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PUBLICATION FONDAMENTALE EN CEM
BASIC EMC PUBLICATION

Compatibilité électromagnétique (CEM) –

Partie 2-8: Environnement – Creux de tension et coupures brèves sur les réseaux d'électricité publics incluant des résultats de mesures statistiques

Electromagnetic compatibility (EMC) –

Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results

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INTERNATIONAL ELECTROTECHNICAL COMMISSION

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results

FOREWORD

1) The IEC (International Electrotechnical Commission) is a worldwide organization for standardization comprising all national electrotechnical committees (IEC National Committees). The object of the IEC is to promote international co-operation on all questions concerning standardization in the electrical and electronic fields. To this end and in addition to other activities, the IEC publishes International Standards. Their preparation is entrusted to technical committees; any IEC National Committee interested in the subject dealt with may participate in this preparatory work. International, governmental and non-governmental organizations liaising with the IEC also participate in this preparation. The IEC collaborates closely with the International Organization for Standardization (ISO) in accordance with conditions determined by agreement between the two organizations.
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3) The documents produced have the form of recommendations for international use and are published in the form of standards, technical specifications, technical reports or guides and they are accepted by the National Committees in that sense.
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The main task of IEC technical committees is to prepare International Standards. However, a technical committee may propose the publication of a technical report when it has collected data of a different kind from that which is normally published as an International Standard, for example “state of the art”.

IEC 61000-2-8, which is a technical report, has been prepared by subcommittee 77A: Low frequency phenomena, of IEC technical committee 77: Electromagnetic compatibility.

It has the status of a basic EMC publication in accordance with IEC Guide 107.

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

Enquiry draft	Report on voting
77A/375/DTR	77A/396/RVC

Full information on the voting for the approval of this technical report can be found in the report on voting indicated in the above table.

This publication has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this publication will remain unchanged until 2010. At this date, the publication will be

- reconfirmed;
- withdrawn;
- replaced by a revised edition, or
- amended.

INTRODUCTION

IEC 61000 is published in separate parts according to the following structure:

Part 1: General

General considerations (introduction, fundamental principles)

Definitions, terminology

Part 2: Environment

Description of the environment

Classification of the environment

Compatibility levels

Part 3: Limits

Emission limits

Immunity limits (in so far as they do not fall under the responsibility of the product committees)

Part 4: Testing and measurement techniques

Measurement techniques

Testing techniques

Part 5: Installation and mitigation guidelines

Installation guidelines

Mitigation methods and devices

Part 6: Generic standards

Part 9: Miscellaneous

Each part is further subdivided into several parts, published either as International Standards, technical specifications or technical reports, some of which have already been published as sections. Others will be published with the part number followed by a dash and completed by a second number identifying the subdivision (example: 61000-6-1).

Detailed information on the various types of disturbances that can be expected on public power supply systems can be found in IEC 61000-2-1.

ELECTROMAGNETIC COMPATIBILITY (EMC) –

Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results

1 Scope

This technical report describes the electromagnetic disturbance phenomena of voltage dips and short interruptions in terms of their sources, effects, remedial measures, methods of measurement, and measurement results (in so far as these are available). They are discussed primarily as phenomena observed on the networks of public electricity supply systems and having an effect on electrical equipment receiving its energy supply from those systems.

“Voltage sag” is an alternative name for the phenomenon voltage dip.

2 Definitions

2.1
voltage dip
voltage sag
sudden reduction of the voltage at a particular point on an electricity supply system below a specified dip threshold followed by its recovery after a brief interval

NOTE 1 Typically a dip is associated with the occurrence and termination of a short circuit or other extreme current increase on the system or installations connected to it.

NOTE 2 A voltage dip is a two-dimensional electromagnetic disturbance, the level of which is determined by both voltage and time (duration).

2.2
short interruption
sudden reduction of the voltage on all phases at a particular point on an electricity supply system below a specified interruption threshold followed by its restoration after a brief interval

NOTE Short interruptions are typically associated with switchgear operation related to the occurrence and termination of short circuits on the system or installations connected to it.

2.3
(voltage dip) reference voltage
<measurement of voltage dips and short interruptions>
value specified as the base on which depth, thresholds and other values are expressed in per unit or percentage terms

NOTE The nominal or declared voltage of the supply system is frequently selected as the reference voltage.

2.4
voltage dip start threshold
<voltage dip measurement>
r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the start of a voltage dip

NOTE Typically values between 0,85 and 0,95 of the reference voltage have been used for this threshold.

2.5
voltage dip end threshold
<voltage dip measurement>
r.m.s. value of the voltage on an electricity supply system specified for the purpose of defining the end of a voltage dip

NOTE Typically, the value used for the end threshold has been the same as the start threshold or has exceeded it by 0,01 of the reference voltage.

2.6
interruption threshold
<measurement of voltage dips and short interruptions>
r.m.s. value of the voltage on an electricity supply system specified as a boundary such that a voltage dip in which the voltage on all phases falls below it is classified as a short interruption

2.7
residual voltage (of voltage dip)
minimum value of r.m.s. voltage recorded during a voltage dip or short interruption

NOTE The residual voltage may be expressed as a value in volts or as a percentage or per unit value relative to the reference voltage.

2.8
depth (of voltage dip)
difference between the reference voltage and the residual voltage

NOTE 1 The depth may be expressed as a value in volts or as a percentage or per unit value relative to the reference voltage.

NOTE 2 Frequently the word 'depth' is used in a descriptive, non-quantitative sense, to refer to the voltage dimension of a voltage dip, without the intention of specifying whether that dimension is expressed as the *residual voltage* or *depth*, as defined above. Care is needed to ensure that this meaning is clear in the context in which it is used.

2.9
duration (of voltage dip)
time between the instant at which the voltage at a particular point on an electricity supply system falls below the start threshold and the instant at which it rises to the end threshold.

NOTE In polyphase events, practice varies in regard to relating the start and end of the dip to the phases concerned. Future practice is likely to be that for polyphase events a dip begins when the voltage of at least one phase falls below the dip start threshold and ends when the voltage on all phases is equal to or above the dip end threshold.

2.10
(voltage dip) sliding reference voltage
<measurement of voltage dips and short interruptions>
r.m.s. value of the voltage at a particular point on an electricity supply system continuously calculated over a specified interval to represent the value of the voltage immediately preceding a voltage dip for use as the reference voltage

NOTE The specified interval is much longer than the duration of a voltage dip.

3 Description of voltage dips and short interruptions

3.1 Source of voltage dips

The primary source of voltage dips observed on the public network is the electrical short circuit occurring at any point on the electricity supply system.

The short circuit causes a very large increase in current, and this, in turn, gives rise to large voltage drops in the impedances of the supply system. Short circuit faults are an unavoidable occurrence on electricity systems. They have many causes, but basically they involve a breakdown in the dielectric between two structures which are intended to be insulated from each other and which normally are maintained at different potentials.

Many short circuits are caused by overvoltages, which stress the insulation beyond its capacity. Atmospheric lightning is a notable cause of such overvoltages. Alternatively, the insulation can be weakened, damaged or bridged as a result of other weather effects (wind, snow, ice, salt spray, etc.), by the impact or contact of animals, vehicles, excavating equipment, etc., and as a result of deterioration with age.

The typical electricity supply system conveys energy from multiple sources (generating stations) to multiple loads (motors; resistive elements for lighting, heating, etc.; the power supply modules of electronic devices; etc.) The entire system, including generators, loads and everything between, is a single, integrated and dynamic system – any change of voltage, current, impedance, etc. at one point instantaneously brings about a change at every other point on the system.

Most supply systems are three-phase systems. The short circuit can occur between phases, phase and neutral, or phase and earth. Any number of phases can be involved.

At the point of the short circuit, the voltage effectively collapses to zero. Simultaneously, at almost every other point on the system the voltage is reduced to the same or, more generally, a lesser extent.

Supply systems are equipped with protective devices to disconnect the short circuit from the source of energy. As soon as that disconnection takes place, there is an immediate recovery of the voltage, approximately to its previous value, at every point except those disconnected. Some faults are self-clearing: the short circuit disappears and the voltage recovers before disconnection can take place.

The sudden reduction of voltage, followed by voltage recovery, as just described, is the phenomenon known as voltage dip (also known as voltage sag).

The switching of large loads, energising of transformers, starting of large motors and the fluctuations of great magnitude that are characteristic of some loads can all produce large changes in current similar in effect to a short circuit current. Although the effect is generally less severe at the point of occurrence, the resulting changes in voltage observed at certain locations can be indistinguishable from those arising from short circuits. In that case they also are categorised as voltage dips. (In the management of public networks, however, limits are applied, as a condition of supply, to the permissible voltage fluctuations from this cause.)

3.2 Voltage dip duration

Unless a self-clearing fault is involved, the duration of voltage dips is governed by the speed of operation of the protective devices.

In the main, the protective devices are either fuses or circuit breakers controlled by relays of various kinds. Protection relays often are designed to have an inverse time characteristic, so that the lower the short circuit current, the longer is the fault clearance time. Fuses have similar characteristics. The time characteristics and settings of the fuses and relays are carefully graduated and co-ordinated, so that a short circuit detected by several devices is cleared at the most appropriate point.

Many short circuits are cleared in the time range 100 ms – 500 ms. Faster times are often achieved for short circuits on major transmission lines, while the clearance of short circuits on distribution circuits can be considerably slower.

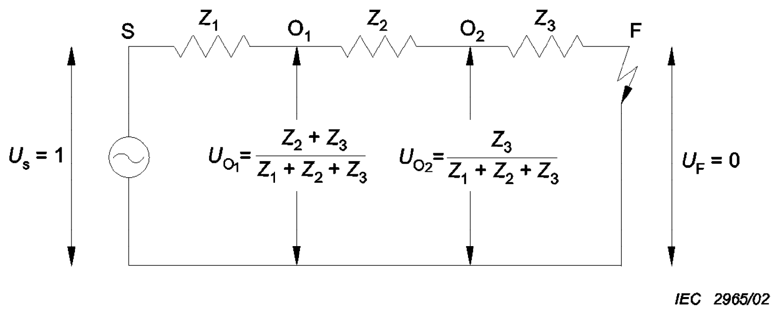
When a current fluctuation other than a short circuit is the source of the voltage dip, the duration is governed by that of the causative event.

Some loads draw a large inrush of current as the voltage recovers at the end of a voltage dip. This has the effect of delaying the recovery of the voltage and extending the duration of the voltage dip. The same effect can occur when transformers go into saturation during voltage recovery.

3.3 Voltage dip magnitude

The magnitude of the voltage dip is governed by the position of the observation point in relation to the site of the short circuit and the source(s) of supply.

The system can be represented by a simple equivalent circuit connecting the observation point to a single equivalent source and to the site of the fault. (see Figure 1.) The entire voltage (100 %) is dissipated over the impedance between the source and the short circuit. The voltage drop to the observation point depends on the relative magnitudes of the two impedances connecting that point to the source and the short circuit. Depending on these impedances, the depth of the voltage dip can be anywhere in the range 0 % to 100 %.



Voltage dips at observation points O_1 and O_2 for short circuit at F and single equivalent source at S (expressed in terms of residual voltage per unit.)

Figure 1 – Equivalent circuit for voltage dips

In broad terms, the nearer the observation point is to the site of the short circuit, the closer the voltage at that point is to the voltage at the fault site. In other words, the voltage dip approaches the maximum possible depth (zero residual voltage) near the short circuit. On the other hand, if an observation point is near a generation source or sources of stored energy, such as rotating machines, the effect is to move the observation point nearer to the equivalent single source as represented in Figure 1. This mitigates the severity of the observed voltage dip. (However, if the dip duration is prolonged, increased current is drawn by decelerating motors, and this can increase the severity of the dip.)

