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Nandikotkur Road, Venkayapalli, Kurnool – 518452

Department of Electrical and Electronics Engineering

Bridge Course
On
Power Quality

1. INTRODUCTION:

The term power quality embraces all the aspects associated with amplitude, phase and frequency of voltage and current waveforms existing in a power circuit. Poor power quality may occur due to transient conditions in the power circuit or from the installation of non-linear loads. There is an increasing use of sensitive loads, such as computers, industrial drives, communications and medical equipment. Nowadays, power quality is a more complex problem than in the past because the new loads are not only sensitive to power quality, but also responsible for adversely affecting the quality of power supply. Although, the distribution power systems may have an impact on the quality of power, it becomes significantly worse at the points where the loads are connected to the distribution grid. A single customer may cause significant reductions in power quality for many other customers. Understanding power quality issues is a good starting point for solving any power quality problem. The power quality terminology and definitions are introduced in detail by Roger and Dugan et al (2003) Sankara et al (2002) and Arindam Ghosh et al (2002). A particularly useful overview of power quality terminology with references to standard documents and other valuable sources is given in IEEE and IEC. Power quality problems and their impacts are also widely described. Following are the core terms and definitions that are used in association with power quality:

- Voltage sag is a decrease in RMS voltage at the power frequency for durations from 0.5 cycles to one minute.
- Voltage swells – An increase in supply voltage beyond the rated value for a duration of 0.5 cycles to one minute.
- Interruption – Loss of supply voltage in one or more phases for one minute or more than one minute.
- Transients – voltage disturbances shorter than sags or swells, which are caused by sudden changes in the power systems.
- Voltage unbalance –The voltages of a three-phase voltage source are not identical in magnitude or the phase differences between them are not 120 electrical degrees.
- Harmonics – Steady-state deviation in the voltage or current waveform from an ideal sine wave, which are sinusoidal voltages or currents having frequencies that are whole multiples of the frequency at which the supply system is designed to operate (50 Hz).
- Long duration voltage interruption – Complete loss of supply voltage in the RMS supply voltage at fundamental frequency for period exceeding one minute.

2. POWER QUALITY PROBLEMS AND THEIR IMPACTS

The power quality issue is defined as an occurrence manifested in voltage, current and frequency deviation. This results in the failure of end-user equipment. Commercial customers have become more particular in their demand for the quality of power they purchase. Variations in voltage can actually damage and disrupt sensitive electronics, such as computers and microprocessors. As the modern society relies on high tech-processes, power quality has become even more critical. Power quality is influenced among other factors by utility operations, customer load types, and equipment designs. Distribution utilities and their customers, along with their engineering equipment manufacturers and vendors, generate, propagate, and receive power quality problems.

2.1 **Power Quality Standards:**

Power quality improvement methods and solutions, which can be implemented independent of any standardization. However, proper standardization provides important guidelines for the implementation of the technical solutions. The power quality standards are mostly concerned with the following three areas:

- Defining the nominal environment
- Defining the terminology
- Limiting the number of power quality problems

The International Electro Technical Commission (IEC) and the Institute of Electrical and Electronics Engineers (IEEE) have proposed their sets of power quality standard. The highlights are given below:

- EN 50160 Voltage Characteristics of Public Distribution Systems
- Standard 519-1992, IEEE Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems.

Proper standardization has to solve the problem of power quality disturbances adequately. Various power quality standards as listed in Table 1 and 2.

Table .1 Current harmonics limits in distribution systems as for on IEEE standards 519-1992.

Bus voltage at PCC	Individual harmonic magnitude (%)	Total voltage distortion (THD in %)
<69 kV	3.0	5.0
69.001 – 161 kV	1.5	2.5
>161kV	1.0	1.5

Table .2 Power quality standards

Phenomena	Classification of power quality standards
Voltage sag/swell and interruption	IEEE 1159: 1995 IEC 61009-2-1: 1990
Harmonics	IEEE 519: 1992,
	IEC 61000-2-1: 1990,
	IEC 61000-4-7: 1991
Transients	IEC 61000-2-1: 1990, IEC 816: 1984
	IEEE 62.41: 1991, IEEE 1159: 1995
Voltage flicker	IEC 61000-4-15: 1997

3. IMPORTANCE OF POWER QUALITY

The increasing emphasis on overall power system efficiency has resulted in continued growth in the application of devices such as high-efficiency, adjustable-speed motor drives and shunt capacitors for power factor correction to reduce losses. This has resulted in an increase in the harmonic content of the power systems and is of great concern about the future impact on system capabilities.

