POWER QUALITY PROBLEMS AND MITIGATION TECHNIQUES
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This book is dedicated to our parents and families.
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Preface

Due to the increased use of power electronic converters in domestic, commercial, and industrial sectors, the quality of power in distribution networks is deteriorating at an alarming rate. This is causing a number of problems such as increased losses, poor utilization of distribution systems, mal-operation of sensitive equipment, and disturbance to nearby consumers, protective devices, and communication systems. These problems are also aggravated by the direct injection of non-steady power from renewable energy sources in the distribution system. It is expected that in the next few years, more than 80% of AC power is to be processed through power converters owing to their benefits of energy conservation, flexibility, network interconnection, and weight and volume reduction in a number of equipment such as lighting, HVAC, computers, fans, and so on. In view of these facts, it is considered timely to write this book to identify, classify, analyze, simulate, and quantify the associated power quality problems and thereby provide mitigation techniques to these power quality problems that will help practicing engineers and scientist to design better energy supply systems and mitigate existing ones.

Motivation

This book is aimed at both undergraduate and postgraduate students in the field of energy conversion and power quality in more than 10,000 institutions around the world. The book aims to achieve the following:

- Easy explanation of the subject matter through illustrations, waveforms, and phasor diagrams using minimum texts, which is one of the most efficient methods of understanding complex phenomenon.
- Simple learning of the subject through numerical examples and problems, which is one of the most favorite techniques of learning by engineering graduates.
- To gain an in-depth knowledge of the subject through computer simulation-based problems, which is the most favored skill of today’s young engineers.
- To get the confidence to find the solutions of latest practical problems, which are encountered in the field of power quality.
- To develop enthusiasm for logical thinking in students and instructors.
- To gain an in-depth understanding of latest topics on power quality in minimum time and with less efforts.

Focus and Target

This book is planned in a unique and different manner compared with existing books on the subject. It consists of rare material for easy learning of the subject matter and a large number of simple derivations are included in a simplified mathematical form for solving most of the power quality problems in analytical form and designing their mitigation devices. Aside from this, the book provides essential theory supported by a reasonable number of solved numerical examples with illustrations, waveforms and phasor diagrams, small review questions, unsolved numerical problems, computer simulation-based problems, and references.
In addition to undergraduate and postgraduate students in the field of power quality, this book will also prove useful for researchers, instructors, and practicing engineers in the field.

This book facilitates simplified mathematical formulations in closed form solution through calculation, computation, and modeling of power quality problems and designing their mitigation devices.

**Structure**

This book consists of 11 chapters. Chapter 1 gives an introduction on power quality (PQ), causes and effects of PQ problems, requirement of PQ improvements, and mitigation aspects of PQ problems. Chapter 2 deals with PQ definitions, terminologies, standards, benchmarks, monitoring requirements, financial loss, and analytical quantification through numerical problems.

In Chapters 3–6, passive shunt and series compensation using lossless passive LC components, active shunt compensation using DSTATCOM (distribution static compensators), active series compensation using DVR (dynamic voltage restorer), and combined compensation using UPQC (unified power quality compensator) are covered for mitigation of current-based PQ problems such as reactive power compensation to achieve power factor correction (PFC) or voltage regulation (VR), load balancing, and neutral current reduction and mitigation of voltage-based PQ problems such as compensation of voltage drop, sag, swell, unbalance, and so on in the single-phase and three-phase three-wire and four-wire loads and supply systems.

In Chapter 7, various types of nonlinear loads, which cause these power quality problems, are illustrated, classified, modeled, quantified, and analyzed for associated power quality problems.

Chapters 8–11 deal with different kinds of power filters such as passive filters, active shunt filters, active series filters, and hybrid filters to meet the requirements of various kinds of power quality problems such as current and voltage harmonic elimination, reactive power compensation, and so on caused by harmonics-producing single-phase and three-phase nonlinear loads. Moreover, these power filters are also used for elimination of voltage harmonics present in the supply systems.

The major strength of this book is its 175 numerical examples, 250 review questions, 175 numerical problems, 250 computer simulation-based problems, and 600 references in different chapters.

