$$T_1 = 1.67\ T \tag{16.4}$$

with T as the measured time between the 30% and 90% level of $\hat{U}$. The straight line through the 30% and 90% level gives the virtual origin point O_1 and the time T' as the difference between the 30% and the zero level. The time to half-value T_2 is the time difference between the virtual origin O_1 and the 50% level in the tail of the waveshape. The tolerances of the time parameter are quite large, because the test results are not strongly influenced by the variation of the time parameter and the generation of the required impulse shape is time-consuming for different test objects. Therefore the recommended front time for a standard lightning impulse according IEC Publ. 60060 is 1.2 μs ± 30% and 50 μs ± 20%.

The generation of an impulse voltage or current is generally done by charging and discharging of capacitors through a resistor which gives a more or less double exponential function. Figure 16.12 shows a simplified typical equivalent circuit for impulse voltage generation without any inductance.

Figure 16.13 is a similar circuit but with a different arrangement of the resistors.

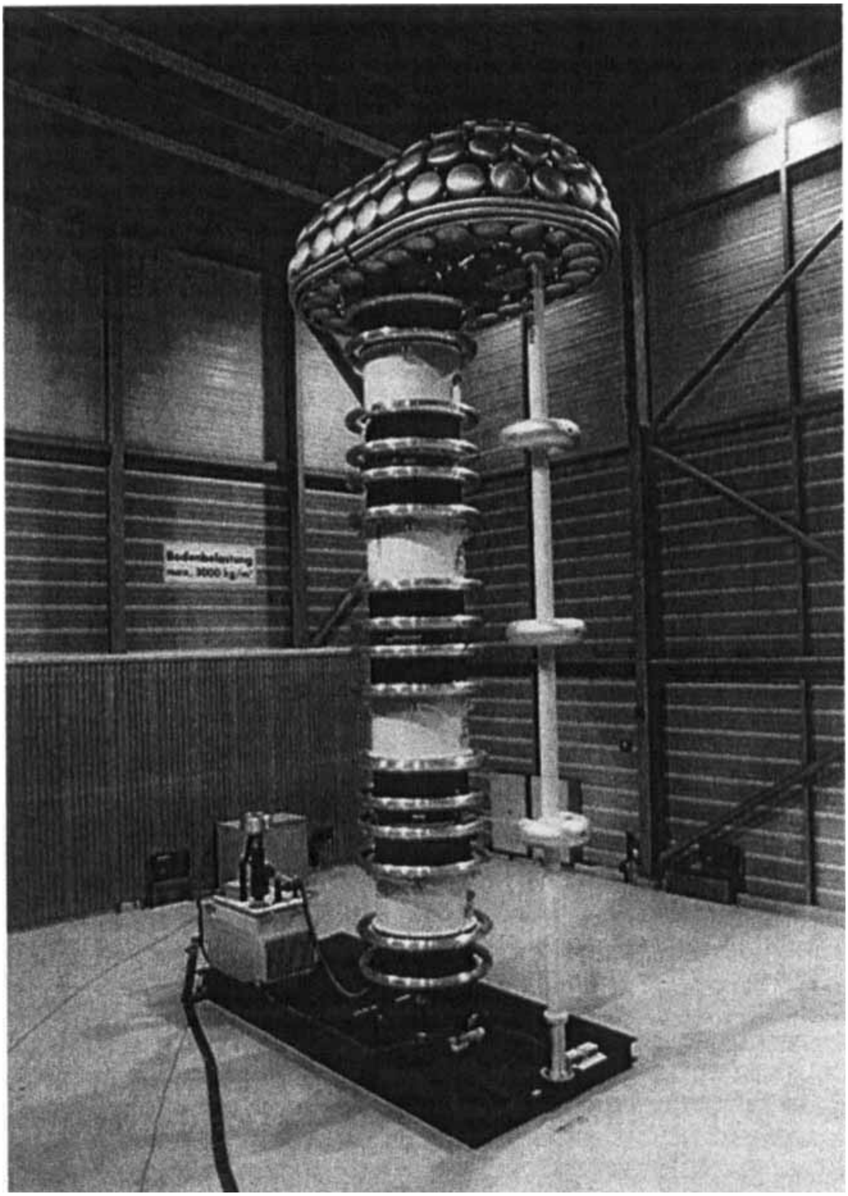

Figure 16.10 AC resonant test system 1200 kV/1 A (Courtesy of Haefely Test AG, Basel)

In both circuits a double exponential waveshape will be generated, but the ratio between the output voltage or the voltage across the load capacitor C_l and the input charging voltage U_0 is different. In circuit type a the voltage across the load capacitor can be calculated according to the