Whether a short circuit results in an observable voltage dip at a particular observation point depends on their positions on the supply system. A short circuit on the transmission system is likely to result in an appreciable voltage dip that is observed over a very wide area, even at a distance of some hundreds of kilometres. On the other hand, a short circuit on a distribution circuit has a much smaller field of observable influence. Observation points on the same circuit are likely to experience severe dips, the dip severity will be moderated considerably on neighbouring circuits, and at larger distances the dip is hardly discernible.

Given an observation point within or near a private installation, it is, of course, possible that a short circuit or other causative event will occur within the same installation. The observed voltage dip that results can equal or exceed a dip caused by a short circuit on the public transmission or distribution system.

The observed magnitude of a voltage dip depends also on the phases involved, both in the short circuit and at the observation point, and on the winding connections (star-delta, star-star, etc.) of any transformers between those two points.

3.3.1 Significance of transformer and load connections

The observed voltage dip magnitude arising from a particular causative event depends on whether the observation point and the event are on the same or different sides of a network or customer transformer. The phasing of the short circuit or other event, the phasing of the measurement system, and the connection methods of the primary and secondary transformer windings are all significant in this regard. For instance, considering the network or installations on either side of a step down transformer connected Dyn or Dy, a single line to ground fault can result, on the primary side, in a voltage dip of 0 V (residual voltage) on one phase, but, on the secondary side, a line to neutral voltage on two phases of 58 % of the pre-existing voltage.

In practice, loads that are sensitive to voltage dips (power converters and drives, motors, control equipment, etc.) are often connected line-to-line in industrial installations. They would therefore be subjected to line-to-line voltage dips rather than line-to-neutral dips. This needs to be taken into account in considering whether measurements are conducted line-to-neutral, line-to-line, or both.

For example, Table 1 provides a summary of the voltage dips that would be observed at the secondary sides of different step down transformers, with a single line-to-ground fault on the primary, causing a 100 % voltage drop on phase 1 on that side. (The supply network is assumed to be a directly grounded neutral system.)

Table 1 – Transformer secondary voltages with a single line-to-ground fault on the primary

Transformer connection [a]	Line-to-neutral voltage			Line-to-line voltage		
	V_1	V_2	V_3	V_{12}	V_{23}	V_{13}
YNyn or YNy	0,0	1,0	1,0	0,58	1,0	0,58
Yy, Yyn, or Dd	0,33	0,88	0,88	0,58	1,0	0,58
YNd or Yd	–	–	–	0,33	0,88	0,88
Dyn or Dy	0,58	1,0	0,58	0,88	0,88	0,33

[a] Capital letters refer to primary winding connection (supply network side) and lower case letters refer to secondary winding connection (load side). N and n designate a grounded primary and secondary transformer neutral, respectively.

See [6][1].

1 Figures in square brackets refer to the bibliography.

3.4 Short interruptions

The operation of a circuit breaker or fuse disconnects part of the system from the source of energy. In the case of a radial circuit, this interrupts the supply to all downstream parts of the system. In the case of a meshed network, disconnections at more than one point are necessary in order to clear the fault. Electricity users within the disconnected segment of network suffer an interruption of supply.

In the case of overhead networks, automatic reclosing sequences are often applied to the circuit breakers that interrupt fault currents. Their purpose is to restore the circuit to normal with the minimum of delay in the event that the fault proves to be a transient (self-clearing) one (as in the case of a flashover, due to over-voltage, resulting in no serious or permanent damage to the components involved). If the first reclosing attempt proves unsuccessful, there may be subsequent attempts at pre-set intervals. If the fault remains after the pre-set sequence of open-reclose operations is completed, the circuit breaker remains in the open position and is not closed again until the necessary repairs have been carried out at the fault site. (Of course, each reclosure while the fault still exists results in an additional voltage dip, the observed depth of which depends on the position of the observation point.)

In addition to the actual isolation of the fault, further switching is often carried out, either automatically or manually, in order to reduce the extent of network and number of users interrupted as a result of the initial fault clearance.

Thus, a single fault can result in a complex series of switching operations, observable to users as a series of interruptions of various durations. Depending on the structure of the network in the particular case and on the positions of individual users relative to the sites of the fault and the relevant switches, some users will experience very brief interruptions, while others may even have to wait for repairs to be completed before supply can be restored.

Interruptions having a duration up to 1 min (or, in the case of some reclosing schemes, up to 3 min) are classified conventionally as short interruptions.

3.5 Causes of voltage dips and short interruptions

As already stated, the cause of voltage dips (which sometimes extend to or are associated with short interruptions) is the major surge of current involved in a short circuit on an electrical system, and occasionally in large-scale load fluctuations. The flow of current through the impedances of the network components results in voltage drops, which briefly depress the voltage delivered to electricity users.

The dielectric breakdown involved in short circuits arises either from the stress of overvoltage or because the insulation is weakened, damaged or bridged in some way. The causes of the faults which have these results are many, including:

- atmospheric events: lightning and wind storms, snow, ice, deposition of salt or atmospheric pollutants on insulators, wind-borne debris;
- mechanical interference and damage: contact by vehicles, construction equipment, excavation equipment, animals and birds, growing trees, vandalism and malicious damage;
- breakdown of network plant: deterioration with age, corrosion, rot, latent manufacturing or construction faults;
- accidents or errors in operation and maintenance;
- major natural events: floods, landslides, earthquakes, avalanches.

A certain incidence of faults due to these causes is inevitable on all networks. Some types of network have a greater exposure to many of these causes or to a greater range of causes. In particular, overhead networks are exposed to most of the causes.

Voltage dips arising from load fluctuations are associated with the starting of large motors, especially those in isolated locations served by long lines, similar motors with gross fluctuations of load, arc furnaces, welding equipment, etc. (However, in the management of public networks, limits are generally applied to such fluctuations as a condition of supply.)

3.6 Example of fault on MV network

Figure 2 illustrates the voltage dips and short interruptions resulting from a fault on an MV feeder. Three cases are shown:

- a transient fault which is found to have cleared at the first reclose operation;
- a semi-permanent fault which still remains at the first reclose operation, but is found to have cleared at the second (delayed) reclose operation;
- a permanent fault which still remains after the full reclose sequence has been completed.

In each case, the voltage dips and interruptions are shown as observed by two customers, one on the same feeder as the fault but upstream from it, and the other on another feeder from the same busbar. (The times shown are for illustration. Actual times depend on the settings adopted for a particular network.)

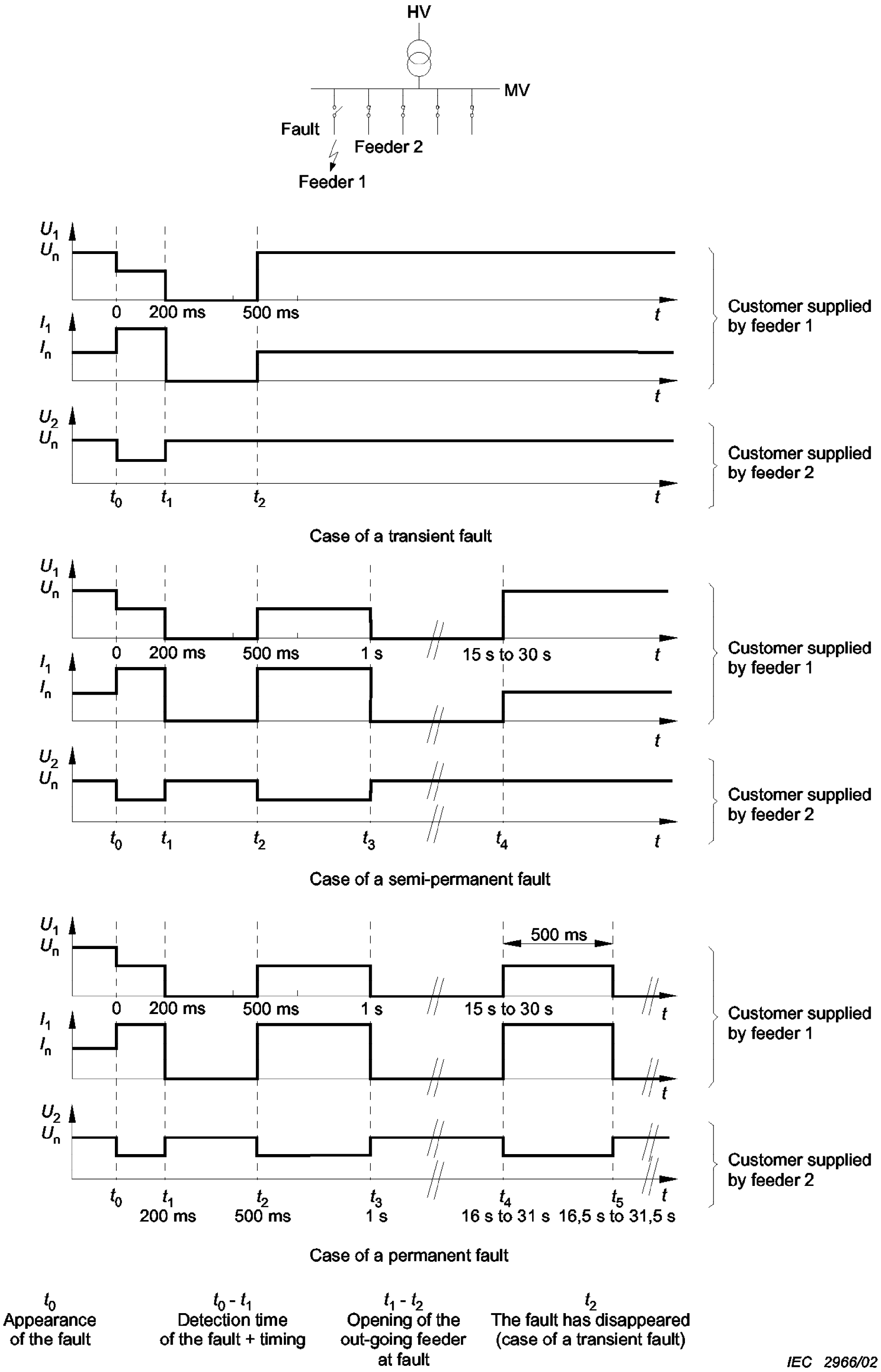


Figure 2 – Voltage dips and short interruptions resulting from fault on MV network

4 Effects of voltage dips and short interruptions

4.1 General effects

In this document within the IEC 61000 series, the relevant effects are those relating to EMC, i.e. the possible degradation of the performance of equipment. As EMC phenomena, voltage dips and short interruptions can cause equipment connected to the supply network to perform in a manner other than that which is intended.

The fundamental relationship between the supply system and the equipment connected to it is that the system exists as an energy source from which the equipment draws whatever energy it needs to carry out its intended function. The amount of energy drawn and the use to which it is put is almost entirely a matter of the design and operation of the utilisation equipment (including the switching and control features incorporated in it), limited only by the capacity of the network to deliver energy at the point of connection of the equipment.

The energy delivery capacity of the network decreases as the voltage decreases. Voltage dips and short interruptions, therefore, cause a temporary diminution or stoppage of the energy flow to the equipment. This leads to a degradation of performance in a manner that varies with the type of equipment involved, possibly extending to a complete cessation of operation.

