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SERIES K: PROTECTION AGAINST INTERFERENCE

Surge protective components: Overview of surge mitigation functions and technologies

Recommendation ITU-T K.96

ITU-T

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Surge protective components: Overview of surge mitigation functions and technologies

Summary

Recommendation ITU-T K.96 presents information on the basic forms of surge mitigation and component technologies available to device and equipment designers. Following this basic Recommendation, further Recommendations in this surge protective components series will describe the applications principles of specific component technologies.

History

Edition	Recommendation	Approval	Study Group	Unique ID*
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Keywords

Current limiters, filters, impulse generators, mitigation, surge, transformers, voltage limiters.

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Surge protective components: Overview of surge mitigation functions and technologies

1 Scope

Surge protective components (SPCs) are used in power, telecommunication surge protective devices (SPDs) and equipment ports. This Recommendation gives an overview of:

- surge mitigation functions both non-linear and linear,
- implementing component technologies and characteristics, and
- information on the impulse (surge) generators used to test surge protective components (SPCs), surge protective devices (SPDs) and equipment ports.

2 References

None.

3 Definitions

3.1 Terms defined elsewhere

This Recommendation uses the following terms defined elsewhere:

3.1.1 avalanche breakdown (of a PN junction) [b-IEC 60050-521]: Breakdown that is caused by the cumulative multiplication of charge carriers in a semi-conductor under the action of a strong electric field, which causes some carriers to gain enough energy to liberate new hole-electron pairs by ionization.

3.1.2 bidirectional transistor [b-IEC 60050-521]: Transistor which has substantially the same electrical characteristics when the terminals normally designated as emitter and collector are interchanged.

3.1.3 bipolar junction transistor [b-IEC 60050-521]: Transistor having at least two junctions and whose functioning depends on both majority carriers and minority carriers.

3.1.4 breakdown (of a reverse-biased PN junction) [b-IEC 60050-521]: Phenomenon, the initiation of which is observed as a transition from a state of high dynamic resistance to a state of substantially lower dynamic resistance for increasing magnitude of reverse current.

3.1.5 diode (semiconductor) [b-IEC 60050-521]: Two-terminal semiconductor device having an asymmetrical voltage-current characteristic.

NOTE – Unless otherwise qualified, this term usually means a device with the voltage-current characteristic typical of a single PN junction.

3.1.6 disruptive discharge [b-IEC 60050-212]: Passage of an electric arc following electric breakdown.

3.1.7 disturbance suppression [b-IEC 60050-161]: Action which reduces or eliminates electromagnetic disturbance.

3.1.8 electromagnetic disturbance [b-IEC 60050-161]: Any electromagnetic phenomenon which may degrade the performance of a device, equipment or system, or adversely affect living or inert matter.

NOTE – An electromagnetic disturbance may be an electromagnetic noise, an unwanted signal or a change in the propagation medium itself.

3.1.9 filter [b-IEEE Std 802.7]: Circuit that selects or rejects one or more components of a signal related to frequency.

3.1.10 forward direction (of a PN junction) [b-IEC 60050-521]: Direction of current that results when the P-type semiconductor region is at a positive voltage relative to the N-type region.

3.1.11 insulation [b-IEC 60664-2-1]: That part of an electrotechnical product which separates the conducting parts at different electrical potentials.

3.1.12 insulation coordination [b-IEC 60664-2-1]: Mutual correlation of insulation characteristics of electrical equipment taking into account the expected micro-environment and other influencing stresses.

3.1.13 isolating transformer [b-IEC 60065]: Transformer with protective separation between the input and output windings.

NOTE – Isolating transformers can be divided into three groups; mains, switched mod and signal (e.g., Ethernet data).

3.1.14 impulse withstand voltage [b-IEC 60664-2-1]: Highest peak value of impulse voltage of prescribed form and polarity applied to a circuit or equipment, which does not cause degradation or result in breakdown or flashover.

3.1.15 low-pass filter [b-IEEE Std 1149.6]: Electrical network that passes lower frequencies, including DC levels, and attenuates higher frequencies.

3.1.16 overvoltage [b-IEC 60664-2-1]: Any voltage having a peak value exceeding the corresponding peak value of maximum steady-state voltage at normal operating conditions.

3.1.17 punch-through (between two PN junctions) [b-IEC 60050-521]: Contact between the space charge regions of two PN junctions as a result of widening of one or both of them.

3.1.18 sparkover [b-IEC 60050-212]: Disruptive discharge in a gaseous or liquid insulating material.

3.1.19 suppression component [b-IEC 60050-161]: A component specially designed for disturbance suppression.

3.1.20 Zener breakdown (of a PN junction) [b-IEC 60050-521]: Breakdown caused by the transition of electrons from the valence band to the conduction band due to tunnel action under the influence of a strong electric field in a PN junction.

3.2 Terms defined in this Recommendation

This Recommendation defines the following terms:

NOTE – Some term definitions, specifically defined for non-linear voltage limiters, are inappropriate for the wide range of mitigation functions covered in this Recommendation. The definitions for these terms have been redefined to make them generic.

3.2.1 band-pass filter: Filter that allows passage of a desired range of frequencies and attenuates frequencies outside the desired range.

NOTE – This definition is based on the definition provided in [b-IEEE Std 802.7].

3.2.2 common-mode choke filter: Series in-line transformer used to mitigate common-mode current flow without affecting differential current flow.

3.2.3 common mode conversion: Process by which a differential mode electrical signal is produced in response to a common mode electrical signal.

NOTE – This definition is based on the definition provided in [b-IEC 60050-161].

3.2.4 common-mode rejection filter: Filter type, usually a balanced filter that attenuates the signal common to both input lines; that signal is called the common-mode signal.

NOTE – This definition is based on the definition provided in [b-IEEE Std 1549].

3.2.5 common-mode surge: Surge appearing equally on all conductors of a group at a given location.

NOTE 1 – The reference point for common-mode surge voltage measurement can be a chassis terminal, or a local earth/ground point.

NOTE 2 – Also known as longitudinal surge or asymmetrical surge.

3.2.6 differential-mode surge: Surge occurring between any two conductors or two groups of conductors at a given location.

NOTE 1 – The surge source maybe be floating, without a reference point or connected to reference point, such as a chassis terminal, or a local earth/ground point.

NOTE 2 – Also known as metallic surge or transverse surge or symmetrical surge or normal surge.

3.2.7 fold-back breakdown (of a bidirectional transistor): Re-entrant breakdown characteristic caused by transistor action producing a region of negative dynamic resistance before reverting back to a low positive dynamic resistance condition.

NOTE – In transistor terms, the initial breakdown is in the BV_{CBO} mode, which changes to the lower voltage BV_{CEO} mode as the breakdown current increases.

3.2.8 high-pass filter: Electrical network that passes higher frequencies, attenuates lower frequencies and blocks DC levels.

NOTE – This definition is based on the definition provided in [b-IEEE Std 1149.6].

3.2.9 neutralizing transformers: Transformers that, through a sensing winding connected to local and remote grounds, introduce a series voltage into a signal circuit pair to oppose differences in local and remote ground potentials and induced common mode voltages.

3.2.10 overcurrent: Any current having a peak value exceeding the corresponding peak value of maximum steady-state current at normal operating conditions.

3.2.11 power fault: Abnormal fault condition, when the local ac power service is in electrical contact (Power Contact) or is magnetically coupled (Power Induction) to another service.

3.2.12 surge: Temporary disturbance on the conductors of an electrical service caused by an electrical event not related to the service.

NOTE – For non-linear SPCs a surge event is defined as an overvoltage or overcurrent or both.

3.2.13 surge protective component (SPC): component specifically included in a device or equipment for the mitigation of the onward propagation of overvoltages or overcurrents or both.

3.2.14 surge protective device (SPD): Device that mitigates the onward propagation of overvoltages or overcurrents or both.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

BV_{CBO} Collector-Base Breakdown Voltage, Emitter Open

BV_{CEO} Collector-Emitter Breakdown Voltage, Base Open

DC Direct Current

DSL Digital Subscriber Line

ECL Electronic Current Limiter

EMC Electromagnetic Compatibility

EPR Earth Potential Rise

FFT	Fast Fourier Transform
GDT	Gas Discharge Tube
GPR	Ground Potential Rise
IC	Integrated Circuit
ICT	Information and Communication Technology
LCR	Inductance, Capacitance Resistance
MOV	Metal-Oxide Varistor
PLC	Power Line Communication
PTC	Positive Temperature Coefficient
SPC	Surge Protective Component
SPD	Surge Protective Device

5 Protection or mitigation or suppression?

The terms "protection" and "protective" are part of the surge protection engineering discipline vocabulary. It should be remembered that these terms imply that, under specified conditions, the surge is reduced to a level below the withstand capability of the following circuit or equipment. However, in the field the incoming surge parameters are the result of many factors, rather than conforming to the standardized impulses from the generators specified in various standards. Likewise the following circuit or equipment withstand can be unknown.