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About the Companion Website

This book has a companion website:
www.wiley.com/go/singh/power

The website includes:
* Solutions to numerical problems
1

Power Quality: An Introduction

1.1 Introduction

The term electric power quality (PQ) is generally used to assess and to maintain the good quality of power at the level of generation, transmission, distribution, and utilization of AC electrical power. Since the pollution of electric power supply systems is much severe at the utilization level, it is important to study at the terminals of end users in distribution systems. There are a number of reasons for the pollution of the AC supply systems, including natural ones such as lightening, flashover, equipment failure, and faults (around 60%) and forced ones such as voltage distortions and notches (about 40%). A number of customer’s equipment also pollute the supply system as they draw nonsinusoidal current and behave as nonlinear loads. Therefore, power quality is quantified in terms of voltage, current, or frequency deviation of the supply system, which may result in failure or mal-operation of customer’s equipment. Typically, some power quality problems related to the voltage at the point of common coupling (PCC) where various loads are connected are the presence of voltage harmonics, surge, spikes, notches, sag/dip, swell, unbalance, fluctuations, glitches, flickers, outages, and so on. These problems are present in the supply system due to various disturbances in the system or due to the presence of various nonlinear loads such as furnaces, uninterruptible power supplies (UPSs), and adjustable speed drives (ASDs). However, some power quality problems related to the current drawn from the AC mains are poor power factor, reactive power burden, harmonic currents, unbalanced currents, and an excessive neutral current in polyphase systems due to unbalancing and harmonic currents generated by some nonlinear loads.

These power quality problems cause failure of capacitor banks, increased losses in the distribution system and electric machines, noise, vibrations, overvoltages and excessive current due to resonance, negative-sequence currents in generators and motors, especially rotor heating, derating of cables, dielectric breakdown, interference with communication systems, signal interference and relay and breaker malfunctions, false metering, interferences to the motor controllers and digital controllers, and so on.

These power quality problems have become much more serious with the use of solid-state controllers, which cannot be dispensed due to benefits of the cost and size reduction, energy conservation, ease of control, low wear and tear, and other reduced maintenance requirements in the modern electric equipment. Unfortunately, the electronically controlled energy-efficient industrial and commercial electrical loads are most sensitive to power quality problems and they themselves generate power quality problems due to the use of solid-state controllers in them.

Because of these problems, power quality has become an important area of study in electrical engineering, especially in electric distribution and utilization systems. It has created a great challenge to both the electric utilities and the manufacturers. Utilities must supply consumers with good quality power for operating their equipment satisfactorily, and manufacturers must develop their electric equipment either to be immune to such disturbances or to override them. A number of techniques...
have evolved for the mitigation of these problems either in existing systems or in equipment to be
developed in the near future. It has resulted in a new direction of research and development (R&D)
activities for the design and development engineers working in the fields of power electronics, power
systems, electric drives, digital signal processing, and sensors. It has changed the scenario of power
electronics as most of the equipment using power converters at the front end need modifications in view of
these newly visualized requirements. Moreover, some of the well-developed converters are becoming
obsolete and better substitutes are required. It has created the need for evolving a large number of circuit
configurations of front-end converters for very specific and particular applications. Apart from these
issues, a number of standards and benchmarks are developed by various organizations such as IEEE
(Institute of Electrical and Electronics Engineers) and IEC (International Electrotechnical Commission),
which are enforced on the customers, utilities, and manufacturers to minimize or to eliminate the power
quality problems.

The techniques employed for power quality improvements in exiting systems facing power quality
problems are classified in a different manner from those used in newly designed and developed
equipment. These mitigation techniques are further subclassified for the electrical loads and supply
systems, since both of them have somewhat different kinds of power quality problems. In existing
nonlinear loads, having the power quality problems of poor power factor, harmonic currents, unbalanced
currents, and an excessive neutral current, a series of power filters of various types such as passive, active,
and hybrid in shunt, series, or a combination of both configurations are used externally depending upon
the nature of loads such as voltage-fed loads, current-fed loads, or a combination of both to mitigate these
problems. However, in many situations, the power quality problems may be other than those of harmonics
such as in distribution systems, and the custom power devices such as distribution static compensators
(DSTATCOMs), dynamic voltage restorers (DVRs), and unified power quality conditioners (UPQCs) are
used for mitigating the current, voltage, or both types of power quality problems. Power quality
improvement techniques used in newly designed and developed systems are based on the modification
of the input stage of these systems with power factor corrected (PFC) converters, also known as improved
power quality AC–DC converters (IPQCs), multipulse AC–DC converters, matrix converters for AC–DC
or AC–AC conversion, and so on, which inherently mitigate some of the power quality problems in them
and in the supply system by drawing clean power from the utility. This book is aimed at providing an
awareness of the power quality problems, their causes and adverse effects, and an exhaustive exposure of
the mitigation techniques to the customers, designers, manufacturers, application engineers, and
researchers dealing with the power quality problems.

