Unit III
Power Quality Monitoring

Introduction

- ✓ Power quality monitoring is the process of gathering, analyzing, and interpreting raw measurement data into useful information.
- ✓ The process of gathering data is usually carried out by continuous measurement of voltage and current over an extended period.
- ✓ The process of analysis and interpretation has been traditionally performed manually, but recent advances in signal processing and artificial intelligence fields have made it possible to design and implement intelligent systems to automatically analyze and interpret raw data into useful information with minimum human intervention.
- ✓ Power quality monitoring programs are often driven by the demand for improving the system wide power quality performance
- ✓ Many industrial and commercial customers have equipment that is sensitive to power disturbances, and, therefore, it is more important to understand the quality of power,Hence many utility companies have implemented extensive power quality monitoring programs.

MONITORING CONSIDERATION

- ✓ The four common objectives of monitoring are follows:

1. Monitoring to characterize system performance

- ✓ A power producer may find this objective important if it has the need to understand its system performance and then match that system performance with the needs of customers.
- ✓ System characterization is a proactive approach to power quality monitoring. By understanding the normal power quality performance of a system, a provider can quickly identify problems and can offer information to its customers to help them match their sensitive equipment's characteristics

2. Monitoring to characterize specific problems:

- ✓ By performing short-term monitoring at specific customer sites or at difficult loads. This is a reactive mode of power quality monitoring, but it frequently identifies the cause of equipment incompatibility, which is the first step to a solution

3. Monitoring as part of an enhanced power quality service:

- ✓ Many power producers are currently considering additional services to offer customers. One of these services would be to offer differentiated levels of power quality to match the needs of specific customers.
- ✓ A provider and customer can together achieve this goal by modifying the power system or by installing equipment within the customer's premises.
- ✓ In either case, monitoring becomes essential to establish the benchmarks for the differentiated service and to verify that the utility achieves contracted levels of power quality.

4. Monitoring as part of predictive or just-in-time maintenance:

- ✓ Power quality data gathered over time can be analyzed to provide information relating to specific equipment performance.
- ✓ For example, a repetitive arcing fault from an underground cable may signify impending cable failure, or repetitive capacitor-switching restrikes may signify impending failure on the capacitor-switching device. Equipment maintenance can be quickly ordered to avoid catastrophic failure

- **The following are the important aspects of the power quality monitoring effort. They are**

5. Site survey :

- ✓ Site surveys are performed to evaluate concerns for power quality and equipment performance throughout a facility. The survey will include inspection of wiring and grounding concerns, equipment connections, and the voltage and current characteristics throughout the facility
- ✓ The initial site survey should be designed to obtain as much information as possible about the customer facility. This information is especially important when the monitoring objective is intended to address specific power quality problems. This information is summarized here.

  - Nature of the problems (data loss, nuisance trips, component failures, control system malfunctions, etc.)
  - Characteristics of the sensitive equipment experiencing problems (equipment design information or at least application guide information)
  - The times at which problems occur
  - Coincident problems or known operations (e.g., capacitor switching) that occur at the same time
  - Possible sources of power quality variations within the facility (motor starting, capacitor switching, power electronic equipment operation, arcing equipment, etc.)

- Existing power conditioning equipment being used
- Electrical system data (one-line diagrams, transformer sizes and impedances, load information, capacitor information, cable data, etc.)

