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Overview of Power Quality and Power Quality Standards

Everybody does not agree with the use of the term *power quality*, but they do agree that it has become a very important aspect of power delivery especially in the second half of the 1990s. There is a lot of disagreement about what *power quality* actually incorporates; it looks as if everyone has her or his own interpretation. In this chapter various ideas will be summarized to clear up some of the confusion. However, the author himself is part of the power quality world; thus part of the confusion. After reading this book the reader might want to go to the library and form his own picture. The number of books on *power quality* is still rather limited. The book "Electric Power Systems Quality" by Dugan et al. [75] gives a useful overview of the various power quality phenomena and the recent developments in this field. There are two more books with the term power quality in the title: "Electric Power Quality Control Techniques" [76] and "Electric Power Quality" [77]. But despite the general title, reference [76] mainly concentrates on transient overvoltage and [77] mainly on harmonic distortion. But both books do contain some introductory chapters on power quality. Also many recent books on electric power systems contain one or more general chapters on power quality, for example, [114], [115], and [116]. Information on power quality cannot be found only in books; a large number of papers have been written on the subject; overview papers as well as technical papers about small details of power quality. The main journals to look for technical papers are the IEEE Transactions on Industry Applications, the IEEE Transactions on Power Delivery and IEE Proceedings—Generation, Transmission, Distribution. Other technical journals in the power engineering field also contain papers of relevance. A journal specially dedicated to power quality is Power Quality Assurance. Overview articles can be found in many different journals; two early ones are [104] and [105].

Various sources use the term "power quality" with different meanings. Other sources use similar but slightly different terminology like "quality of power supply" or "voltage quality." What all these terms have in common is that they treat the interaction between the utility and the customer, or in technical terms between the power system and the load. Treatment of this interaction is in itself not new. The aim of the power system has always been to supply electrical energy to the customers.

What is new is the emphasis that is placed on this interaction, and the treatment of it as a separate area of power engineering. In Section 1.2 the various terms and interpretations will be discussed in more detail. From the discussion we will conclude that "power quality" is still the most suitable term. The various power quality phenomena will be discussed and grouped in Section 1.3. Electromagnetic compatibility and power quality standards will be treated in detail in Section 1.4. But first Section 1.1 will give some explanations for the increased interest in power quality.

1.1 INTEREST IN POWER QUALITY

The fact that power quality has become an issue recently, does not mean that it was not important in the past. Utilities all over the world have for decades worked on the improvement of what is now known as power quality. And actually, even the term has been in use for a rather long time already. The oldest mentioning of the term "power quality" known to the author was in a paper published in 1968 [95]. The paper detailed a study by the U.S. Navy after specifications for the power required by electronic equipment. That paper gives a remarkably good overview of the power quality field, including the use of monitoring equipment and even the suggested use of a static transfer switch. Several publications appeared soon after, which used the term power quality in relation to airborne power systems [96], [97], [98]. Already in 1970 "high power quality" is being mentioned as one of the aims of industrial power system design, together with "safety," "reliable service," and "low initial and operating costs" [99]. At about the same time the term "voltage quality" was used in the Scandinavian countries [100], [101] and in the Soviet Union [102], mainly with reference to slow variations in the voltage magnitude.

The recent increased interest in power quality can be explained in a number of ways. The main explanations given are summarized below. Of course it is hard to say which of these came first; some explanations for the interest in power quality given below, will by others be classified as consequences of the increased interest in power quality. To show the increased interest on power quality a comparison was made for the number of publications in the INSPEC database [118] using the terms "voltage quality" or "power quality." For the period 1969–1984 the INSPEC database contains 91 records containing the term "power quality" and 64 containing the term "voltage quality." The period 1985–1996 resulted in 2051 and 210 records, respectively. We see thus a large increase in number of publications on this subjects and also a shift away from the term "voltage quality" toward the term "power quality."

- **Equipment has become more sensitive to voltage disturbances.**

  Electronic and power electronic equipment has especially become much more sensitive than its counterparts 10 or 20 years ago. The paper often cited as having introduced the term power quality (by Thomas Key in 1978 [1]) treated this increased sensitivity to voltage disturbances. Not only has equipment become more sensitive, companies have also become more sensitive to loss of production time due to their reduced profit margins. On the domestic market, electricity is more and more considered a basic right, which should simply always be present. The consequence is that an interruption of the supply will much more than before lead to complaints, even if there are no damages or costs related to it. An important paper triggering the interest in power quality appeared in the journal Business Week in 1991 [103]. The article cited Jane

Clemmensen of EPRI as estimating that "*power-related problems cost U.S. companies $26 billion a year in lost time and revenue*." This value has been cited over and over again even though it was most likely only a rough estimate.

- **Equipment causes voltage disturbances.**

  Tripping of equipment due to disturbances in the supply voltage is often described by customers as "bad power quality." Utilities on the other side, often view disturbances due to end-user equipment as the main power quality problem. Modern (power) electronic equipment is not only sensitive to voltage disturbances, it also causes disturbances for other customers. The increased use of converter-driven equipment (from consumer electronics and computers, up to adjustable-speed drives) has led to a large growth of voltage disturbances, although fortunately not yet to a level where equipment becomes sensitive. The main issue here is the nonsinusoidal current of rectifiers and inverters. The input current not only contains a power frequency component (50 Hz or 60 Hz) but also so-called harmonic components with frequencies equal to a multiple of the power frequency. The harmonic distortion of the current leads to harmonic components in the supply voltage. Equipment has already produced harmonic distortion for a number of decades. But only recently has the amount of load fed via power electronic converters increased enormously: not only large adjustable-speed drives but also small consumer electronics equipment. The latter cause a large part of the harmonic voltage distortion: each individual device does not generate much harmonic currents but all of them together cause a serious distortion of the supply voltage.

- **A growing need for standardization and performance criteria.**

  The consumer of electrical energy used to be viewed by most utitilies simply as a "load." Interruptions and other voltage disturbances were part of the deal, and the utility decided what was reasonable. Any customer who was not satisfied with the offered reliability and quality had to pay the utility for improving the supply.

  Today the utilities have to treat the consumers as "customers." Even if the utility does not need to reduce the number of voltage disturbances, it does have to quantify them one way or the other. Electricity is viewed as a product with certain characteristics, which have to be measured, predicted, guaranteed, improved, etc. This is further triggered by the drive towards privatization and deregulation of the electricity industry.

  Open competition can make the situation even more complicated. In the past a consumer would have a contract with the local supplier who would deliver the electrical energy with a given reliability and quality. Nowadays the customer can buy electrical energy somewhere, the transport capacity somewhere else and pay the local utility, for the actual connection to the system. It is no longer clear who is responsible for reliability and power quality. As long as the customer still has a connection agreement with the local utility, one can argue that the latter is responsible for the actual delivery and thus for reliability and quality. But what about voltage sags due to transmission system faults? In some cases the consumer only has a contract with a supplier who only generates the electricity and subcontracts transport and distribution. One could state that any responsibility should be defined by contract, so that the generation company with which the customer has a contractual agreement would be responsible for reliability and quality. The responsibility of the local distribution would only be towards the generation companies with whom they have a contract to deliver to given customers. No matter what the legal construction is, reliability and quality will need to be well defined.

- **Utilities want to deliver a good product.**

  Something that is often forgotten in the heat of the discussion is that many power quality developments are driven by the utilities. Most utilities simply want to deliver a good product, and have been committed to that for many decades. Designing a system with a high reliability of supply, for a limited cost, is a technical challenge which appealed to many in the power industry, and hopefully still does in the future.
- **The power supply has become too good.**

  Part of the interest in phenomena like voltage sags and harmonic distortion is due to the high quality of the supply voltage. Long interruptions have become rare in most industrialized countries (Europe, North America, East Asia), and the consumer has, wrongly, gotten the impression that electricity is something that is always available and always of high quality, or at least something that should always be. The fact that there are some imperfections in the supply which are very hard or even impossible to eliminate is easily forgotten. In countries where the electricity supply has a high unavailability, like 2 hours per day, power quality does not appear to be such a big issue as in countries with availabilities well over 99.9%.
- **The power quality can be measured.**

  The availability of electronic devices to measure and show waveforms has certainly contributed to the interest in power quality. Harmonic currents and voltage sags were simply hard to measure on a large scale in the past. Measurements were restricted to rms voltage, frequency, and long interruptions; phenomena which are now considered part of power quality, but were simply part of power system operation in the past.

1.2 POWER QUALITY, VOLTAGE QUALITY

There have been (and will be) a lot of arguments about which term to use for the utility–customer (system–load) interactions. Most people use the term "power quality" although this term is still prone to criticism. The main objection against the use of the term is that one cannot talk about the quality of a physical quantity like power. Despite the objections we will use the term power quality here, even though it does not give a perfect description of the phenomenon. But it has become a widely used term and it is the best term available at the moment. Within the IEEE, the term power quality has gained some official status already, e.g., through the name of SCC 22 (Standards Coordinating Committee): "Power Quality" [140]. But the international standards setting organization in electrical engineering (the IEC) does not yet use the term power quality in any of its standard documents. Instead it uses the term *electromagnetic compatibility*, which is not the same as power quality but there is a strong overlap between the two terms. Below, a number of different terms will be discussed. As each term has its limitations the author feels that power quality remains the more general term which covers all the other terms. But, before that, it is worth to give the following IEEE and IEC definitions.

The definition of power quality given in the IEEE dictionary [119] originates in IEEE Std 1100 (better known as the Emerald Book) [78]: *Power quality is the concept of powering and grounding sensitive equipment in a matter that is suitable to the operation of that equipment.* Despite this definition the term power quality is clearly used in a more general way within the IEEE: e.g., SCC 22 also covers standards on harmonic pollution caused by loads.

The following definition is given in IEC 61000-1-1: *Electromagnetic compatibility is the ability of an equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment* [79].

Recently the IEC has also started a project group on power quality [106] which should initially result in a standard on measurement of power quality. The following definition of power quality was adopted for describing the scope of the project group: *Set of parameters defining the properties of the power supply as delivered to the user in normal operating conditions in terms of continuity of supply and characteristics of voltage (symmetry, frequency, magnitude, waveform).*

Obviously, this definition will not stop the discussion about what power quality is. The author's impression is that it will only increase the confusion, e.g., because power quality is now suddenly limited to "normal operating conditions."

From the many publications on this subject and the various terms used, the following terminology has been extracted. The reader should realize that there is no general consensus on the use of these terms.