1.2 State of the Art on Power Quality

The power quality problems have been present since the inception of electric power. There have been
several conventional techniques for mitigating the power quality problems and in many cases even the
equipment are designed and developed to operate satisfactorily under some of the power quality problems.
However, recently the awareness of the customers toward the power quality problems has increased
tremendously because of the following reasons:

- The customer’s equipment have become much more sensitive to power quality problems than these
  have been earlier due to the use of digital control and power electronic converters, which are highly
  sensitive to the supply and other disturbances. Moreover, the industries have also become more
  conscious for loss of production.
- The increased use of solid-state controllers in a number of equipment with other benefits such as
decreasing the losses, increasing overall efficiency, and reducing the cost of production has resulted in
the increased harmonic levels, distortion, notches, and other power quality problems. It is achieved, of
course, with much more sophisticated control and increased sensitivity of the equipment toward power
quality problems. Typical examples are ASDs and energy-saving electronic ballasts, which have
substantial energy savings and some other benefits; however, they are the sources of waveform
distortion and much more sensitive to the number of power quality disturbances.
• The awareness of power quality problems has increased in the customers due to direct and indirect penalties enforced on them, which are caused by interruptions, loss of production, equipment failure, standards, and so on.
• The disturbances to other important appliances such as telecommunication network, TVs, computers, metering, and protection systems have forced the end users to either reduce or eliminate power quality problems or dispense the use of power polluting devices and equipment.
• The deregulation of the power systems has increased the importance of power quality as consumers are using power quality as performance indicators and it has become difficult to maintain good power quality in the world of liberalization and privatization due to heavy competition at the financial level.
• Distributed generation using renewable energy and other local energy sources has increased power quality problems as it needs, in many situations, solid-state conversion and variations in input power add new problems of voltage quality such as in solar PV generation and wind energy conversion systems.
• Similar to other kinds of pollution such as air, the pollution of power networks with power quality problems has become an environmental issue with other consequences in addition to financial issues.
• Several standards and guidelines are developed and enforced on the customers, manufacturers, and utilities as the law and discipline of the land.

In view of these issues and other benefits of improving power quality, an increased emphasis has been given on quantifying, monitoring, awareness, impacts, and evolving the mitigation techniques for power quality problems. A substantial growth is observed in developing the customer’s equipment with improved power quality and improving the utilities’ premises. Starting from conventional techniques used for mitigating power quality problems in the utilities, distribution systems, and customers’ equipment, a substantial literature has appeared in research publications, texts, patents, and manufacturers’ manuals for the new techniques of mitigating power quality problems. Most of the technical institutions have even introduced courses on the power quality for teaching and training the forthcoming generation of engineers in this field.

A remarkable growth in research and development work on evolving the mitigation techniques for power quality problems has been observed in the past quarter century. A substantial research on power filters of various types such as passive, active, and hybrid in shunt, series, or a combination of both configurations for single-phase two-wire, three-phase three-wire, and three-phase four-wire systems has appeared for mitigating not only the problems of harmonics but also additional problems of reactive power, excessive neutral current, and balancing of the linear and nonlinear loads. Similar evolution has been seen in custom power devices such as DSTATCOMs for power factor correction, voltage regulation, compensation of excessive neutral current, and load balancing; DVRs and series static synchronous compensators (SSSCs) for mitigating voltage quality problems in transient and steady-state conditions; and UPQCs as a combination of DSTATCOM and DVR for mitigating current and voltage quality problems in a number of applications. These mitigation techniques for power quality problems are considered either for retrofit applications in existing equipment or for the utilities’ premises. An exponential growth is also made in devising a number of circuit configurations of input front-end converters providing inherent power quality improvements in the equipment from fraction of watts to MW ratings. The use of various AC–DC and AC–AC converters of buck, boost, buck–boost, multilevel, and multipulse types with unidirectional and bidirectional power flow capability in the input stage of these equipment and providing suitable circuits for specific applications have changed the scenario of power quality improvement techniques and the features of these systems.

### 1.3 Classification of Power Quality Problems

There are a number of power quality problems in the present-day fast-changing electrical systems. These may be classified on the basis of events such as transient and steady state, the quantity such as current, voltage, and frequency, or the load and supply systems.

The transient types of power quality problems include most of the phenomena occurring in transient nature (e.g., impulsive or oscillatory in nature), such as sag (dip), swell, short-duration voltage variations, power frequency variations, and voltage fluctuations. The steady-state types of power quality problems
include long-duration voltage variations, waveform distortions, unbalanced voltages, notches, DC offset, flicker, poor power factor, unbalanced load currents, load harmonic currents, and excessive neutral current.

