Chapter 2
Basics of High-Voltage Test Techniques

Abstract High-voltage (HV) testing utilizes the phenomena in electrical insulations under the influence of the electric field for the definition of test procedures and acceptance criteria. The phenomena—e.g., breakdown, conductivity, polarization and dielectric losses—depend on the insulating material, on the electric field generated by the test voltages and shaped by the electrodes as well as on environmental influences. Considering the phenomena, this chapter describes the common basics of HV test techniques, independent on the kind of the stressing test voltage. All details related to the different test voltages are considered in the relevant Chaps. 3–8.

2.1 External and Internal Insulations in the Electric Field

In this section definitions of phenomena in electrical insulations are introduced. The insulations are classified for the purpose of high-voltage (HV) testing. Furthermore environmental influences to external insulation and their treatment for HV testing are explained.

2.1.1 Principles and Definitions

When an electrical insulation is stressed in the electric field, ionization causes electrical discharges which may grow from one electrode of high potential to the one of low potential or vice versa. This may cause a high current rise, i.e., the dielectric looses its insulation property and thus its function to separate different potentials in an electric apparatus or equipment. For the purpose of this book, this phenomenon shall be called "*breakdown*" related to the stressing voltage:

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Definition The breakdown is the failure of insulation under electric stress, in which the discharge completely bridges the insulation under test and reduces the voltage between electrodes to practically zero (collapse of voltage).

Note In IEC 60060-1 (2010) this phenomenon is referred to as "*disruptive discharge*". There are also other terms, like "*flashover*" when the breakdown is related to a discharge over the surface of a dielectric in a gaseous or liquid dielectric, "*puncture*" when it occurs through a solid dielectric and "*sparkover*" when it occurs in gaseous or liquid dielectrics.

In homogenous and *slightly non-homogenous fields* a breakdown occurs when a critical strength of the stressing field is reached. *In strongly non-homogenous fields, a local stress concentration causes a localized electrical partial discharge (PD)* without bridging the whole insulation and without breakdown of the stressing voltage.

Definition A partial discharge is a localized electrical discharge that only partly bridges the insulation between electrodes, for details see Chap. 4.

Figure 1.2 shows the application of some important insulating materials. Till today atmospheric air is applied as the most important dielectric of the external insulation of transmission lines and the equipment of outdoor substations.

Definition External insulation means air insulation including the outer surfaces of solid insulation of equipment exposed to the electric field, atmospheric conditions (air pressure, temperature, humidity) and to other environmental influences (rain, snow, ice, pollution, fire, radiation, vermin).

External insulation recovers its insulation behaviour in most cases after a breakdown and is then called a *self-restoring insulation*. In opposite to that, the *internal insulation* of apparatus and equipment—such as transformers, gas-insulated switchgear (GIS), rotating machines or cables—is more affected by discharges, often even destroyed when a breakdown is caused by a HV stress.

Definition Internal insulation of solid, liquid or gaseous components is protected from direct influences of external conditions such as pollution, humidity and vermin.

Solid and liquid- or gas-impregnated laminated insulation elements are non-self-restoring insulations. Some insulation is partly self-restoring, particularly when it consists e.g., of gaseous and solid elements. An example is the insulation of a GIS which uses SF_6 gas and solid spacers. In case of a breakdown in an oil- or SF_6 gas-filled tank, the insulation behaviour is not completely lost and recovers partly. After a larger number of breakdowns, partly self-restoring elements have a remarkably reduced breakdown voltage and are not longer reliable.

The insulation characteristic has consequences for HV testing: Whereas for HV testing of external insulation, the atmospheric and environmental influences have to be taken into consideration, internal insulation does not require related special test conditions. In case of self-restoring insulation, breakdowns may occur during HV tests. For partly self-restoring insulation, a breakdown would only be acceptable in the self-restoring part of the insulation. In case of non-self restoring insulation no breakdown can be accepted during a HV test. For the details see Sect. 2.4 and the relevant subsections in Chaps. 3 and 6–8.

The test procedures should guarantee the *accuracy* and the *reproducibility* of the test results under the actual conditions of the HV test. The different test procedures necessary for external and internal insulations should deliver comparable test results. This requires regard to various factors such as

- random nature of the breakdown process and the test results,
- polarity dependence of the tested or measured characteristics,
- acclimatisation of test object to the test conditions,
- simulation of service conditions during the test,
- correction of differences between standard, test and service conditions, and
- possible deterioration of the test object by repetitive voltage applications.

2.1.2 HV Dry Tests on External Insulation Including Atmospheric Correction Factors

HV dry tests have to be applied for all external insulations. The arrangement of the test object may affect the breakdown behaviour and consequently the test result. The electric field at the test object is influenced by *proximity effects* such as distances to ground, walls or ceiling of the test room as well as to other earthed or energized structures nearby. As a rule of thumb, the *clearance* to all external structures should be not less than 1.5 times the length of the possible discharge path along the test object. For maximum AC and SI test voltages above 750 kV (peak), recommendations for the minimum clearances to external earthed or energized structures are given in Fig. 2.1 (IEC 60060-1:2010). When the necessary clearances are considered, the test object will not be affected by the surrounding structures.

Atmospheric conditions may vary in wide ranges on the earth. Nevertheless, HV transmission lines and equipment with external insulations have to work nearly everywhere. This means on one hand that the atmospheric service conditions for HV equipment must be specified (and for these conditions it must be tested), and on the other hand the test voltage values for insulation coordination (IEC 60071: 2010) must be related to a *standard reference atmosphere* (IEC 60060-1:2010):

- temperature $T_0 = 20$ °C (293 K)
- absolute air pressure $p_0 = 1{,}013$ hPa (1,013 mbar)
- absolute humidity $h_0 = 11$ g/m^3

The temperature shall be measured with an expanded uncertainty $t \leq 1$ °C, the ambient pressure with $p \leq 2$ hPa. The absolute humidity h can be directly measured with so-called ventilated dry-and wet-bulb thermometers or determined from the relative humidity R and the temperature t by the formula (IEC 60060-1:2010):

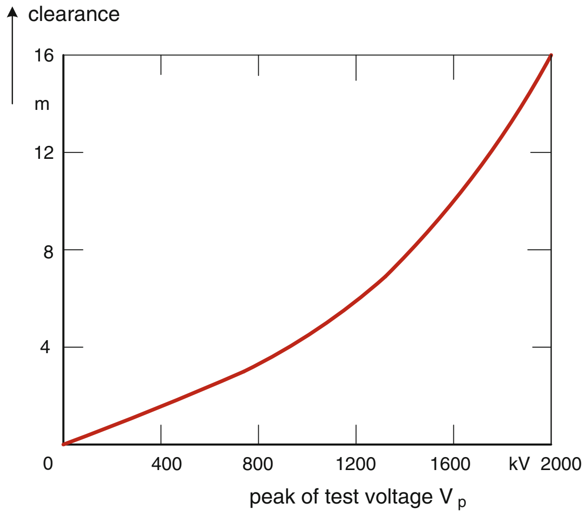


Fig. 2.1 Recommended clearances between test object and extraneous energized or earthed structures

$$h = \frac{6.11 \cdot R \cdot e^{\frac{17.6 \cdot t}{243+t}}}{0.4615 \cdot (273 + t)}. \tag{2.1}$$

If HV equipment for a certain altitude shall be designed according to the pressure-corrected test voltages, the relationship between altitude H/m and pressure p/hPa is given by

$$p = 1{,}013 \cdot e^{\frac{H}{8150}}. \tag{2.2}$$

A test voltage correction for air pressure based on this formula can be recommended for altitudes up to 3,000 m. For more details see Pigini et al. (1985), Ramirez et al. (1987) and Sun et al. (2009). The temperature t and the pressure p determine the *air density*δ, which influences the breakdown process directly:

$$\delta = \frac{p}{p_0} \cdot \frac{273 + t_0}{273 + t}. \tag{2.3}$$

The air density delivers together with the air density correction exponent m (Table 2.1) the air density correction factor

$$k_1 = \delta^m. \tag{2.4}$$

The humidity affects the breakdown process especially when it is determined by partial discharges. These are influenced by the kind of test voltage. Therefore, for different test voltages different humidity correction factors k_2 have to be applied, which are calculated with the parameter k and the humidity correction exponent w

$$k_2 = k^w, \tag{2.5}$$

Table 2.1 Air density and humidity correction exponents m and w according to IEC 60060-1:2010

g	m	w
<0.2	0	0
0.2–1.0	$g(g - 0.2)/0.8$	$g(g - 0.2)/0.8$
1.0–1.2	1.0	1.0
1.2–2.0	1.0	$(2.2 - g)(2.0 - g)/0.8$
>2.0	1.0	0

with

$$\begin{aligned}
\text{DC}: &\quad k = 1 + 0.014(h/\delta - 11) - 0.00022(h/\delta - 11)^2 &\quad \text{for } 1\ \text{g/m}^3 < h/\delta, < 15\ \text{g/m}^3,\\
\text{AC}: &\quad k = 1 + 0.012(h/\delta - 11) &\quad \text{for } 1\ \text{g/m}^3 < h/\delta < 15\ \text{g/m}^3,\\
\text{LI/SI}: &\quad k = 1 + 0.010(h/\delta - 11) &\quad \text{for } 1\ \text{g/m}^3 < h/\delta < 20\ \text{g/m}^3.
\end{aligned}$$

The correction exponents m and w describe the characteristic of possible partial discharges and are calculated utilizing a parameter

$$g = \frac{V_{50}}{500 \cdot L \cdot \delta \cdot k}, \tag{2.6}$$

with

V_{50} Measured or estimated 50 % breakdown voltage at the actual atmospheric conditions, in kV (peak),
L Minimum discharge path, in m,
δ Relative air density and
k Dimension-less parameter defined with formula (2.5).

Note For withstand tests it can be assumed $V_{50} \approx 1.1 \cdot V_t$ (test voltage). Depending on the parameter g (Eq. 2.6), Table 2.1 or Fig. 2.2 delivers the exponents m and w.

According to IEC 60060-1:2010 the atmospheric correction factor

$$K_t = k_1 \cdot k_2, \tag{2.7}$$

shall be used to correct a measured breakdown voltage V to a value under standard reference atmosphere

$$V_0 = V/K_t. \tag{2.8}$$

Vice versa when a test voltage V_0 is specified for standard reference atmosphere, the actual test voltage value can be calculated by the converse procedure:

$$V = K_t \cdot V_0. \tag{2.9}$$

Because the converse procedure uses the breakdown voltage V_{50} (Eq. 2.6), the applicability of Eq. (2.9) is limited to values of K_t close to unity, for $K_t < 0.95$ it is

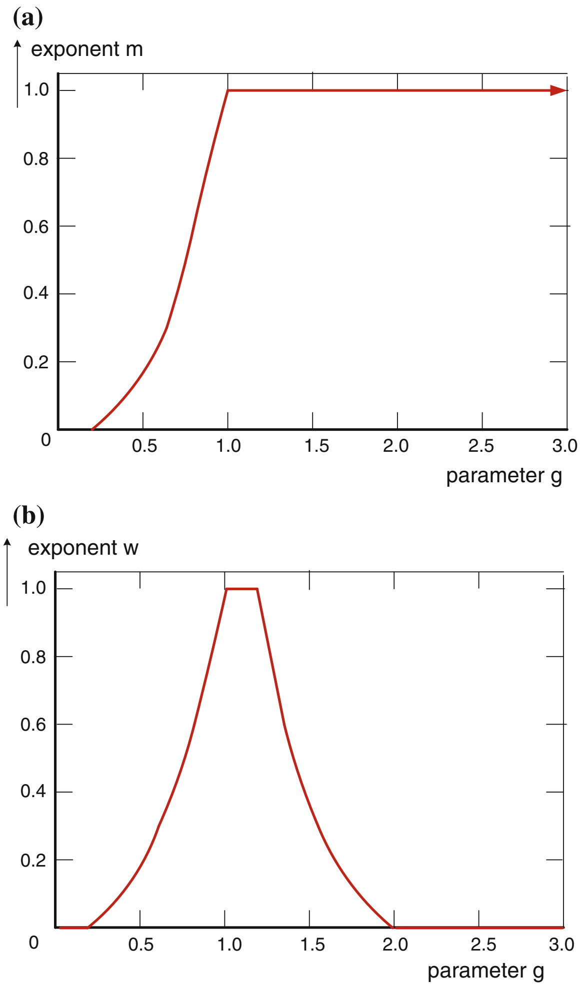


Fig. 2.2 Correction exponents according to IEC 60060-1:2010. **a** *m* for air density. **b** *w* for air humidity

recommended to apply an iterative procedure which is described in detail in Annex E of IEC 60060-1:2010.

It is necessary to mention that the present procedures for atmospheric corrections are not yet perfect (Wu et al. 2009). Especially the humidity correction is limited only to air gaps and not applicable to flashovers directly along insulating surfaces in air. The reason is the different absorption of water by different surface materials. Furthermore the attention is drawn to the limitations of the application of humidity correction to $h/\delta \leq 15\ \mathrm{g/m^3}$ (for AC and DC test voltages), respectively $h/\delta \leq 20\ \mathrm{g/m^3}$ (for LI and SI test voltages). The clarification of the humidity correction for surfaces as well as the extension of their ranges requires further research work (Mikropolulos et al. 2008; Lazarides and Mikropoulos 2010; 2011) as well as the atmospheric correction in general for altitudes above 2,500 m

(Ortega and Waters et al. 2007; Jiang et al. 2008; Jiang and Shu et al. 2008). Nevertheless, also the available correction to and from reference atmospheric conditions is important in HV testing of external insulation as it should be shown by two simple examples.

Example 1 In a development test, the 50 % LI breakdown voltage of an air insulated disconnector [breakdown (flashover) path L = 1 m, not at the insulator surface] was determined to $V_{50} = 580$ kV at a temperature of $t = 30$ °C, an air pressure of $p = 980$ hPa and a humidity of $h = 12$ g/m^3. The value under reference atmospheric conditions shall be calculated:

Air density	$\delta = (995/1{,}013) \cdot (293/303) = 0.95$;
Parameter	$k = 1 + 0.010 \cdot ((12/0.95) - 11) = 1.02$;
Parameter	$g = 580/(500 \cdot 1 \cdot 0.95 \cdot 1.02) = 1.20$;
Table 2.1: delivers the air density correction exponent	$m = 1.0$;
and the humidity correction exponent	$w = (2.2 - 1.2)\ (2.0 - 1.2)/0.8 = 1.0$;
With the density correction factor	$k_1 = 0.95$;
and the humidity correction factor	$k_2 = 1.02$;
one gets the atmospheric correction factor	$K_t = 0.95 \cdot 1.02 = 0.97$.
Under reference conditions the 50 % breakdown voltage would be	$\mathbf{V_{0-50} = 580/0.97 = 598\ kV.}$

Example 2 The same disconnector shall be type tested with a LI voltage of $V_0 = 550$ kV in a HV laboratory at higher altitude under the conditions $t = 15$ °C, $p = 950$ hPa and $h = 10$ g/m^3. Which test voltage must be applied?

Air density	$\delta = (950/1013)\ (293/288) = 0.954$;
parameter	$k = 1 + 0.010\ ((10/0.95) - 11) = 0.995$;
parameter	$g = 598/(500 \cdot 1 \cdot 0.95 \cdot 0.995) = 1.265$;
Table 2.1: delivers the air density correction exponent	$m = 1.0$;
and the humidity correction exponent	$w = (2.2 - 1.265)(2.0 - 1.265)/0.8 = 0.86$;
With the density correction factor	$k_1 = 0.954$;
and the humidity correction factor	$k_2 = 0.995^{0.86} = 0.996$;
one gets the atmospheric correction factor	$K_t = 0.954 \cdot 0.996 = 0.95$.
Under the actual laboratory conditions the test voltage is	$\mathbf{V = 550 \cdot 0.95 = 523\ kV}$.

The two examples show, that the differences between the starting and resulting values are significant. The application of atmospheric corrections is essential for HV testing of external insulation.

2.1.3 HV Artificial Rain Tests on External Insulation

External HV insulations (especially outdoor insulators) are exposed to natural rain. The effect of rain to the flashover characteristic is simulated in artificial rain (or *wet) tests* (Fig. 2.3). The artificial rain procedure described in the following is applicable for tests with AC, DC and SI voltages, whereas the arrangement of the test object is described in the relevant apparatus standards.

The test object is sprayed with droplets of water of given resistivity and temperature (Table 2.2). The rain shall fall on the test object under an angel of about 45°, this means that the horizontal and vertical components of the *precipitation rate* shall be identical. The precipitation rate is measured with a special collecting vessel with a horizontal and a vertical opening of identical areas between 100 and 700 cm^2. The rain is generated by an artificial rain equipment consisting of nozzles fixed on frames. Any type of nozzles which generates the appropriate rain conditions (Table 2.2) can be applied.

Note 1 Examples of applicable nozzles are given in the old version of IEC 60-1:1989-11 (Fig. 2, pp. 113–115) as well as in IEEE Std. 4–1995.

The precipitation rate is controlled by the water pressure and must be adjusted in such a way, that only droplets are generated and the generation of water jets or fog is avoided. This becomes more and more difficult with increasing size of the test objects which requires larger distances between test object and artificial rain equipment. Therefore, the requirements of IEC 60060-1:2010 are only related to equipment up to rated voltages of $V_m = 800$ kV, Table 2.2 contains an actual proposal for the UHV range.

The reproducibility of wet test results (*wet flashover voltages*) is less than that for dry HV breakdown or withstand tests. The following precautions enable acceptable wet test results:

- The water temperature and resistivity shall be measured on a sample collected immediately before the water reaches the test object.
- The test object shall be pre-wetted initially for at least 15 min under the conditions specified in Table 2.2 and these conditions shall remain within the specified tolerances throughout the test, which should be performed without interrupting the wetting.

Note 2 The pre-wetting time shall not include the time needed for adjusting the spray. It is also possible to perform an initial pre-wetting by unconditioned tap water for 15 min, followed without interruption of the spray by a second pre-wetting with the well conditioned test water for at least 2 min before the test begins.

- The test object shall be divided in several zones, where the precipitation rate is measured by a collecting vessel placed close to the test object and moved slowly over a sufficient area to average the measured precipitation rate.

Fig. 2.3 Artificial rain test on an 800 kV support insulator (Courtesy HSP Cologne)

Table 2.2 Conditions for artificial rain precipitation

Precipitation condition	Unit	IEC 60060-1:2010 range for equipment of $V_m \leq 800$ kV	Proposed range for UHV equipment $V_m > 800$ kV
Average precipitation rate of all measurements:			
• Vertical component	(mm/min)	1.0–2.0	1.0–3.0
• Horizontal component	(mm/min)	1.0–2.0	1.0–3.0
Limits for any individual measurement and for each component	(mm/min)	±0.5 from average	1.0–3.0
Temperature of water	(°C)	Ambient temperature ±15 K	Ambient temperature ±15 K
Conductivity of water	(μS/cm)	100 ± 15	100 ± 15

- Individual measurements shall be made at all measuring zones considering also one at the top and one near the bottom of the test object. A measuring zone shall have a width equal to that of the test object (respectively its wetted parts) and a maximum height of 1–2 m. The number of measuring zones shall cover the full height of the test object.

- The spread of results may be reduced if the test object is cleaned with a surface-active detergent, which has to be removed before the beginning of wetting.
- The spread of results may also be affected by local anomalous (high or low) precipitation rates. It is recommended to detect these by localized measurements and to improve the uniformity of the spray, if necessary.

The test voltage cycle for an artificial rain test shall be identical to that for a dry test. For special applications different cycles are specified by the relevant apparatus committees. A density correction factor according to Sect. 2.1.2, but no humidity correction shall be applied.

Note 3 IEC 60060-1:2010 permits one flashover in AC and DC wet tests provided that in a repeated test no further flashover occurs.

Note 4 For the UHV test voltage range, it may be necessary to control the electric field (e.g., by toroid electrodes) to the artificial rain equipment and/or to surrounding grounded or energized objects including walls and ceiling to avoid a breakdown to them. Also artificial rain equipment on a potential different from ground might be taken into consideration.

