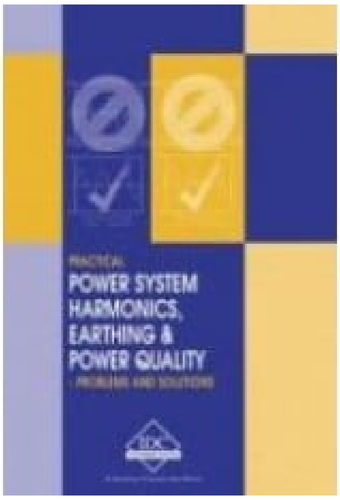
PH-E - Practical Power Systems Harmonics, Earthing & Power Quality - Problems and Solutions



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Short Description

This manual deals with the various types of power quality problems that have a wide ranging effect on the power systems equipment and apparatus in any plant. You will have the opportunity to learn the fundamentals of power quality problems such as surges and voltage sags. Other problems having wide ranging effects on power system equipment such as voltage swells, voltage fluctuations, supply interruptions, frequency variations, harmonics and noise are also discussed in detail.

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Issues related to control of the occurrence of these problems by appropriate system design and mitigation of the effects of these by adoption of appropriate protective measures and by the addition of power conditioning equipment are also discussed. Also, aspects related to designing of the systems, proper installation practices, analysis of the probable reasons and corrective measures are discussed in detail. Practical examples from actual projects will be used extensively to illustrate the principles and drive home the point

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1 Power Quality Overview

Inadequate power quality is one of the main reasons for unsatisfactory operation and failure of electrical equipment. In this chapter, we will have an introduction to the subject of power quality. We will define the meaning of power quality and the various quality parameters. We will briefly discuss the need for good power quality and the approach for solving problems due to power quality.

Learning objectives

- What is power quality?
- Parameters related to power quality
- Need for quality power
- Solving power quality problems

Important note

The terms '*earth'* as well as '*ground'* have both been in general use to describe the common signal/power reference point and have been used interchangeably around the world in the Electro-technical terminology. IEEE standard 142: 1991 (Green Book) however, presents a convincing argument for the use of the term 'ground' in preference to 'earth.' An electrical ground needs not necessarily be anywhere near the earth (meaning soil). For a person working in the top floor of a high-rise building, electrical ground is far above the earth. In deference to this argument, we will adopt the term *ground* in this manual to denote the common electrical reference point. The term *earth* where used will refer to the soil mass.

1.1 Introduction

Before we start on our discussions on power quality, we will get a few things clear in our mind.

- When we talk about power here and elsewhere in this text, it is AC power that we are discussing.
- AC power is the one which we obtain from the normal electrical mains.
- Contrary to expectations, this mains power obtained from the local electrical supplier (or the utility grid or whatever else this agency is called) is far from perfect. So, we will have to define what perfect power or good quality power is.
- Power quality problems originate often from within an installation.

In this overview, we will learn what is meant by power quality and the factors that make the power quality less than perfect. We will learn about the various parameters that determine power quality, the impact of these parameters when they go beyond specified limits. We will discuss in detail the different aspects of power quality and measures to be adopted to mitigate the effects of poor power quality in later chapters.

In an ideal power system with perfect power quality, the following should be realized.

- A constant voltage at a constant frequency
- Perfectly sinusoidal voltage waveform
- Perfectly balanced voltages in case of a three-phase supply system
- No transient sub-cycle voltage variations
- No interruptions of power

It is also important that these conditions are maintained regardless of the variations of connected load or its nature.