The second classification can be made on the basis of quantity such as voltage, current, and frequency. For the voltage, these include voltage distortions, flicker, notches, noise, sag, swell, unbalance, undervoltage, and overvoltage; similarly for the current, these include reactive power component of current, harmonic currents, unbalanced currents, and excessive neutral current.

The third classification of power quality problems is based on the load or the supply system. Normally, power quality problems due to nature of the load (e.g., fluctuating loads such as furnaces) are load current consisting of harmonics, reactive power component of current, unbalanced currents, neutral current, DC offset, and so on. The power quality problems due to the supply system consist of voltage- and frequency-related issues such as notches, voltage distortion, unbalance, sag, swell, flicker, and noise. These may also consist of a combination of both voltage- and current-based power quality problems in the system. The frequency-related power quality problems are frequency variation above or below the desired base value. These affect the performance of a number of loads and other equipment such as transformers in the distribution system.

1.4 Causes of Power Quality Problems

There are a number of power quality problems in the present-day fast-changing electrical systems. The main causes of these power quality problems can be classified into natural and man-made in terms of current, voltage, frequency, and so on. The natural causes of poor power quality are mainly faults, lightening, weather conditions such as storms, equipment failure, and so on. However, the man-made causes are mainly related to loads or system operations. The causes related to the loads are nonlinear loads such as saturating transformers and other electrical machines, or loads with solid-state controllers such as vapor lamp-based lighting systems, ASDs, UPSs, arc furnaces, computer power supplies, and TVs. The causes of power quality problems related to system operations are switching of transformers, capacitors, feeders, and heavy loads.

The natural causes result in power quality problems that are generally transient in nature, such as voltage sag (dip), voltage distortion, swell, and impulsive and oscillatory transients. However, the man-made causes result in both transient and steady-state types of power quality problems. Table 1.1 lists some of the power quality problems and their causes.

However, one of the important power quality problems is the presence of harmonics, which may be because of several loads that behave in a nonlinear manner, ranging from classical ones such as transformers, electrical machines, and furnaces to new ones such as power converters in vapor lamps, switched-mode power supplies (SMPS), ASDs using AC–DC converters, cycloconverters, AC voltage controllers, HVDC transmission, static VAR compensators, and so on.

1.5 Effects of Power Quality Problems on Users

The power quality problems affect all concerned utilities, customers, and manufacturers directly or indirectly in terms of major financial losses due to interruption of process, equipment damage, production loss, wastage of raw material, loss of important data, and so on. There are many instances and applications such as automated industrial processes, namely, semiconductor manufacturing, pharmaceutical industries, and banking, where even a small voltage dip/sag causes interruption of process for several hours, wastage of raw material, and so on.

Some power quality problems affect the protection systems and result in mal-operation of protective devices. These interrupt many operations and processes in the industries and other establishments. These also affect many types of measuring instruments and metering of the various quantities such as voltage, current, power, and energy. Moreover, these problems affect the monitoring systems in much critical, important, emergency, vital, and costly equipment.