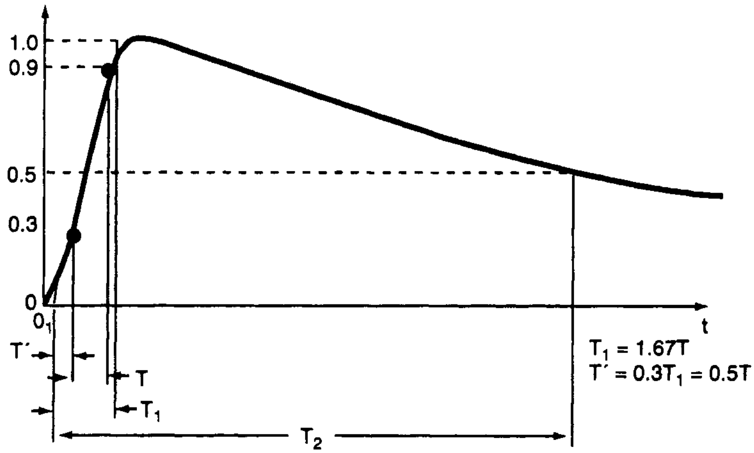

Figure 16.11 *Standard lightning impulse voltage*

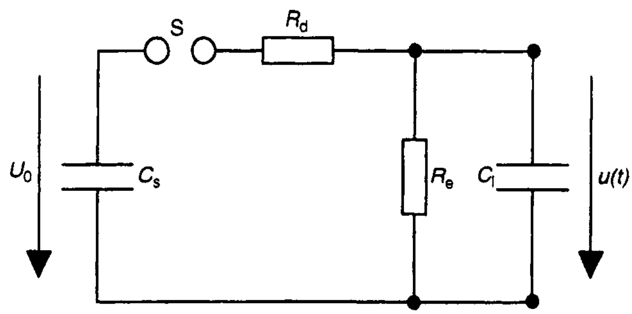

Figure 16.12 *Simplified equivalent circuit of an impulse generating circuit type a*
C_s = charging or impulse capacitor ($C_s \gg C_l$), R_d = damping resistor, R_e = earthing resistor ($R_e \gg R_d$), C_l = load capacitor (test object, divider, etc.), S = spark gap

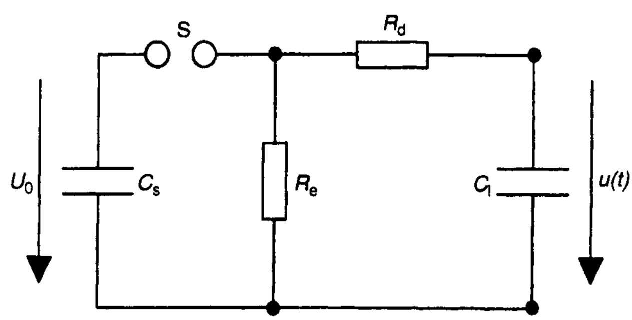

Figure 16.13 *Simplified equivalent circuit of an impulse generating circuit type b*
C_s = charging or impulse capacitor ($C_s >> C_l$), R_d = damping resistor, R_e = earthing resistor ($R_e >> R_d$), C_l = load capacitor (test object, divider, etc.), S = spark gap

following equation neglecting the influence of the inductance of the circuit and the discharge through the resistor R_e during the charging time of C_l:

$$u(t) = U_0 \frac{C_l}{C_s + C_l} \frac{R_d}{R_e} \tag{16.5}$$

The output voltage is not only given by the ratio of the capacitor but also by the ratio of the resistors. In circuit type b the output voltage is only determined by the ratio of the capacitors and is therefore higher then in circuit a:

$$u(t) = U_0 \frac{C_l}{C_s + C_l} \tag{16.6}$$

An empirically based estimation of the output voltage $u(t)$ of circuit type b is given by the equation

$$u(t) = U_0 \frac{C_l}{C_s + C_l} 0.95 \tag{16.7}$$

which takes into account the damping effect of the resistors.

For a given capacitance of the capacitor C_l the front time is determined by the load capacitance and the damping resistance. Assuming that the load cannot be changed, the front time can be adjusted by variation of the damping resistance. Under the same conditions the time to half-value is mainly determined by the earthing resistance and the impulse capacitance, assuming that the impulse capacitance is much higher than the load capacitance in order to reach a high output voltage. For tests with standard lightning impulse the value of the resistance should be calculated depending on the test object and the generator to be used. The solutions of the differential equations are not consistent and therefore assumptions are given in the following equations:

$$T_t \approx R_e (C_s + C_l) \tag{16.8}$$

$$T_f \approx R_d \frac{C_s C_l}{C_s + C_l} \tag{16.9}$$

with T_f as time constant of the front and T_t as time constant of the tail. The relation between these two time constants and the front time T_1 and time to half-value T_2 are given for the circuit type b in the following equations, assuming a standard lightning impulse 1.2/50 μs,

$$T_1 = 2.96\ T_f \tag{16.10}$$

$$T_2 = 0.73\ T_t \tag{16.11}$$

The generation of impulse voltages with high amplitude is normally done with a multistage impulse generator, named the Marx generator according to the inventor. The principle of such a generator is the parallel charging of a number of impulse capacitors and the discharging in series of these capacitors. The equivalent simplified circuit, again for the type b circuit, is shown in Figure 16.14.