6. Choosing monitoring locations

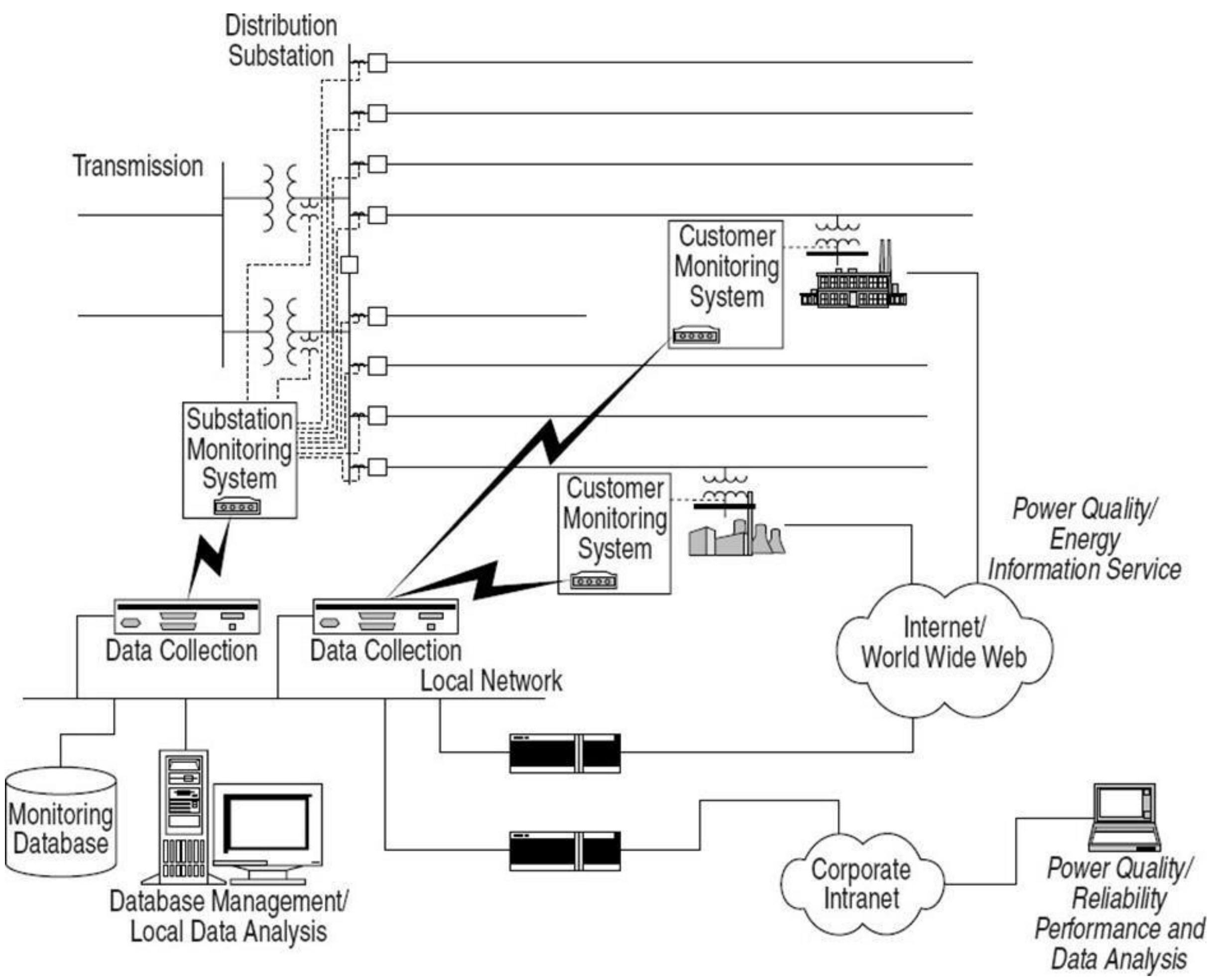
- ✓ It is very important that monitoring locations should be selected carefully. Based on the monitoring objectives.
- ✓ It is best to start monitoring as close as possible to the sensitive equipment being affected by Power quality variations. It is important that the monitor sees the same variations that the sensitive Equipment sees.
- ✓ High frequency transients, in particular, can be significantly different if there is Significant separation between the monitor and the affected equipment. Another important location is the main service entrance.
- ✓ All of the equipment can experience transients and voltage variations measured at this location in the facility. This is also the best indication of disturbances caused by the utility system.

