

Chapter 2

Characterisation and Generation of High Impulse Voltages and Currents

Transmission and distribution of electrical energy involves the application of high-voltage apparatus like power transformers, switchgear, overvoltage arrestors, insulators, power cables, transformers, etc., which are exposed to high transient voltages and currents due to internal and external overvoltages. Before commissioning, they are therefore tested for reliability with standard impulse voltages or impulse currents. Depending on the apparatus and the type of their proposed application, one differentiates between various types of waveforms of test voltages and test currents. These waveforms are defined by several parameters with tolerances during generation and uncertainties during measurement. For data evaluation of these waveforms, measured, as a rule, with digital recorders, partially standardised evaluation procedures are applied. Thereby, experimental data obtained from extensive investigations with respect to the evaluation of peak oscillations, which are superimposed on a lightning impulse voltage, are taken into account as a function of the oscillation frequency. In the second part of this chapter, various circuits for the generation of high impulse voltages and impulse currents will be discussed in principle.

2.1 Parameters of High-Voltage Impulses

For testing high-voltage apparatus, several waveshapes of the high-voltage test impulses are standardised. In addition to switching and lightning impulse voltages with aperiodic waveform, oscillating switching and lightning impulse voltages, which are generated by transportable generators for on-site tests, are also standardised. Lightning impulse voltages are again sub-divided into full and chopped lightning impulse voltages, with the chopping occurring at widely variable times. Impulse voltages with an approximately linear rise are designated wedge-shaped and those with a very steep front as steep-front impulse voltages. An analytic representation of impulse voltages is given in [Sect. 3.1](#) and calculation of the spectrum in [Sect. 3.2](#).

Definitions of impulse parameters of high-voltage impulses are somewhat different from those commonly adopted in pulse techniques for low-voltage systems. That is considered essential in order to account for the special conditions during generation and measurement of high-voltage impulses. Fixing of these parameters is to be considered using theoretical investigation with mathematically prescribed functions, among others, calculation of the transfer characteristic of measuring systems with the help of the convolution integral (see Chap. 3).

2.1.1 Lightning Impulse Voltages

The electrical strength of high-voltage apparatus against external overvoltages that can appear in power supply systems due to lightning strokes is tested with *lightning impulse voltages*. One differentiates thereby between *full* and *chopped lightning impulse voltages* [1, 2]. A *standard full lightning impulse voltage* rises to its peak value $\hat{u}$ in less than a few microseconds and falls, appreciably slower, ultimately back to zero (Fig. 2.1a). The rising part of the impulse voltage is referred to as the *front*, the maximum as the *peak* and the decreasing part as the *tail*. The waveform can be represented approximately by superposition of two exponential functions with differing time constants (see Sect. 3.1).

Chopping of a lightning impulse voltage in the test field is done by a chopping gap, whereby one differentiates between *chopping on the tail* (Fig. 2.1b), *at the peak* and *on the front* (Fig. 2.1c). The *standard chopped lightning impulse voltage* has a *time to chopping* between 2 μs (chopping at the peak) and 5 μs (chopping on the tail) (Fig. 2.1b). The voltage collapse on the tail shall take place appreciably faster than the voltage-rise on the front. Due to such rapid voltage collapse, the test object is subjected to an enormously high stress. Special requirements may be placed on the form of chopped impulse voltages for individual high-voltage apparatus.

Lightning impulse voltages chopped on the front have times to chopping between 2 μs and low down to 0.5 μs . At short times to chopping, the waveform at the front between $0.3\hat{u}$ and the chopping instant is nearly linear. If variations from linearity are found within $\pm 5\%$ of the front-time, one speaks of a wedge-shaped impulse voltage with a virtual steepness:

$$S = \frac{\hat{u}}{T_c}. \quad (2.1)$$

The various lightning impulse voltages are identified in the test specifications by the following time parameters:

- *front time* T_1 and *time to half-value* T_2 for full lightning impulse voltages
- *front time* T_1 and *time to chopping* T_c for standard chopped impulse voltages ($2\ \mu\text{s} \leq T_c \leq 5\ \mu\text{s}$)

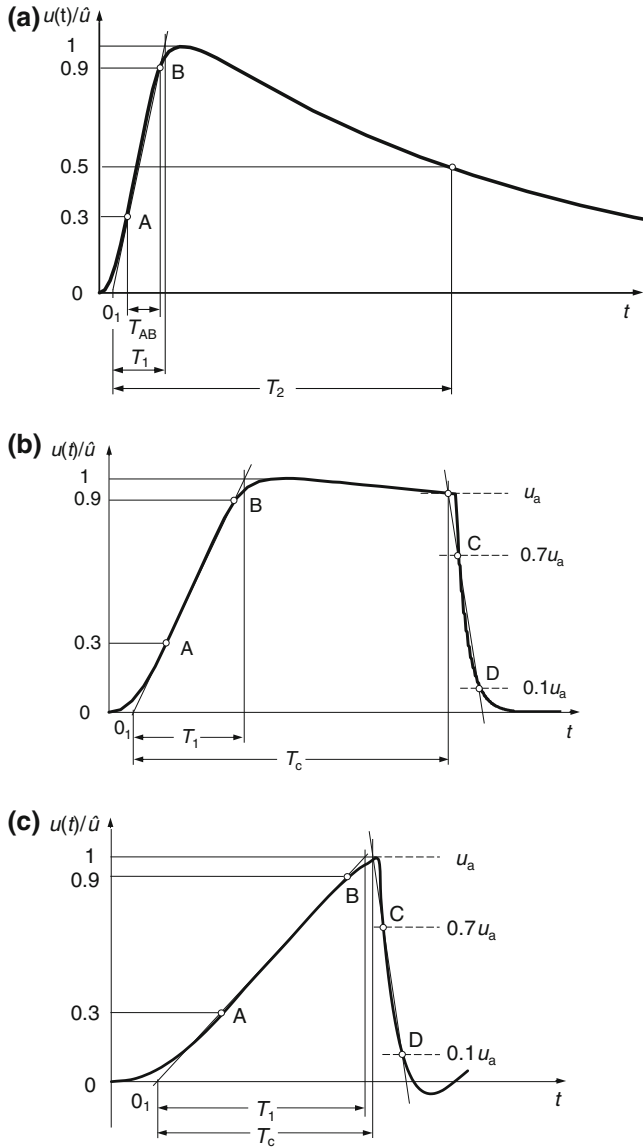


Fig. 2.1 Examples of lightning impulse voltages with aperiodic waveform (as per [1]). **a** full lightning impulse voltage, **b** lightning impulse voltage chopped on the tail, **c** lightning impulse voltage chopped on the front or wedge-shaped impulse voltage

- *time to chopping* T_c for lightning impulse voltages chopped on the front ($T_c < 2 \mu\text{s}$)
- *front time* T_1 and *virtual steepness* S for wedge-shaped impulse voltages.

Starting point for the determination of the time parameters is the *virtual origin* O_1 . It is fixed as that point of time which precedes the point A of the impulse voltage at $0.3\hat{u}$ by the time $0.3T_1$ (Fig. 2.1a, b, c). Graphically, O_1 is obtained as the point of intersection of the straight line through the points A and B with the zero line. Definition of the virtual origin O_1 is essential since the origin O of the recorded waveform is often not recognisable due to superposed disturbance voltages and limited bandwidth of the measuring system.

The *front time* T_1 is the time between the virtual origin O_1 and the point of intersection of the straight line through A and B with the peak line (Fig. 2.1):

$$T_1 = \frac{1}{0.6} T_{AB}, \quad (2.2)$$

wherein T_{AB} is the time interval between the points A at $0.3\hat{u}$ and B at $0.9\hat{u}$ on the front of the impulse voltage. For lightning impulse voltages, T_1 is defined as $< 20 \mu\text{s}$, since otherwise it is considered as a switching impulse voltage (see Sect. 2.1.2).

The *time to half-value* T_2 is the time interval between the virtual origin O_1 and the point at $0.5\hat{u}$ on the tail of a full lightning impulse voltage (Fig. 2.1a).

The *time to chopping* T_c is the time interval between the virtual origin O_1 and the virtual instant of chopping which is the point of intersection of the straight line through the points C at $0.7u_a$ and D at $0.1u_a$ with the horizontal at the level of u_a . For an impulse voltage chopped on the tail or at the peak, u_a is defined by the point of intersection of the straight line through C and D with the impulse voltage (Fig. 2.1b). In the case of a lightning impulse voltage chopped on the front, u_a is the same as the peak value $\hat{u}$ (Fig. 2.1c). Fixation of the virtual time to chopping takes into account that the beginning of chopping is not always clearly recognisable in the recorded waveform. Reasons for that are the finite duration of chopping and a limited bandwidth of the measuring system, which lead to a rounded form of the recorded waveform in the chopping region [3]. Furthermore, electromagnetically coupled disturbances, which appear due to the firing of the chopping gap, can get superposed in the region of the peak. The duration of the voltage collapse is defined as $T_{CD}/0.6$, where T_{CD} is the time interval between the points C and D.

For characterising a full impulse voltage, numerical values of front times and times to half-value in microseconds are introduced as symbols. The standard 1.2/50 lightning impulse voltage has accordingly a front time $T_1 = 1.2 \mu\text{s}$ and a time to half-value $T_2 = 50 \mu\text{s}$.

Figure 2.1 shows the impulse parameters for smooth waveforms in which the peak value $\hat{u}$ is equal to the *value of the test voltage*. In testing practice, however, an overshoot or oscillation could be superposed on the peak of the impulse voltage; depending on its duration or frequency, it can subject the test object to varying degrees of stressing. The impulse parameters are therefore based, as per definition, on a fictitious *test voltage curve* which is calculated from the recorded data of the lightning impulse voltage applying special evaluation procedures (see Sect. 2.1.1.2). Making use of appropriate software, it is then possible to adopt a uniform

method for evaluating impulse voltages with or without overshoot or oscillation of any frequency superposed on the peak. An *equivalent smooth lightning impulse voltage* is, per definition, an impulse voltage without peak oscillation or overshoot, whose test voltage value and time parameters are the same as those for the calculated fictitious test voltage curve of a lightning impulse voltage with peak oscillation or overshoot. An impulse voltage chopped on the front is essentially defined as the test voltage curve.