The behaviour of the spark gap S is the most important part for a high reproducibility of the impulse shape and amplitude. The breakdown process and the breakdown time of a spark gap depend on the value and

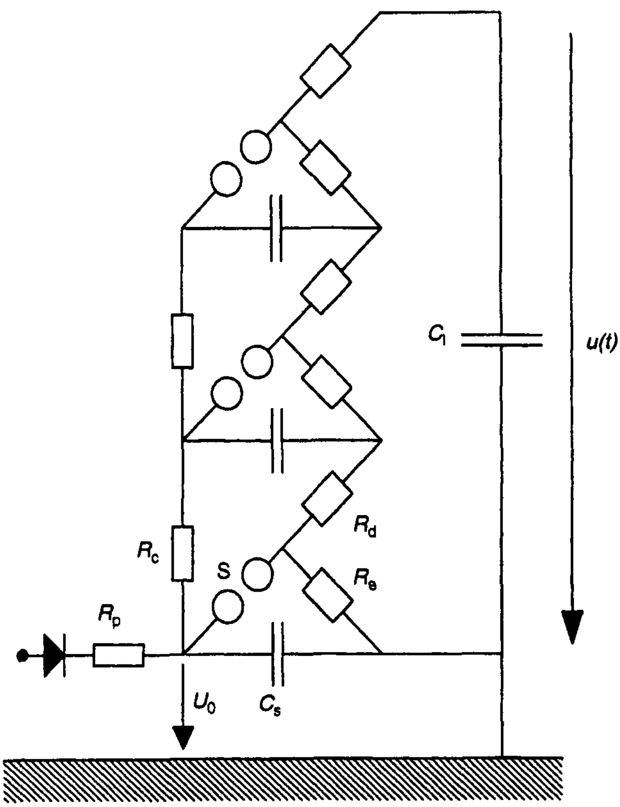

Figure 16.14 Simplified equivalent circuit of a multistage impulse generator
C_s = charging or impulse capacitor per stage ($C_s >> C_l$), R_d = damping resistor per stage, R_e = earthing resistor per stage ($R_e >> R_d$), S = spark gap per stage, C_l = load capacitor (test object, divider, etc.), R_p = protection resistor, R_c = charging resistor per stage

the uniformity of the electrical field. Therefore sphere gaps are generally used for spark gaps, with an electrode material of tungsten to reduce the damage of the surface by the arc. Furthermore it is necessary that the breakdown of the spark gap occurs at the same charging voltage to generate impulses with identical amplitude and time parameters.

This behaviour can be reached by triggering the spark gap. Two methods may be used for that purpose: the triggering at constant distance of the spark gap or the triggering at constant voltage. For the first method the spark gap should have a distance which is greater than the breakdown distance at the desired voltage. Then the impulse capacitors will be charged in parallel up to the required charging voltage. Because of different time constants in the stages the impulse capacitors reach the full charging voltage at different times, which should be taken into account. When all capacitors are fully charged the distance of the spark gap will be reduced and the breakdown takes place at the flashover distance, which is constant for a given charging voltage. Then all capacitors are connected in series through the spark gaps and the damping resistors R_d and they charge the load capacitance C_l and generate the required impulse by discharging later on through the earthing resistors R_e.

The second method is more often used and based on a triggering device within the bottom spark gap. The spark gap distance is slightly higher than the required breakdown distance at a preselected charging voltage. Then the impulse capacitor will be charged up to the preselected voltage and kept constant. A trigger impulse at the bottom spark gap, normally generated by a simple spark plug, generates a breakdown of the bottom spark gap and due to natural overvoltages at the spark gaps in the other stages all spark gaps flash over and the impulse capacitors are connected in series for generating the impulse voltage. This method has a high reproducibility and reliability which is necessary for impulse tests, in particular for transformer impulse tests where a comparison between impulses at different charging voltages is required.

The simulation of switching operations within a network can be done by the same type of generator by generating switching impulse voltages. The standard switching impulse voltage is shown in Figure 16.15 and has a time to peak T_p of 250 μs and a time to half-value T_2 of 2500 μs. Furthermore, a time T_d is defined as the time at which the value of the switching impulse is above 90% of the peak value $\hat{U}$.

The determination of the parameter can be clearly seen in Figure 16.15. The tolerances are much higher compared to the lightning impulse due to the smaller influence of the breakdown behaviour of the tested insulating material. The time to peak has a tolerance of 20%, the time to a half-value of 60%. Similar to the estimation for lightning impulse the time to peak and the time to half-value can be calculated by the simplified equations:

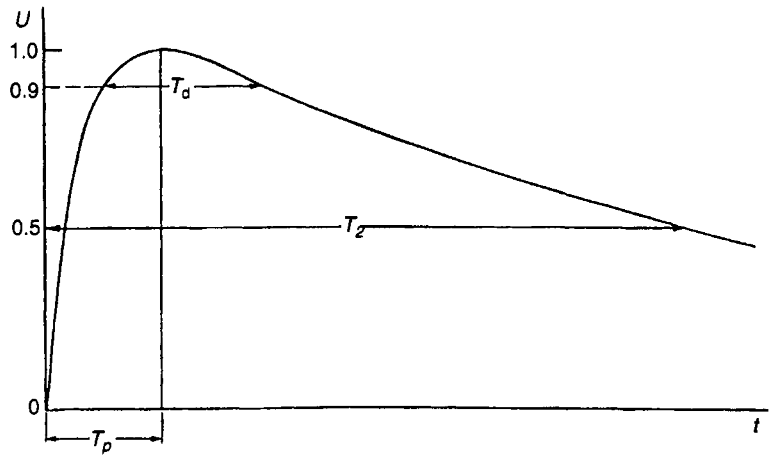

Figure 16.15 Standard switching impulse voltage

$$T_p = \frac{T_f T_t}{T_t - T_f} \ln\left(\frac{T_r}{T_f}\right) \tag{16.12}$$

$$T_2 = T_t \ln\left(\frac{2}{\eta}\right) \tag{16.13}$$

with η as the efficiency factor, given by the ratio of the output voltage to the charging voltage.