Nowadays, the users of electrical power are quite aware of power quality issues. More and more customers are becoming better informed about such power quality issues as interruptions, sags and switching transients and thus the utilities are challenged by customers to improve the quality of the power delivered. Both electric utilities and end users of electric power are increasingly concerned about the quality of electric power. The increased interest in power quality is mainly a result of the following factors:

- Equipment has become more sensitive to voltage disturbances.
- Some equipment causes voltage disturbances.
- A growing need for standardization and performance criteria.
- In order to be competitive, utilities are forced to deliver a good product.

4. POWER QUALITY IMPROVEMENT TECHNIQUES AND SOLUTIONS

Power quality improvement techniques and solutions are also discussed. The problems can be viewed as the difference between the quality of power supplied and the quality of the power required for reliable operation of the load equipment. With reference to this viewpoint, power quality problems can be resolved in to one of the three ways, listed as follows:

- Reducing the power supply disturbances

- Improving the load equipment immunity to disturbances
- Inserting corrective equipment between the electrical supply and the sensitive loads.

Conventional mitigation techniques include adding filters at the point in power system where power quality problem occurs. Harmonic resonance problems are sometimes found with the use of passive capacitor banks. Using synchronous condenser, resonance problems are eliminated, but they are expensive and their operation and maintenance are more costly. Both capacitor banks and synchronous condenser have a slow response. Static VAR Compensation (SVC) generates a considerable amount of harmonics that may have to be filtered. Due to their high cost, the SVCs are not economical for small power users. Tap-switching and ferro resonant voltage regulators were the only devices to compensate for under voltages and over voltages. However, it was not possible to compensate for short duration sags because fast control devices were not available.

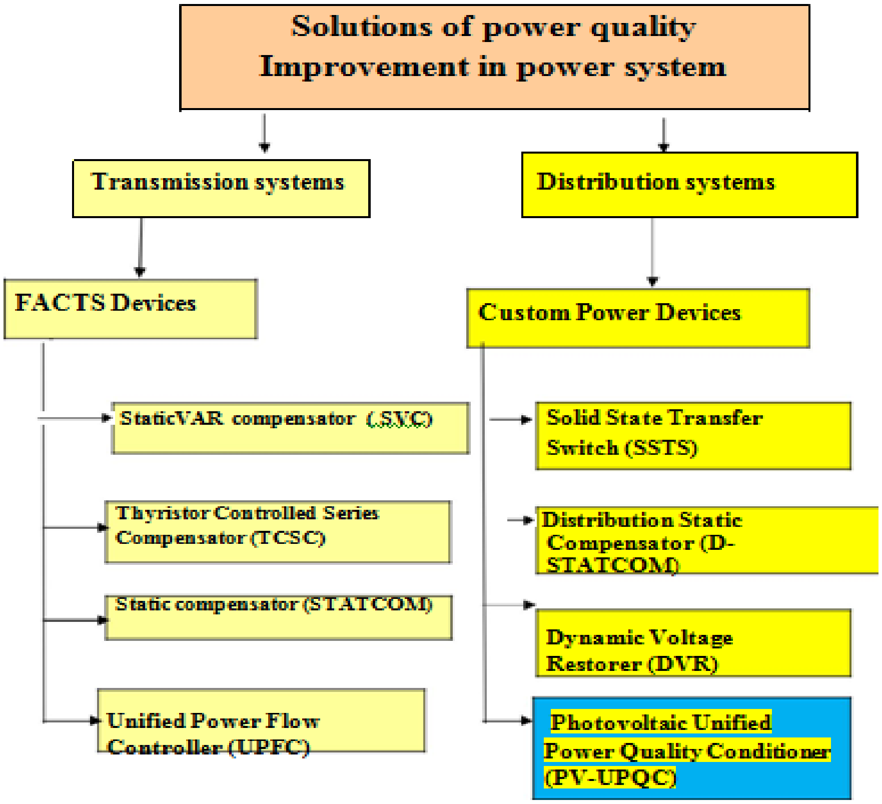

Fig.1: Hierarchy of power quality improvement techniques

It must be appreciated that the above discussed conventional techniques are not flexible enough. Therefore it is imperative that better and flexible correcting devices are used for power quality problems. The implementation of such devices has become possible due to advances in power electronics and availability of fast acting controllers. Power electronic controllers provide a flexible choice and better performance to improve the power quality problems.

