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Guide to the Application of the European Standard EN 50160

This draft Technical Report is submitted to CENELEC members for vote by correspondence.
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It has been drawn up by Technical Committee CENELEC TC 8X.

CENELEC members are the national electrotechnical committees of Austria, Belgium, Czech Republic, Denmark, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Luxembourg, Malta, Netherlands, Norway, Portugal, Slovakia, Spain, Sweden, Switzerland and United Kingdom.

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CENELEC

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Foreword

This draft Technical Report was prepared by the Technical Committee CENELEC TC 8X, System aspects for electrical energy supply.

The draft is now circulated for consultation at national level and voting in accordance with IR, Part 2, Subclause 6.1.3 for acceptance as a Technical Report.

The following dates are proposed:

- latest date by which the existence of the TR has to be announced at national level (doa) -
- latest date by which the TR has to be implemented at national level by publication of an identical national standard or by endorsement (dop) -
- latest date by which the national standards conflicting with the tR have to be withdrawn (dow) - (Approved)

General

This Technical Report (TR) has been prepared by BTTF 68-6 and finalised by TC8 X/WG1 based on an application guide written by the former UNIPEDE group of experts NORMCOMP: “Electricity product characteristics and electromagnetic compatibility”[1].

The aim of this Technical Report is to provide some background information and explanation on the standard EN 50160 “Voltage characteristics of electricity supplied by public distribution systems” [2].

By its very nature, a standard has to be concise and cannot give a comprehensive background of the subject being dealt with. It was accordingly decided to prepare a Technical Report providing additional information and clarification of the standard.

Background of the definition of supply voltage characteristics

From the very beginning of their association, the member states of the European Communities decided to create a wide economic area without barriers to internal trade.

For this purpose a number of directives have been issued by the Commission of the European Community (EC), to remove the differences in the legislation of the Member States, which could affect the free exchange of goods and services.

One such directive is the Directive 85/374 on Product Liability [3]. This states in Article 2 that “product” includes electricity for the purpose of the directive. Consequently, it was considered necessary to define the essential characteristics of the electricity supply.

The task of preparing a standard, based on the UNIPEDE document DISNORM 12 [4], was assigned to CENELEC (European Committee for Electrotechnical Standardisation). The request specified the different aspects to be covered, which were exclusively related to the following characteristics of the supply voltage: **frequency, magnitude, waveform** and **symmetry** of the three-phase-voltages.

For this task CENELEC set up a new task force, BTTF 68-6, in which representatives of most of its member countries participated. EN 50160 was prepared by this task force, and was duly ratified by CENELEC.

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1 Application of the cenelec standard

1.1 Introduction

The standard takes account of the fact that electricity distribution systems have to be developed taking into account the problem of providing adequate conditions for the operation of customers' equipment and, at the same time, avoiding unnecessary increases in the cost of the electricity supply. There is an economic balance to be struck between the costs attributable to creating a more benign environment for the use of equipment connected to the public electricity network which will be borne by all customers and the costs of achieving immunity of the equipment to the environment in which it is intended to be used which will rightly be borne by the customer purchasing the equipment.

1.2 Scope of the standard EN 50160

It is important to note that the scope of the standard is confined to the electricity supplied at the supply terminals, and does not deal with the supply system or the customer´s installation or equipment. The diagram below in Figure 1 illustrates the point which is defined in EN 50160 as "the supply terminals" and also the relationship between the impulse withstand requirements of the supply terminals, the customer's installation and the customer's electrical equipment. The appropriate categories of impulse voltage withstand for each zone are also highlighted. It should be stressed that the supply terminals, referred to in both the standard and this application guide, and the origin of the installation, referred to in both IEC 60664-1, Insulation coordination for equipment within low-voltage systems [5], and IEC 60364-4-44, Electrical installations of buildings – Part 4: Protection for safety - Chapter 44: Protection against overvoltages (HD 384.4.443) [6], are one and the same point.

As the standard is intended to deal only with the characteristics of the voltage at specified points on the public distribution networks, it does not deal directly with the characteristics of networks themselves, such as short circuit power. Clearly, however, the network characteristics will have an effect upon the magnitude of several of the phenomena described by the standard.

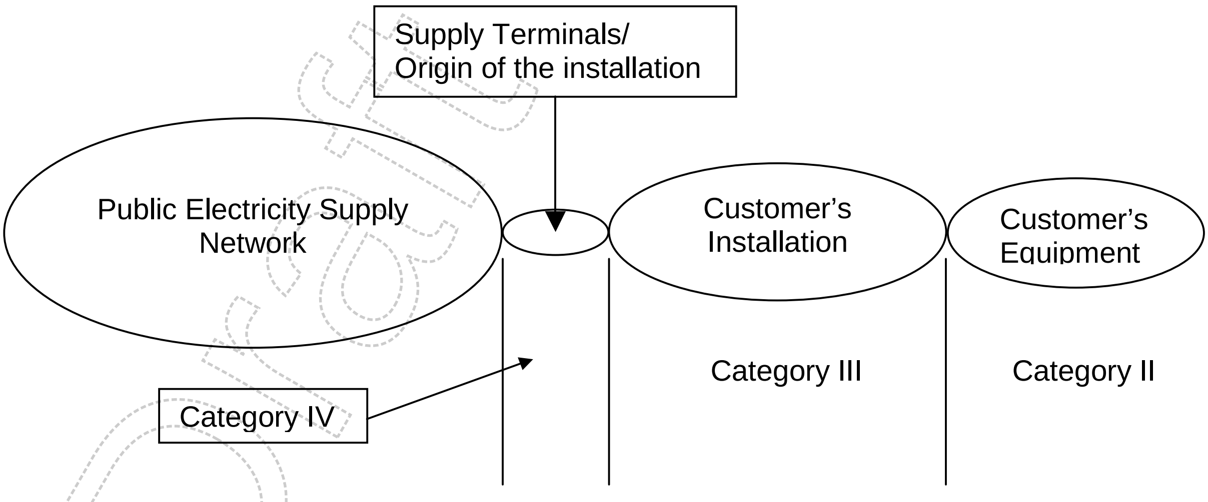


Figure 1 - Illustration of location of supply terminals

The standard is applicable only under **normal operating conditions** of the supply system. This **includes** also the correct operation of protection devices in the case of a fault in the network (blowing of a fuse, operation of a circuit-breaker etc.); the operation of loads agreed between customer and distribution network operator (DNO – see 2.3 below) and changes in network configuration.