This efficiency factor is mainly determined by the value of the impulse capacitors and the load capacitor. For a multistage generator with *n* stages the efficiency for lightning impulse can be estimated by the following equations, whereby the factor 0.95 takes the influence of the resistors into account:

$$\eta \approx \frac{C_s/n}{C_s/n + C_l} \times 0.95 \tag{16.14}$$

For switching impulses the efficiency is much lower and the factor can be as low as 0.50.

The inductance of the test circuit is also important and should be explained in detail. The circuit shown in Figures 16.12 to 16.14 are without any inductance, because normally the circuit is aperiodic damped and the impulse follows more or less a double exponential function. The minimum value of the resistance is given by the equation

$$R_d \geq 2 \cdot \sqrt{\frac{L \cdot (C_s/n + C_1)}{C_s/n \cdot C_1}} \tag{16.15}$$

with L as the inductance of the complete circuit. It is clear that with given impulse capacitors and load capacitor the damping resistor value for an aperiodic damped impulse is determined by the inductance. At a given front time the required damping resistor may be lower than the value for an aperiodic damped shape and then the impulse may show some oscillations if the inductance cannot be reduced due to the size of the test circuit and the inner inductance of the capacitors. In Figure 16.16 typical lightning impulses are shown, which are used for the definition of the overshoot and oscillations near the peak of the impulse.

More details concerning the determination of the peak value, the mean curve and the test voltage are described in the IEC recommendation [2]. Because of these limits the capacitive load of a circuit is determined by its inductance and by its resistance due to the tolerance of the front time. A load diagram for an impulse generator is shown as an example in Figure 16.17.

The so-called working area is between the two tolerance curves and above the 5% overshoot line according to the relevant recommendation [2]. The influence of the load capacitance on the tail (resp. earthing resistance) is much weaker so that only one resistor element is normally necessary to cover the whole capacitive load range.

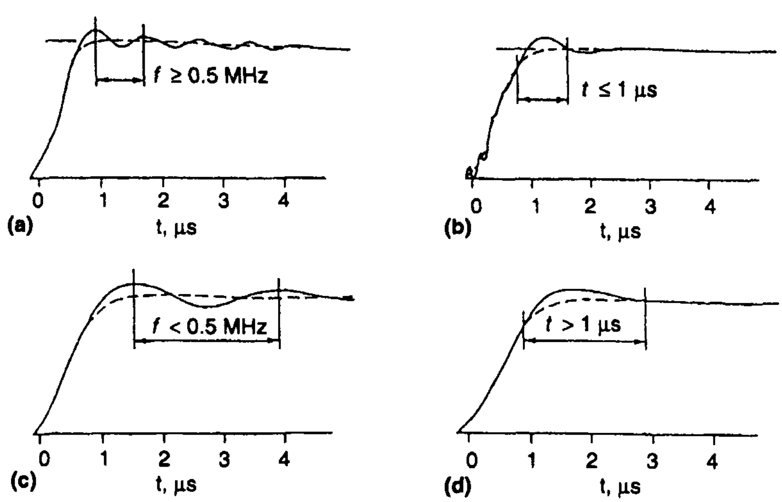

Figure 16.16 Examples of lightning impulses with overshoot or oscillations according [2]

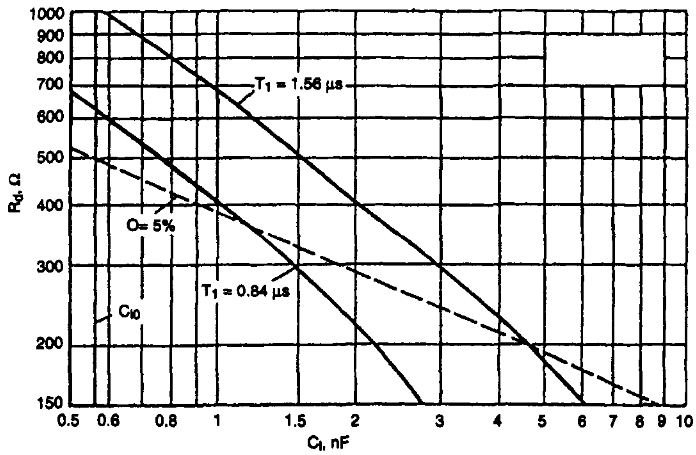

Figure 16.17 Load diagram for standard lightning impulse

Figure 16.18 shows an impulse test system with 12 stages for on site test with oscillating impulses. Figure 16.19 shows an impulse test system with 24 stages for laboratory tests with lightning and switching impulses.