These modern power electronics based systems are called custom power devices. There are many custom power devices and they are divided in to two groups. They are as follows.

- Network reconfiguring type

  Solid-State Transfer Switch (SSTS). These devices are much faster than their mechanical devices.
- Compensating types

The compensating devices either compensate a load and correct its power factor or improve the quality of the supply voltage. The hierarchy of all the feasible power quality solutions is shown in Fig.1.

5. OVERVIEW OF MAJOR CUSTOM POWER DEVICES

Custom Power embraces a family of power electronic devices which is applicable to distribution systems to provide power quality solutions. This technology has been made possible due to the widespread availability of cost effective high power semiconductor devices such as Gate-Turn-Off (GTO) thyristors and Insulated Gate Bipolar Transistors (IGBTs).

5.1 Network Reconfiguring Device - Solid State Transfer Switch (SSTS)

The SSTS provides a seamless transfer of electrical energy from a primary source to an alternate source without service interruption to even the most critical and sensitive loads. As a result, power quality problems become transparent to the critical or sensitive customer loads that the SSTS protects. Fig.2 depicts the Solid State Transfer Switch System.

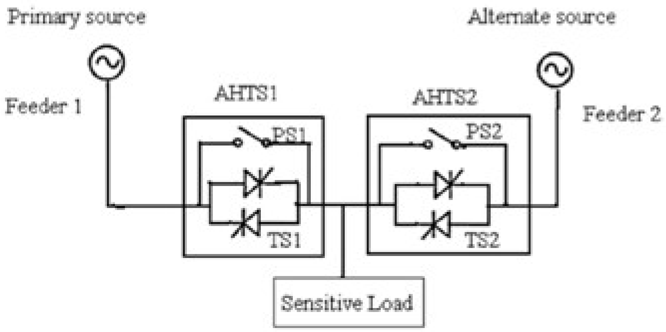

Fig.2: Solid State Transfer Switch System

During normal operation, line current is bypassed by the parallel switch. When the transfer operation is required, the PS1 is opened and TS1 is turned on, simultaneously. The opposite side Thyristor switch (TS2) begins to conduct, the current flows from alternate source to the load. The parallel switch (PS2) is closed and the current bypassed form primary source. The limitation of this system is that there is no compensation of sag and swell devices.

6. COMPENSATING TYPES

- Compensating type devices are as follows.
- Distribution Static Compensator (DSTATCOM) to compensate load reactive power and current harmonics.
- Dynamic Voltage Restorer (DVR) for supporting the load voltage.
- UPQC with PV which solves the power quality problems.

6.1 Distribution Static Compensator (DSTATCOM)

The primary aims of DSTATCOM are:

- Power factor correction
- Current harmonics filtering
- DC Load offset cancellation
- Load balancing

It can be used for voltage regulation at the distribution bus, being an active filtering device. It is connected in parallel with the PCC. DSTATCOM is often referred as a shunt active power filter. It consists of a voltage source PWM converter equipped with a DC capacitor and an interface inductor, as shown in Fig.3. The advantages of the voltage-source PWM converter are higher efficiency, lower cost and smaller physical size. The current-source PWM inverter cannot be used in multilevel or multi-step mode configurations to allow compensation in higher power ratings. The limitation of this system is that it provides only current harmonic compensation.

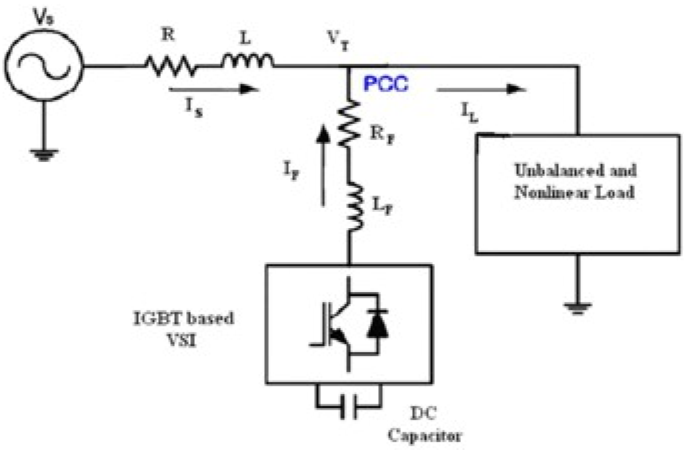

Fig.3: Block diagram of DSTATCOM system

6.2 Dynamic Voltage Restorer (DVR)

DVR structures, control techniques and rating requirements are developed by Arindam Ghosh. Fig.4 shows that DVR system is a series-connected custom power device, the aim of which is to protect sensitive loads from supply side disturbances except outages. The DVR can act as a series active filter, isolating the source from harmonics generated by loads.