2.1.1.1 Tolerances and Uncertainties

While generating lightning impulse voltages, deviations from the impulse parameters of the test standards laid down for high-voltage apparatus are permissible. The *tolerances* for lightning impulse voltages amount to [1]:

- $\pm 3 \%$ on the value of the test voltage
- $\pm 30 \%$ on the front time T_1 and
- $\pm 20 \%$ on the time to half-value T_2 .

The reason for the large amount of tolerances on the time parameters lies in the varying degrees of interaction of the test objects with the generator circuit, due to which the waveform and thus, the time parameters of the generated lightning impulse voltage are affected to a greater or smaller extent. The elements of the lightning impulse voltage generator with which the waveform is obtained need not be changed each time the load presented by the test object is marginally altered. No tolerances are fixed for the time to chopping T_c .

During impulse voltage tests on a high-voltage apparatus according to specifications, the value of the test voltage and the time parameters shall be determined within prescribed limiting values of the *expanded uncertainty*. These amount to [2]:

- 3 % for the value of the test voltage of full and chopped lightning impulse voltages with times to chopping $T_c \geq 2 \mu\text{s}$,
- 5 % for the value of the test voltage of lightning impulse voltages chopped on the front with times to chopping $0.5 \mu\text{s} \leq T_c < 2 \mu\text{s}$, and
- 10 % for the time parameters.

Note: Uncertainties are given without any polarity sign but are to be understood as positive and negative limiting values.

The expanded uncertainty is a parameter that characterises the range of values lying above and below the measured results, which under given conditions are considered as possible with an overall probability of around 95 % (see [Chap. 9](#)). The uncertainty of the impulse parameters of an impulse voltage applied to the test object comprises of the uncertainty of the measuring system which is stated in the calibration certificate for the scale factor and the time parameters as a result of detailed calibration and other uncertainty contributions which are to be observed in

an impulse voltage test. The latter take into account the actual conditions during voltage measurement, which deviate from those during calibration. Deviations could be caused, e.g., through a change in ambient temperature, deviations in the voltage waveform or long-term drift in the measuring system.

Note: The prescribed limiting values for the expanded uncertainty and tolerance of the test voltage value for full impulse voltages are identical, which is basically unsatisfactory from the viewpoint of measurement technique.

2.1.1.2 Superimposed Oscillations

Test voltages actually appearing in a test circuit can contain oscillations at the peak as well as oscillations on the front. Reasons for such oscillations are the inductances and capacitances of the impulse voltage generator and those of the test and measuring circuits including the high voltage leads and a not-optimal sequence during ignition of the generator sphere gaps or reflection phenomena. In order to capture these oscillations correctly, the measuring system must possess a sufficiently high bandwidth (at least 10 MHz for front oscillations and 5 MHz for peak oscillations). Oscillations in the test circuit must be clearly distinguished from those that could occur on account of intrinsic resonance in the voltage divider due to faulty construction. When oscillations do occur in the test circuit due to intrinsic resonance in the voltage divider, these are reproduced at the output of the divider with enhanced amplitude. Such a voltage divider is then unsuited for measurement of the oscillating test voltage.

Oscillations at the peak of lightning impulse voltages require a special evaluation process for determining the test voltage value that is responsible for the stressing of the test object. It is well known for a long time that stressing of the insulation of high-voltage apparatus depends on the frequency of the superimposed peak oscillation. Accordingly, an impulse voltage with high-frequency peak oscillation does not stress the insulation as much as one with low-frequency peak oscillation, when both have the same maximum value. In earlier test standards, the maximum value of a lightning impulse voltage with superimposed oscillation of frequency $f < 500$ kHz was prescribed as the test voltage value, whereas for $f \geq 500$ kHz, the test voltage value was determined as the peak value $\hat{u}$ of the *mean curve 2* through the oscillating curve *1* (Fig. 2.2).

The factor with which earlier the amplitude of the superimposed oscillation at the peak was to be multiplied therefore amounted to $k = 1$ or $k = 0$ (see Fig. 2.4b, curve *1*). Such evaluation is, not in the least from the viewpoint of measurement technique, unsatisfactory since the frequency of oscillation at the peak cannot be determined exactly in the critical range of 500 kHz. An unequivocal decision as to which of the evaluation methods shall be used is therefore not possible. Additional fact is that the form of the mean curve through the peak oscillation is not precisely defined, but depends on the optical impression of the observer.

Recent investigations in many high-voltage testing laboratories on the breakdown strength of gaseous, liquid and solid insulations against lightning impulse

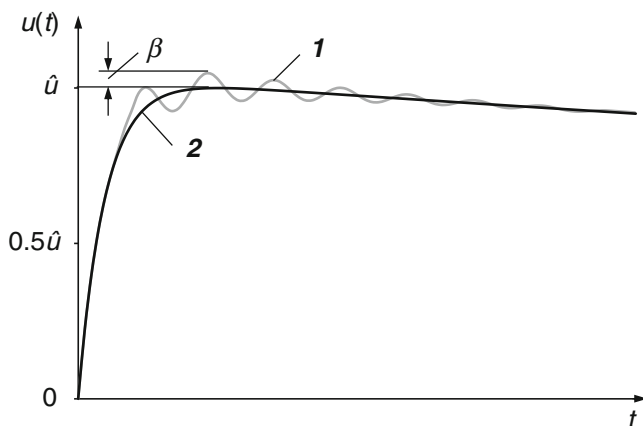


Fig. 2.2 Earlier evaluation of a lightning impulse voltage *I* with high-frequency peak oscillation of frequency $f \geq 500$ kHz (in principle). A mean curve *2* was drawn through the oscillating impulse voltage, whose peak value $\hat{u}$ was taken to be the test voltage value

voltages with superimposed oscillations at the peak substantiate basically the frequency-dependent stressing of the insulation, however, in a modified form [4]. In an exhaustive series of experiments with test models, the breakdown values of impulse voltages with, as well as without peak oscillations were measured. The example in Fig. 2.3 shows schematically the voltage waveforms just prior to the breakdown. Here, curve *1* representing the impulse voltage with damped oscillation was obtained by the superposition of the smooth impulse voltage *3* (the *base curve*) with the oscillation *4*. Curve *2* is the equivalent smooth impulse voltage (the *test voltage curve*), which leads to the same breakdown voltage of the test models as the oscillating impulse voltage *I*. The amplitude, frequency and phase displacement of the superimposed oscillation were widely varied during the investigations.

The results of the breakdown tests on all the investigated insulating materials, test models and test parameters can be summarised in a diagram showing the experimentally determined values of the k -factor against the frequency f of the peak oscillation [4]. Despite the spread in the values for various insulating materials, it is clearly visible that the k -factor, and with it, the effect of the peak oscillation on the breakdown reduces continuously above 100 kHz and totally disappears for $f \geq 5$ MHz (Fig. 2.4a). The straight line through the empirically obtained values, shown in the semi-logarithmic representation and decreasing with the logarithm of frequency, characterises the basic frequency behaviour of the k -factor. In place of the earlier accepted abrupt change of the k -factor at 500 kHz, a gradual transition in the frequency range from 100 kHz up to 5 MHz has proved to be correct.

With the frequency-dependent k -factor, for the peak value U_t of the equivalent smooth lightning impulse voltage *2*, which also leads to breakdown just like the oscillating impulse voltage *I*, the relationship (Fig. 2.3):

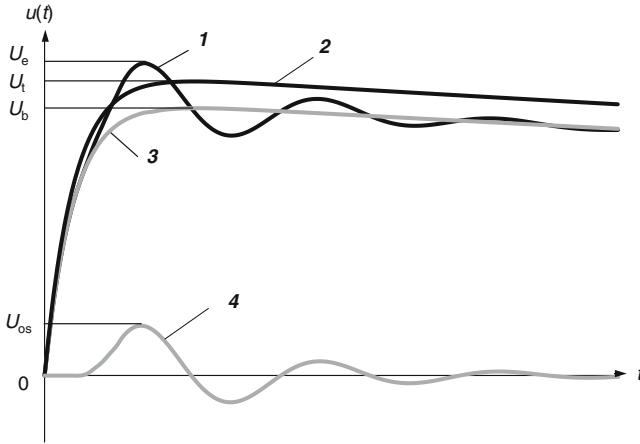


Fig. 2.3 Oscillating impulse voltage **1** and equivalent smooth lightning impulse voltage **2**, both of which according to [4] lead to the breakdown of the test models. The oscillating impulse voltage **1** was generated by superposition of the oscillation **4** on the smooth impulse voltage **3**

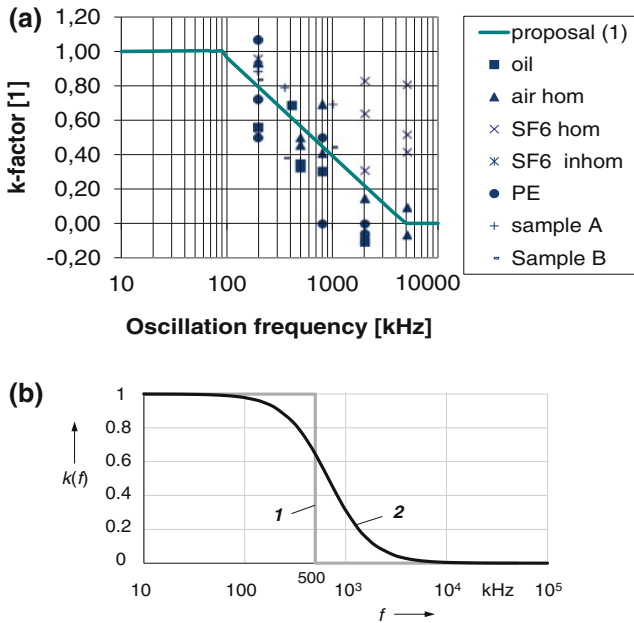


Fig. 2.4 Test voltage function $k(f)$ with which the peak oscillation of a lightning impulse voltage is weighted in order to characterise the stressing of an insulation. **a** experimentally determined values of k -factor for solid, liquid and gaseous insulations [4], **b** definition of the test voltage function $k(f)$ in test standards, **1** test voltage function according to earlier definition $k = 1$ for $f < 500$ kHz and $k = 0$ for $f \geq 500$ kHz, **2** test voltage function according to Eq. (2.4) as per definition in [1]

$$\boxed{U_t = U_b + k(f) \cdot U_{os} = U_b + k(f) \cdot (U_e - U_b)} \quad (2.3)$$

was found where U_b denotes the peak value of the base voltage **3**, U_{os} the amplitude of the superimposed oscillation **4** and U_e the extreme value of the oscillating impulse voltage **1**.