An option that is sometimes implemented in either the design or installation of the equipment is to incorporate a protective device for the purpose of interrupting the supply in the event of the voltage falling below a set threshold, thereby preventing damage or other unwanted effects in conditions of reduced voltage. Such protection can have the effect of converting a voltage dip into a long interruption for the equipment concerned. The long interruption is not caused by the voltage dip, but is the intended result of a protective feature that is designed to respond in that way to reduced voltage.

As with all disturbance phenomena, the gravity of the effects of voltage dips and short interruptions depends not only on the direct effects on the equipment concerned, but also on how important and critical is the function carried out by that equipment. For example, modern manufacturing methods often involve complex continuous processes utilising many devices acting together. A failure or removal from service of any one device, in response to a voltage dip or short interruption, can necessitate stopping the entire process, with the consequence of loss of product and damage or serious fouling of equipment. This can be one of the most serious and expensive consequences of voltage dips and short interruptions. Such consequential damage or loss, however, is a function of the design of the process and is an indirect or secondary effect of the voltage dip or short interruption.

EMC considerations are concerned with the direct effects on the performance of the actual appliances drawing an energy supply from the electricity network. Some of the more common effects are described more particularly for certain types of equipment in the subclauses that follow. The list is not an exhaustive one.

NOTE A sudden phase shift can accompany the voltage dip and can have a significant effect on some equipment. This phenomenon is not discussed further in this report.

4.2 Effects on some particular devices

4.2.1 IT and process control equipment

Generally, the principal functional units of this equipment require d.c. power supplies, and these are provided by means of power supply modules which convert the a.c. supply from the public power supply system. Usually, it is the minimum voltage reached during a voltage dip that is significant for the power supply modules. Figure 3 shows the well-known ITIC curve for minimum immunity objectives concerning dips. (It includes also voltages above the normal range.) The user of the equipment must consider whether the consequences of dips that are more severe than shown by the curve are such that additional measures are necessary in order to maintain satisfactory performance. Depending on the application of the equipment, failures can have safety or other implications. Traffic signalling failure is one of many possible examples.

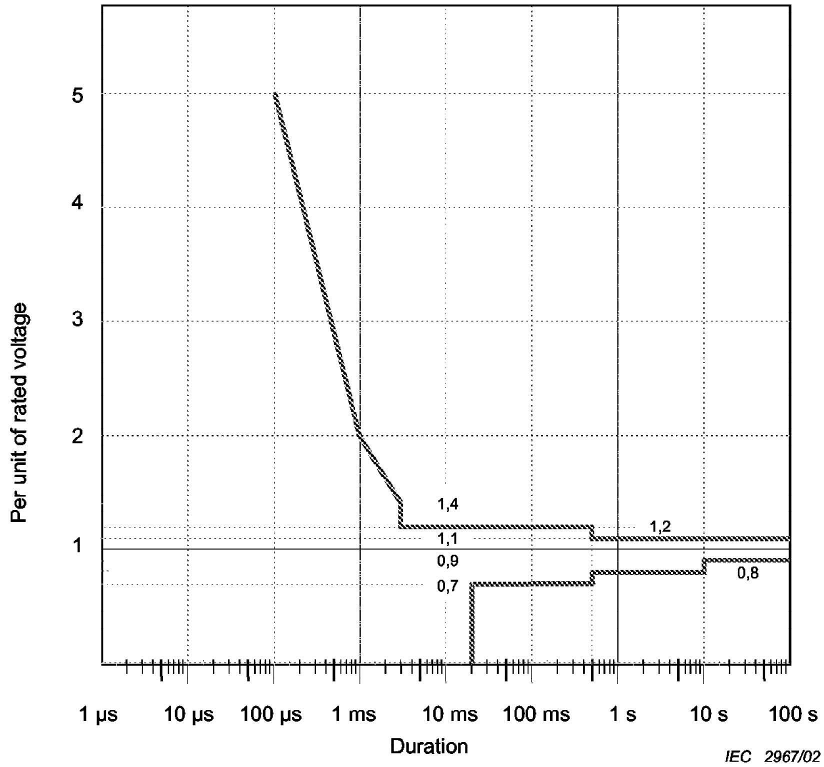


Figure 3 – ITIC (CBEMA) curve for equipment connected to 120 V 60 Hz systems

4.2.2 Relays and contactors

AC relays and contactors can drop out when the voltage is reduced below about 80 % of nominal for a duration of more than one cycle. The consequences vary with the application, but can be very severe in safety or financial terms.

4.2.3 Asynchronous motors

The point of operation of an asynchronous motor is governed by the balance between the torque-speed characteristic of the motor, which depends on the square of the voltage, and that of the mechanical load. During a voltage dip, the torque of the motor initially decreases, reducing the speed, while there can be an increase in the current until a new point of operation is reached.

Induction motors with a maximum torque higher than 2,2 times the rated value are very tolerant of dips presenting a positive phase sequence residual voltage above 70 % of the rated voltage. There is a current increase in the region of 25 % to 35 %, while the power drawn from the network is rather constant or decreases by a small amount. (If the torque defined by the load is rather constant, the speed decreases by only a small percentage, corresponding to the increase of slip due to the much lower flux in the motor.) Effects are mainly thermal, with a time constant much greater than even the longest dips. The over-current with voltage recovery is generally limited and, for directly connected motors, does not exceed the usual starting current.

Dips of larger depth are equivalent to short interruptions in their effect on the operation of the motor. Two different behaviours are found, according to the value of the mechanical time constant (ratio of total inertia to the rated torque of the motor).

- Where the mechanical time constant is high compared with the duration of the dip the speed decreases only slightly. The time constant of the flux is generally in the region of a few hundred milliseconds, so that there is the possibility of the back electromotive force (e.m.f) being in phase opposition to the supply voltage during recovery. The resulting transient inrush current can be greater than the normal starting current.
- Where the mechanical time constant is low compared with the duration of the dip the speed decrease is such that the motor virtually stops. The inrush current with voltage recovery corresponds to the normal starting current.

NOTE The possibility of motor protection relays or contactors dropping out must be considered – see 4.2.2.

The voltage recovery following a dip can also be a critical phase if there is a large number of motors connected to the same bus. In that case the high inrush current at the voltage recovery can produce a secondary voltage drop, delaying voltage recovery and retarding the re-acceleration of motors to normal speed. In some cases, it can be impossible to re-accelerate, thus requiring disconnection of motors.

4.2.4 Synchronous motors

Operation of a synchronous motor is defined on the output side by torque and speed, and on the input side by voltage and active power. Flux, reactive power and internal rotor angle are variables that are linked to the voltage and torque. The voltage dip can be tolerated provided new, stable operating conditions are established. This is generally the case for dips presenting a residual voltage of 75 % or 80 % (positive sequence). Also, the excitation circuit may be affected, and should be considered.

More severe conditions prevent new stable operating conditions being established, and create a loss of synchronism by increasing the rotor angle up to the limit of stability. Whether this critical angle is reached depends on the duration of the voltage dip, the level to which the voltage is reduced and the mechanical time constant. Complete analysis is complex and must take into account the damping cage, which can develop an asynchronous torque.

4.2.5 Power drive systems

In the case of power drive systems (PDS), which can be sensitive to even minor voltage dips, the effects of voltage dips and short interruptions can be quite complex, since the component parts must be considered as well as the complete assembly. Such systems generally contain a power converter/inverter, motor, control element and a number of auxiliary components.

The effect on the control element can be critical, since it has the function of managing the response of the other elements to the voltage dip or short interruption. The reduction in voltage results in a reduction in the power that can be transferred to the motor, and thence to the driven equipment, and can lead to loss of control. Regenerative converters can be especially sensitive or require specific management, particularly if the voltage dip or short interruption coincides with reversed power flow.

The converter has little or no available energy storage capability. Generally, the driven equipment has some energy storage capability, which can be used under certain conditions.

4.2.6 Lighting

High-pressure discharge lamps are extinguished by voltage dips that reduce the voltage to less than about 90 % of the nominal value. As a result of the consequent cooling and loss of pressure they may require several minutes to restart. Lighting systems containing electronic components can be affected as in 4.2.1.

5 Remedial measures

5.1 General considerations

The standard approach to electromagnetic compatibility is to apply co-ordinated emission and immunity limits. The attempt is made, on the one hand, to prevent electromagnetic disturbance from being emitted at an excessive level and, on the other hand, to provide the equipment exposed to disturbance with an adequate level of immunity – a level that enables it to operate as intended.

In the case of voltage dips and short interruptions, however, which are a natural response of an electrical system to short circuits or any surge of current, the disturbance level has two dimensions, residual voltage and duration. An emission limit would have to cover both dimensions.

The residual voltage cannot, in general, be altered. It extends over the range from zero volts to about the normal level of the supply voltage, depending on the relative positions of the observation point, short circuit and sources of generation.

The duration can be altered to some extent, since it is largely determined by the speed with which short circuits are cleared. However, a necessary feature of short circuit protection is the graduation of the operating times of switches, relays, etc. at different points on the network to ensure that each short circuit is cleared at the most appropriate point. This means that the clearance time and, consequently, the duration of voltage dips and short interruptions depend on the position of the short circuit. (If the causative event is other than a short circuit, the duration depends on the event concerned.)

Thus, there is limited scope for emission limitation in terms of the *level* of the disturbance. (There may be some scope in particular cases to influence the *frequency* with which dips and short interruptions occur, by taking action to reduce the exposure of a network to fault.) Therefore it is necessary to consider whether it is possible to provide immunity in equipment that is exposed to voltage dips and short interruptions.

With regard to voltage dips that are moderate in depth and duration, some equipment can have a certain level of inherent immunity, for example by virtue of its inertia or energy storage capacity. Alternatively, it may be possible to make design adjustments so that this property is provided.

However, for short interruptions and the more severe voltage dips immunity is not, in its strict sense, a feasible concept. The essential character of the event is that it involves the complete cessation or severe diminution of the energy supply for a brief interval. No electrical device can continue to operate as intended in the absence of its energy supply.

Therefore, such immunity as can be provided from these disturbances tends to be extrinsic – it is a matter of either providing for fast restoration of energy from an alternative source or arranging for the equipment and its associated process to adapt in an intended manner to the brief interruption or diminution of power.

– Some remedial measures use an energy storage capability to supply, for a limited time, the energy that is missing from the system supply. This can compensate for voltage dips of any residual voltage and even short interruptions. The capability of equipment to ride through voltage dips and interruptions over a certain time depends on the relationship between the energy stored and the power requirement of the process concerned. In many cases, a certain reaction time must be taken into account (several milliseconds). Since the storage of energy is very costly, the protection of a process tends to be directed at parts that are especially sensitive.
– Other remedial measures, having no energy storage capability, cannot cover supply interruptions but have the ability to compensate voltage dips with a residual voltage down to about 50 %. They differ in the level of voltage reduction that they are able to ride through. Generally, the duration of the dip is not an important parameter in these methods. Omission of the energy source results in costs that are typically lower.

The examples below are provided for more complete information on the disturbance phenomena of voltage dips and short interruptions. Mitigation, as such, is beyond the scope of this technical report. It needs to be approached on the basis of both economic and technical analysis, such as that outlined in IEEE 1346-1998 [5].

5.2 Some examples of remedial measures

5.2.1 Rotating machine with additional inertia

A simple method to ride through voltage dips and short interruptions for rotating equipment is to increase its inertia. However, the use of this method is limited to special applications e.g. in steel works, where it is often used additionally to smooth steep load changes. The capabilities of such a configuration depend on the relationship between inertia and actual load, but are typically in the range of several seconds.