In a practical system however, all the above cannot be realized. Normally, power received from the supplier at the point of supply to the consumer is expected to have the following attributes:

- Voltage within specified limits
- Frequency within specified limits

Often, these are the only two parameters that a supplier commits to, but the other attributes too are equally important, whether specified or not. These are:

- Sinusoidal waveform without appreciable distortion
- In the case of a three phase supply, symmetry of line/phase voltages (equal in magnitude and shifted in phase by 120 electrical degrees) to be maintained within limits
- Control of transients or surges in the supply voltage (sub-cycle disturbances)
- Control of repeated voltage changes giving rise to flicker in lamps
- Power interruptions

1.2 Limits on electrical parameters

From the above introduction it will be clear that power quality (or lack of it) is mainly concerned with maintaining specific parameters of the electric supply within a given set of limits. But why are such limits necessary? Why not fix a specific value to each parameter? The answer to this lies in the physical laws governing the flow of electricity and the practical considerations of design. For example, consider a system with a ring main distribution feeder having a single source. The voltage will be highest at a point close to the source but will gradually decrease as we move away from the source due to the voltage drop. A larger conductor size may reduce (but not eliminate) the voltage drop but will make the design expensive. Thus, it is clear that any system will have to evolve a range of acceptable values for each parameter. The acceptable range will depend on the capabilities of the equipment connected to this electrical system.

In a distribution system, which is not usually provided with any facility for controlling the voltage, the voltage parameters will require closer control, say + 5% to – 5%. But in a transmission network, where voltage can be corrected using on-load tap-changers on the step down transformers, a larger variation can be allowed. Usually, limits of + 10% to –15% are considered acceptable.

Even during normal operations, the voltage at a given point in the system hardly remains constant. The loads of a system constantly keep changing and as a result the voltage drop keeps changing too. A load with a highly fluctuating current profile (such as an electrical arc furnace) can produce very heavy voltage fluctuations during certain phases of its operating cycle.

Also, it is impossible to totally prevent interruption of supply. Even in the best-maintained systems, equipment failures and short circuit faults can occur and if the process or parts of it cannot tolerate a supply interruption, then a mechanism for ensuring power to those loads where interruptions can have catastrophic results has to be worked out. Similarly, the dynamic nature of a power system operation causes constant frequency swings representing the shifting of system equilibrium point between generation and loads. The presence of non-linear equipment in a system gives rise to harmonics and so on.

What are the limits that need to be applied to each parameter primarily depends on the behavior of the loads which are connected to the system and how much of a variation can normally be tolerated by these loads. The national regulatory authorities of each country therefore try to define these limits through the applicable standards and codes of practices (examples being the National Electrical Code of USA and British Wiring regulations, as well as other specific standards governing the relevant equipment). The supplier (of electrical power) has thus an obligation to maintain the stipulated limits at the point of power supply to each consumer. It may also happen that a bulk purchaser of electricity may lay down more stringent requirements if there is such a need in his specific case. These may be spelt out in the power supply agreement between the supplier and the consumer. On their part, the suppliers can also impose operational limits on the consumers by asking them to restrict demand, avoid load fluctuations, limit the injection of high frequency currents into the system (we will discuss about how this can happen as we proceed) and maintain certain minimum power factor. These limits are necessary so that an individual consumer does not pollute the power supply system or cause large variations in the supply parameters, thus affecting the quality of power supply to the other consumers.

It also follows that the designers of power consuming/switching equipment such as motors or switchgear will have to design their equipment to operate satisfactorily within the accepted supply limits and deliver rated output. Conversely, when the supply parameters do not remain within the specified limits, the above equipment may not perform satisfactorily. Therefore, power quality needs to be strictly maintained in any electrical system within agreed set of operational limits to ensure that the electrical equipment fed from the system can operate without problems over their entire design life.

1.3 What is power quality?

Before we go any further into the details of power quality aspects, let us first try to define what we mean by the term power quality. A reasonable definition of quality power can be:

Power made available at stipulated voltage and frequency without distortion of waveform or loss of symmetry and with minimum instances/duration of variations beyond the specified limits or unscheduled interruptions.

From this definition, a few aspects would be clear to the reader. The first is that it is generally accepted that any electrical parameter cannot remain absolutely constant and some variations will occur. So also, an unscheduled interruption is a possibility that has to be anticipated. What is important is that:

1. The variations should be within acceptable limits.
2. The number of instances of variations should be as few as possible.
3. Unscheduled interruptions should be as few as possible
4. Duration of off-limit variations as well as interruptions should be as short as possible.

It is clear that to improve power quality in a system, the stress should be on preventing the variations from going beyond specified limits, on preventing interruptions and on reducing the number and duration of such variations and interruptions. We will learn in this chapter as to how all these can be achieved in practical systems.