- **Voltage quality** (the French *Qualité de la tension*) is concerned with deviations of the voltage from the ideal. The ideal voltage is a single-frequency sine wave of constant frequency and constant magnitude. The limitation of this term is that it only covers technical aspects, and that even within those technical aspects it neglects the current distortions. The term voltage quality is regularly used, especially in European publications. It can be interpreted as the quality of the product delivered by the utility to the customers.
- A complementary definition would be **current quality**. Current quality is concerned with deviations of the current from the ideal. The ideal current is again a single-frequency sine wave of constant frequency and magnitude. An additional requirement is that this sine wave is in phase with the supply voltage. Thus where voltage quality has to do with what the utility delivers to the consumer, current quality is concerned with what the consumer takes from the utility. Of course voltage and current are strongly related and if either voltage or current deviates from the ideal it is hard for the other to be ideal.
- **Power quality** is the combination of voltage quality and current quality. Thus power quality is concerned with deviations of voltage and/or current from the ideal. Note that power quality has nothing to do with deviations of the product of voltage and current (the power) from any ideal shape.
- **Quality of supply** or quality of power supply includes a technical part (voltage quality above) plus a nontechnical part sometimes referred to as "quality of service." The latter covers the interaction between the customer and the utility, e.g., the speed with which the utility reacts to complaints, or the transparency of the tariff structure. This could be a useful definition as long as one does not want to include the customer's responsibilities. The word "supply" clearly excludes active involvement of the customer.

- **Quality of consumption** would be the complementary term of quality of supply. This would contain the current quality plus, e.g., how accurate the customer is in paying the electricity bill.
- In the IEC standards the term **electromagnetic compatibility** (EMC) is used. Electromagnetic compatibility has to do with mutual interaction between equipment and with interaction between equipment and supply. Within electromagnetic compatibility, two important terms are used: the "emission" is the electromagnetic pollution produced by a device; the "immunity" is the device's ability to withstand electromagnetic pollution. Emission is related to the term current quality, immunity to the term voltage quality. Based on this term, a growing set of standards is being developed by the IEC. The various aspects of electromagnetic compatibility and EMC standards will be discussed in Section 1.4.2.

1.3 OVERVIEW OF POWER QUALITY PHENOMENA

We saw in the previous section that power quality is concerned with deviations of the voltage from its ideal waveform (voltage quality) and deviations of the current from its ideal waveform (current quality). Such a deviation is called a "power quality phenomenon" or a "power quality disturbance." Power quality phenomena can be divided into two types, which need to be treated in a different way.

- A characteristic of voltage or current (e.g., frequency or power factor) is never exactly equal to its nominal or desired value. The small deviations from the nominal or desired value are called "voltage variations" or "current variations." A property of any variation is that it has a value at any moment in time: e.g., the frequency is never exactly equal to 50 Hz or 60 Hz; the power factor is never exactly unity. Monitoring of a variation thus has to take place continuously.
- Occasionally the voltage or current deviates significantly from its normal or ideal waveshape. These sudden deviations are called "events." Examples are a sudden drop to zero of the voltage due to the operation of a circuit breaker (a voltage event), and a heavily distorted overcurrent due to switching of a nonloaded transformer (a current event). Monitoring of events takes place by using a triggering mechanism where recording of voltage and/or current starts the moment a threshold is exceeded.

The classification of a phenomenon in one of these two types is not always unique. It may depend on the kind of problem due to the phenomenon.

1.3.1 Voltage and Current Variations

Voltage and current variations are relatively small deviations of voltage or current characteristics around their nominal or ideal values. The two basic examples are voltage magnitude and frequency. On average, voltage magnitude and voltage frequency are equal to their nominal value, but they are never exactly equal. To describe the deviations in a statistical way, the probability density or probability distribution function should be used. Figure 1.1 shows a fictitious variation of the voltage magnitude as a function of time. This figure is the result of a so-called Monte Carlo simulation (see

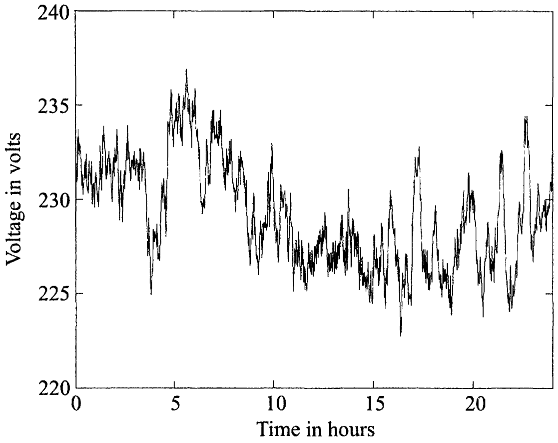

Figure 1.1 Simulated voltage magnitude as a function of time.

Section 2.5.5). The underlying distribution was a normal distribution with an expected value of 230 V and a standard deviation of 11.9 V. A set of independent samples from this distribution is filtered by a low-pass filter to prevent too large short-time changes. The probability density function of the voltage magnitude is shown in Fig. 1.2. The probability density function gives the probability that the voltage magnitude is within a certain range. Of interest is mainly the probability that the voltage magnitude is below or above a certain value. The probability distribution function (the integral of the density function) gives that information directly. The probability distribution function for this fictitious variation is shown in Fig. 1.3. Both the probability density function and the probability distribution function will be defined more accurately in Section 2.5.1.

An overview of voltage and current variations is given below. This list is certainly not complete, it merely aims at giving some example. There is an enormous range in end-user equipment, many with special requirements and special problems. In the power quality field new types of variations and events appear regularly. The following list uses neither the terms used by the IEC nor the terms recommended by the IEEE. Terms commonly used do not always fully describe a phenomenon. Also is there still

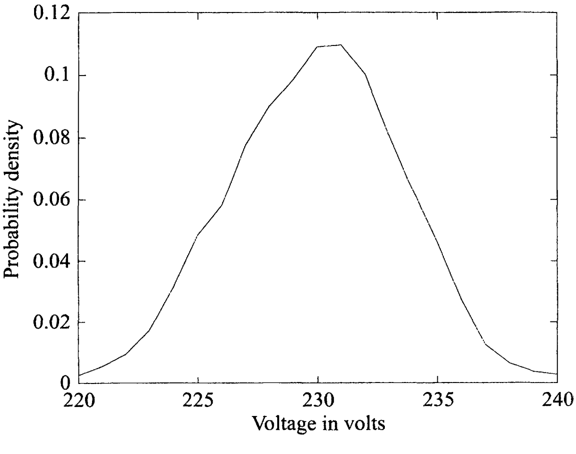

Figure 1.2 Probability density function of the voltage magnitude in Fig. 1.1.

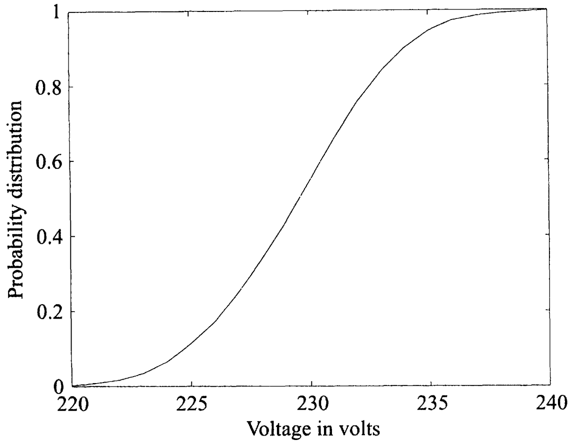

Figure 1.3 Probability distribution function of the voltage magnitude in Fig. 1.1.

some inconsistency between different documents about which terms should be used. The terms used in the list below, and in a similar list in Section 1.3.2 are not meant as an alternative for the IEC or IEEE definitions, but simply an attempt to somewhat clarify the situation. The reader is advised to continue using officially recognized terms, where feasible.

1. **Voltage magnitude variation.** Increase and decrease of the voltage magnitude, e.g., due to

- variation of the total load of a distribution system or part of it;
- actions of transformer tap-changers;
- switching of capacitor banks or reactors.

Transformer tap-changer actions and switching of capacitor banks can normally be traced back to load variations as well. Thus the voltage magnitude variations are mainly due to load variations, which follow a daily pattern. The influence of tap-changers and capacitor banks makes that the daily pattern is not always present in the voltage magnitude pattern.

The IEC uses the term "voltage variation" instead of "voltage magnitude variation." The IEEE does not appear to give a name to this phenomenon. Very fast variation of the voltage magnitude is referred to as voltage fluctuation.

2. **Voltage frequency variation.** Like the magnitude, also the frequency of the supply voltage is not constant. Voltage frequency variation is due to unbalance between load and generation. The term "frequency deviation" is also used. Short-duration frequency transients due to short circuits and failure of generator stations are often also included in voltage frequency variations, although they would better be described as events.

The IEC uses the term "power frequency variation"; the IEEE uses the term "frequency variation."

3. **Current magnitude variation.** On the load side, the current is normally also not constant in magnitude. The variation in voltage magnitude is mainly due to variation in current magnitude. The variation in current magnitude plays an important role in the design of power distribution systems. The system has to be designed for the maximum

current, where the revenue of the utility is mainly based on average current. The more constant the current, the cheaper the system per delivered energy unit.

Neither IEC nor IEEE give a name for this phenomenon.

4. **Current phase variation.** Ideally, voltage and current waveforms are in phase. In that case the power factor of the load equals unity, and the reactive power consumption is zero. That situation enables the most efficient transport of (active) power and thus the cheapest distribution system.

Neither IEC nor IEEE give a name for this power quality phenomenon, although the terms "power factor" and "reactive power" describe it equally well.

5. **Voltage and current unbalance.** Unbalance, or three-phase unbalance, is the phenomenon in a three-phase system, in which the rms values of the voltages or the phase angles between consecutive phases are not equal. The severity of the voltage unbalance in a three-phase system can be expressed in a number of ways, e.g.,

- the ratio of the negative-sequence and the positive-sequence voltage component;
- the ratio of the difference between the highest and the lowest voltage magnitude, and the average of the three voltage magnitudes; and
- the difference between the largest and the smallest phase difference between consecutive phases.

These three severity indicators can be referred to as "negative-sequence unbalance," "magnitude unbalance," and "phase unbalance," respectively.

The primary source of voltage unbalance is unbalanced load (thus current unbalance). This can be due to an uneven spread of (single-phase) low-voltage customers over the three phases, but more commonly unbalance is due to a large single-phase load. Examples of the latter can be found among railway traction supplies and arc furnaces. Three-phase voltage unbalance can also be the result of capacitor bank anomalies, such as a blown fuse in one phase of a three-phase bank.

Voltage unbalance is mainly of concern for three-phase loads. Unbalance leads to additional heat production in the winding of induction and synchronous machines; this reduces the efficiency and requires derating of the machine. A three-phase diode rectifier will experience a large current unbalance due to a small voltage unbalance. The largest current is in the phase with the highest voltage, thus the load has the tendency to mitigate the voltage unbalance.

The IEEE mainly recommends the term "voltage unbalance" although some standards (notably IEEE Std.1159) use the term "voltage imbalance."

6. **Voltage fluctuation.** If the voltage magnitude varies, the power flow to equipment will normally also vary. If the variations are large enough or in a certain critical frequency range, the performance of equipment can be affected. Cases in which voltage variation affects load behavior are rare, with the exception of lighting load. If the illumination of a lamp varies with frequencies between about 1 Hz and 10 Hz, our eyes are very sensitive to it and above a certain magnitude the resulting light flicker can become rather disturbing. It is this sensitivity of the human eye which explains the interest in this phenomenon. The fast variation in voltage magnitude is called "voltage fluctuation," the visual phenomenon as perceived by our brain is called "light flicker." The term "voltage flicker" is confusing but sometimes used as a shortening for "voltage fluctuation leading to light flicker."

