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## Guide on methods of measurement of short duration transients on low voltage power and signal lines

Guide on methods of measurement of short duration transients on low-voltage power and signal lines

Guide sur les méthodes de mesure des transitoires de courte durée sur les lignes de puissance et de contrôle basse tension

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## Guide sur les méthodes de mesure des transitoires de courte durée sur les lignes de puissance et de contrôle basse tension

## Guide on methods of measurement of short duration transients on low voltage power and signal lines

Bureau central de la Commission Electrotechnique Internationale 3, rue de Varembé Genève Suisse

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

# GUIDE ON METHODS OF MEASUREMENT OF SHORT DURATION TRANSIENTS ON LOW VOLTAGE POWER AND SIGNAL LINES

## FOREWORD

1) The formal decisions or agreements of the IEC on technical matters, prepared by Technical Committees on which all the National Committees having a special interest therein are represented, express, as nearly as possible, an international consensus of opinion on the subjects dealt with.

2) They have the form of recommendations for international use and they are accepted by the National Committees in that sense.

3) In order to promote international unification, the IEC expresses the wish that all National Committees should adopt the text of the IEC recommendation for their national rules in so far as national conditions will permit. Any divergence between the IEC recommendation and the corresponding national rules should, as far as possible, be clearly indicated in the latter.

## PREFACE

This report has been prepared by IEC Technical Committee No. 77: Electromagnetic Compatibility between Electrical Equipment including Networks.

The text of this report is based on the following documents:

| Six Months' Rule | Report on Voting |
|---|---|
| 77(CO)20 | 77(CO)21 |

Further information can be found in the Report on Voting indicated in the table above.

# GUIDE ON METHODS OF MEASUREMENT OF SHORT DURATION TRANSIENTS ON LOW VOLTAGE POWER AND SIGNAL LINES

## INTRODUCTION

Transients appearing on power and signal lines are capable of producing a variety of effects ranging from minor equipment performance degradation to catastrophic insulation breakdown. They have a wide variety of waveforms, which depend upon the mechanism of generation. Furthermore, those that originate from switching a.c. power on and off will have a form that depends upon the exact moment in the power cycle at which switching takes place, but in addition can have very complicated micro (detailed) and macro (overall) waveform characteristics.

Because of this variety and the frequently random time of occurrence, there is considerable difficulty in making a suitable measurement of a transient. The advent of new technologies in device design and manufacture has increased concern for identifying more precisely the effects of transients.

In particular, a solid-state device can be susceptible even to an overvoltage of very short (nanosecond) time duration. Furthermore, because of variations in the waveforms, to have a precise measurement of any given transient would require the measurement of a large number of parameters. Even if one measures the exact waveform of a transient, for control purposes, one must then describe the transient with a finite number of parameter values.

The choice of these parameters and their expected range of values is still a matter of some speculation, and the proper method of measurement is still considered by some to be an open question. Modern types of test equipment provide measurement capabilities not available previously, but they must be used with particular care.

Accordingly, there is a need for well-defined and accepted methods of measuring transients for two major reasons, namely so that:

*a)* measurements made by different laboratories may be compared;

*b)* meaningful limits may be placed on transients generated by particular types of equipment and on the susceptibility of particular equipment to transients.

This guide has been prepared to assist in meeting these requirements. Note that in this guide the concern is with transient phenomena which are not line-frequency related and are of duration no greater than 40 ms. It is also not concerned with sustained voltage changes or fluctuations.

## 1. Scope

This report is intended to give guidance on methods of measurement of short duration transients on low voltage power and signal lines.

## 2. Characteristics of transients

Transients may be classified according to their origin as follows:

*a)* those produced by the environment, that is to say, by lightning;

*b)* those produced by electrical switching or faults;

*c)* those produced internally within the circuits of particular equipment.