The inclusion of an SPC should reduce the onward level of the incoming surge, but not necessarily to the withstand level of the "protected" item and that withstand level may be unknown. For these reasons the ITU-T prefers to use the term "surge mitigation" (make (something bad) less severe, serious, or painful) instead of "surge protection". If surge protection is achieved then it is a successful case of surge mitigation.

In [b-IEEE Std C62.50] a protection design technique is described for telecom equipment ports that conform to the surge withstand levels of a specific standard. The surge levels applied to the SPC will be greater than that the equipment withstand, otherwise the SPC function is redundant. At these higher levels the surge mitigation should result in an onward open-circuit surge voltage no greater than the equipment surge test generator open-circuit voltage and an onward short-circuit current no greater than the equipment surge test generator short-circuit current. This is an approach that forces a defined level of coordination between the mitigation level and the following equipment withstand.

The electromagnetic compatibility (EMC) area has its own vocabulary as all types of electromagnetic disturbances are considered, not just lightning and power fault and the protective function is termed suppression, see clause 6.2.

6 Surge mitigation functions

6.1 Non-linear protective functions

These functions have a predetermined threshold level beyond which their characteristic changes to limit the surge level. To avoid degrading normal system operation the threshold level set to be higher than the maximum expected system voltage and current. Overvoltages and overcurrents are classified as surge levels that exceed the threshold value of the limiter.

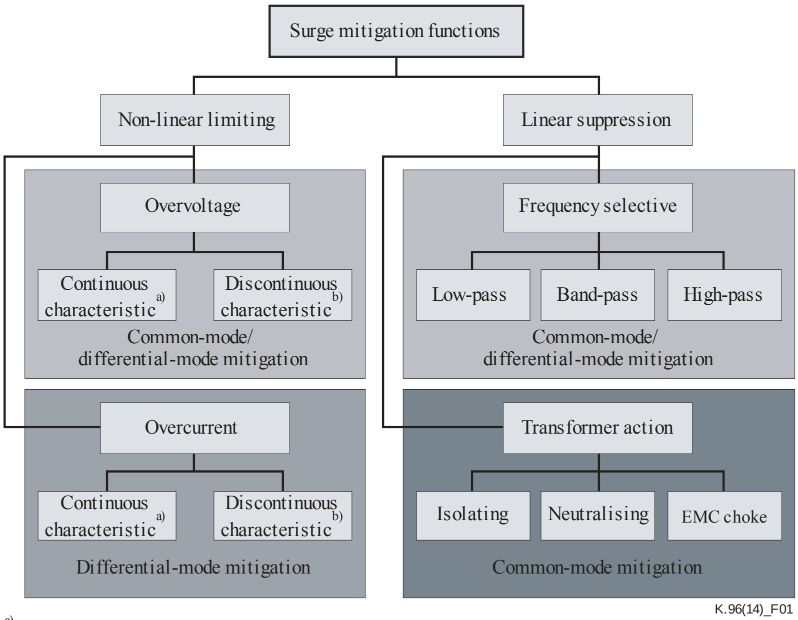
6.2 Linear suppression functions

These functions selectively attenuate electromagnetic disturbances, such as surge, by use of transformer action or frequency selective filtering. These approaches can only be used in specific circumstances.

7 Component technologies and characteristics

7.1 Surge mitigation functions

Figure 1 shows the various types of surge mitigation functions. The left side of the figure shows non-linear functions and the right side shows linear attenuating functions. Some functions can be used to mitigate common-mode and differential-mode surges, while others are limited to differential-mode or common mode surges



a) Clamping characteristic
b) Switching characteristic, has a switching transition

Figure 1 – Common Surge Mitigation Functions

7.2 Non-linear limiting

This form of surge mitigation operates by limiting (clipping) surge amplitudes that exceed a predetermined threshold value to values either close to that of the threshold or much lower than the threshold.

Surge mitigation controlled by an integrated circuit (IC) and a power element can be multimode. For example in a direct current (DC) supply feed using such an arrangement the IC can maintain the conditioned voltage to a fixed level for various combinations of surge voltage and time, but when these combinations are exceeded, the power element is switched off to prevent over-dissipation and the conditioned voltage falls to zero. This sophisticated form of surge mitigation is not covered by this Recommendation.

Gated thyristors, as standardized in [b-IEEE Std C62.37], can be used for individual or combined over-current and overvoltage protection.

7.2.1 Overvoltage limiting

Voltage limiting components draw little current until the voltage exceeds the predetermined threshold voltage of the component.

7.2.1.1 Continuous characteristic

These components use solid-state materials. Metal-oxide varistors (MOVs) use the properties of sintered material and silicon semiconductor components use the properties of single or multiple PN junctions. All components have a clamping vi characteristic, but the clamping characteristic varies with technology, see Figure 2 for two examples.

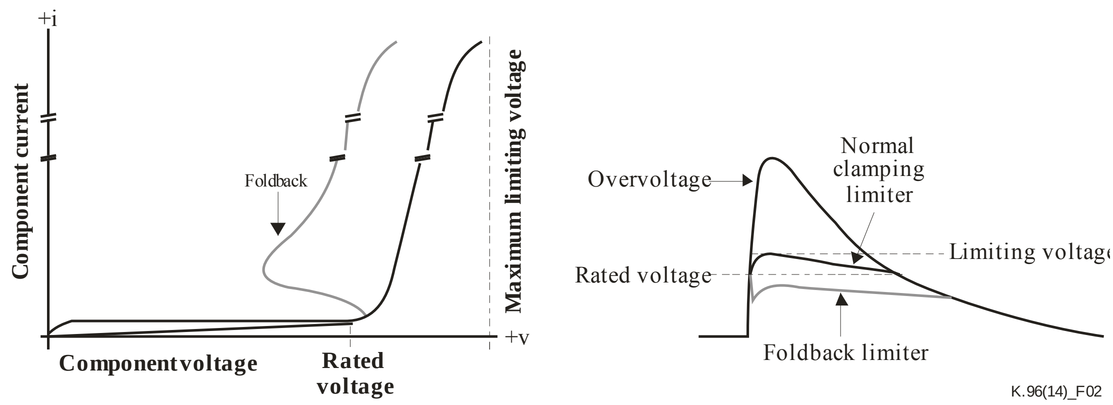


Figure 2 – Overvoltage limiting – Continuous (clamping) characteristics

Technologies with these characteristics are:

- metal-oxide varistors (MOVs)
- forward direction semiconductor diodes
- Zener breakdown semiconductor diodes
- avalanche breakdown semiconductor diodes
- punch-through semiconductor bipolar junction transistor diodes
- fold-back semiconductor bidirectional transistor diodes.

7.2.1.2 Discontinuous characteristic

These components use solid-state materials or gases. Figure 3 shows the vi characteristics for a solid-state thyristor and a gas discharge tube (GDT). The vi characteristic is not continuous but has a break or breaks where switching transitions occur.

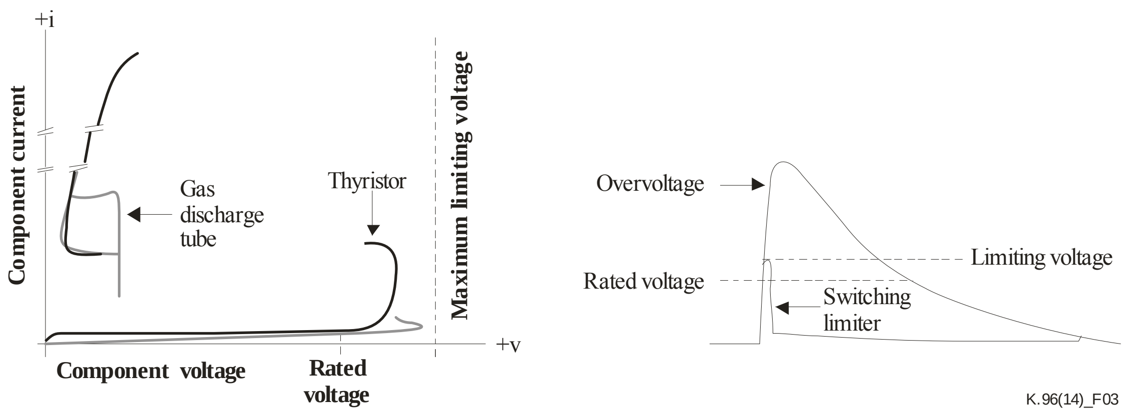


Figure 3 – Overvoltage limiting – Discontinuous (switching) characteristics

Technologies with these characteristics are:

- spark gaps
- gas discharge tubes

•	fixed voltage and gated thyristors

7.2.2 Overcurrent limiting

Current limiting components develop comparatively little voltage until the current exceeds the predetermined threshold current of the component.