16.4 Impulse current

Analogue to the impulse voltage, the impulse current is defined by its peak value and its time parameter, front time T_1 and time to half-value T_2. In addition the peak value of the first undershoot i_2 is also defined. Figure 16.20 shows a standard impulse current.

The front time T_1 is given by the following equation:

$$T_1 = 1.25\,T \tag{16.16}$$

with T as the measured time between the 10% and 90% level of $\hat{U}$. The time T_2 is the difference between the virtual zero point 0_1 and the 50% level in the tail of the impulse. The undershoot is typically for an impulse current and therefore the definition is necessary. The generation of an impulse current is similar to the generation of an impulse voltage. The main difference is that normally the capacitors are all connected in parallel to increase the capacitance and to reduce the inductance of the circuit. Current impulses with short front times need a special arrangement of the capacitors due to the fact that the front time or steepness of the current impulse depends on the derivative of the current according to the equation

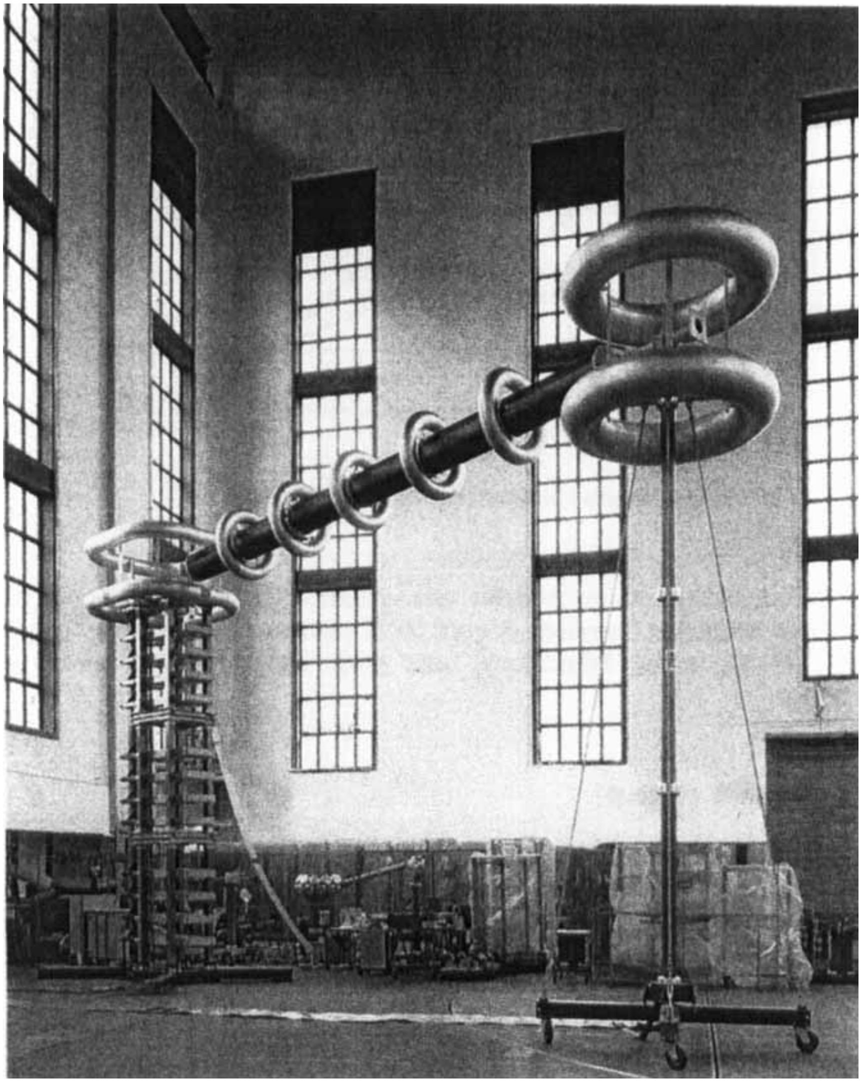

Figure 16.18 *Impulse test system for on-site tests with oscillating impulses 1800 kV*
(Courtesy of High Volt Prüftechnik, Dresden)

$$\frac{di}{dt} = \frac{U}{L} \tag{16.17}$$

with U as charging voltage and L as inductance of the complete test circuit. It is clear that a lower inductance leads to a higher current steepness, but in many cases the inductance is given and the steepness can