When energy is supplied to the public networks from small private generators, it is important to keep the level of disturbances within acceptable limits. In this context private generation is in the same position as any customer's installation and therefore has to comply with the related emission standards and agreed limits for the voltage supplied. As such the voltage supplied from the generator must comply with the requirements of EN 50160.

The standard lists several specific examples of exceptional conditions which are beyond the DNO's control and which can cause one or more of the characteristics to depart from the values given. Under such conditions EN 50160 does not apply. The following table lists the exceptional conditions and gives some examples of the cause:

Table 1 - Non-exhaustive list of exceptional conditions and examples

Exceptional condition:	**Example of cause:**
Extreme weather conditions and other natural disasters	Storms of extreme severity, landslides, earth quakes, avalanches, floods
Third party interference	Sabotage, vandalism
Acts by public authorities	Constraints imposed by government for public safety concerns
Industrial action	Withdrawal of labour, strike
Force majeure	Major accidents
Power shortages resulting from external events	Generation restrictions or interruption of transmission lines

Exceptional weather conditions are for example conditions where the severity exceeds the legally required design conditions of the network equipment. Another example would be conditions under which the DNO is prevented from carrying out repair or maintenance work due to weather conditions of extreme severity or duration (long lasting blizzards, flood situations, landslides, extreme wind conditions etc.).

The standard also does not apply if the DNO is prevented from carrying out necessary alterations to the supply system, by government or other public authorities.

An example of a condition in which the standard is not applicable, is when a part of the supply system is out of operation, due either to a fault of large impact or to the need to carry out maintenance or construction work. Under these circumstances, if supply can be maintained to all or as many customers as possible, even at the expense of some deterioration of one or more of the voltage characteristics, this is generally accepted to be preferable to an outright interruption.

Because the public distribution networks are the unintended carriers of electromagnetic disturbances emitted by equipment within the customers' installations, it is necessary that such emissions be subject to appropriate limits. These limits are either specified in relevant product standards or prescribed for particular installations by the public authorities or the DNO. Compliance with these limits by the customers' installations and equipment is a necessary precondition to keep the voltage characteristics at the supply terminals within the given values of EN 50160. The same principle applies to all connections to the supply system, including private generation embedded in it.

The standard allows for its requirements to be superseded by terms of a contract between a customer and the electricity DNO. In this case the values of voltage characteristics are a matter of mutual agreement between customer and DNO.

Such a contract is most likely to arise for customers with relatively large electricity demand, supplied from the MV network. It may also arise in sparsely populated or difficult terrain, such as mountain regions, where supply costs are high. In such an area a customer may be willing to accept a supply, at lower cost, which does not entirely comply with EN 50160.

EN 50160 is a product standard giving the voltage characteristics which can be expected at the supply terminals in low voltage and medium voltage public networks.

This standard does not describe the average situation in the public supply networks but the maximum values or variations of the voltage characteristics under normal operating conditions which can be expected by a customer to be present at their supply terminals at any point on the network.

The standard does not have the function of specifying the requirements for electrical equipment or network impedance.

Although the standard handles some of the phenomena dealt with by the EN 61000 series of standards it merely describes the possible variations of these phenomena at the supply terminals of the public electricity system.

The stated voltage characteristics define the conditions at the supply terminals. Care should be taken to ensure co-ordination between the characteristics of the supply voltage, any voltage changes within the installation, and the requirements of the equipment within the installation. In the case of any mismatch between the characteristics of the supply and the requirements of the equipment, the opportunity to either improve the resilience of the equipment or to improve the quality of the supply voltage provided by the DNO should be investigated.

EN 50160 details the characteristics of the voltage waveform at the supply terminals, it does not detail how to measure these characteristics. Specific methods describing how to measure voltage and other power quality parameters may be found in IEC 61000-4-30 Testing and measurement techniques – Power quality measurement methods [7].

1.3 Definitions

It is considered appropriate that this document gives additional explanation to some of the defined terms in EN 50160:

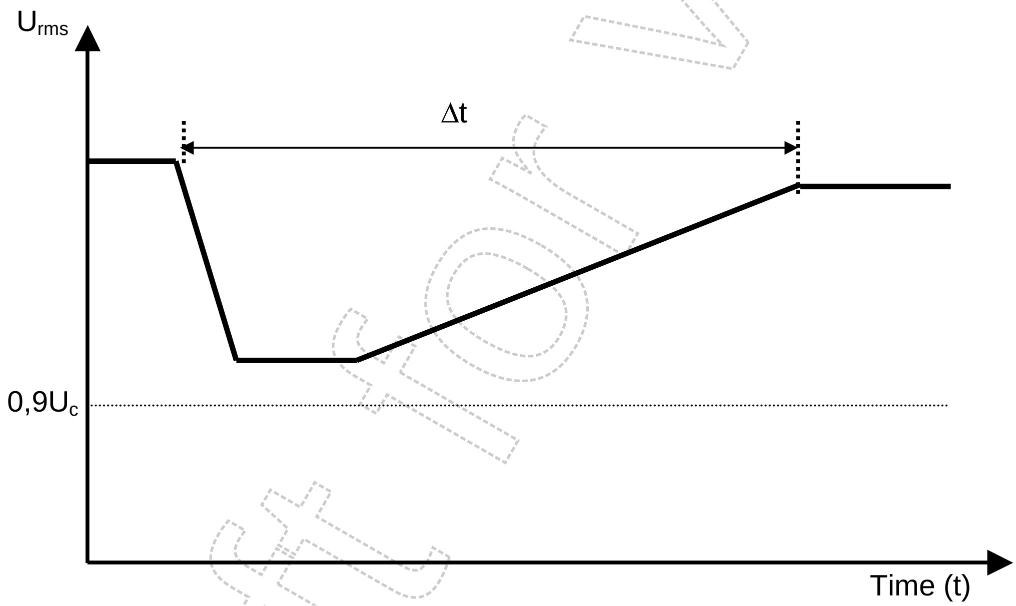
1.3.2
supplier
*t*his term needs clarification in the context of the open market for energy. At the time of writing EN 50160 the term "supplier" was often used to describe the organisation responsible for all functions relating to the distribution network - operating the public distribution network, metering energy usage and selling energy to the customer. Today it is common for these three functions to be dealt with by separate businesses, e.g. Distribution Network Operator (DNO), meter operator and energy supplier respectively. However in the context of EN 50160, the term "supplier" is used to describe the organisation responsible for operating the distribution network, in modern parlance the DNO. Therefore this document will use the term DNO in all instances in place of supplier

The standard is the basis of the bilateral agreement between the DNO and the individual customer.