7.2.2.1 Continuous characteristic

These components can be electronic circuits or materials whose resistance increases with temperate rise caused by self-heating. Electronic circuits, electronic current limiters (ECL) can be made with constant current or re-entrant characteristics, see Figure 4.

Thermally operated components, positive temperature coefficient (PTC) thermistors have a re-entrant characteristic under d.c. conditions. Under short duration surge conditions, PTC thermistors do not usually change in resistance. Under longer term a.c. surge conditions, the PTC thermistor temperature rise causes an increase in resistance gradually decreasing the current flow. Thermal equilibrium is reached when the PTC thermistor voltage and the circuit current flow results in the appropriate component dissipation to maintain the temperature.

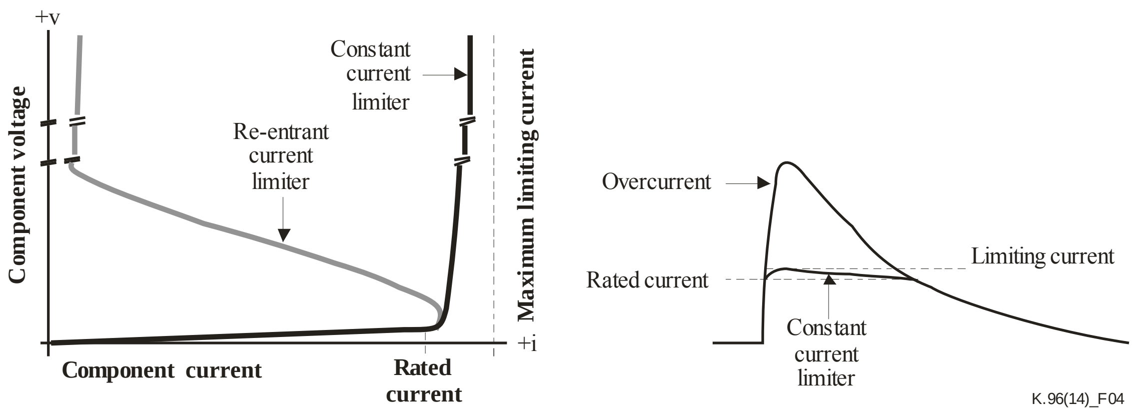


Figure 4 – Overcurrent limiting – Continuous (clamping) characteristic

Technologies with these characteristics are:

•	electronic current limiters (ECL)

•	polymer positive temperature coefficient (PTC) thermistors

•	ceramic positive temperature coefficient (PTC) thermistors

7.2.2.2 Discontinuous characteristic

These components can be electronic circuits, called electronic current limiters (ECL), or one operation components like fuses. The iv characteristic is not continuous but has a break where switching occurs, see the current-voltage characteristic of Figure 5. Unlike fuses, ECLs operate under impulse conditions; see the time-current characteristic of Figure 5.

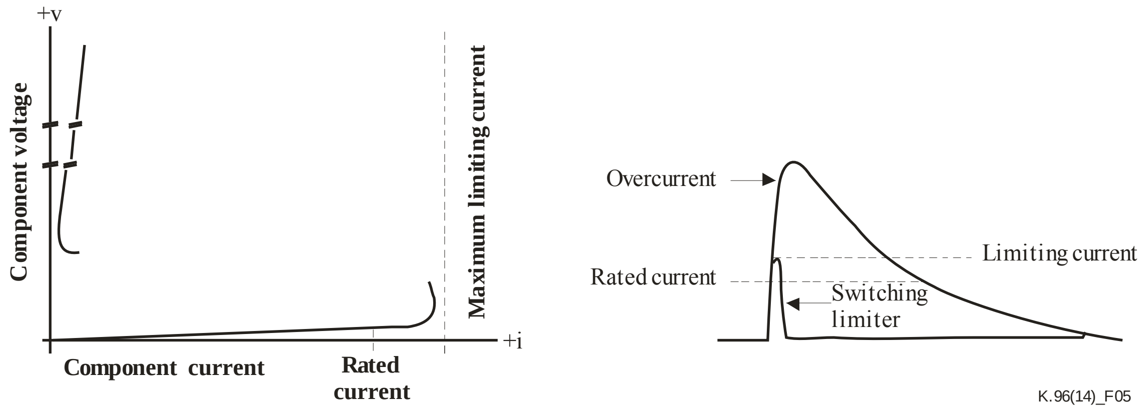


Figure 5 – Overcurrent limiting – Discontinuous (switching) characteristic

Technologies with these characteristics are:

- electronic current limiters (ECL) (self-restoring)
- fuses (one shot)

7.3 Linear suppression

Linear suppression circuits or components reduce all levels of surge by a given reduction factor. The terminology in this area is not so specific as the traditional lightning and power fault protection focus. Table 1 lists non-linear surge protection terms with their corresponding linear suppression terms.

Table 1 – Comparison of non-linear protection and linear suppression terms

Non-linear protection	Linear suppression
surge	electromagnetic disturbance
surge protection	disturbance suppression
surge protective component	suppression component

7.3.1 Frequency selective

Filters select out or reject certain parts of the frequency spectrum as described in [b-Standler] chapter 13: Filters.

For frequency filtering to be effective there must be little or no overlap of the service and surge spectrum. Figure 6 shows the fast Fourier transform (FFT) spectrum obtained from unity amplitude 1.2/50 and 10/1000 impulses using the equations given in [b-C62.45-2002]. The "knee" of these particular spectrums is roughly at a frequency period of ten times the surge duration.

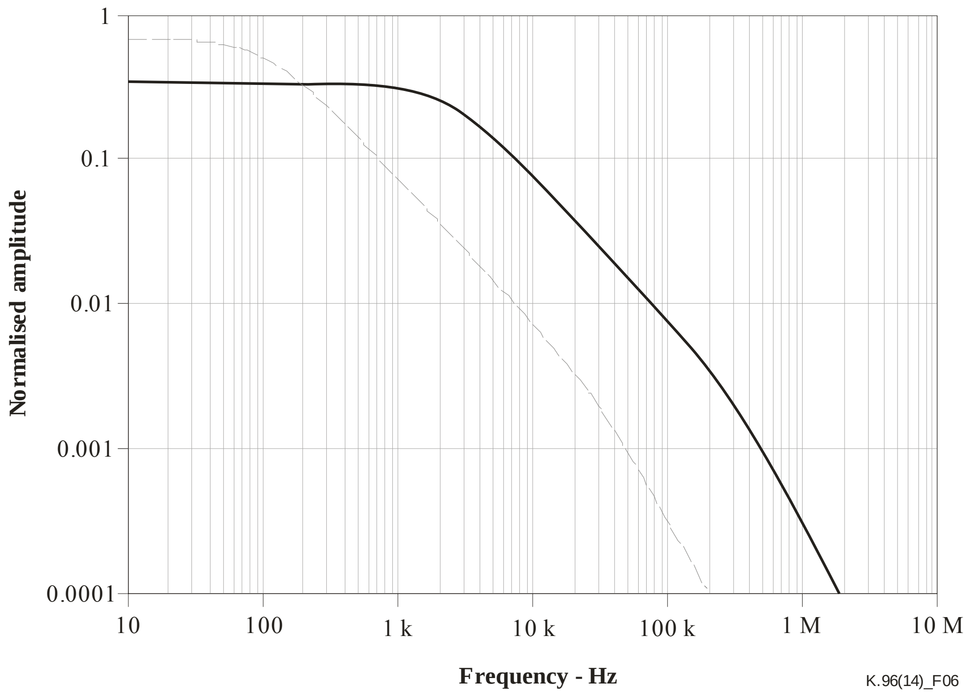


Figure 6 – 1.2/50 and 10/1000 surge waveform frequency spectrums

7.3.1.1 Low-pass filter

Because the surge frequency spectrum overlaps power service frequencies, like 50 Hz and 60 Hz, low-pass filters can only remove some of the surge frequency spectrum appearing on the power service. In addition, during power faults, when higher than normal power frequency voltage occurs, a low-pass filter is ineffective in reducing the level of power fault. Figure 7 shows a low-pass filter characteristic with the Figure 6 surge frequency spectrum overlaid.