Further investigations are concerned with the development of a method with the objective of introducing the results obtained about the effect of the frequency of superimposed oscillations into the test specifications [5–10]. A good approximation of the basic form of the experimentally determined k -factors versus frequency f of the peak oscillation is—besides the straight line in Fig. 2.4a—given by the *test voltage function*:

$$k(f) = \frac{1}{1 + 2.2f^2} \quad (2.4)$$

with f in MHz (curve **2** in Fig. 2.4b). The test voltage function $k(f)$, with the advantage of continuity, replaces the earlier, for many decades long valid valuation of peak oscillations according to curve **1** in Fig. 2.4b.

The test voltage function $k(f)$ is the basis for a standardised filtering method for calculating the test voltage curve, which shall characterise the effective stressing of the high-voltage apparatus by full impulse voltages with peak oscillations and such of those chopped on the tail [1]. Herein, the results of the breakdown tests conducted with oscillating impulse voltages in [4] are extrapolated to the stressing of high-voltage apparatus during voltage tests. The method is briefly described with the help of the curves in Fig. 2.3. Starting point of the evaluation is the data record of an oscillating test voltage **1**, on which the base curve **3** is fitted as a smooth impulse voltage as per Eq. (3.8). The difference between the curves **1** and **3** gives the superimposed oscillation **4**, which is filtered with the test voltage function $k(f)$ according to Eq. (2.4). By superposition of the filtered oscillation on the base curve **3**, one obtains the test voltage curve, from which the test voltage value U_t and the time parameters are determined. For an oscillating impulse voltage chopped on the tail, filtering is effected on a corresponding full oscillating impulse voltage that is obtained at a reduced voltage level. The result is then finally extrapolated to the chopped waveform in corresponding voltage and time formats.

Note: The test voltage curve obtained with filtering process indicates—in contrast to the experimental investigations in [4] with equivalent smooth impulse voltage corresponding to curve **2** in Fig. 2.3—for frequencies up to about 10 MHz, a superimposed peak oscillation with frequency-dependent amplitude.

An alternative to the tedious filtering method is the manual evaluation method [1]. It provides an equivalent smooth impulse voltage as the test voltage curve comparable to the curve **2** in Fig. 2.3. At first, the base curve **3** is laid out graphically as a mean curve through the recorded oscillating impulse voltage **1**. The difference between the two curves **1** and **3** represents the superimposed oscillation **4** with the amplitude U_{os} . From the duration of the half-period of oscillation in the time region of the extreme value of the curve **1**, one obtains the frequency of

oscillation f , with which the factor $k(f)$ as per Eq. (2.4) and hence the test voltage value U_t as per Eq. (2.3) is calculated. The base curve, upscaled true to the scale factor to the peak value U_t , then represents the smooth test voltage corresponding to curve 2 in Fig. 2.3 from which even the time parameters are determined. Since the graphical analysis of the oscillating impulse voltage is dependent on the subjective sensibility of the investigator and can contribute an additional uncertainty component, computer-aided data processing with appropriate software is highly recommended. The base curve can be then calculated as a double exponential waveform as per Eq. (3.8) and fitted to the oscillating impulse voltage.

With both these evaluation methods, even the noise (see Sect. 5.2) generated in the digital recorder and the front oscillation are eliminated totally, although in the filtering method, only for oscillating frequencies of 10 MHz and higher. The experimental determination of k -factors (see Fig. 2.4a) and also their approximate representation by the test voltage function $k(f)$ as per Eq. (2.4) are coupled with uncertainties. In order to limit the uncertainty components resulting therefrom (see App. A2.2) while determining the test voltage value as well as the time parameters, application of the evaluating methods is restricted to overshoots of maximal 10 % of the base voltage.

Oscillations on the front of a lightning impulse voltage affect the determination of the virtual origin O_1 and hence the time parameters also. Even oscillations on the front can be entirely or partially eliminated with both the above mentioned evaluation methods for peak oscillations with $k(f)$ as per Eq. (2.4). For removal of the front oscillations, there exist other methods of calculation, among others, the digital filtering of the recorded data, cutting-off the Fourier spectrum of the oscillating lightning impulse voltage at higher frequencies or sectional matching through an exponential element, a parabola or a straight line [11–13]. As a result, one obtains, as was usual in the graphical evaluation of earlier days, a mean curve passing through the front oscillation. The points at 0.3 and 0.9 $\hat{u}$ of the mean curve are utilised for determining O_1 and T_1 (Fig. 2.5). Oscillations on the front occur predominantly on the initial portion of the impulse voltage and affect then only the determination of the point A at 0.3 $\hat{u}$. If, as in the example in Fig. 2.5, evaluation of the front at 0.3 $\hat{u}$ is not unique, it is recommended as a simple approximate solution that the central of the three intersecting points be taken—which means then that calculation of the complete mean curve becomes superfluous [14].

Investigations with waveforms calculated with and without oscillation on the front show that every smoothing method corrupts the impulse waveform more or less strongly. The front time of a smoothened impulse voltage is therefore not identical with that of the original waveform without oscillation on the front. Decisive for the quality of filtering is the frequency separation in the spectra of the oscillation and the impulse voltage. A high-frequency oscillation can be eliminated by filtering better than the oscillation whose frequency lies in the characteristic region of the impulse voltage. In an impulse voltage chopped on the front, the superimposed oscillation can stretch up to the peak. In the region of the peak, filtering should be undertaken only very carefully, in order to avoid a misrepresentation of the peak value.

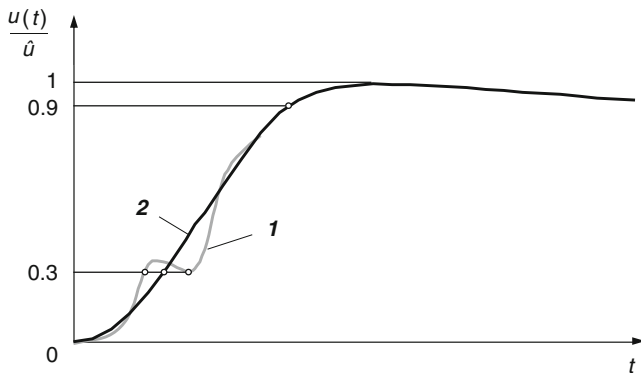


Fig. 2.5 Evaluation of a lightning impulse voltage with front oscillation. *1* measured original waveform with three intersection points at $0.3\hat{u}$, *2* mean curve through the front oscillation

2.1.2 Switching Impulse Voltages

During tests with *switching impulse voltages*, the stressing of the power apparatus by internal overvoltages consequent to switching operations in the supply network is simulated. The idealised waveform of an *aperiodic switching impulse voltage* is, like that of a full lightning impulse voltage, defined by superposition of two exponential functions; however, the time constants here are appreciably larger (see Sect. 3.1). Besides the test voltage value (peak value), switching impulse voltages are characterised by two time parameters, which, in contrast to lightning impulse voltages, are with reference to the *true origin* O of the waveform (Fig. 2.6). The truly existing deviation in the initial part of the switching impulse voltage is negligible on account of the larger values of the time parameters. The time to peak T_p is defined as the time between the true origin O and the instant of the peak, the time to half-value as the time between O and the point at $0.5\hat{u}$ on the tail of the switching impulse voltage.

In addition to T_p and T_2 , a few other time parameters are also defined. The time duration T_d is fixed as the *time above 90 %* during which the voltage is greater than $0.9\hat{u}$. In special cases, switching impulse voltages can also swing below the zero line in the tail region. It may therefore be necessary to specify the *time to zero* T_z between the true origin O and the instant of the first zero-crossing of the tail of the switching impulse voltages. Further, even the front time T_1 as per Eq. (2.2) is defined for switching impulse voltages. It serves as a criterion for distinguishing between lightning impulse voltages and switching impulse voltages. The latter have a front time of at least 20 μs .

Switching impulse voltages are identified by the numerical values of T_p and T_2 . The standard switching impulse voltage 250/2500 has a time to peak of 250 μs (tolerance: $\pm 20\%$) and a time to half-value of $T_2 = 2500\text{ }\mu\text{s}$ (tolerance: $\pm 60\%$). The large tolerances permit the testing of various types of high-voltage apparatus without having to adjust the elements of the impulse voltage generator each time to

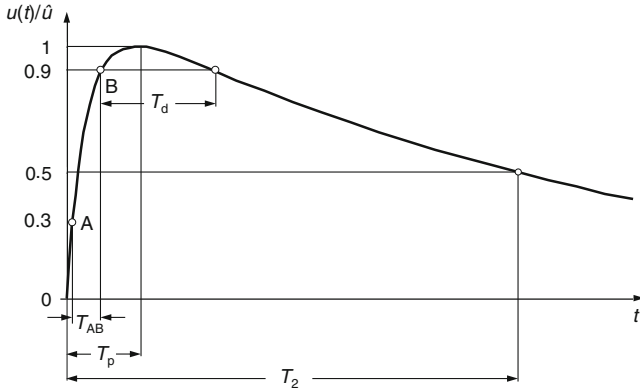


Fig. 2.6 Switching impulse voltage and its impulse parameters (aperiodic waveform)

match the varying loads. The permissible uncertainties of measurement agree with those for lightning impulse voltages and amount to 3 % for the test voltage value (peak value) and 10 % for the time parameters. The uncertainty comprises of the uncertainty of the approved measuring system and, wherever necessary, other uncertainty components during the impulse voltage test (see Sect. 2.1.1.1).