2.1.4 HV Artificial Pollution Tests on External Insulation

Outdoor insulators are not only exposed to rain, but also to pollution caused by salt fog near the sea shore, by industry and traffic or simply by natural dust. Depending on the position of a transmission line or substation, the surrounding is classified in several different *pollution classes* between low (*surface conductivity* $\kappa_s \leq 10\ \mu$S) and extreme ($\kappa_s \geq 50\ \mu$S) (Mosch et al. 1988). The severity of the pollution class can also be characterized by the equivalent salinity (SES in kg/m^3), which is the salinity [content of salt (in kg) in tap water (in m^3)] applied in a salt-fog test according to IEC 60507 (1991) that would give comparable values of the leakage current on an insulator as produced at the same voltage by natural pollution on site (Pigini 2010).

Depending on the pollution class, the artificial pollution test is performed with different intensities of pollution, because the test conditions shall be representative of wet pollution in service. This does not necessarily mean that any real service condition has to be simulated. In the following the performance of typical pollution tests is described without considering the representation of the pollution zones. The pollution flashover is connected with quite high pre-arc currents supplied via the wet and polluted surface from the necessary powerful HV generator (HVG). In a pioneering work, Obenaus (1958) considered a flashover model of a series connection of the pre-arc discharge with a resistance for the polluted surface. Till today the *Obenaus model* is the basis for the selection of pollution test procedures and the understanding of the requirements on test generators (Slama et al. 2010; Zhang et al. 2010). These requirements to HV test circuits are

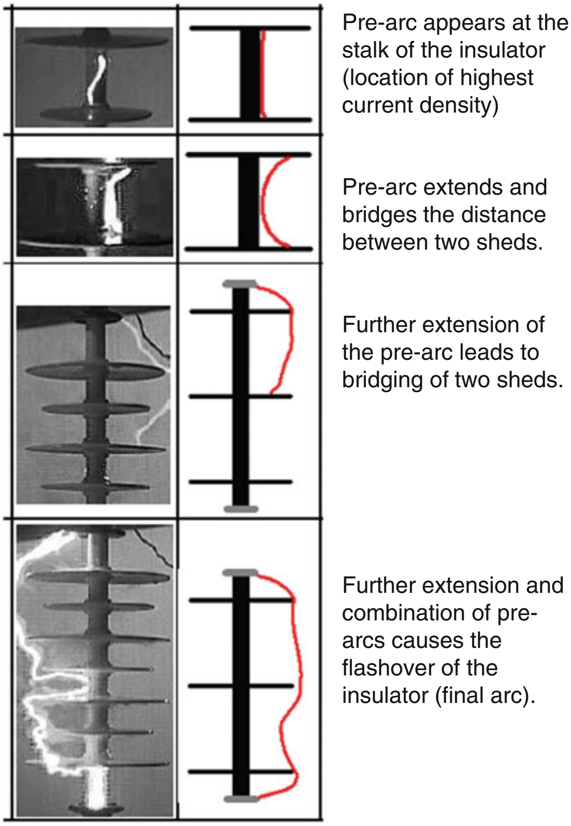


Fig. 2.4 Phases of a pollution flashover of an insulator (Courtesy of FH Zittau, Germany)

considered in the relevant Chaps. 3 and 6–8. Pollution tests of insulators for high altitudes have to take into consideration not only the pollution class, but also the atmospheric conditions (Jiang et al. 2009).

The test object (insulator) must be cleaned by washing with tap water and then the pollution process may start. Typically the pollution test is performed with subsequent applications of the test voltage which is held constant for a specified test time of at least several minutes. Within that time very heavy partial discharges, so-called pre-arcs, appear (Fig. 2.4). It may happen that the wet and polluted surface dries (which means electrically withstand of the tested insulator and passing the test) or that the pre-arcs are extended to a full flashover (which means failing the test). Because of the random process of the pollution flashover, remarkable dispersion of the test results can be expected. Consequently the test must be repeated several times to get average values of sufficient confidence or to estimate distribution functions (see Sect. 2.4). Two pollution procedures shall be described:

The *salt-fog method* uses a fog from a salt (NaCl) solution in tap water with defined concentrations between 2.5 and 20 kg/m^3 depending on the pollution zone. A spraying equipment generates a number of fog jets each generated by a pair of nozzles. One nozzle supplies about 0.5 l/min of the salt solution, the other one the compressed air with a pressure of about 700 kPa which directs the fog jet to the test object. The spraying equipment contains usually two rows of the described double nozzles. The test object is wetted before the test. The test starts with the application of the fog and the test voltage value which should be reached—but not overtaken—as fast as possible. The whole test may last up to 1 h.

The *pre-deposit method* is based on coating the test object with a conductive suspension of Kieselgur or Kaolin or Tonoko in water ($\approx$40 g/l). The conductivity of the suspension is adjusted by salt (NaCl). The coating of the test object is made by dipping, spraying or flow-coating. Then it is dried and should become in thermal equilibrium with the ambient conditions in the pollution chamber. Finally the test object is wetted by a steam-fog equipment (steam temperature $\leq$ 40 °C). The surface condition is described by the *surface conductivity* (μS) measured from the current at two probes on the surface (IEC 60-1:1989, Annex B.3) or by the equivalent amount of salt per square centimetre of the insulating surface [so-called salt deposit density (S.D.D.) in mg/cm^2]. The test can start with voltage application before the test object is wetted, or after wetting, when the conductivity has reached its maximum. Details depend on the aim of the test, see IEC 60507:1991.

Both described procedures can be performed with different aim of the pollution test:

- determination of the withstand voltage for a certain insulator of specified degree of pollution and a specified test time,
- determination of the maximum degree of pollution for a certain insulator at a specified test voltage and specified test time.

Pollution tests require separate *pollution chambers*, usually with bushings for the connection of the test voltage generator. Because of the salt fog and humidity, the HV test system itself is outside under clean conditions. Inside a salt-fog chamber, the clearances around the test object should be $\geq$0.5 m/100 kV but not less than 2 m. When no pollution chamber is available, also tents from plastic foil may be applied, to separate the pollution area from the other areas of a HV laboratory.

2.1.5 HV Tests on Internal Insulation

In a HV test field, the HV components of test systems are designed with an external indoor insulation usually. When internal insulation shall be tested, the test voltage must be connected to the internal part of the apparatus to be tested. This is usually done by bushings which have an external insulation. For reasons of the insulation co-ordination or of the atmospheric corrections, cases will arise that the HV withstand test level of the internal insulation exceeds that of the external insulation (bushing). Then the withstand level of the bushing must be enhanced to permit application of the required test voltages for the internal insulation. Usually special "test bushings" of higher withstand level, which replace the "service bushings" during the test, are applied. A further possibility is the immersion of the external insulation in liquids or compressed gases (e.g., SF_6) during the test.

In rare cases, when the test voltage level of the external insulation exceeds that of the internal insulation a test at the complete apparatus can only be performed when the internal insulation is designed according to the withstand levels of the external insulation. If this cannot be done, then the apparatus should be tested at the internal test voltage level, and the external insulation should be tested separately using a dummy.

Internal insulation is influenced by the ambient temperature of the test field, but usually not by pressure or humidity of the ambient air. Therefore, the only requirement is the temperature equilibrium of the test object with its surrounding when the HV test starts.

2.1.6 Hints to Further Environmental Tests and HV Tests of Apparatus

There are also other environmental HV tests, e.g., under *ice* or *snow*. They are made with natural conditions in suitable open-air HV laboratories or in special climatic chambers (Sklenicka et al. 1999). Other environmental influences which are simulated in HV tests are UV light (Kindersberger 1997), sandstorms (Fan and Li 2008) and *fire* under transmission lines. The HV test procedures for apparatus and equipment are described in the relevant "vertical" standards, examples are given in the chapters of the different test voltages.

2.2 HV Test Systems and Their Components

This section supplies a general description of HV test systems and their components, which consist of the *HV generator*, the *power supply unit*, the *HVvoltage measuring system*, the *control system* and possibly additional measuring equipment, e.g., for PD or dielectric measurement. In all cases the test object cannot be neglected, because it is a part of the *HV test circuit*.

A *HV test system* means the complete set of apparatus and devices necessary for performing a HV test. It consists of the following devices (Fig. 2.5).

The *HV generator* (HVG) converts the supplied low or medium voltage into the high test voltage. The type of the generator determines the kind of the test voltage. For the generation of high alternating test voltages (HVAC), the HVG is a test transformer (Fig. 2.6a). It might be also a resonance reactor which requires a capacitive test object (TO) to establish an oscillating circuit for the HVAC generation (see Sect. 3.1). For the generation of high direct test voltages (HVDC) the HVG is a special circuit of rectifiers and capacitors (e.g., a Greinacher or Cockroft-Walton

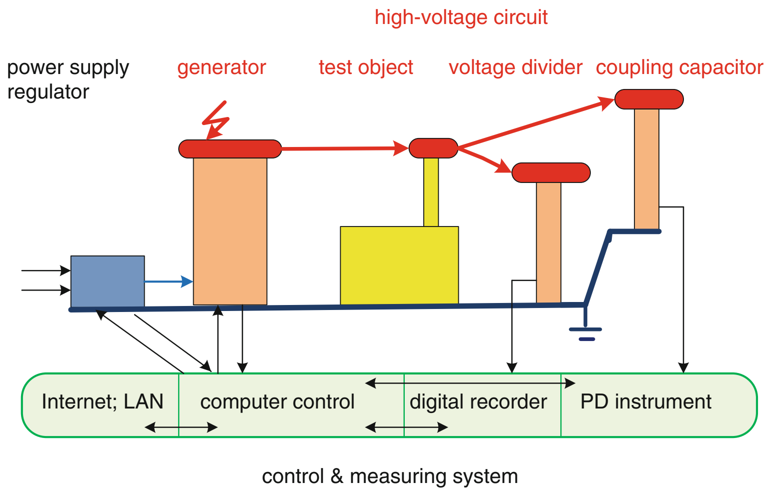


Fig. 2.5 Principle circuit of a HV test system

generator, Fig. 2.6b, see Sect. 6.1), and for the generation of high lightning or switching impulse (LI, SI) voltages, it is a special circuit of capacitors, resistors and switches (sphere gaps) (e.g., a Marx generator, Fig. 2.6c, see Sect. 7.1).

The test object does not only play a role for HVAC generation by resonant circuits, there is an interaction between the generator and the test object in all HV test circuits. The voltage at the test object may be different from that at the generator because of a voltage drop at the HV lead between generator and test object or even a voltage increase because of resonance effects. This means the voltage must be measured directly at the test object and not at the generator (Fig. 2.5). For this voltage measurement a sub-system—usually called *HV measuring system*—is connected to the test object (Fig. 2.7a, see Sect. 2.3). Further sub-systems, e.g., for dielectric measurement, can be added. Up to few 10 kV such systems can be designed as compact units including voltage source (Fig. 2.7b). Very often PD measurements are performed during a HVAC test. For that a *PD measuring system* is connected to the AC test system (Fig. 2.7c). All these systems consist of a HV component (e.g., voltage divider, coupling or standard capacitor), measuring cable for data transfer and a low-voltage instrument (e.g., digital recorder, peak voltmeter, PD measuring instrument, tan delta bridge).

All the components of a HV test system and the test object described above form the HV circuit. This circuit should be of lowest possible impedance. This means, it should be as compact as possible. All connections, the *HV leads* and the *ground connections* should be straight, short and of low inductance, e.g., by copper foil (width 10–25 cm, thickness depending of current). In HV circuits used also for PD measurement, the HV lead should be realized by PD-free tubes of a diameter appropriate to the maximum test voltage. Any loop in the ground connection has to be avoided.

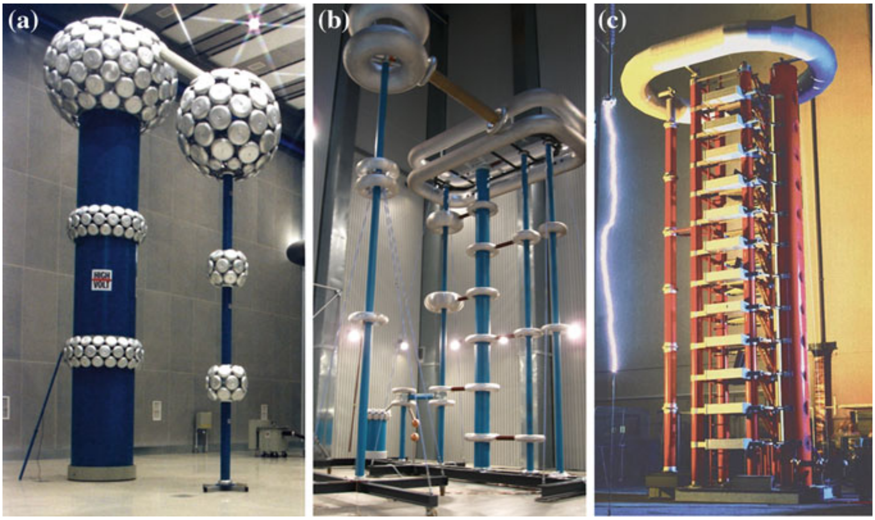


Fig. 2.6 HV generators. **a** For AC test voltage 1,000 kV at Cottbus Technical University. **b** For DC test voltage 1,500 kV at HSP Cologne. **c** For LI/SI test voltages 2,400 kV at Dresden Technical University

The necessary power for the HV tests is supplied from the power grid—in case of on-site testing also from a Diesel-generator set—via the *power supply unit* (Fig. 2.5). This unit consists of one or several *switching cubicles* and a *regulation unit* (regulator transformer or motor-generator set or thyristor controller or frequency converter). It controls the power according to the signals from the control system in such a way, that the test voltage at the test object is adjusted as required for the HV test. For safety reasons the switching cubicle shall have two circuit breakers in series; the first switches the connections between the grid and the power supply unit (power switch), the second one that between the power supply unit and the generator (operation switch). For the reduction of the required power from the grid in case of capacitive test objects, the power supply unit is often completed by a fixed or even adjustable *compensation reactor*.

When the generator is the heart of HV test system then the control and measuring sub-system—usually called *control and measuring system* (Fig. 2.8; Baronick 2003)—is its brain. Older controls were separated from the measuring systems and the adjustment of the test voltage was manually made by the operator (The brain was that of the operator). As a next step, programmable logic controllers have been introduced. Now a state-of-the-art control system is a *computer control* which enables the pre-selection of the test procedure with all test voltage values, gives the commands to the power supply unit, overtakes the data from the measuring systems, performs the test data evaluation and prints a test record. In that way one operator can supervise very complex test processes. The test data can be transferred to a local computer network (LAN) e.g., for combining with test data from other laboratories or even to the Internet. The latter can also be used in case of technical problems for *remote service*.

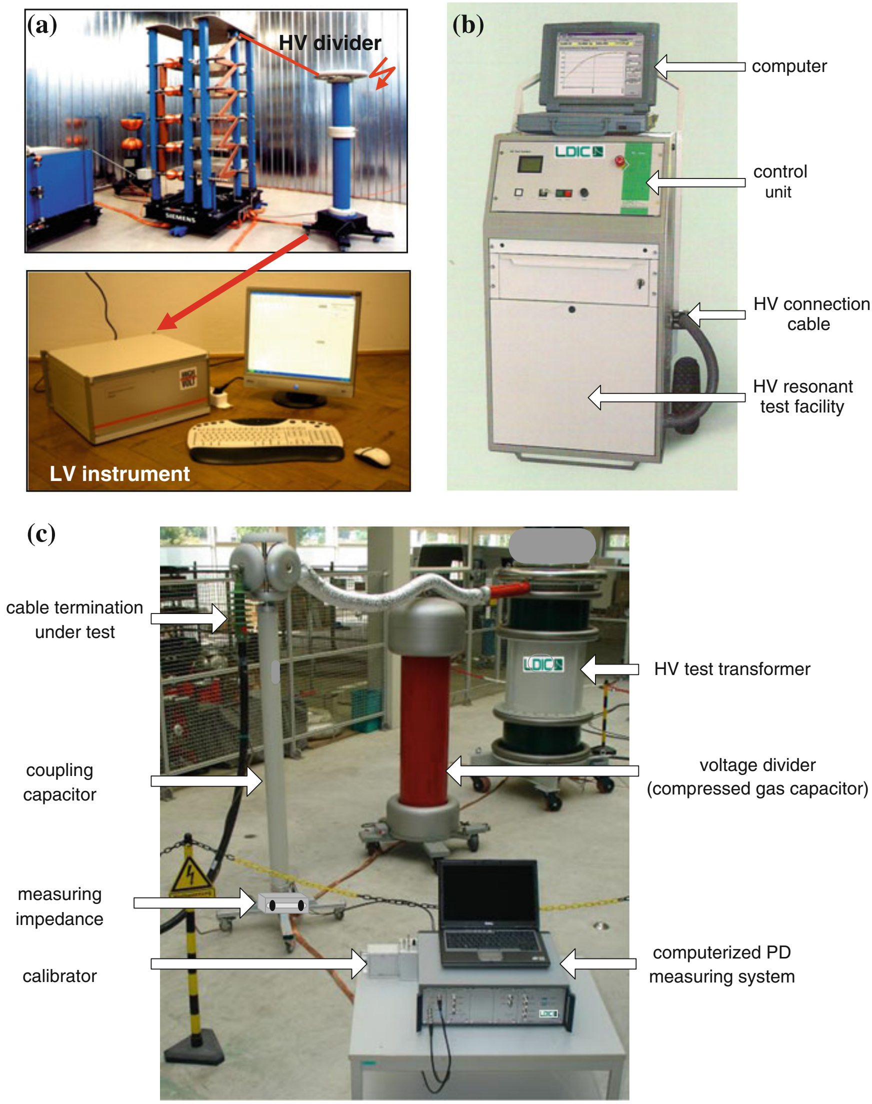


Fig. 2.7 Measuring systems. **a** Voltage measuring system with digital recorder including impulse generator. **b** Compact capacitance/loss factor measuring system with integrated AC voltage source (Courtesy of Doble-Lemke). **c** Partial discharge measuring system including AC voltage test circuit (Courtesy of Doble-Lemke)

A HV test system is only complete when it is connected to a *safety system* which protects the operators and the participants of a HV test. Among others, the safety system includes a fence around the test area which is combined with the electrical *safety loop*. The test can only be operated when the loop is closed, for details see Sect. 9.2.

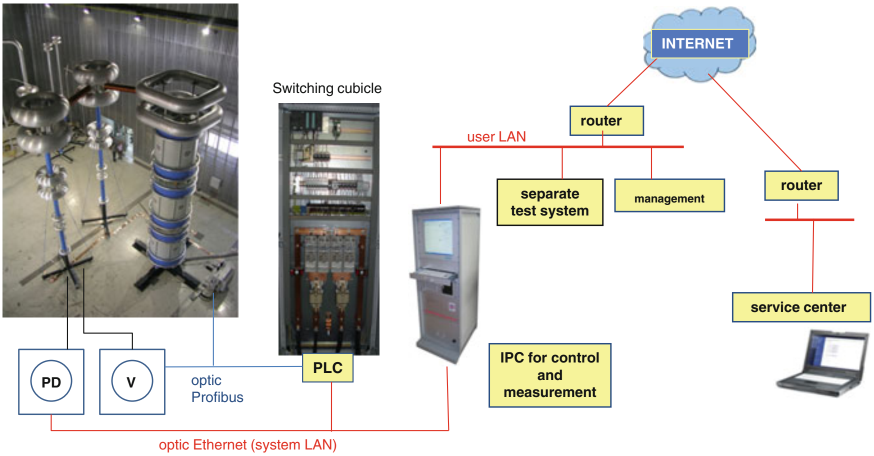


Fig. 2.8 Computerized control and measuring system

2.3 HV Measurement and Estimation of the Measuring Uncertainty

This section is related to voltage measurement and describes *HV measuring systems*, their *calibration* and the estimation of their *uncertainties of measurements*. Precise measurement of high test voltages is considered to be a difficult task for many years (Jouaire and Sabot et al. 1978; "Les Renardieres Group" 1974). This situation is also reflected by the older editions of the relevant standard IEC 60060-2. For good practice in HV test fields, this Sect. 2.3 on HV measurement and uncertainty estimation is closely related to the newest edition of the standard IEC 60060-2:2010.