Harmonic currents increase losses in a number of electrical equipment and distribution systems and cause wastage of energy, poor utilization of utilities’ assets such as transformers and feeders, overloading of power capacitors, noise and vibrations in electrical machines, and disturbance and interference to electronics appliances and communication networks.
<table>
<thead>
<tr>
<th>Problems</th>
<th>Category</th>
<th>Categorization</th>
<th>Causes</th>
<th>Effects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transients</td>
<td>Impulsive</td>
<td>Peak, rise time, and duration</td>
<td>Lightning strikes, transformer energization, capacitive switching</td>
<td>Power system resonance</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oscillatory</td>
<td>Line, capacitor, or load switching</td>
<td>System resonance</td>
</tr>
<tr>
<td>Short-duration</td>
<td>Voltage variation</td>
<td>Sag, Magnitude, duration</td>
<td>Motor starting, single line to ground faults</td>
<td>Protection malfunction, loss of production</td>
</tr>
<tr>
<td>Swell</td>
<td></td>
<td>Magnitude, duration</td>
<td>Capacitor switching, large load switching, faults</td>
<td>Protection malfunction, stress on computers and home appliances</td>
</tr>
<tr>
<td>Interruption</td>
<td>Duration</td>
<td></td>
<td>Temporary faults</td>
<td>Loss of production, malfunction of fire alarms</td>
</tr>
<tr>
<td>Long-duration</td>
<td>Voltage variation</td>
<td>Sustained, interruption, duration</td>
<td>Faults</td>
<td>Loss of production</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Undervoltage</td>
<td>Switching on loads, capacitor de-energization</td>
<td>Increased losses, heating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Overvoltage</td>
<td>Switching off loads, capacitor energization</td>
<td>Damage to household appliances</td>
</tr>
<tr>
<td>Voltage imbalance</td>
<td></td>
<td>Voltage, symmetrical components</td>
<td>Single-phase load, single-phasing</td>
<td>Heating of stones</td>
</tr>
<tr>
<td>Waveform distortion</td>
<td>DC offset</td>
<td>Volts, amperes</td>
<td>Geomagnetic disturbance, rectification</td>
<td>Saturation in transformers</td>
</tr>
<tr>
<td></td>
<td>Harmonics</td>
<td>THD, harmonic spectrum</td>
<td>ASDs, nonlinear loads</td>
<td>Increased losses, poor power factor</td>
</tr>
<tr>
<td></td>
<td>Inharmonics</td>
<td>THD, harmonic spectrum</td>
<td>ASDs, nonlinear loads</td>
<td>Acoustic noise in power equipment</td>
</tr>
<tr>
<td></td>
<td>Notching</td>
<td>THD, harmonic spectrum</td>
<td>Power electronic converters</td>
<td>Damage to capacitive components</td>
</tr>
<tr>
<td></td>
<td>Noise</td>
<td>THD, harmonic spectrum</td>
<td>Arc furnaces, arc lamps, power converters</td>
<td>Capacitor-overloading, disturbances to appliances</td>
</tr>
<tr>
<td>Voltage flicker</td>
<td>Frequency of occurrence</td>
<td></td>
<td>Arc furnaces, arc lamps</td>
<td>Human health, irritation, headache, migraine</td>
</tr>
<tr>
<td>Voltage fluctuations</td>
<td>Modulating frequency</td>
<td></td>
<td>Load changes</td>
<td>Protection malfunction, light intensity changes</td>
</tr>
<tr>
<td>Power frequency</td>
<td></td>
<td></td>
<td>Faults, disturbances in isolated customer-owned systems and islanding operations</td>
<td>Damage to generator and turbine shafts</td>
</tr>
</tbody>
</table>
1.6 Classification of Mitigation Techniques for Power Quality Problems

In view of increased problems due to power quality in terms of financial loss, loss of production, wastage of raw material, and so on, a wide variety of mitigation techniques for improving the power quality have evolved in the past quarter century. These include passive components such as capacitors, reactors, custom power devices, a series of power filters, improved power quality AC–DC converters, and matrix converters.

However, the power quality problems may not be because of harmonics in many situations such as in distribution systems where problems of poor voltage regulation, low power factor, load unbalancing, excessive neutral current, and so on are observed. Some of these power quality problems such as poor power factor because of reactive power requirements may be mitigated using lossless passive elements such as capacitors and reactors. Moreover, the custom power devices such as DSTATCOMs, DVRs, and UPQCs are extensively used for mitigating the current, voltage, or both types of power quality problems.

In the presence of harmonics in addition to other power quality problems, a series of power filters of various types such as active, passive, and hybrid in shunt, series, or a combination of both configurations in single-phase two-wire, three-phase three-wire, and three-phase four-wire systems are used externally as retrofit solutions for mitigating power quality problems through compensation of nonlinear loads or voltage-based power quality problems in the AC mains. Since there are a large number of circuits of filters, the best configuration of the filter is decided depending upon the nature of loads such voltage-fed loads, current-fed loads, or a combination of both to mitigate their problems.

Power quality improvement techniques used in newly designed and developed equipment are based on the modification of the input stage of these systems with PFC converters, also known as IPQCs, multipulse AC–DC converters, matrix converters for AC–DC or AC–AC conversion, and so on, which inherently mitigate some of the power quality problems in them and in the supply system by drawing clean power from the utility. There are a large number of circuits of the converters of boost, buck, buck–boost, multilevel, and multipulse types for unidirectional and bidirectional power flow with and without isolation in single-phase and three-phase supply systems to suit very specific applications. These are used as front-end converters in the input stage as a part of the total equipment and in many situations they make these equipment immune to power quality problems in the supply system.