To quantify voltage fluctuation and light flicker, a quantity called "flicker intensity" has been introduced [81]. Its value is an objective measure of the severity of the light flicker due to a certain voltage fluctuation. The flicker intensity can be treated as a variation, just like voltage magnitude variation. It can be plotted as a function of time, and probability density and distribution functions can be obtained. Many publications discuss voltage fluctuation and light flicker. Good overviews can be found in, among others, [141] and [142].

The terms "voltage fluctuation" and "light flicker" are used by both IEC and IEEE.

7. **Harmonic voltage distortion.** The voltage waveform is never exactly a single-frequency sine wave. This phenomenon is called "harmonic voltage distortion" or simply "voltage distortion." When we assume a waveform to be periodic, it can be described as a sum of sine waves with frequencies being multiples of the fundamental frequency. The nonfundamental components are called "harmonic distortion."

There are three contributions to the harmonic voltage distortion:

1. The voltage generated by a synchronous machine is not exactly sinusoidal due to small deviations from the ideal shape of the machine. This is a small contribution; assuming the generated voltage to be sinusoidal is a very good approximation.
2. The power system transporting the electrical energy from the generator stations to the loads is not completely linear, although the deviation is small. Some components in the system draw a nonsinusoidal current, even for a sinusoidal voltage. The classical example is the power transformer, where the nonlinearity is due to saturation of the magnetic flux in the iron core of the transformer. A more recent example of a nonlinear power system component is the HVDC link. The transformation from ac to dc and back takes place by using power-electronics components which only conduct during part of a cycle.

   The amount of harmonic distortion originating in the power system is normally small. The increasing use of power electronics for control of power flow and voltage (flexible ac transmission systems or FACTS) carries the risk of increasing the amount of harmonic distortion originating in the power system. The same technology also offers the possibility of removing a large part of the harmonic distortion originating elsewhere in the system or in the load.
3. The main contribution to harmonic voltage distortion is due to nonlinear load. A growing part of the load is fed through power-electronics converters drawing a nonsinusoidal current. The harmonic current components cause harmonic voltage components, and thus a nonsinusoidal voltage, in the system.

Two examples of distored voltage are shown in Figs. 1.4 and 1.5. The voltage shown in Fig. 1.4 contains mainly harmonic components of lower order (5, 7, 11, and 13 in this case). The voltage shown in Fig. 1.5 contains mainly higher-frequency harmonic components.

Harmonic voltages and current can cause a whole range of problems, with additional losses and heating the main problem. The harmonic voltage distortion is normally limited to a few percent (i.e., the magnitude of the harmonic voltage components

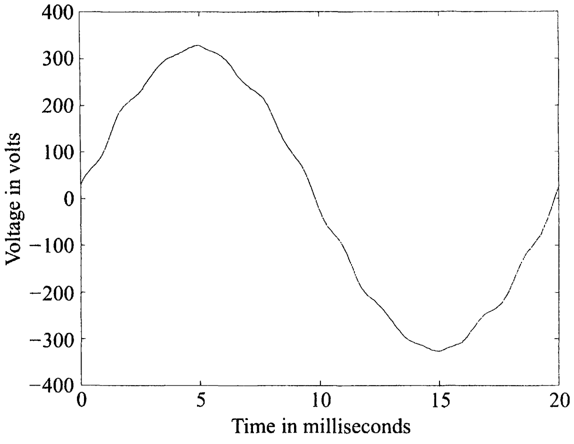

Figure 1.4 Example of distorted voltage, with mainly lower-order harmonic components [211].

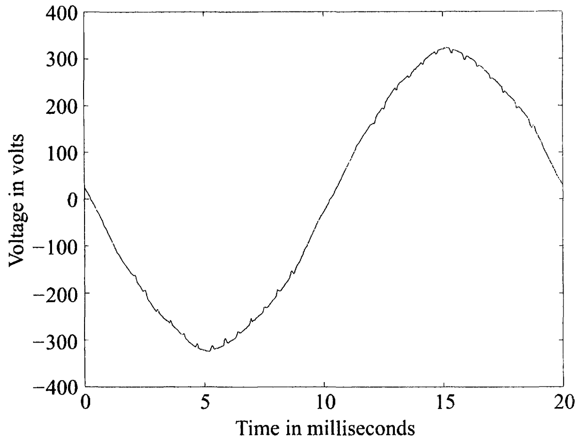

Figure 1.5 Example of distorted voltage, with higher-order harmonic components [211].

is up to a few percent of the magnitude of the fundamental voltage) in which case equipment functions as normal. Occasionally large harmonic voltage distortion occurs, which can lead to malfunction of equipment. This can especially be a big problem in industrial power systems, where there is a large concentration of distorting load as well as sensitive load. Harmonic distortion of voltage and current is the subject of hundreds of papers as well as a number of books [77], [194], [195].

The term "harmonic distortion" is very commonly used, and "distortion" is an IEC term referring to loads taking harmonic current components. Also within the IEEE the term "distortion" is used to refer to harmonic distortion; e.g., "distortion factor" and "voltage distortion."

8. **Harmonic current distortion**. The complementary phenomenon of harmonic voltage distortion is harmonic current distortion. The first is a voltage quality phenomenon, the latter a current quality phenomenon. As harmonic voltage distortion is mainly due to nonsinusoidal load currents, harmonic voltage and current distortion are strongly linked. Harmonic current distortion requires over-rating of series components like transformers and cables. As the series resistance increases with frequency, a distorted current will cause more losses than a sinusoidal current of the same rms value.

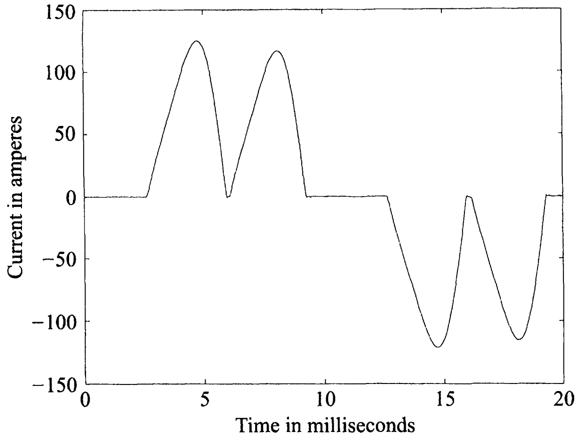

Figure 1.6 Example of distorted current, leading to the voltage distortion shown in Fig. 1.4 [211].

Two examples of harmonic current distortion are shown in Figs. 1.6 and 1.7. Both currents are drawn by an adjustable-speed drive. The current shown in Fig. 1.6 is typical for modern ac adjustable-speed drives. The harmonic spectrum of the current contains mainly 5th, 7th, 11th, and 13th harmonic components. The current in Fig. 1.7 is less common. The high-frequency ripple is due to the switching frequency of the dc/ac inverter. As shown in Fig. 1.5 this high-frequency current ripple causes a high-frequency ripple in the voltage as well.

9. **Interharmonic voltage and current components.** Some equipment produces current components with a frequency which is not an integer multiple of the fundamental frequency. Examples are cycloconverters and some types of heating controllers. These components of the current are referred to as "interharmonic components." Their magnitude is normally small enough not to cause any problem, but sometimes they can excite unexpected resonances between transformer inductances and capacitor banks. More dangerous are current and voltage components with a frequency below the fundamental frequency, referred to as "sub-harmonic distortion." Sub-harmonic currents can lead to saturation of transformers and damage to synchronous generators and turbines.

Another source of interharmonic distortion are arc furnaces. Strictly speaking arc furnaces do not produce any interharmonic voltage or current components, but a

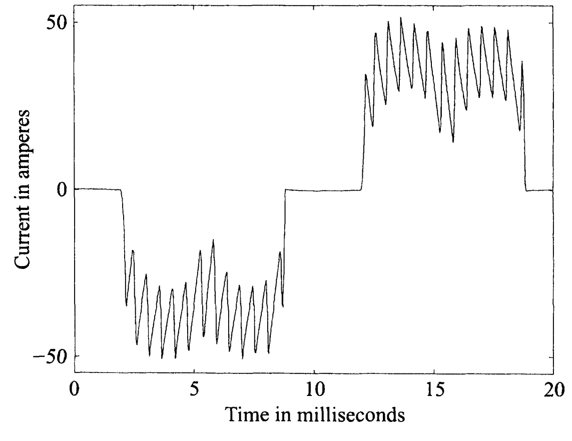

Figure 1.7 Example of distorted current, leading to the voltage distortion shown in Fig. 1.5 [211].

number of (integer) harmonics plus a continuous (voltage and current) spectrum. Due to resonances in the power system some of the frequencies in this spectrum are amplified. The amplified frequency components are normally referred to as interharmonics due to the arc furnace. These voltage interharmonics have recently become of special interest as they are responsible for serious light flicker problems.

A special case of sub-harmonic currents are those due to oscillations in the earth-magnetic field following a solar flare. These so-called geomagnetically induced currents have periods around five minutes and the resulting transformer saturation has led to large-scale blackouts [143].

10. **Periodic voltage notching.** In three-phase rectifiers the commutation from one diode or thyristor to the other creates a short-circuit with a duration less than 1 ms, which results in a reduction in the supply voltage. This phenomenon is called "voltage notching" or simply "notching." Notching mainly results in high-order harmonics, which are often not considered in power engineering. A more suitable way of characterization is through the depth and duration of the notch in combination with the point on the sine wave at which the notching commences.

An example of voltage notching is shown in Fig. 1.8. This voltage wave shape was caused by an adjustable-speed drive in which a large reactance was used to keep the dc current constant.

The IEEE uses the term "notch" or "line voltage notch" in a more general way: any reduction of the voltage lasting less than half a cycle.

11. **Mains signaling voltage.** High-frequency signals are superimposed on the supply voltage for the purpose of transmission of information in the public distribution system and to customer's premises. Three types of signal are mentioned in the European voltage characteristics standards [80]:

- *Ripple control signals*: sinusoidal signals between 110 and 3000 Hz. These signals are, from a voltage-quality point-of-view, similar to harmonic and interharmonic voltage components.
- *Power-line-carrier signals*: sinusoidal signals between 3 and 148.5 kHz. These signals can be described both as high-frequency voltage noise (see below) and as high-order (inter)harmonics.
- *Mains marking signals*: superimposed short time alterations (transients) at selected points of the voltage waveform.

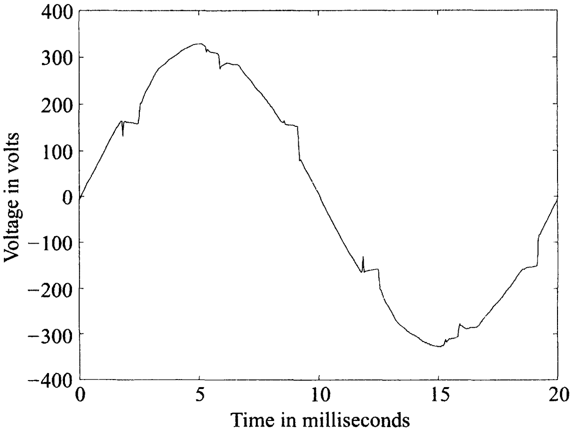

Figure 1.8 Example of voltage notching [211].