5.2.2 Rotating machine with flywheel and engine or emergency power system

A large mass together with a motor/generator rotates at very high speed in a vacuum and stores energy of up to several megawatt-seconds. The energy is supplied to the system via a converter. The power available typically reaches up to several hundred kilowatts.

5.2.3 Uninterruptible power supply (UPS)

Uninterruptible power supply systems are widely used to protect sensitive equipment from voltage changes and outages of the supply system. Typically, the load is supplied via a converter. Its d.c. part is connected to an energy source such as batteries. Their storage capability varies over a wide range, depending on the specific requirements, and is limited mainly by the costs of energy storage. Actual applications range from small LV loads up to loads of several hundred kilowatts.

5.2.4 Superconducting magnetic energy storage (SMES)

Superconducting magnetic energy storage can have a capacity of several megawatt-seconds stored in a superconducting reactor. Typically, it can compensate for outages or deep voltage dips of several hundred milliseconds at loads with high power demand, depending on design.

5.2.5 Static var compensator (SVC)

A static var compensator consists typically of capacitors and/or passive filter circuits with a thyristor controlled reactor in parallel, and supplies continuously adjustable reactive power (balanced or unbalanced) to the system, thereby enabling adjustment of the voltage. Typically, SVCs are connected to the MV or HV system, with a rating from several megavars (Mvar) up to several hundred megavars. Mainly, they enable control of the voltage at large nodes in the distribution system, but they can be designed to compensate for voltage dips, with a rather limited capability in that application. The typical voltage regulating capability of an SVC is 10 % – 20 % of the system voltage.

5.2.6 Dynamic voltage restorer (DVR)

During voltage dips, dynamic voltage restorers add the missing voltage magnitude, both balanced and unbalanced, by means of power electronics via a transformer in series with the load. For residual voltages down to 50 %, the voltage can be restored within several milliseconds. Applications exist for loads in the range of several tens of kilowatts (LV) up to several tens of megawatts (MV).

5.2.7 Ferroresonant transformers

Ferroresonant (constant voltage) transformers are sometimes used to mitigate voltage dips. They are designed to operate in a state of magnetic saturation in order to maintain, under certain conditions, a constant output voltage despite variations in the input voltage.

6 Measurement of voltage dips and short interruptions

6.1 Conventions adopted in the measurement of voltage dips and short interruptions

All voltage values relating to voltage dips are r.m.s. values, taken over a minimum of one half of the period of the voltage at the supply frequency, 10 ms and $8^1/_3$ ms for 50 Hz and 60 Hz, respectively.

NOTE In IEC 61000-4-30[2], the basic voltage measurement is considered to be the r.m.s. voltage measured over one cycle and refreshed each half cycle.

[2] To be published.

An important dimension of a voltage dip is its magnitude in voltage terms. This has been expressed both as the value to which the voltage is depressed during the event and the amount by which that value is less than the pre-existing voltage or other reference value. In this technical report the former convention is adopted in quantifying that dimension of voltage dips, and the term used is the "residual voltage".

The measurement of voltage dips involves recording the value of the voltage during the dip, the duration of the event, and number of events within the measurement period. The latter two quantities are recorded for short interruptions. In order to record these values and to enable results to be compared, it is necessary to adopt certain rather arbitrary conventions.

The sections that follow describe the conventions that have been used or considered in various voltage dip surveys, without recommending any particular practice.

6.1.1 Reference voltage for measurement purposes

6.1.1.1 Fixed reference voltage

The residual voltage in a voltage dip is usually expressed in relative terms, per cent or per unit. The basis of the relationship is conventionally the nominal or declared system voltage at the observation point. This is especially relevant when the matter of interest is the possible effect on utilisation equipment. Thus, the reference voltage for measurements on low and medium voltage networks is usually the nominal or declared voltage of the network concerned.

6.1.1.2 Sliding reference voltage

A different approach can be appropriate when the subject of investigation includes a comparison between voltage dips at different points on the network, possibly operating at different voltages, resulting from a single short circuit event. This is often the case when measurements are taken on higher voltage networks. Moreover, it is useful to know how measurements on high voltage networks correspond to the dips as experienced by utilisation equipment, most of which is connected to low or medium voltage networks.

The normal voltage range on high voltage networks can be more freely variable than is the case on low or medium voltage networks, being only one component of the operating regime for the network, along with, for example, transformer tapping range. An event which gives rise to a given depth of voltage dip measured on a high voltage network is likely to result in a great variety of residual voltages at different observation points on lower voltage networks, even if they are directly downstream. This is because the voltages preceding the dip at the different points will vary according to the disposition of taps and connections on intervening transformers.

In these conditions the voltage dip can be measured relative to the preceding voltage, to enable the change of voltage to be recorded. In this case, in order to represent the voltage preceding the onset of the voltage dip, the reference voltage is a value that is continuously calculated over a certain interval, much longer that the duration of a voltage dip. It is then referred to as a sliding reference voltage.

When a sliding reference voltage is used, it is necessary to take account of the fact that the value that is critical for utilisation equipment is often an absolute voltage value. For example, assuming that the voltage level preceding the dip is in the range $0{,}9U_n – 1{,}1U_n$ at a particular point, a voltage reduction of r per unit, relative to a sliding reference value, can mean an actual residual voltage as low as $0{,}9.r.U_n$ or as high as $1{,}1.r.U_n$ (U_n = nominal voltage). This is not necessarily sufficiently precise for assessing the effect on equipment.

6.1.2 Dip duration: Voltage thresholds marking start and end

The selection of voltage thresholds to mark the start and end of a voltage dip depends on whether the reference voltage is a sliding value representing the immediately preceding voltage or a fixed value such as the nominal or declared voltage. The case of a fixed reference voltage is taken first.

At any given observation point on the supply network, the voltage is constantly varying in response to the incessant variations and switchings of loads at various points on the network. Usually, the network is designed to maintain these voltage variations within a certain band, at least under normal supply conditions. In the midst of this constant movement of the voltage within the intended band of variation, voltage changes of the type defined as voltage dips arise in the event of a short circuit or equivalent surge of current. In such an event, the voltages resulting from it can have any value between 0 % and 100 % of the pre-existing voltage, depending on the locations of the observation points relative to the location of the causative event.

Therefore, at some observation points that are rather remote from the site of the causative event, especially those at which the pre-existing voltage is near the top of the intended band of voltage variation, the residual voltage can remain high enough to still be within that band. In measurements at such a point, this residual voltage, being within the intended range, does not need to be distinguished from the voltage variations arising from normal fluctuations of the local load. By convention, it is excluded for the purposes of dip measurement.

For this reason, many voltage dip measurements have been based on a voltage threshold corresponding to the lower limit of the intended band of variation. Only events in which the voltage falls to a value below this threshold are recorded as dips. Each voltage dip is reckoned as starting at the instant at which the voltage falls below the threshold and ending at the instant at which the voltage recovers at least to that value.

However, in the case of an observation point at which the voltage, at a given time, happens to be near the bottom of the intended band of variation, it is likely that the normal variations and switchings of load will result in small voltage oscillations about the lower limit of the band. (The normal band of variation is considered as applying to the average voltage over a short interval, such as 10 min – therefore the voltage within this interval has values both below and above the average.) The recorded number of voltage dips at such an observation point could be greatly inflated by these load-induced voltage variations, if the threshold were set as above.

One method of excluding these variations is to apply a further margin below the normal band of voltage variation. In this approach, an observed event is recorded as a voltage dip only when the residual voltage falls below a threshold that is set at a specified margin below the intended band of voltage variation. In recording the duration of the voltage dip, the two instants at which the voltage crosses that threshold mark the start and end of the event.

An alternative method, using two thresholds, has also been used to exclude load-induced voltage oscillations near the bottom of the intended band of variation. This classifies as voltage dips only those events in which the voltage, having fallen below a threshold corresponding to the bottom of the band, recovers to a second threshold that is set at a slight margin (typically 1 % of the reference voltage) above the first threshold. (By analogy, the term “hysteresis” has been applied to the margin between the two thresholds.)

In the original development of this approach the second threshold was used only for the purpose of classifying an event as a voltage dip – given an event that was so classified, the first threshold was used to mark both its start and end. As a variation on this approach, a practice developed of adopting the second threshold, just described, as marking the end of the observed voltage dip.

To summarise, for the case of a fixed reference voltage the possible settings for the start and end thresholds are as follows:

– start threshold set at either the lower limit of the bandwidth of normal voltage variation or a value at a specified margin below that limit;
– end threshold set at the same value as the start threshold or at a small margin above it (hysteresis).

When the reference voltage is a sliding value, calculated continuously to represent the voltage level immediately before the dip, this process has a smoothing effect which automatically eliminates most of the variations due to local load fluctuations. In this case, therefore, the start and end thresholds can be selected at a value quite close to the sliding reference voltage.

In the event that there is a downward trend in the voltage, independent of the dip, the value to which the voltage recovers at the end of the dip is somewhat less than the value immediately before the event. Therefore, in order to ensure that the end of the dip is recognised, it may be necessary to set the end threshold at a value slightly below the reference value, e.g. 99 % of the sliding reference voltage. For uniformity, the start threshold can be set at the same value.

In the case of multi-phase measurements, voltage dips whose durations overlap in time have conventionally been counted as a single event. In some cases the practice has been to measure the duration from the instant at which the first phase or line voltage falls below the start threshold to the instant at which the last phase or line voltage rises to or above the end threshold.

6.1.3 Distinguishing between voltage dips and short interruptions

Notionally, an interruption implies complete disconnection from all sources of supply and, therefore, zero voltage. In practice, however, the disconnected portion of network can include significant sources of stored energy, preventing the voltage from reaching zero during a very short interruption. Furthermore, the theoretically most severe voltage dip implies zero voltage. Such a voltage dip is, effectively, an interruption, although a connection to the voltage source remains. Thus, there can be a difficulty for the measuring instrument in distinguishing short interruptions from voltage dips.

For this reason, in measuring voltage dips and short interruptions, it is necessary to adopt a boundary voltage, greater than zero, in order to distinguish between these phenomena. An event in which the residual voltage falls below the adopted boundary value is classified as a short interruption; otherwise it is a voltage dip.

As a result, a given short circuit can result in both voltage dips and short interruptions at different observation points, depending on whether the residual voltage observed at each such point is above or below the conventionally selected boundary level.

6.2 Measurement of voltage dips

Although voltage dips are often complex in shape, a simplified approach has been taken in campaigns in which voltage dip measurements are taken at several sites in order to obtain statistical data. The approach has been to treat dips as if they are all simple single depth events. A single data pair is recorded for each dip. The residual voltage is the lowest voltage occurring during the event. The duration is measured from the instant at which the voltage falls below the start threshold to that at which it becomes equal to or greater than the end threshold. These thresholds are set as described above.

Some measured events, however, are found to be more complex, with the voltage taking several levels during the course of the event, possibly with the voltage fall, rise or both being extended over an appreciable interval within the duration of the dip. In such a case, to characterise the dip as having a residual voltage equivalent to the lowest voltage reached and a duration corresponding to the start and end thresholds can be a serious overstatement of the magnitude of the disturbance.

In order to deal with the complexity of non-rectangular dips it would be possible to designate several gradations on the voltage scale and to record the duration for which the voltage is at or below each such mark. This would result in the recording of several residual voltage-duration pairs of data to describe each voltage dip.

However, this approach has not been used in any of the measurement campaigns whose results are presented in this report.