1.3.1
customer
the term customer is defined in EN 50160 as "The purchaser of electricity from a supplier". As detailed above the function of the organisation described by the term "supplier" has altered in the context of an open energy market, in this document, the term "Distribution Network Operator" is used in place of "supplier". In the light of this the term "customer" should be regarded as the end-user of electricity in the installation connected to the supply terminals of the distribution network since the customer may purchase their electricity from an unrelated third party

1.3.13
rapid voltage change
a rapid voltage change is a quick transition in r.m.s. voltage between two steady-state conditions. The characteristic parameters are the difference between the steady-state value reached after the change, and the initial steady-state value; and the time duration for the transition between the two states. In this context the voltage is considered to be in a steady-state if it remains within specified limits for at least 1 second. See IEC 61000-4-30 Power quality measurement methods subclause A.4

Rapid voltage changes can be caused by a sudden increase or decrease in load sometimes associated with fault switching.



NOTE The purpose of this figure is for demonstration only, therefore the y axis (Urms) in this figure starts above zero; and the x axis (time) will depend upon the size of the motor current and the network impedance.

Figure 2 - A rapid voltage change caused by motor starting

If caused by the inrush current of a motor, the rapid voltage change starts with a step reduction followed by a ramped recovery ending at a voltage value less than that existing before switching (Figure 2)

The front can be as short as 10ms, whilst the recovery ramp can last several tens of cycles of the supply voltage. The period over which this characteristic may be observed, Δt, depends on the specific circumstances since it will be influenced by factors such as the size of the motor, the supply impedance and the method of starting applied to the motor.

If during a rapid voltage change the voltage drops below a level of 0,9 x Uc, it would be considered, under EN 50160, to be a voltage dip.

1.3.17
supply voltage dip
the following explanation has been taken from the definitions provided in IEC 61000-2-8 Electromagnetic compatibility (EMC) – Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results [8], and 61000-4-30:

Voltage dip:

A 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).

NOTE 3 In some areas of the world a voltage dip is referred to as sag. The two terms are considered interchangeable, however this standard [61000-4-30] will only use the term voltage dip.

1.4 Groups of voltage characteristics

EN 50160 contains the following two groups of characteristics:

a) characteristics for which values are specified in definite terms;

b) characteristics for which only indicative values are given.

1.4.1 Definite values

For the following characteristics it is feasible to set limits which can be complied with for most of the time:

- power frequency;
- supply voltage variations;
- rapid voltage changes (including flicker severity);
- supply voltage unbalance;
- harmonic voltages;
- interharmonic voltage;
- mains-borne signalling voltages.

Generally an observation period of one week is chosen because it is the shortest interval to obtain representative and reproducable measurement results.

Limits are set with a view to compliance for a percentage of the observation time, e. g. 95 % of the observations in any period of one week. In the case of supply voltage variation and power frequency measurements, further limits are specified for the observation periods within which the average measurements shall remain for 100 % of the time, excluding situations arising from faults or voltage interruptions.

For those phenomena for which limits are only specified for 95 % of the observation periods, there remains the possibility of relatively rare excursions beyond these specified limits. The essential randomness of the factors involved precludes declaring any bounds within which there could be a reasonable expectation that such excursions could be contained.

Because of the random nature of these phenomena, no limit is set for the remainder of the time. However, experience shows that in practice the frequency with which excursions outside the 95 % limits occur decreases very rapidly with the magnitude of such excursions.

Interharmonics have been included even though no indications of limit values have been given. Limits will be established once additional experience enables this to be done.

1.4.2 Indicative values

The remaining characteristics of the voltage are, by their nature, so unpredictable and so variable from place to place and from time to time, that it is only possible to set indicative values, which are intended to provide readers with information on the range of magnitude which can be expected.

The characteristics which are dealt with in this way are

- voltage dips,
- long interruptions,
- short interruptions,
- temporary and transient overvoltages.

1.5 Voltage terminology

In EN 50160 the following voltage terms are used:

- supply voltage;
- nominal voltage $U_{n;}$
- declared voltage $U_{c.}$

The following explanations should help to avoid misinterpretation.

<u>Supply voltage</u>

The r.m.s. value of the voltage occurring at the supply terminal at a given time. This value may differ from one supply terminal to another. Moreover, because of the voltage drop within the customer's installation the voltage at the utilisation points inside the installation can be appreciably lower than that at the supply terminals.

The actual value of the supply voltage may sometimes be used as a reference value for measurement.

<u>Nominal voltage (U_n) and declared voltage (U_c)</u>

Voltage limits or values specified in percentage terms by EN 50160 are based on the nominal voltage in the case of low voltage (LV) supply characteristics and declared supply voltage in the case of medium voltage (MV) supply characteristics.

The actual r.m.s. value of the supply voltage is usually different from the nominal value. Standardised values for nominal LV are given in HD 472 S1, Nominal voltages for low voltage public electricity supply systems, [9].

MV supply networks are sometimes operated with reference to a voltage which differs from the nominal voltage. This is done for example to obtain an average LV supply voltage inside the stated supply voltage range.

In LV supply networks the declared voltage is normally equal to the nominal voltage ($U_c = U_n$). Hence where EN 50160 refers to the nominal or declared voltages these must be interpreted as interchangeable, as appropriate.

2 Description of main voltage characteristics

2.1 Power frequency

EN 50160 states that the nominal value of the frequency is 50 Hz. Taking into account the fact that the frequency in a supply system depends on the interaction between generators and load and that the range of variation is smaller the higher the ratio between generation capacity and load fluctuations, a distinction is made between power supply systems with synchronous interconnection to adjacent systems and weaker isolated systems such as those which typically exist on certain islands.

Under normal operating conditions it should be possible to control the frequency on an interconnected network to within a very narrow operating range, hence EN 50160 specifies a range of 50 Hz ± 1 % for 99,5 % of a year. For the remaining 0,5 % of the year a range of 50 Hz –6 % to + 4 % is specified, this extended range is necessary to take account of the rare cases where there is a sudden loss of a large amount of generation.