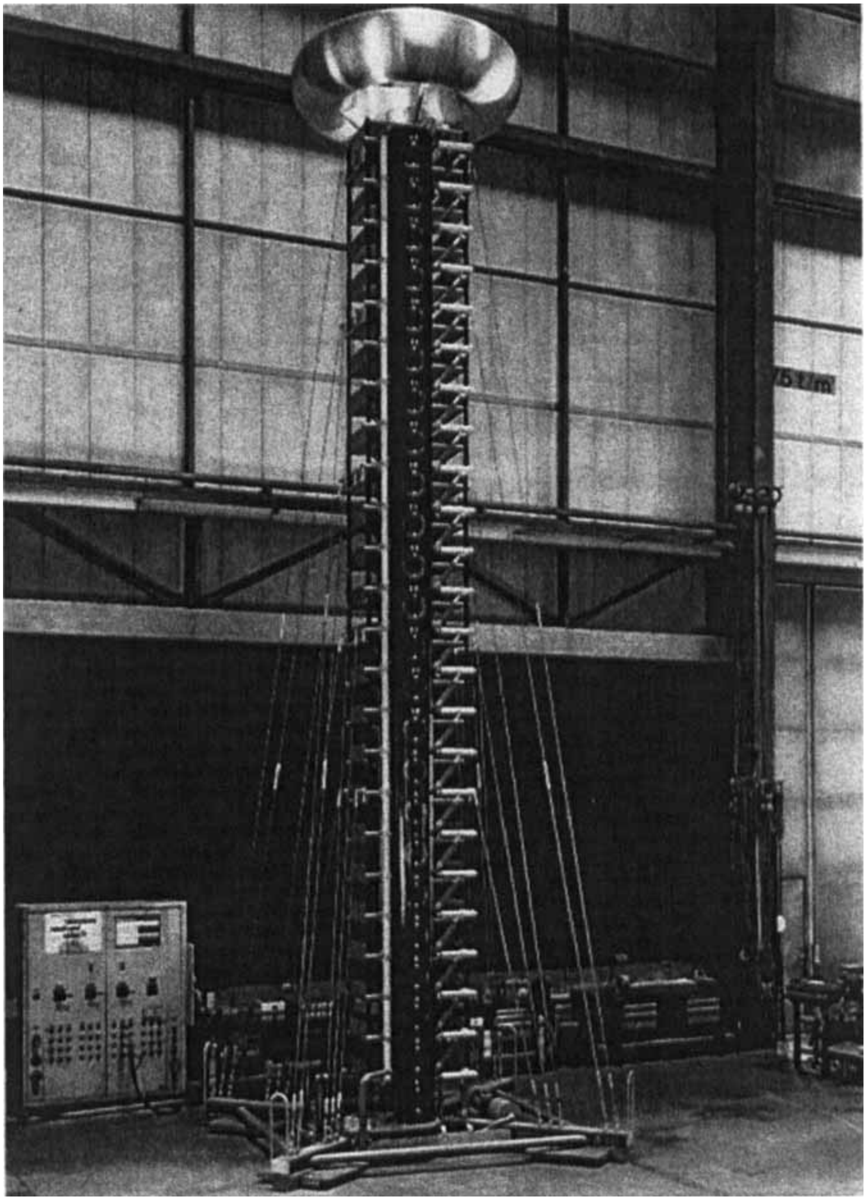

Figure 16.19 Impulse test system 2400 kV
(Courtesy of Haefely Test AG, Basel)

only be reached by increasing the charging voltage. This should also be realised without a significant increase in the inductance. Figure 16.21 shows an impulse current test system with a single spark gap as main switch.

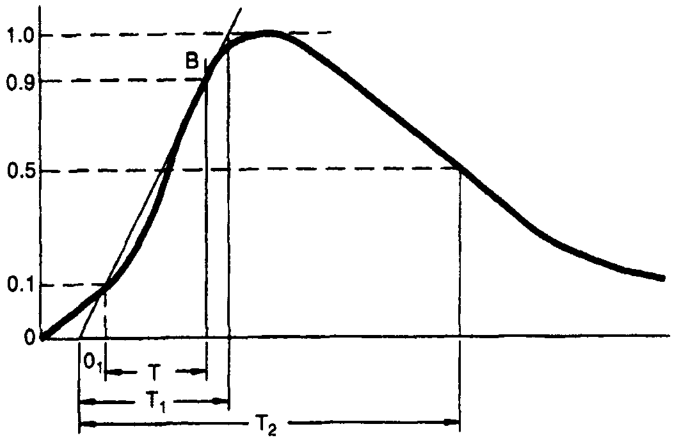

Figure 16.20 Standard impulse current

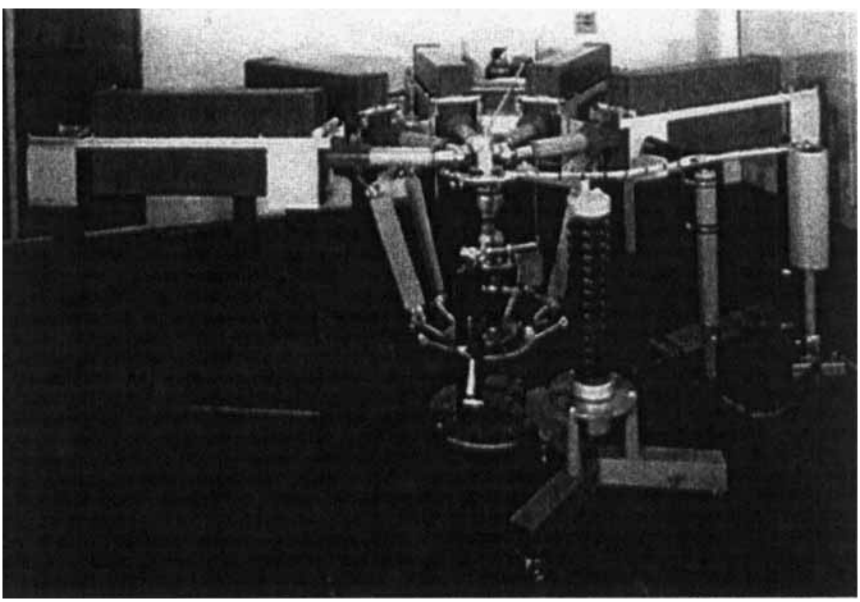

Figure 16.21 Impulse current test system 100 kA
(Courtesy of Haefely Test AG, Basel)

16.5 Test conditions

The insulation co-ordination comprises the selection of electrical strength of the equipment and its application. The dielectric stress may be divided into the following classes during the service:

- power frequency voltage (AC or DC)
- temporary overvoltages
- switching overvoltages
- lightning overvoltages.