Mains signaling voltage can interfere with equipment using similar frequencies for some internal purpose. The voltages, and the associated currents, can also cause audible noise and signals on telephone lines.

The other way around, harmonic and interharmonic voltages may be interpreted by equipment as being signaling voltages, leading to wrong functioning of equipment.

12. **High-frequency voltage noise**. The supply voltage contains components which are not periodic at all. These can be called "noise," although from the consumer point of view, all above-mentioned voltage components are in effect noise. Arc furnaces are an important source of noise. But also the combination of many different nonlinear loads can lead to voltage noise [196]. Noise can be present between the phase conductors (differential mode noise) or cause an equal voltage in all conductors (common-mode noise). Distinguishing the noise from other components is not always simple, but actually not really needed. An analysis is needed only in cases where the noise leads to some problem with power system or end-user equipment. The characteristics of the problem will dictate how to measure and describe the noise.

A whole range of voltage and current variations has been introduced. The reader will have noticed that the distinction between the various phenomena is not very sharp, e.g., voltage fluctuation and voltage variation show a clear overlap. One of the tasks of future standardization work is to develop a consistent and complete classification of the various phenomena. This might look an academic task, as it does not directly solve any equipment or system problems. But when quantifying the power quality, the classification becomes less academic. A good classification also leads to a better understanding of the various phenomena.

1.3.2 Events

Events are phenomena which only happen every once in a while. An interruption of the supply voltage is the best-known example. This can in theory be viewed as an extreme voltage magnitude variation (magnitude equal to zero), and can be included in the probability distribution function of the voltage magnitude. But this would not give much useful information; it would in fact give the unavailability of the supply voltage, assuming the resolution of the curve was high enough. Instead, events can best be described through the time between events, and the characteristics of the events; both in a stochastic sense. Interruptions will be discussed in sufficient detail in Chapters 2 and 3 and voltage sags in Chapters 4, 5, and 6. Transient overvoltage will be used as an example here. A transient overvoltage recording is shown in Fig. 1.9: the (absolute value of the) voltage rises to about 180% of its normal maximum for a few milliseconds. The smooth sinusoidal curve is a continuation of the pre-event fundamental voltage.

A transient overvoltage can be characterized in many different ways; three often-used characteristics are:

1. **Magnitude**: the magnitude is either the maximum voltage or the maximum voltage deviation from the normal sine wave.
2. **Duration**: the duration is harder to define, as it often takes a long time before the voltage has completely recovered. Possible definitions are:
   - the time in which the voltage has recovered to within 10% of the magnitude of the transient overvoltage;
   - the time-constant of the average decay of the voltage;
   - the ratio of the Vt-integral defined below and the magnitude of the transient overvoltage.

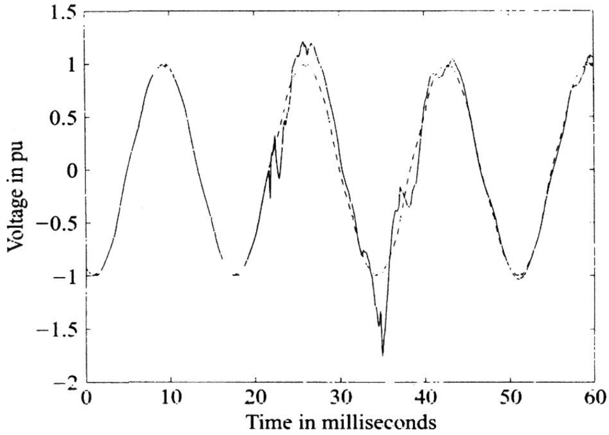

Figure 1.9 Example of transient overvoltage event: phase-to-ground voltage due to fault clearing in one of the other phases. (Data obtained from [16].)

3. **Vt-integral**: the Vt-integral is defined as

$$V_t = \int_0^T V(t)dt \tag{1.1}$$

where $t = 0$ is the start of the event, and an appropriate value is chosen for T, e.g., the time in which the voltage has recovered to within 10% of the magnitude of the transient overvoltage. Again the voltage $V(t)$ can be measured either from zero or as the deviation from the normal sine wave.

Figure 1.10 gives the number of transient overvoltage events per year, as obtained for the average low-voltage site in Norway [67]. The distribution function for the time

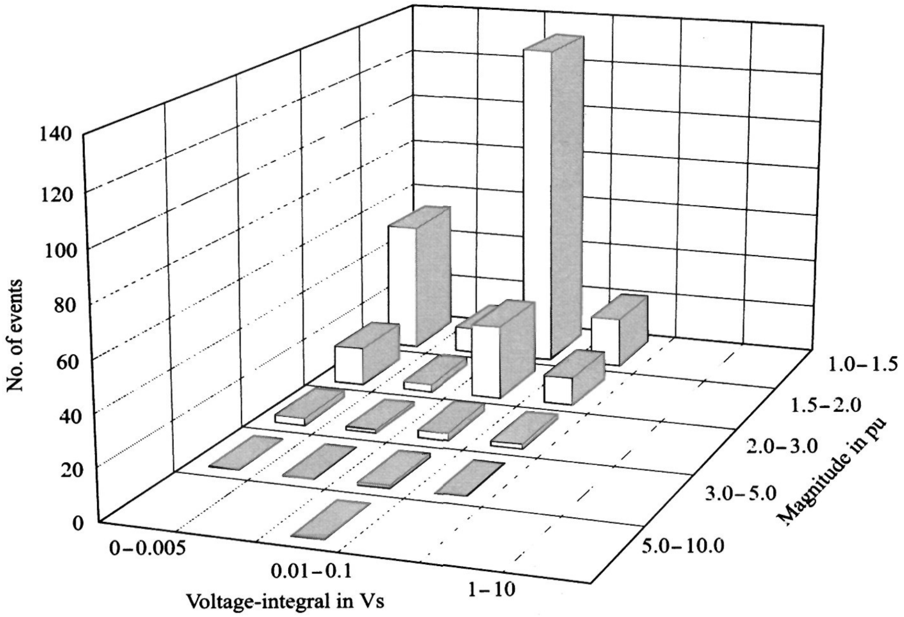

Figure 1.10 Number of transient overvoltage events per year, as a function of magnitude and voltage integral. (Data obtained from [67].)

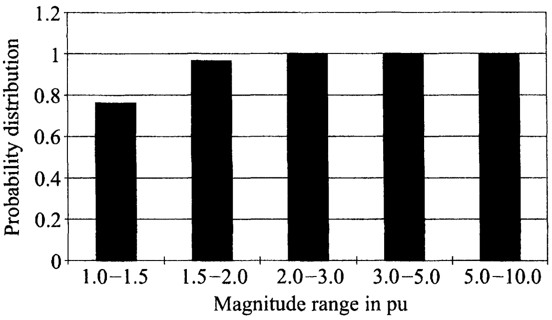

Figure 1.11 Probability distribution function of the magnitude of transient overvoltage events, according to Fig. 1.10.

between events has not been determined, but only the number of events per year with different characteristics. Note that the average time between events is the reciprocal of the number of events per year. This is the normal situation; the actual distribution function is rarely determined in power quality or reliability surveys [107].

Figures 1.11 through 1.14 give statistical information about the characteristics of the events. Figure 1.11 gives the probability distribution function of the magnitude of the event. We see that almost 80% of the events have a magnitude less than 1.5 pu. Figure 1.12 gives the corresponding density function. By using a logarithmic scale the number of events in the high-magnitude range is better visible. Figure 1.13 gives the probability distribution function of the Vt-integral; Fig. 1.14 the probability density function.

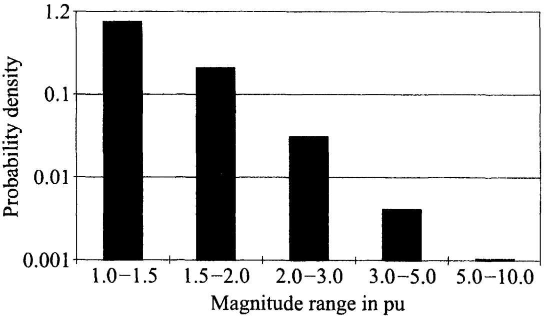

Figure 1.12 Probability density function of the magnitude of transient overvoltage events, according to Fig. 1.10.

An overview of various types of power quality events is given below. Power quality events are the phenomena which can lead to tripping of equipment, to interruption of the production or of plant operation, or endanger power system operation. The treatment of these in a stochastic way is an extension of the power system reliability field as will be discussed in Chapter 2. A special class of events, the so-called "voltage magnitude events," will be treated in more detail in Section 1.3.3. Voltage magnitude events are the events which are the main concern for equipment, and they are the main subject for the rest of this book.

Note that below only "voltage events" are discussed, as these can be of concern to end-user equipment. But similarly a list of "current events" could be added, with their possible effects on power system equipment. Most power quality monitors in use, continuously monitor the voltage and record an event when the voltage exceeds certain

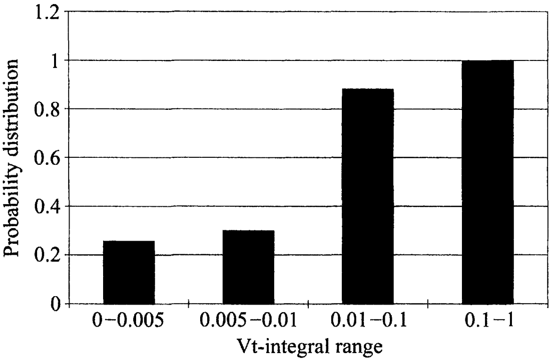

Figure 1.13 Probability distribution function of the Vt-integral of transient overvoltage events, according to Fig. 1.10.

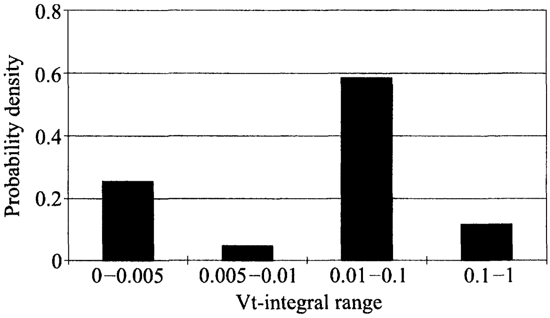

Figure 1.14 Probability density function of the Vt-integral of transient overvoltage events, according to Fig. 1.10.

thresholds, typically voltage magnitude thresholds. Although the currents are often also recorded they do not normally trigger the recording. Thus an overcurrent without an over- or undervoltage will not be recorded. Of course there are no technical limitations in using current signals to trigger the recording process. In fact most monitors have the option of triggering on current as well.

1. **Interruptions.** A "voltage interruption" [IEEE Std.1159], "supply interruption" [EN 50160], or just "interruption" [IEEE Std.1250] is a condition in which the voltage at the supply terminals is close to zero. Close to zero is by the IEC defined as "lower than 1% of the declared voltage" and by the IEEE as "lower than 10%" [IEEE Std. 1159].