A low-pass filter can be used in equipment to reduce self-generated switching spikes such as in switching mode power supplies and inverters used in photo-voltaic systems.

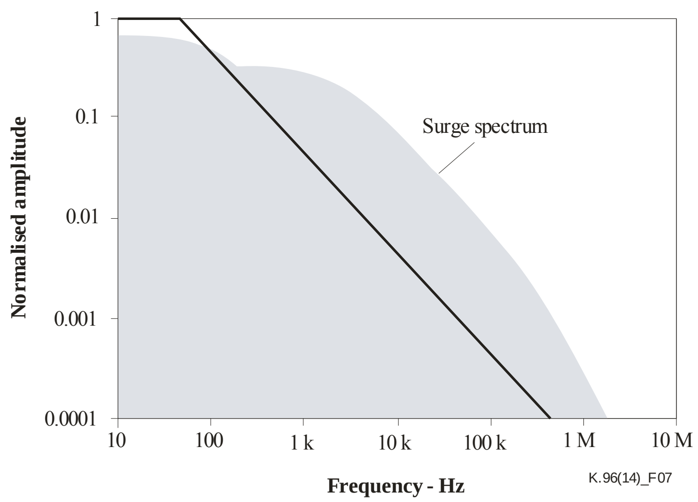


Figure 7 – Low-pass filter characteristic

7.3.1.2 Band-pass filter

Where the service frequency spectrum is narrow, a band-pass filter can essentially remove the surge. An example of a band-pass filter is the quarter-wave stub surge protector used in high frequency coaxial systems. In addition, the quarter-wave stub protector has lower intermodulation distortion than a conventional protection approach using a gas discharge tube (GDT). Figure 8 shows a band-pass filter characteristic with the Figure 6 surge frequency spectrum overlaid.

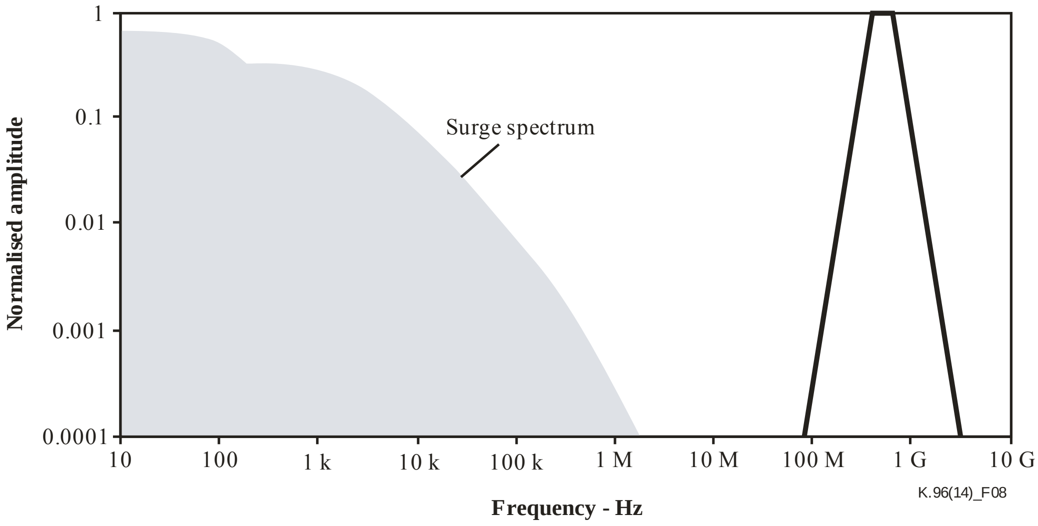


Figure 8 – Band-pass filter characteristic

7.3.1.3 High-pass filter

Where the service frequency spectrum is above the surge frequency spectrum a high-pass filter can essentially remove the surge. Figure 9 shows a high-pass filter characteristic with the Figure 6 surge frequency spectrum and a.c. power service overlaid. A high-pass filter can be used to filter out both the a.c. power service and the surge spectrum for applications like power line communication (PLC).

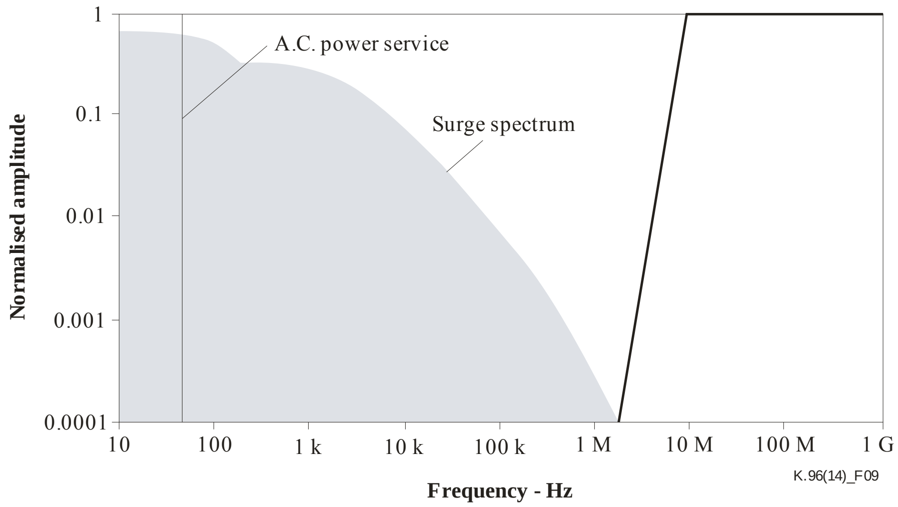


Figure 9 – High-pass filter characteristic

7.3.2 Transformer action

All the transformers describe here mitigate common-mode surges. Additional protection must be added if differential-mode surges occur.

7.3.2.1 Isolating transformer

The isolating transformer (see Figure 10) reduces the propagation of common-mode surges, not through any transformer action, but by withstanding the common-mode surge across its insulation barrier as described in chapter 14B of [b-Standler]. A typical application of an isolation transformer is in Ethernet ports.

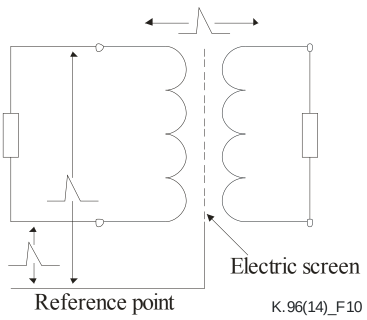


Figure 10 – Isolating transformer common-mode surge mitigation

7.3.2.2 Neutralizing transformer

The neutralizing transformer (see Figure 11) is a 2n + 1 winding, voltage-operated transformer that reduces the propagation of a common-mode surge in a communications wire pair. It transfers primary winding voltage to the communications wire pair, which opposes the common-mode surge voltage on the communications wire pair as described in [b-Brunssen]

Neutralizing transformers are typically used in power substations to buck out the ground potential rise differences between separated grounds on the communication line caused by a.c. discharges. Such transformers are large as they operate at the power frequency in wire-line communications facilities serving electric power stations. The neutralizing transformer can also buck out magnetically induced voltages on the communication line.

A phase-to-ground fault on a power transmission system can result in a ground potential rise (GPR) or increase in ground potential at the power station with respect to remote earth. The GPR can be disruptive and damaging to wire-line communications facilities entering the power station unless mitigative devices are employed. A neutralizing transformer bucks out this potential difference in communication lines.

A neutralizing transformer consists of closely coupled windings on a ferromagnetic core. The transformer primary winding is connected between power station and remote grounds. A secondary winding is placed in series with each conductor of the communications wire line pair entering the power station. The GPR voltage difference is applied to the transformer primary. The secondary windings, in series with the communications lines, are connected in anti-phase so their transformed voltage opposes the GPR voltage difference. Ideally the communication line transformed voltage and the GPR voltage difference cancel out, neutralizing the GPR voltage difference.