For a given stress the behaviour of the internal insulation may be influenced by its degree of ageing and the behaviour of external insulation in addition by the atmospheric conditions. A correction of the test voltage due to ageing processes is not possible, because the test value already takes into account the reduction of the electrical strength during the lifetime of the insulation. The influence of the atmospheric conditions, however, can be considered by using correction factors. This allows tests under different laboratory conditions but with the same external insulation stress.

The standard atmospheric conditions are an air temperature of $t_0 = 20$ °C, an air pressure of $b_0 = 1013$ mbar and an absolute humidity of $h_0 = 11$ g/m^3 according to Reference 1. b_0 is the standard atmospheric pressure, b is the actual pressure at the instant of measurement with t the actual temperature. The atmospheric correction factor K_t has two parts, the air density factor k_1 and the humidity factor k_2. The disruptive discharge voltage of air is proportional to the atmospheric correction factor K_t, which results from the product of k_1 and k_2.

The air density factor k_1 depends on the relative air density δ and can be expressed by the following equation:

$$k_1 = \delta^m \tag{16.18}$$

where δ is given by the equation

$$\delta = \frac{b}{b_0}\,\frac{(273 + t_0)}{(273 + t)} \tag{16.19}$$

and m as function of g, which depends on the type of predischarges and is defined according the equation

$$g = \frac{U_B}{500\,L\,\delta\,k} \tag{16.20}$$

where U_B is the 50% disruptive discharge voltage at the actual atmospheric conditions in kV, L the minimum discharge path in m at the actual relative air density δ, and the value of k according to Figure 16.22.

Figure 16.23 shows the value of m and w as function of the factor g.

The humidity correction factor k_2 is expressed as

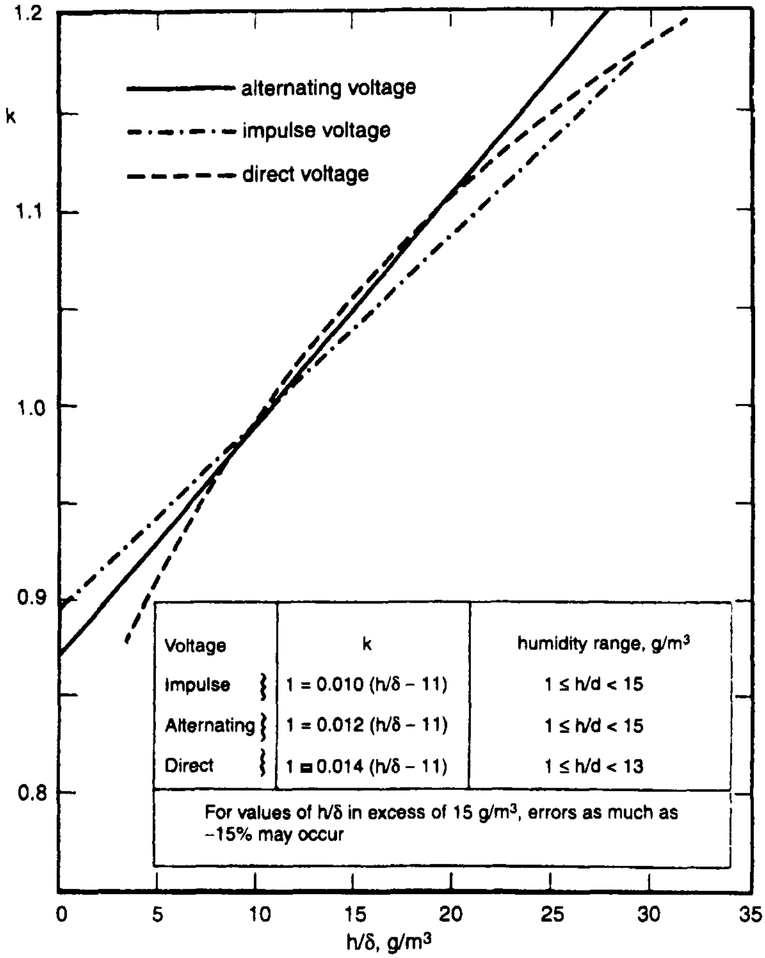

Figure 16.22 Value of k as function of the humidity h related to the air density δ

$$k_2 = k^w$$

The values of k and w are given in Figures 16.22 and 16.23, respectively, as functions of the humidity h related to the air density δ and the factor g described by eqn 16.20. It should be noted that the exponent values m and w are still under consideration and that the values given in Figure 16.23 are approximations.

