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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

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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 1.1 Power quality problems: causes and effects [15,23]

Problems	Category	Categorization	Causes	Effects
Transients	Impulsive	Peak, rise time, and duration	Lightning strikes, transformer energization, capacitor switching	Power system resonance
	Oscillatory	Peak magnitude and frequency components	Line, capacitor, or load switching	System resonance
Short-duration voltage variation	Sag	Magnitude, duration	Motor starting, single line to ground faults	Protection malfunction, loss of production
	Swell	Magnitude, duration	Capacitor switching, large load switching, faults	Protection malfunction, stress on computers and home appliances
	Interruption	Duration	Temporary faults	Loss of production, malfunction of fire alarms
Long-duration voltage variation	Sustained interruption	Duration	Faults	Loss of production
	Undervoltage	Magnitude, duration	Switching on loads, capacitor de-energization	Increased losses, heating
	Overvoltage	Magnitude, duration	Switching off loads, capacitor energization	Damage to household appliances
Voltage imbalance		Symmetrical components	Single-phase load, single-phasing	Heating of motors
Waveform distortion	DC offset	Volts, amperes	Geomagnetic disturbance, rectification	Saturation in transformers
	Harmonics	THD, harmonic spectrum	ASDs, nonlinear loads	Increased losses, poor power factor
	Interharmonics	THD, harmonic spectrum	ASDs, nonlinear loads	Acoustic noise in power equipment
	Notching	THD, harmonic spectrum	Power electronic converters	Damage to capacitive components
	Noise	THD, harmonic spectrum	Arc furnaces, arc lamps, power converters	Capacitor overloading, disturbances to appliances
Voltage flicker		Frequency of occurrence, modulating frequency	Arc furnaces, arc lamps	Human health, irritation, headache, migraine
Voltage fluctuations		Intermittent	Load changes	Protection malfunction, light intensity changes
Power frequency variations			Faults, disturbances in isolated customer-owned systems and islanding operations	Damage to generator and turbine shafts

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)

IEE/IET Proceedings on Generation, Transmission and Distribution (GTD)
IET Power Electronics (PE)
IET Renewable Power Generation (RPG)
Electrical Engineering in Japan
Electric Power Systems Research
International Journal of Electrical Engineering Education
International Journal of Electric Power Components and Systems (EPCS)
International Journal of Electrical Power & Energy Systems (EPES)
European Transactions on Electrical Power Engineering (ETEP)
European Journal of Power Electronics (EPE)
International Journal of Emerging Electric Power Systems
Journal of Power Electronics (JPE)
International Journal of Power Electronics
International Journal of Power Electronics and Drive Systems (IJPEDS)
International Journal of Power Electronics and Systems
International Journal of Energy Technology and Policy
International Journal of Global Energy Issues (IJGEI)
International Journal of Power System and Power Electronics Engineering (IJPSPEE)
International Journal of Power Electronics and Energy (IJPEE)
IEEE Applied Power Electronics Conference (APEC)
IEEE Energy Conversion Congress and Exposition (IEEE-ECCE)
IEEE International Telecommunications Energy Conference (IEEE-INTELEC)
European Power Electronics Conference (EPEC)
IEEE Industrial Electronics Conference (IECON)
IEEE International Symposium on Industrial Electronics (ISIE)
IEEE Industry Applications Society (IAS) Annual Meeting
IEEE International Conference on Power Electronics and Electric Drives (PEDS)
IEEE International Conference on Power Electronics, Drives and Energy Systems for Industrial Growth (PEDES)
IEEE Intersociety Energy Conversion Engineering Conference (IECEC)
IEEE International Power Electronics Specialist Conference (PESC)
IEEE Canadian Electrical and Computer Engineering Conference (CECEC)
IEEE International Electric Machines and Drives Conference (IEMDC)
International Power Electronics Conference (IPEC)
International Power Electronics Congress (CIEP)
IEEE Power Quality Conference
International Conference on Electrical Machines (ICEM)
Power Conversion Intelligent Motion (PCIM)
IEEE India International Power Electronics Conference (IICPE)
National Power Electronics Conference (NPEC)

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?

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