In some cases the purpose of voltage dip measurement at a specific site is to monitor whether the terms of a supplier-user contract are being fulfilled or whether conditions critical to a particular machine or process are being breached. In such cases it is likely that there is a particular voltage threshold which is the focus of attention, either because it is specified in the contract or because it is the value that is critical for the machine or process involved. The start and end of the actual dip and its ultimate depth may all be irrelevant. There is no record taken unless the voltage falls below the specified threshold. When it does so, the only information required is the duration for which it remains at or below that value.

6.3 Measurement of short interruptions

Short interruptions are measured in the same way as voltage dips. A voltage boundary is selected below which the event is designated a short interruption. This boundary has in the past been variously set at 1 %, 5 % and 10 % of the reference voltage.

When these measurements are part of the campaign referred to above, the boundary voltage is used only to identify an event as either a voltage dip or short interruptions. However, the duration of the short interruption is based on the same start and end thresholds used for voltage dips. In the case of a non-rectangular event, this overstates the duration of the short interruption.

6.4 Classification of measurement results

In collecting or presenting the results of a measurement campaign for voltage dips and short interruptions, it is necessary to have regard to the two dimensional nature of the phenomenon. This suggests a two dimensional matrix or tabular approach, with the rows containing the classification of depths or residual voltages, and the columns containing the duration classifications.

6.4.1 Results based on the assumption of rectangular shape

Table 2 shows the tabulation developed by UNIPEDE. For a given measurement site, each cell is intended to contain the number of voltage dips of the corresponding depth and duration occurring within a specified period, usually one year.

The last row represents short interruptions. (In earlier measurements a voltage of 1 % of the reference voltage was used as the boundary between voltage dips and short interruptions.)

Table 2 – Classification of measurement results

Residual voltage u % of U_{ref}	Duration s							
	0,01 < Δt ≤ 0,02	0,02 < Δt ≤ 0,1	0,1 < Δt ≤ 0,5	0,5 < Δt ≤ 1	1 < Δt ≤ 3	3 < Δt ≤ 20	20 < Δt ≤ 60	60 < Δt ≤ 180
90 > u ≥ 85								
85 > u ≥ 70								
70 > u ≥ 40								
40 > u ≥ 10								
10 > u ≥ 0								

NOTE 1 Measurement results in the first column and first row are likely to be inflated by transients and load fluctuations, respectively.

NOTE 2 0,01 and 0,02 s in the first two duration headings correspond to a half period and to one period of the 50 Hz voltage. For 60 Hz systems corresponding values would be used.

A similar table is used to compile the results from all the sites in the measurement campaign. In this case each cell can contain:

– a percentile (typically 95th) of the number of dips recorded in that cell for all sites;
– the maximum number recorded in the cell;
– the average number for the cell for all sites;
– or other statistic.

When several types of network are involved, it is appropriate to produce a separate table for each type. For example, overhead networks should be distinguished from underground networks.

6.4.2 Results allowing for complex dip shapes

A similar table could be used to collect the results of measurements when several depth-duration pairs are recorded for each voltage dip. Each dip would then have several entries on the table, one for each of the designated gradations on the voltage scale. It would be necessary to provide an additional column in the table to provide for zero duration. The rows would correspond to the selected gradations of the voltage. In a multi-site measurement campaign, the results from all the sites could be consolidated into a single table as described above for the case of a simple dip shape, with each cell containing a specified statistic calculated from the complete measurement results.

As far as is known, this rather complex approach has not been used in practice.

6.5 Aggregation of measurement results

Reclosing operations can result in multiple voltage dips or interruptions from the same primary causative event. Such repetitive disturbances are unlikely to affect equipment and processes multiple times. It can therefore be misleading to count these disturbances as separate events.

To take account of this effect, the concept of aggregation can be applied for statistical analyses and regulatory or customer reports. It consists in applying a set of rules which define how to group events occurring within a limited interval of time and to characterise the resulting equivalent event in terms of amplitude and duration.

For example, all events within a 1 min interval can be counted as one single event whose amplitude and duration are those of the most severe dip observed during this interval.

It must be noted that the choice of aggregation method can have a significant impact on the number and characteristics of the recorded events. Moreover, the resulting equivalent events do not necessarily reflect exactly the impact on equipment and processes.

7 Available measurement results

Some results are presented below, in the format in which they were provided to IEC.

7.1 UNIPEDE statistics

Nine countries of Europe co-operated in the UNIPEDE DISDIP measurement campaign [8] to determine the number of voltage dips and short interruptions per year experienced by electricity users connected to LV and MV networks.

The measurements were carried out either on LV networks as close as possible to the LV busbars of MV/LV substations or on MV lines to which MV/LV substations were directly connected. Where measurement was carried out through a voltage transformer, the necessary correction was applied to represent the phase-neutral voltage experienced by LV users.

The aim was to reflect the wide range of environmental and geographical conditions found in several countries with different climates and network configurations. Results were produced for 85 measurement sites, with the period of measurement being at least a year in almost all cases.

The thresholds adopted were 90 % of the nominal voltage for the start and end of the voltage dip, with durations extending from 10 ms to 1 min. For short interruptions the voltage threshold was 0 %, corresponding to the last row in Tables 3 – 8.

Of the 85 measurement sites, 33 were on underground networks and the remaining 52 were on mixed networks with varying proportions of overhead lines and underground cables.

Tables 3, 4 and 5 present the results for the underground networks.

Table 3 shows the maximum number of events recorded corresponding to the individual cells of the table. Since no two of these maxima necessarily occur at the same site, the summation of all the cells of the table has no meaning. For information, therefore, the number for the site recording the greatest number of dip-interruption events is appended at the end of the table.

Table 4 gives the means of the numbers of events occurring within each cell. (In this case the mean number of events at all measuring sites, appended to the table, is the same as the mean of the cell values.)

Table 5 contains the maximum number of events in each cell after discarding the highest 5 % of the numbers recorded for that cell – i.e. the value in each cell is the 95th percentile of the distribution of numbers of events within that cell. The 95th percentile of all dip-interruption events at all sites is appended to the table.

Tables 6, 7 and 8 present the corresponding values for mixed networks.

Table 3 – Underground networks: voltage dip incidence – maximum

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	63	38	8	1	1	0
70 > *u* ≥ 40	8	29	4	0	0	0
40 > *u* ≥ 0	6	17	1	3	0	0
u = 0 (interruptions)	1	1	2	1	1	10
Highest number of dips/site: 124						

Table 4 – Underground networks: voltage dip incidence – mean

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	13,4	9,5	0,4	0,2	0,1	0
70 > *u* ≥ 40	1,5	5,9	0,3	0	0	0
40 > *u* ≥ 0	0,1	1,8	0,2	0,2	0	0
u = 0 (interruptions)	0,1	0,1	0,3	0,1	0,1	0,7
Mean number of dips/site: 35						

Table 5 – Underground networks: voltage dip incidence – 95th percentile

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	23	19	3	1	0	0
70 > *u* ≥ 40	5	19	1	0	0	0
40 > *u* ≥ 0	1	8	1	0	0	0
u = 0 (interruptions)	0	0	1	0	1	1
95th percentile of dips/site: 63						

Table 6 – Mixed networks: voltage dip incidence – maximum

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	111	99	20	8	3	1
70 > *u* ≥ 40	50	59	14	3	1	0
40 > *u* ≥ 0	5	26	11	4	1	1
u = 0 (interruptions)	5	25	104	10	15	24
Highest number of dips/site: 306						

Table 7 – Mixed networks: voltage dip incidence – mean

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 m	**100 ≤ *t* < 500** m	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	26,8	27,6	3,4	1,2	0,3	0,02
70 > *u* ≥ 40	3,1	15,1	1,3	0,4	0,02	0
40 > *u* ≥ 0	0,4	6,5	1	0,4	0,1	0,02
u = 0 (interruptions)	0,3	3,5	7,4	1,2	1,1	2,1
Mean number of dips/site: 103						

Table 8 – Mixed networks: voltage dip incidence – 95th percentile

Residual voltage *u* % of reference voltage	**Duration *t***					
	10 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s
90 > *u* ≥ 70	61	68	12	6	1	0
70 > *u* ≥ 40	8	38	4	1	0	0
40 > *u* ≥ 0	2	20	4	2	1	0
u = 0 (interruptions)	0	18	26	5	4	9
95th percentile of dips/site: 256						

7.2 **Statistics from EPRI survey** [9] [10]

For this survey, measurement results were collected over a two-year period (1993 to 1995) from the MV distribution system of 24 utilities throughout the United States. The actual number of sites at which monitors were installed totalled 277, on 95 different feeders. There were very few cable circuits in this survey.

In most cases, line-to-neutral voltages were measured at MV. The RMS voltage was calculated over one cycle. Any events within a 1-min period were classified as one dip, characterised by the minimum voltage on any phase and the duration of the event associated with that phase.

Statistical results of the frequency and the magnitude of voltage dips are illustrated in the following figures. (Data relating to the duration of voltage dips has not yet been published.) The returns from each site were given a sampling weight corresponding to the site's probability of having been selected from all possible monitoring locations.

Figure 4 represents the number of dips and interruptions per site per 30 days.

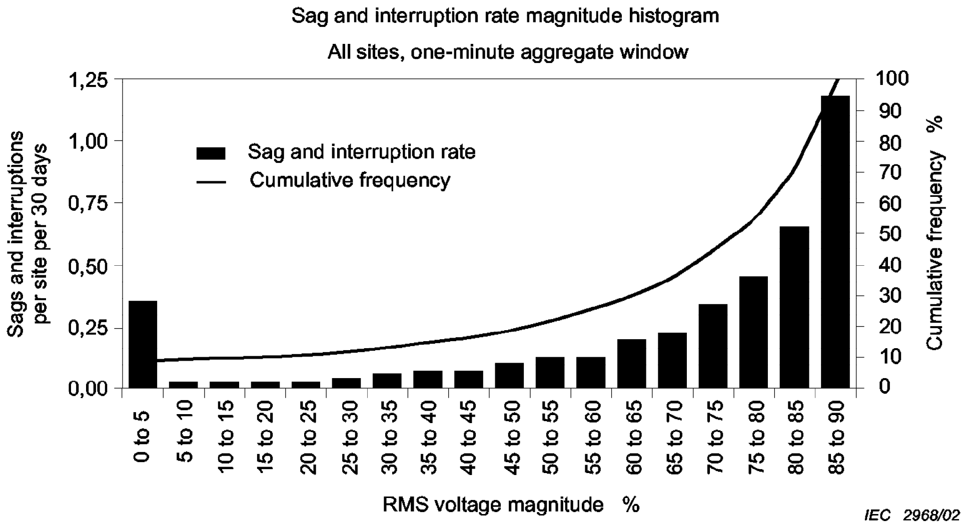


Figure 4 – Histogram of sag and interruption rates

Figure 5 illustrates the number of sites recording a given number of voltage dips below 4 different voltage thresholds. This corresponds to the $SARFI_x$ index, where:

$SARFI_x$ (*System Average RMS (Variation) Frequency Index)* = $\Sigma N_i/N_t$,

where

x = rms voltage threshold;

N_i = number of customers per year experiencing voltage dips below x;

N_t = number of customers served from the section of the system concerned.