7. Options for permanent power quality monitoring equipment

- ✓ The categories of instruments that can be incorporated permanently into overall monitoring system include the followings.
- ✓ By using permanent power quality monitoring equipment's we can become less careful about the duration of monitoring. Because monitoring equipment's will provide information as part of the system
- ✓ **Digital fault recorders (DFRs).** These may already be in place at many substations. DFR manufacturers do not design the devices specifically for power quality monitoring. However, a DFR will typically trigger on fault events and record the voltage and current waveforms that characterize the event. This makes them valuable for characterizing rms disturbances, such as voltage sags, during power system faults. DFRs also offer periodic waveform capture for calculating harmonic distortion levels.
- ✓ **Smart relays and other IEDs.** Many types of substation equipment may have the capability to be an intelligent electronic device (IED) with monitoring capability. Manufacturers of devices like relays and re closers that monitor the current anyway are adding on the capability to record disturbances and make the information available to an overall monitoring system controller. These devices can be located on the feeder circuits as well as at the substation.
- ✓ **Voltage recorders.** Power providers use a variety of voltage recorders to monitor steady- state voltage

variations on distribution systems. Typically, the voltage recorder provides a trend that gives the maximum, minimum, and average voltage within a specified sampling window. With this type of sampling, the recorder can characterize a voltage sag magnitude adequately.

- ✓ **In-plant power monitors.** It is now common for monitoring systems in industrial facilities to have some power quality capabilities. These monitors, particularly those located at the service entrance, can be used as part of a utility monitoring program. Capabilities usually include wave shape capture for evaluation of harmonic distortion levels, voltage profiles for steady-state rms variations, and triggered waveshape captures for voltage sag conditions.



8.Finding the source of a disturbance

The first step in identifying the source of a disturbance is to correlate the disturbance waveform with possible causes. Once a category for the cause has been determined (e.g., load switching, capacitor switching, remote fault condition, recloser operation), the identification becomes more straightforward. The following general guidelines can help:

- High-frequency voltage variations will be limited to locations close to the source of the disturbance. Low-voltage (600 V and below) wiring often damps out high-frequency components very quickly due to circuit resistance, so these frequency components will only appear when the monitor is located close to the source of the disturbance.
- Power interruptions close to the monitoring location will cause a very abrupt change in the voltage. Power interruptions remote from the monitoring location will result in a decaying voltage due to stored energy in rotating equipment and capacitors.
- The highest harmonic voltage distortion levels will occur close to capacitors that are causing resonance problems. In these cases, a single frequency will usually dominate the voltage harmonic spectrum.

POWER QUALITY MEASUREMENT EQUIPMENT

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.

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
- Multimeters
- 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, other instruments 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

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. Many problems canbe detected without the requirement for detailed monitoring using expensive instrumentation.

Multimeters:

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. This is very important because significant distortion levels are

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:

Conventional analyzers that summarize events with specific information such as overvoltage and undervoltage magnitudes, sags and surge magnitude and duration, transient magnitude and duration, etc.

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 a 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 (Fig. 5.2). However, a simple conventional disturbance monitor can be valuable for initial checks at a problem location.