The time to peak T_p , on the basis of its definition, appears to be a measurement parameter simple to determine. However, during automatic data processing, small digitising errors of the recorder or superimposed oscillations in the extended time duration of the peak region can lead to erroneous values of the time to peak. Then the uncertainty for T_p prescribed in the test standards cannot be maintained. Since due to its significance in testing practice, the time to peak must be maintained as a time parameter, its determination is done, not directly but as the time interval T_{AB} between 0.3 and $0.9\hat{u}$, multiplied with the factor K :

$$\boxed{T_p = K \cdot T_{AB}}. \quad (2.5)$$

For the switching impulse voltage 250/2500 with double exponential waveform as per Eq. (3.8), the calculation results in $T_{AB} = 99.1 \mu\text{s}$ and thus $K = 2.523$. For other values of T_p and T_2 within the permissible tolerance limits of the standard switching impulse voltage 250/2500, K can be calculated approximately from the numerical Eq. (2.1):

$$K = 2.42 - 3.08 \times 10^{-3} T_{AB} + 1.51 \times 10^{-4} T_2 \quad (2.6)$$

in which, for T_{AB} and T_2 , the measured numerical values in microseconds are to be substituted. The error during calculation of T_p with K as per Eq. (2.6) lies within $\pm 1.5 \%$, which, as a rule, might be negligible during tests. For other switching impulse voltages, Eq. (2.6) is invalid. The factor $K = T_p/T_{AB}$ is then obtained from the waveform of a switching impulse voltage calculated as per Eq. (3.8), which has the same time T_{AB} as the measured waveform. For on-site tests with switching impulse voltages, a value of $K = 2.4$ is uniformly defined (see Sect. 2.1.3).

2.1.3 Impulse Voltages for On-Site Tests

Voltage tests on equipments of the electrical power supply systems are conducted not in a test laboratory alone, but more often directly at the location of the equipment itself [15, 16]. Thereby, the orderly setting up, error-free commissioning, trouble-free operation after repair or long-term behaviour etc., can be verified. Very often, difficult ambient conditions are prevalent for these *on-site tests* and also generating and measuring systems other than the stationary ones in a test laboratory would be required. In addition to aperiodic lightning and switching impulse voltages as per Figs. 2.1a and 2.6, *oscillating impulse voltages* can also be used. As an example, Fig. 2.7 shows an oscillating switching impulse voltage (curve 1) and its upper envelope (curve 2). Because of the superimposed oscillation, an almost doubling of the peak value of a smooth impulse voltage is attained, so that the transportable generator required for the on-site test could be correspondingly smaller.

Determination of the origin and the front time of oscillating lightning or switching impulse voltages is carried out in the same manner as corresponding aperiodic impulse voltages, i.e., for lightning impulse voltages, the virtual origin O_1 and for switching impulse voltages, the true origin O is decisive. The time to half-value T_2 is defined as the time interval between O_1 or O , as the case may be, and the instant at which the upper envelope of the oscillating impulse voltage declines to 50 % of the maximum value (Fig. 2.7). The time to peak T_p of a switching impulse voltage for on-site tests is obtained from the time T_{AB} as per Eq. (2.5) with a uniformly prescribed value of $K = 2.4$.

Due to the complicated ambient conditions, greater tolerances, and partly even greater measurement uncertainties are valid for the aperiodic and oscillating switching impulse voltages generated during on-site tests than those generated in high-voltage test laboratories. The tolerance limits for the test voltage values of the generated lightning or switching impulse voltages amount to $\pm 5\%$. For lightning

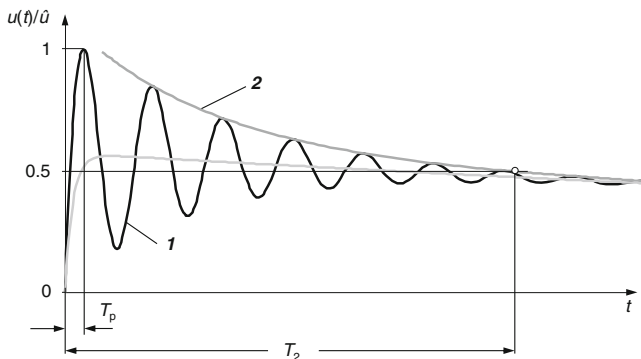


Fig. 2.7 Oscillating switching impulse voltage **1** for on-site tests. The upper envelope **2** is decisive for determining the time to half-value T_2

impulse voltages, the permissible values for the front time lie between 0.8 and 20 μs , for the time to half-value between 40 and 100 μs , and for the oscillation frequency between 15 and 400 kHz. Switching impulse voltages are specified with times to peak between 20 and 400 μs , times to half-value between 1,000 and 4,000 μs and oscillation frequencies between 1 and 15 kHz. The maximum permissible expanded uncertainties during on-site tests amount to 5 % for the value of the test voltage, 10 % for the time parameters and 10 % for the oscillation frequency [15].

2.1.4 Steep-Front Impulse Voltages

Very rapidly rising voltages are used, for example, during tests on insulators. Standardisation of *steep-front impulse voltages* applied in tests is not uniform but is left to the Technical Committees responsible for the individual power apparatus. With conventional impulse voltage generators of low-inductance of about 1 μH per stage, maximum steepness of 2.5 kV/ns can be attained. Impulse voltages of even greater steepness are obtained from impulse voltage generators together with a “peaking circuit” or with an exploding wire (see Sect. 2.3.3). By appropriate design of the circuit, steep-front impulse voltages with steepnesses up to 100 kV/ns, corresponding to a rise time of 5 ns per 500 kV, can be generated.

Figure 2.8 shows schematically the output voltage u_1 of an impulse voltage generator and the steep-front impulse voltage u_2 appearing at the output of the peaking circuit. With optimal matching between the elements of the impulse voltage generator and the peaking circuit, u_2 can be made to set in at the time of the peak of u_1 . The waveform on the tail depends on the circuit arrangement of the generator and the test object including the voltage divider. High-frequency oscillations can get superimposed on the steep-front impulse voltage due to inductances of switching elements in the test circuit or as a consequence of reflection phenomena. Pulse type electromagnetic fields can be generated between the electrodes of a strip-line arrangement connected to the peaking circuit. Equipments and even large complex systems are tested with such an electrode arrangement with regard to their electromagnetic compatibility (EMC) (see Ref. [2] in Chap. 1, [17], see Ref. [5] in Chap. 6).

2.2 Parameters of High-Current Impulses

Tests with high impulse currents are performed in order to simulate the stressing of power apparatus in the grid caused by lightning strokes and short-circuits. The waveform of impulse currents can be very different depending on the planned test purpose. Basically one differentiates between impulse currents with exponential waveform and those with rectangular waveform. Even short-time alternating currents belong to the category of impulse currents in an extended sense. They

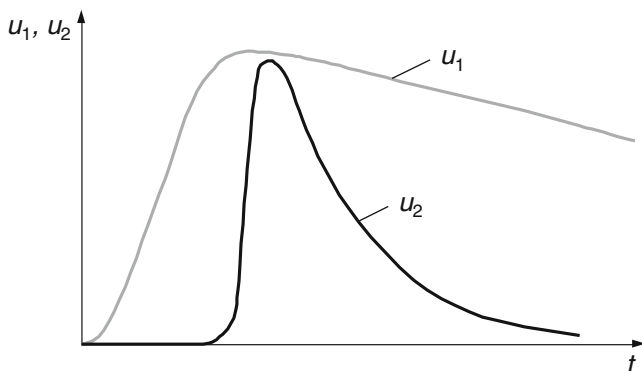


Fig. 2.8 Steep-front impulse voltage u_2 at the output of the peaking circuit connected to an impulse voltage generator with the output voltage u_1 (see Ref. [2] in [Chap. 1](#))

have a limited number of periods of power frequency and a superposed transient direct current component. Impulse currents are characterised by their peak value and several time parameters. The impulse charge and the energy content can also be of significance. The analytical representation of impulse currents appears in [Sects. 3.3](#) and [3.5](#) and calculation of its spectrum in [Sect. 3.4](#).

2.2.1 Exponential Impulse Currents

The *exponential impulse current* shows a relatively fast, nearly exponential rise up to the peak, which is followed by a rather slow decline to zero. Depending on the circuit of the generator and the test object, the decline takes place either exponentially or like a heavily damped sinusoidal oscillation ([Fig. 2.9](#)). In the latter case, one must reckon with the impulse current even crossing the zero line.

The characterising parameters of an exponential impulse current are, besides the value of the test current (peak value $\hat{i}$), the front time T_1 and the time to half-value T_2 . Both the time parameters are referred to the virtual origin O_1 which is determined as the point of intersection of the straight line through the impulse front and the zero line. In contrast to impulse voltages, the straight line through the front passes through the points A at $0.1\hat{i}$ and B at $0.9\hat{i}$. The front time works out to

$$T_1 = 1.25T_{AB}, \quad (2.7)$$

wherein T_{AB} is the time between the two points A and B. Thus, T_{AB} corresponds to the definition of the rise time T_a of an impulse common in the low-voltage range (see [Sect. 4.5](#)). The time to half-value T_2 is fixed as the time between the virtual zero and the instant at which the impulse current has declined to its 50 % value [[18](#)].

Exponential impulse currents are characterised by their front time and time to half-value in microseconds. As an example, the 8/20 impulse current has a front

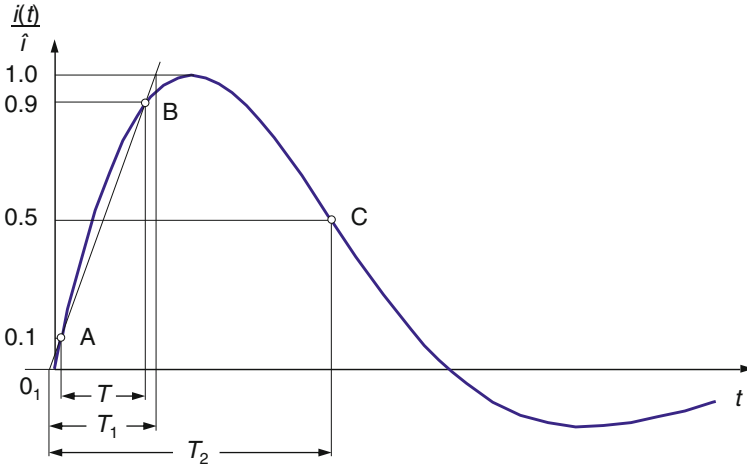


Fig. 2.9 Example of an exponential impulse current with the tail crossing the zero line

time $T_1 = 8 \mu\text{s}$ and a time to half-value $T_2 = 20 \mu\text{s}$. The tolerance limits while generating an 8/20 impulse current amount to $\pm 10 \%$ for the peak value and $\pm 20 \%$ for each of the time parameters. Tolerances specified for other impulse forms may differ. Limiting values of the expanded uncertainty are 3% for the peak value and 10% for the time parameters.