1.7 Literature and Resource Material on Power Quality

Power quality has become an important area of specialization in engineering. Many technical institutions, industries, and R&D organizations are offering regular and short-term courses on power quality and many of them have developed laboratories for research and teaching the power quality. There are a number of texts, standards, and patents relating to power quality and many journals, magazines, and conferences, among others, are publishing a number of research publications and case studies on power quality. Some of the journals, magazines, and conferences dealing with power quality are as follows:

IEEE Transactions on Aerospace and Systems
IEEE Transactions on Energy Conversion
IEEE Transactions on Industrial Electronics
IEEE Transactions on Industry Applications
IEEE Transactions on Industrial Informatics
IEEE Transactions on Magnetics
IEEE Transactions on Power Delivery
IEEE Transactions on Power Electronics
IEEE Transactions on Power Systems
IEEE Transactions on Smart Grid
IEEE Transactions on Sustainable Energy
IEEE Industry Applications Magazine
IEE/IET Proceedings on Electric Power Applications (EPA)
1.8 Summary

Recently, power quality has become an important subject and area of research because of its increasing awareness and impacts on the consumers, manufacturers, and utilities. There are a number of economic and reliability issues for satisfactory operation of electrical equipment. As power quality problems are increasing manifold due to the use of solid-state controllers, which cannot be dispensed due to many financial benefits, energy conservation, and other production benefits, the research and development in mitigation techniques for power quality problems is also becoming relevant and important to limit the pollution of the supply system. In such a situation, it is quite important to study the causes, effects, and mitigation techniques for power quality problems.
1.9 Review Questions

1. What is power quality?
2. What are the power quality problems in AC systems?
3. Why is power quality important?
4. What are the causes of power quality problems?
5. What are the effects of power quality problems?
6. What is a nonlinear load?
7. What is voltage sag (dip)?
8. What is voltage swell?
9. What are the harmonics?
10. What are the interharmonics?
11. What are the subharmonics?
12. What is the role of a shunt passive power filter?
13. What is the role of a series passive power filter?
14. What is an active power filter?
15. What is the role of a shunt active power filter?
16. What is the role of a series active power filter?
17. What is the role of a DSTATCOM?
18. What is the role of a DVR?
19. What is the role of a UPQC?
20. What is a PFC?
21. What is an IPQC?
22. Why is the excessive neutral current present in a three-phase four-wire system?
23. How can the excessive neutral current be eliminated?
24. Which are the standards for harmonic current limits?
25. What are the permissible limits on harmonic current?

References

2

Power Quality Standards and Monitoring

2.1 Introduction

There has been exponentially growing interest in power quality (PQ) in the past quarter century, which may be witnessed by the published literature in terms of research publications, texts, standards, patents, and so on. Some of the main reasons for this have been enhanced sensitivity of equipment, awareness of consumers, increased cost of electricity globally, increased use of solid-state controllers in energy-intensive equipment with the aim of energy conservation, power loss reduction, better utilization of utility assets, environmental pollution such as interference to telecommunication systems, malfunction of protection systems, and so on.

The power quality problems affect the customers in a number of ways such as economic penalty in terms of power loss, equipment failure, mal-operation, interruption in the process, and loss of production. In view of these facts, various terms and definitions are used to quantify the power quality problems in terms of different performance indices. Moreover, a number of standards have been developed by various organizations and institutes that are enforced on the customers, manufacturers, and utilities to maintain an acceptable level of power quality. Apart from these factors, various techniques and instruments are developed to study and monitor the level of power quality pollution and their causes. Many industries are developing a number of instruments, recorders, and analyzers to measure, record, and analyze the data at the site or in the research laboratories. In view of these increasing issues of power quality and awareness of power quality, it is considered relevant to introduce various terminologies, definitions, standards, and monitoring systems to quantify and assess the threshold level of power quality.

This chapter deals with the state of the art on power quality standards and monitoring, power quality terminologies, power quality definitions, power quality standards, power quality monitoring, monitoring equipment, summary, numerical examples, review questions, numerical and computer simulation-based problems, and references.

2.2 State of the Art on Power Quality Standards and Monitoring

There have been power quality problems and issues since the inception of electric power. However, the terminology of power quality does not date back to the early days and it has been identified by various other names. In the past few decades, it has become a very common terminology and widely known as power quality. Similarly, several standards have been developed, modified, recommended, and enforced depending upon the evolution of technology to maintain and quantify the level of power quality. At present, there is a long list of standards on various aspects of power quality, such as permissible level of
deviations, mitigation, and monitoring. Some of them are given here; however, new standards are continuously being developed, with modifications in the existing ones on various aspects such as limits, monitoring, and mitigation devices.

Several standards such as IEEE 519-1992, IEC 61000, and many others in different countries have been developed on the permissible limits in the levels of deviations and distortions in various electrical quantities such as voltage, current, and power factor. Moreover, there are several standards on the level of power quality in specific equipment such as lighting and variable-frequency drives in many countries. Table 2.1 shows a list of some currently available standards on various aspects of power quality.

### 2.3 Power Quality Terminologies

Since the power quality issues, awareness, and mitigation techniques are reported to a level of concern, various terminologies are defined to quantify power quality problems.