The terms "*uncertainty*", "*error*" and "*tolerance*" are often mixed up. Therefore, the following clarification seems needed: The uncertainty is a parameter which is associated with the result of a measurement. It characterizes the dispersion of the results due to the characteristics of the measuring system. The *error* is the measured quantity minus a reference value for this quantity and the tolerance is the permitted difference between the measured and the specified value. Tolerances play a role for standard HV test procedures (Sects. 3.6, 6.5 and 7.6). Uncertainties are important for the decision, whether a measuring system is applicable or not for acceptance testing.

2.3.1 HV Measuring Systems and Their Components

Definition: A HV measuring system(MS) is a "complete set of devices suitable for performing a HV measurement". Software for the calculation of the result of the measurement is a part of the measuring system (IEC 60060-2:2010).

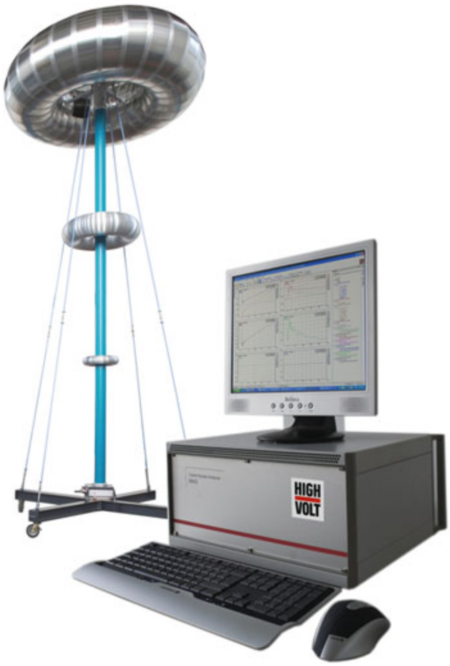


Fig. 2.9 HV measuring system consisting of voltage divider, coaxial cable and PC-based digital recorder

A HV measuring system (Fig. 2.9) which should be connected directly to the test object consists usually of the following components

- A *converting device* including its HV and earth connection to the test object which converts the quantity to be measured (*measurand*: test voltage with its voltage and/or time parameters) into a quantity compatible with the measuring instrument (low-voltage or current signal). It is very often a voltage divider of a type depending on the voltage to be measured (Fig. 2.10). For special application also a voltage transformer, a voltage converting impedance (carrying a measurable current) or an electric field probe (converting amplitude and time parameters of an electric field) may be used. The clearances between the converting device and nearby earthed or energized structures may influence the result of the measurement. Such *proximity effects* shall be considered by the uncertainty estimation (see Sect. 2.3.4). To keep the contribution of the proximity effect to the uncertainty of measurement small, the clearances of movable converting devices should be as those recommended for the test object (see Sect. 2.1.2 and Fig. 2.1). If the converting device is always in a fixed position and the measuring system is calibrated on site, the proximity effect can be neglected.
- A *transmission system* which connects the output terminals of the converting device with the input terminals of the measuring instrument. It is very often a coaxial cable with its terminating impedance, but may also be an optical link which includes a transmitter, an optical cable and a receiver with an amplifier. For special application also cable connections with amplifiers and/or attenuators are in use.

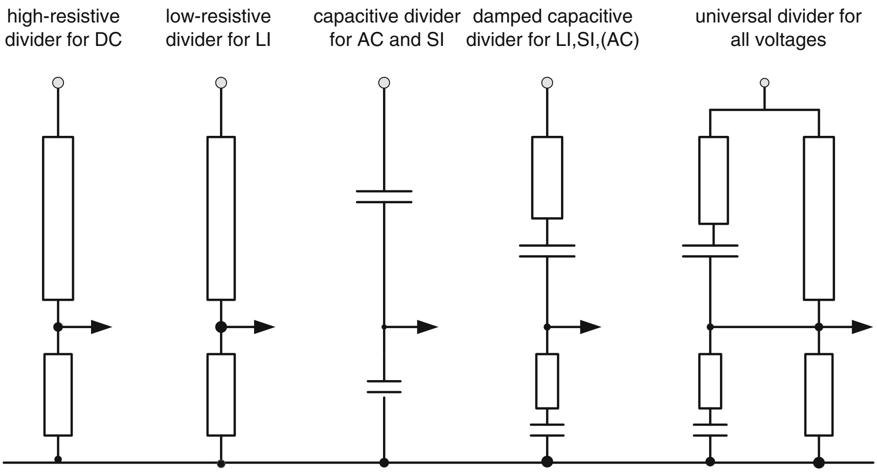


Fig. 2.10 Kinds and applications of voltage dividers

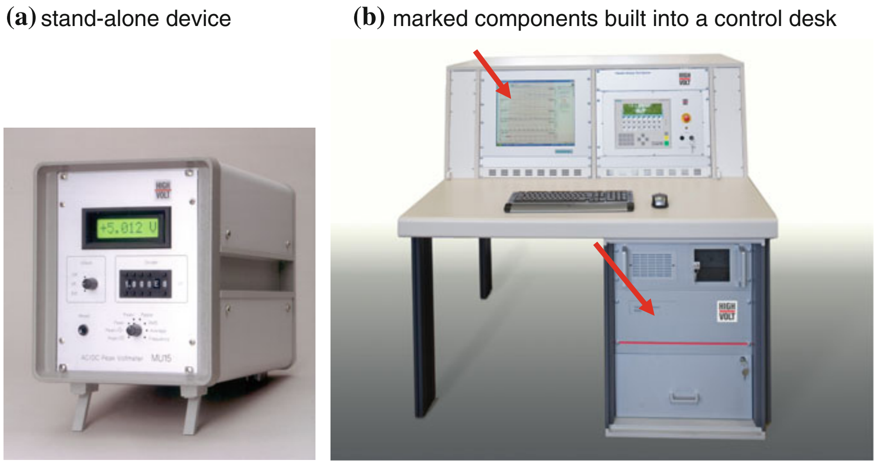


Fig. 2.11 Instruments for HV measurement. **a** Digital AC/DC peak voltmeter. **b** LI/SI digital recorder

- A *measuring instrument* suitable to measure the required test voltage parameters from the output signal of the transmission system. Measuring instruments for HV application are usually special devices which fulfil the requirements of the IEC Standards 61083 (part 1 and 2 for LI/SI test voltages has been published, part 3 and 4 for AC/DC voltages is under preparation). The conventional analogue peak voltmeters are replaced by digital peak voltmeters and more and more by digital recorders (Fig. 2.11). Digital recorders measure both test voltage and time parameters. This is mandatory for LI/SI test voltages, but more and more also for AC/DC test voltages with respect to changes in time by voltage

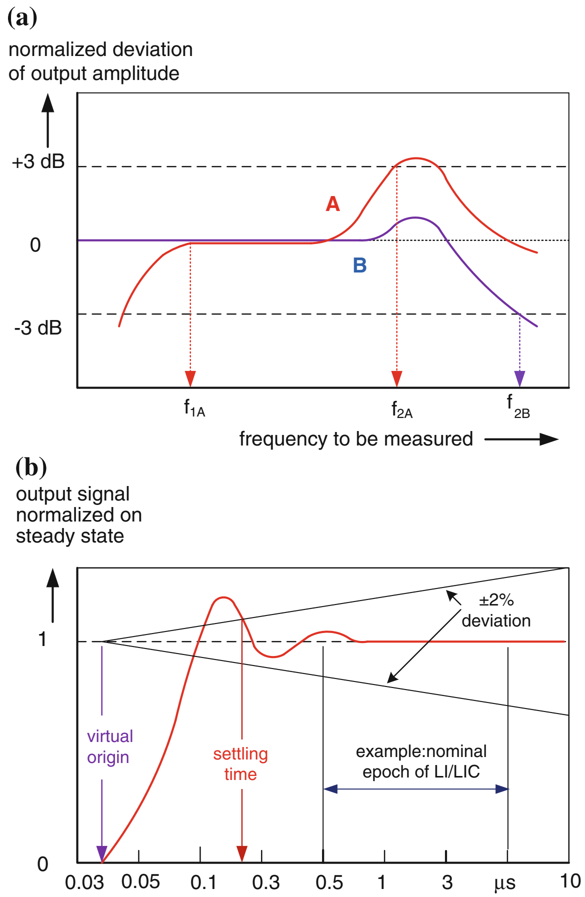


Fig. 2.12 Response of measuring systems (IEC 60060-2:2010). **a** Frequency response (*curve A* with lower and upper limit frequency, *curve B* with upper frequency limit, related to AC/DC measurement). **b** Unit step response after a step-voltage input (related to LI/SI voltage measurement, see Sect. 7.3)

drop (see Sects. 3.2.1 and 6.2.3.2), harmonics (AC, see Sect. 3.2.1) or ripple (DC, see Sect. 6.2.1).

Each HV measuring system is characterized by its *operating conditions*, as they are the rated operating voltage, the measurement ranges, the operating time (or kind and number of LI/SI voltage applications) and the environmental conditions. The dynamic behaviour of a measuring system can be described as an output signal depending on frequency (frequency response for AC and DC voltage measuring systems, Fig. 2.12a) or on a voltage step (*step response* for LI/SI voltage measuring systems, Fig. 2.12b) or by a sufficiently low uncertainty of LI/SI parameter measurement within the nominal epoch of the measuring system.

Note The nominal epoch of an impulse voltage, which will be explained more in detail in Sects. 7.2 and 7.3, is the range between the minimum and the maximum of the relevant LI/SI time parameter for which the measuring system is approved. The nominal epoch is derived from the upper and lower tolerances of the front time parameter of the impulse voltage.

All these rated values have to be supplied by the manufacturer of the measuring system (respectively its components) after type and routine tests. They should fit to the requirements and the conditions of the HV test field where the measuring system shall be applied.

Furthermore each voltage measuring system is characterized by its *scale factor*, this means the value by which the reading of the instrument must be multiplied to obtain the input quantity of the HV measuring system (voltage and time parameters). For measuring systems that display the value of the input quantity directly, the scale factor is unity. In that case—and transmission by a coaxial cable—the scale factor of the instrument is the inverse of the scale factor of the converting device. A correctly terminated coaxial cable has the scale factor unity, other types of transmission systems may have one different from unity.

The scale factor must be calibrated to guarantee a voltage measurement traceable to the National Standard of measurement. The *calibration* consists of two main parts. On one hand the value of the scale factor shall be determined including the necessary dynamic behaviour. On the other hand, the uncertainty of the HV measurement shall be estimated. When the uncertainty and the dynamic behaviour are within the limits given by IEC 60060-2:2010, the *approved measuring system* (AMS) is applicable for measurement in an accredited HV test field (see the relevant Chaps. 3, 6 and 7).

2.3.2 Approval of a HV Measuring System for an Accredited HV Test Field

A HV measuring system is qualified for the use in an accredited HV test field by several successful tests and checks described in IEC 60060-2:2010. It becomes an "*AMS*" when it has passed the following tests and checks:

- The *type test* by the manufacturer on the system or its components on sample(s) from the production shall demonstrate the correct design and conformity with the requirements. These requirements include the determination of

– the scale factor value, its linearity and its dynamic behaviour,
– its short and long term stability,
– the ambient temperature effect, i.e., the influence of the ambient temperature,
– the proximity effect, i.e., the influence of nearby grounded or energized structures,
– the software effect i.e., the influence of software on the dispersion of measurements,
– the demonstration of withstand in a HV test.

- The *routine test* on each system or each of its components by the manufacturer shall demonstrate the correct production and the conformity with the requirements by

– the scale factor value, its linearity and its dynamic behaviour and also
– the demonstration of withstand in a HV test.

- The *performance test* on the "complete measuring system" shall characterize it at its place in the HV test field "under operation conditions" by determination of

– the scale factor value, its linearity and its dynamic behaviour;
– the long term stability (from repetitions of performance tests) and
– the proximity effects.

The user is responsible for the performance tests and should repeat them annually, but at least once in 5 years (IEC 60060-2:2010).

- The *performance check* is a "simple procedure"—usually the comparison with a second AMS or with a standard air gap (see Sect. 2.3.5)—"to ensure that the most recent performance test is still valid". The user is responsible for the performance checks and should repeat them according to the stability of the AMS, but at least annually (IEC 60060-2:2010).

The mentioned single tests are described together with the uncertainty estimation in Sect. 2.3.4. For the reliable operation of the measuring system a *HV withstand test* of the converting device is necessary as a type test and, if the clearances in the laboratory of use are limited, also in a first performance test. The usually required withstand test voltage level is 110 % of the rated operating voltage of the converting device. The test procedure shall follow those typical for the relevant test voltages (Sects. 3.6, 6.5 and 7.6). In case of a converting device for outdoor application, the type test should include an artificial rain test.

This first performance test shall also include an *interference test* of the transmission system (coaxial cable) and the instrument of LI/SI measuring systems disconnected from the generator, but in their position for operation. This test generates an interference condition at the short-circuited input of the transmission system by firing the related impulse voltage generator at a test voltage representative for the highest operating voltage of the measuring system. The interference test is successful, when the measured amplitude of the interference is less than 1 % of the test voltage to be measured.

The results of all tests and checks shall be reported in the "*record of performance*" of the measuring system, which shall be established and maintained by the user of the AMS (IEC 60060-2:2010). This record shall also contain a detailed technical description of the AMS. It is the right of an inspector of an acceptance test of any apparatus to see the record of performance for the used HV measuring system.

As required in performance tests, the scale factor, the linearity and the dynamic behaviour of a complete measuring system can be determined by different methods. The most important and preferred method is the comparison with a reference measuring system (RMS), in the following called "*comparison method*" (IEC 60060-2:2010) and described in the following subsection.

Note An alternative is the "*component method*" which means the determination of the scale factor of the measuring system from the scale factors of its components (IEC 60060-2:2010). The scale factor of the components can be determined by the comparison with a reference component of lower uncertainty or by simultaneous measurements of input and output quantities or by calculation based on measured impedances. For each component, the uncertainty contributions must be estimated similar to those for the whole system qualified by the comparison method. Then these uncertainties of components must be combined to the uncertainty of measurement

2.3.3 Calibration by Comparison with a Reference Measuring System

The assigned scale factor of a measuring system shall be determined by calibration. Using the comparison method, the reading of the measuring system (AMS, index X) is compared for approval with the reading of the *reference measuring system* (RMS, index N) (Fig. 2.13). Both measuring systems indicate the same voltage V, which is the reading multiplied with the relevant scale factor F:

$$V = F_N \cdot V_N = F_X \cdot V_X \tag{2.10}$$

This simple equation delivers the scale factor of the measuring system under calibration:

$$F_X = (F_N \cdot V_N)/V_X \tag{2.11}$$

Note Because the usual symbol of the uncertainty is the letter "u" or "U" (ISO/IEC Guide 98-3:2008), for the voltage the symbol "V" is used.

For practical cases it is recommended to arrange the two dividers in the same distance from a support which is directly connected to the test voltage generator. This symmetric arrangement works well when the two voltage dividers have about the same size (Fig. 2.14). All HV and earth connections shall be without loops and as short and straight as possible.

When the rated voltage of the RMS is higher or equal to that of the system under calibration, one can assume ideal conditions, because the calibration can be performed in minimum at $g = 5$ voltage levels including the lowest and highest of the assigned operating range (Fig. 2.15). In this case the calibration includes also the linearity test.

However, as RMS are not available up to the highest test voltages, IEC 60060-2:2010 allows that the comparison may be made at voltages as low as 20 % of the assigned measurement range. An additional linearity test shows that the calibrated scale factor is applicable up to the upper limit of the measurement range which is often the rated operating voltage (see Sect. 2.3.4). In that case the symmetric

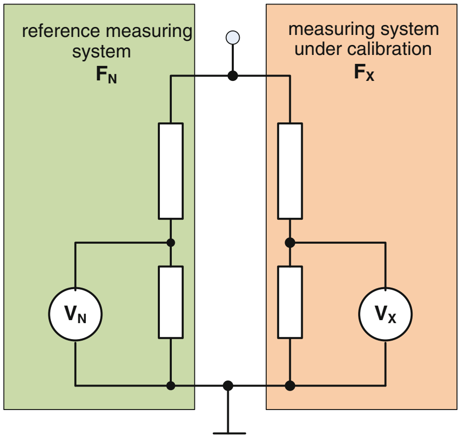


Fig. 2.13 Principle arrangement of the measuring systems for calibration using the comparison method

arrangement of the two measuring systems as in Fig. 2.14 is impossible, but one should use sufficient clearances (Fig. 2.1) that the RMS is not influenced by the often much larger system under calibration.

The used RMS shall have a calibration traceable to national and/or international standards of measurement maintained by a *National Metrology Institute* (NMI) (Hughes et al. 1994; Bergman et al. 2001). This means that RMS calibrated by a NMI or by an *accredited calibration laboratory* (ACL) with NMI accreditation are traceable to national and/or international standards. The requirements to RMS are given in Table 2.3. The calibration of RMS can be made with *transfer RMS* (TRMS) of lower uncertainty ($U_M \leq 0.5$ % for voltage and $U_M \leq 3$ % for impulse time parameter measurement). The *traceability* is maintained by inter-comparisons of RMS's of different calibration laboratories (Maucksch et al. 1996).

Calibrations can be performed by accredited HV test laboratories provided that a correctly maintained RMS and skilled personnel are available and traceability is guaranteed. This may be possible in larger test fields, the usual way is to order calibration by an ACL.