As an example, given below in Figure 1.1 the results of a study made in a typical system indicating various deviations during the course of a specific period.

Figure 1.1

Typical power quality problems

It is evident from this figure that transient disturbances and voltage spikes together form the bulk of the deviations followed by low voltage conditions. Total blackout period is less than 11 minutes on an average per month. We will discuss in detail in the next section about the indicators of power quality in any system and their effects.

1.4 Power quality indicators

Inadequate power quality is indicated if one or more of the following occur frequently in a system.

- Changes in amplitude of the AC voltage. This can be either for short periods or for long periods. Such changes can take the form of:

    - Voltage variations such as sag and swell and repeated voltage

fluctuations
    - Surges or transient sub-cycle disturbances
    - Interruption (an extreme form of amplitude change)
    - Noise
- Frequency disturbances produced from the generating source, which can be a utility grid, or a stand-alone power source such as an emergency engine generator.
- Waveform asymmetry, which may cause the voltage vectors of the three phases to be different in values and the phase angle shift to vary from the normal value of 120 electrical degrees.
- Changes in the AC voltage waveform appearing as harmonics

We will discuss these problems briefly in this section.

1.4.1 Sag

Sag is a temporary reduction in the normal AC voltage. Momentary sag is a variation, which lasts for a period of 0.5 cycles to about 2 seconds, usually the result of a short circuit somewhere in the power system. Instances of longer duration of low voltage are called Sustained sags (see Figure 1.2).

Figure 1.2

Sag-momentary and sustained

1.4.2 Swell

Swell is the opposite of sag and refers to the increase of power frequency voltage. A momentary swell lasts from 0.5 cycles to 2 seconds. A sustained swell lasts for longer periods (see Figure 1.3).

Figure 1.3

Swell-momentary and sustained

1.4.3 Surges or transients

Surge is a sub cycle disturbance lasting for durations of less than half a cycle and mostly less than a millisecond. The earlier terminology for such disturbances was transient or spikes. Surges generally occur due to atmospheric disturbances such as lightning or due to switching of large transformers, inductors or capacitors. Figures 1.4 and 1.5 show the waveforms of such surges.

Figure 1.4

Surge voltage with oscillatory decay

Figure 1.5

Surge caused by lightning

A surge with oscillatory decay is generally a result of switching. A lightning surge on the other hand occurs as train of steep pulses of decreasing with definite time delay between them and all in one direction only.

1.4.4 Interruption

Interruption means the complete loss of voltage. A momentary interruption lasts from half cycle period to less than 2 seconds. Longer interruptions are called Sustained interruptions. Momentary interruption is usually the result of a line outage with the supply being restored automatically from another source or by auto-reclosing operation. Refer to Figure 1.6 for illustration. An interruption can be instantaneous or of slowly decaying type.

Figure 1.6

Examples of supply interruption

In the figures above, the one at the top shows the RMS voltage value during a momentary interruption. The figure on the lower left depicts the waveform of a sustained interruption where the voltage drops to zero almost instantaneously. The waveform on the lower right shows an interruption where the voltage decays slowly.

1.4.5 Frequency disturbance

Frequency disturbances originate from a power system and arise out of an unbalance between generation and loads. A system operating normally with the generation being equal to the loads stays near the rated frequency. Any disturbance of this equilibrium by reduction of generation or a sudden change in loading can produce changes in system frequency till the generation and load attain a new point of equilibrium. Such normal changes however do not produce very abrupt or large frequency changes but the frequency remains well within the defined range. But more severe system changes such as the outage of a generator or tripping of a heavily loaded transmission line can produce very high rates of change of frequency and can result in the frequency going beyond normal limits.

Maintaining the frequency of a supply system is important for two reasons:

- Speed of motors connected to the system changes with frequency and affects the throughput of equipment driven by them.
- Any co-generation units working in parallel with the utility will be forced to follow the system frequency. Extreme cases of under/over frequency can prove harmful for the prime movers, particularly steam turbines and may lead to premature failures.