An Alternative method for preventing the coupling transformer saturation is also in use. DVR coupling transformer can experience saturation during the transient period after voltage sag. For preventing this, usually, a rating of magnetic flux that is double that of the steady-state limit is chosen.

DVR structure also makes use of batteries for energy storage. In this case, the real power required for voltage sag compensation is drawn from the batteries connected across the dc link. The DVR cannot mitigate any interruptions, unless it is batteries supported. The batteries supported DVR injects current harmonics into the distribution network.

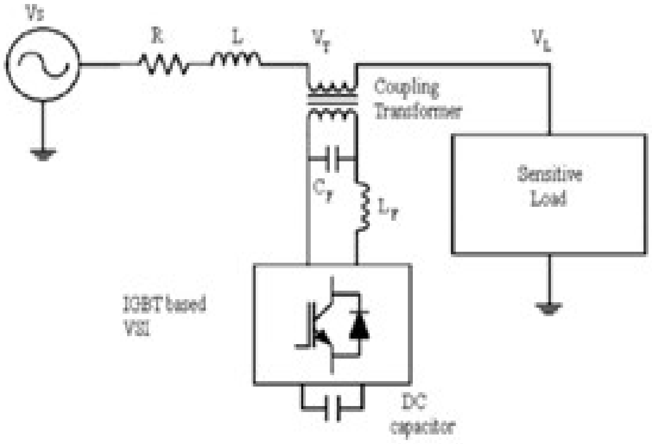

Fig.4: Block diagram of DVR system

The DVR coupling transformer performs two important functions like voltage boost and electrical isolation. However, it increases the DVR costs, requires considerable space and contributes to DVR losses. As mentioned above, the transformer can be driven into saturation in some conditions. The DVR acts as an additional energy source. Introducing it into the system has effects seen both by system and customer. The limitation of this system is that it compensates voltage harmonics and sag only.

The performance of UPQC for mitigating the effect of supply voltage sag at the load or at the PCC in a distributed network will also be studied in the course. This method prevents the propagation of the load current harmonics to the utility and improves the power quality. This method prevents the propagation of the load current harmonics to the utility and improved the input power factor of the load. The drawback of this system is that there is no active power supply for compensation of voltage interruption.

8. POWER QUALITY BENCHMARKING AND MONITORING

Electric utilities throughout the world are embracing the concept of benchmarking service quality. Utilities realize that they must understand the levels of service quality provided throughout their distribution systems and determine if the levels provided are appropriate. This is certainly becoming more prevalent as more utilities contract with specific customers to provide a specified quality of service over some period of time. The typical steps in the power quality benchmarking process are

1. Select benchmarking metrics. The EPRI RBM project defined several performance indices for evaluating the electric service quality.
2. Collect power quality data. This involves the placement of power quality monitors on the system and characterization of the performance of the system. A variety of instruments and monitoring systems have been recently developed to assist with this labor-intensive process.
3. Select the benchmark. This could be based on past performance, a standard adopted by similar utilities, or a standard established by a professional or standards organization such as the IEEE, IEC, ANSI, or NEMA.

4. Determine target performance levels. These are targets that are appropriate and economically feasible. Target levels may be limited to specific customers or customer groups and may exceed the benchmark values.

The benchmarking process begins with selection of the metrics to be used for benchmarking and evaluating service quality. The metrics could simply be estimated from historical data such as average number of faults per mile of line and assuming the fault resulted in a certain number of sags and interruptions. However, electricity providers and consumers are increasingly interested in metrics that describe the actual performance for a given time period. The indices developed as part of the EPRI RBM project are calculated from data measured on the system by specialized instrumentation.

Electric utilities throughout the world are deploying power quality monitoring infrastructures that provide the data required for accurate benchmarking of the service quality provided to consumers. These are permanent monitoring systems due to the time needed to obtain accurate data and the importance of power quality to the end users where these systems are being installed. For most utilities and consumers, the most important power quality variation is the voltage sag due to short-circuit faults. Although these events are not necessarily the most frequent, they have a tremendous economic impact on end users. The process of benchmarking voltage sag levels generally requires 2 to 3 years of sampling. These data can then be quantified to relate voltage sag performance with standardized indices that are understandable by both utilities and customers.