Voltage interruptions are normally initiated by faults which subsequently trigger protection measures. Other causes of voltage interruption are protection operation when there is no fault present (a so-called protection maltrip), broken conductors not triggering protective measures, and operator intervention. A further distinction can be made between pre-arranged and accidental interruptions. The former allow the end user to take precautionary measures to reduce the impact. All pre-arranged interruptions are of course caused by operator action.

Interruptions can also be subdivided based on their duration, thus based on the way of restoring the supply:

- automatic switching;
- manual switching;
- repair or replacement of the faulted component.

Various terminologies are in use to distinguish between these. The IEC uses the term long interruptions for interruptions longer than 3 minutes and the term short interruptions for interruptions lasting up to 3 minutes. Within the IEEE the terms momentary, temporary, and sustained are used, but different documents give different duration values. The various definitions will be discussed in Chapter 3.

2. **Undervoltages.** Undervoltages of various duration are known under different names. Short-duration undervoltages are called "voltage sags" or "voltage dips." The latter term is preferred by the IEC. Within the IEEE and in many journal and conference papers on power quality, the term voltage sag is used. Long-duration undervoltage is normally simply referred to as "undervoltage."

A voltage sag is a reduction in the supply voltage magnitude followed by a voltage recovery after a short period of time. When a voltage magnitude reduction of finite duration can actually be called a voltage sag (or voltage dip in the IEC terminology) remains a point of debate, even though the official definitions are clear about it. According to the IEC, a supply voltage dip is a sudden reduction in the supply voltage to a value between 90% and 1% of the declared voltage, followed by a recovery between 10 ms and 1 minute later. For the IEEE a voltage drop is only a sag if the during-sag voltage is between 10% and 90% of the nominal voltage.

Voltage sags are mostly caused by short-circuit faults in the system and by starting of large motors. Voltage sags will be discussed in detail in Chapters 4, 5, and 6.

3. **Voltage magnitude steps.** Load switching, transformer tap-changers, and switching actions in the system (e.g., capacitor banks) can lead to a sudden change in the voltage magnitude. Such a voltage magnitude step is called a "rapid voltage change" [EN 50160] or "voltage change" [IEEE Std.1159]. Normally both voltage before and after the step are in the normal operating range (typically 90% to 110% of the nominal voltage).

An example of voltage magnitude steps is shown in Fig. 1.15. The figure shows a 2.5 hour recording of the voltage in a 10 kV distribution system. The steps in the voltage magnitude are due to the operation of transformer tap-changers at various voltage levels.

4. **Overvoltages.** Just like with undervoltage, overvoltage events are given different names based on their duration. Overvoltages of very short duration, and high magnitude, are called "transient overvoltages," "voltage spikes," or sometimes "voltage surges." The latter term is rather confusing as it is sometimes used to refer to overvoltages with a duration between about 1 cycle and 1 minute. The latter event is more correctly called "voltage swell" or "temporary power frequency overvoltage." Longer

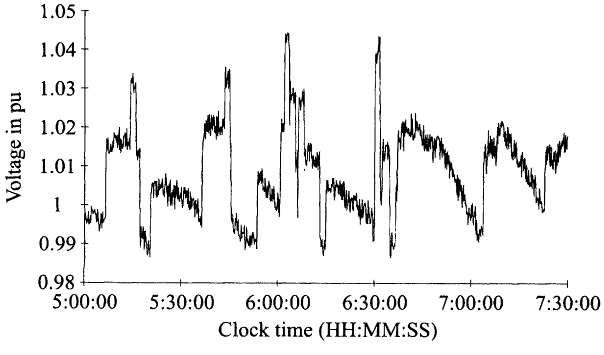

Figure 1.15 Example of voltage magnitude steps due to transformer tap-changer operation, recorded in a 10 kV distribution system in southern Sweden.

duration overvoltages are simply referred to as "overvoltages." Long and short overvoltages originate from, among others, lightning strokes, switching operations, sudden load reduction, single-phase short-circuits, and nonlinearities.

A resonance between the nonlinear magnetizing reactance of a transformer and a capacitance (either in the form of a capacitor bank or the capacitance of an underground cable) can lead to a large overvoltage of long duration. This phenomenon is called ferroresonance, and it can lead to serious damage to power system equipment [144].

5. **Fast voltage events.** Voltage events with a very short duration, typically one cycle of the power system frequency or less, are referred to as "transients," "transient (over)voltages," "voltage transients," or "wave shape faults." The term transient is not fully correct, as it should only be used for the transition between two steady states. Events due to switching actions could under that definition be called transients; events due to lightning strokes could not be called transients under that definition. But due to the similarity in time scale both are referred to as voltage transients. Even very short-duration voltage sags (e.g., due to fuse clearing) are referred to as voltage transients, or also "notches."

Fast voltage events can be divided into impulsive transients (mainly due to lightning) and oscillatory transients (mainly due to switching actions).

6. **Phase-angle jumps and three-phase unbalance.** We will see in Chapter 4 that a voltage sag is often associated with a phase-angle jump and some three-phase unbalance. An interesting thought is whether or not a jump in phase-angle without a drop in voltage magnitude should be called a voltage sag. Such an event could occur when one of two parallel feeders is taken out of operation. The same holds for a short-duration, three-phase unbalance without change in magnitude, thus where only the phase-angle of the three voltages changes.

To get a complete picture, also short-duration phase-angle jumps and short-duration unbalances should be considered as events belonging to the family of power quality phenomena.

1.3.3 Overview of Voltage Magnitude Events

As mentioned in the previous section, the majority of events currently of interest are associated with either a reduction or an increase in the voltage magnitude. We will refer to these as "voltage magnitude events."

A voltage magnitude event is a (significant) deviation from the normal voltage magnitude for a limited duration. The magnitude can be found by taking the rms of the voltage over a multiple of one half-cycle of the power-system frequency.

$$V_{rms} = \sqrt{\frac{1}{N}\sum_{k=1}^{N} V^2(k\Delta t)} \tag{1.2}$$

where $V(t)$ is the voltage as a function of time, sampled at equidistant points $t = k\Delta t$. The rms value is taken over a period $N\Delta t$, referred to as the "window length." Alternatively, the magnitude can be determined from the peak voltage or from the fundamental-frequency component of the voltage. Most power quality monitors determine the rms voltage once every cycle or once every few cycles. The moment the rms voltage deviates more than a pre-set threshold from its nominal value, the voltage as a function of time is recorded (the rms voltage, the sampled time-domain data, or both).

Most events show a rather constant rms voltage for a certain duration after which the rms voltage returns to a more or less normal value. This is understandable if one realizes that events are due to changes in the system followed by the restoration of the original system after a certain time. Before, during, and after the event, the system is more or less in a steady state. Thus the event can be characterized through one duration and one magnitude. We will see in Chapter 4 that it is not always possible to uniquely determine magnitude and duration of a voltage magnitude event. For now we will assume that this is possible, and define the magnitude of the event as the remaining rms voltage during the event: if the rms voltage during the event is 170 V in a 230 V system, the magnitude of the event is $\frac{170}{230} = 73.9\%$.

Knowing the magnitude and duration of an event, it can be represented as one point in the magnitude-duration plane. All events recorded by a monitor over a certain period can be represented as a scatter of points. Different underlying causes may lead to events in different parts of the plane. The magnitude-duration plot will come back several times in the forthcoming chapters. Various standards give different names to events in different parts of the plane. A straightforward classification is given in Fig. 1.16. The voltage magnitude is split into three regions:

- *interruption*: the voltage magnitude is zero,
- *undervoltage*: the voltage magnitude is below its nominal value, and
- *overvoltage*: the voltage magnitude is above its nominal value.

In duration, a distinction is made between:

- very short, corresponding to transient and self-restoring events;
- short, corresponding to automatic restoration of the pre-event situation;
- long, corresponding to manual restoration of the pre-event situation;
- very long, corresponding to repair or replacement of faulted components.

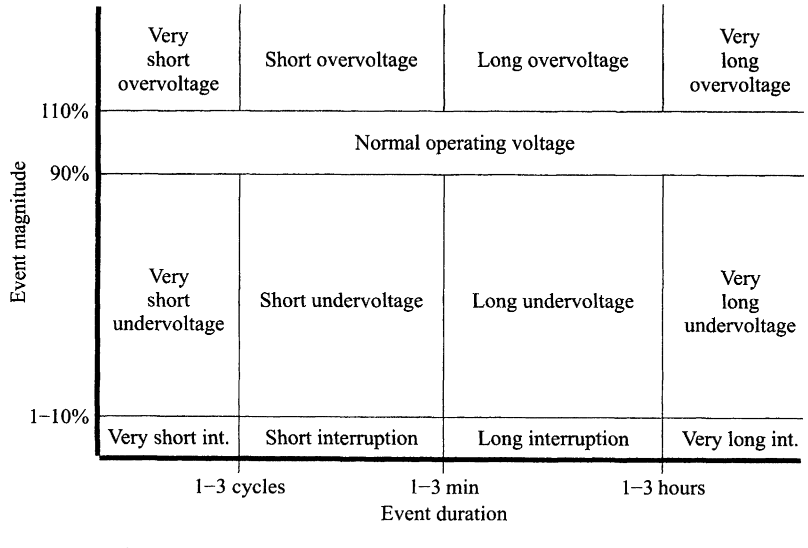

Figure 1.16 Suggested classification of voltage magnitude events.

The various borders in Fig. 1.16 are somewhat arbitrary; some of the indicated values (1–3 minutes, 1–10%, 90%, and 110%) are those used in existing IEC and IEEE standards. For monitoring purposes, strict thresholds are needed to distinguish between the different events. An example is the threshold dividing between interruptions and undervoltages. This one is placed (somewhat arbitrarily) at 1% of nominal according to the IEC and at 10% according to the IEEE (see below). Any other small value would be equally defendable.

The classification in Fig. 1.16 is only aimed at explaining the different types of events: the terms mentioned in the figures are not all used in practice. Both IEC and IEEE give different names to events in some of the regions of the magnitude-duration plane. The IEC definitions are summarized in Fig. 1.17 and the IEEE definitions in Fig. 1.18. The IEC definitions were obtained from CENELEC document EN 50160 [80], the IEEE definitions from IEEE Std.1159-1995.

The method of classifying events through one magnitude and one duration has been shown to be very useful and has resulted in a lot of information and knowledge about power quality. But the method also has its limitations, which is important to realize when using this classification. Four points should be especially kept in mind.

1. The during-event rms voltage is not always constant, leading to ambiguities in defining the magnitude of the event. It may also lead to ambiguities in defining the duration of the event.
2. Fast events (one cycle or less in duration) cannot be characterized, resulting in unrealistic values for magnitude and duration or in these disturbances simply being neglected.
3. Repetitive events can give erroneous results: they either lead to an over-estimation of the number of events (when each event in a row of events is counted as a separate event), or an under-estimation of the severity of the events (when a row of identical events is counted as one event).