For island networks it is necessary to have a wider operating range to take account of the lower ratio between generation and demand, hence EN 50160 quotes a range of 50 Hz ± 2 % for 95 % of a week. For the remaining 5 % of the week a range of 50 Hz ± 15 % is specified, this extended range is to take account of the risk of losing a large amount of generation or the switching of a large amount of load. Under certain fault conditions parts of an interconnected system may become isolated and continue to operate as “island” networks.

In practical terms the statistical assessment requires definition of a basic measurement, which could be carried out by determining the mean value of frequency over successive fixed time intervals of 10 s.

Compliance with the limits given will then be assessed over an observation period of one year (one week, including Saturday and Sunday in island systems), by a statistical analysis carried out over the sequence of 10 s measurements.

2.2 Magnitude of the supply voltage

Magnitudes of the supply voltage correspond

- for LV to the nominal voltage given at 2.2 of EN 50160,
- for MV to the declared voltage as stated at 3.2 of EN 50160.

2.3 Supply voltage variations

In general LV networks do not have active voltage control. The networks are designed on a statistical basis taking account of the fact that the network operator has limited control over the connection of new loads by customers and no control in general over the use of these loads.

MV networks typically employ on-line tap changers located on the high voltage side of the HV/MV transformers. Operation of a tap-changer results in a voltage change in the range of a few percent. For reasons of stability, tap changer operation is subject to an intentional initial delay of a few minutes duration, with further changes delayed by fractions of a minute.

Variations of supply voltage arise from the independent switching on and off of literally hundreds or thousands (in the case of networks) of items of utilisation equipment in each network, and are characterised by daily, weekly and seasonal cycles.

In assessing supply voltage magnitude, measurement has to take place over a relatively long period of time to avoid the instantaneous effects on the measurement caused by individual load switching (e.g. motor starting, inrush currents) and faults.

For these reasons the 10 min r.m.s. value is used to characterise these slow variations with their associated long cycle times. Variations outside of these limits of shorter duration are characterised as voltage dips or overvoltages.

Examples of possible effects due to undervoltages are given in IEC 61000-2-8.

CENELEC 109th Technical Board (BT) has agreed that until the year 2008 the acceptable range for low voltage is to be as specified in HD 472 S1

NOTE At the time of writing HD 472 S1 still specifies these exemptions to expire after 2003; however this is to be modified in accordance with the decision taken by 109th BT.

2.4 Rapid voltage changes

2.4.1 Magnitude of rapid voltage changes

Typical rapid voltage changes are often a result of load switching and do not exceed a magnitude of +5 % or –5 % of the nominal or declared voltage. This limitation is possible because connection of loads capable of creating rapid voltage changes is usually subjected to regulations. However, under certain conditions higher values up to 10 % may occasionally occur. These higher values can occur for instance in rural areas at the end of long lines for a farm supply where high power motor equipment (blowers, pumps, compressors etc.) is used.

EN 50160 suggests that under normal operating conditions a rapid voltage change, on the LV network, will generally not exceed 5 % U_c, but a change of up to 10 % U_c, with a short duration might-occur some times per day in some circumstances.

While for MV networks, under normal operating conditions rapid voltage changes generally do not exceed 4 % U_c but changes of up to 6 % U_c with a short duration might occur some times per day in some circumstances. The reason for the narrower range for the MV network is due to the more stringent design limits applied to connections to MV networks when compared to LV networks. This is on account of the larger number of customers that are affected by events on the MV network.

2.4.2 Flicker severity

Flicker is the effect produced on the visual human perception by a changing emission of light from lamps which are subjected to rapid fluctuations of their supply voltage. In this case the voltage fluctuations consist of a series of rapid voltage changes, spaced in time close enough to stimulate the response of the eye-brain defined as flicker.

As the annoyance created by flicker is a function of both the intensity of perception and the duration of exposure, the severity of the disturbance is described by two parameters: the short term severity P_{st} (measured over 10 min), and the long term severity P_{lt} (measured over 120 min).

A limit is given only for the long term flicker severity, $P_{lt,}$(95 percentile) parameter, because this is considered to be more significant when describing the supply voltage.

Maintenance of Flicker levels at or below the levels specified in EN 50160 requires equipment to comply with the relevant emission limits. The disturbance generated by some equipment arises from current generated by the equipment flowing through the network impedance. The level of the disturbance is a function of the magnitude of both current and impedance. The emission limits for such equipment are established on the basis of a reference network impedance, as set out in IEC 60725, Considerations on reference impedances for use in determining the disturbance characteristics of household appliances and similar electrical equipment, [10].

2.4.3 Supply voltage dips

A voltage dip is a sudden reduction of the r.m.s. voltage value below 90 % of the declared value, followed by a return to a value higher than 90 % of the declared one, in a time varying from 10 ms to 60 s. Figure 3 shows a simplified form of a voltage dip, to point out the fundamental parameters by which it is characterised: depth (Δ u) and duration (Δ t). This definition of voltage dips is a convention derived from practical experience. For a detailed description of voltage dips the reader is referred to IEC 61000-2-8 and measurement methods the reader is referred to IEC 61000-4-30.