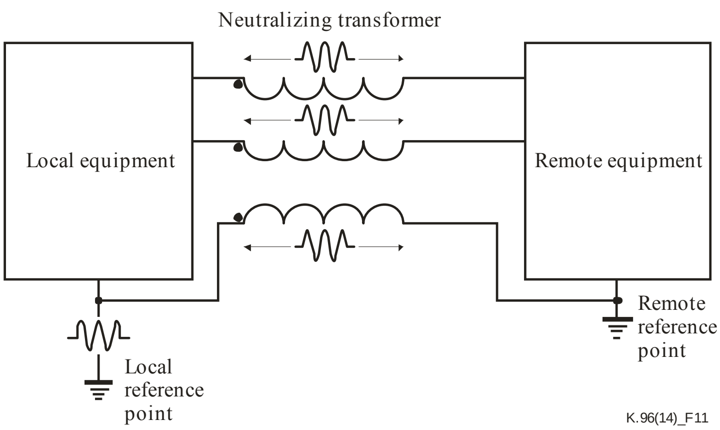


Figure 11 – Neutralizing transformer common-mode surge mitigation

7.3.2.3 EMC choke

The EMC choke is a current operated transformer that reduces the propagation of a common-mode surge, as described in chapter 12D of [b-Standler].

Rather than a "choke", EMC chokes are actually two winding transformers, see Figure 12. For a twisted pair each winding is placed in series with a conductor and poled (phased) to give a transformer action that presents high impedance to common-mode signals and low impedance to the wanted differential signal. Coaxial cables can be wrapped around a magnetic core to give the same effect. Typically these transformers are wound on a toroidal magnet core. A reference points at both ends of the cable provides the return path for the common-mode surge current in order for the EMC choke work.

Transformer core saturation can result in additional stress conditions as described in [b-Maytum et al].

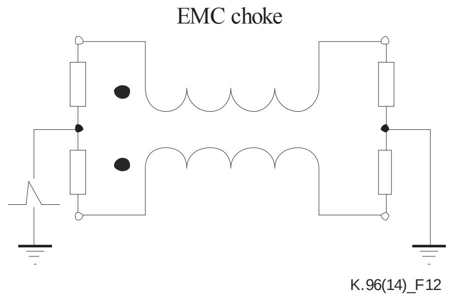


Figure 12 – EMC choke common-mode surge mitigation

Appendix I

Impulse (surge) generators used for low-voltage surge testing

(This appendix does not form an integral part of this Recommendation.)

I.1 Introduction

This appendix covers:

- Types of impulse generator
- Impulse generator parameters
- Impulse generators typically used for surge protector testing
- The 1.2/50-8/20 combination-wave generator
- Expanding single output generators to multiple output
- Impulse generator variants

I.2 Types of impulse generator

Impulse generators can be classified into three types:

1. Generators with a defined voltage waveform typically used for high-voltage insulation testing
2. Generators with a defined current waveform typically used for high-current component and device testing
3. Generators with defined voltage and current waveforms. These generators can be subdivided into:
   a) Circuit defined generators
   b) Waveform defined generators

I.3 Impulse generator parameters

I.3.1 Glossary of terms

The following terms are used in this appendix to describe the impulse and generator parameters.

I.3.1.1 virtual front time; T_1:

The front time T_1 of a voltage impulse is 1/0.6 times the interval T between the instants when the impulse is 30% and 90% of the peak value [b-IEC 60060-1].

The front time T_1 of a surge current impulse is 1.25 times the interval T between the instants when the impulse is 10% and 90% of the peak value [b-IEC 62475].

NOTE – Some standards use the 10% and 90% front time measurement for the voltage impulse.

I.3.1.2 virtual origin; O_1:

For the impulse voltage waveform, it is the instant at which a straight line drawn through the 30% and 90% amplitude values crosses the time axis [b-IEC 60060-1].

For the impulse current waveform, it is the instant at which a straight line drawn through the 10% and 90% amplitude values crosses the time axis [b-IEC 60060-1].

I.3.1.3 virtual time to half-value; T_2 [b-IEC 60060-1][b-IEC 62475]: Interval of time between the instant of virtual origin O_1 and the instant when the voltage or current has decreased to half the peak value

I.3.1.4 designation of an impulse shape [b-IEC 60099-4]: Combination of two numbers, the first representing the virtual front time (T_1) and the second the virtual time to half-value on the tail (T_2).

NOTE 1 – It is written as T_1/T_2, both in microseconds, the sign "/" having no mathematical meaning.

NOTE 2 – Some standards use alternative designations such as A/B or $T_1 \times T_2$.

NOTE 3 – Combination wave generators have both voltage and current impulse designations given separated by a hyphen e.g., 1.2/50-8/20.

NOTE 4 – Waveshapes defined as maximum front time and minimum time to half value are expressed as $<T_1/>T_2$.

I.3.1.5 Undershoot [b-IEEE Std 4]**:** The peak value of an impulse voltage or current that passes through zero in the opposite polarity of the initial peak.

I.3.1.6 charge (impulse): time integral of the impulse current.

I.3.1.7 I^2t (impulse): time integral of the square of the impulse current.

NOTE 1 – I^2t is called the action integral for atmospheric lightning, joule integral for fuses and specific energy (W/R) for AC surge protectors.

NOTE 2 – The units for I^2t are A^2s, but assuming the current flows in a virtual 1 Ω resistor may be expressed in energy units J (fuses) or W/Ω (AC surge protectors).

I.3.1.8 combination wave generator [b-IEC 61000-4-5]: generator with 1.2/50 µs or 10/700 µs open-circuit voltage waveform and respectively 8/20 µs or 5/320 µs short-circuit current waveform.

I.3.1.9 effective impedance (impulse generator) [b-IEC TR 62066]: quotient of the generator open-circuit peak voltage value and the generator short-circuit peak current value.

NOTE – Some standards use the alternative term fictive impedance.

I.3.2 Virtual parameters

This clause covers the virtual (calculated) waveform parameters and their applicability. Figure I.1 shows an impulse designation based on the extrapolation of the 10% to 90% front-time levels. All current lightning surge impulses in this document use the 10% to 90% front-time designation. The Telcordia <2/>10, <10/>250, <10/>360 and <10/>1000 [b-GR-1089-CORE] impulse generators uniquely use the 10% to 90% front-time designation for the voltage impulse. All other impulse generators use a 30% to 90% front-time designation for the voltage impulse. The 8/20 current waveform is not necessarily unidirectional and has a maximum undershoot value specified.

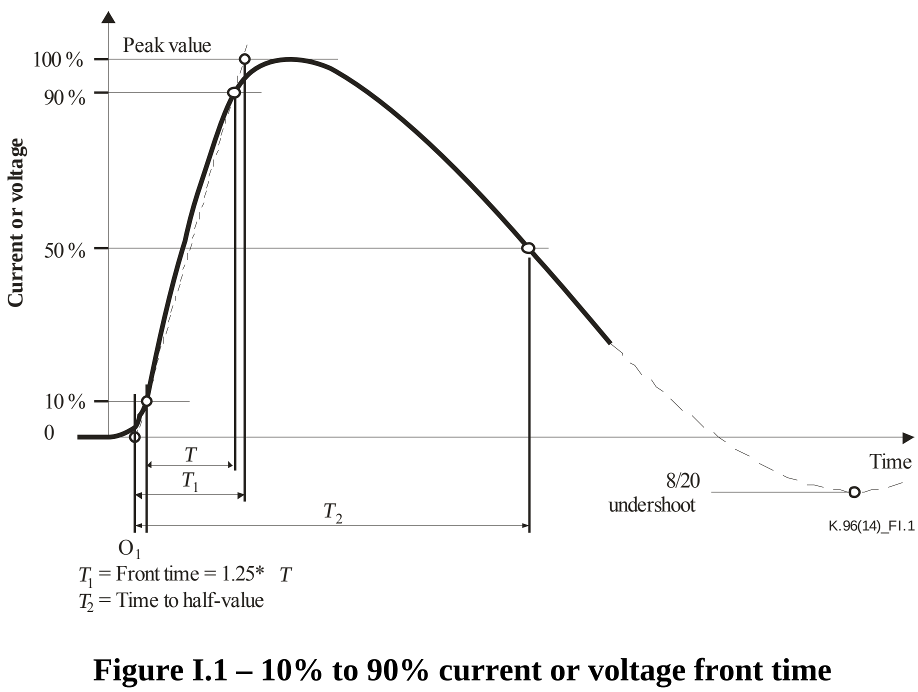


Figure I.1 – 10% to 90% current or voltage front time

Figure I.2 shows a voltage impulse designation based on the extrapolation of the 30% to 90% front-time. All 30% to 90% front-time designated voltage impulses use nominal time values. The 30% to 90% front-time measurement is used to give more consistent measurement values. The start of the voltage impulse often includes high frequency noise resulting from the generator switch closure. The waveform ringing could extend into the 10% amplitude region, causing variations in the 10% to 90% front-time measurement. Moving the 10% level to 30% avoided these initial aberrations.