The polarity reversal after the exponential impulse current has crossed the zero line shall not be more than 30% of the peak value. Otherwise, there is the danger of the test object getting damaged by the current of opposite polarity. Calculations in Sect. 3.3 show that the condition for maximum polarity reversal in the simple impulse current circuit of Fig. 2.16 is achieved only for $T_2 > 20 \mu\text{s}$. The polarity reversal must however, be limited by an appropriate chopping device if need be.

The charge of an impulse current $i(t)$ is defined as the time integral over the absolute value of the waveform:

$$Q = \int_0^{\infty} |i(t)| dt. \quad (2.8)$$

The upper integration limit is so chosen that the residual contribution of the integral is negligible. Yet another measured quantity is the *Joule integral* as the time integral of the square of the impulse current:

$$W = \int_0^{\infty} i^2(t) dt, \quad (2.9)$$

by which the maximum permissible energy conversion in the test object or the measuring resistor is calculated. The values of Q and W at a test shall not be less than the values specified in the test standard for the power apparatus, i.e., the lower tolerance limit is zero.

2.2.2 Rectangular Impulse Currents

Figure 2.10 shows the typical waveform of a *rectangular impulse current*, also known as the *long-duration impulse current*. It is characterised by the value of the test current, $\hat{i}$, and two time parameters, the *duration* T_d of the peak and the *total duration* T_t [18]. The maximum value of the current, including the superimposed oscillation, is the value of the impulse current. Rectangular impulse currents often have a more or less pronounced droop. The time parameter T_d is specified as the time during which the current is consistently greater than $0.9\hat{i}$. Such a definition can lead to misunderstandings if oscillations are superimposed on the rectangular current as shown in Fig. 2.10, and they go below the $0.9\hat{i}$ value. Rated values for T_d are 500, 1,000 and 2,000 μs or even longer times up to 3,200 μs . On account of the long duration of the peak, the test with rectangular impulse currents represents a heavy stressing of the test object.

An additional time parameter is the total duration T_t , during which the current is greater than $0.1\hat{i}$, with the requirement $T_t \leq 1.5 T_d$. With that, indirectly a condition is imposed on the front time, on which there are no further requirements. For characterising the waveform of a rectangular impulse current, the values of T_d/T_t are given.

As upper tolerance during generation of rectangular impulse currents, +20 % is specified for both $\hat{i}$ and T_d , and 0 is the lower limit. A possible polarity reversal of the rectangular impulse current below the zero line shall not exceed 10 % of the test current value $\hat{i}$. For the charge as per Eq. (2.8) and the Joule integral as per Eq. (2.9), the lower limit of tolerance is again 0. Permissible measurement uncertainties amount to 3 % for the peak value and 10 % for the time parameters.

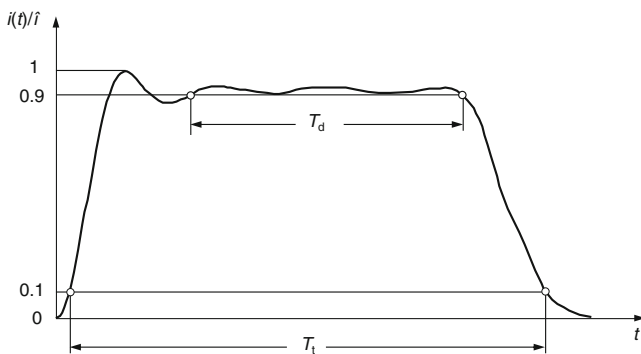


Fig. 2.10 Example of a *rectangular impulse current* with superimposed oscillation

2.2.3 Short-Time Alternating Currents

High alternating currents are caused by short circuits in power supply networks and usually last for a few periods. The stressing of the relevant power apparatus is thus tested in the power laboratory using *short-time alternating currents*. The *switching* or *actuating angle* Ψ characterises the instant at which the short circuit begins in comparison to the zero-crossing of the voltage. It determines predominantly the waveform of the short-time alternating current. In general, the form is an unsymmetrical one, which is characterised by an alternating current of power frequency superimposed with a transient DC component (Fig. 2.11a). In the extreme case, the peak value $\hat{i}$ of the short-time alternating current attains, due to the superimposed DC component, nearly double the value of the stationary alternating current. The maximum current amplitude can thus be several 100 kA. After exponential decay of the DC component, the short-time current lags the voltage by the *phase* or *impedance angle* which depends on the resistance and inductance of the shorted circuit. A symmetrical short-time current without any DC component comes into existence for certain switching and phase conditions (Fig. 2.11b).

In test standards, besides the *true r.m.s. value*:

$$I_{\text{rms}} = \sqrt{\frac{1}{T} \int_0^T i^2(t) dt}, \quad (2.10)$$

other r.m.s values of short-time currents are defined [18]. The *symmetrical ac component (r.m.s. value)* is given by the difference between the upper and lower envelopes of the short-time current divided by $2\sqrt{2}$. As *conventional r.m.s. value* of the alternating current, one defines the difference between the peak value of one half-wave and the mean peak value of the two neighbouring half-waves of opposite polarity divided by $2\sqrt{2}$ (the *three-crest method*). As tolerance limits during generation of short-time alternating currents $\pm 5\%$ is specified for the peak and r.m.s values. The expanded uncertainty shall not exceed 5 %.

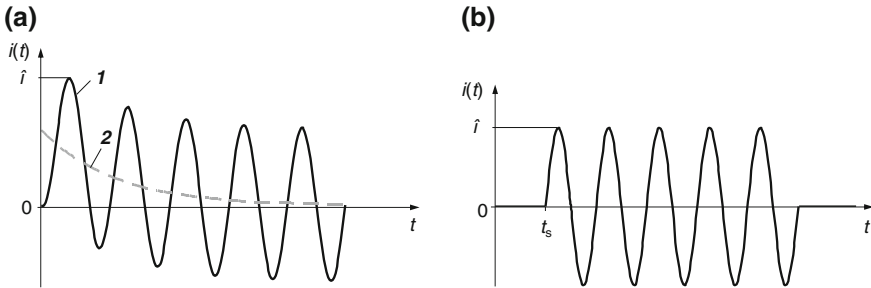


Fig. 2.11 Examples of short-time alternating currents. **a** symmetrical short-time alternating current I with transient DC component 2 , **b** symmetrical short-time alternating current

2.3 Generation of High Impulse Voltages and Currents

The basic principle of predominantly used generator circuits for generating high-impulse voltages and currents consists of a storage capacitor being slowly charged and, at a predetermined voltage, discharged quickly by a high-voltage switch on to a network and the test object. The waveform of the impulse voltage or the impulse current is determined by the network, which, to be sure, is influenced equally by the connected test object. The measuring system used is therefore to be connected directly to the test object and not to the output terminals of the generator (see Sect. 6.1). The constructional elements of the generators are to be designed with as low an inductance as possible and for a very high impulse loading. In addition to generator circuits with capacitive storage, other possibilities also come into consideration, e.g., inductive storage and transformers for the generation of switching impulse voltages.

2.3.1 Generators for Lightning and Switching Impulse Voltages

For the generation of lightning and switching impulse voltages, essentially there are two basic circuits available (Fig. 2.12). Common to both circuits is the impulse capacitor C_s , which is charged to the voltage U_0 relatively slowly by a rectified alternating current via the charging resistor R_L . When U_0 reaches the firing voltage of the sphere gap FS, it breaks down and C_s discharges in a very short time through the discharge circuit, which consists of the damping resistor R_d , the load capacitor C_b and the discharge resistor R_e . Unavoidable inductances of the circuit elements as well as their leads are not indicated. They can be combined in the equivalent circuit and taken into account by an inductance connected in series with R_d . The impulse voltage $u(t)$ can be obtained at the terminals of C_b and fed to the test object. Its impedance in turn affects the circuit and influences the waveform of the generated impulse voltage more or less. While R_d is primarily responsible for the charging of C_s , and thereby for the front time T_1 of the impulse voltage, R_e affects the discharge of C_b , and thereby the time to half-value T_2 .

Both the circuits in Fig. 2.12 differ from one another in the location of the discharge resistor R_e : in circuit A it is located behind the damping resistor R_d and in circuit B in front of it. The firing voltage of the sphere gap is adjusted by varying the spacing between the spheres, which also specifies the peak value of the generated impulse voltage $u(t)$. The ignition spark is extinguished after the discharge of C_s and C_b , the switching sphere gap FS opens and C_s can be charged again from the direct voltage source through R_L . The magnitude of the direct voltage U_0 or the charging current amplitude determines the ignition repetition rate of the switching sphere gap and thereby the impulse rate. In small impulse generators up to 10 kV, instead of the sphere gap, electronic switches are preferred.

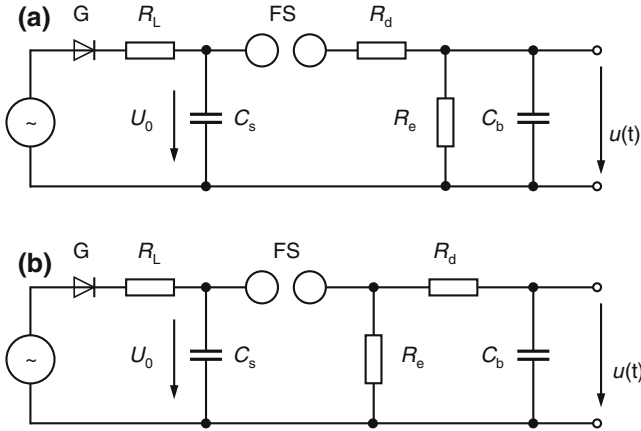


Fig. 2.12 Single-stage basic circuits for the generation of impulse voltages. **a** basic circuit A, **b** basic circuit B

The relationship between the switching elements and the waveform of the generated lightning or switching impulse voltage will be derived in Sect. 3.1.