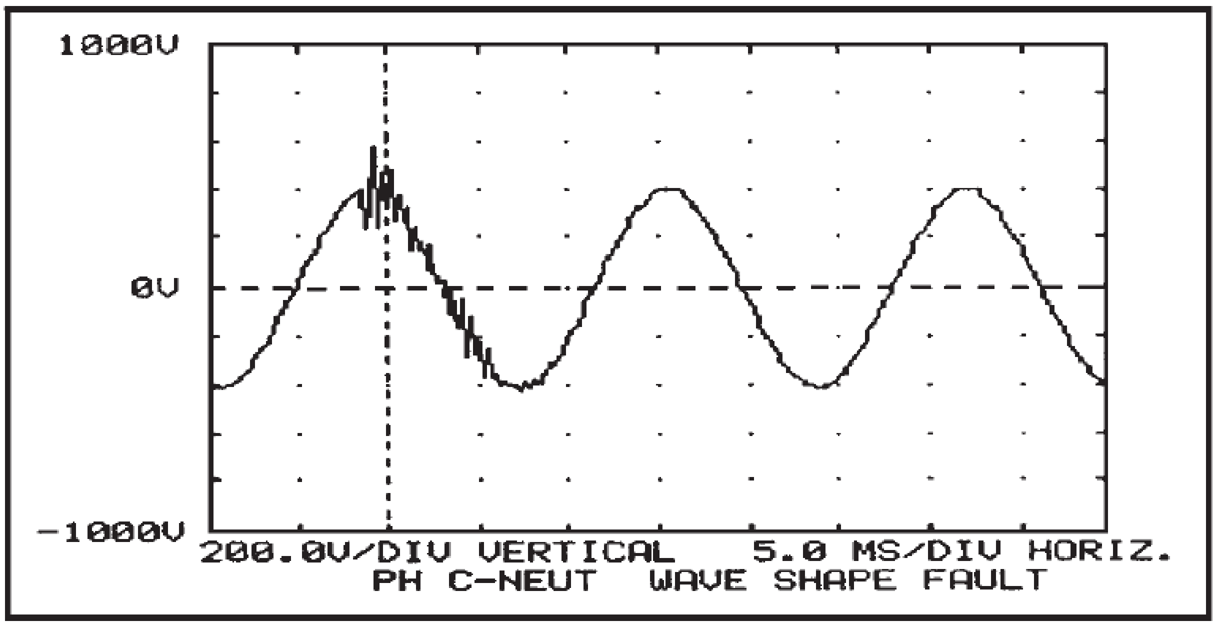


Figure 3.2 Graphics-based analyzer output.

Spectrum analyzers and harmonic analyzers

Harmonic analyzers have several capabilities. They capture harmonic waveforms and display them on a screen. They calculate the K factor to de rate transformers and the total harmonic distortion (THD) in percent of the fundamental. They also measure the corresponding frequency spectrum, i.e., the harmonic frequency associated with the current and voltage up to the fiftieth harmonic.

They display the harmonic frequency on a bar graph or as the signal's numerical values. Some measure single-phase current and voltage while others measure three-phase current and voltage. All of them measure the power factor (PF). The power factor provides a measurement of how much of the power is being used efficiently for useful work. Some can store data for a week or more for later transfer to a PC for analysis.

This makes them powerful tools in the analysis of harmonic power quality problems. Some of the more powerful analyzers have add-on modules that can be used for computing fast Fourier transform (FFT) calculations to determine the lower-order harmonics. However, any significant harmonic measurement requirements will demand an instrument that is designed for spectral analysis or harmonic analysis. Important capabilities for useful harmonic measurements include Capability to measure both voltage and current simultaneously so that harmonic power flow information can be obtained.

- Capability to measure both magnitude and phase angle of individual harmonic components (also needed for power flow calculations).
- Synchronization and a sampling rate fast enough to obtain accurate measurement of harmonic components up to at least the 37th harmonic (this requirement is a combination of a high sampling rate and a sampling interval based on the 60-Hz fundamental).
- Capability to characterize the statistical nature of harmonic distortion levels (harmonics levels change with changing load conditions and changing system conditions).

There are basically three categories of instruments to consider for harmonic analysis:

Simple meters. It may sometimes be necessary to make a quick check of harmonic levels at a problem location. A simple, portable meter for this purpose is ideal. There are now severalhand-held instruments of this type on the market. Each instrument has advantages and disadvantages in its operation and design. These devices generally use microprocessor-based circuitry to perform the necessary calculations to determine individual harmonics up to the 50th harmonic, as well as the rms, the THD, and the telephone influence factor (TIF). Some of these devices can calculate harmonic powers (magnitudes and angles) and can upload stored waveforms and calculated data to a personal computer.

General-purpose spectrum analyzers. Instruments in this category are designed to perform spectrum analysis on waveforms for a wide variety of applications. They are general signal analysis instruments. The advantage of these instruments is that they have very powerful capabilities for a reasonable price since they are designed for a broader market than just power system applications. The disadvantage is that they are not designedspecifically for sampling power frequency waveforms and, therefore, must be used carefully to assure accurate harmonic analysis. There are a wide variety of instruments in this category.

Special-purpose power system harmonic analyzers. Besides the general-purpose spectrum analyzers just described, there are also a number of instruments and devices that have been designed specifically for power system harmonic analysis. These are based on the FFT with sampling rates specifically designed for determining harmonic components in power signals. They can generally be left in the field and include communications capability for remote monitoring.

Flicker meters

Over the years, many different methods for measuring flicker have been developed. These methods range from using very simple rms meters with flicker curves to elaborate flicker meters that use exactly tuned filters and statistical analysis to evaluate the level of voltage flicker. This section discusses various methods available for measuring flicker.