Table 2.3 Requirements to reference measuring systems (RMS)

Test voltage	DC (%)	AC (%)	LI, SI (%)	Front-chopped LIC (%)
Expanded uncertainty of **voltage** measurement U_M	1	1	1	3
Expanded uncertainty of **time parameter** measurement U_{MT}	–	–	5	5

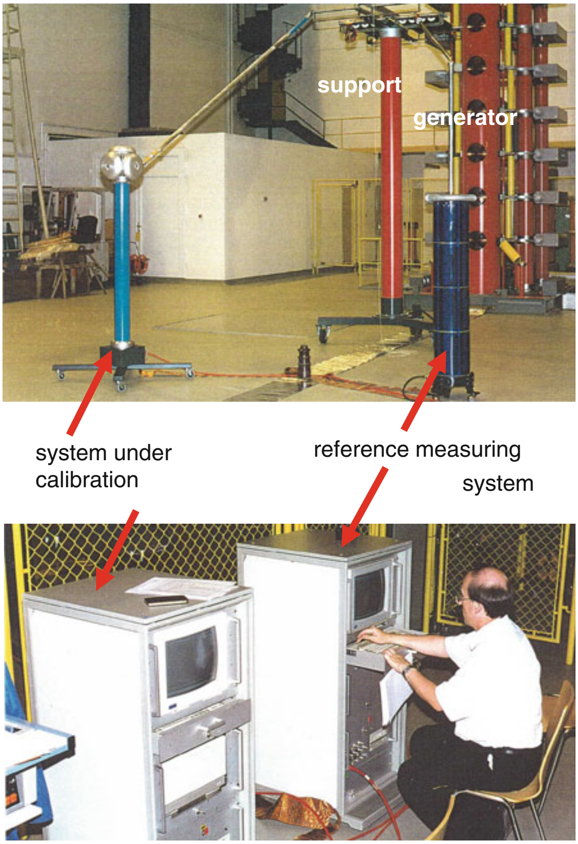


Fig. 2.14 Practical arrangement for LI voltage calibration using the comparison method (Courtesy of TU Dresden)

2.3.4 Estimation of Uncertainty of HV Measurements

The calibration process consists of the described comparisons with $n \geq 10$ applications on each of the $g = 1$ to $h \geq 5$ voltage levels provided the rated operating voltage of the RMS is not less than that of the AMS under calibration (Fig. 2.15). One application means for LI/SI voltage the synchronous readings of one impulse, for AC/DC voltage the synchronous readings at identical times. From each reading the scale factor according to Eq. (2.11) is calculated and for each voltage level V_g, its scale factor F_g is determined as the *mean value* of the n applications (usually $n = 10$ applications are sufficient):

$$F_g = \frac{1}{n}\sum_{i=1}^{n} F_{i,g}. \tag{2.12}$$

Under the assumption of a *Gauss normal distribution* the dispersion of the outcomes of the comparisons is described by the *relative standard deviation* (also called "variation coefficient") of the scale factors F_i:

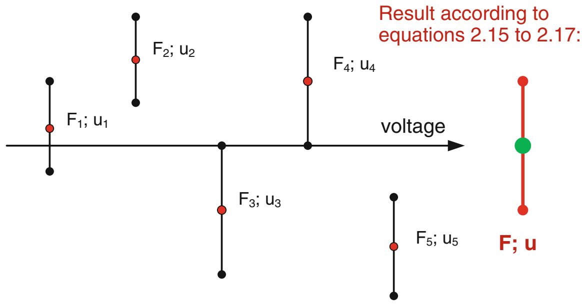


Fig. 2.15 Calibration over the full voltage range (IEC 60060-2:2010)

$$s_g = \frac{1}{F_g}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(F_{i,g} - F_g\right)^2}. \tag{2.13}$$

The standard deviation of the mean value F_g is called the "*Type A standard uncertainty* u_g" and calculated for a Gauss normal distribution by

$$u_g = \frac{s_g}{\sqrt{n}}. \tag{2.14}$$

After the comparison at all $h \geq 5$ voltage levels V_g, the calibrated *AMS scale factorF* is calculated as the mean value of the F_g:

$$F = \frac{1}{h}\sum_{g=1}^{h} F_g, \tag{2.15}$$

with a Type A standard uncertainty as the largest of those of the different levels

$$u_A = \max_{g=1}^{h} u_g. \tag{2.16}$$

Additionally one has to consider the *non-linearity* of the scale factor by a Type B contribution

Note *Type A uncertainty* contributions to the standard uncertainty are related to the comparison itself and based on the assumption that the deviations from the mean are distributed according to a Gauss normal distribution with parameters according to (2.12) and (2.13) (Fig. 2.16a), whereas the *Type B uncertainty* contributions are based on the assumption of a *rectangular distribution* of a width $2a$ with the mean value $x_m = (a_+ + a_-)/2$ and the standard uncertainty $u = a/\sqrt{3}$ (Fig. 2.16b), details are described in IEC 60060-2:2010 and below in this subsection.

$$u_{B0} = \frac{1}{\sqrt{3}} \cdot \max_{g=1}^{h}\left|\frac{F_g}{F} - 1\right|. \tag{2.17}$$

When the RMS rated operating voltage is lower than that of the AMS under calibration, IEC 60060-2:2010 allows the comparison over a limited voltage range

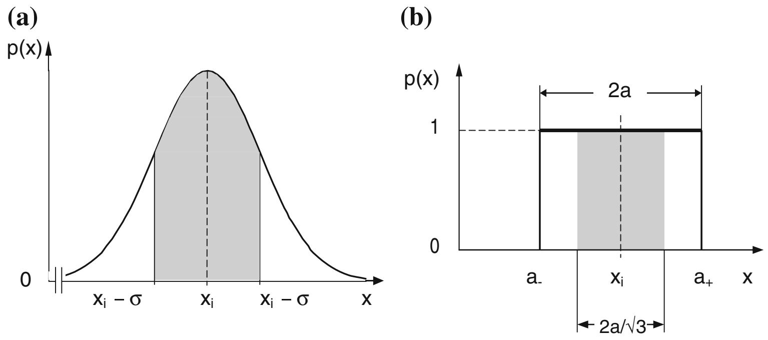
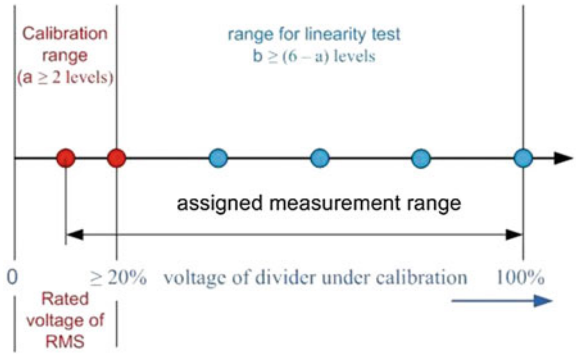


Fig. 2.16 Assumed density distribution functions for uncertainty estimation **a** Gauss normal density distribution for Type A uncertainty. **b** Rectangular density distribution for Type B uncertainty

Fig. 2.17 Calibration over a limited voltage range and additional linearity test (IEC60060-2:2010)



($V_{\mathrm{RMS}} \geq 0.2\ V_{\mathrm{AMS}}$) using only $a \geq 2$ levels. The comparison shall be completed by a *linearity test* with $b \geq (6 - a)$ levels (Fig. 2.17). Then the scale factor F is estimated by

$$F = \frac{1}{a}\sum_{g=1}^{a} F_g, \tag{2.18}$$

the standard uncertainty by

$$u_A = \max_{g=1}^{a} u_g, \tag{2.19}$$

and the non-linearity contribution of the calibration by

$$u_{B0} = \frac{1}{\sqrt{3}} \cdot \max_{g=1}^{a} \left| \frac{F_g}{F} - 1 \right|. \tag{2.20}$$

Table 2.4 Comparison at the first level $V_1 \approx 0.2\ V_r$

No. of application	RMS measured voltage (V_N/kV)	AMS measured voltage (V_X/kV)	Scale factor F_i (Eq. 2.11)
$i = 1$	201.6	200.8	1.0291
2	200.7	200.9	1.0240
3	201.4	200.9	1.0276
4	199.9	199	1.0296
5	201.2	199.9	1.0317
6	201.3	200.3	1.0301
7	200.9	200.4	1.0276
8	201.3	200.4	1.0296
9	201.2	199.9	1.0317
$n = 10$	200.6	200.7	1.0245
Result by Eqs. (2.12)–(2.16)			$\mathbf{F_1 = 1.028}$ $\mathbf{s_1 = 2.73}$ % $\mathbf{u_1 = 0.86}$

Table 2.5 Scale factor and Type A uncertainty estimation (results of comparison at the five voltage levels)

No voltage level g	V_X/V_{Xr} (%)	Scale factor F_g	Standard deviation s_g(%)	Standard uncertainty u_g(%)
$g = 1$ (Example!)	20	1.0286	2.73	0.86
2	39	1.0296	1.94	0.61
3	63	1.0279	1.36	0.43
4	83	1.0304	2.15	0.68
$h = 5$	98	1.028	1.4	0.44
Result		**New scale factor** $\mathbf{F_X = 1.0289}$		**Type A uncertainty** $\mathbf{u_A = 0.86}$ %

An additional non-linearity contribution comes from the range of the linearity test and shall be calculated as described below under "*non-linearity effect*".

Example 1 A 1,000 kV LI voltage measuring system (AMS) with a scale factor of $F_{X0} = 1{,}000$ (calibrated 3 years ago) has shown peak voltage deviations of more than 3 % by comparison with a second AMS during a performance check. Therefore, it has to be calibrated by comparison with a RMS. A 1,200 kV LI reference measuring system (RMS) is available for that calibration. It has been decided to perform the comparison at $g = 5$ voltage levels with $n = 10$ applications each. The RMS is characterized by a scale factor $F_N = 1{,}025$ and an expanded uncertainty of measurement of $U_N = 0.80$ %. Table 2.4 shows the comparison at the first level. As a result, one gets the scale factor F_1 for that first voltage level ($g = 1$) and the related standard deviation s_1 and standard uncertainty u_1.

Table 2.5 summarizes the results of all five comparison levels and as a final result the new scale factor F_X and the Type A standard uncertainty u_A according to the Eqs. (2.15) and (2.16).

The uncertainty evaluation of Type B is related to all influences different from the statistical comparison. It includes the following contributions to the uncertainty.

2.3.4.1 Non-Linearity Effect (Linearity Test)

When the AMS is calibrated over a limited range, the linearity test is used to show the validity of the scale factor up to the rated operating voltage. It is made by comparison with an AMS of sufficient rated voltage or with the input (DC) voltage of a LI/SI test voltage generator (when the AMS is related to these voltages) or with a standard measuring gap according to IEC 60052:2002 or with a field probe (see Sect. 2.3.6). It does not matter when the linearity test shows a ratio R different from the scale factor, it is only important that it is stable over the range of the linearity test (Fig. 2.18). If this is guaranteed also other methods to investigate the linearity could be applied. The maximum deviation of the investigated $g = b$ ratios $R_g = V_x/V_{CD}$ (V_{CD} is the output of comparison device) from their mean value R_m delivers the Type B estimation of the standard uncertainty (Fig. 2.18) related to non-linearity effects:

$$u_{B1} = \frac{1}{\sqrt{3}} \cdot \max_{g=1}^{b} \left| \frac{R_g}{R_m} - 1 \right|. \tag{2.21}$$

2.3.4.2 Dynamic Behaviour Effect

For the investigation of the dynamic behaviour it is recommended to determine the scale factor of the AMS at $i = k$ different values within a frequency range or within a range of impulse shapes both representative for its use (e.g., for the rated frequency range or the nominal epoch). Then the related standard uncertainty contribution is evaluated from the maximum deviation of an individual scale factor F_i from the nominal scale factor F:

$$u_{B2} = \frac{1}{\sqrt{3}} \cdot \max_{i=1}^{k} \left| \frac{F_i}{F} - 1 \right|. \tag{2.22}$$

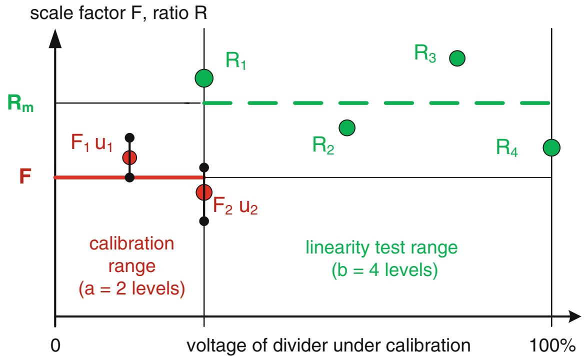
The dynamic behaviour can also be investigated by the unit step response method. For details see Sect. 7.4.1.

2.3.4.3 Short-Term Stability Effect

The short-term stability is often determined by the *self-heating* of the AMS, especially its converting device. The test shall be performed at rated operating voltage, it starts with the determination of the scale factor F_1 when the test voltage is reached and is terminated with a new determination of the scale factor F_2 when the pre-defined test time, usually the anticipated *time of use* or the assigned operating time, is over:

$$u_{B3} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_2}{F_1} - 1 \right|. \tag{2.23}$$

Fig. 2.18 Linearity test with a linear device in the extended voltage range (IEC 60060-2:2010)



The short time contribution to the measuring uncertainty should be given in the manufacturer's data of components.

2.3.4.4 Long-Term Stability Effect

A starting value for the contribution of the long-term stability may also be given by the manufacturer. Then it can also be determined for the time of use T_{use} from the change of the scale factor within the time of two *performance checks* (from F_1 to F_2 made at times T_1 respectively T_2, often the projected time of use is $T_{use} = T_2 - T_1$):

$$u_{B4} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_2}{F_1} - 1 \right| \cdot \frac{T_{use}}{T_2 - T_1}. \tag{2.24}$$

2.3.4.5 Ambient Temperature Effect

Usually the measuring system is specified for a certain temperature range. The scale factor is determined for the minimum and maximum temperature of that range. The larger deviation F_T from the nominal scale factor F is used to estimate the standard uncertainty contribution:

$$u_{B5} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_T}{F} - 1 \right|. \tag{2.25}$$

Often the uncertainty contribution related to the temperature effect within the specified temperature range may be taken from manufacturer's data.

2.3.4.6 Proximity Effect

The uncertainty contribution due to nearby earthed structures my be determined from the scale factors F_{min} and F_{max} at minimum and maximum distances from those structures:

$$u_{B6} = \frac{1}{\sqrt{3}} \cdot \left| \frac{F_{\max}}{F_{\min}} - 1 \right|. \tag{2.26}$$

The proximity effect for smaller HV measuring systems is often investigated by the manufacturer of the converting device and can be taken from the manual.

2.3.4.7 Software Effect

When digital measuring instruments, especially digital recorders, are used, a correct measurement is assumed when *artificial test data* (which are given in IEC 61083-2:2011) are within certain tolerance ranges, also given in IEC 61083-2:2011. It should not be neglected that there may be remarkable standard uncertainty contributions caused by that method. The assumed uncertainty contribution by the software is only related to the maximum width of these tolerance ranges T_{oi} given in IEC 61083-2:

$$u_{B7} = \frac{1}{\sqrt{3}} \cdot \max_{i=1}^{n}(T_{\mathrm{oi}}). \tag{2.27}$$

Note Only those tolerance ranges T_{oi} of artificial test data similar to the recorded impulse voltage must be taken into consideration.

Example 2 The AMS characterized in the first example is investigated with respect to the Type B standard uncertainty contributions. For the uncertainty estimation of the calibration also the standard uncertainties of the RMS which are not included in its measuring uncertainty must be considered. Table 2.6 summarizes both and mentions the source of the contribution.

Table 2.6 Type B uncertainty contributions

Uncertainty contribution	Symbol of contribution	Uncertainty contribution for RMS	Uncertainty contribution for AMS
Non-linearity effect Eq. (2.22)	u_{B1}	included in calibration: $u_N = U_N/2 = 0.4\ \%$	included in calibration u_A
Dynamic behaviour effect Eq. (2.23)	u_{B2}	included in calibration	0.43 % from deviation within nominal epoch
Short-term stability effect Eq. (2.24)	u_{B3}	included in calibration	0.24 % from deviation before and after a 3 h test
Long-term stability effect Eq. (2.25)	u_{B4}	included in calibration	0.34 % from consecutive performance tests
Ambient temperature effect Eq. (2.26)	u_{B5}	0.06 % because outside of specified temperature range	0.15 % from manufacturers data
Proximity effect Eq. (2.27)	u_{B6}	included in calibration	can be neglected because of very large clearances
Software effect Eq. (2.28)	u_{B7}	included in calibration	can be neglected because no digital recorder applied

2.3.4.8 Determination of *expanded uncertainties*

IEC 60060-2:2010 recommends a simplified procedure for the determination of the expanded uncertainty of the scale factor calibration and of the HV measurement. It is based on the following assumptions which meet the situation in HV testing:

- *Independence*: The single measured value is not influenced by the preceding measurements.
- *Rectangular distribution*: Type B contributions follow an rectangular distribution.
- *Comparability*: The largest three uncertainty contributions are of approximately equal magnitude.

Note IEC 60060-2:2010 does not require the application of this simplified method, all procedures in line with the ISO/IEC Guide 98-3:2008 (GUM) are also applicable. In the Annexes A and B of IEC 60060-2:2010 a further method directly related to the GUM is described.

The relation between the standard uncertainty and the calibrated new scale factor can be expressed by the term ($F \pm u$) which characterizes a range of possible scale factors (Not to forget, F is a mean value and u is the standard deviation of this mean value!). Under the assumption of a Gauss normal density distribution (Fig. 2.17a) this range covers 68 % of all possible scale factors. For a higher confidence, the calculated standard uncertainty can be multiplied by a "covering factor" $k > 1$. The range ($F_X \pm k \cdot u$) means the scale factor plus/minus its "expanded uncertainty" $U = k \cdot u$. Usually a coverage factor $k = 2$ is applied which covers a confidence range of 95 %.

To determine first the *expanded uncertainty of the calibration*U_{cal}, the standard uncertainty u_N of measurement of the RMS from its calibration, the Type A standard uncertainty from the comparison and the Type B standard uncertainties related to the reference measuring system are combined according to the geometric superposition:

$$U_{\text{cal}} = k \cdot u_{\text{cal}} = 2 \cdot \sqrt{u_N^2 + u_A^2 + \sum_{i=0}^{N} u_{\text{BiRMS}} 2}. \qquad (2.28)$$

The *expanded uncertainty of calibration* appears on the calibration certificate together with the new scale factor. But in case of a HV acceptance test, the *expanded uncertainty of a HV measurement* is required. When the AMS is calibrated and all possible ambient conditions are considered (ambient temperature range, range of clearances, etc.), then the expanded uncertainty of HV measurement can be pre-calculated by the standard uncertainty of the calibration u_{cal} and the Type B contributions of the AMS u_{BiAMS}

$$U_M = k \cdot u_M = 2 \cdot \sqrt{u_{\mathrm{cal}}^2 + \sum_{i=0}^{N} u_{\mathrm{BiAMS}}^2} \cdot \qquad (2.29)$$

The pre-calculated expanded uncertainty of measurement should also be mentioned on the calibration certificate together with the pre-defined conditions of use. The user of the HV measuring system has only to estimate additional uncertainty contributions when the HV measuring system has to operate outside the conditions mentioned in the calibration certificate.

Example 3 For the calibrated AMS the expanded uncertainties of calibration and HV measurement shall be calculated under the assumption of certain ambient conditions mentioned in the calibration certificate. The calculation uses the results of the two examples above:

Calibration results:		
Reference measuring system (RMS):		
RMS: measuring uncertainty	$U_N = 0.80\ \%$	$u_N = 0.4\ \%$
RMS: temperature effect		$u_{B5} = 0.06\ \%$
Calibration by comparison		$u_A = 0.86\ \%$
Expanded calibration uncertainty (95 % confidence, $k = 2$)		$U_{\mathrm{cal}} = 1.90\ \%$
Standard uncertainty of calibration		$u_{\mathrm{cal}} = 0.95\ \%$
HV measurement:		
AMS: non-statistical influences		$u_{B2} = 0.43\ \%$
		$u_{B3} = 0.24\ \%$
		$u_{B4} = 0.\ 4\ \%$
		$u_{B5} = 0.15\ \%$
Expanded uncertainty of measurement (95 % confidence)		$U_M = 2.26\ \%$
Precise measurement result:		$V = V_x\ (1 \pm 0.0226)$

The HV measuring system shall be adjusted according to its new scale factor of $F = 1.0289$ (Table 2.5), possibly with a change of the instrument scale factor to maintain the direct reading of the measured HV value on the monitor. IEC 60060-2:2010 requires an uncertainty of HV measurement of $U_M \leq 3\ \%$. Because of $U_M = 2.26\ \% < 3\ \%$ (Example 3), the system can be used for further HV measurement. But it is recommended to investigate the reasons for the relatively high expanded uncertainty U_M for improvement of the measuring system.

2.3.4.9 Uncertainty of Time Parameter Calibration

IEC 60060-2:2010 (Sect. 5.11.2) describes a comparison method for the estimation of the expanded uncertainty of time parameter measurement. Furthermore in its

Annex B.3, it delivers an additional example for the evaluation according to the ISO/IEC Guide 98-3:2008. Instead of the consideration of the dimensionless scale factor for voltage measurement, the method applies to the time parameter (e.g., the LI front time T_{1X}) itself, considers the error of the time measurement T_{1N} by the reference measuring system as negligible and gets from the comparison directly the mean error ΔT_1,

$$\Delta T_1 = \frac{1}{n}\sum_{i=1}^{n}\left(T_{1X,i} - T_{1N,i}\right), \tag{2.30}$$

the standard deviation

$$s(\Delta T_1) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(\Delta T_{1,i} - \Delta T_1\right)^2}, \tag{2.31}$$

and the Type A standard uncertainty

$$u_A = \frac{s(\Delta T_1)}{\sqrt{n}}. \tag{2.32}$$

The Type B contributions to the measuring uncertainty of time parameters are determined as maximum differences between the errors of individual measurements and the mean error of the time parameter T_1 for different LI front times, e.g., the two limit values of the nominal epoch of the measuring system.