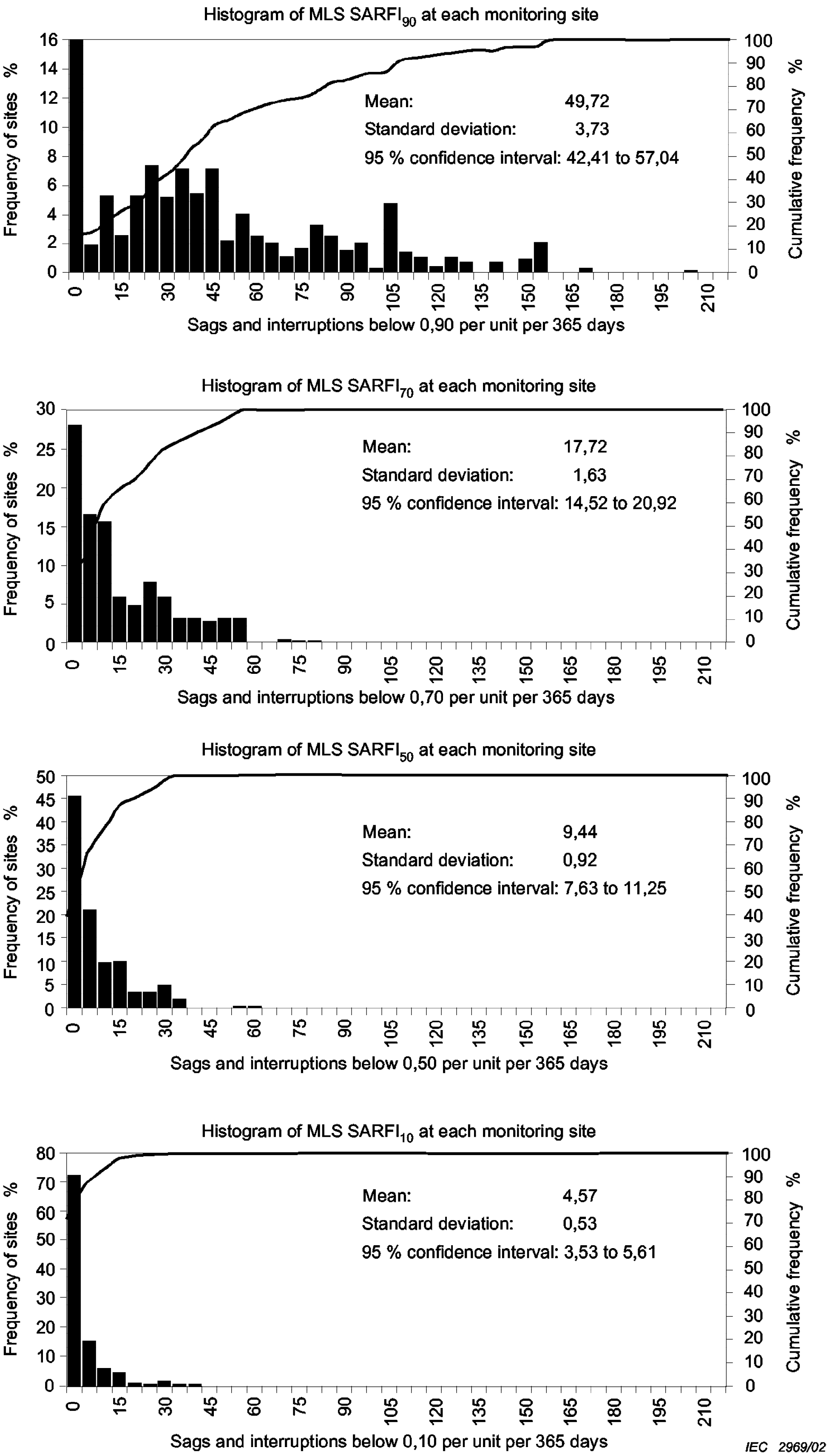


Figure 5 – Annual number of sags and interruptions below 4 voltage thresholds

7.3 Some statistics from individual countries

7.3.1 Country A

These measurements have been performed on the HV and MV systems over a period of one year, using 27 instruments at HV and 36 instruments at MV.

The thresholds adopted were 90 % (start), 92 % (end) and 10 % (interruption), based on the nominal voltage as the reference value. RMS voltage values were calculated over 10 ms windows.

An event was considered as a voltage dip when at least one of the three voltages dropped below the start threshold. An event was considered as a short interruption when all the three voltages dropped below the 10 % threshold.

The measuring equipment was set up to detect events whose duration was longer than or equal to 20 ms and in which the residual voltage was lower than or equal to 90 % of the reference voltage. However, the following tables show only events whose duration was longer than or equal to 50 ms, and whose amplitude was lower than or equal to 80 %.

Short interruptions were counted separately from voltage dips, resulting in separate statistics in the tables below.

Tables 9 and 10 show the distribution of the measured dips and interruptions as a percentage of the total number of detected events (over 20 000) on the HV and MV systems.

Table 9 – Voltage dips and short interruptions on the HV system

Residual voltage *u* % of reference voltage	**Duration *t***				
	50 ≤ *t* < 200 ms	**200 ≤ *t* < 400** ms	**400 ≤ *t* < 600** ms	**0,6 ≤ *t* < 1** s	**1 ≤ *t*** s
80 > *u* ≥ 75	7,4 %	2,7 %	0,6 %	0,8 %	0,6 %
75 > *u* ≥ 70	3,9 %	1,5 %	0,2 %	0,3 %	0 %
70 > *u* ≥ 50	4,7 %	2,5 %	0,2 %	0,4 %	0,4 %
50 > *u* ≥ 30	0,9 %	0,4 %	0,2 %	0,2 %	0 %
30 > *u*	3,2 %	0,6 %	0,2 %	0 %	1,1 %
Short interruptions	0 %	0,3 %	0,1 %	0 %	3,5 %

Table 10 – Voltage dips and short interruptions on the MV system

Residual voltage *u* % of reference voltage	**Duration *t***				
	50 ≤ *t* < 200 ms	**200 ≤ *t* < 400** ms	**400 ≤ *t* < 600** ms	**0,6 ≤ *t* < 1** s	**1 ≤ *t*** s
80 > *u* ≥ 75	6,5 %	2,4 %	0,8 %	0,9 %	0 %
75 > *u* ≥ 70	2,7 %	1,4 %	1,1 %	1,3 %	0 %
70 > *u* ≥ 50	7,1 %	2,4 %	1,6 %	1,3 %	0 %
50 > *u* ≥ 30	2,2 %	1,8 %	0,6 %	0,6 %	0 %
30 > *u*	5,7 %	2,4 %	0,8 %	0 %	0,2 %
Short interruptions	1,3 %	2,4 %	0,2 %	0 %	4,7 %

7.3.2 Country B

A measurement campaign was carried out over a period of three years, 1996 – 1998, using 45 dip recorders and recording the results at each selected site for one full year. Generally, the measurements were taken phase-ground, but the available voltage transformer connections necessitated phase-phase measurements in some cases.

The thresholds adopted were 90 % (start), 91 % (end) and 1 % (interruption), based on the nominal voltage as the reference value.

Voltage dips were classified by depth and duration in accordance with the tabulation developed by UNIPEDE. Dips that involved more than one phase were designated as a single event if they overlapped in time. Events that were separated in time (without overlap) were counted as separate dips.

It was found that a quarter of the recorded events had durations in the range 10 ms to 20 ms. It was also evident that different measuring instruments responded differently to these events, which are probably voltage transients. Therefore it was decided to disregard events with durations less than 20 ms.

The tables that follow give the results for three types of network: medium voltage overhead – 109 measurement sites, medium voltage underground – 11 sites, and high voltage (400 kV) – 9 sites.

In each case both the maximum and mean incidence rates are presented. For maximum values (Tables 11, 14 and 16) each table cell contains the annual number of voltage dips at the site recording the greatest number of dips at the corresponding depth (residual voltage) and duration. For mean values (Tables 13, 15 and 17) each cell contains the arithmetic mean of the annual numbers recorded at all sites at the corresponding depth (residual voltage) and duration.

In addition, Table 12 contains the 95th percentiles for MV overhead networks. In this table each cell is the maximum number of dips after excluding the 5 % of sites recording the greatest number of dips of the corresponding depth (residual voltage) and duration. (The number of measurement sites was not sufficient to enable similar tables to be produced for the other network types.)

Table 11 – MV overhead networks: voltage dip incidence – maximum

Residual voltage *u* % of reference voltage	**Duration *t***						
	20 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s	**60 ≤ *t* < 180** s
90 > *u* ≥ 85	541	61	24	25	53	51	10
85 > *u* ≥ 70	1 532	203	136	20	7	1	1
70 > *u* ≥ 40	1 146	225	38	26	8	1	1
40 > *u* ≥ 1	97	424	31	28	5	1	3
1 > *u* ≥ 0 (interruptions)	2	20	7	27	27	6	10

Table 12 – MV overhead networks: voltage dip incidence – 95th percentile

Residual voltage *u* % of reference voltage	Duration *t*						
	20 ≤ *t* < 100 ms	100 ≤ *t* < 500 ms	0,5 ≤ *t* < 1 s	1 ≤ *t* < 3 s	3 ≤ *t* < 20 s	20 ≤ *t* < 60 s	60 ≤ *t* < 180 s
90 > *u* ≥ 85	150	37	9	6	3	2	1
85 > *u* ≥ 70	238	93	14	5	1	0	0
70 > *u* ≥ 40	141	128	15	5	1	0	0
40 > *u* ≥ 1	55	113	12	4	1	0	0
1 > *u* ≥ 0 (interruptions)	0	4	1	6	7	2	3

Table 13 – MV overhead networks: voltage dip incidence – mean

Residual voltage *u* % of reference voltage	Duration *t*						
	20 ≤ *t* < 100 ms	100 ≤ *t* < 500 ms	0,5 ≤ *t* < 1 s	1 ≤ *t* < 3 s	3 ≤ *t* < 20 s	20 ≤ *t* < 60 s	60 ≤ *t* < 180 s
90 > *u* ≥ 85	47,1	11,7	2,3	1,2	1,5	1,1	0,2
85 > *u* ≥ 70	63,9	28,1	5,3	1,0	0,2	0	0
70 > *u* ≥ 40	36,5	31,9	3,6	1,1	0,2	0	0
40 > *u* ≥ 1	10,4	24,2	2,5	0,8	0,2	0	0
1 > *u* ≥ 0 (interruptions)	0	0,8	0,3	1,1	1,4	0,4	0,6

Table 14 – MV underground networks: voltage dip incidence – maximum

Residual voltage *u* % of reference voltage	Duration *t*						
	20 ≤ *t* < 100 ms	100 ≤ *t* < 500 ms	0,5 ≤ *t* < 1 s	1 ≤ *t* < 3 s	3 ≤ *t* < 20 s	20 ≤ *t* < 60 s	60 ≤ *t* < 180 s
90 > *u* ≥ 85	105	34	8	20	43	11	10
85 > *u* ≥ 70	64	54	28	2	0	0	0
70 > *u* ≥ 40	65	126	9	2	0	0	0
40 > *u* ≥ 1	26	53	3	1	0	0	0
1 > *u* ≥ 0 (interruptions)	0	9	5	6	3	1	2

Table 15 – MV underground networks: voltage dip incidence – mean

Residual voltage *u* % of reference voltage	**Duration *t***						
	20 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s	**60 ≤ *t* < 180** s
90 > *u* ≥ 85	37,4	12,1	1,8	1,9	4,2	1,2	1,1
85 > *u* ≥ 70	24,0	20,4	4,4	0,5	0	0	0
70 > *u* ≥ 40	14,2	19,7	2,1	0,2	0	0	0
40 > *u* ≥ 1	5,6	12,5	0,8	0,1	0	0	0
1 > *u* ≥ 0 (interruptions)	0	0,8	0,7	0,6	0,7	0,2	0,5

Table 16 – HV (400 kV) networks: voltage dip incidence – maximum

Residual voltage *u* % of reference voltage	**Duration *t***						
	20 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s	**60 ≤ *t* < 180** s
90 > *u* ≥ 85	50	11	2	0	0	0	0
85 > *u* ≥ 70	61	15	1	0	0	0	0
70 > *u* ≥ 40	20	14	1	0	0	0	0
40 > *u* ≥ 1	2	1	0	6	0	0	0
1 > *u* ≥ 0 (interruptions)	0	0	2	4	0	0	0

Table 17 – HV (400 kV) networks: voltage dip incidence – mean

Residual voltage *u* % of reference voltage	**Duration *t***						
	20 ≤ *t* < 100 ms	**100 ≤ *t* < 500** ms	**0,5 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 60** s	**60 ≤ *t* < 180** s
90 > *u* ≥ 85	27,7	3,1	0,4	0	0	0	0
85 > *u* ≥ 70	30,2	7,6	0,3	0	0	0	0
70 > *u* ≥ 40	7,1	2,9	0,2	0	0	0	0
40 > *u* ≥ 1	0,9	0,1	0	1,1	0	0	0
1 > *u* ≥ 0 (interruptions)	0	0	0,2	0,6	0	0	0

7.3.3 Country C

For this country, measurement results are available as follows:

- two measurement sites on underground networks for the three years 1996-1998 inclusive;
- three measurement sites on mixed networks (overhead/underground) for the same three years;
- three measurement sites on mixed networks for a single year, 1999;
- three measurement sites on overhead networks for the year 1999.