Flicker standards. Although the United States does not currently have a standard for flicker measurement, there are IEEE standards that address flicker. IEEE Standards 141-19936 and 519-19927 both contain flicker curves that have been used as guides for utilities to evaluate the severity of flicker within their system. Both flicker curves, from Standards 141 and 519, are shown in Fig. 5.3. In other countries, a standard methodology for measuring flicker has been established. The IEC flicker meter is the standard for measuring flicker in Europe and other countries currently adopting IEC standards. The IEC method for flicker measurement, defined in IEC Standard 61000-4-158 (formerly IEC 868), is a very comprehensive approach to flicker measurement and is further described in “Flicker Measurement Techniques” below. More recently, the IEEE has been working toward adoption of the IEC flicker monitoring standards with an additional curve to account for the differences between 230-V and 120-V systems.

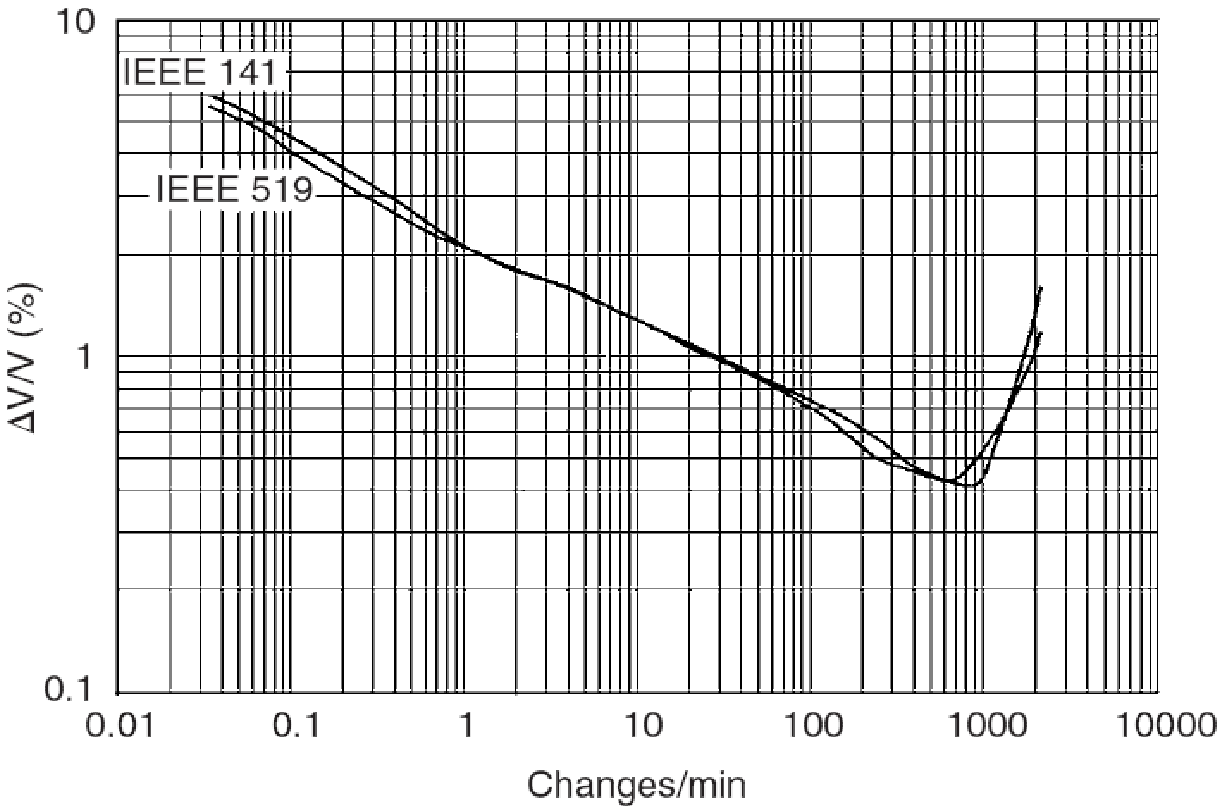


Figure 3.3 Flicker curves from IEEE Standards 141 and 519.