Generally, in well-regulated systems with adequate spinning reserve capacity, frequency is not a problem. We will not therefore discuss this issue in detail in this text. However, in systems where frequency is a problem, the following measures may be useful for avoiding difficulties due to frequency-sensitive loads:

- Providing variable speed drives for control of motor speeds independent of supply frequency
- Planning for a separate generator operated from a prime-mover or some form of uninterrupted power system (UPS) whose frequency can be regulated independent of the system frequency

Co-generation units may have to be provided with means of isolation from the utility source in the case of large variations of supply frequency and continue to supply specified plant loads independently.

1.4.6 Waveform asymmetry

A generator in any practical 3-phase electrical system is designed to produce a perfectly symmetrical output. The line/phase voltages of each phase will be equal in magnitude with a phase displacement of 120 electrical degrees. However, the voltage experienced by a consumer or specific parts of the consumer's internal distribution system or sometimes a specific load may experience an asymmetrical voltage. Asymmetrical voltage is usually a result of an unbalanced load and less often unbalanced system impedance. An unbalanced load or a balanced load with an unbalanced system impedance produce different voltage drops in each line and as a result, the voltage available at the consumer point can become asymmetrical even though the source may generate a perfectly symmetrical output. An extreme case of asymmetry happens when one line gets broken (a condition which is commonly known as single-phasing). Apart from these, large single-phase loads can be found in traction systems and in industries deploying induction furnaces. These loads can introduce large unbalances in the system require specific corrective measures. Asymmetry poses a problem to three phase motors and converters but does not affect single-phase loads except by way of a change of voltage.

To know how an asymmetry will affect the connected loads, it is necessary to mathematically resolve the voltages using a technique called symmetrical components. We will discuss this in detail in a later chapter.

1.4.7 Waveform distortion (Harmonics)

Distortion of the sine waveform of an AC voltage or current can happen as a result of two conditions.

- Magnetic saturation of transformer cores
- Presence of large non-linear loads

Magnetic saturation causes sudden change in the inductive reactance of a coil and results both in distortion of the magnetizing input current in a transformer as well as the output waveform.

Loads that draw distorted currents when supplied with sinusoidal voltage are called non-linear. Loads that are resistances, capacitances or inductances (operating in the linear, unsaturated zone) or a combination of these circuit elements have the same wave shapes for voltage and current. Both are normally pure sinusoids and such loads are said to be linear. Most induction motors fed directly from AC mains also behave as a combination of resistance and inductive reactance and therefore can be considered as linear loads. However, the current waveform gets distorted when power electronic devices are introduced in the system to control the speed of AC (or DC) motors. These devices chop off part of the AC waveform using thyristors or power transistors, which are used as static switches. These are called non-linear loads.

Such altered waveforms may be mathematically analyzed using Fourier transforms as a combination of vectors of the power frequency (50/60 Hz) and others whose frequency is a multiple of the power frequency. The power frequency component is called the *Fundamental*frequency component and higher multiples are called *Harmonic* frequency components or simply as *harmonics*. It should be remembered that all electrical generators produce only voltage at fundamental frequency. But there has to be a source of harmonic frequency voltage if a harmonic current has to flow. It is therefore construed theoretically that all harmonic producing loads are current sources of harmonics. These sources drive harmonic currents through the rest of the system consisting of the fundamental frequency source as well as other loads connected to it. The current flowing through the different impedance of the system appears as harmonic voltages. It is usual for the voltage waveform of such a system to appear distorted. Also, the harmonic currents flowing through the other loads of the system give rise to several abnormalities (refer to Table 1.1 for the effects harmonics have on different system components).

Table 1.1

Effects harmonics have on different system components

Capacitors: Amplify harmonics on electrical distribution system
Electrical wiring: Phase and neutral conductors undersized
Engine generators: Transferring capability and operation disrupted
Induction motors: May fail prematurely due to fifth harmonic
Metering: Inaccurate measurement of power
Over-current protection: Breaker and fuse nuisance tripping
Sensitive electronic loads: Voltage drop between neutral and earth
Transformers: Decreased efficiency and overheating
Uninterruptible power systems: Line and load interaction

Higher frequency harmonics can be propagated by the power conductors acting as antennae and appear as induced noise voltages in nearby signal circuits.