These measurements were taken at the MV busbars of HV/MV substations.

In addition to the usual tables of results, a single characteristic value was determined for each set of tabulated results. This was evaluated by applying a weighting to the value in each cell and then taking the summation of all the weighted cell values.

The cell weighting coefficients are given in Table 18. For each cell the coefficient is given by the product of the mid-interval values of the *duration* and *depth* (not residual voltage) intervals. For example, the cell corresponding to the duration interval 0,5 s – 0,75 s and the depth interval $0{,}3U_{ref}$ – $0{,}6U_{ref}$ (residual voltage $0{,}4U_{ref}$ – $0{,}7U_{ref}$) has the weighting coefficient 0,28125 = 0,625 × 0,45. However, on the assumption that there is no further increase in severity beyond 1 s, the coefficient is calculated on the basis of the same duration mid-interval value of 0,875 for the final four columns.

Table 18 – Voltage dip severity weighting coefficients

Residual voltage *u*	**Depth *u'***	**Duration *t***							
% of U_N		**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	10 < *u'* ≤ 15	0,008	0,022	0,047	0,078	0,109	0,109	0,109	0,109
85 > *u* ≥ 70	15 < *u'* ≤ 30	0,014	0,039	0,084	0,141	0,197	0,197	0,197	0,197
70 > *u* ≥ 40	30 < *u'* ≤ 60	0,027	0,079	0,169	0,281	0,394	0,394	0,394	0,394
40 > *u* ≥ 10	60 < *u'* ≤ 90	0,045	0,131	0,281	0,469	0,656	0,656	0,656	0,656
10 > *u* ≥ 0	90 < *u'* ≤ 100	0,057	0,166	0,356	0,594	0,831	0,831	0,831	0,831

The weighted sum obtained after multiplying the individual cell values by the corresponding coefficients contained in Table 18 is shown at the end of each of the following tables 19 to 26. For comparison, it is accompanied by the direct sum resulting from the summation of the actual, unweighted, cell values.

Tables 19 and 20 contain the results for two measuring sites on underground networks for the 3-year period 1996-1998. These two tables contain the maximum and mean values, respectively, of the annual number of voltage dips recorded for each combination of the classified intervals of residual voltage and duration. In the case of the maximum values, the mean of the three annual numbers is determined for each of the two sites and the greater of the two results is presented for each cell of the table. In the case of the mean values, the number in each cell is simply the mean of six values – three annual figures for each of two sites.

Tables 21 and 22 contain the same information for mixed networks in the same 3-year period. They are calculated as just described, except that there were three measurement sites instead of two.

Table 19 – Underground networks: 2 measurement sites, 1996-1998 – maximum number of dips/year

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	1,67	0,33	0,00	0,33	0,00	0,00	0,00	0,00
85 > *u* ≥ 70	3,67	3,33	0,67	0,33	0,00	0,00	0,00	0,00
70 > *u* ≥ 40	0,67	2,67	0,33	1,33	0,00	1,33	0,00	0,00
40 > *u* ≥ 10	0,00	0,33	0,00	0,00	0,00	0,00	0,00	0,00
10 > *u* ≥ 0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Direct sum: 17,0 Weighted sum: 1,5								

Table 20 – Underground networks: 2 measurement sites, 1996-1998 – mean number of dips/year

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	1,17	0,17	0,00	0,17	0,00	0,00	0,00	0,00
85 > *u* ≥ 70	3,67	2,50	0,50	0,33	0,00	0,00	0,00	0,00
70 > *u* ≥ 40	0,33	1,33	0,17	1,00	0,00	0,67	0,00	0,00
40 > *u* ≥ 10	0,00	0,17	0,00	0,00	0,00	0,00	0,00	0,00
10 > *u* ≥ 0	0,00	0,00	0,00	0,00	0,00	0,00	0,00	0,00
Direct sum: 12,2 Weighted sum: 1,0								

Table 21 – Mixed networks: 3 measurement sites, 1996-1998 – maximum number of dips/year

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	4,00	1,33	1,00	0,67	0,33	0,67	0,33	0,00
85 > *u* ≥ 70	8,67	5,33	2,33	2,33	1,33	0,33	0,00	0,00
70 > *u* ≥ 40	3,00	3,67	2,67	4,00	0,67	1,00	0,00	0,00
40 > *u* ≥ 10	0,67	1,33	0,67	1,00	1,00	1,67	0,00	0,00
10 > *u* ≥ 0	0,00	0,33	0,33	0,67	0,00	1,00	0,33	0,00
Direct sum: 52,7 Weighted sum: 8,3								

Table 22 – Mixed networks: 3 measurement sites, 1996-1998 – mean number of dips/year

	Duration t							
Residual voltage u % of U_N	**$20 \le t$ < 100** ms	**$100 \le t$ < 250** ms	**$250 \le t$ < 500** ms	**$0,5 \le t$ < 0,75** s	**$0,75 \le t$ < 1** s	**$1 \le t$ < 3** s	**$3 \le t$ < 20** s	**$20 \le t$ < 180** s
$90 > u \ge 85$	2,67	0,89	0,56	0,33	0,11	0,22	0,11	0,00
$85 > u \ge 70$	5,78	4,78	1,11	1,44	0,67	0,11	0,00	0,00
$70 > u \ge 40$	1,78	2,56	1,78	1,44	0,22	0,67	0,00	0,00
$40 > u \ge 10$	0,22	0,89	0,22	0,56	0,44	1,11	0,00	0,00
$10 > u \ge 0$	0,00	0,11	0,11	0,22	0,00	0,33	0,11	0,00
Direct sum: 31,6 Weighted sum: 4,1								

Table 23 shows the results for three measurement sites on mixed networks for a single year, 1999. The number in each cell is the greatest of the numbers recorded at the three sites with the corresponding duration and residual voltage. Table 24 contains the means of these values for the same set of measurements.

Tables 25 and 26 contain the corresponding results for three measurement sites on overhead networks in the same year.

Table 23 – Mixed networks: 3 measurement sites, 1999 – maximum number of dips

	Duration t							
Residual voltage u % of U_N	**$20 \le t$ < 100** ms	**$100 \le t$ < 250** ms	**$250 \le t$ < 500** ms	**$0,5 \le t$ < 0,75** s	**$0,75 \le t$ < 1** s	**$1 \le t$ < 3** s	**$3 \le t$ < 20** s	**$20 \le t$ < 180** s
$90 > u \ge 85$	2	3	1	0	0	0	0	0
$85 > u \ge 70$	7	13	1	0	1	0	0	0
$70 > u \ge 40$	5	4	1	2	1	1	0	0
$40 > u \ge 10$	1	1	0	0	1	1	0	1
$10 > u \ge 0$	0	1	0	1	1	1	0	4
Direct sum: 55 Weighted sum: 10,8								

Table 24 – Mixed networks: 3 measurement sites, 1999 – mean number of dips

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	1,67	1,67	1,00	0,00	0,00	0,00	0,00	0,00
85 > *u* ≥ 70	4,67	5,33	0,33	0,00	0,33	0,00	0,00	0,00
70 > *u* ≥ 40	3,00	2,33	0,67	1,00	0,67	0,33	0,00	0,00
40 > *u* ≥ 10	0,67	0,33	0,00	0,00	0,33	0,33	0,00	0,33
10 > *u* ≥ 0	0,00	0,33	0,00	0,33	0,33	0,33	0,00	1,33
Direct sum: 27,7 Weighted sum: 4,1								

Table 25 – Overhead networks: 3 measurement sites, 1999 – maximum number of dips

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	10	4	3	1	0	1	1	0
85 > *u* ≥ 70	7	17	17	9	4	1	1	0
70 > *u* ≥ 40	2	12	3	1	5	0	0	0
40 > *u* ≥ 10	0	8	0	1	0	4	0	2
10 > *u* ≥ 0	0	0	0	3	0	1	6	0
Direct sum: 124 Weighted sum: 21,8								

Table 26 – Overhead networks: 3 measurement sites, 1999 – mean number of dips

	Duration *t*							
Residual voltage *u* % of U_N	**20 ≤ *t* < 100** ms	**100 ≤ *t* < 250** ms	**250 ≤ *t* < 500** ms	**0,5 ≤ *t* < 0,75** s	**0,75 ≤ *t* < 1** s	**1 ≤ *t* < 3** s	**3 ≤ *t* < 20** s	**20 ≤ *t* < 180** s
90 > *u* ≥ 85	7,00	2,00	1,00	1,00	0,00	0,67	0,33	0,00
85 > *u* ≥ 70	6,67	12,00	7,67	3,33	1,33	0,33	0,33	0,00
70 > *u* ≥ 40	1,00	7,33	1,33	0,67	2,00	0,00	0,00	0,00
40 > *u* ≥ 10	0,00	3,00	0,00	0,33	0,00	1,33	0,00	0,67
10 > *u* ≥ 0	0,00	0,00	0,00	1,00	0,00	0,33	2,00	0,00
Direct sum: 64,7 Weighted sum: 8,5								

7.3.4 Country D

In 1987 the national federation of electricity companies, comprising 10 electric utilities, conducted a measurement campaign from July to September – the period during which most outages caused by lightning generally occur.

This campaign had two purposes: The first was to evaluate the actual incidence of voltage dips and short interruptions. The second was to provide probability data so that the electricity users and the makers of equipment exposed to disturbances could design their system configurations and make a practical assessment of the costs and benefits of remedial measures.

The vast majority of electricity users are supplied from 6,6 kV distribution substations which, in turn, are connected to 77 kV busbars. The number of special customers connected to the network above 77 kV is negligible by comparison. Most 77 kV busbars are equipped with automatic oscillogram units, triggered by under-voltage relay in the case of fault, thereby recording the voltage during voltage dips. Therefore these were selected as the source of the required data.

In the case of 77 kV busbars which were not equipped with oscillogram units, 154 kV or higher voltage busbars were substituted. This was also the case for distribution substations supplied directly from 154 kV or higher voltage network.

The following assumptions were made in evaluating the results.