### 2.1 *Environment-produced transients*

These transients arise from lightning and are most severe on overhead and unscreened cable sections. At the point closest to the point at which the transient is generated, the rise time can be short and the amplitude high. The rise time and fall time can be considerably lengthened and the amplitude reduced as the transient propagates along the network. Typically, such transients have rise times of the order of microseconds and fall times from 50 µs to 50 ms and may be oscillatory. The effects on inner conductors are reduced in the case of screened cables and cables buried in areas of low ground resistivity.

### 2.2 *Appliance-produced transients*

Transients produced by appliances arise from three basic causes:

*a)* the operation of a mechanical or semiconductor switch;

*b)* turn-on currents associated with the saturation properties of an iron-core transformer or starting currents in motors;

*c)* faults within equipment.

The transient produced by a switch or fault can range from a simple surge or dip (sag) to a very complex waveform caused by repeated "restriking" of an arc as the contacts of a mechanical switch separate. The most serious transients usually arise as a result of breaking an inductive circuit, for example, the blowing of a fuse. In many cases, special techniques, such as placing capacitors across the contacts, will reduce the magnitude of the transients generated, and in other cases suppression can be obtained by the use of semiconductor devices. The transients can have rise times of the order of a few nanoseconds in the immediate vicinity of the switch, that is to say, within a fraction of a metre; however, at distances of several metres from the switch, the rise time will be considerably increased due to attenuation of the line of the higher frequency components. Switching of transformers produces transients which may be of the order of several times the peak line voltage but will have rise times of the order of tens of microseconds.

### 2.3 *Parameters to be measured*

Because of the complex and variable nature of transients, it is difficult to specify which parameters should be measured. Under such circumstances, it is useful to examine the susceptibility characteristics of the equipment under consideration and to divide these into several categories in order to determine the parameters to be measured (see Clause 4):

*a)* those which are susceptible to a restricted band of frequencies, such as radio or carrier frequency receivers;

*b)* those which are susceptible to a broad band of low radio frequencies (for example, a mains rectifier). For such devices the peak voltage is usually the critical parameter; but energy may also be an important parameter;

*c)* those which are susceptible to a broad band of frequencies in the higher frequency bands. The critical quantity is the rate of rise of the pulse. Digital equipment is often susceptible to this parameter, and destruction of devices may also occur.

Some general measurement capabilities can be desirable but one may not be able to measure all parameters with a single instrument. For convenience, these parameters may be classified according to whether they give information in the time or frequency domains.

Figure 1, page 62, illustrates the possible complex nature of a typical transient and some of the time domain parameters that may be used to describe it. In addition, effective pulse strength (voltage × time) and energy content may be significant.

The most common frequency domain parameter used to describe a transient is the spectrum amplitude. The frequency vs. phase characteristic may also be important but is not usually measured because of difficulties in both measurement and use of the data. Where the interference is discontinuous in nature, time weighting techniques such as those used in the C.I.S.P.R. instrument may also be applied. The unweighted component is of interest in any case.

### 2.3.1 *Relation between time domain and frequency domain parameters*

Figure 2 a), page 63, shows a representative waveform of one type of transient disturbance produced during a switching-off operation of a 220 V auxiliary conductor.

Figure 2 b), page 63, shows a spectrum amplitude representation of such a waveform. The relationship between the spectrum amplitude plot and the time domain waveform is best explained by comparing the relevant characteristics for a trapezoidal pulse.

The spectrum amplitude of a symmetrical trapezoidal pulse with the mean pulse time $T$ is, in the frequency range below $f = 1/\pi T$, independent of frequency (this portion of the spectrum amplitude curve is parallel to the abscissa) and has a magnitude equal to the amplitude-time area of the pulse. Above the frequency $f = 1/\pi T$ the envelope of the spectrum varies as $1/f$. If the trapezoidal pulse has rise and fall times $t$, the envelope of the spectrum amplitude above the frequency $1/\pi t$ varies as $1/f^2$.