The maximum energy stored in the impulse capacitor C_s :

$$W = \frac{1}{2} C_s U_0^2 \quad (2.11)$$

identifies the output capacity of the impulse voltage generator. The *utilisation efficiency* η is defined as the quotient of the peak value $\hat{u}$ of the generated impulse voltage and the charging voltage U_0 :

$$\eta = \frac{\hat{u}}{U_0} = f\left(\frac{C_s}{C_b}\right). \quad (2.12)$$

For achieving a high utilisation efficiency and thereby a high peak value, $C_s \gg C_b$. For example, in the circuit B of Fig. 2.12b with $C_s = 5C_b$, $\eta \approx 0.8$ for a 1.2/50 lightning impulse voltage. The utilisation efficiency of circuit B is basically greater than that of circuit A and is greater for lightning impulse voltages than for switching impulse voltages. Data about the utilisation efficiency of an impulse voltage generator are supplied in the form of a diagram by the manufacturer.

Single-stage basic circuits according to Fig. 2.12 are realised for impulse voltages up to a maximum of 300 kV. With the *voltage multiplier circuit* after E. Marx, relatively compact generators for lightning impulse and switching impulse voltages—also known as *Marx generators* in the English speaking regions—with charging voltages up to 10 MV can be constructed. Figure 2.13 shows the principle of a multistage lightning impulse voltage generator in circuit B, built up of a number of n identical stages. The basic principle of the multiplier circuit is that the individual impulse capacitors C_s' of each stage are at first slowly charged to a voltage U_0' and are suddenly connected in series by the firing of the switching

sphere gaps, so that the individual stage voltages add up to a total charging voltage nU_0' . The external load capacitor C_b is then charged through the series connection of all the damping resistors R_d' and discharged through all the R_e' and R_d' . In comparison to the single stage circuit of Fig. 2.12b, we have $R_e = nR_e'$, $R_d = nR_d'$, $C_s = C_s'/n$ and $U_0 = nU_0'$.

Other voltage multiplier circuits with a modification or combination of the two basic circuits are also in use. Impulse voltage generators are as a rule supplied with interchangeable sets of resistors and capacitors for generation of lightning or switching impulse voltages. During the charging process, external discharges can occur, which are suppressed by various methods. Figure 2.14 shows two different types of construction of impulse voltage generators with a total charging voltage of 3 MV. The individual stages of the generators are clearly recognisable. While impulse voltage generators are usually built up of rectangular type of individual stages with metallic framework (Fig. 2.14a), the individual stages of the generator in Fig. 2.14b have a triangular surface area with insulating side-plates [19].

Important precondition for the trouble-free functioning of the voltage multiplier circuit is the sure and time-staggered firing of the sphere gaps arranged one above the other. To ensure this, the lowest sphere-gap is set to a slightly reduced spacing, so that it fires somewhat earlier than the other sphere gaps. This can also be achieved by a triggered auxiliary discharge. Due to the firing of the lowest sphere gap, double the voltage appears for a very short time on the sphere gap lying above it, which leads to a fast firing. The other sphere gaps are also fired accordingly. Further, it is important that by the photoemission emanating from the firing of a sphere gap, a sufficiently large number of initial electrons is generated for a rapid firing of the sphere gap above it.

With increasing number of stages of an impulse voltage generator, it can happen that one or more of the sphere gaps may not fire. In particular, at low charging voltages of less than 20 % of the maximum total charging voltage, an assured firing is not always guaranteed. A solution is obtained by the controlled firing of all the sphere gaps, which is achieved in specially designed generators either electrically or optically with potential-free laser sources. Impulse voltage generators with triggered sphere gaps are required in combined alternating and impulse voltage tests, where the impulse voltage has got to be applied at a defined phase disposition of the alternating voltage. Reproducibility of the impulse voltage depends quite considerably on the stability of the charging direct voltage [20]. Electromagnetic fields developed during the firing of the sphere gaps affect the measuring system and could also influence the measured results. Such interference effects can be prevented only to a limited extent by shielding the measuring system (see Sects. 6.1 and 7.1).

The polarity of the impulse voltage generated can be changed by a simple polarity reversal of the rectifier G in Fig. 2.13. After a voltage impulse is generated or whenever the charging process is interrupted, dangerously high residual charges can remain in the capacitors. It is therefore not sufficient to earth the capacitors of the lowermost stages alone for short durations, since they get re-charged thereafter. In modern types of impulse generators, after switching off, residual charges of all

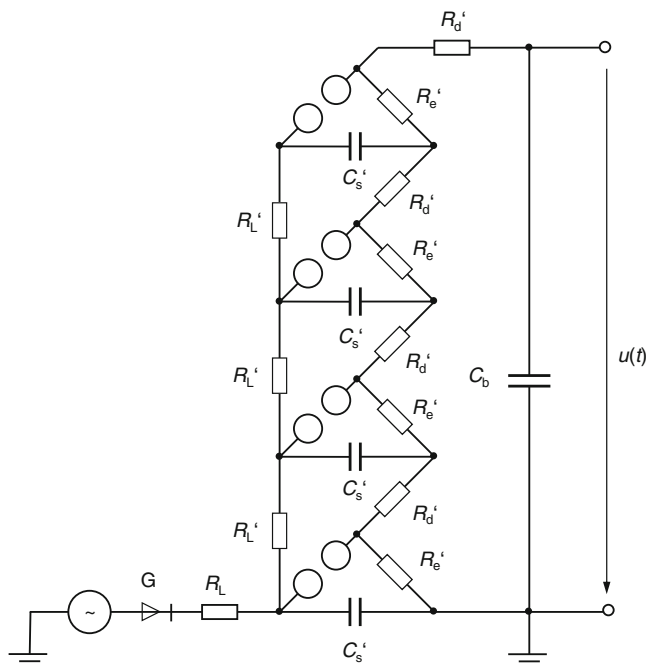


Fig. 2.13 Voltage multiplier circuit of the basic circuit B after E. Marx for the generation of impulse voltages of several megavolts

the capacitors are automatically conducted away to earth by a continuously rotating metallic band. The impulse repetition rate of a generator at maximal charging voltage is restricted by the manufacturer to one or two impulses per minute in order not to thermally overload the constructional elements.

The test object and the impulse voltage measuring system are connected in parallel to the load capacitor C_b . Their capacitances, including the stray capacitances add to C_b and hence affect the waveform of the impulse voltage generated. If necessary, the resistances R_e and R_d must be matched in order to maintain the tolerances permissible on the front time and time to half-value. The effect of various capacitances of the test object on the time parameters would be minimal, provided the generator is operated with as large a C_b as possible.

Occasionally, the load capacitor C_b in Fig. 2.13, as also the discharge resistor R_e in the comparable circuit A are provided with a low-voltage unit and used as a capacitive or resistive voltage divider. With such an arrangement, the voltage at the output terminals of the generator can surely be measured, however, not the impulse voltage being applied to the test object. For this purpose, the sequence prescribed is Generator—Test Object—Measuring Divider (see Sect. 6.1). As a rule, even the dynamic performance of dividers built up with C_b is inadequate since the required capacitances in the high-voltage and low-voltage units are realisable only with capacitors possessing high inductances.



Fig. 2.14 Two types of construction of impulse voltage generators. **a** total charging voltage 3.2 MV, 320 kJ (HIGHVOLT Prüftechnik Dresden GmbH), **b** total charging voltage 3 MV, 300 kJ (Haefely Test AG)

The tendency, already present in the basic circuit, towards oscillations due to the inductances of the constructional elements and of the test object connected in parallel to the load capacitor C_b , is further enhanced in the voltage multiplier circuit of Fig. 2.13. Long high-voltage leads from the generator to the test object also contribute towards damped oscillations, which are superimposed on the peak of the impulse voltage and thus enhance the stressing of the test object. In particular, lightning impulse voltages with short front times have an overshoot at the peak, since due to reduction of the damping resistance R_d the inductances in the test circuit play a greater role. With low values of the load capacitance C_b , non-optimal firing of the gaps of the individual generator stages leads to a damped oscillation on the front of the impulse voltage with a frequency above 1 MHz.

The enhanced stressing of the test object by an oscillation or overshoot at the peak of the lightning impulse voltage is certainly taken care of during data evaluation using the frequency-dependent test voltage function $k(f)$ (see Sect. 2.1.1); however, it is of course better to arrest the oscillating tendency by appropriate circuit arrangements right at the outset. For reducing the oscillation, the lightning impulse voltage generator can be extended by various compensatory circuits [21–23]. However, an elongation of the front time is usually coupled with it, which

cannot be always tolerated. Furthermore, it has to be noted that a distinct short-duration overshoot at the peak places an enhanced requirement on the dynamic properties of the measuring system. If the bandwidth of the measuring system is insufficient, the overshoot is not captured correctly, so that the maximum value of the test voltage is shown to be too low.

During impulse voltage test of inductances with $L_b < 40$ mH, which, for example, is represented by the low-voltage winding of a power transformer, the tail of the lightning impulse voltage is heavily deformed and the time to half-value reduced to less than 40 μ s, i.e., lower than the permissible tolerance limit. Even an undershoot of the lightning impulse voltage below the zero line is possible. As a rule, the voltage of a single stage is adequate for the test. With an inductance $L_d = 400$ μ H connected in parallel with the damping resistor R_d (see Fig. 2.12b), the time to half-value can again be increased. For still lower inductances $L_b < 4$ mH, an inductance $L_d < 100$ μ H connected parallel to R_d and an additional resistor $R_b = R_d L_b / L_d$ parallel to the load capacitor C_b offer a solution (see Ref. [2] in Chap. 1, [24–26]).

The influence of the load represented by the test object and that due to the circuit elements on the waveform of the generated impulse voltage can be investigated theoretically by several methods and software for calculating linear circuits, with the aim of optimising the generator circuit [27–32]. The reverse way of arriving at the corresponding values of circuit elements for given values of the time parameters T_1 and T_2 is treated in [33].

Switching impulse voltages can also be generated with testing transformers which are excited by a voltage jump. In one circuit, the network alternating voltage at its peak value and in the other, the charge of a capacitor is switched on to the low-voltage winding. The switching impulse voltages appearing at the high-voltage terminals of the transformer have waveforms mostly other than the standard ones—especially, the time to peak and time to half-value are longer. By proper layout of the testing transformers, oscillating switching impulses will appear (see Refs. [2, 5] in Chap. 1, [34]).