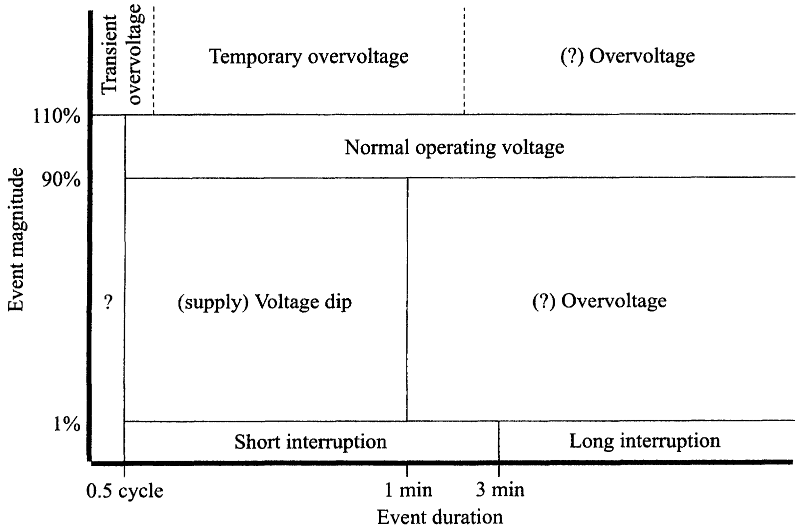

Figure 1.17 Definitions of voltage magnitude events as used in EN 50160.

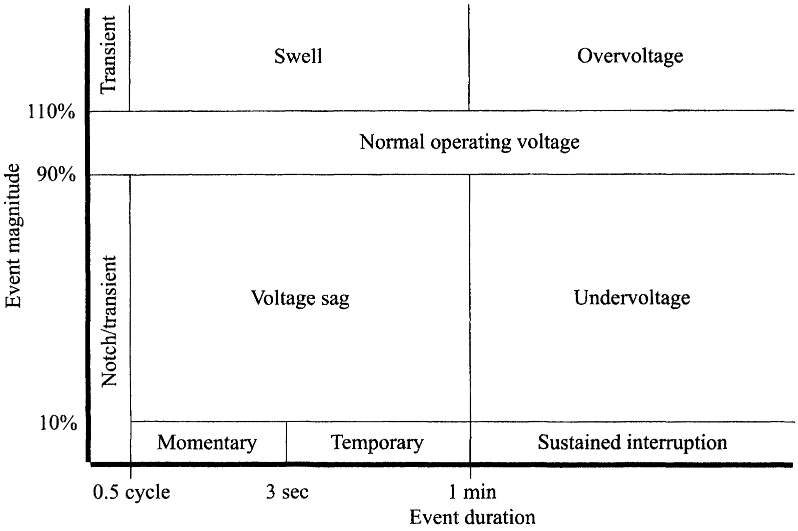

Figure 1.18 Definitions of voltage magnitude events as used in IEEE Std.1159-1995.

4. Equipment is sometimes sensitive to other characteristics than just magnitude and duration.

We will come back to these problems in more detail in Chapters 3 and 4.

Similar classifications can be proposed for voltage frequency events, for voltage phase-angle events, for three-phase voltage unbalance events, etc. But because most equipment problems are due to an increase or decrease in voltage magnitude, the emphasis is on voltage magnitude events.

1.4 POWER QUALITY AND EMC STANDARDS

1.4.1 Purpose of Standardization

Standards that define the quality of the supply have been present for decades already. Almost any country has standards defining the margins in which frequency and voltage are allowed to vary. Other standards limit harmonic current and voltage distortion, voltage fluctuations, and duration of an interruption. There are three reasons for developing power quality standards.

1. **Defining the nominal environment.** A hypothetical example of such a standard is: "*The voltage shall be sinusoidal with a frequency of 50 Hz and an rms voltage of 230 V.*" Such a standard is not very practical as it is technically impossible to keep voltage magnitude and frequency exactly constant. Therefore, existing standards use terms like "nominal voltage" or "declared voltage" in this context. A more practical version of the above standard text would read as: " *The nominal frequency shall be 50 Hz and the nominal voltage shall be 230 V,*" which comes close to the wording in European standard EN 50160 [80].

Defining nominal voltage and frequency does not say anything about the actual environment. To do this the deviations from the nominal values have to be known. Most countries have a standard giving the allowed variation in the rms voltage, a typical range being between from 90% to 110%.

2. **Defining the terminology.** Even if a standard-setting body does not want to impose any requirements on equipment or supply, it might still want to publish power quality standards. A good example is IEEE Std.1346 [22] which recommends a method for exchanging information between equipment manufacturers, utilities, and customers. The standard does not give any suggestions about what is considered acceptable.

   This group of standards aims at giving exact definitions of the various phenomena, how their characteristics should be measured, and how equipment should be tested for its immunity. The aim of this is to enable communication between the various partners in the power quality field. It ensures, e.g., that the results of two power quality monitors can be easily compared and that equipment immunity can be compared with the description of the environment. Hypothetical examples are: "*A short interruption is a situation in which the rms voltage is less than 1% of the nominal rms voltage for less than 3 minutes.*" and "*The duration of a voltage dip is the time during which the rms voltage is less than 90% of the nominal rms voltage. The duration of a voltage dip shall be expressed in seconds. The rms voltage shall be determined every half-cycle.*" Both IEEE Std.1159 and EN 50160 give these kind of definitions, hopefully merging into a future IEC standard.

3. **Limit the number of power quality problems.** Limiting the number of power quality problems is the final aim of all the work on power quality. Power quality problems can be mitigated by limiting the amount of voltage disturbances caused by equipment, by improving the performance of the supply, and by making equipment less sensitive to voltage disturbances. All mitigation methods require technical solutions which can be implemented independently of any standardization. But proper standardization will provide important incentives for the implementation of the technical solutions. Proper standardization will also solve the problem of responsibility for power quality disturbances. Hypothetical examples are:

   > *The current taken by a load exceeding 4 kVA shall not contain more than 1% of any even harmonic. The harmonic contents shall be measured as a 1-second average.* and *Equipment shall be immune to voltage variations between 85% and 110% of the nominal voltage. This shall be tested by supplying at the equipment terminals, sinusoidal voltages with magnitudes of 85% and 110% for a duration of 1 hour. If the piece of equipment has more than one distinctive load state, it shall be tested for each load state separately, or for what are conceived the most sensitive states.*

   In this field both IEC and IEEE lack a good set of standards on power quality. The IEC has set up a whole framework on electromagnetic compatibility which already includes some power quality standards. The best example is the harmonic standard IEC-61000-2-3 which limits the amount of harmonic current produced by low-power equipment. The IEEE has a good recommended practice for the limitation of harmonic distortion: IEEE 519 [82] which gives limits both for the harmonic currents taken by the customer and for the voltages delivered by the utility.

1.4.2 The IEC Electromagnetic Compatibility Standards

Within the International Electrotechnical Committee (IEC) a comprehensive framework of standards on electromagnetic compatibility is under development. Electromagnetic compatibility (EMC) is defined as: *the ability of a device, equipment or system to function satisfactorily in its electromagnetic environment without introducing intolerable electromagnetic disturbances to anything in that environment* [79].

There are two aspects to EMC: (1) a piece of equipment should be able to operate normally in its environment, and (2) it should not pollute the environment too much. In EMC terms: immunity and emission. There are standards for both aspects. Agreement on immunity is at first a matter of agreement between the manufacturer and the customer. But the IEC sets minimum requirements in immunity standards. The third term of importance is "electromagnetic environment," which gives the level of disturbance against which the equipment should be immune. Within the EMC standards, a distinction is made between radiated disturbances and conducted disturbances. Radiated disturbances are emitted (transmitted) by one device and received by another without the need for any conduction. Conducted disturbances need a conductor to transfer from one device to another. These conducted disturbances are within the scope of power quality; radiated disturbances (although very important) are outside of the normal realm of power system engineering or power quality.

A schematic overview of the EMC terminology is given in Fig. 1.19. We see that the emission of a device may consist of conducted disturbances and radiated disturbances. Radiated disturbances can reach another device via any medium. Normally, radiated disturbances only influence another device when it is physically close to the emitting device. Conducted disturbances reach another device via an electrically conducting medium, typically the power system. The device being influenced no longer has to be physically close as the power system is a very good medium for the conduction of many types of disturbances. Of course also here the rule is that a device which is electrically closer (there is less impedance between them) is more likely to be influenced. A device connected to the power system is exposed to an electrical environment not only due to the combined emission of all other devices connected to the system but also due to all kinds of events in the power system (like switching actions, short-circuit faults, and lightning strokes). The immunity of the device should be assessed with reference to this electromagnetic environment. A special type of disturbances, not shown in the

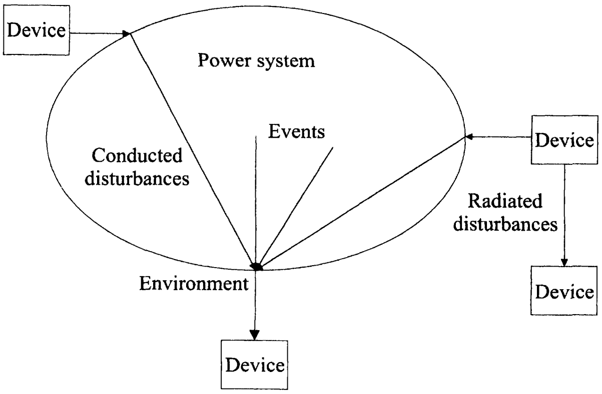

Figure 1.19 Overview of EMC terminology.

figure, are radiated disturbances which induce conducted disturbances in the power system.

Immunity Requirements. Immunity standards define the minimum level of electromagnetic disturbance that a piece of equipment shall be able to withstand. Before being able to determine the immunity of a device, a performance criterion must be defined. In other words, it should be agreed upon what kind of behavior will be called a failure. In practice it will often be clear when a device performs satisfactorily and when not, but when testing equipment the distinction may become blurred. It will all depend on the application whether or not a certain equipment behavior is acceptable.

The basic immunity standard [IEC-61000-4-1] gives four classes of equipment performance:

- Normal performance within the specification limits.
- Temporary degradation or loss of function which is self-recoverable.
- Temporary degradation or loss of function which requires operator intervention or system reset.
- Degradation or loss of function which is not recoverable due to damage of equipment, components or software, or loss of data.

These classes are general as the description should be applicable to all kinds of equipment. This classification is further defined in the various equipment standards.

Emission Standards. Emission standards define the maximum amount of electromagnetic disturbance that a piece of equipment is allowed to produce. Within the existing IEC standards, emission limits exist for harmonic currents [IEC 61000-3-2 and 61000-3-6], and for voltage fluctuations [IEC 61000-3-3, 61000-3-5, and 61000-3-7]. Most power quality phenomena are not due to equipment emission but due to operational actions or faults in the power system. As the EMC standards only apply to equipment, there are no "emission limits" for the power system. Events like voltage sags and interruptions are considered as a "fact-of-life." These events do, however, contribute to the electromagnetic environment.