Flicker measurement techniques

RMS strip charts. Historically, flicker has been measured using rms meters, load duty cycle, and a flicker curve. If sudden rms voltage deviations occurred with specified frequencies exceeding values found in flicker curves, such as one shown in Fig. 5.3, the system was said to have experienced flicker. A sample graph of rms voltage variations is shown in Fig. 5.4 where large voltage deviations up to 9.0 V rms (_V/V _ ± 8.0 percent on a 120-V base) are found. Upon comparing this to the flicker curve in Fig. 5.3, the feeder would be experiencing flicker, regardless of the duty cycle of the load producing the flicker, because any sudden total change in voltage greater than 7.0 V rms results in objectionable flicker, regardless of the frequency. The advantage to such a method is that it is quite simple in nature and the rms data required are rather easy to acquire. The apparent disadvantage to such a method would be the lack of accuracy and inability to obtain the exact frequency content of the flicker.

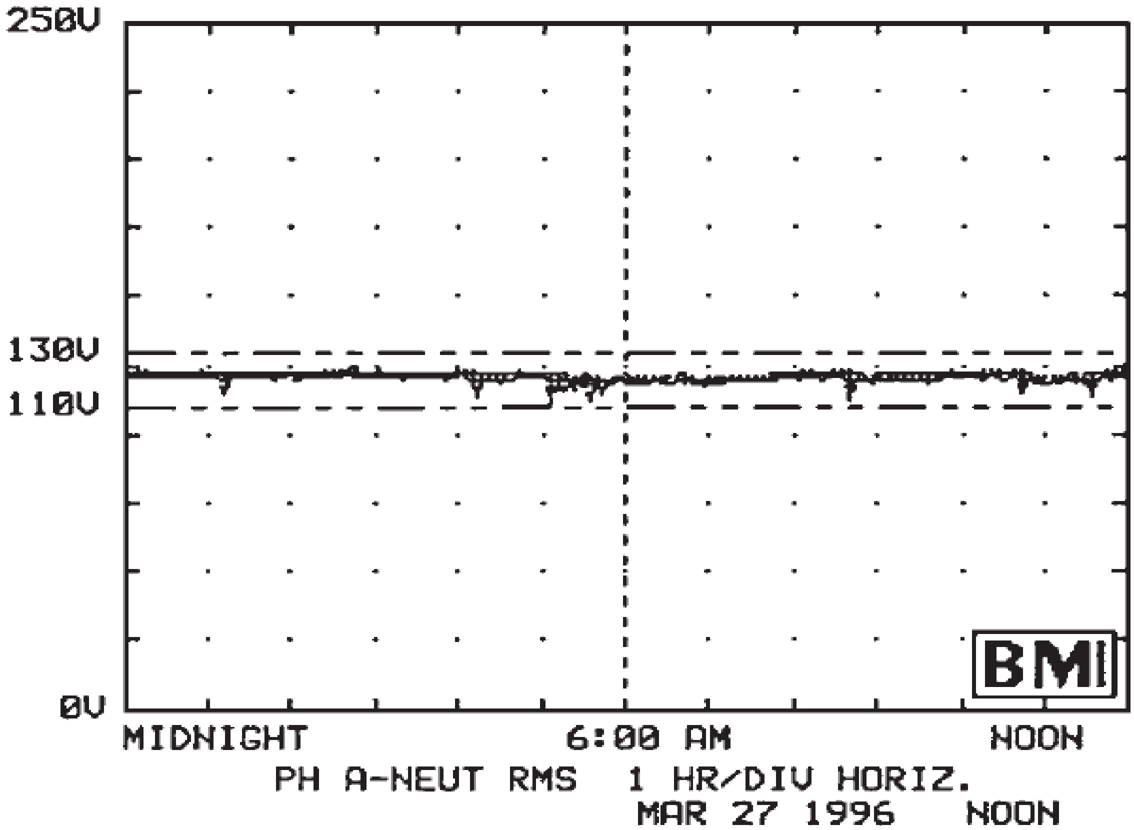


Figure 3.4 RMS voltage variations.