Oscillating switching impulses for on-site tests are, as a rule, generated with impulse voltage generators in which the damping resistor R_d in the basic circuit of Fig. 2.12b is either replaced or extended by an inductance. Due to the superimposed oscillation, the maximum value is nearly double that of an aperiodic impulse voltage which is generated with the same value of the charging voltage (see Refs. [2, 5] in Chap. 1, [34]).

2.3.2 Generation of Chopped Impulse Voltages

Chopped impulse voltages are generated with the help of a sphere gap connected parallel to the load capacitor C_b of the lightning impulse voltage generator. A triggered sphere gap is necessary to obtain a reproducible chopping on the tail of impulse voltages (see Ref. [1] in Chap. 1). Impulse voltages chopped on the front

can be generated without triggering, if the sphere gap is irradiated by UVC light. Due to such irradiation, a sufficient number of initial electrons to initiate the firing is generated in the breakdown path, on account of which the reproducibility of chopping improves [35]. Reproducibility obtained in this manner should be adequate for most of the applications, among others, the calibration of measuring systems with chopped impulse voltages. To obtain different steepnesses of the impulse voltage of the same maximum value, the spacing between the spheres has to be varied. Atmospheric ambient conditions affect the peak value as well (see Sect. 6.2).

For generation of chopped impulse voltages more than 600 kV, the use of a multiple spark gap is recommended (see Ref. [4] in Chap. 1, [36]). It consists of n sphere gaps arranged above one another and obtaining the same potential difference via a parallel connected n -stage voltage divider made up of resistors or capacitors. Firing of the multiple spark gap is initiated by the triggering of the lowest two or three sphere gaps. Overvoltages appear in the voltage divider due to firing of the gaps, on account of which the upper sphere gaps also fire. Triggering can be effected electronically or by laser pulses. Gas-filled sphere gaps or multiple-plate gaps are utilised for achieving a very fast breakdown.

2.3.3 Generation of Steep-Front Impulse Voltages

In conventional impulse voltage generators built with low-inductive elements, impulse voltages with a maximum steepness of up to 2.5 kV/ns can be generated. Still greater steepnesses cannot be directly obtained due to the unavoidable self-inductances of the generator elements—of the order of more than 1 μH per stage—and the connecting leads. For generation of steep-front impulse voltages with appreciably higher steepnesses, the lightning impulse voltage generator is operated with an auxiliary circuit—the “peaking circuit” [37–40]. In the principle drawing of Fig. 2.15, C_1 is the load capacitor of the lightning impulse voltage generator **1** with a capacitance of 1...2 nF. In the peaking circuit **2**, L represents the unavoidable inductance of the connecting leads and the switching elements that lie in series with the resistor R_1 . On attaining the peak value of the lightning impulse voltage u_1 , the spark gap FS fires and the capacitor C_2 of the peaking circuit with a capacitance of (0.1...0.2) C_1 is very quickly charged and slowly discharged again through the load R_2 .

The charging process, and with that, the steepness of the output voltage u_2 depends, besides upon the resistor R_1 , on the inductance L of the peaking circuit and the breakdown time of the spark gap FS. In order to keep the inductance L as low as possible, low-inductance elements such as ceramic capacitors and carbon composition resistors are made use of in the circuit. Compressed-gas filled sphere gaps or multi-plate spark gaps serve as spark gaps. The drop in the tail of the steep-front impulse voltage is determined by the load resistor R_2 . With the help of a fast chopping gap at the output of the peaking circuit, even steep-front impulse

voltages of nearly rectangular waveforms can be generated. In test practice, various variants of the principle drawing of Fig. 2.15 have come up. By careful construction, rise times of the steep-front impulse voltage low down to a few nanoseconds and steepnesses of the order of 100 kV/ns can be achieved.

Steep-front impulse voltages can as well be generated with exploding wires as switches [41]. For generating very steep impulse voltages, a copper wire connected at the terminals of the impulse voltage generator is made to melt in an explosive manner by the application of a lightning impulse voltage. Together with the circuit inductances and capacitances, a steep-front impulse voltage develops, whose peak value and time parameters depend on the length and diameter of the wire. The peak value of the steep-front impulse voltage generated by an exploding wire can be a multiple of the total charging voltage of the generator. The maximum achievable steepness of the voltage is of the order of 10 kV/ns. The set-up with an exploding wire is also used for commutation of an impulse current with steep front on to a test object that is connected parallel to the wire and the impulse generator.

In test set-ups for proving the electromagnetic compatibility of electronic equipments or for investigation of the screening effect of electronic switching cabinets, a horizontal strip-line is connected to the peaking circuit of Fig. 2.15 so that a pulse-like electromagnetic field (EMP) develops between the strip-line and earth. Depending on the application, the strip-line set-up can assume large dimensions so that entire constructional groups all the way from distributor panels of power supply systems to automobiles can be tested [42]. Rise times of the electromagnetic field of the order of a few nanoseconds, which are comparable to those of high-altitude nuclear explosions (NEMP), are obtained with such EMP generators [43]. Largest set-ups of this type are naturally to be found in military establishments.

2.3.4 Generators for Exponential Impulse Currents

For generating exponential impulse currents in a test laboratory, as a rule, a circuit with a capacitive energy storage is used (Fig. 2.16). The capacitor C is charged to a prescribed voltage U_0 and discharged suddenly on to the test object P via the

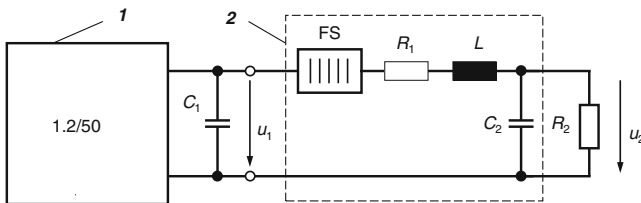


Fig. 2.15 Generation of steep-front impulse voltages with a lightning impulse voltage generator 1 and the peaking circuit 2 with multiple-plate spark gap FS

resistor R and inductance L by means of a switch, which could be a thyristor or a triggered spark gap. On the built-in measuring resistor R_m , a voltage $u_m(t)$ proportional to the current $i(t)$ can be tapped. The waveform of the generated impulse current depends not only on R , L and C but also on R_m and the impedance of the test object (see Sect. 3.3).

Test standards provide a multiplicity of different waveforms. By appropriate selection of plug-ins in table-top units or changing of elements in larger units, impulse current generators can be made to suit the requirements comparatively easily. Calculation of the desired waveforms and the elements is undertaken with the help of various methods [44, 45]. A method described in [46] applies commercial software with which the circuit elements of an impulse current generator in modular construction can be calculated for a prescribed waveform. If the characteristic data of the test object are not known, these can also be determined with this method of calculation. Thereby, the otherwise time-consuming experimental preparatory work required for matching the circuit elements to the desired waveform is eliminated.

Compact table-top models with peak values of a few 10 kA up to spatially extended impulse current set-ups with 200 kA or more are in use. The maximum charging voltage U_0 of table-top models and larger set-ups ranges from 10 to 200 kV. Impulse current generators of very high current amplitudes are constructed in modular form with several impulse capacitors connected in parallel and arranged in a partially circular or totally circular arrangement (Fig. 2.17).

Note: In order to avoid dangerously high open-circuit voltages, the output terminals of impulse current generators must be short-circuited through the low-ohmic test object or, if the generator is not in operation, through a shorting link.

In principle, impulse voltage generators can also be rearranged in such a manner that in short-circuit conditions they generate impulse currents [47]. Achievable current magnitudes lie below those subjectively expected values, e.g., 40–70 kA for an 8/20 current impulse, depending on the capacitance of the impulse capacitors C_s of a 2 MV impulse voltage generator.

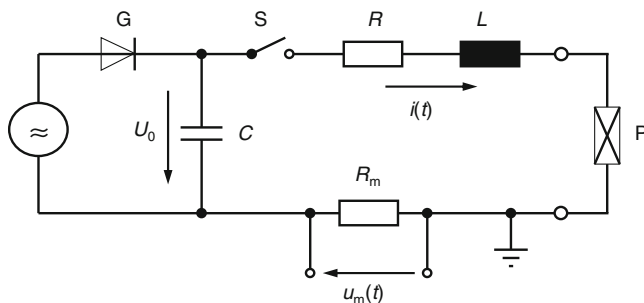


Fig. 2.16 Principle diagram of a generator with capacitive energy storage for the generation of exponential impulse currents

The waveform and thereby the impulse parameters of the exponential impulse current are determined by the impedances of the entire circuit, including those of the connected test object, the measuring system and the connecting leads. Figure 2.18 shows the influencing of the time parameters T_1 and T_2 by an enhanced resistance R_p of the test object P in the discharge circuit of a table-top model type 20 kA impulse current generator with a charging voltage of 10 kV in the circuit as per Fig. 2.16. The same effect is also caused by an enhanced measuring resistance R_m . Whereas by a short-circuit across the output terminals of the generator, i.e., $R_p = 0$, an impulse current 8/20 is generated, with increasing R_p , the front time decreases and the time to half-value increases. Furthermore, with increasing resistance, the voltage drop across it increases and the generator can no longer generate the specified maximum current amplitude. If the values of C and L in the equivalent circuit are known, the effect of the resistance on T_1 and T_2 can also be calculated (see Sect. 3.3).