For external influences, the procedure of the Type B uncertainty estimation follows the principles described above for voltage measurement Eqs. (2.22–2.27). For the expanded uncertainty of time calibration and time parameter measurement an analogous application of Eqs. (2.28) and (2.29) is recommended.

A performance test includes the calibration of the scale factor, for impulse voltages also of the time parameters, and the described full set of tests of the influences on the uncertainty of measurement. The data records of all tests shall be included to the record of performance. The comparison itself and its evaluation can be aided by computer programs (Hauschild et al. 1993).

2.3.5 HV Measurement by Standard Air Gaps According to IEC 60052:2002

The breakdown voltages of uniform and slightly non-uniform electric fields, as e.g., those between sphere electrodes in atmospheric air, show high stability and low dispersion. Schumann (1923) proposed an empirical criterion to estimate the critical field strength at which self-sustaining electron avalanches are ignited. If modified, this criterion can also be used to calculate the breakdown voltage V_b of uniform fields versus the gap spacing S. For a uniform electric field in air at standard conditions the breakdown voltage can be approximated by the empirical equation

$$V_b/\mathrm{kV} \; = 24.4\left[S + \left(\frac{S}{13.1\,\mathrm{cm}}\right)^{0.5}\right]. \tag{2.33}$$

This equation is applicable for sphere gaps if the spacing is less than one-third of the sphere diameter Fig. (2.19).

Based on such experimental and theoretical results, *sphere-to-sphere gaps* are used for peak voltage measurement since the early decades of the twentieth century (Peek 1913; Edwards and Smee 1938; Weicker and Hörcher 1938; Hagenguth et al. 1952) and led to the first standard of HV testing, the present IEC 60052:2002. Meanwhile it is fully understood that this applicability is based on the so-called streamer breakdown mechanism, e.g., Meek (1940), Pedersen (1967), and breakdown voltage-gap distance characteristics of sphere gaps can also be calculated with sufficient accuracy (Petcharales 1986).

For a long time *measuring sphere gaps* with gap diameters up to 3 m formed the impression of HV laboratories. But the voltage measurement by sphere gaps is connected with the breakdown of the test voltage therefore their application is not simple. Furthermore they need a lot of clearances (see below), well maintained clean surfaces of the spheres and atmospheric corrections (see Sect. 2.1.2) for measurement according to the standard.

Today they are not used for daily HV measurement and do not play the same important role in HV laboratories as in the past. Their main application is for *performance checks* of AMSs (see Sect. 2.3.2) or linearity checks (see Sect. 2.3.4). For acceptance tests on HV apparatus the inspector may require a check of the applied AMS by a sphere gap to show that it is not manipulated. For these applications mobile measuring gaps with sphere diameters $D \leq 50$ cm are sufficient.

The IEC Standard on voltage measurement by means of sphere gaps has been the oldest IEC standard related to HV testing. Its latest edition IEC 60052 Ed.3:2002 describes the measurement of AC, DC, LI and SI test voltage with horizontal and vertical sphere-to-sphere gaps with sphere diameters $D = (2 \ldots 200$ cm) and one of the spheres earthed. The spacing S for voltage measurement is required $S \leq 0.5\,D$, for rough estimations it can be extended up to $S = 0.75\,D$. The surfaces shall be smooth with maximum roughness below 10 μm and free of irregularities in the region of the sparking point. The curvature has to be as uniform as possible, characterized by the difference of the diameter of no more than 2 %. Minor damages on that part of the hemispherical surface, which is not involved in the breakdown process, do not deteriorate the performance of the measuring gap. To avoid erosion of the surface of the sphere after AC and DC breakdowns, pre-resistors may be applied of 0.1–1 M′Ω.

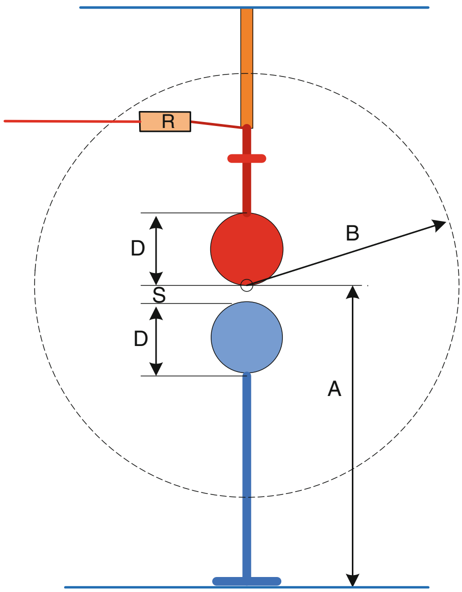


Fig. 2.19 Vertical measuring sphere gap (explanations in the text)

Surrounding objects may influence the results of sphere gap measurements. Consequently the dimensions and *clearances* for standard air gaps are prescribed in IEC 60052 and shown in Figs. 2.19 and 2.20. The required range of the height A above ground depends on the sphere diameter, and is for small spheres $A = (7 \ldots 9)\ D$ and for large spheres $A = (3 \ldots 4) \cdot D$. The clearance to earthed external structures depends on the gap distance S, and shall be between $B = 14\ S$ for small and $B = 6\ S$ for large spheres.

The dispersion of the breakdown voltage of a measuring gap depends strongly from the availability of a free starting electron, especially for gaps with $D \leq 12.5$ cm and/or measurement of peak voltages $U_p \leq 50$ kV. Starting electrons can be generated by photo ionization (Kuffel 1959; Kachler 1975). The necessary high energy radiation may come from the far ultra-violet (UVC) content of nearby corona discharges at AC voltage, or from the breakdown spark of the open switching gaps of the used impulse generator, or a special mercury-vapour UVC lamp with a quartz tube.

Note In the past, even a radioactive source inside the measuring sphere has been applied. For safety reasons this is forbidden now.

Table 2.7 gives the relationship of the measured breakdown voltage U_b depending on the distance S between electrodes for some selected sphere diameters $D \leq 1$ m which are mainly used for the mentioned checks, for other sphere diameters see IEC 60052:2002. A voltage measurement with a sphere gap means to establish a relation between an instrument at the power supply input of the HVG (e.g., a primary voltage measurement at the input of a test transformer) and the known breakdown voltage of the standard measuring gap in the HV circuit

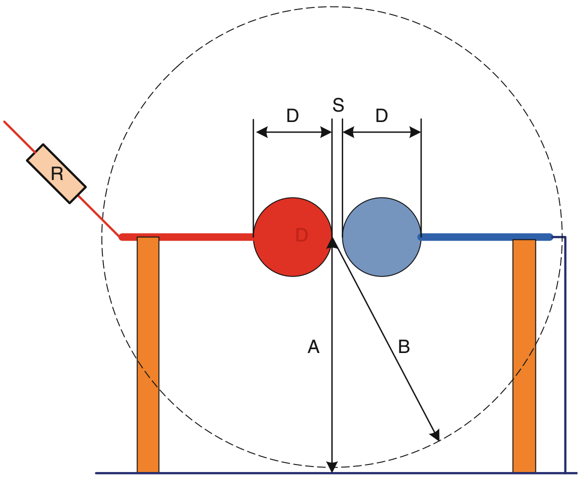


Fig. 2.20 Horizontal measuring sphere gap

depending on its gap distance *D* (Table 2.7). This is similar to the calibration by comparison (Sect. 2.3.3).

For *AC voltage measurement* a progressive stress test (see Sect. 2.4) delivers 10 successive breakdown voltage readings by the instrument. Their mean value (Eq. 2.12) and the relative standard deviation (Eq. 2.13) are determined. The voltage shall be raised sufficiently slowly to allow accurate readings. The mean value characterizes the breakdown voltage according to the gap parameters (*D*, *S*). When the standard deviation is ≤ 1 %, one can assume that the measuring gap was correctly maintained and the relative expanded uncertainty of measurement is ≤ 3 %.

Note With $n = 10$ measurements and a standard deviation of 1 % one gets a standard uncertainty of $u = 0.32$ % (Eq. 2.14). This means there are about 1.2 % for the other contributions to the standard uncertainty when the expanded uncertainty ($k = 2$) shall be ≤ 3 % (Eq. 2.29).

For *LI/SI voltage measurement*, the pre-selected breakdown voltages (*D*, *S* in Table 2.7) are compared e.g., with charging voltage of the impulse voltage generator. The 50 % breakdown voltages U_{50} are determined in a multi-level test of $m = 5$ voltage levels with $n = 10$ impulse voltages each (see Sect. 2.4), and the corresponding reading is taken as the pre-selected reading. When the evaluated standard deviation is within 1 % for LI and 1.5 % for SI voltages it is assumed that the measuring gap works correctly.

For *DC voltage measurement*, sphere gaps are not recommended because external influences as dust or small fibres are charged in a DC field and cause a high dispersion. Therefore, a *rod–rod measuring gap* shall be applied if the humidity is not higher than 13 g/m^3 (Feser and Hughes 1988; IEC 60052:2002). The rod electrodes of steel or brass should have a square cross section of 10–25 mm for each side and sharp edges. When the gap distance *S* is between 25 and 250 cm the breakdown is caused by the development of a streamer discharge

Table 2.7 Peak value of breakdown voltages of selected standard sphere gaps

Gap distance S/mm	50 % breakdown voltage V_{b50}/kV at sphere diameter D/mm[b]							
	100		250		500		1,000	
	AC, DC[a], −LI, −SI	+LI, +SI	AC, DC[a], −LI, −SI	+LI, +SI	AC, DC[a], −LI, −SI	+LI, +SI	AC, DC[a], −LI, −SI	+LI, +SI
5	16.8	16.8						
10	31.7	31.7	31.7	31.7				
15	45.5	45.5	45.5	45.5				
20	59	59.0	59.0	59.0	59.0	59.0		
30	84	85.5	86.0	86.0	86.0	86.0	86.0	86.0
50	123	130	137	138	138	138	138	138
75	(155)[c]	(170)	195	199	202	202	203	203
100			244	254	263	263	266	266
150			(314)	(337)	373	380	390	390
200			(366)	(395)	460	480	510	510
300					(585)	(620)	710	725
400					(670)	(715)	875	900
500							1,010	1,040
600							(1,110)	(1,150)
750							(1,230)	(1,280)

Explanations:
[a] For measurement of DC test voltages >130 kV standard sphere gaps are not recommended, apply rod–rod gaps and see Eq. (2.34)
[b] For correctly maintained standard sphere gaps, the expanded uncertainty of measurement of AC, LI and SI test voltages is assumed to be $U_M \approx 3\ \%$ for a confidence level of 95 %. There is no reliable value for DC test voltages
[c] The values in brackets are for information, no level of confidence is assigned to them

of a required average voltage gradient $e = 5.34$ kV/cm. Then the breakdown voltage can be calculated by

$$V_b/\text{kV} = 2 + 5.34 \cdot \text{S/cm}. \tag{2.34}$$

The length of the rods in a vertical arrangement shall be 200 cm, in a horizontal gap 100 cm. The rod–rod arrangement should be free of PD at the connection of the rods to the HV lead, respectively to earth. This is realized by toroid electrodes for field control. For a horizontal gap the height above ground should be ≥400 cm. The test procedure is as that for AC voltages described above.

2.3.6 Field Probes for Measurement of High Voltages and Electric Field Gradients

The ageing of the insulation and thus the reliability of HV apparatus is mainly governed by the maximum electrical field strength. Even if the field distribution in dielectric materials can well be calculated based on the Maxwell equations using advanced computer software, the validity of the theoretical results should be validated experimentally. For this purpose *capacitive sensors*, commonly referred to as field probes, can be used. The field distribution, however, may substantially be affected by the presence of such field probes which should thus be designed as small as possible to minimize the field distortion und thus the inevitable measuring uncertainty (Les Renardieres Group 1974; Malewski et al. 1982). In specific cases, however, field probes can be designed such that the field is not disturbed, as in the case of coaxial electrode configurations representative for bushings, power cables and SF_6 switchgears. Moreover, field probes can be integrated in the earth electrode of a plane-to-plane electrode arrangement of Rogowski profile, as sketched in Fig. 2.21. Under this condition the voltage applied to the HV electrode can simply be deduced from the field strength at the sensing electrode.

The fundamental measuring principle is based on the first Maxwell equation which reads:

$$\mathrm{rot}\,\vec{H} = \partial\vec{D}/\partial t + \vec{G}, \tag{2.35}$$

with $\vec{H}$—vector of the magnetic field strength, $\vec{D}$—vector of the electric displacement flux density, $\vec{G}$—vector of the current density at the sensor electrode.

For gaseous dielectrics the conductivity is extremely low so that the second term in Eq. (2.35) can be neglected:

$$\mathrm{rot}\,\vec{H} = \partial\vec{D}/\partial t, \tag{2.36a}$$

In contrast to this the conductivity of the sensing electrode is extremely high so that for this case the first term in Eq. (2.35) can be neglected:

$$\mathrm{rot}\,\vec{H} = \vec{G}, \tag{2.36b}$$

Combining the Eqs. (2.36a and 2.36b) and substituting the density of the displacement flux by the electrical field strength, i.e., $\vec{D} = \varepsilon \cdot \vec{E}$, one gets

$$\vec{G} = \partial\vec{D}/\partial t \;=\; \varepsilon \cdot \partial\vec{E}/\partial t, \tag{2.37}$$

with ε—permittivity of the dielectric between both electrodes.

For the here considered homogenous field configuration the field gradient occurs perpendicular to the surface of the sensing electrode. Thus, instead of the vector presentation the simple scalar presentation valid for one dimensional configurations is applicable. Consequently the current $I(t)$ captured by the sensor can simply be expressed by the current density G multiplied with the area A of the sensing electrode:

$$I(t) = A \cdot G = A \cdot \varepsilon \cdot \mathrm{d}E(t)/\mathrm{d}t. \tag{2.38}$$

To convert the current induced at the sensor surface into an equivalent voltage signal $V_m(t)$ it is a common practice to connect the sensor via a measuring

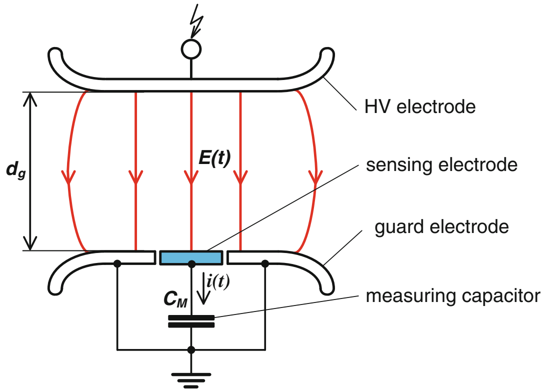


Fig. 2.21 Principle of a field probe for measurements of high alternating voltages

capacitance C_m to earth potential, see Fig. 2.21. As this provides a capacitive voltage divider, the time-dependent voltage $V_h(t)$ applied to the HV electrode can simply be determined from the voltage $V_m(t)$ measurable across C_m using the following equation:

$$V_h(t) = \frac{d_{g \cdot C_m}}{A \cdot \varepsilon} \cdot V_m(t) = S_f \cdot V_m(t), \tag{2.39}$$

with S_f—scale factor, d_g—gap distance.

In principle the measuring capacitance C_m shown in Fig. 2.21 could also be replaced by a resistor, in the following denoted as R_m. Under this condition one gets from Eq. (2.38):

$$V_m(t) = R_m \cdot A \cdot \varepsilon \cdot \mathrm{d}E(t)/\mathrm{d}t. \tag{2.40}$$

Based on this, the peak voltage V_{hp} applied to the top electrode can be determined by

$$V_{\mathrm{hp}} = \frac{d_g}{R_m \cdot A \cdot \varepsilon} \cdot \int_0^t V_m(t)\mathrm{d}t = \frac{d_g}{R_m \cdot A \cdot \varepsilon \cdot 2\pi f} \cdot V_{\mathrm{mp}} = S_f \cdot V_{\mathrm{mp}} \tag{2.41}$$

From this equation follows that the scale factor S_f is inversely proportional to the test frequency f, so that not only R_m but also the test frequency f must be exactly known, to determine the peak value of the applied high voltage from the measured low voltage, where harmonics should not appear because they may cause severe measuring errors.

Example Consider an arrangement according to Fig. 2.21 in ambient air with $\varepsilon_0 = 8.86$ pF/V m. Assuming a gap distance $d_g = 10$ cm and an area of the sensing electrode $A_s = 10\ \mathrm{cm}^2$ as well as a capacitance $C_m = 2$ nF, one gets the following scale factor:

$$S_f = \frac{d_g \cdot C_m}{A \cdot \varepsilon_0} = \frac{(10\,\mathrm{cm}) \cdot (2\,\mathrm{nF})}{(10\,\mathrm{cm}^2) \cdot (8.86\,\mathrm{pF/m})} = 22.6 \times 10^3.$$

If, for instance, a low voltage of $V_m = 5$ V across C_m is measured, the applied high voltage becomes $V_m = 113$ kV. Substituting the capacitor C_m by a measuring resistor of $R_m = 500$ kΩ and assuming a test frequency $f = 50$ Hz, one gets the following scale factor:

$$S_f = \frac{d_g}{R_m \cdot A_s \cdot \varepsilon_0 \cdot 2\pi f} = 18 \times 10^3.$$

The curves plotted in the graph according to Fig. 2.22, which are based on the above calculations, enable a simple determination of the applied high voltage V_h from the measured low voltage V_m. In this context it has to be taken into account that the scale factor is dependent on the test frequency, if a measuring resistor is used.

The main disadvantage of the arrangement shown in Fig. 2.21 is that it is only capable for measuring the field gradients occurring adjacent to earth potential. To measure also arbitrarily oriented field vectors in the space between HV and LV electrodes, *spherical sensors* are employed (Feser and Pfaff 1984). As illustrated in Fig. 2.23a, the surface of such a sphere is subdivided into six partial sensors to receive the three cartesian components of the electromagnetic field. To minimize the inevitable field disturbance caused by the metallic probe, it is battery powered and the whole components required for signal processing are integrated in the hollow sphere. The evaluated data are transmitted to earth potential via a fiber optic link. An essential benefit of the spherically shaped probe is that the admissible radius depending on the field strength to be measured can be calculated without large expenditure.

Practical realized spherical field probes are capable for measuring field strengths up to about 1 kV/cm where the measuring frequency ranges between approx. 20 Hz and 100 MHz. The application is not only restricted to field strength measurements. If calibrated with a reference measuring system it can also be employed for high voltage measurements if the field is free of space charges which could be caused by corona discharges.

As the field probe provides a capacitive sensor it has to be taken into account that the induced charge and thus the measurable current $i(t)$ is a consequence of the displacement flux which is correlated with the time dependent field strength $E(t)$. Thus, only time dependent voltages, such as LI, SI, AC and other transients, induce a measurable displacement current. To measure also DC voltages, the desired alternating displacement current could be generated if the sensing electrode is periodically shielded by a rotating electrode connected to earth potential. This approach, schematically shown in Fig. 2.23b, is applied by the so-called f*ield mill* (Herb et al. 1937; Kleinwächter 1970). Here the sensing electrode is established by two half-sectioned discs providing the measuring electrodes, which must be well isolated from each other. The vane electrode is connected to the guard electrode on earth potential. If the vane electrode is rotating in front of the measuring electrodes, an alternating displacement flux exposes these both electrodes

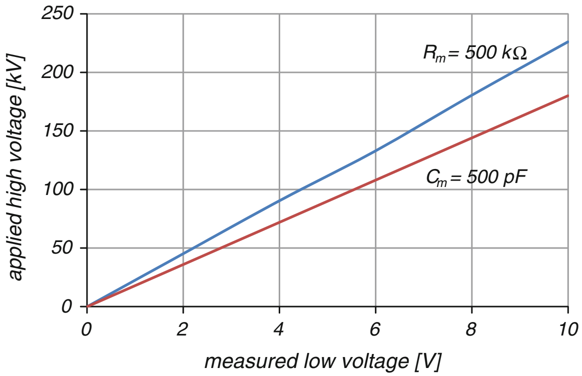


Fig. 2.22 Applied high voltage versus low voltage measurable across a capacitive respectively a resistive measuring impedance using parameters given in the text

and induces thus an alternating current. This is correlated with the electrostatic field strength on the electrode surface which is usually indicated by means of a high sensitive amplifier, where the input impedance must be extremely high.