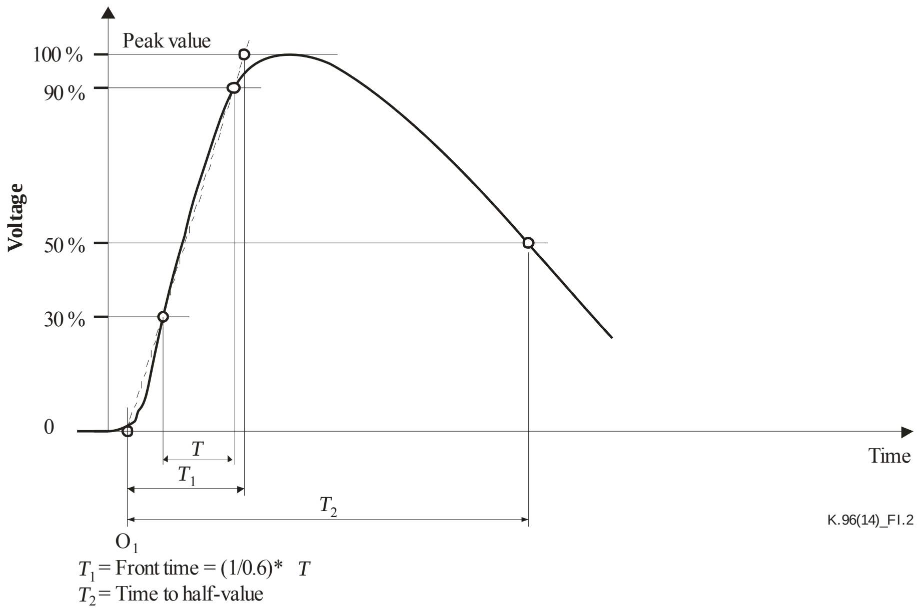


Figure I.2 – 30% to 90% voltage front time

I.4 Impulse generators typically used for surge protector testing

I.4.1 Introduction

This clause lists commonly used or referenced impulse generators. Tables I.1 to I.4 cover generator types with voltage, current and voltage & current defined waveforms. A bibliographic reference is given for each designation of generator. Where there are duplicate designations, the most commonly used one is indicated. Clause I.7 gives further details on the duplicate designation generators.

I.4.2 Impulse generators with a defined voltage waveform

These generators are used for the high-voltage insulation/dielectric testing of components, devices and equipment. Capacitive loads will slow down the voltage front time. To compensate for capacitive loads above 5 nF, some generators have a selectable output resistance value and may even change the generator discharging capacitor value. Inductive loads, such as transformers, motor windings and electrical generator windings require the careful design of the waveshaping network to avoid ringing on the voltage impulse. The generator design objective is to produce a precision voltage impulse. The generator design must be robust enough to survive the discharge current caused by any insulation breakdown. Generator #1 is the most commonly used variant of generators #1 and #2, see Table I.1.

Table I.1 – Voltage Impulse Generators

<table>
<tr><th>Generator Reference</th><th>Designation</th><th>Condition</th><th>Edge</th><th>Time and Tolerance</th><th>Amplitude</th></tr>
<tr><td rowspan="3">1</td><td rowspan="3">1.2/50
[b-IEEE Std 4]
[b-IEC 60060-1]
(IEC/IEEE)</td><td rowspan="2">Open-Circuit Voltage</td><td>Front</td><td>1.2 μs ± 30%</td><td rowspan="2">±3%
See Note 2</td></tr>
<tr><td>Decay</td><td>50 μs ± 20%</td></tr>
<tr><td>Short-Circuit Current</td><td colspan="3">See Note 1</td></tr>
<tr><td rowspan="2">2</td><td rowspan="2">1.2/50
[b-ITU-T K.44]
[b-IEC 60950-1]
(ITU-T/IEC)</td><td>Open-Circuit Voltage</td><td colspan="2">Generator circuit defined</td><td>–0% to +5%</td></tr>
<tr><td>Short-Circuit Current</td><td colspan="3">See Note 1</td></tr>
<tr><td colspan="6">NOTE 1 – Current waveshape not defined.
NOTE 2 – An amplitude tolerance is ±5% is allowed for impulse testing to [b-IEC/TR 60664-2-1]</td></tr>
</table>

I.4.3 Impulse generators with a defined current waveform

These generators are used for high-current component and device testing, see Table I.2.

The 8/20 waveform is typically produced by an LCR series circuit that has a damping factor of less than one. Such a design requires that the load voltage is kept to be much smaller than the charging voltage, e.g., a 1:10 voltage ratio. These generators produce a current through the load with an 8/20 waveshape, unlike the 1.2/50-8/20 generator which has its current waveform measured into a short-circuit.

The amount of energy developed in an MOV or fuse is governed by the applied waveform. The possible range in developed energy is reduced by tighter waveform tolerances. Generator #3 is the preferred and most commonly used one because it has a ±10% waveform tolerance compared with the ±20% of generator #4.

Generator #5 has its current waveform expressed as charge and I^2t values which can be simulated by a 10/350 waveform.

Table I.2 – Current impulse generators

<table>
<tr><th>Generator Reference</th><th>Designation</th><th>Condition</th><th>Edge</th><th>Time and tolerance</th><th>Amplitude</th></tr>
<tr><td rowspan="3">3</td><td rowspan="3">8/20
[b-IEEE Std 4]
[b-IEC 62475]
[b-IEC 61643-11]
(IEEE/IEC)</td><td>Open-circuit voltage</td><td colspan="3">See Note</td></tr>
<tr><td rowspan="2">Short-circuit current</td><td>Front</td><td>8 μs ±10%</td><td rowspan="2">±10%
0 to –20% undershoot</td></tr>
<tr><td>Decay</td><td>20 μs ±10%</td></tr>
<tr><td rowspan="3">4</td><td rowspan="3">8/20
[b-IEC 62475]
(IEC)</td><td>Open-circuit voltage</td><td colspan="3">See Note</td></tr>
<tr><td rowspan="2">Short-circuit current</td><td>Front</td><td>8 μs ±20%</td><td rowspan="2">±10%
0 to –30% undershoot</td></tr>
<tr><td>Decay</td><td>20 μs ±20%</td></tr>
</table>

Table I.2 – Current impulse generators

Generator Reference	Designation	Condition	Edge	Time and tolerance	Amplitude
5	10/350 [b-IEC 61643-11] (IEC)	Open-circuit voltage	See Note		
		Short-circuit current, I_{imp}	Waveform charge $0.5*I_{imp}$ C –10% to +20%		±10%
			Waveform I^2t $0.25*(I_{imp})^2$ A^2s –10% to +45%.		
NOTE – Voltage waveshape not defined. Usually the minimum peak charging voltage or minimum open-circuit for the specified 8/20 current value is given.					

I.4.4 Impulse generators with defined voltage and current waveforms

Table I.3 lists some commonly used impulse generators. The 1.2/50-8/20 generator #7 is commercially available and established in test laboratories. Although generator #8 might be referenced most people would use generator #7 for testing.

A similar situation exists for the 10/1000 impulse generators #11 and #12. Generator #11 is commercially available and established in test laboratories. Although generator #12 might be referenced most people would use generator #11 for testing.

For the 10/700 generators, #9 and #10, the choice is application dependent. For telecommunication applications the ITU-T generator #10 [b-ITU-T K.44] is the automatic choice and most commonly available both commercially and in test laboratories. General EMC work will often reference the IEC generator #9 [b-IEC 61000-4-5]. The IEC generator #9 is available commercially, but is possible to use the ITU-T generator with extra series resistors (see clause I.7.4).