The Electromagnetic Environment. To give quantitative levels for the immunity of equipment, the electromagnetic environment should be known. The electromagnetic environment for disturbances originating in or conducted through the power system, is equivalent to the voltage quality as defined before. The IEC electromagnetic compatibility standards define the voltage quality in three ways:

1. **Compatibility levels** are reference values for coordinating emission and immunity requirements of equipment. For a given disturbance, the compatibility level is in between the emission level (or the environment) and the immunity level. As both emission and immunity are stochastic quantities, electromagnetic compatibility can never be completely guaranteed. The compatibility level is chosen such that compatibility is achieved for most equipment most of the time: typically 95% of equipment for 95% of the time. It is not always possible to influence both emission and immunity: three cases can be distinguished:

- *Both emission and immunity can be affected.* The compatibility level can in principle be freely chosen. But a high level will lead to high costs of equipment immunity and a low level to high costs for limiting the emission. The compatibility level should therefore be chosen such that the sum of both costs is minimal. An example of a disturbance where both emission and immunity can be affected is harmonic distortion. A very good example of this process is described in IEEE Std.519 [82].
- *The emission level cannot be affected.* The compatibility level should be chosen such that it exceeds the environment for most equipment most of the time. An example of a disturbance where the emission level cannot be affected are voltage sags: their frequency of occurrence depends on the fault frequency and on the power system, both of which cannot be affected by the equipment manufacturer. Note that the EMC standards only apply to equipment manufacturers. We will later come back to the choice of compatibility levels for these kind of disturbances.
- *The immunity level cannot be affected.* The compatibility level should be chosen such that it is less than the immunity level for most equipment most of the time. An example of a disturbance where the immunity level cannot be affected is voltage fluctuation leading to light flicker.

2. **Voltage characteristics** are quasi-guaranteed limits for some parameters, covering any location. Again the voltage characteristics are based on a 95% value, but now only in time. They hold at any location, and are thus an important parameter for the customer. Voltage characteristics are a way of describing electricity as a product. Within Europe the EN 50160 standard defines some of the voltage characteristics. This standard will be discussed in detail in Section 1.4.3.
3. **Planning levels** are specified by the supply utility and can be considered as internal quality objectives of the utility.

These ideas were originally developed for disturbances generated by equipment, for which other equipment could be sensitive: mainly radio frequency interference. These ideas have been extended towards variations like harmonic distortion or voltage fluctuations. The concept has not yet been applied successfully towards events like voltage sags or interruptions.

EMC and Variations. Variations can be stochastically described through a probability distribution function, as shown in Fig. 1.20. The curve gives the probability that the disturbance level will not exceed the given value. The compatibility level can, according to the recommendations in the IEC standards, be chosen at the 95% percentile, as indicated in Fig. 1.20. The curve can hold for one site or for a large number of sites. When the curve represents a large number of sites it is important that it gives the disturbance level not exceeded for most of the sites (typically 95% of the sites). Consider as an example that the compatibility level of total harmonic distortion (THD) is 0.08. Suppose the THD is measured at 100 sites during 1000 10-minute intervals. A compatibility level of 0.08 implies that at 95 sites (out of 100) at least 950 THD samples (out of 1000) have a value of 0.08 or less.

In case a higher reliability is required for the successful operation of a device, a higher level than 95% should be chosen, e.g., 99.9%.

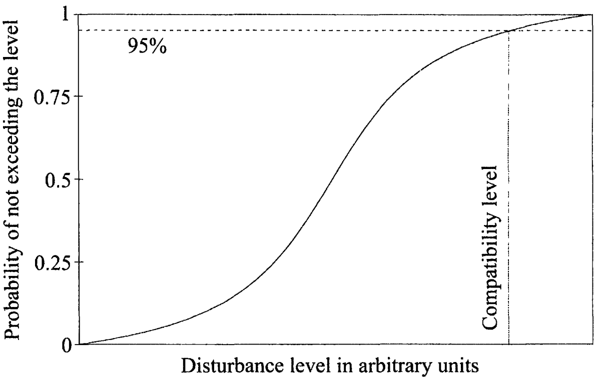

Figure 1.20 Probability distribution function for a variation, with the compatibility level indicated.

EMC and Events. The EMC framework has not been developed for events and its application to them has not been defined yet. For important power quality phenomena like voltage sags and interruptions, the EMC standards can thus not be used. This explains for a large part why the EMC standards are not (yet) well known in the power quality field. Still an attempt should be made at applying the concepts of electromagnetic compatibility to events.

Events only happen occasionally and are not present all of the time; applying a 95% criterion is therefore no longer possible. An immunity to 95% of voltage sags would depend on the way of counting the sags. Counting all sags below 200 V (in a 230 V supply) would give a much higher number than counting all sags below 150 V. The immunity requirement in the latter case would be much stricter than in the former.

In some power quality monitoring surveys a 95% criterion in space is applied. The electromagnetic environment is defined as the level of disturbance (number of events) not exceeded for 95% of the sites. But the knowledge of the environment in itself does not say anything about equipment immunity requirements. The immunity requirement should be based on the minimum time between events exceeding the immunity level. Figure 1.21 shows the time between events exceeding a certain disturbance level as a function of the disturbance level (the severity of the event). The more severe the event the more the time between events (the lower the event frequency). A piece of equipment or an industrial process to which the equipment belongs will have a certain reliability requirement, i.e., a certain minimum time between events leading to tripping of the equipment or interruption of the process. By using the curve in Fig. 1.21 this can be translated into an immunity requirement. As we will see later, the actual situation is more complicated: the severity of an event is a multidimensional quantity as at least magnitude and duration play a role.

A possible compatibility level would be the level not exceeded more than ten times a year by 95% of the customers. This can be done for any dimension of the event, leading to a multidimensional compatibility level. This concept has been applied to the results of the Norwegian power quality survey [67]. The frequency of transient overvoltage events, for the 95% site, is shown in Fig. 1.22. The 95% site is chosen such that 95% of the sites have less transient overvoltage events per year than this site. From Fig. 1.22 we can see that reasonable compatibility levels are:

- 2.5 pu for the magnitude of the transients.
- 0.3 Vs for the Vt-integral.

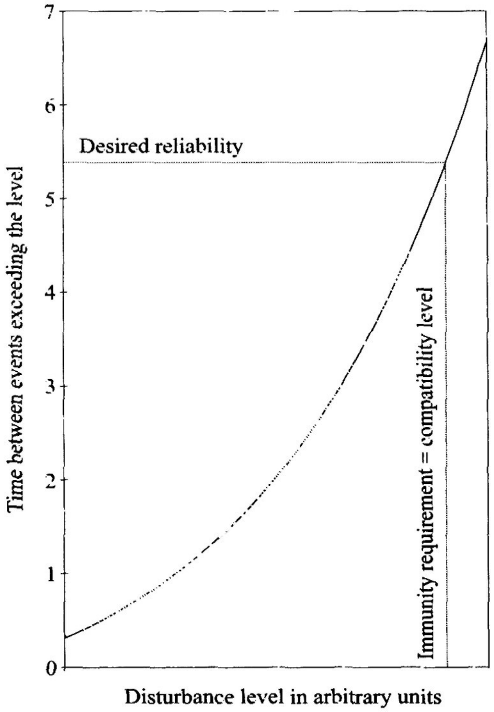

Figure 1.21 Time between events as a function of the disturbance level.

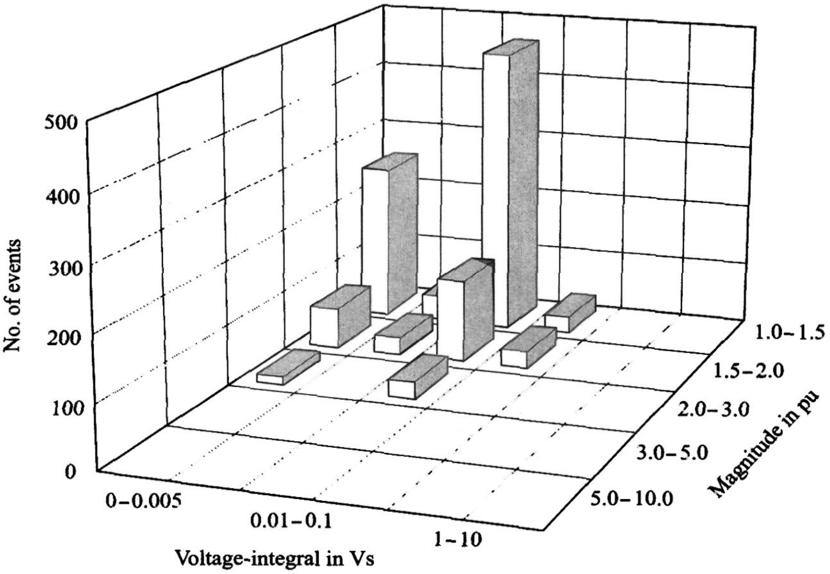

Figure 1.22 Maximum number of transient overvoltage events for 95% of the low-voltage customers in Norway. (Data obtained from [67].)

As a next step, these levels could be used as a basis for equipment immunity requirements. This concept could be worked out further by giving compatibility levels for 10 events and 1 event per year. Compatibility levels for 1 event per year cannot be obtained from Fig. 1.22 because of the short monitoring period (about one year).

1.4.3 The European Voltage Characteristics Standard

European standard 50160 [80] describes electricity as a product, including its shortcomings. It gives the main characteristics of the voltage at the customer's supply terminals in public low-voltage and medium-voltage networks under normal operating conditions.

Some disturbances are just mentioned, for others a wide range of typical values are given, and for some disturbances actual voltage characteristics are given.

Voltage Variations. Standard EN 50160 gives limits for some variations. For each of these variations the value is given which shall not be exceeded for 95% of the time. The measurement should be performed with a certain averaging window. The length of this window is 10 minutes for most variations; thus very short time scales are not considered in the standard. The following limits for the low-voltage supply are given in the document:

- **Voltage magnitude**: 95% of the 10-minute averages during one week shall be within ±10% of the nominal voltage of 230 V.
- **Harmonic distortion**: For harmonic voltage components up to order 25, values are given which shall not be exceeded during 95% of the 10-minute averages obtained in one week. The total harmonic distortion shall not exceed 8% during 95% of the week. The limits have been reproduced in Table 1.1. These levels appear to originate from a study after harmonic distortion performed by a CIGRE working group [83], although the standard document does not refer to that study. In reference [83] two values are given for the harmonic voltage distortion:
    - — **low value**: the value likely to be found in the vicinity of large disturbing loads and associated with a low probability of causing disturbing effects;
    - — **high value**: value rarely found in the network and with a higher probability of causing disturbing effects.