Another option for the measurement of high DC voltages by means of a field probe is the replacement of the electrical method by a mechanical one. That means the measuring impedance C_m shown in Fig. 2.21 is replaced by a sensitive force measurement system, as first applied by Kelvin in 1884 for absolute measurement of DC voltages. The principle applied is based on the Coulomb law discovered in 1785. For a homogeneous field the force attracting the sensing electrode of an area A if subjected to a field gradient E can be expressed by:

$$F_e = \frac{1}{2} \cdot \varepsilon \cdot A \cdot E^2. \tag{2.42}$$

Example If, for instance, a voltage of $V_h = 100$ kV is applied to the top electrode and the gap distance is $d_g = 10$ cm, then the field strength at the sensing electrode achieves 10 kV/cm. Inserting these values in Eq. (2.42), the force attracting the sensing electrode becomes $F_e \approx 3.5 \times 10^{-2}$ N $\approx$ 3.6 p.

The torsion due to the attracted sensing electrode is usually amplified and indicated by a spot light and mirror system. As the electric force is proportional to the quadratic value of the field gradient and thus also proportional to the quadratic value of the applied test voltage, the indication is independent from the polarity. Thus, *electrostatic voltmeters* are capable not only for DC voltage measurements but also for measuring the r.m.s. value of HVAC test voltages, as treated in Sect. 3.4.

2.4 Breakdown and Withstand Voltage Tests and Their Statistical Treatment

Electrical discharges and breakdown of insulations are stochastic processes which must be described by statistical methods. This subsection gives an introduction to

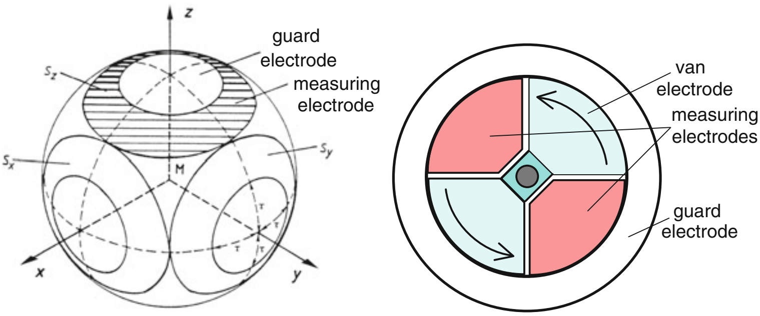


Fig. 2.23 Field probes using fixed and rotating electrodes

the planning, performing and evaluation of HV tests on a statistical basis. It describes tests with voltages increasing up to the breakdown ("progressive stress method") and with multiple application of pre-given voltages and estimation of breakdown probabilities ("multiple level method", "up-and-down method"). Life-time tests of insulation are performed with pre-given voltages, but progressive test durations and can be evaluated accordingly. Also standardized HV withstand tests are described and valuated from the viewpoint of statistics. The subsection submits first tools for the application of statistical methods and supplies hints to the special literature, e.g., (Hauschild and Mosch 1992).

2.4.1 Random Variables and the Consequences

The phenomena of *electrical discharges*—as most others in nature, society and technology—are based on stochastic processes and characterized by their randomness (Van Brunt 1981; Hauschild et al. 1982). This is often ignored and only an average trend is considered in order to interpret a relationship being investigated. Quite often, however, it is not the mean value, but an extreme value that determines the performance of a system. In technology this is often taken into account by applying a "safety factor". A rather better approach is the statistical description of stochastic phenomena. Therefore, *HV tests* shall be selected, performed and evaluated on a statistical basis: They are *random experiments (trials)* and described by *random variables* (sometimes also called "random variates").

When a pre-given *constant voltage stress*—e.g., a certain LI test voltage—is applied to an insulation—e.g., an air gap—one can observe the random event "breakdown" (A) or the complimentary event "withstand"(A^*). The relative breakdown frequency$h_n(A)$ is the relation between the number of breakdowns k and the number of applications n

$$h_n(A) = k/n. \tag{2.43}$$

The relative *withstand frequency* follows to

$$h_n(A*) = (n - k)/n = 1 - h_n(A). \tag{2.44}$$

The relative frequency depends on the number of performed tests (often called *sample size*) and the respective test series as shown for the breakdown frequency in Fig. 2.24. The relative frequencies vary around a fixed value and reach it as the limiting value "*breakdown probability*" p:

$$\lim_{n\to\infty} h_n(A) = p. \tag{2.45}$$

The *probability of a withstandq* follows accordingly

$$\lim_{n\to\infty} h_n(A*) = q. \tag{2.46}$$

Because a characteristic value of withstand cannot be measured ("Nothing happens!"), the withstand probability is determined from the complementary breakdown probability $q = 1 - p$. Consequently the statistical definition of a withstand voltage is a voltage which causes a breakdown with low probability, usually $p \leq 0.10$. The relative breakdown frequency is a *point estimation* of the breakdown probability.

The larger the number of applications for the estimation of the frequency, the better is the adaptation of the estimate to the true, but unknown probability (Fig. 2.24). A confidence estimation delivers a feeling for the accuracy of the estimation by the width of the calculated confidence region. This region covers the true but unknown value of p with a certain *confidence level*, e.g., $\varepsilon = 95\ \%$. From the sample the upper and the lower limit of the confidence region are determined on the basis of the assumption of a theoretical distribution function, in this case based on the *binomial distribution function* and the Fisher (F) distribution as test distribution.

Explanation: The binomial distribution is based on two complementary events A and A^* (as breakdown and withstand) occurring with the known probabilities p and q (Bernoulli trial). The binomial distribution indicates the probability $P(X = k)$ with which the event A will occur k-times in n independent trials.

$$P(X = k) = \binom{n}{k} p^k (1 - p)^{n-k} \tag{2.47}$$

where $\mathrm{k} = 0, 1, 2, \ldots, n$ and

$$\binom{n}{k} = \frac{n!}{k! \cdot (n-k)!} = \frac{n \cdot (n-1) \cdot \ldots (n-k+1)}{1 \cdot 2 \cdot 3 \cdot \ldots \cdot k}$$

Figure 2.25 shows the 95 % *confidence limits* depending on the relative breakdown frequency and the number of applications (sample size).

Example For $h_n(A) = 0.7$ and $n = 10$ applications, Fig. 2.25 delivers the lower limit $p_l = 0.37$ and the upper limit $p_u = 0.91$. With a statistical confidence $\varepsilon = 95\ \%$, the real probability is within a range of $0.37 \leq p \leq 0.91$. For $n = 100$ applications one would get

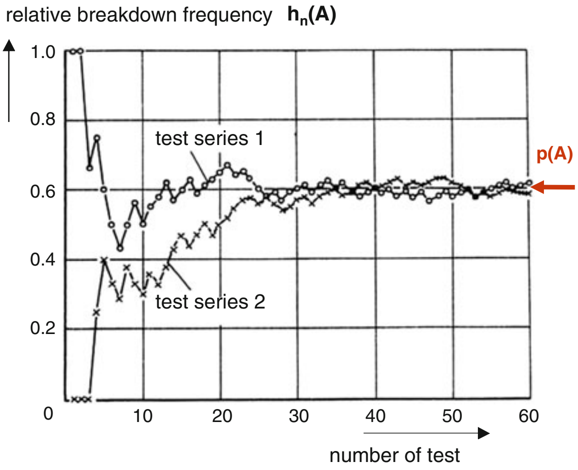


Fig. 2.24 Relative breakdown frequencies of two test series depending on the number of tests performed

the much smaller range $0.60 \leq p \leq 0.78$. Again, with increasing sample size the estimation becomes better, this means the confidence region becomes smaller.

When a constant voltage test has been performed for the estimation of the breakdown probability, it must be checked whether the test is "independent" or not. *Independence* means that the previous voltage applications have no influence on the result of the application under consideration. This can be shown by the investigation of the trend (Table 2.8). A sample of $n = 100$ is subdivided into five samples of $n^* = 20$ each. If the relative frequencies of the sub-samples scatter around that of the whole sample, it could be considered as independent (case a). If there is a clear trend (case b) it would be dependent and any statistical evaluation is forbidden. Independence can only be ensured due to an improvement of the test procedure, e.g., breaks of sufficient duration between single stresses. Further details of constant voltage tests are described in (Hauschild and Mosch 1992).

There is a second group of HV breakdown tests with increasing stress, e.g., continuously raising AC or DC test voltages or LI or SI voltages raising in steps until breakdown (Fig. 2.26). Now the breakdown is sure, but the height of the breakdown voltage is random. This group of tests is called "progressive stress tests". The random variable is the breakdown voltage V_b. But in life-time tests at constant voltage, the time-to-breakdown T_b becomes the random variable. In both cases we have a continuous variable.

Note In case of stepwise increasing voltages, the starting value may be varied to get continuous outputs (realizations) of the random variable.

The evaluation of progressive stress tests follows the typical treatment of *random variables* in mathematical statistics as described in many text books as e.g., by Mann et al. (1974), Müller et al. (1975), Storm (1976) or Vardeman (1994). Descriptions especially related to HV tests are given by Lalot (1983), Hauschild and Mosch (1984) (in German) and (1992) (in English), Carrara and

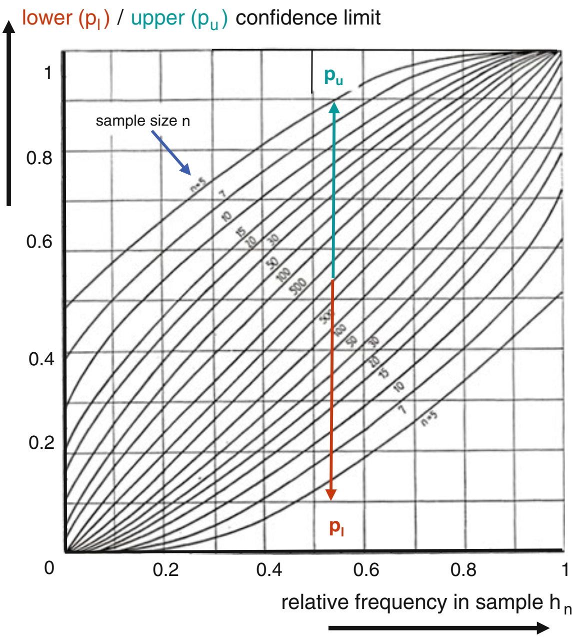


Fig. 2.25 Confidence limits of the breakdown probability for a confidence level $\varepsilon = 95$ %. Depending on sample size

Table 2.8 Check of independence of two tests with sample size $n = 100$

(a) Independent sample: Sphere-plane gap in atmospheric air (withstand: **-**; breakdown: **x**)	breakdown frequency h_{20}	h_{100}
- x x x - - - x - x x x x x x x x - x - x	0.65	
x - x- - x x x x x - x x- x x x x x x	0.75	
- x x x x - x x x x x x - x - x x x –	0.70	
x x x - x x - x - x - - - x - x x x - x	0.6	0.68
x x - x x x x - - x - x - x x x x x x -	0.7	

(b) Dependent sample: As above, but enclosed air in a tank (withstand: **-**; breakdown: **x**)	h_{20}	h_{100}
x x x x x x x x x x x x x x x x x x - x	0.95	
x - x- x x - x x - - x x x - x - - x x -	0.55	
- - - x x x - x - - - x - x x - x- x x	0.5	
- x x - - - - - - x - - - x - x - - x x	0.35	0.48
- - - - - - x - - - - - - - - - - - - -	0.05	

Hauschild (1990) and Yakov (1991) as well as in Appendix A of (IEC 60060-1:2010).

The distribution of a random variable X with realizations x_i found in a progressive stress test is described by a *distribution function*. It is defined by

$$F(x_i) = P(X < x_i), \tag{2.48}$$

and it indicates the probability P with which the random variable X will assume a value below the considered value x_i. A distribution function (Fig. 2.27) is any mathematical function with the following properties:

$0 \leq F(x_i) \leq 1$ (realizations between impossible and sure events),
$F(x_i) \leq F(x_{i+1})$ (monotonously increasing),
$\lim_{x \to -\infty} F(x) = 0$ and $\lim_{x \to +\infty} F(x) = 1$ (boundary conditions).

Note Instead of the distribution function also the density function delivers a complete mathematical description, but it is not meaningful for HV test evaluation.

A distribution function is characterized by parameters describing the mean value and the dispersion, sometimes in addition to the position of the function. The evaluation of a progressive stress test means the selection of a well adapted type of distribution function and the estimation of its parameters. The parameter estimation can be made as a point or confidence estimation based on formulas of functional parameters (e.g., the mean value), quantiles (realization of the random variable related to a pre-given probability) or intervals (difference between two quantiles) (Fig. 2.27).

2.4.2 HV Tests Using the Progressive Stress Method

The *progressive stress method* (PSM) with continuous increasing voltage shall be considered for an electrode arrangement in SF_6 gas (Fig. 2.26a). The initial voltage v_0 must be low enough to avoid any influence on the result, the rate of rise of the voltage shall be so that a reliable voltage measurement can be performed, and the interval between two individual tests shall guarantee the *independence* of the realizations v_b. The independence may be checked by a graphic plot of the measurements. Other independence tests are described in the above mentioned literature.

Example Figure 2.28 shows the sequence of four test series at four different pressures of the SF_6 gas. A series is considered to be independent if the realizations fluctuate in a random manner around a mean value. A dependence must be assumed, if there is a falling, raising or periodically fluctuating tendency. According to this simple rule, the series at gas pressures of 0.40, 0.25, and 0.15 MPa can be considered as independent and are well suited for a statistical evaluation. That at 0.10 MPa is dependent and shall not be statistically evaluated. The reason for the dependence should be clarified and the series repeated under improved conditions.

Each independent series shall be evaluated statistically, this means graphically represented and approximated by a theoretical distribution function. Both tasks can be connected when a so-called *probability grid* is used for the representation. A probability grid uses the inverse function of the considered theoretical distribution function on the ordinate. For each type of theoretical distributions, a probability

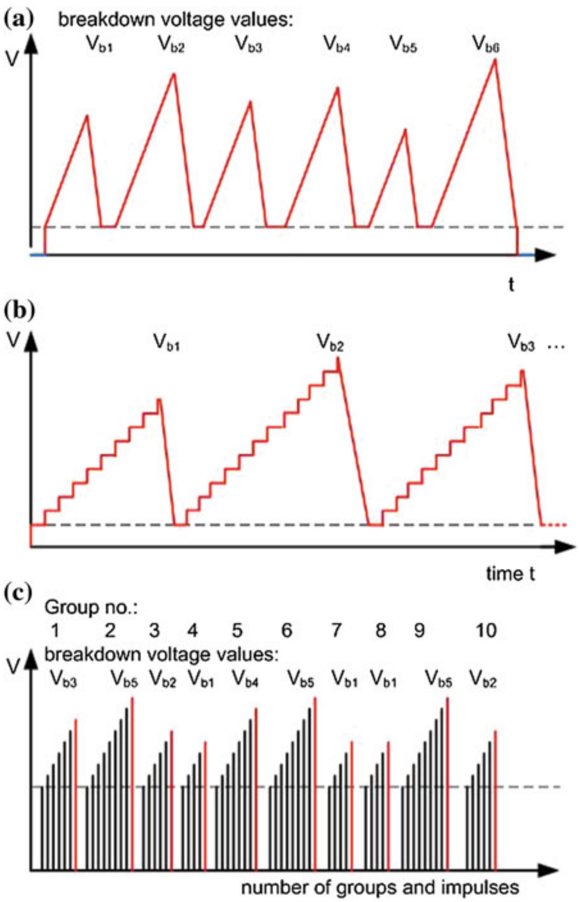


Fig. 2.26 Procedures of progressive stress tests. **a** Continuous increasing AC or DC voltage. **b** Stepwise increasing AC or DC voltage. **c** Stepwise increasing LI or SI voltage

grid can be constructed. Any empirical distribution of the same type as the grid appears as a straight line.

The following theoretical distribution functions are recommended for HV applications:

The *Gauss or normal distribution* is characterized by the parameters μ (estimated by the arithmetic mean value or the 50 % quantile u_{50}) and the standard deviation σ [estimated by the mean square root of $(x_i - \mu)$ or the difference of quantiles $(x_{84} - x_{50}) = (x_{50} - x_{16})$]:

$$F\left(x;\mu;\sigma^2\right) = \frac{1}{\sqrt{2\pi\sigma}} \int\limits_{-\infty}^{x} \mathrm{e}^{-\frac{\left(z-\sigma^2\right)}{2\sigma^2}} \mathrm{d}z. \tag{2.49}$$

The application of a certain distribution function should be based on its stochastic model: A normal-distributed random variable is the result of a large

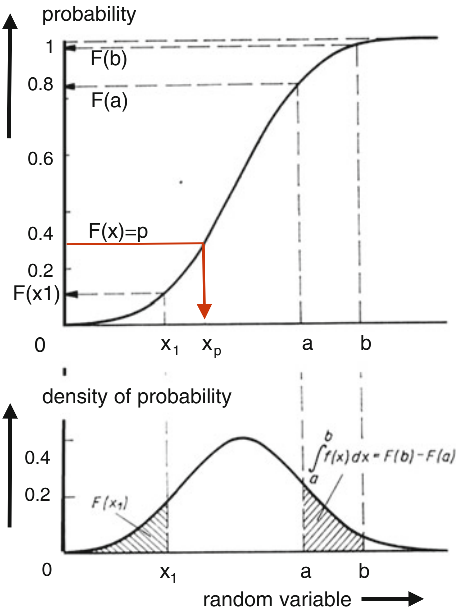


Fig. 2.27 Distribution (**a**) and density (**b**) function with the definitions of quantile x_1 and probability interval $(F(b) - F(a))$

number of independent, randomly distributed influences when each of these makes only an insignificant contribution to the sum. This model is very well applicable to many random events, also to breakdown processes with partial discharges.

The *Gumbel or double exponential distribution* is—as the normal distribution—an unlimited function ($-\infty < x < +\infty$) characterized by two parameters, its 63 % quantile η and the dispersion measure γ [estimated by $\gamma = (x_{63} - x_{05})/3$]:

$$F(x;\eta;\gamma) = 1 - \mathrm{e}^{-\mathrm{e}^{\frac{x-\eta}{\gamma}}}. \tag{2.50}$$

Stochastic model: The double exponential distribution describes the distribution of realisations according to an extreme value, in case of HV tests it is the minimum of the electric strength. It is a mathematical description of the simple fact that "the breakdown of a slightly uniform electric field takes place at the weakest point". It can be well applied if there are slightly uniform insulations which show a quite high dispersion (Mosch and Hauschild 1979).