For reference, see the following terms and definitions, which are defined in detail in IEEE Standards [24]:

- **Flicker**: Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time.
- **Fundamental (component)**: The component of order 1 (e.g., 50 Hz, 60 Hz) of the Fourier series of a periodic quantity.
- **Imbalance (voltage or current)**: The ratio of the negative-sequence component to the positive-sequence component, usually expressed as a percentage. Syn: unbalance (voltage or current).
- **Impulsive transient**: A sudden non-power frequency change in the steady-state condition of voltage or current that is unidirectional in polarity (primarily either positive or negative).
- **Instantaneous**: When used to quantify the duration of a short-duration root-mean-square (rms) variation as a modifier, it refers to a time range from 0.5 to 30 cycles of the power frequency.
- **Interharmonic (component)**: A frequency component of a periodic quantity that is not an integer multiple of the frequency at which the supply system is operating (e.g., 50 Hz, 60 Hz).
- **Long-duration rms variation**: A variation of the rms value of the voltage or current from the nominal value for a time greater than 1 min. The term is usually further described using a modifier indicating the magnitude of a voltage variation (e.g., undervoltage, overvoltage, and voltage interruption).
- **Momentary interruption**: A type of short-duration rms voltage variation where a complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time period between 0.5 cycle and 3 s.

<table>
<thead>
<tr>
<th>Standards</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE Standard 1159-1995</td>
<td>Recommended Practice for Monitoring Electric Power Quality</td>
</tr>
<tr>
<td>IEEE Standard 1100-1999</td>
<td>Recommended Practice for Powering and Grounding Sensitive Electronic Equipment</td>
</tr>
<tr>
<td>IEEE Standard 1366-2012</td>
<td>Electric Power Distribution Reliability Indices</td>
</tr>
<tr>
<td>IEC 61000-2-2</td>
<td>Compatibility Levels for Low-Frequency Conducted Disturbances and Signaling in Public Supply Systems</td>
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<tr>
<td>IEC 61000-2-4</td>
<td>Compatibility Levels in Industrial Plants for Low-Frequency Conducted Disturbances</td>
</tr>
<tr>
<td>IEC 61000-3-2</td>
<td>Limits for Harmonic Current Emissions (Equipment Input Current Up to and Including 16 A Per Phase)</td>
</tr>
<tr>
<td>IEC 61000-4-15</td>
<td>Flicker Meter – Functional and Design Specifications</td>
</tr>
<tr>
<td>EN 50160</td>
<td>Voltage Characteristics of Public Distribution Systems</td>
</tr>
</tbody>
</table>
• **Root-mean-square variation**: A term often used to express a variation in the rms value of a voltage or current measurement from the nominal value. See sag, swell, momentary interruption, temporary interruption, sustained interruption, undervoltage, and overvoltage.

• **Short-duration rms variation**: A variation of the rms value of the voltage or current from the nominal value for a time greater than 0.5 cycle of the power frequency but less than or equal to 1 min. When the rms variation is voltage, it can be further described using a modifier indicating the magnitude of a voltage variation (e.g., sag, swell, and interruption) and possibly a modifier indicating the duration of the variation (e.g., instantaneous, momentary, and temporary).

• **Sustained interruption**: A type of long-duration rms voltage variation where the complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time greater than 1 min.

• **Temporary interruption**: A type of short-duration rms variation where the complete loss of voltage (<0.1 pu) on one or more phase conductors is for a time period between 3 s and 1 min.

• **Voltage change**: A variation of the rms or peak value of a voltage between two consecutive levels sustained for definite but unspecified durations.

• **Voltage fluctuation**: A series of voltage changes or a cyclic variation of the voltage envelope.

• **Voltage interruption**: The disappearance of the supply voltage on one or more phases. It is usually qualified by an additional term indicating the duration of the interruption (e.g., momentary, temporary, and sustained).

• **Waveform distortion**: A steady-state deviation from an ideal sine wave of power frequency principally characterized by the spectral content of the deviation.

For the purposes of standardization, the following additional terms and definitions are also used [24]:

• **Accuracy**: The quality of freedom from mistake or error, that is, of conformity to truth or to a rule (as in instrumentation and measurement). The accuracy of an indicated or recorded value is expressed by the ratio of the error of the indicated value to the true value. It is usually expressed in percent. See accuracy rating of an instrument (as indicated or recorded value).

• **Calibration**: The adjustment of a device to have the designed operating characteristics, and the subsequent marking of the positions of the adjusting means, or the making of adjustments necessary to bring operating characteristics into substantial agreement with standardized scales or marking. Comparison of the indication of the instrument under test, or registration of the meter under test, with an appropriate standard (as in metering).