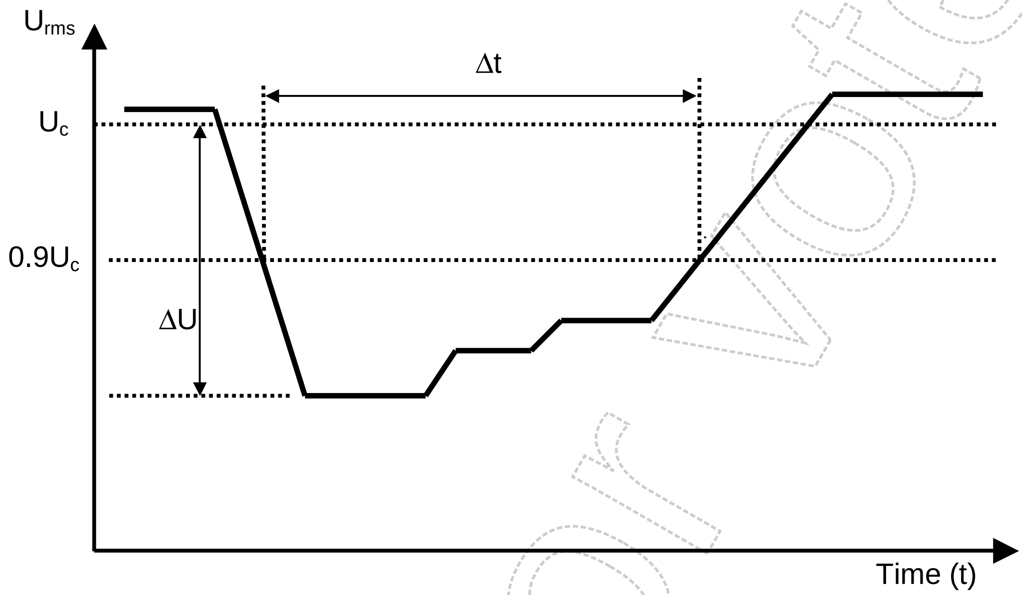


Figure 3 - Simplified form of a voltage dip

<u>Depth (ΔU)</u>

Requirements of practical measurement make it necessary to relate the voltage level recorded during a voltage dip against a reference voltage, typically the nominal voltage or declared voltage rather than to the actual supply voltage at the starting time of the dip. This ensures that a reduction of the supply voltage down to 0 V corresponds to a reduction of 100 %.
From IEC 61000-2-8 the modern convention for describing the depth of a voltage dip is to quote the residual voltage, i.e. the minimum value of voltage recorded during the dip, as a % or pu value of the reference voltage. Therefore the depth of a voltage dip is the difference between the reference voltage and the residual voltage.

A voltage dip is classified as one event, irrespective of the shape and of the number of phases affected. This is because whilst most industrial and commercial customers receive a three phase supply these installations often also contain single phase equipment which is sensitive to voltage dips.

A multiphase event is considered a single occurrence if the events on the different phases overlap in time.

It is also necessary to make a distinction between a voltage dip and an interruption (lack of supply voltage). As a matter of fact, short interruptions, lasting less than 60 s could also be seen as a 100 % voltage dip and there would be inevitable confusion when making a classification. EN 50160 has adopted a conventional (at the time of writing) threshold of 1 % of the declared voltage (depth of 99 %). If the supply voltage value drops below 1 % U_c the event is considered a short interruption, otherwise it is classified a voltage dip.

The causes and effects of voltage dips are described in the UNIPEDE Report [11].

The indicative value of "the expected number of voltage dips in a year may be from up to a few tens up to one thousand", is based on the values given in Table 2 which is taken from the UNIPEDE Report quoted below.

Duration (Δt)

From IEC 61000-4-30 the duration of a voltage dip is defined as the time interval between when the voltage falls below the dip threshold, until the time when the voltage is equal to or above the dip threshold plus any hysteresis voltage that may be applied. Where hysterisis is a margin applied to measurement thresholds to avoid hunting, when the measured parameter hovers around the threshold level.

The lower limit for duration is naturally 10 ms (half a 50 Hz cycle), the minimum time period over which an r.m.s. value can be calculated. The upper limit of duration is 180 s, considering effects of load switching and of transformer tap changer operation in the supply network or in the customer's installation.

The UNIPEDE survey

To obtain better knowledge of voltage dips occurring in the European MV supply networks, the former UNIPEDE group of experts DISDIP carried out a co-ordinated measurement campaign over a period of three years, in nine countries with different climatic conditions and network configurations.

The survey was carried out at 126 sites with standardised measurement and evaluation criteria, with the maximum duration of a dip set at 60 s in order to include the more seldom occurring longer duration dips. The measurements were taken at the LV busbars of distribution transformers, at various locations with the aim of ensuring that the results could be seen as representative of public LV networks in general.

Table 2 summarises the results obtained in the survey. Each cell of the table represents a combination of the results from all locations and gives the number of events belonging to the corresponding classes of depth and duration, which may be expected to occur per year with a probability of 95 % of not being exceeded. It should be noted that, according to the criteria stated above, data on the lowest row are to be considered as interruptions and not as voltage dips.

The cell values observed during one year at every measurement location have been sorted from the lowest to the highest value.

Table 2 contains, separately for each cell, the value which is exceeded at only 5 % of the locations. As each cell is therefore calculated independent from the others, the 95 % value of each cell may concern a different choice of locations. This means that the sum of values over all cells per row or per column do not give the precise 95 % values of the whole survey per depth or per duration. The real 95 % values, per depth or per duration, or per depth and duration, are normally lower than the corresponding sum which can be calculated from the rows or columns of Table 2.

Table 2 - UNIPEDE survey on the characteristics of voltage dips: Frequency of occurrence per annum and per location with a 95 % probability of not being exceeded

Depth (% of nominal voltage)		Duration (d) [2)]					
		(ms)	(ms)	(s)	(s)	(s)	(s)
From	to	10≤d<100	100≤d<500	0,5≤d<1,0	1≤d<3,0	3≤d<20	20≤d<60
10	30 [1)]	111	68	12	6	1	0
30	60	13	38	5	1	0	0
60	99	12	20	4	2	1	0
99	100	1	12	16	3	3	4

[1)] *For a further survey the former UNIPEDE DISDIP decided to split this class into two classes: 10 - 15 and 15 – 30*

[2)] *For dip duration (d) the range of each column has been set as follows: t1 ≤ d < t2, where t1 is the first value shown and t2 the second value.*

As the results of the UNIPEDE measurements have shown, the majority of voltage dips have a duration less than 1 second (Subclause 2.5 of EN 50160).

Depth and duration of voltage dips can be obtained by measuring the r.m.s. value of the voltage every half cycle between two zero-crossings of the voltage.

Although the UNIPEDE survey gives a more precise idea on what can be expected with respect to voltage dips, utilities normally can only provide qualitative information about the situation in particular network areas, based on experience. However, sometimes more specific information on the frequency and severity of dips is desirable, especially when customers are operating processes which are sensitive to supply disturbances. In such cases as well as in the case of customers‘ complaints, a more detailed investigation is usually undertaken.

2.5 Short and long interruptions of the supply voltage

Concerning the duration of a supply voltage interruption, UNIPEDE DISDIP and IEC 61000-2-1, Electromagnetic compatibility (EMC) - Part 2: Environment - Section 1: Description of the environment - Electromagnetic environments for low frequency conducted disturbances and signalling in public power supply systems [12], name an upper limit of 1minute, related only to short interruptions.

EN 50160 subdivides voltage interruptions into

- short supply interruptions (duration ≤ 3 min),
- long supply interruptions (duration > 3 min).

This classification takes into account the characteristics of protection and automatic reclosing systems in use in supply networks.