Finally, after the appropriate data have been acquired, the service provider must determine what levels of quality are appropriate and economically feasible. Increasingly, utilities are making these decisions in conjunction with individual customers or regulatory agencies.

The economic law of diminishing returns applies to increasing the quality of electricity as it applies to most quality assurance programs. Electric utilities note that nearly any level of service quality can be achieved through alternate feeders, standby generators, UPS systems, energy storage, etc. However, at some point the costs cannot be economically justified and must be balanced with the needs of end users and the value of service to them.

IEEE Standard 1366-1998 was established to define the benchmarking metrics for this area of power quality. The metrics are defined in terms of system average or customer average indices regarding such things as the number of interruptions and the duration of interruption (SAIDI, SAIFI, etc.).

Interest in expanding the service quality benchmarking into areas other than traditional reliability increased markedly in the late 1980s. This was largely prompted by experiences with power electronic loads that produced significant harmonic currents and were much more sensitive to voltage sags than previous generations of electromechanical loads. In 1989, the EPRI initiated the EPRI Distribution Power Quality (DPQ) Project, RP 3098-1, to collect power quality data for distribution systems across the United States. Monitors were placed at nearly 300 locations on 100 distribution feeders, and data were collected for 27 months.

The DPQ database contains over 30 gigabytes of power quality data and has served as the basis for standards efforts and many studies. The results were made available to EPRI member utilities in 1996.

Upon completion of the DPQ project in 1995, it became apparent that there was no uniform way of benchmarking the performance of specific service quality measurements against these data. In 1996, the EPRI completed the RBM project, which provided the power quality indices to allow service quality to be defined in a consistent manner from one utility to another. The indices were patterned after the traditional reliability indices with which utility engineers had already become comfortable. Indices were defined for

1. Short-duration rms voltage variations. These are voltage sags, swells, and interruptions of less than 1 min.
2. Harmonic distortion.
3. Transient overvoltages. This category is largely capacitor-switching transients, but could also include lightning-induced transients.
4. Steady-state voltage variations such as voltage regulation and phase balance.

7. POWER QUALITY MONITORING DEVICES

The objectives for power quality monitoring program determine the methods of collecting data and the type of measurement equipment. Depending on the power quality problems such as harmonics, sag, swell, interruption, flicker equipments must have required features and the measurement must be done in a specific way.

Power quality monitoring includes classification and characterization of electrical disturbances, propagation of disturbances, and measurement campaigns, which is optimizing the number of monitoring points.

They include everything from very fast transient over voltages (microsecond time frame) to long-duration outages (hours or days time frame). Power quality problems also include steady-state phenomena, such as harmonic distortion, and intermittent phenomena, such as voltage flicker.

7.1. Types of Instruments

Although instruments have been developed that measure a wide variety of disturbances, a number of different instruments may be used, depending on the phenomena being investigated. Basic categories of instruments that may be applicable include

- Wiring and grounding test devices
- Multi meters
- Oscilloscopes
- Disturbance analyzers
- Harmonic analyzers and spectrum analyzers
- Combination disturbance and harmonic analyzers

- Flicker meters
- Energy monitors

Besides these instruments, which measure steady-state signals or disturbances on the power system directly, there are other instruments that can be used to help solve power quality problems by measuring ambient conditions:

1. Infrared meters can be very valuable in detecting loose connection sand overheating conductors. An annual procedure of checking the system in this manner can help prevent power quality problems due to arcing, bad connections, and overloaded conductors.

2. Noise problems related to electromagnetic radiation may require measurement of field strengths in the vicinity of affected equipment. Magnetic gauss meters are used to measure magnetic field strengths for inductive coupling concerns. Electric field meters can measuret he strength of electric fields for electrostatic coupling concerns.

3. Static electricity meters are special-purpose devices used to measure static electricity in the vicinity of sensitive equipment. Electrostatic discharge (ESD) can be an important cause of power quality problems in some types of electronic equipment.