Table I.3 – Voltage and current impulse generators

Generator reference	Designation	Condition	Edge	Time and tolerance	Amplitude
6	1.2/50-8/20 (1.2/50-7.3/22) [b-C62.45-2002] (IEEE) See Note 1	Open-circuit voltage	Front	1.2 µs ±30% µs	±10%
			Decay	50 µs ±20%	
		Short-circuit current	Front	8 µs –31% to +13%	±10%
			Decay	20 µs –20% to +40%	
7	1.2/50-8/20 [b-GR-1089-CORE] [b-IEC 61000-4-5] (IEC/Telcordia) See Note 2	Open-circuit voltage	Front	1.2 µs ±30%	±10%
			Decay	50 µs ±20%	
		Short-circuit current	Front	8 µs ±20%	±10% 0 to –30% undershoot
			Decay	20 µs ±20%	
8	<10/>250 [b-GR-1089-CORE] (Telcordia)	Open-circuit voltage	Front	10 µs –60% to 0	0% to +16%
			Decay	250 µs 0 to +60%	
		Short-circuit current	Front	10 µs –30% to 0	0% to +16%
			Decay	250 µs 0 to +20%	

Table I.3 – Voltage and current impulse generators

Generator reference	Designation	Condition	Edge	Time and tolerance	Amplitude
9	10/700 [b-IEC 61000-4-5] (IEC) See Note 3	Open-circuit voltage	Front	10 µs ±30%	0% to +15%
			Decay	700 µs ±20%	
		Short-circuit current	Front	5 µs ±20%	0% to +15%
			Decay	320µs ±20%	
10	10/700 [b-ITU-T K.44] [b-IEC 60950-1] (ITU-T/IEC) See Note 4	Open-circuit voltage	Front	10 µs ±30%	±10%
			Decay	700 µs ±20%	
		Short-circuit current	Front	5 µs ±20%	±10%
			Decay	320µs ±20%	
11	<10/>1000 [b-GR-1089-CORE] (Telcordia)	Open-circuit voltage	Front	10 µs –40% to 0	0 to +15%
			Decay	1000 µs 0 to +50%	
		Short-circuit current	Front	10 µs –40% to 0	0 to +15%
			Decay	1000 µs 0 to +50%	
12	10/1000 [b-C62.45-2002] (IEEE)	Open-circuit voltage	Front	10 µs –50% to 0	±10%
			Decay	1000 µs 0 to +100%	
		Short-circuit current	Front	10 µs –50% to 0	±10%
			Decay	1000 µs ±20%	

NOTE 1 – The #6 1.2/50-8/20 generator effective impedance is 2 Ω ±12.5% [b-C62.45-2002].

NOTE 2 – The #7 1.2/50-8/20 generator effective impedance is 2 Ω ±10% [b-IEC 61000-4-5].

NOTE 3 – The #9 10/700 generator [b-IEC 61000-4-5] short-circuit current waveshape is 5/320 for single output and 5/320 for dual output. The dual output current tolerance is 5 µs ±20% front, 320 µs ±20% duration and ±10% amplitude.

NOTE 4 – The #10 10/700 generator [b-ITU-T K.44] short-circuit current waveshape is 5/320 for single output and 4/250 for dual output. The dual output current tolerance is 4 µs ±20% front, 250 µs ±20% duration and ±10% amplitude.

Table I.4 lists additional generators from Telcordia [b-GR-1089-CORE] and the TIA [b-TIA-968-B]. There are two different versions of the <2/>10 generator and a third variant of the "10/700" generator #19, which in practice is similar to the ITU-T #10 [b-ITU-T K.44].

Table I.4 – Other voltage and current impulse generators

Generator reference	Designation	Condition	Edge	Time and tolerance	Amplitude
13	<2/>10 [b-GR-1089-CORE] (Telcordia) See Note 1	Open-circuit voltage	Front	2 µs –50% to 0	0% to +20%
			Decay	10 µs 0 to +70%	
		Short-circuit current	Front	2 µs –50% to 0	0% to +20%
			Decay	10 µs 0 to +70%	

Table I.4 – Other voltage and current impulse generators

14	<2/>10 [b-TIA-968-B] (TIA) See Note 2	Open-circuit voltage	Front	2 µs –50% to 0	0% to +10%
			Decay	10 µs 0 to +90%	
		Short-circuit current	Front	2 µs –50% to 0	0% to +25%
			Decay	10 µs 0 to +90%	
15	<10/>160 [b-TIA-968-B] (TIA) See Note 3	Open-circuit voltage	Front	10 µs –40% to 0	0% to +10%
			Decay	160 µs 0 to +63%	
		Short-circuit current	Front	10 µs –50% to 0	0% to +15%
			Decay	160 µs 0 to +31%	
17	<10/>360 [b-GR-1089-CORE] (Telcordia)	Open-circuit voltage	Front	10 µs –25% to 0	0% to +15%
			Decay	360 µs 0 to +30%	
		Short-circuit current	Front	10 µs –25% to 0	0% to +15%
			Decay	360 µs 0 to +30%	
18	<10/>560 [b-TIA-968-B] (TIA) See Note 4	Open-circuit voltage	Front	10 µs –40% to 0	0% to +10%
			Decay	560 µs 0 to +54%	
		Short-circuit current	Front	10 µs –50% to 0	0% to +15%
			Decay	560 µs 0 to +36%	
19	"10/700" [b-TIA-968-B] (TIA)	Open-circuit voltage	Front	9 µs ±30%	0 to +10%
			Decay	720 µs ±20%	
		Short-circuit current	Front	5 µs ±30%	0 to +10%
			Decay	320 µs ±20%	

NOTE 1 – The #13 <2/>10 generator effective impedances are 5 Ω, 8 Ω, 10 Ω or 15 Ω depending on application [b-GR-1089-CORE].

NOTE 2 – The #14 <2/>10 generator effective impedance is 2.5 Ω [b-TIA-968-B].

NOTE 3 – The #15 <10/>160 generator effective impedance is 7.5 Ω to each output [b-TIA-968-B].

NOTE 4 – The #17 <10/>560 generator effective impedance is 8 Ω [b-TIA-968-B].

I.5 1.2/50-8/20 combination wave generator

In 1966, a group of engineers set out to characterize the surge environment of low voltage AC power circuits. The outcome in 1980 was the IEEE 587 standard. It was this standard that created the 1.2/50-8/20 combination wave generator. Combination means that the generator was formulated by combining the existing 1.2/50 voltage waveform, used for insulation testing, and the existing 8/20 current waveform, used for component testing. The research results set the generator to produce a 6 kV maximum (nominal) open-circuit 1.2/50 voltage and 3 kA short-circuit 8/20 current [b-Martzloff].

The effective impedance (peak open-circuit voltage divided by peak short-circuit current) of the 1.2/50-8/20 Combination wave generator is 2 Ω. The 1.2/50-8/20 combination wave generator is often used with external resistors to reduce the prospective current or share currents to multiple outputs. The prospective short circuit current is the defined by the voltage setting, the 2 Ω effective impedance and the external series resistance(s).

When connected to a resistive load, the actual load waveshape will depend on the value of resistance. A low value of resistance will result in an 8/20 waveshape and a high value of resistance will result in a 1.2/50 waveshape. Figure I.3 shows how the front time and half-value time typically varies with load resistance values in the 0 to 20 Ω range.

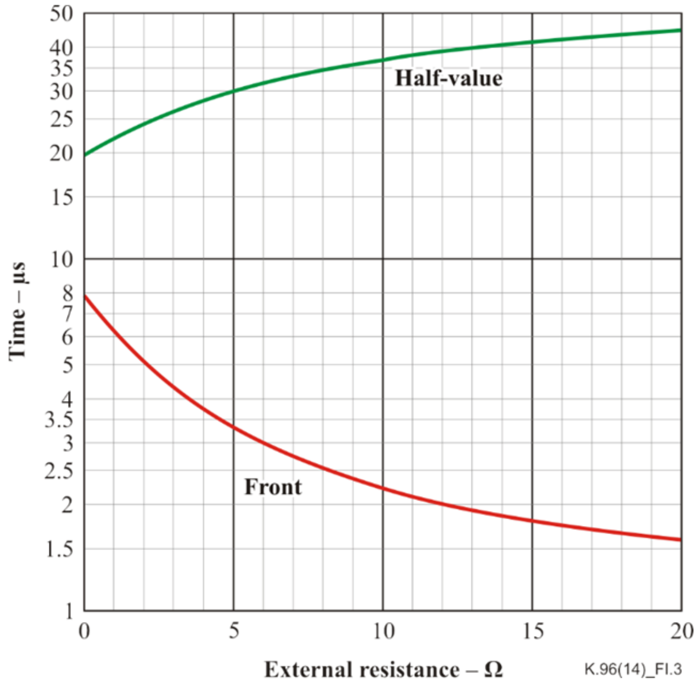


Figure I.3 – 1.2/50-8/20 combination wave generator output waveshape variation with external resistance

Standard configurations [b-IEC 61000-4-5] use external current limiting resistor values of 10 Ω and 40 Ω. Into a short-circuit, these resistive feeds will give waveshapes of 2.2/37 (10 Ω) and 1.3/51 (40 Ω).

I.6 Expanding single output generators to multiple output

I.6.1 Current waveform generators

As these generators have defined a current waveform, the multiple output design will use the added series resistors to provide current sharing between the outputs. The operation of current source generators requires that the load voltage is relatively small compared with the generator charging voltage. The multiple output design must make the combined voltage of the surge protector in conduction and the current sharing resistor voltage drop much smaller than the generator charging voltage.