Note that on Figure 2 b) the abscissa is marked in megahertz on a logarithmic scale and the ordinate is given in decibels with respect to 1 µVs. (1 µVs corresponds to $10^6$ µV in 1 MHz.) The spectrum amplitude representation can be calculated using standard Fourier integral techniques. When the pulses are repeated at regular intervals, a discrete spectrum rather than a continuous spectrum is obtained. In that case, a representation corresponding to Figure 2 b) can be used, but the curve shown corresponds to the amplitude of the discrete components (envelope curve) which are spaced on the frequency scale at a distance corresponding to the repetition rate.

Accordingly, the following interpretation can be placed on Figure 2 b), page 63:

*a)* the low-frequency or flat portion of the curve is a level determined by the effective area under the voltage-time curve shown in Figure 2 a), page 63;

*b)* the high-frequency portion, above about 20 MHz, falls off at a rate inversely proportional to the square of the frequency, and the points at which this rate of fall-off begins are determined by the rate of rise of the initial part of the waveform (that is to say to the amplitude $U_1$);

*c)* the peak in the spectrum amplitude curve appears at a frequency equal to the frequency of oscillation of the transient. Thus, if one is given a spectrum corresponding to that in Figure 2 b), one can interpret it in terms of the important characteristics of the originating transient waveform.

Furthermore, as shown in Figure 2 b), at point $p$ which is the point of intersection of the actual curve with the low frequency (horizontal) portion of the curve, by extending from this point a line with slope proportional to $1/f$ (shown dotted on Figure 2 b)) and one with a slope proportional to $1/f^2$ (the actual spectrum curve shown in the solid line), one can obtain, from the scales shown on the right-hand portion of Figure 2 b) the actual maximum voltage dB(V) and the rate of rise dB(kV/μs) [10]*.

Measuring practice sets limits on the viewing time in time domain measurements and on bandwidth in frequency domain measurements. Therefore, if transients of unknown characteristics (amplitude, rise time, duration, repetition frequency) are to be measured, the measurements should be performed both in the time domain and the frequency domain. In this way, maximum information about the transients can be obtained.

### 2.3.2 *Importance of various transient parameters*

*a) Rise time*

The rise time characterizes the transient in its amplitude-frequency relation (see Fourier series development). The shorter the rise time, the more extensive is the disturbing action in the frequency spectrum. Normally one would expect the risks of performance degradation of a susceptible device to be dependent on its acceptance bandwidth, among other factors. It has been reported that, in practice, the rise time/amplitude relation shows that 5% of the disturbances have significant components above 10 MHz and only 1% above 30 MHz. (However, even very low level components at VHF may interfere with radio reception.)

*b) Amplitude*

The amplitude is especially significant for long transients (for example, >1 μs). It can be the most significant quantity relating to performance degradation or semiconductor device destruction.

*c) Energy*

The energy of the transient, although related to the amplitude, is also dependent on the internal impedance of the disturbance source and is an important parameter with regard to component destruction.

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* The figures in square brackets refer to "Bibliography and references", page 90.

*d) Duration*

The importance of the parameter depends on the time constant of the susceptible equipment in question. For logic systems, the chances of release of the circuits controlled by the synchronization clock may be increased.

*e) Range of frequencies*

As mentioned in paragraph *a)*, the spectrum of the disturbance may not be significant above 10 MHz to 30 MHz (maximum).

*f) Repetition frequency*

In general, a knowledge of the repetition frequency is important for estimating the disturbing effect of transients. For analogue systems, its importance depends on the time constant of the susceptible equipment and can involve an integration phenomenon. For logic systems, the risks of failure may be most severe if the transient and control signal are in phase.