On medium voltage overhead networks it is common practice to perform an automatic reclosure after the initial tripping of a line circuit breaker on a fault.

The time delay between tripping and reclosing depends on local conditions. A customer with sensitive equipment is therefore recommended to ask his DNO for detailed information. The delay times can range from 300 ms to several seconds or even minutes.

In the case of a successful auto-reclose operation which restores supply, the customers supplied by the line are affected by a voltage dip, with a duration equal to the operating time of the circuit breaker and the time delay of the protective relay of about 100 ms up to 500 ms, followed by an interruption until the circuit breaker auto-recloses. The other lines connected to the same busbar as the line with the fault will experience a voltage dip with a duration equal to the operating time of the circuit breaker and a depth dependent on the network impedance (related to distance) between the fault location and the substation busbar. The time delay between the circuit breaker tripping and reclosing is often referred to as the “dead-time”, dead-times can vary between a minimum of 1 second up to about 60 s. For the exact timings in use in any particular area the reader is advised to consult the local DNO.

If, on reclosing, the fault is still present, another voltage dip will occur on the faulted line and on the other lines supplied by the same busbars; and the circuit breaker will trip again. For lines controlled by circuit breakers set with multiple reclosures, the customers supplied by the line will experience another short interruption followed by restoration of supply or a final tripping of the circuit breaker, depending on whether the fault has cleared spontaneously or persists. Where multiple reclosures are not used the circuit breaker will trip and “lock-out” i.e. not reclose, under these conditions the customers supplied by the line will suffer a long interruption until the fault is cleared and the circuit breaker is reclosed.

In this latter case, the supply will be interrupted until the fault is located and the faulted section of line is isolated for inspection and repair. If an alternative source of supply is provided this can be brought into service either by manual or automatic switching. For networks with automatic switching, the delay is commonly ranging between 30 s and 3 min.

It must be stressed that these techniques are applied in order to provide the best possible continuity of supply, and to minimise the number of customers affected by the long interruption caused by a permanent fault. As a consequence the customers connected to the healthy lines may be affected by a few additional voltage dips.

As far as faults on underground networks are concerned, the probability that a fault clears spontaneously when the voltage is switched off is very low, so auto-reclosing is not used on an all-underground network.

Customers supplied at low voltage are affected by the events on the medium voltage network to which their supply lines are connected and by those occurring on their specific and adjacent low voltage circuits.

The protection and supply restoration schemes have been considered an intrinsic feature of ”normal operation” of a supply system and this explains why the duration of short interruptions has been increased to three minutes, instead of keeping the duration of one minute.

2.6 Temporary (Power frequency) overvoltages between live conductors and earth

Faults on the MV network can result in temporary power frequency overvoltages between live conductors and earth on the LV network. The duration and magnitude of these overvoltages will be dependent on the fault conditions, particularly the MV earth impedance.

2.6.1 LV distribution systems

The majority of public LV distribution systems are operated with a solidly grounded neutral. Therefore when ground faults occur on the MV network that raise the ground potential in the vicinity of the LV network it is possible for an overvoltage to exist between the phase and earth (ground) conductors of the LV network. The duration is limited by the time taken for the MV protection and circuit breaker to clear the fault, typically no more than 5 s. The magnitude is generally limited at 1,5 kV r.m.s., this figure is dependent upon the impedance of the LV ground connection and the magnitude of the MV earth fault current.

2.6.2 MV distribution systems

Events causing temporary overvoltages on the MV networks are mainly of two types:

- single line to earth faults;
- ferroresonance.

2.6.2.1 Overvoltages due to single line to earth faults

In MV networks with isolated or impedance grounded neutral, this kind of fault can produce line to ground temporary overvoltages on the healthy phases. The overvoltage will last for the duration of the fault (from parts of a second up to some hours).The magnitude of the overvoltage does generally not exceed twice the nominal phase to ground voltage, i.e. it is $\sqrt{3}\times U$, where U can be up to $1{,}1\times U_n$ if the voltage is at the maximum of the acceptable MV range.

2.6.2.2 Overvoltages due to ferroresonance

Ferroresonance is a phenomena associated with the saturation of magnetic cores. The overvoltages that result are not power frequency overvoltages, but are characterised by a heavy distortion due to presence of subharmonic and harmonic voltage components, generally from a few Hz up to 150 Hz. Ferroresonance is a rare phenomenon compared to single line earth faults. In practice two conditions might cause this kind of overvoltage in MV networks:

- open conductors;
- grounded voltage transformers in MV networks with an isolated neutral.

<u>Open circuit condition</u>

This condition stems from one or two-phase open circuits (fuse operation, broken conductors, etc.) that remain energised by the healthy phase, via the primary winding of a MV/LV transformer, under light load condition.

Phase to ground overvoltages maximum magnitude is in the range 2,5 – 3 times nominal voltage with a waveform affected by harmonic distortion (up to 150 Hz). These overvoltages appear only on the particular feeder with the open circuit condition.

<u>Grounded voltage transformers in isolated neutral MV networks</u>

Line to ground overvoltages appear due to ferroresonance effects if excited by a sudden change in the network condition e.g. fault application/clearing, switching operations, etc.

The overvoltages maximum magnitude is in the range 1,8 – 2,5 times nominal voltage with a waveform affected by subharmonic and/or harmonic distortion (from a few Hz to 150 Hz); these overvoltages do not affect the line to line voltage.

2.7 Transient overvoltages between live conductors and earth

Transient overvoltages present very different characteristics and might be classified in relation to amplitude, frequency of occurrence, duration, surge main frequency, rate of voltage change and energy content. In the following sub-sections a short description is given of transient overvoltages occurring in LV and MV distribution systems grouped in relation to duration.

The energy content of a transient overvoltage varies considerably according to the origin. An induced overvoltage due to lightning generally has a higher amplitude but lower energy content than an overvoltage caused by switching, because of the generally longer duration of the latter.

Unlike other phenomena, transient overvoltages are usually lower at the sockets within installations than in the public electricity supply system.

This explains why, within requirements for LV installations, such as IEC 60364.4.44 (HD 384.4.443) and basic safety publications, in particular the IEC 60664 series, the categories applicable to equipment used within the installation are based on lower values. For equipment that is to be used at the origin of the installation, the same value as specified in EN 50160 is specified.

2.7.1 LV distribution system

Conventionally transient overvoltages are unlikely to exceed 6 kV peak in public networks, but higher values may occur. Equipment in public networks is generally specified and selected on this basis.