Regardless of the type of instrumentation needed for a particular test, there are a number of important factors that should be considered when selecting the instrument. Some of the more important factors include

- Number of channels (voltage and/or current)
- Temperature specifications of the instrument
- Ruggedness of the instrument
- Input voltage range (e.g., 0 to 600 V)
- Power requirements
- Ability to measure three-phase voltages
- Input isolation (isolation between input channels and from each input to ground)
- Ability to measure currents
- Housing of the instrument (portable, rack-mount, etc.)
- Ease of use (user interface, graphics capability, etc.)
- Documentation
- Communication capability (modem, network interface)
- Analysis software

The flexibility (comprehensiveness) of the instrument is also important. The more functions that can be performed with a single instrument, the fewer the number of instruments required.

7.1.1 Wiring and Grounding Testers:

Many power quality problems reported by end users are caused by problems with wiring and/or grounding within the facility. These problems can be identified by visual inspection of wiring, connections, and panel boxes and also with special test devices for detecting wiring and grounding problems.

- Important capabilities for a wiring and grounding test device include
- Detection of isolated ground shorts and neutral-ground bonds
- Ground impedance and neutral impedance measurement or indication
- Detection of open grounds, open neutrals, or open hot wires
- Detection of hot/neutral reversals or neutral/ground reversals

Three-phase wiring testers should also test for phase rotation and phase-to-phase voltages. These test devices can be quite simple and provide an excellent initial test for circuit integrity.

7.1.2 Multi Meters:

After initial tests of wiring integrity, it may also be necessary to make quick checks of the voltage and/or current levels within a facility. Overloading of circuits, under voltage and overvoltage problems, and unbalances between circuits can be detected in this manner. These measurements just require a simple multi meter. Signals used to check for these include

- Phase-to-ground voltages
- Phase-to-neutral voltages
- Neutral-to-ground voltages
- Phase-to-phase voltages (three-phase system)
- Phase currents
- Neutral currents

The most important factor to consider when selecting and using a multimeter is the method of calculation used in the meter. All the commonly used meters are calibrated to give an rms indication for the measured signal. However, a number of different methods are used to calculate the rms value. The three most common methods are

1. Peak method. Assuming the signal to be a sinusoid, the meter reads the peak of the signal and divides the result by 1.414 (square root of 2) to obtain the rms.

2. Averaging method. The meter determines the average value of a rectified signal. For a clean sinusoidal signal (signal containing only one frequency), this average value is related to the rms value by a constant.

3. True rms. The rms value of a signal is a measure of the heating that will result if the voltage is impressed across a resistive load. One method of detecting the true rms value is to actually use a thermal detector to measure a heating value. More modern digital meters use a digital calculation of the rms value by squaring the signal on a sample by-sample basis, averaging over the period, and then

taking the square root of the result. These different methods all give the same result for a clean, sinusoidal signal but can give significantly different answers for distorted signals.

7.1.3 Disturbance Analyzers

Disturbance analyzers and disturbance monitors form a category of instruments that have been developed specifically for power quality measurements. They typically can measure a wide variety of system disturbances from very short duration transient voltages to long-duration outages or under voltages. Thresholds can be set and the instruments left unattended to record disturbances over a period of time. The information is most commonly recorded on a paper tape, but many devices have attachments so that it can be recorded on disk as well.

There are basically two categories of these devices:

1. Conventional analyzers that summarize events with specific information such as overvoltage and under voltage magnitudes, sags and surge magnitude and duration, transient magnitude and duration, etc.
2. Graphics-based analyzers that save and print the actual waveform along with the descriptive information which would be generated by one of the conventional analyzers

It is often difficult to determine the characteristics of a disturbance or a transient from the summary information available from conventional disturbance analyzers. For instance, an oscillatory transient cannot be effectively described by a peak and duration. Therefore, it is almost imperative to have the waveform capture capability of a graphics-based disturbance analyzer for detailed analysis of a power quality problem. However, a simple conventional disturbance monitor can be valuable for initial checks at a problem location.

8. Conclusion

The increased use of non-linear loads has lead to reduction in the quality of power that reaches the end user. This may lead to damage or malfunctioning of sensitive customer equipment and loss of money. So there is a need for consumers to gain knowledge about the nature of power they receive and how to take steps accordingly so that equipment they use may give better performance. This course lays emphasis on the nature of various power quality issues and their effects on consumer equipment. Also power quality standards prescribed by organizations such as IEEE and IEC are mentioned so that power quality problems may be maintained within proper limits. Also this course deals with different solutions that can be implemented at customer end so that PQ problems can be eliminated. This course also provides information about the necessity about PQ benchmarking and monitoring processes. The principles of operation of devices available for PQ monitoring are also discussed.