## 3. Characteristics of mechanisms of coupling between transient sources and potentially susceptible devices

The transients of concern here are assumed to be coupled to the susceptible device primarily by conduction. They are usually initiated by some switching action on the connected power line. The switching action could be at any point either locally (on the immediate low-voltage distribution circuit) or at a more remote point on a high-voltage transmission line. Transients may also originate from atmospheric effects, for example, lightning, either as a direct strike on a high-voltage line or from a ground stroke by induction into a high-voltage or low-voltage distribution circuit. When the susceptible device is located close to the original disturbance, the coupling is primarily by induction.

In such a path, the effect of the coupling is described in terms of three basic parameters:

*a)* the attenuation characteristic as a function of frequency of the line;

*b)* the nature of the loading on the line;

*c)* the geometry in relation to the ground plane.

Since power lines are very rarely loaded in their characteristic impedance, one can expect multiple reflections to occur on the line at each discontinuity, for example, wherever a load is connected. Reflection characteristics are of considerable importance in shaping transients, especially those produced by switching operations. The consequence is ringing, at a frequency usually in the range of tens of kilohertz to tens of megahertz, which causes the spectrum amplitude of the transient to have a peak at that particular frequency.

Similar ringing is also possible as a result of conducted transients produced by appliances; however, the separation between discontinuities is smaller and therefore the ringing frequency can be much higher. However, it should be noted that the attenuation of the line increases with frequency, so that the ringing would usually be observed only for transients which are measured at positions relatively close to the source.

The possibility of coupling as the result of induction (both inductive and capacitive coupling) between a power line and a communication line must also be considered. This is especially important in industrial plants where power cables and control or signal cables run side by side over relatively large distances. Generally, such coupling mechanisms can be reduced by using twisted pair or coaxial cables and by placing the cables in screwed metal conduits.

Another source of coupling is a finite ground plane impedance. Many transients, for example, are propagated in common mode on transmission lines and the return current flows through the ground plane. If the ground return path is not of very low impedance or the points of connection to the ground return path are close to similar return points for a sensitive circuit, significant differences in potential can be produced. Balanced symmetrical circuits can be used to minimize the effects of common-mode coupling, but any small imbalance in the sensitive circuit may be critical.

In the case of direct coupling along the power cable from one equipment to another, low-pass filters can often be used to suppress unwanted effects.

### 3.1 *Propagation modes*

The four general modes of propagation for power lines are shown in Figure 3, page 64. Similar modes of propagation exist on signal lines. As shown in Figure 3, there are two main modes of conducted propagation: asymmetrical or common-mode (CM) and symmetrical or differential/balanced mode (DM). Nearly all commercial products have a protective conductor. In some domestic installations, a two-wire power system with no protective conductor is used. Most low-voltage installations have the protective conductor connected to earth at the service entrance.

For some purposes, measurements are made from each phase to earth. The relations between phase *A*, *B*, common mode, $U_{CM}$, and differential mode, $U_{DM}$, open-circuit voltages are shown in Figure 4, page 65.

If the phase voltages are, respectively, $\underline{A}$ and $\underline{B}$, then

$$U_{CM} = \frac{\underline{A} + \underline{B}}{2}$$

$$U_{DM} = \underline{A} - \underline{B}$$

Measured impedances between phase and earth are shown in Figure 5, page 66 [1]. This impedance plays a critical role in controlling the insertion loss between the transient source and the point of measurement. Consider the various paths as illustrated in Figure 6*a)*, page 67, [2]. It has been found that the mean differential mode insertion loss shown in Figure 6*b)*, page 68, was controlled by the mismatch of the various impedances. The method of signal injection used a current probe technique shown in Figure 6*c)*, page 69. Note that the differential mode loss is more or less independent of frequency up to 30 MHz.

The differential mode impedance has a well-defined value, for example, 50 Ω for a coaxial line and higher for a balanced line. In common mode, up to perhaps several tens of kilohertz, the impedance can be expected to have a value approximately equal to the reactance of a line of equivalent length and grounded by a low or zero impedance.