The *Weibull distribution* is also a distribution describing extreme values, but it is limited and characterized by three parameters, its 63 % quantile $\eta = x_{63}$, the Weibull exponent δ as a measure of dispersion and the initial value x_0

$$F(x;\eta;\delta;x_0) = 1 - \mathrm{e}^{-\left(\frac{x-x_0}{\eta}\right)^{\delta}} \quad x > x_0, \tag{2.51a}$$

$$F(x;\eta;\delta;x_0) = 0 \quad x \le x_0, \tag{2.51b}$$

$$\delta = 1.2898/\log(x_{63}/x_{05}). \tag{2.51c}$$

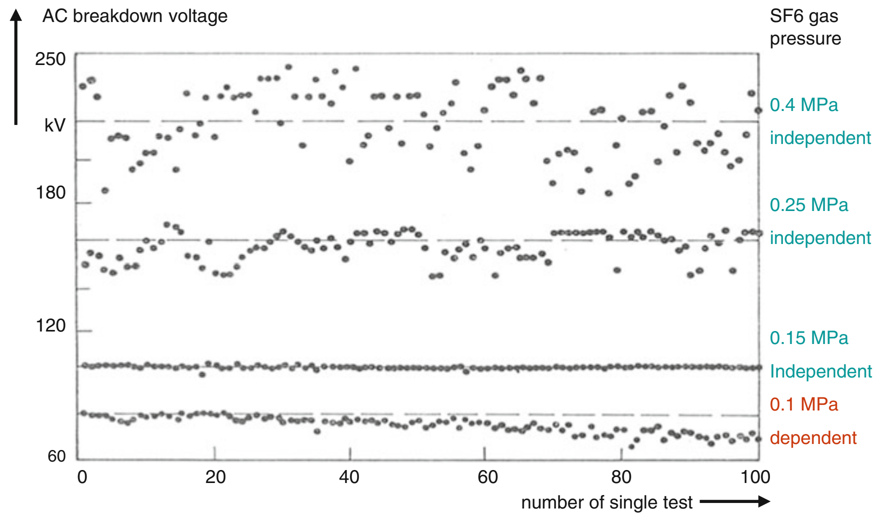


Fig. 2.28 Graphical check of independence of four test series in SF_6 gas

The Weibull distribution is highly adaptable in its structure and therefore applicable for many problems (Cousineau 2009). For the case $x_0 = 0$ it is the ideal function for breakdown time investigation (two-parameter Weibull distribution), see e.g., Bernard (1989) and Tsuboi et al. (2010). In the case $x_0 > 0$, the initial value becomes an absolute meaning, e.g., as an ideal withstand voltage of the breakdown probability $p = 0$! Therefore consequences must be carefully considered when it is applied to breakdown voltage problems.

For all three theoretical distribution functions a *probability grid* can be constructed. Figure 2.29 shows the comparison of the different ordinates of these grids. It can be seen that in the region x_{15}–x_{85} the grids are very similar, but for very low and very high probabilities remarkable differences exist. This means that for estimation of withstand voltages the correct selection of a theoretical distribution function for the adaptation of empirical data (test results) is very important.

In HV tests the *empirical distribution function* is usually determined from a quite limited number of realizations, e.g., $10 \leq n \leq 100$. In that case it is recommended to arrange the realisations x_i according to increasing magnitude between x_{min} and x_{max} and to complete them by their relative, *cumulative frequencies*

$$h_{\Sigma i} = \sum_{m=1}^{i} \frac{h_m}{(n+1)} \tag{2.52}$$

where n is the total number of realizations and h_m is the absolute frequency of the mth voltage value (Eq. 2.43). Then the data are plotted as a “stair” in a suited probability grid. If the empirical (stair) function can be approximated by a straight line, the adaptation with the theoretical function of the grid is acceptable.

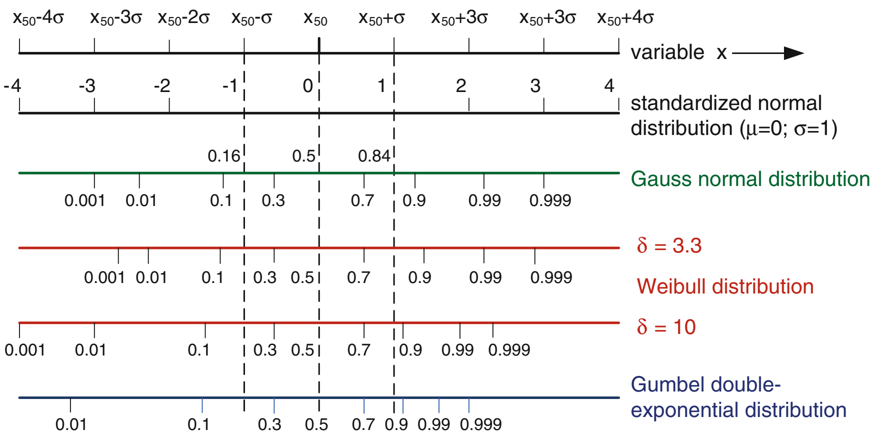


Fig. 2.29 Comparison of ordinates of probability grids with identical 50 % quantiles (logarithmic abscissa for Weibull distribution)

Example Figure 2.30 shows, the stair function can be well adapted by a straight line in the Gauss grid of a normal distribution. This means a normal distribution describes the randomness of the performed test sufficiently. Its parameters can be estimated by quantiles: The mean value by $u_{50} = 953$ kV and the standard deviation by $s = u_{50} - u_{16} = 18.2$ kV.

A *confidence estimation* of the parameters can be performed using so-called test distributions, the t-distribution for confidence estimates of the mean value and the χ^2-distribution for the standard deviation. For details see e.g., Hauschild and Mosch (1992).

The *maximum likelihood method* delivers the most efficient estimation of parameters including their confidence limits. As the term "likelihood" is a synonym for "probability", the method delivers estimates of parameters of the selected distribution function, which are those of maximum probability for the given sample. The method has been introduced many years ago, but got its broad application with numerical calculations by personal computers (PC). It can be applied for all classes of HV breakdown tests and any type of theoretical distribution function (Carrara and Hauschild 1990; Yakov 1991; Vardeman 1994).

The mathematical calculations are based on the so-called "*likelihood function* L". It is proportional to the probability p_R to obtain a description of the investigated sample (realizations x_i with $i = 1 \ldots$ n) using a distribution function, e.g., with the parameters δ_1 and δ_2. The n realizations of the sample are distributed to m levels of the random variable x_i (breakdown voltage or time). The likelihood function L is based on the probability p_R which is proportional to the product of the probabilities f_{Ri}:

$$L = Ap_R = A\prod_{i=1}^{m} f_{Ri}(x_i/\delta_1, \delta_2) = L(x_i/\delta_1,\delta_2). \tag{2.53}$$

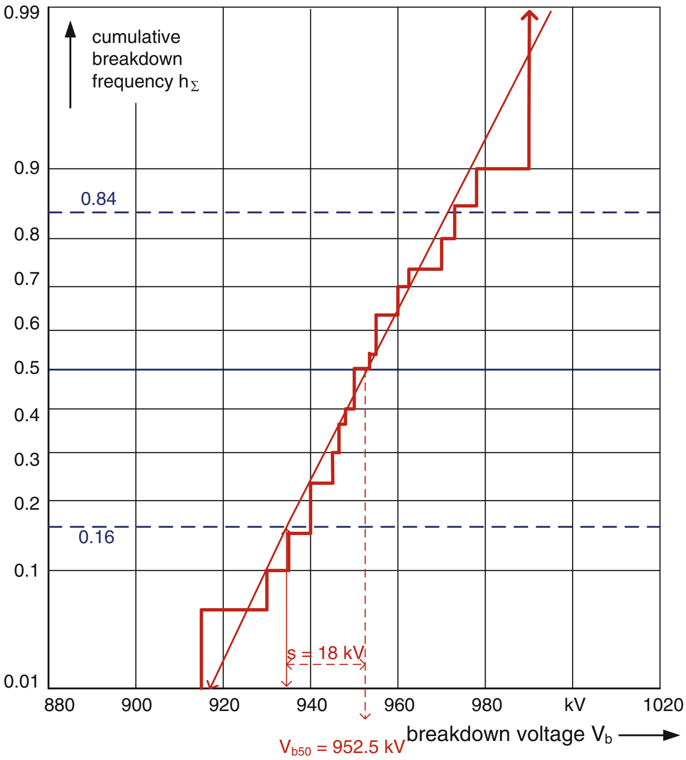


Fig. 2.30 Cumulative frequency distribution function on a Gauss grid

The factor "A" is for normalization only. The most likely *point estimates* of the parameters δ_1 and δ_2 are those which maximize L as shown in Fig. 2.31 (δ^*_1 and δ^*_2). They are calculated from the maximum conditions $dL/d\delta_1 = 0$ and $dL/d\delta_2 = 0$, usually performed with the logarithms where the same parameters indicate the maximum

$$d(\ln L)/d\delta_1 = 0 \quad \text{and} \quad d(\ln L)/d\delta_2 = 0. \tag{2.54}$$

The three-dimensional diagram shows the likelihood function (L normalized to its maximum) on the area of the two parameters. By help of a cross section through the "likelihood mountain" one can define the confidence limits of the parameters ($\delta_{1\min}$, $\delta_{1\max}$, $\delta_{2\min}$, $\delta_{2\max}$). Each parameter combination of the *confidence region* (Fig. 2.31) delivers one straight line on the probability grid (Fig. 2.32). The upper and lower border lines of the bundle of straight lines are considered as confidence limit for the whole distribution function. Figure 2.32 shows this schematically in the relevant probability grid used for the approximation. The maximum-likelihood method can also be applied to "*censored*" *test results*, e.g., when a life-time test is terminated after a certain time and only k of the n test objects have broken down. Then the likelihood function gets the form

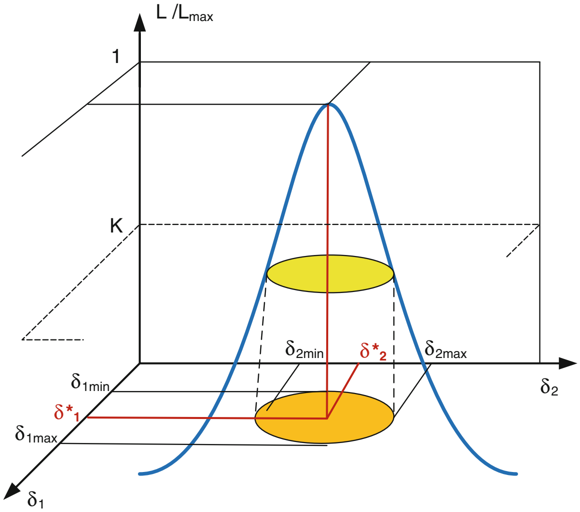


Fig. 2.31 Point and confidence estimation by the maximum likelihood function (schematically)

$$L = A \cdot p_R = A \cdot \prod_{i=1}^{k} f_{Ri}(x_i/\delta_1, \delta_2) \cdot \prod_{i=k+1}^{n-k} (1 - f_{Ri}(x_i/\delta_1, \delta_2)). \qquad (2.55)$$

The same sample as shown in Fig. 2.30 is evaluated by a commercially available PC program of the ML method (Speck et al. 2009) under the assumption of a Weibull distribution (Fig. 2.33). The program delivers after *independence tests* a plot of the *cumulative frequency distribution* on a Weibull grid with logarithmic abscissa. The parameters are estimated as follows: initial value $v_0 = 750$ kV, 63 % quantile $V_{b63} = (v_0 + x_{63}) = (750 + 211)$ kV and dispersion parameter $\delta = 8.4$. The evaluated lower 95 % confidence limit of the cumulative frequency function should be taken for technical conclusions.

2.4.3 HV Tests Using the Multiple-Level Method

The *multiple-level method* (MLM) means the application of constant voltage tests (see Sect. 2.4.1) at several voltage levels (Fig. 2.34). For each level the test delivers an estimation of the breakdown probability including its confidence limits (Fig. 2.25). The relationship between stressing voltage and breakdown probability is not a distribution function in the statistical sense and therefore called "*performance function*" (sometimes also called "*reaction function*"). The performance function is not necessarily monotonically increasing, it can decrease (Fig. 2.35), e.g., in case of a change of the discharge mechanism depending on the height of the voltage. But it delivers exactly the information necessary for the reliability estimation and insulation coordination of a power system: The performance function supplies the probability of a breakdown in case of a certain overvoltage stress.

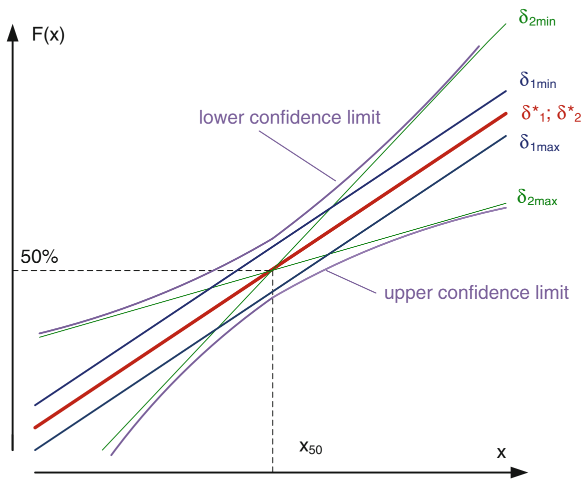


Fig. 2.32 Confidence limits of the distribution function derived from Fig. 2.31 (schematically)

In most cases also the performance function shows a monotonic increase and can be mathematically described by a theoretical distribution function. Figure 2.36 shows the difference between the performance function $V(x)$ (simulated by a standardized normal distribution with $\mu = 0$ and $\sigma = 1$) and derived cumulative frequency functions $S_{\Delta x}(x)$ of different heights Δx of the voltage steps in the test. For statistical reasons, the principle relation is $S_{\Delta x}(x) > V(x)$. Both functions have a different meaning: *cumulative frequency functions* consider the probability of breakdown *at all stresses up to a certain stress* value, performance functions do it *at a certain stress.* Cumulative frequency functions from stepwise increased voltages should be converted into *performance functions* (Hauschild and Mosch 1992).

A MLM test shall be performed at $m \geq 5$ voltage levels and $n \geq 10$ stresses per level. The number of stresses is not necessarily identical at all levels. If withstand voltages are considered, the number of stresses at low breakdown frequency might be higher. Then the *independence* of the outcomes of each level must be checked (see Table 2.8) and confidence estimations for the breakdown probability are determined (Fig. 2.25) and plotted in a probability grid.

Example From earlier experiments it can be expected that the performance function is monotonic increasing and can be approximated by a double exponential distribution function. Therefore, the point and confidence estimations are plotted in a Gumbel grid (Fig. 2.37). Because a straight line can be drawn through all confidence regions, the assumption of a double exponential or Gumbel distribution is confirmed. The small reduction of the relative breakdown frequency between 1,083 and 1,089 kV is not significant as it can be seen from the confidence limits. The parameters can be estimated from quantiles, $v_{63} = 1{,}112$ kV and $\gamma = (v_{63} - v_{31}) = 12$ kV.

Also the maximum likelihood estimation can be applied when the performance function is approximated by a certain distribution function (parameters δ_1, δ_2). According to Fig. 2.34 there are $j = 1 \ldots m$ voltage levels and apply at each level n_j

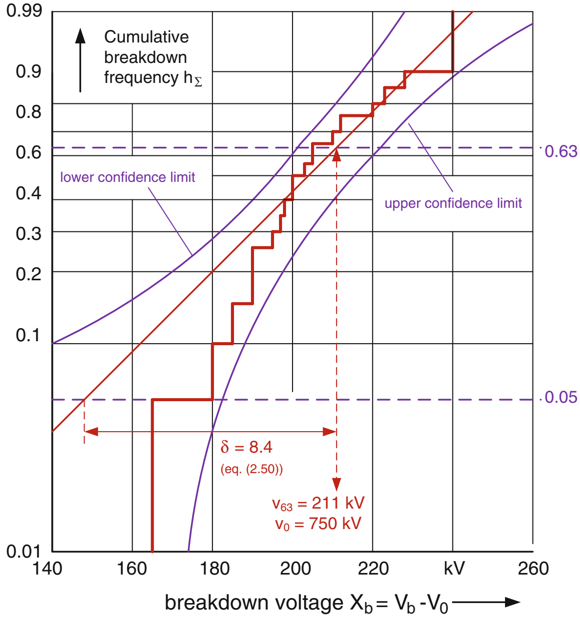


Fig. 2.33 Cumulative frequency function with confidence limits on Weibull grid

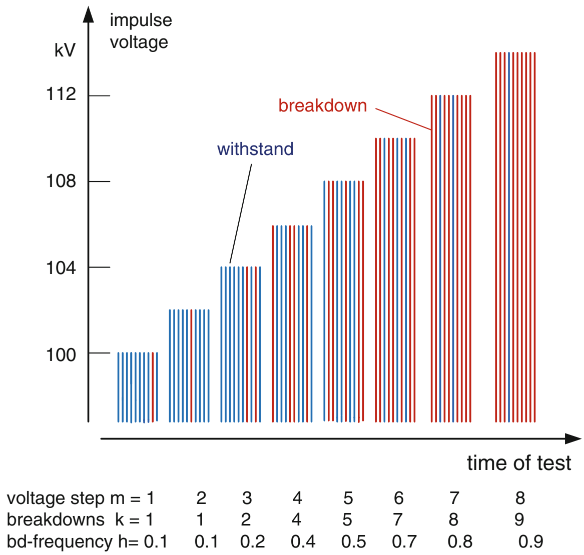


Fig. 2.34 Test procedure according to the multi-level method with $m = 8$ voltage steps and $n = 10$ impulses per step

stresses. The probability of obtaining k_j breakdowns and $w_j = (n_j - k_j)$ withstands at the voltage u_j is expressed by the *binomial distribution* (Eq. 2.47) on the basis of the breakdown probabilities given by the performance function $V(v_j) = V(v_j/\delta_1, \delta_2)$. The corresponding *likelihood function* for all m voltage levels with n_j stresses is given by

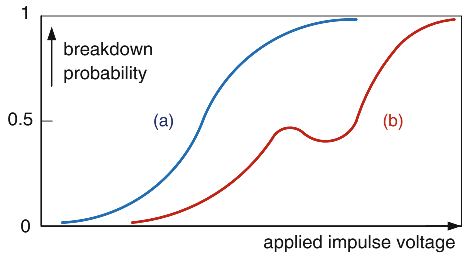


Fig. 2.35 Performance functions with monotonic (**a**) and non-monotonic (**b**) increase

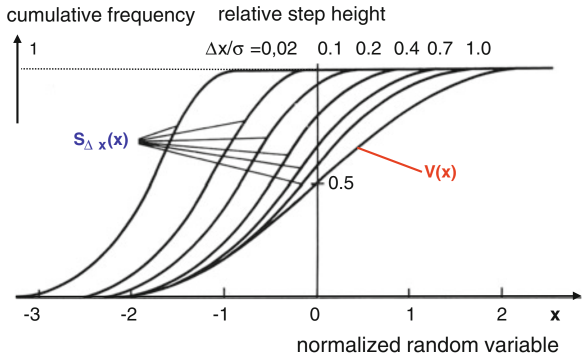


Fig. 2.36 Calculated cumulative frequency functions $S_{\Delta x}(x)$ determined at different step heights $\Delta x/\sigma$ based on an identical performance function $V(x)$

$$L = \prod_{j=1}^{m} V\left(v_j/\delta_1, \delta_2\right)^{kj}\left(1 - V\left(v_j/\delta_1, \delta_2\right)\right)^{wj}. \tag{2.56}$$

Varying the parameters δ_1 and δ_2 the maximum of Eq. (2.56) is found as described above. One gets point and confidence estimates as well as a confidence region for the whole performance function which is also shown in Fig. 2.33.

For practical applications of the maximum likelihood method the application of suitable software is necessary. An optimum software package (Speck et al. 2009) contains all necessary steps of the HV test data evaluation, from several independence tests, tests for best fitting with a theoretical distribution function, representation of the empirical performance function (or the cumulative frequency distribution) on probability grid up to point and confidence estimations for the parameters and the whole performance (or distribution) function.