– Each distribution line has the same number of electricity users. Therefore, by identifying the distribution lines affected by each of the dips recorded by the oscillogram units, the number of users involved could be evaluated.
– The number of voltage dips and short interruptions is directly proportional to the number of faults on transmission lines. Therefore, by extrapolating from the number of faults at each voltage level occurring during the 3-month measurement period to the annual number available from national statistics, the annual number of dips and interruptions could be evaluated.

The ranges of possible dip durations and depths (residual voltage) were divided into seven and five intervals, respectively. For each of the resulting depth-duration combinations, using the assumptions above and relating the number of users affected to the total number of users connected, a calculation was made of the probability that any user will be affected in any year by a dip of the corresponding severity.

The results are shown in Table 27.

Table 27 – Average probability *p* of voltage dips and short interruptions per customer

Residual voltage *u* % of U_N	**Duration (cycles)**						
	< 3	**3 – 6**	**6 – 9**	**9 – 12**	**12 – 15**	**15 – 18**	**18 – 120**
90 > u ≥ 80	4	29	11	3	1	1	6
80 > u ≥ 60	3	12	4	1	0	0	2
60 > u ≥ 40	0	7	3	1	0	0	1
40 > u ≥ 20	0	4	2	0	0	0	1
20 > u ≥ 0	0	2	1	0	0	0	1

8 Discussion of results and general conclusions

8.1 Comparison of results

Only a limited comparison is possible between the foregoing results. There are considerable disparities between the various surveys, with respect to:

- the number of measuring points adopted, and their positions on the selected networks;
- the dip and interruption thresholds chosen;
- the length of the survey period, both in total and in the duration for which recording was maintained at each measurement site;
- types of measurement instrumentation;
- effort to ensure that the measurement points are a representative sample of the networks.

There are further disparities in the analysis and presentation of the data, such as:

- differences in the intervals chosen on both the depth and duration scales;
- whether results are presented in absolute, relative or probability terms;
- whether dip incidence is expressed per electricity user or per measurement point;
- whether the number presented is a maximum, mean, percentile or other statistic;
- the method of aggregating results.

Yet despite these differences, some common features can be discerned.

- The surveys have much in common with respect to the relative density with which dips are distributed in the depth-duration plane.
- There is confirmation that dips occur throughout the entire extent of the depth-duration plane.
- There is confirmation that the type of network has an impact on dip incidence, and that overhead networks have higher incidence rates.
- The high incidence rates near zero duration and near the normal voltage range are suggestive of inflation by voltage transients and ordinary load fluctuation, respectively.
- Where surveys involve rather large numbers of measurement sites, a very wide range of incidence rates is found, presumably reflecting differences due to network type and configuration, climatic conditions and other features of both the natural and constructed environments.
- Further evidence of the dispersion of incidence rates is seen in the differences between maximum, mean, percentiles and other measures of the number of voltage dips recorded.

8.2 Conclusions from the results

The most important conclusion to be drawn from the results is that voltage dips and short interruptions are a reality in the electromagnetic environment. They can be expected at any place, at any time and at levels involving voltages down virtually to zero and durations up to and above one second. The frequency of their occurrence and the probability of their occurrence at any level are highly variable both from place to place and from one year to another.

It is clear that quite high annual rates of voltage dips are possible on overhead networks – reflecting the exposure of these networks to fault causes, especially severe climatic conditions, that are additional to the range of causes that affect all networks.

NOTE Electricity users supplied from local underground networks can, of course, be affected by voltage dips originating on upstream parts of the network, considerable parts of which can be of overhead construction.

Another conclusion is that it is very desirable to make an effort to achieve international standardisation in how this phenomenon is surveyed, measured and reported. The aim should be to bring about coherence and consistency in place of the many disparities that have been listed in 8.1. Yet the present state of knowledge of this disturbance is probably insufficient to permit a prescriptive specification of what exactly the approach should be in all respects. Inevitably, there will have to be a compromise between the desirability of achieving maximum knowledge and the burden and expense of instrumentation and the collection, storage and analysis of data, along with the management effort required to install and maintain the necessary equipment and facilities.

It should be noted that most of the surveys did not involve monitoring any one site for much more than a year. Yet it has to be remembered that many of the causes of network faults that are the main source of voltage dips, particularly those causes associated with climatic conditions, are variable over a much longer time frame. It is common that events such as lightning or wind storms are found to reach particular peaks of severity at intervals of ten years or more, without this being capable of validly being described as a departure from the normal climate of the region concerned. Similarly, an individual circuit or section of the network may fall victim to a local storm at a time when the general climatic conditions of the region concerned appear to be quite ordinary.

This raises the question of how many measurement sites need to be selected and over how many years the survey should continue in order to provide a true representation of the types and frequency of the voltage dips to be expected. This complexity is added to the normal requirement to select sites in a manner that does not introduce bias in the results obtained.

Thus, it has to be recognised that some of the results that have been reported could have been biased in either direction by conditions that were particularly favourable or unfavourable at the times and locations selected for measurement.

8.3 General conclusions

Voltage dips have been an intrinsic feature of public electricity supply since the earliest times. Yet in recent decades they have become an increasingly troublesome disturbance, giving rise to inconvenience and even considerable economic loss. The reason is that some modern electricity utilisation equipment, either in its own design or because of control features incorporated in it, has become more sensitive to voltage dips. There is therefore a need for an increased awareness of the phenomenon among the suppliers and users of electricity and the manufacturers of equipment using electricity.

This awareness must encompass all the conclusions already mentioned, including the voltage and duration values observed, the frequency with which dips can occur and the variability of that frequency, with the uncertainty that arises therefrom. The effect of a dip on the user's equipment must be considered, with particular regard to the depth-duration characteristics that are critical, and the user must take due account of the possible consequences of any deterioration of performance or lapse in operation of that equipment. In the light of those consequences, the installation should, from the very first stage of planning, be designed to minimise disturbance and loss arising from voltage dips, having regard to the economic considerations that apply.

The normal approach to electromagnetic compatibility is to observe co-ordinated limits for both emission and immunity for the disturbance phenomenon involved. The special constraints that apply to voltage dips and short interruptions with regard to that approach have already been described – the limitation of emissions is virtually impracticable, while intrinsic immunity is subject to the limitations described in 5.1.

A distinction can be made between, on the one hand, equipment that can be given individual and expert attention in its intended place of installation and, on the other hand, equipment that is placed on the open market at the disposal of non-expert users who can purchase and connect it to the network at their own discretion.

Because the first type is likely to be part of a large installation, there is scope for consultation and co-operation between the three main parties – user, equipment manufacturer or supplier and electricity supplier, with an expert installer also likely to be involved. For some locations and in some countries it may be possible for the electricity supplier to provide basic information on the level and frequency of voltage dips to be expected at the location concerned, subject to the uncertainties that are unavoidable. However, his scope for altering these values is limited, since, at any location, most dips originate in upstream events that are quite distant.

The user, in consultation with all the parties, can then make a balanced assessment of the possible effects of the expected dips and make economically viable decisions regarding any mitigating action that can be taken, using methods of which examples have been given in 5.2 above.

The second type of equipment, which can be described as consumer goods, should be provided with the maximum possible level of intrinsic immunity. Moreover, adequate steps should be taken to inform the potential user of the limitations of that immunity and of any options that may be available to him to mitigate dips that are beyond the immunity level.

It would be desirable if compatibility levels for voltage dips could be produced for the guidance of manufacturers of equipment of this type, so that they could consider the optimum balance between product cost and the level of immunity to be provided. However, the level and quality of information that is needed to establish the compatibility level is not yet available.

In setting such a compatibility level, account would have to be taken of the two-dimensional nature of voltage dips. As described in Annex A of IEC 61000-2-2 [3], the compatibility level (for a one-dimensional phenomenon) is a point on the disturbance level scale such that there is only a small probability of its being exceeded by the actual disturbance level in the electromagnetic environment concerned. In the case of voltage dips, therefore, the compatibility level would be a curve on the depth-duration plane such that there is a small probability of dips of greater depth (lesser residual voltage) and longer duration.

The way in which the results of voltage dip surveys have been presented has placed an emphasis on the number of disturbance events, as distinct from the disturbance level, that is not consistent with the general EMC approach to electromagnetic disturbances. From the point of view of immunity, however, it must be recognised that if an equipment has immunity from voltage dips up to a certain level, then the number of dips up to that level is entirely irrelevant – the equipment is not affected by them.

On the other hand, dips beyond that level will prevent the equipment from operating as intended. If the degradation of performance is significant, there is likely to be a rate of occurrence that the user would perceive as so undesirable that any greater rate would not be seen as being more undesirable.

For a significant degradation of performance, this rate is likely to be quite low – of the order of 2-4 times per year. Taking this consideration into account and recognising also that quite a significant probability is associated with all parts of the depth-duration plane suggests a possible approach to establishing compatibility levels for voltage dips.

This approach would be to establish a number of compatibility levels (curves on the disturbance level plane), each associated with a specified rate of occurrence. For example, the compatibility level associated with a rate of 2 per year would be the curve on the depth-duration plane such that there is only a small probability that dips beyond that level of depth and duration would occur at the rate of more than two per year. Similar curves could be established for rates of 3 per year and 4 per year (possibly also 1 per year and even 0 per year).

With such an arrangement a manufacturer of a product intended for electrotechnically inexpert users could select the compatibility level against which he would provide a level of intrinsic immunity, taking into account the cost of that immunity and the value of the function provided by the product. Similarly the user would be aware that the product is liable to be disturbed by dips at a rate of up to 2 per year (for example), and would have the option of accepting the disturbance or taking any action he deemed appropriate.

Curves of this type could be drawn if survey results were available that provided sufficient resolution in the depth and duration dimensions and which satisfied concerns regarding the representative nature of the results.

8.4 Recommendations

The recommendations below are proposed as a common basis for the measurement of voltage dips and presentation of the data. While the parameters suggested here should be considered as a starting point for a voltage dip measurement survey, it is for the person conducting the survey to consider whether these values are appropriate for the particular site(s) being monitored.

a) The measurement should be carried out over a period of at least three years at each selected site.
b) Monitoring should be conducted at the MV bus-bars of the HV/MV substations. The available connections will determine whether the measurements are made phase to phase or phase to earth.
c) Measurement methods should be in accordance with IEC 61000-4-30 [4].
d) The thresholds should be 90 % start, 91 % end (hysteresis 1 %) and 10 % interruption, based on the nominal/declared voltage as the reference voltage. The report of the results should record both the actual values of the threshold and/or hysteresis level used and the reason for selecting those values.
e) Voltage dips should be classified by depth and duration in accordance with Table 28. Dips that involve more than one phase should be designated as a single event if they overlap in time.
f) The method for populating the table cells should be declared – actual incidence, 95^{th} percentile, maximum, mean etc.
g) Aggregation rules, if used, should be declared.

Table 28 – Recommended presentation of results

Residual voltage ***u*** % of U_{ref}	**Duration** s							
	0,02 < Δt ≤ 0,1	*0,1 < Δt ≤ 0,25*	*0,25 < Δt ≤ 0,5*	*0,5 < Δt ≤ 1*	*1 < Δt ≤ 3*	*3 < Δt ≤ 20*	*20 < Δt ≤ 60*	*60 < Δt ≤ 180*
90 > *u* ≥ 80								
80 > *u* ≥ 70								
70 > *u* ≥ 60								
60 > *u* ≥ 50								
50 > *u* ≥ 40								
40 > *u* ≥ 30								
30 > *u* ≥ 20								
20 > *u* ≥ 10								
10 > *u* ≥ 0 (interruptions)								

NOTE 0,01 s and 0,02 s in the first two duration headings correspond to a half and one period of the 50 Hz voltage. For 60 Hz systems corresponding values would be used.

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