## 4. Susceptibility/Immunity

Certain types of electrical equipment are potentially susceptible to transients unless suitable preventive measures have been incorporated to provide immunity in the environment. In general, long-term experience in the use of cables, connectors, capacitors, insulating materials, transformers, switches, etc., has established the margins required to enable transient overvoltages to be withstood, and for many components the appropriate overvoltage tests are specified. However, for equipment incorporating semiconductor devices there are various forms of susceptibility likely to occur, including catastrophic damage and temporary malfunction. Some of these effects are discussed below, in particular, because transient measuring and analysis equipment must not suffer these effects.

### 4.1 *Damage effects*

Damage effects are largely confined to semiconductor devices although insulation failure of other components can occur because of particularly high amplitude transients, for example, nearby lightning strokes. Power semiconductor devices connected to the supply lines are subjected to the full transient voltage, but devices of adequate rating are selected for such applications based upon earlier experience of device failures. Semiconductor devices in low-level signal and control circuits are only coupled indirectly to the supply lines, but damage can occur since the devices in general have a fairly low voltage and/or current rating. These coupling mechanisms involve high frequency components of the transients and may be difficult to assess in many applications, so that preventive measures to protect the devices require some consideration. Examples of damage effects are given below.

#### 4.1.1 *Power semiconductor devices*

These devices can be damaged by voltage transients (spikes) with durations as short as about 1 ns. The likelihood of damage is a function of transient amplitude, duration, polarity, rate of rise, position on the supply waveform, etc., as well as the device parameters. The initial breakdown of the device is likely to be followed by a high current discharge from the supply, which causes catastrophic damage. Typical devices which have been found liable to damage are rectifier diodes in electronic equipment and thyristors used for motor speed control.

#### 4.1.2 *Low-level signal and control circuits*

While these circuits are not generally directly connected to the low-voltage supply mains, there is coupling between them via the d.c. supply circuit and by induced effects in signal and control cables, so that transients of reduced amplitude can be injected into the circuits. Various semiconductor devices liable to damage by relatively low-level transients are incorporated in these circuits, for example, integrated circuits, certain discrete devices (such as field effect transistors and special purpose diodes (such as tunnel diodes).

### 4.2 *Malfunction effects*

Various forms of equipment malfunction can be caused by transients generated on low-voltage supply lines, which may or may not be coupled to signal lines, on a wide range of types of equipment. Some of these effects could create safety hazards, for example, fire or explosion in chemical manufacturing plants or sudden changes in motor speed. However, the majority of the malfunctions likely to occur are relatively harmless, possibly producing only a temporary effect which is quite acceptable to the user, for example, a small transient change in a meter reading.

In practice, two different types of transients on the supply are found to be the cause of most of the observed malfunctions, that is to say voltage spikes with durations of the order of 1 µs and voltage dips or sags (reductions lasting for about 10 ms and longer). Voltage dips are not covered in this guide, apart from the following note.

*Note.* — Voltage dips (sags), that is to say reductions in the supply voltage to electronic equipment lasting for about 10 ms or longer, can upset the operation of the equipment because of the effects of reduction in the internal stabilized d.c. voltage supply. The effects can be very drastic on certain types of equipment and examples are given as follows:

*a) Digital systems*
Serious malfunctioning of digital systems will occur if the d.c. voltage supply is reduced significantly. The effects produced can include corruption of data system "lock-up", loss of programme, etc.

*b) Control systems*
These systems are liable to suffer serious malfunctioning, causing disruption of the control function.

*c) Instrumentation*
Most types of instrumentation are likely to malfunction seriously as a result of voltage dips (sags).

*d) Alarm and trip systems*
False operation of these systems is likely to be caused by voltage dips (sags).

#### 4.2.1 *Effects of voltage spikes*

*a) Digital systems*

Equipment which incorporates digital systems (such as computers, microprocessors, and instrumentation) can be affected by voltage spikes which are coupled into the logic circuits and corrupt the data. The effects may be overcome by various error correction techniques but in extreme cases the corruption may cause serious effects (for example, incorrect control function, systems "lock-up", unwanted change of programme, and feeding incorrect data into a store).