The tail of the impulse current generated by the circuit of Fig. 2.16 consists of a more or less distinct oscillation, which could also partially pass below the zero line (Fig. 2.9). For an 8/20 impulse current, such undershoot of the opposite polarity amounts approximately to about one third of the current's main peak value (see Sect. 3.3). Undershoot of this order of magnitude is undesirable while testing lightning arrestors and other power apparatus. By increasing the value of R in

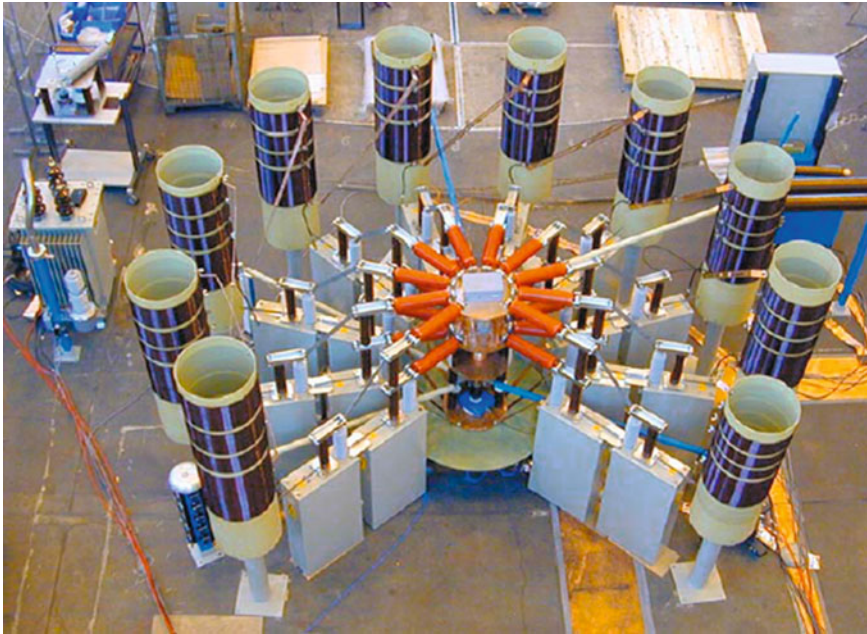


Fig. 2.17 Example of a 200 kA impulse current generator (100 kV, 250 kJ) in modular construction (HIGHVOLT Prüftechnik Dresden GmbH)

Fig. 2.16, such undershoots are certainly reduced; however, on the other hand, the peak value also reduces.

An effective improvement in the case of oscillating impulse currents is brought about by the *crowbar technique* (Fig. 2.19). Very high current impulses, with an exponentially reducing tail, can be generated with it. The most important element of the extended generator circuit is the triggered *crowbar gap* CFS with the gap resistance R_{CR} [48, 49]. The indicated circuit elements L_1, R_1 and L_2, R_2 account for the self-inductances and the lead resistances of the generator circuit and the test object. The crowbar gap is at first kept open. After firing of the gap FS at time $t = 0$, the capacitor C charged to a voltage U_0 discharges through the circuit elements and the test object P as in the circuit of Fig. 2.16. Current through the test object increases (Fig. 2.20). At the time of the current peak $t = t_p$, the crowbar gap is fired with the help of the trigger gap TF: hereby, the circuit with L_2, R_2 and the test object P is short-circuited through the gap resistance R_{CR} . At the time of the peak t_p , in case $L_2 \gg L_1$, nearly the entire energy stored earlier in the capacitor C discharges into the test object. After attaining the peak, the impulse current decreases exponentially with the time constant $L_2/(R_{CR} + R_2)$; an undershoot of the opposite polarity does not occur in this case (curve 2 in Fig. 2.20).

Exponential impulse currents can also be generated with inductive energy storage systems. Here, a coil is charged with direct current through a charging circuit and an initially closed switch lying in parallel to the load; then, suddenly by

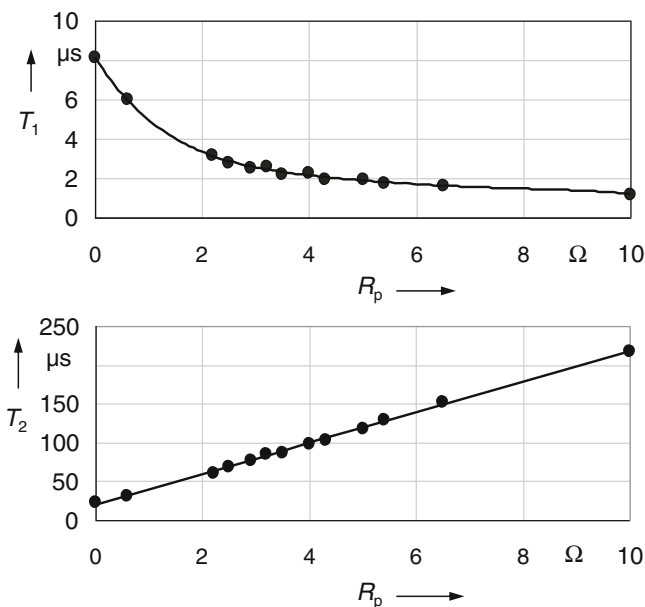


Fig. 2.18 Influencing of the time parameters T_1 and T_2 of impulse currents by the load resistor R_p in the discharge circuit of the impulse generator of Fig. 2.16

opening the switch, it is commutated into the test object. In practice, circuit-breakers or wires which evaporate explosively at very high current amplitudes and thus interrupt the charging circuit (see Ref. [2] in Chap. 1, [41, 50]), have been used as fast commutating switches.

For simulation of multiple lightning strokes, impulse current generators which can generate a fast sequence of impulse currents with different impulse forms and of both polarities have been used [51, 52].

2.3.5 Generation of Rectangular Impulse Currents

The principle diagram of a generator for the generation of *rectangular (long-duration) impulse currents* with duration of more than 1 μs for testing lightning arrestors is shown in Fig. 2.21. The series connected LC-elements form an n-stage ladder network. The capacitances C' connected in parallel are charged by direct voltage U_0 from a rectified alternating voltage and discharged into the terminating resistor R_1 and the test object P through a triggered spark gap FS. For the terminating resistance, we have:

$$R_1 = \sqrt{\frac{L}{C}} \quad (2.13)$$

with $L = nL_i$ and $C = nC'$. Wherever required, the resistive part of the test object P is to be taken into account by R_1 in Eq. 2.13. The duration of the peak T_d of the rectangular pulse as per Fig. 2.10 can be approximately calculated as:

$$T_d \approx 2 \frac{n-1}{n} \sqrt{LC}. \quad (2.14)$$

From Eqs. (2.13) and (2.14), L and C can be arrived at for the specified rectangular current of duration T_d . Numerical calculations for a generator with $n = 8$

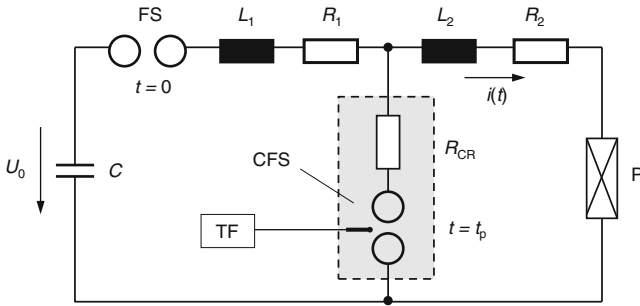


Fig. 2.19 Current impulse generator with crowbar gap CFS to prevent undershoot on the tail of impulse currents

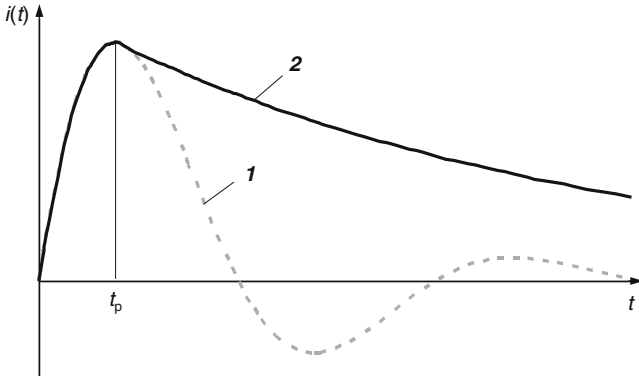


Fig. 2.20 Impulse form 1 without crowbar gap and impulse form 2 with crowbar gap (schematic)

elements show that an asymmetrical set-up of the ladder network is more advantageous in order to obtain, as far as possible, a rectangular current pulse without large overshoots or undershoots at the beginning or at the end. The values of the inductances $L_1 \dots L_n$ differ considerably, while the individual stage capacitances C' of the ladder network remain constant (see Ref. [1] in [Chap. 1](#), [53]).

2.3.6 Generation of Short-Circuit Alternating Currents

Short-circuit alternating currents for testing power apparatus in power supply networks are generated in high-power testing fields by means of powerful machines up to the highest current amplitudes of several 100 kA. The short-circuit current required for testing circuit-breakers is restricted to a few periods or half-periods, so that the maximum duration of the test lies in the range of 1 s (see Ref. [2] in [Chap. 1](#), [18]). The processes can be described with the help of the simple equivalent circuit in [Fig. 2.22](#).

The short-circuit path is simulated by the resistance R and the inductance L of the test object and the connecting leads. At the switching instant $t = t_0$, the

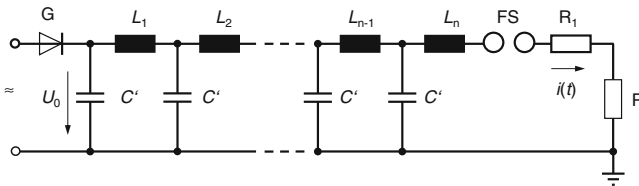
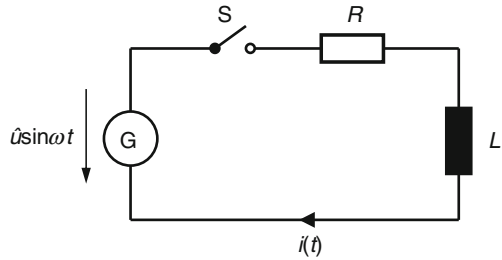


Fig. 2.21 Principle of the circuit diagram of a generator for *rectangular* impulse currents

Fig. 2.22 Equivalent circuit of test set-up with generator G for generation of short-circuit alternating currents



alternating voltage with instantaneous value $u(t_0) = \hat{u} \sin \Psi$ is switched on to the short-circuit path, where ψ is the switching angle (see Sect. 3.5). Under the assumption of a rigid alternating voltage which remains unchanged on the test object at $\hat{u} \sin(\omega t + \Psi)$, a short-circuit alternating current $i(t)$ as per Eq. (3.36) flows for a prescribed duration or number of periods. In stationary operation, the short-circuit current lags behind the voltage by a phase angle φ on account of the inductive load. Depending on the switching angle Ψ , a more or less large DC component that declines exponentially with time is superposed on the stationary short-circuit current (Fig. 2.11a). The short-circuit alternating current with superposed DC component, by which the peak value is increased up to nearly twice the magnitude, represents an extremely heavy stressing of the test object. Short-circuit alternating currents of smaller magnitudes can also be generated with a static generator that is controlled by a digital-to-analogue converter with the desired waveform.

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