1.4.8 Noise

Noise, or interference, can be defined as an undesirable electrical voltage, which distorts or interferes with a desired signal. Noise could be transient (temporary) or constant. Unpredictable transient noise can be caused, for example, by lightning. Constant noise can be due to the 50 or 60 Hz AC ‘hum’ from power circuits or its harmonic multiples of power frequency close to the data communications cable. This unpredictability makes the design of a data communications system quite challenging. Noise can be generated from within the sensitive equipment itself (internal noise) or from an outside source (external noise). Generation and propagation of electrical noise requires a source of noise, a mechanism coupling the source to the ‘victim’ circuit and a circuit conveying sensitive communication signals. Typical sources of noise are devices, which produce quick changes (spikes) in voltage or current or harmonics.

Noise generally manifests itself in two forms. In one form, the noise may be a result of an external disturbance such as a high-energy electromagnetic pulse from a lightning. In this case, noise appears on all the conductors (including the neutral) of a power system as identical pulses. This type of noise is called as Common mode noise. The other form of noise is the result of a disturbance from the power system itself. This kind of noise called as Transverse mode or differential mode noise.

Noise is not in the strict sense a power quality issue but it is an effect of other power quality problems. Noise can get transmitted into communication and signal circuits and cause problems such as component failures, malfunction of controls etc. A good design should therefore ensure that noise is not generated and when generated by equipment or originating from an external source, is not propagated into a system containing noise-sensitive equipment.

1.5 Need for improving power quality

Power quality problems can either originate from the power supply system (which may include problems caused by neighboring consumers) or from the concerned installation itself. Many of the problems of power quality may manifest themselves as equipment failures such as burn-out of motors, failure of electronic cards, nuisance tripping of circuit-breakers and so on. It is up to the engineers in charge of the installation to recognize these as symptoms of power quality, especially when the problems become frequent or repetitive, and take appropriate action.

Many of the possible issues of power quality need to be taken into consideration while planning and installation. In the case of large facilities, observations at the supplier’s installation from where power supply will be obtained as well as a study of available records and system parameters at the point of common coupling will be necessary to detect any inherent deficiency in the system. Making suitable provisions in the initial design of the electrical systems of a facility and equipment specifications and adopting correct installation practices will go a long way in avoiding a lot of downtime, loss of production and expensive retrofits at a later stage.

In spite of the best of precautions, problems can still happen during the operation of a facility. This may happen due to addition of new equipment within a facility, changes in the supplier’s installation such as addition of new consumers as well as temporary configuration changes in the system. It is then necessary to correctly pinpoint the source of the problem and introduce appropriate remedies. Identifying a power quality problem requires proper instruments, with measurements being done at different points in the system and even at different times of the day. The readings thus obtained should be correctly interpreted to understand the real reasons, which may call for adequate theoretical knowledge of the principles involved and familiarity with the system under study. We will discuss these aspects in detail in further chapters in this text.

1.6 Summary

Quality power can be defined as power made available at stipulated voltage and frequency without distortion of waveform and with minimum instances/duration of variations going beyond the specified limits or unscheduled interruptions. In other words, power quality is mainly concerned with controlling critical electrical parameters from straying beyond specified limits, avoiding interruptions of electrical supply and minimizing the duration of power interruptions and abnormal variations, should they happen. The most common instances of power quality problems are surges and voltage sags. Other problems are voltage swells, voltage fluctuations, supply interruptions, frequency variations, harmonics and noise. All these problems have wide-ranging effects on power system equipment. It is possible to control the occurrence of these problems by appropriate system design. Mitigating the effects of these problems is also possible by adopting appropriate protective measures and by the addition of power conditioning equipment. Also, adequate care during the design of a system and proper installation practices will go a long way in preventing serious problems from arising. In case problems do happen in an installation, a proper site analysis must be conducted to study the problems in depth, analyze the probable reasons and institute necessary corrective measures. We will discuss these aspects in detail in the ensuing chapters.