I.6.1.1 Single and dual output 8/20 current generators

There are single output and dual output 8/20 current generators commercially available. The circuit diagram for a dual output generator with a common source capacitor is given in [b-IEC 61643-311]. If such dual output generators are to be used as a single output generator, then the unused output should be short-circuited to maintain the current waveshape.

I.6.1.2 Single output 8/20 current generator with resistive sharing

The generator effective resistance, R_E, can be approximated to the generator peak voltage divided by the peak short circuit current. To avoid changing the current waveshape too much any added series resistance should not be more than 20% of R_E. For n conductors, the external series resistor, R_n, in each line should not exceed $0.2nR_E$. For example, an 8/20 generator producing 40 kA, 8/20 at a voltage setting of 12 kV has an effective resistance of 12/40 = 0.3 Ω. If 8 conductors are to be tested the series resistance in each conductor is Rn = 0.2×8×0.3 = 0.48 Ω. Allowing for the external 20% series resistance the prospective current in each conductor would be approximately 40/(8×1.2) = 4.2 kA. These values assume a switching-type SPC, in a switched condition.

A clamping-type SPC developing a clamping voltage, V_C, would further reduce the current as the clamping voltage would subtract from the 12 kV generator source voltage. If the clamping voltage was 600 V (0.6 kV) then the conductor current would be reduced to 4.2×(12-0.6)/12 = 4.0 kA.

I.6.1.2.1 Effects of asynchronous voltage-switching surge protection

For surge protectors using switching voltage limiters, a critical condition is when all the n conductors except one are drawing current. In this condition there must be enough voltage available to cause the remaining voltage limiter to operate.

The 8 conductor design example in clause I.6.1.2, with one unswitched SPC has a net external series resistance of 0.48/(n-1) = 0.069 Ω. The voltage developed across the external resistance will be 12×0.069/(0.069+0.3) = 2.2 kV. Thus provided the switching-type element has a switching voltage below 2.2 kV all the surge protectors switching elements will be forced into conduction.

I.6.2 Voltage and current waveform generators

As these generators have defined voltage and current waveforms, the multiple output design will use the added series resistors to both limit the peak current and provide current sharing between the outputs.

I.6.2.1 1.2/50-8/20 generator

The operation of the 1.2/50-8/20 impulse generator has been covered in I.5. Because the waveshape varies with external resistance value the stress level, for a given peak current, will increase with increasing generator voltage. For example, 500 A at 6 kV (10 Ω. external resistance) will result in an impulse I^2t of 6.6 A^2s. Lowering the voltage to 2 kV (2 Ω external resistance) will result in an I^2t of 4 A^2s. Thus for a given current the actual generator voltage used will influence the I^2t stress level.

I.7 Generator variants

I.7.1 Introduction

Anomalies occur due to the way in which different standards organizations define a certain waveshape generator. The two differences that can occur are due to tolerance values and current sharing resistances. Users need to be aware of which generator variant they have and if its performance will have an adverse effect on the test result.

I.7.2 8/20 current generators

Table I.2 shows that the 8/20 current generator has two tolerance sets. Generator #3 is the preferred and most commonly used one because it has a ±10% waveform tolerance compared the ±20% of generator #4.

I.7.3 10/1000 generators

In 1955, Bell Telephone Laboratories standardized on a 10/600 waveshape for protection testing [b-Bodle *et al*]. The recommendations of a 1961 Bell Laboratories field study report resulted in the adoption of a 10/1000 waveshape [b-Bodle & Gresh] The chosen front time of 10 µs was less than 99.5% of the recorded values and the chosen half-value time of 1000 µs was greater than 95% of the recorded values.

The study covered five voice-grade trunk routes with a mixture of aerial and underground cabling. Measurements made on modern, short distance DSL-capable lines show front times in the microsecond region.

A Canadian Bell-Northern Research 1968-1969 field study [b-Bennison et al] studied three types of facility. The report suggested the following waveforms, 1000 V, 10/1000 to cover 99.8% of all paired and coaxial cable lightning surges and 2000 V, 4/200 to cover 99.8% of all open wire circuit lightning surges. The report showed an inverse correlation existed between the surge voltage and decay for higher level surges.

As a result of these recommendations, the 1000 V, 100 A, <10/>1000 impulse was standardized on by Telecordia for many of its NEBS (Network Equipment – Building System) documents [b-GR-1089-CORE]. This is the <10/>1000 generator #11 in Table I.3.

Generator #11 is different to the IEEE version [b-C62.45-2002] of a 10/1000 generator listed #12 in Table I.3. The IEEE 10/1000 generator defines a 10/1000 waveform mostly based on nominal and not limit values. The Telcordia <10/>1000 generator delivers higher stress levels than the IEEE 10/1000 generator. Mixing up these two 10/1000 generator variants is unlikely as commercially available 10/1000 generators are based on the Telcordia (#11) variant. To enable the testing of common mode (longitudinal) coordination between surge protectors and equipment a dual output generator is available with independent outputs of 2 kV, 200A, <10/>1000.

I.7.4 10/700 generators

For a single output the IEC 10/700 generator [b-IEC 61000-4-5] is exactly the same as the ITU-T 10/700 generator [b-ITU-T K.44]. The two generators diverge for multiple outputs. Figure I.4 shows the dual output 10/700 generator. The IEC and ITU-T have different resistance values for the output current sharing resistors R3 and R4. The IEC uses 50 Ω and the ITU-T uses the same 25 Ω value as the single output version.

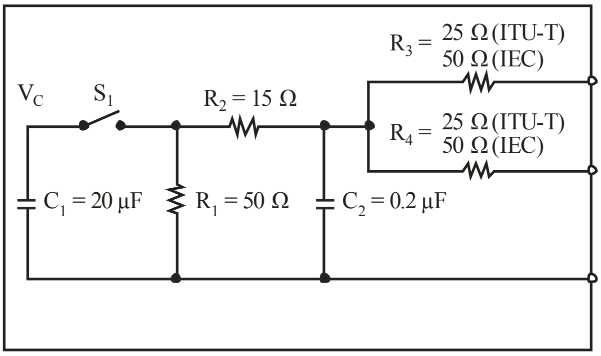


Figure I.4 – Dual output 10/700 generator circuits

The IEC postulates a magnetic coupling of the impulse to the cable – constant AT value – and so doubles the output resistance to 50 Ω, maintaining the same total output current as the single output case. The ITU-T simply added an extra 25 Ω output to the single generator. For the dual output case the IEC generator has an extra 25 Ω of resistance in each the output terminal compared to the ITU-T generator.

Long duration impulses like the 10/700 are the usually result of long external lines or ground potential rise with little magnetic coupled as the IEC postulates. Often a differential surge is created from a common mode surge by a flashover or asynchronous operation of a surge protector. In this differential mode current flows in both wires of a twisted pair. The ITU-T approach creates a higher peak wire current in the differential mode than in the common mode, which would not be the physical reality. The TIA [b-TIA-968-B] overcomes this discrepancy and equalizes the differential and common mode wire stresses by transversely testing at 2/3 of the generator common mode test voltage.

When testing a single wire, there will be no difference in the results between the ITU-T and IEC generators. In two or more wire testing with the IEC generator will result in lower stress levels than the ITU-T generator would give.

I.7.5 <2/>10 generators

The two <2/>10 generators of Table I.4 are different in effective impedances, voltage front-time designation and tolerances. Although the same nominal values, the Telcordia <2/>10 uses a 10% to 90% front-time designation for voltage, whereas the TIA <2/>10 uses the standard 30% to 90% front-time designation for voltage. The Telcordia <2/>10 #13 generator should only be used for [b-GR-1089-CORE] (GR-1089-CORE and related GR documents) testing. The TIA <2/>10 #14 generator should only be used for [b-TIA-968-B] (TIA-968-B) power port testing.

I.7.6 1.2/50-8/20 combination wave generators

The two 1.2/50-8/20 generators of Table I.3 have the same tolerances for the open-circuit voltage waveform, but different tolerances for the short-circuit current waveform. This difference is because the [b-C62.45-2002] (IEEE) does not allow a current underswing like [b-IEC 61000-4-5] (IEC). As noted in clause I.4.4, the 1.2/50-8/20 generator #7, [b-IEC 61000-4-5], is commercially available and established in test laboratories. Although generator #6, [b-C62.45-2002], might be referenced in documentation most people would be using the generator #7 for testing.

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[b-IEEE Std 802.7] IEEE Std 802.7-1989, *IEEE Recommended Practices for Broadband Local Area Networks.*

[b-IEEE Std 1149.6] IEEE Std 1149.6-2003, *IEEE Standard for Boundary-Scan Testing of Advanced Digital Networks*.

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