It should be noted however that equipment for use in consumers' fixed installations and utilisation equipment has lower withstand requirements, in accordance with HD 384.4.443, based on the appropriate overvoltage category in relation to its intended use.

The rise time covers a wide range from milliseconds down to much less than a microsecond. Where surge protective devices are installed they should be selected taking account of the more severe energy content associated with switching overvoltages.

2.7.1.1 Long duration surges (> 100 µs)

The origins are mainly:

- operation of current-limiting fuses (generally: amplitude: up to 1 kV – 2 kV, waveform: unidirectional, high energy levels)
- switching of power factor correction capacitors (generally: amplitude: up to 2 - 3 times nominal peak voltage, waveform: oscillatory with frequency in the range a fraction to a few kHz, high energy levels).
- transference of transient overvoltages from MV to the LV of the transformers by electromagnetic coupling (generally: amplitude: up to 1 kV, waveform: oscillatory with frequency in the range a fraction to a few 10 kHz).

2.7.1.2 Medium duration surges (1 µs to 100 µs)

The origin of these overvoltages are mainly related to lightning, typical instances are listed below:

- a direct lightning strike on the LV line conductors (no controlled surges: amplitude: up to 20 kV, waveform: unidirectional, high energy levels);
- induction coupling of a lightning strike in the vicinity of a LV line. Generally the amplitude will not exceed 6 kV, but it can be up to 20 kV, the waveform is typically unidirectional and sometimes a unidirectional oscillatory waveform;
- resistive coupling associated with lightning ground currents flowing in the common earth paths of a network. Generally the amplitude will not exceed 10 kV, the waveform has high energy levels and is typically unidirectional or sometimes a unidirectional oscillatory waveform;
- transference of surges from MV to LV by capacitive transformer coupling. Where the surge is due to a direct lightning strike on the MV, this in turn can lead to a rapid drop in voltage caused by the operation of gap-type arresters to clear the fault. The amplitude of the overvoltage on the LV network will generally not exceed 6 kV, typically with a unidirectional or sometimes oscillatory waveform;
- arcing associated with switching on the LV network can resonate with the natural frequency of the local network. The amplitude of the overvoltage can be up to several times the nominal voltage. The waveform is typically oscillatory and complex with a frequency in the range from a few tens kHz to 1 MHz.

- operation of circuit breakers with very short arcing times, < 2 µs. The amplitude is typically up to several times the nominal voltage. The waveform is oscillatory, with a frequency in the range from a few ten kHz to 1 MHz;

- operation of switching devices within the customer's installation. These overvoltages generally have a low energy content and attenuate quickly with distance. Typically they will not exceed 2,5 kV.

2.7.1.3 Short duration surges (< 1 µs)

The origins are mainly

- local load switching of small inductive currents and short wiring (amplitude generally up to 1 kV – 2 kV, oscillatory waveform with frequency from a few MHz to a few tens of MHz),

- fast transients due to switching in LV by air-gap switches (relays and contactors) giving a succession of clearings and reignitions (bursts of surges, one surge: rise time of about 5 ns, duration of about 50 ns).

2.7.2 MV distribution systems

2.7.2.1 Long duration surges (> 100 µs)

These overvoltages are mainly caused by switching events (disconnection of inductive loads with/without virtual chopping, opening/closing of power factor compensating capacitors with/without restrikes on MV feeders, etc.), fault application, arcing ground faults, transient overvoltages transferred from the HV to MV winding of the transformer by electromagnetic coupling.

At certain points of the systems the amplitude of these overvoltages is limited by the protection levels of gaps and/or arrresters required for insulation coordination (amplitude generally up to 3 - 5 times peak line to earth voltage, oscillatory waveform with frequency in the range from a few hundred Hz to some hundreds kHz).

2.7.2.2 Medium duration surges 1 µs to 100 µs

The origins are mainly

- induction from lightning strikes in the vicinity of MV lines and less commonly from direct lightning strikes on MV lines. Along the line the maximum amplitude of these stresses is limited by the clearances of the line; in primary HV/MV substations and MV/LV secondary transformers it is limited by the protection measures, e.g. arc gaps and/or diverters,

- circuit Breaker operation prone to reignition, e.g. vacuum circuit breakers (amplitude depending on protection levels assured by insulation co-ordination; in general up to 8 - 10 times the peak value of the nominal voltage, oscillatory waveform with a frequency of a few MHz).

The majority of the stresses are of induced type, the amplitude depending on clearance sparkover voltage and the protection levels ensured by insulation co-ordination, unidirectional waveform sometimes oscillatory, the rise time is in the range of 1 µs – 50 µs, with the half value time about 100 µs high energy content.

2.7.2.3 Short duration surges < 1 µs

The origin is mainly due to switching in gas insulated switchgear (GIS) using e.g. SF_6. The amplitude of the overvoltage is typically up to a few times the peak value of the nominal voltage. The waveform is oscillatory with a frequency higher than 1 MHz.

2.8 Supply voltage unbalance

The unbalance of a three phase supply voltage consists of a loss of symmetry of the phase voltage vectors (magnitude and/or angle), created mainly by unbalanced load.

Practically the unbalance voltage, u_u of the supply voltage is defined by the negative sequence component U_i expressed in p.u. or % of the positive sequence component U_d ($u_u = U_i/U_d$).

Under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of the negative phase sequence component of the supply voltage shall be within the range from 0 % to 2 % of the positive phase sequence component. In some areas with large amounts of single phase or two phase connected customers' installations, unbalances up to about 3 % at three-phase supply terminals occur.

The very short term effect of unbalance is generally not of interest; therefore gaps between elementary measurements may be allowed.

EN 50160 only quotes values for the negative sequence component because this component is often the most relevant when considering the possibility of interference with appliances connected to the system. The values quoted are suitable to address medium or long term effects (for example thermal effects), and are equal to the compatibility levels published in the relevant international standard.

2.9 Harmonic voltage

The general approach of EN 50160 is to express all voltage characteristics by reference to the nominal voltage or declared voltage, as appropriate. However, it is typical for measurement instruments to reference harmonic measurements to the value of the fundamental voltage at the time of measurement. Thus, although it defines harmonic voltages in relation to the fundamental voltage (subclause 1.3.21 of EN 50160), it gives LV values (Table 1) in relation to the nominal voltage, and MV values (Table 2) in relation to the declared voltage (subclauses 2.11 and 3.11 of EN 50160, respectively).