TABLE 1.1 Harmonic Voltage Limits According to EN 50160

Order	Relative Voltage	Order	Relative Voltage
3	5%	15	0.5%
5	6%	17	2%
7	5%	19	1.5%
9	1.5%	21	0.5%
11	3.5%	23	1.5%
13	3%	25	1.5%

TABLE 1.2 Harmonic Voltage Levels in Europe [83]

Order	Low	High	Order	Low	High
3	1.5%	2.5%	15	≤0.3%	
5	4%	6%	17	1%	2%
7	4%	5%	19	0.8%	1.5%
9	0.8%	1.5%	21	≤0.3%	
11	2.5%	3.5%	23	0.8%	1.5%
13	2%	3%	25	0.8%	1.5%

The values found by the CIGRE working group have been summarized in Table 1.2. The values used in EN 50160 are obviously the values rarely exceeded anywhere in Europe. This is exactly what is implemented by the term "voltage characteristics."

- **Voltage fluctuation**: 95% of the 2-hour long-term flicker severity values obtained during one week shall not exceed 1. The flicker severity is an objective measure of the severity of light flicker due to voltage fluctuations [81].
- **Voltage unbalance**: the ratio of negative- and positive-sequence voltage shall be obtained as 10 minute averages, 95% of those shall not exceed 2% during one week.
- **Frequency**: 95% of the 10 second averages shall not be outside the range 49.5 .. 50.5 Hz.
- **Signaling voltages**: 99% of the 3- second averages during one day shall not exceed 9% for frequencies up to 500 Hz, 5% for frequencies between 1 and 10 kHz, and a threshold decaying to 1% for higher frequencies.

Events. Standard EN 50160 does not give any voltage characteristics for events. Most event-type phenomena are only mentioned, but for some an indicative value of the event frequency is given. For completeness a list of events mentioned in EN 50160 is reproduced below:

- **Voltage magnitude steps**: these normally do not exceed ±5% of the nominal voltage, but changes up to ±10% can occur a number of times per day.
- **Voltage sags**: frequency of occurrence is between a few tens and one thousand events per year. Duration is mostly less than 1 second, and voltage drops rarely below 40%. At some places sags due to load switching occur very frequently.
- **Short interruptions** occur between a few tens and several hundreds times per year. The duration is in about 70% of the cases less than 1 second.
- **Long interruptions of the supply voltage**: their frequency may be less than 10 or up to 50 per year.
- **Voltage swells** (short overvoltages in Fig. 1.16) occur under certain circumstances. Overvoltages due to short-circuit faults elsewhere in the system will generally not exceed 1.5 kV rms in a 230 V system.
- **Transient overvoltage** will generally not exceed 6 kV peak in a 230 V system.

The 95% Limits. One of the recurring criticisms on the EN 50160 standard is that it only gives limits for 95% of the time. Nothing is said about the remaining 5% of the time. Looking at the voltage magnitude as an example: 95% of the time the voltage is between 207 V and 253 V (10% variation around the nominal voltage of 230 V), but during the remaining 5% of the time the voltage could be zero, or 10 000 V, and the voltage would still conform with the voltage characteristics.

The voltage magnitude (rms value) is obtained every 10 minutes—that gives a total of $7 \times 24 \times 6 = 1008$ samples per week; all but 50 of those samples should be in the given range. If we only consider normal operation (as is stated in the document) it would be very unlikely that these are far away from the ±10% band. Understanding this requires some knowledge of stochastic theory. In normal operation, the voltage at the customer is determined by a series of voltage drops in the system. All of those are of a stochastic character. According to stochastic theory, a variable which is the sum of a sufficient number of stochastic variables, can be described by a normal distribution. The normal distribution is one of the basic distributions in stochastic theory: its probability density function is

$$f(v) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(v-\mu)^2}{2\sigma^2}} \tag{1.3}$$

where v is the value of the stochastic variable, μ its expected value, and σ its standard deviation. The well-known bell-shape of this function is shown in Fig. 1.23 for $\mu = 230\,\text{V}$ and $\sigma = 11.7\,\text{V}$.

There is no analytical expression for the probability distribution function, but it can be expressed in the so-called error function Φ:

$$F(v) = \int_0^v f(\phi)d\phi = \Phi\left[\frac{v-\mu}{\sigma}\right] \tag{1.4}$$

The voltage characteristics standard gives the expected value (230 V) and the 95% interval (207 .. 253 V). Assuming that the voltage is normally distributed we can calculate the standard deviation which results in the given 95% confidence interval. As 95% of the voltage samples are between 207 and 253 V, 97.5% is below 253 V, thus:

$$\Phi\left[\frac{253\,\text{V} - 230\,\text{V}}{\sigma}\right] = 0.975 \tag{1.5}$$

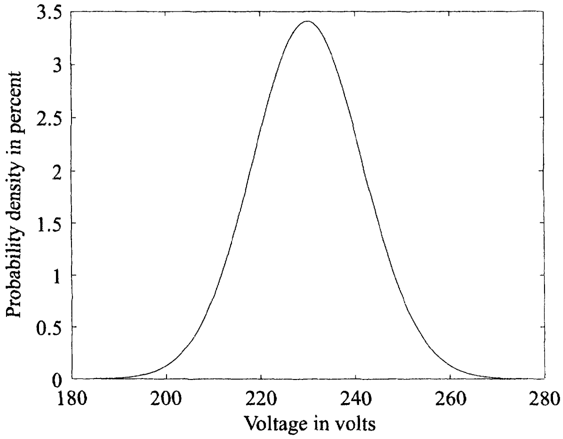

Figure 1.23 Probability density function of the normal distribution.

From a table of the error function, which can be found in almost any book on statistics or stochastic theory, we find that $\Phi(1.96) = 0.975$ which gives $\sigma = 11.7\,\text{V}$. Knowing expected value and standard deviation of the normal distribution, the whole distribution is known. It is thus no longer difficult to calculate the probability that the voltage deviates more than 10% from its nominal value. The results of this calculation are given in Table 1.3. The first column gives the probability that the voltage is within the voltage range in the second, third, and fourth columns. The voltage range is given in standard deviations, in volts and as a percentage of the nominal voltage. The voltage is thus between 200 and 260 V for 99% of the time. The last column indicates how often the voltage is outside of the range, assuming all samples to be stochastically independent. In reality there is strong correlation between the samples which makes that large deviations become even more unlikely. Further, there are voltage regulation mechanisms (capacitor banks, transformer tap-changers) which become active when the voltage deviates too much from its nominal value. Finally, one should realize that the 95% value given in the standard does not hold for the average customer but for the worst-served customer. All this leads to the conclusion that voltage magnitude variations of much more than 10% are extremely unlikely.

From this reasoning one should absolutely not draw the conclusion that the voltage magnitude will never be lower than a value like 80%. The main assumption used is that the voltage variations are due to the sum of a number of small voltage drops. During, e.g., a voltage sag, this no longer holds. This brings us back to the principal difference between "events" and "variations": for variations the normal distribution can be used; for events it is the time between events which is of main importance. The probabilities in Table 1.3 thus only hold for voltage magnitude variations; absolutely nothing is said yet about voltage magnitude events.

Scope and Limitations. Standard EN 50160 contains some well-defined limits and measurement protocols, but it falls short of putting responsibility with any party. This is of course understandable when one realizes that the document describes the "voltage characteristics" which is the electromagnetic environment as it is now, not as it should be, and not even as it will be in future. Of course the underlying thought is that the situation will not become worse and that it is up to the utilities to ensure this.

When interpreting this standard it is also very important to realize that it only applies under "normal operating conditions." The document specifies a list of situations to which the limits do not apply. This list includes "operation after a fault," but also "industrial actions" and such vague terms as "force majeure" and "power shortages due to external events." This list removes a lot of the potential value from the document. A description of the electromagnetic environment should include all events and

TABLE 1.3 Probability of Voltage Exceeding Certain Levels

Probability	Voltage Range			Frequency
95%	$\mu \pm 1.96\sigma$	207–253 V	±10%	50 per week
99%	$\mu \pm 2.58\sigma$	200–260 V	±13%	10 per week
99.9%	$\mu \pm 3.29\sigma$	193–268 V	±17%	1 per week
99.99%	$\mu \pm 3.90\sigma$	184–276 V	±20%	5 per year
99.999%	$\mu \pm 4.42\sigma$	178–282 V	±23%	1 per 2 years
99.9999%	$\mu \pm 4.89\sigma$	173–287 V	±25%	1 per 20 years

variations to which a customer is exposed, not just those which occur during "normal operating conditions." A voltage sag during a severe lightning storm (exceptional weather) is equally damaging as a sag during a sunny afternoon in May.

Looking at the document in a more positive light, one can say that it only gives limits for what we have called "variations"; voltage quality "events" are not covered by the document.

What Next? Despite all its shortcomings, EN 50160 is a very good document. It is probably the best that could be achieved under the circumstances. One should realize that it is the first time that the electromagnetic environment has been described in such detail in an official document. Although limits are only given for some of the phenomena, and although the standard only applies during normal operation, and although absolutely no guarantees are given, at least a first step is set. Based on this standard one can see a number of developments:

- Utilities all over Europe have started to characterize their voltage quality by using the measurements as defined in EN 50160; thus 10-minute averages are taken of the rms voltage, 10-minute averages of the harmonic voltages, etc. The values not exceeded during 95% of the time are then used to characterize the local voltage quality. A problem is that some utilities then compare the results with the EN 5160 limits and state that their voltage quality confirms with the European standards. Understanding the concept of voltage characteristics, it is

TABLE 1.4 Voltage Characteristics as Published by Göteborg Energi

Phenomenon	Basic Level
	Voltage Variations
Magnitude variations	Voltage shall be between 207 and 244 V
Harmonic voltages	Up to 4% for odd harmonic distortion Up to 1% for even harmonic distortion Up to 6% THD Up to 0.3% for interharmonic voltages
Voltage fluctuations	Not exceeding the flicker curve
Voltage unbalance	Up to 2%
Frequency	In between 49.5 and 50.5 Hz
	Voltage Events
Magnitude steps	Frequent events shall be less than 3% in magnitude
Voltage sags	No limits
Short interruptions	No limits
Long interruptions	
accidental	On average less than one in three years On average shorter than 20 minutes Individual interruptions shorter than 8 hours
planned	On average less than one in 18 years On average shorter than 90 minutes Individual interruptions shorter than 8 hours
Transients	The utility tries to minimize size and frequency of transients which influence customers

no surprise that the local voltage quality is better than the limits given in the standard. This result should thus absolutely not be used by a utility to show that their supply is good enough. The statement "our supply confirms with EN 50160" is nonsense, as the standard does not give requirements for the supply, but only existing characteristics of the worst supply in Europe.

- Some utilities have come up with their own voltage characteristics document, which is of course better than the one described in the standard. The local utility in Gothenburg, Sweden has distributed a flyer with the limits given in Table 1.4. The term "voltage characteristics" is actually not used in the flyer; instead the term "basic level" is used [108].
- Measurements are being performed all over Europe to obtain information about other power quality phenomena. For voltage sags, interruptions, and transient voltages no limits are given in the existing document. A voltage characteristic for voltage sags, and for other events, is hard to give as already mentioned before. An alternative is to give the maximum number of events below a certain severity, for 95% of the customers. Figure 1.22 gives this voltage characteristic for transient overvoltage, as obtained through the Norwegian Power Quality survey [67]. Such a choice of voltage characteristic would be in agreement with the use of this same 95% level for the definition of the compatibility level.