• **Common-mode voltage**: The voltage that, at a given location, appears equally and in phase from each signal conductor to ground.

• **Coupling**: The association of two or more circuits or systems in such a way that power or signal information may be transferred from one system or circuit to another.

• **Current transformer (CT)**: An instrument transformer designed for use in the measurement or control of current (as in metering).

• **Dropout**: A loss of equipment operation (discrete data signals) due to noise, voltage sags, or interruption.

• **Electromagnetic compatibility (EMC)**: A measure of equipment tolerance to external electromagnetic fields. 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.

• **Electromagnetic disturbance**: An electromagnetic phenomenon that may be superimposed on a wanted signal. Any electromagnetic phenomenon that may degrade the performance of a device, a piece of equipment, or a system.

• **Equipment grounding conductor**: The conductor used to connect the noncurrent-carrying parts of conduits, raceways, and equipment enclosures to the grounding electrode at the service equipment (main panel) or secondary of a separately derived system.

• **Failure mode**: The manner in which failure occurs; generally categorized as electrical, mechanical, thermal, and contamination.
• **Frequency deviation**: An increase or decrease in the power frequency from the nominal value. The duration of a frequency deviation can be from several cycles to several hours.

• **Ground**: A conducting connection, whether intentional or accidental, by which an electric circuit or equipment is connected to the earth, or to some conducting body of relatively large extent that serves in place of the earth. Grounds are used for establishing and maintaining the potential of the earth (or of the conducting body) or approximately that potential, on conductors connected to it, and for conducting ground currents to and from earth (or the conducting body).

• **Ground loop**: A potentially detrimental loop formed when two or more points in an electrical system that are nominally at ground potential are connected by a conducting path such that either or both points are not at the same ground potential.

• **Harmonic**: A sinusoidal component of a periodic wave or quantity having a frequency that is an integral multiple of the fundamental frequency. For example, a component having a frequency twice the fundamental frequency is called a second harmonic.

• **Harmonic components**: The components of the harmonic content expressed in terms of the order and rms values of the Fourier series terms describing the periodic function.

• **Harmonic content**: The function obtained by subtracting the DC and fundamental components from a nonsinusoidal periodic function. The deviation from the sinusoidal form, expressed in terms of the order and magnitude of the Fourier series terms describing the wave. Distortion of a sinusoidal waveform characterized by indication of the magnitude and order of the Fourier series terms describing the wave.

• **Immunity (to a disturbance)**: The ability of a device, equipment, or system to perform without degradation in the presence of an electromagnetic disturbance.

• **Impulse**: A pulse that begins and ends within a time so short that it may be regarded mathematically as infinitesimal, although the area remains finite. An impulse is a surge of unidirectional polarity.

• **Isolated equipment ground**: An isolated equipment grounding conductor run in the same conduit or raceway as the supply conductors. This conductor may be insulated from the metallic raceway and all ground points throughout its length. It originates at an isolated ground-type receptacle or equipment input terminal block and terminates at the point where neutral and ground are bonded at the power source.

• **Isolation**: Separation of one section of a system from undesired influences of other sections.

• **Maximum demand**: The largest of a particular type of demand occurring within a specified period.

• **Momentary**: When used as a modifier to quantify the duration of a short-duration variation, it refers to a time range from 30 cycles to 3 s.

• **Momentary interruption**: A type of short-duration variation. The complete loss of voltage (<0.1 pu) on one or more phase conductors for a time period between 0.5 cycle and 3 s.

• **Noise**: Electrical noise is unwanted electrical signals that produce undesirable effects in the circuits of the control systems in which they occur.

• **Nominal voltage**: A nominal value assigned to a circuit or system for the purpose of conveniently designating its voltage class (as 208 V/120 V, 480 V/277 V, 600 V).

• **Nonlinear load**: A load that draws a nonsinusoidal current wave when supplied by a sinusoidal voltage source.

• **Normal-mode voltage**: The voltage that appears differentially between two signal wires and that acts on the circuit in the same manner as the desired signal.

• **Notch**: A switching (or other) disturbance of the normal power voltage waveform, lasting less than a half cycle, which is initially of opposite polarity to the waveform and is thus subtracted from the normal waveform in terms of the peak value of the disturbance voltage. This includes complete loss of voltage for up to a half cycle.

• **Oscillatory transient**: A sudden, non-power frequency change in the steady-state condition of voltage or current that includes either positive or negative polarity value.

• **Overvoltage**: When used to describe a specific type of long-duration variation, it refers to a measured voltage having a value greater than the nominal voltage for a time greater than 1 min. The typical values are 1.1–1.2 pu.