This deviates from the general practice (also followed by several standards) which is to express harmonic voltage components as a percentage relative to the fundamental.

It must also be mentioned that many instruments used for harmonic measurements of power supply systems express their output with reference to the fundamental component of the voltage, especially those indicating the Total Harmonic Distortion Factor (THD). This may be covered by application of a conversion factor to any measurement of harmonics expressed as a percentage of the fundamental, before comparing it with the values in Table 1 and 2. In practice, however, this will not lead to significant differences since the scaling factor will be very close to unity.

Harmonic values are specified only up to order 25, for the practical reason that for higher orders the values are generally so small as to be impractical to measure and because of the difficulty of giving values which would be relevant to all networks.

NOTE 1 Up to the 17^{th} harmonic order the values given in Table 1 of EN 50160 are equal to the compatibility levels published in the relevant international standard.

NOTE 2 Maintenance of Harmonic levels at or below the levels specified in EN 50160 requires equipment to comply with the relevant emission limits. The disturbance generated by some equipment arises from current generated by the equipment flowing through the network impedance. The level of the disturbance is a function of the magnitude of both current and impedance. The emission limits for such equipment are established on the basis of a reference network impedance, as set out in IEC 60725 [10].

For medium voltage networks the same values of harmonics are given as in LV systems even if the expected values are normally less than 80 % of the values in LV systems. This was done because of the higher risk of resonance effects, diversity of loads and the sometimes nearly arithmetic superposition of harmonics with the same phase angle in MV systems especially for the low order harmonics.

Under normal operating conditions, during each period of one week, 95 % of the 10 min mean r.m.s. values of each individual harmonic voltage shall be less than or equal to the value given in Table 1 of EN 50160.

EN 50160 declares that in case of network resonances higher values of an individual harmonic may occur. Normally those resonance effects are more severe in MV networks than in LV networks. The highest resonant voltage occurs under low load conditions. The value of a low order individual harmonic due to network resonance can be up to twice the value in the same network without the effect of resonance.

The THD of the supply voltage (including all harmonics up to the order 40) shall be less than or equal to 8 %. The limitation to order 40 is accepted as conventional in many countries.

2.10 Interharmonic voltage

Interharmonics at frequencies close to the fundamental frequency, even at low levels, give rise to flicker (see 2.4.2 of EN 50160). In certain cases interharmonics can cause interference to ripple control systems.

As far as standardisation is concerned interharmonics are still under consideration, but the specification of the measurement instrumentation practically corresponds to that used for harmonics.

2.11 Mains signalling voltage on the supply voltage

With regard to signal transmission over the public supply network it is necessary to distinguish between:

- ripple control systems (frequency range from 100 Hz to 3 kHz);

- mains communication systems (frequency range 3 kHz to 148,5 kHz).

The voltage levels given in EN 50160 are based on the following:

- between 100 Hz and 900 Hz: The values are taken from the so-called “Meister-curve“ which defines the maximum permissible ripple control voltages in LV networks. It consists of a horizontal part for the low frequency range with a maximum level of 20 V, followed by a decrease starting at 500 Hz, according to the function 10 000/f (f in Hz). The Meister-curve can also be found in EN 61000-2-2, Electromagnetic Compatibility (EMC) - Part 2: Environment - Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low voltage power supply systems [13];

- between 900 Hz and 3 kHz: The value of 5 % Un corresponds with the maximum level for control voltages as given in EN 61000-2-2 for the frequency range from 500 Hz to 2 kHz;

- between 3 kHz and 148,5 kHz: The values are defined on basis of EN 50065-1, Signalling on low-voltage electrical installations in the frequency range 3 kHz to 148,5 kHz - Part 1: General - requirements, frequency bands and electromagnetic disturbances [14], being doubled taking into account the defined measuring method.

Levels are equal for LV and MV in the range from 100 Hz to 9 kHz; for frequencies above 9 kHz the MV-part of EN 50160 does not give levels because of lack of experience and with respect to possible future developments.

The values given in EN 50160 for mains communication equipment/systems (MCES) operating at frequencies > 3 kHz are based on the maximum transmitter output levels according to EN 50065-1, noting that those levels express what is measured by a meter having an internal impedance equal to that of the transmission line, so that the actual levels on the line are to be doubled.

The respective limits for the signalling voltages have to be maintained in accordance with EN 50065-1 in order to avoid interference with some products, especially audio receivers.

3 References

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[3] Council Directive 85/374 on the approximation of the laws of the Member States relating to the liability for defective products, Official Journal of 07.08.1985).

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[6] IEC 60364-4-44, 2001: Electrical Installations of buildings – Part 4 Protection for Safety - Chapter 44 Protection against overvoltages

[7] IEC 61000-4-30, 2003: "Electromagnetic Compatibility (EMC) – Part 4-30 Testing and Measurement Techniques – Power Quality Measurement Methods".

[8] IEC 61000-2-8, 2002: Technical Report "Electromagnetic compatibility (EMC) – Part 2-8: Environment – Voltage dips and short interruptions on public electric power supply systems with statistical measurement results".

[9] IEC 60038 (6th edition), 1983: „IEC standard voltages" / HD 472 S1, November 1988 "Nominal voltages for low voltage public electricity supply systems", amendment 1-1994.

[10] IEC/TR3 60725 (1981-01): "Considerations on reference impedances for use in determining the disturbance characteristics of household appliances and similar electrical equipment".

[11] UNIPEDE Report 91 en 50.02: "Voltage dips and short interruptions in electricity supply systems".

[12] IEC 61000-2-1, 1990: "Electromagnetic compatibility (EMC) - Part 2: Environment - Section 1: Description of the environment - Electromagnetic environments for low frequency conducted disturbances and signalling in public power supply systems".

[13] IEC 61000-2-2, 1990 / EN 61000-2-2, 2002: "Electromagnetic Compatibility (EMC) - Part 2: Environment - Section 2: Compatibility levels for low-frequency conducted disturbances and signalling in public low voltage power supply systems".

[14] EN 50065-1, 2000: "Signalling on low-voltage electrical installations in the frequency range 3kHz to 148,5kHz. Part 1: General requirements, frequency bands and electromagnetic disturbances".

[15] UNIPEDE Application guide to the European Standard EN 50160 on "Voltage characteristics of electricity supplied by public distribution systems", 1995