The selection of the test voltage according to the recommendations is different for voltages up to 300 kV and above. Tables 16.1 and 16.2 show the relation between the rated power frequency voltage and the rated withstand voltages.

Table 16.1 Standard insulation levels for 52 kV ≤ U_m ≤ 300 kV

1	2	3	4
Highest voltage for equipment U_m (RMS)	Base for pu values $U_m \sqrt{2}/\sqrt{3}$ (peak)	Rated lightning impulse withstand voltage (peak)	Rated power-frequency short duration withstand voltage (RMS)
kV	kV	kV	kV
52	42.5	250	95
72.5	59	325	140
123	100	450	185
145	118	550	230
170	139	650	275
245	200	750	325
	200	850	360
	200	950	395
	200	1050	460

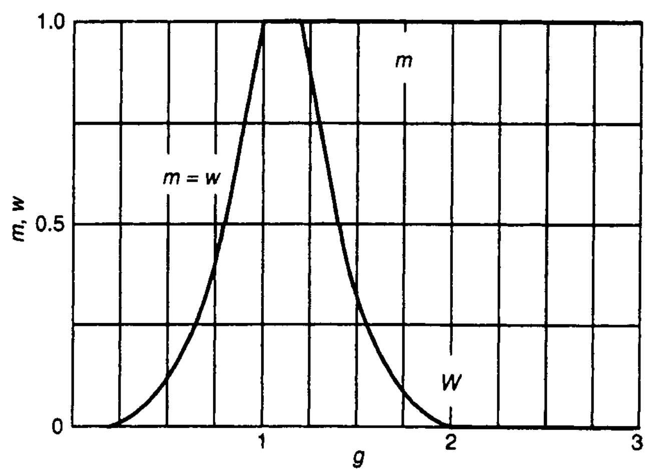

Figure 16.23 Value of m and w as function of the factor g

Equipment with rated voltages between 52 kV and 300 kV are tested in general by a short duration (1 min) power frequency test and by a lightning impulse voltage test (15 impulses). Equipment with a rated voltage above 300 kV the performance under operating or temporary overvoltages at power frequency can be checked by an extension of the test time to demonstrate the suitable design regarding ageing and pollution. The performance under impulse voltage can be checked by the relevant

Table 16.2 Standard insulation levels for $U_m \geq 300$ kV

1	2	3	4	5	6
Highest voltage for equipment U_m (RMS)	Base for pu values $U_m\sqrt{2}/\sqrt{3}$ (peak)	Rated switching impulse withstand voltage (peak)		Ratio between rated lightning and switching impulse withstand voltage	Rated lightning impulse withstand voltage (peak)
kV	kV	pu	kV		kV
				1.13	850
300	245	3.06	750		
				1.27	950
				1.12	950
300	245	3.47	850		
				1.24	1050
				1.12	950
362	296	2.86	850		
				1.24	1050
				1.11	1050
362	296	3.21	950		
				1.24	1175
				1.11	1050
420	343	2.76	950		
				1.24	1175
				1.12	1175
420	343	3.06	1050	1.24	1300
				1.36	1425
				1.11	1300
525	429	2.74	1175	1.21	1425
				1.32	1555
				1.10	1425
765	625	2.08	1300	1.19	1550
				1.38	1880
				1.09	1550
765	625	2.28	1425	1.26	1880
				1.47	2100
				1.16	1880
765	625	2.48	1550	1.26	1950
				1.55	2400

impulse tests, lightning and switching impulse. It should be taken into account that the ratio between the rated switching impulse withstand voltage and the rated power frequency voltage decreases with increasing rated power frequency voltage from 3.47 to 2.08 in extreme cases. The ratio between the lightning and switching voltage is more or less independent on the rated power frequency voltage, but this means that the ratio between rated lightning and rated power frequency voltages also decreases with increasing voltage level, and this should be taken into account for insulation co-ordination.

16.6 Conclusions

1. Insulation co-ordination describes the relationship between the different kinds of test voltages at different voltage levels.
2. DC voltages are generated by a multistage rectifier. Voltage drop and ripple can be calculated with simple equations.
3. AC voltages are generated by transformers or by a transformer cascade. Capacitive loads lead to a voltage increase, but this phenomenon can be used to generate high peak values with a resonance test set-up.
4. Impulse voltage are generated by a multistage Marx generator with variable resistors to form the shape of the impulse. The same generator can produce lightning as well as switching impulses.
5. Impulse currents are also generated by capacitors, but the inductance of the circuit should be kept as small as possible.
6. Test conditions should take into account the correction factors and their influence on the disruptive discharge voltage.

16.7 References

1 IEC Publication 60071. 'Insulation co-ordination. Part 1: Definitions, principles and rules', Ed. 70, 2000; 'Part 2: Application guide', 1996
2 IEC Publication 60060. 'High voltage test technique. Part 1: General definitions', 1989; 'Part 2: Measuring technique', 1994
3 IEC Publication 60230. 'Impulse tests on cables and their accessories', 1966
4 IEC Publication 60076. 'Power transformers. Part 3: Insulation levels and dielectric tests', 1980
5 IEC Publication 60722. 'Guide to lightning and switching impulse testing of power transformers and reactors', 1982