2.4.4 HV Tests for Selected Quantiles Using the Up-and-Down Method

A whole *performance function* is not always required, e.g., the withstand voltage of an insulation can be confirmed, when the test voltage value u_t is lower than the 10 % quantile v_{10}. In that case it is sufficient to determine the value v_{10}, in other

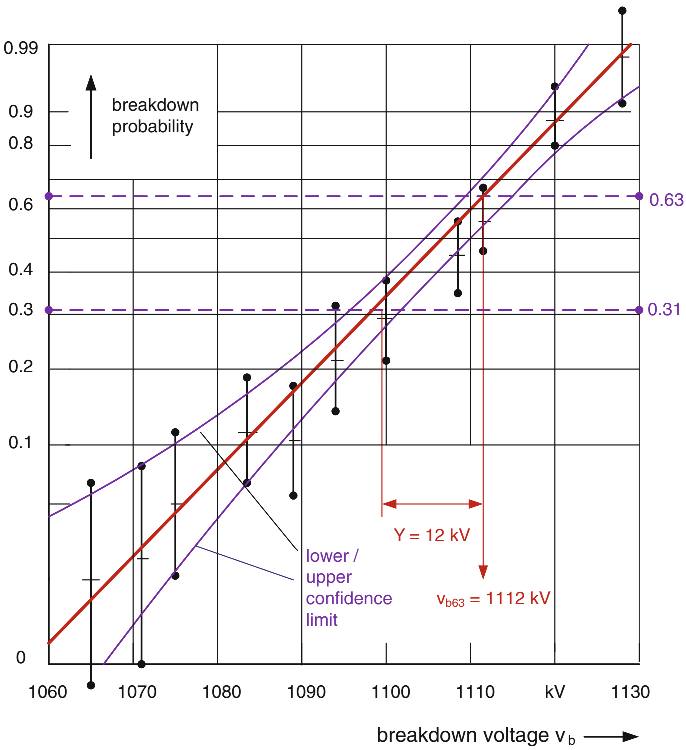


Fig. 2.37 Performance function with its confidence region according to a ML estimation and confidence limits of the single breakdown probabilities and *a*

cases it might be sufficient to look for the quantiles v_{50} or v_{90}. The related up-and-down test method (UDM) which is based on the constant voltage tests (Sect. 3.4.1) has been introduced by Dixon and Mood (1948).

The method requires that the voltage is initially raised in fixed voltage steps Δv, from an initial value v_{00} at which certainly no breakdown occurs, until a breakdown occurs at a certain voltage (Fig. 2.38: v_1 is the first counted value). Now the voltage is reduced by Δv, if no breakdown occurs the voltage is increased in steps again until the next breakdown, otherwise in case of breakdown it is reduced by Δv. The procedure is repeated until a predetermined number $n \geq 20$ of voltage values $v_1, v_2, \ldots v_n$ have been obtained. The mean value of these applied voltages is a first estimate for the *50 % breakdown voltage*v_{50}:

$$v_{50}* = \frac{1}{n}\sum_{l=1}^{n} v_l. \tag{2.57}$$

A more detailed evaluation considers the influence of the step height Δv and uses the number of breakdowns k and the number of withstands q. The sum of the two complimentary events is identical with the number of voltage applications $n = k + q$ starting with the first breakdown. Additionally, the number of voltage levels or steps v_i (with $i = 0 \ldots r$) is taken into account. It is counted $i = 0$ from the step of the lowest breakdown. On a certain voltage level v_i, there are k_i breakdowns. Then the 50 % breakdown voltage can be estimated by

$$v_{50} = v_0 + \Delta v\left(\frac{\sum_{i=1}^{r} i \cdot k_i}{k} \pm \frac{1}{2}\right). \tag{2.58}$$

Example The test in Fig. 2.38 starts at $v_{00} = 120$ kV and has voltage steps of $\Delta v = 5$ kV. Including the first breakdown there are $l = 20$ voltage applications. The first estimate of v_{50}* by Eq. (2.57) delivers v_{50}* = 145.5 kV.

The lowest voltage level at which a breakdown occurs is $v_0 = 140$ kV. The number of breakdowns is $k = 9$, that of withstands is $q = 11$ and there are $i = 3$ voltage steps above the lowest breakdown voltage. With these data Eq. (2.58) delivers $v_{50} = 145.3$ kV. The difference between the two methods is very small, for most practical conclusions it can be neglected.

The UDM test is independent when the single voltage applications do not show a decreasing or increasing mean tendency. A UDM test according to the breakdown procedure starts at an initial voltage at which the breakdown is sure and goes down until the first withstand. It also delivers v_{50}, if the withstands are counted as the breakdowns above. Furthermore it should be mentioned that there are methods for the estimation of the standard deviation of the performance function, but the method cannot be recommended (see e.g., Hauschild and Mosch 1992). Confidence limits shall be calculated by the maximum likelihood function (see below) and not by the only roughly estimated dispersions.

Carrara and Dellera (1972) proposed an "*extended up-and-down-method*" which applies series of stresses (Fig. 2.39) for the determination of pre-selected quantiles instead of single stresses (Fig. 2.38). For the determination of a certain quantile, a certain number of impulses in one series is necessary. Table 2.9 gives the relation between the order p of the quantile and the required number of impulses in one series. The "*withstand procedure*" starting with a withstand voltage v_{00} and raising the voltage delivers the quantiles v_p of the order $p \leq 0.50$, the "*breakdown procedure*" starting with a breakdown voltage and decreasing voltage to withstands delivers the quantiles of the order $p \geq 0.50$.

Figure 2.39b shows the estimation of the statistical withstand voltage determined as the 10 % breakdown voltage (quantile u_{10}) using the *withstand procedure* with $n = 7$ stresses per series. As soon as only withstands occur in a series, the voltage is increased by Δv to the next higher level. As soon as a breakdown occurs the voltage is decreased to the next lower level.

When the *breakdown procedure* is applied, the voltage is decreased when in a series only breakdowns occur and only increased when the first withstand appears. The expected *quantile* for this breakdown procedure is v_{90}. The evaluation of the point estimation of the quantile can be performed according to the simplified evaluation by Eq. (2.57).

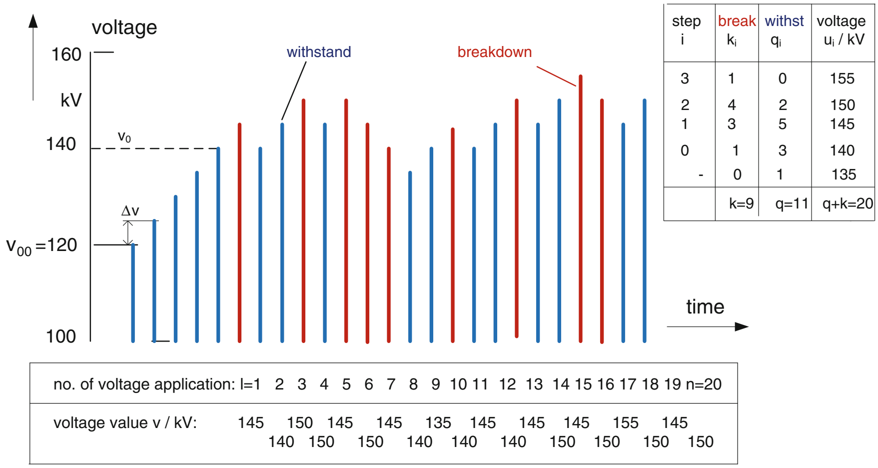


Fig. 2.38 Up-and-down method (*UDM*) for the estimation of the 50 % quantile v_{50}

Table 2.9 Number of stresses n per UDM group for the estimation of the order p of quantiles

n	70	34	14	7	4	3	2	1	
p	0.01	0.02	0.05	0.10	0.15	0.20	0.30	0.50	(withstand procedure)
p	0.99	0.98	0.95	0.90	0.85	0.80	0.70	0.50	(breakdown procedure)

Also the computer-aided maximum-likelihood method can be applied for the UDM tests provided related software is available (Speck 1987; Bachmann et al. 1991): The principle corresponds to the MLM (see Sect. 2.4.3). For each of the applied voltage levels the relative breakdown frequency including its confidence region is estimated (Fig. 2.40 for estimation of v_{10} with $n = 7$ stresses per series) and plotted in a suited probability grid (Fig. 2.40: Gauss grid). The maximum of the likelihood function delivers the expected quantile v_{10} including its confidence limits. The confidence region ($\varepsilon = 95\ \%$) of all quantiles is calculated and plotted as a violet line.

2.4.5 Statistical Treatment of Life-Time Tests

A *life-time test* is the stress of the insulation at a certain constant AC or DC voltage (or a series of impulses). The random variable is the breakdown time (or the number of impulses) which can be evaluated according to the PSM (see Sect. 2.4.2). When this test is performed at several voltage levels, the relationship between breakdown voltage and breakdown time—usually known as the *life-time characteristic* (LTC)—can be evaluated (Speck et al. 2009). It is described for a p-order quantile of the breakdown voltage v_p by

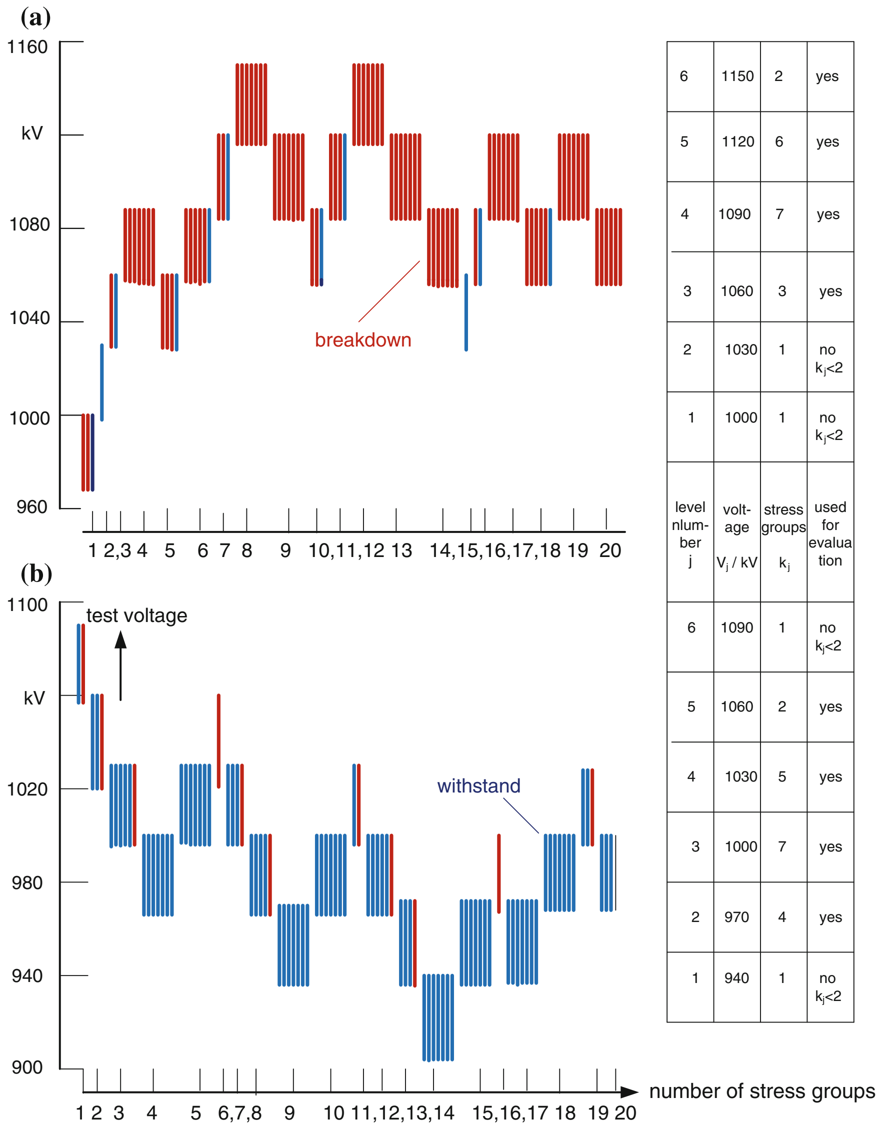


Fig. 2.39 Up-and-down test for the determination of the 90 % quantile v_{90} (**a**), and respectively the 10 % quantile v_{10} (**b**)

$$v_p = k_d t_p^{-1/n} \quad \text{or} \quad t_p = \left(\frac{k_d}{v_p}\right)^n, \tag{2.59}$$

where t_p—p-order quantile of breakdown time, n—life time exponent mainly characterizing the insulating material and k_d—a constant mainly characterising the

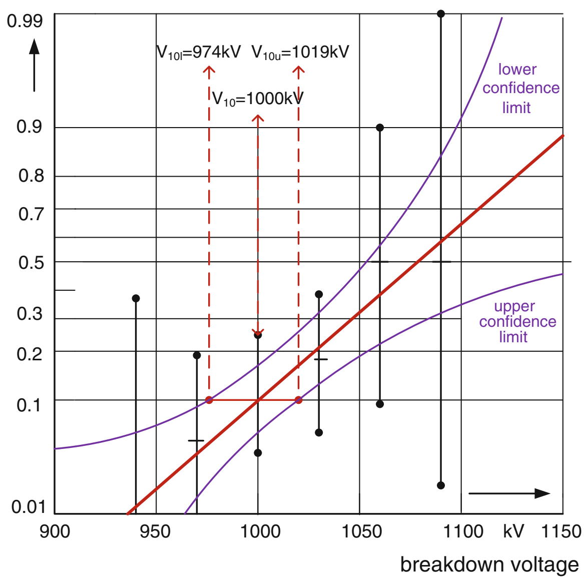


Fig. 2.40 ML evaluation of an extended UDM test for the determination of the performance function in the vicinity of the 10 % quantile

field geometry. In a logarithmic grid the formula delivers a falling straight line which allows the estimation of the parameters n and k_d.

The breakdown time can be described by a Weibull distribution under the consideration of Eq. (2.59) and the relation that v_q is the applied voltage of the constant voltage test $v_q = v_t$:

$$F(t, v_t) = 1 - \exp\left(-\left(t\left(\frac{v_t}{k_d}\right)^n\right)^\delta\right). \tag{2.60}$$

Now the computer-aided maximum likelihood method (Speck 1987; Speck et al. 2009) is applied for the unknown triplet of the parameters k_d, n and δ. The maximum of the likelihood function delivers the best estimation for the triplet. In the usual way also confidence limits can be estimated. The life time-characteristic (Fig. 2.41) includes confidence limits now.

The method enables also the evaluation of censored life-time data, this means test objects are also considered, which have not yet broken down when the test has been terminated.

2.4.6 Standardized Withstand Voltage Tests

At a *standardized withstand voltage test*, the test object has to withstand a test voltage according to the insulation coordination (IEC 60071-1:2006) during an agreed *test procedure*. In the following the procedures for type and routine tests

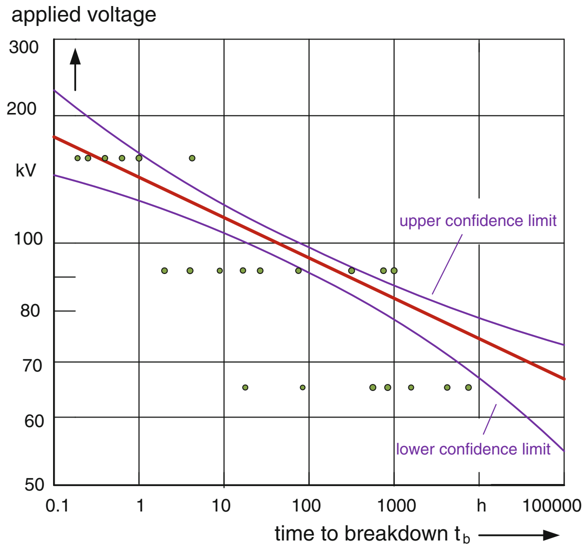


Fig. 2.41 Life-time characteristic including confidence intervals

are considered statistically in brief. The procedures have a long tradition, had been introduced without detailed statistical considerations but are connected with the remarkable experience of test field engineers. A simple change of the procedures would not be accepted and cannot be recommended. But it seems to be necessary that the statistical consequences of these procedures are understood.

The stochastic nature of electrical discharges causes, that a defective test object is not always rejected in a test. With a certain low probability it may pass the test and fail during the operation. This is called the risk of the user. But it may also happen that a test object without defects is rejected in the test. This is the risk of the manufacturer. Which risk is higher depends on the design and the quality of production of the object. If there is only a very small distance between real breakdown voltage and test voltage the risk of the user might be higher than that of the manufacturer. But with a sufficient safety margin the risk of both sides is acceptable.

For AC and DC test voltages (Fig. 2.42a, IEC 60060-1:2010) the voltage shall be rapidly increased up to 75 % of the test voltage value. Then it shall be raised with about 2 % of the test voltage value per second. When the test voltage value is reached it has to be maintained within ±1 % for the test duration T_t, which is very often 1 min. Then the voltage shall be decreased to 50 % and switched off. Such a test is a kind of constant voltage test, the test voltage is a single stress and without knowing any details from the development, a statistical judgement of the single test is impossible. But if many test objects of the same type are tested, one should have a statistical evaluation of failure statistics for improvement of design and/or production.

AC and DC withstand tests are more and more completed by PD measurement ("*PD monitored withstand tests*"). Then a step test procedure has to be applied

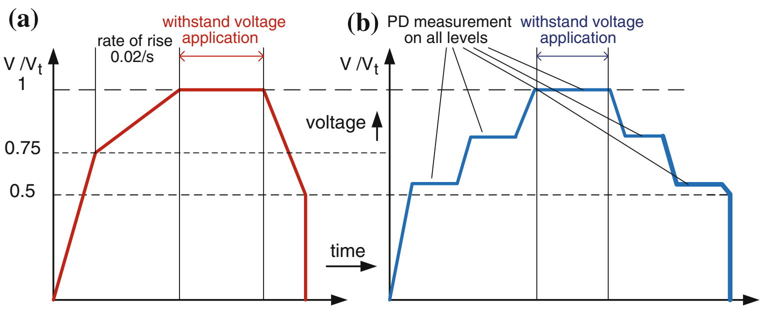
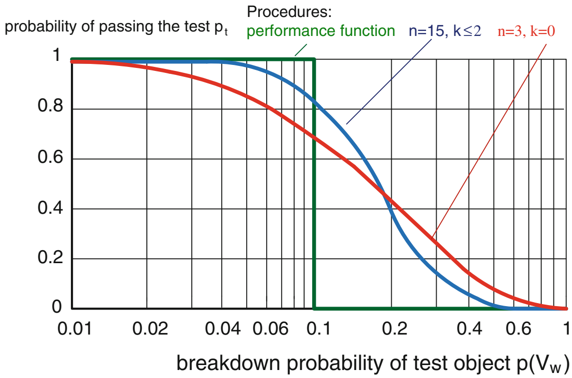


Fig. 2.42 Conventional (**a**), and PD monitored (**b**) withstand test procedure for AC and DC test voltages

Fig. 2.43 Probability of passing a LI/SI voltage test depending on the breakdown probability of the test object for different test procedures



(Fig. 2.42b). The upwards and downwards steps should be at identical voltages to enable a comparison of the PD characteristics before and after the withstand test. The PD measurement should also be performed at the withstand test voltage for the specified test duration. Also the duration of the steps for PD measurement must be specified. For all steps, a duration $T \geq 1$ min is necessary. Which step voltage is considered for the withstand test is also a matter of specification. The combination of withstand and PD testing is the most efficient method for AC/DC testing today.

For *LI and SI withstand tests* several methods are recommended (IEC 60060-1:2010):

(A1) A withstand test of external insulations is passed, when it can be shown that the 10 % quantile of the performance function is higher than the specified withstand voltage. The 10 % quantile may be taken from a measured performance function or from an up-and-down test (see Sect. 2.4.4).

(A2) For external insulations $n = 15$ test voltage impulses shall be applied and $k \leq 2$ breakdowns are allowed

(B) For internal insulations $n = 3$ test voltage impulses may be applied and no breakdown is allowed.

By help of the *binomial distribution* (Eq. 2.47) the methods can be compared: Fig. 2.43 shows a diagram of the probability of passing the test depending on the *breakdown probabilityp* of the test object at the test voltage. The method A1 has a sharp criterion: When the breakdown probability reaches $p = 0.10$, the test object fails the test. The procedure A2 is not sharp, because at $p = 0.08$, 10 % of the test objects fail, although according to procedure A1 they are considered as acceptable. But when $p = 0.30$—a too high breakdown probability—there is 15 % probability of passing the test in case of method A1. The procedure B is still worse: A test object of the high breakdown probability $p = 0.30$ will pass the test with even 30 % probability.

The example shows, no manufacturer shall design its products with a breakdown probability of 0.10 at the test voltage value. The breakdown probability for design should be $p < 0.01$!

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