*b) Control systems*

Control equipment can be affected by induced voltage spikes causing a malfunction of the system.

*c) Instrumentation*

Incorrect indication by some types of equipment can be produced by the effects of spikes.

*d) Alarm and trip systems*

Undesired operation or failure of operation of these systems can be triggered by voltage spikes.

*e) Equipment incorporating power semiconductor devices*

Motor speed control by semiconductors can be affected by voltage spikes and typically takes the form of a sudden transient increase in speed. Heating controls are not so drastically affected by single voltage spikes, but repetitive spikes could cause a large change in temperature.

## 5. Instrumentation

In this clause various methods of measurement are described. In some cases the instruments are available commercially, in others they have been constructed in laboratories for particular experiments. The objective is to provide the user with guidance on the significant characteristics of all such instruments.

In general, an instrument can be considered to consist of four basic parts as follows:

*a)* detector;

*b)* processor;

*c)* output display;

*d)* control system.

These parts are related as shown in Figure 7, page 70.

The basic type of instrument is determined by the type of detector. Instruments having similar detectors but produced by different manufacturers may differ principally in the ways in which other functions are performed. Indeed, in some cases these functions may be adjustable or in fact performed to various extents by auxiliary apparatus under the control of the operator.

The instruments are described in several categories. In each case, fundamental principles of operation are described along with the relationship between fundamental parameters and those frequently stated in commercial literature.

### 5.1 *Obtaining statistical data on parameters of transients*

The fact that transients are so variable from one instance to the next, means that, except where some particular significance can be associated with a particular event, significance must be associated with a range of expected transient parameters. In particular, it is of interest to know not only the maximum value of a particular parameter that may occur but also the mean value and the associated variance of that parameter. For many systems, there is a minimum repetition rate that can cause effective equipment performance degradation, so that unless a succession of transients can appear in a short period, those transients are of no consequence.

This sub-clause identifies parameters that must be considered in the instruments selected for gathering such data.

*a) Required qualities*

Such an instrument should:

- be portable;

- operate automatically, for example, record very low occurrence interference (less than once a month);
- not lose information when a power break occurs;
- have external triggering facilities in order that only certain types of transients are recorded;
- record the time of occurrence (day, hour, minute, second);
- enable setting of a known threshold level;
- record direction of origin of transient;
- be insensitive to conducted or radiated disturbances.

*b) Characteristics*

- Dead time:

  The dead time is the time during which the recorder is incapable of resolving separate transients. It may vary from 100 μs to 1 s.

- Range of frequencies:

  Accuracy of 3 dB from 20 Hz to 50 MHz (in order to take into account paragraphs *a)* and *e)* of Sub-clause 2.3.2).

- Repetition frequency:

  From 10 times/millisecond to 1/month.

- Power supply:

  Battery floating (except where used for long test periods).

### 5.2 *Transient counter*

These are generally fairly simple instruments designed to detect and count transients which exceed one or more pre-selected amplitudes. They may also incorporate facilities which respond to transient duration and indicate transient polarity. In some cases, the recorders are battery operated to maintain operation regardless of mains perturbations. Typically these counters respond to transients with durations longer than 0.1 μs to 1 μs. The accuracy is usually about 5% to 10%. The input resistance is typically 10 kΩ to 1 MΩ.

Various forms of readout are used:

*a)* electromechanical counter;

*b)* printout;

*c)* pen recorder.

The maximum rate at which transients can be recorded may be limited, for example, about 25 Hz with electromechanical counter readout.

### 5.3 *Peak voltmeter*

These instruments, which are also referred to as peak-hold or memory voltmeters, measure the transient peak amplitude and store the data until reset. The response to short duration transients is determined by the effective charge time constant of the