Fast Fourier transforms. Another method that has been used to measure flicker is to take raw samples of the actual voltage waveforms and implement a fast Fourier transform on the demodulated signal (flicker signal only) to extract the various frequencies and magnitudes found in the data. These data would then be compared to a flicker curve. Although similar to using the rms strip charts, this method more accurately quantifies the data measured due to the magnitude and frequency of the flicker being known. The downside to implementing this method is associated with quantifying flicker levels when the flicker-producing load contains multiple flicker signals. Some instruments compensate for this by reporting only the dominant frequency and discarding the rest.

Flicker meters. Because of the complexity of quantifying flicker levels that are based upon human perception, the most comprehensive approach to measuring flicker is to use flicker meters. A flicker meter is essentially a device that demodulates the flicker signal, weights it according to established “flicker curves,” and performs statistical analysis on the processed data.

Generally, these meters can be divided up into three sections. In the first section the input waveform is demodulated, thus removing the carrier signal. As a result of the demodulator, a dc offset and higher-frequency terms (sidebands) are produced. The second section removes these unwanted terms using filters, thus leaving only the modulating (flicker) signal remaining. The second section also consists of filters that weight the modulating signal according to the particular meter specifications. The last section usually consists of a statistical analysis of the measured flicker.

The most established method for doing this is described in IEC Standard 61000-4-15.8 The IEC flicker meter consists of five blocks, which are shown in Fig. 5.5.

Block 1 is an input voltage adapter that scales the input half-cycle rms value to an internal reference level. This allows flicker measurements to be made based upon a percent ratio rather than be dependent upon the input carrier voltage level.

Block 2 is simply a squaring demodulator that squares the input to separate the voltage fluctuation (modulating signal) from the main voltage signal (carrier signal), thus simulating the behavior of the incandescent lamp.

Block 3 consists of multiple filters that serve to filter out unwanted frequencies produced from the demodulator and also to weight the input signal according to the incandescent lamp eye-brain response. The basic transfer function for the weighting filter is

$$H(s) = \frac{k\omega_1 s}{s^2 + 2\lambda s + \omega_1^{\,2}} \cdot \frac{1 + s/\omega_2}{(1 + s/\omega_3)(1 + s/\omega_4)} \tag{5.1}$$

Block 4 consists of a squaring multiplier and sliding mean filter. The voltage signal is squared to simulate the nonlinear eye-brain response, while the sliding mean filter averages the signal to simulate the short-term storage effect of the brain. The output of this block is considered to be the instantaneous flicker level. A level of 1 on the output of this block corresponds to perceptible flicker.

Block 5 consists of a statistical analysis of the instantaneous flicker level. The output of block 4 is divided into suitable classes, thus creating a histogram. A probability density function is created based upon each class, and from this a cumulative distribution function can be formed.

Flicker level evaluation can be divided into two categories, short term and long-term. Short-term evaluation of flicker severity PST is based upon an observation period of 10 min. This period is based upon assessing disturbances with a short duty cycle or those that produce continuous fluctuations. PST can be found using the equation

$$P_{ST} = \sqrt{0.0314P_{0.1} + 0.0525P_{1s} + 0.0657P_{3s} + 0.28P_{10s} + 0.08P_{50s}} \quad (5.2)$$

where the percentages P0.1, P1s, P3s, P10s, and P50s are the flicker levels that are exceeded 0.1, 1.0, 3.0, 10.0, and 50.0 percent of the time, respectively. These values are taken from the cumulative distribution curve discussed previously. A PST of 1.0 on the output of block 5 represents the objectionable (or irritable) limit of flicker.

For cases where the duty cycle is long or variable, such as in arc furnaces, or disturbances on the system that are caused by multiple loads operating simultaneously, the need for the long-term assessment of flicker severity arises. Therefore, the long-term flicker severity PLT is derived from PST using the equation

$$P_{LT} = \sqrt[3]{\frac{\sum_{i=1}^{N} P_{STi}^{3}}{N}} \quad (5.3)$$

where N is the number of PST readings and is determined by the duty cycle of the flicker-producing load. The purpose is to capture one duty cycle of the fluctuating load. If the duty cycle is unknown, the recommended number of PST readings is 12 (2-h measurement window). The advantage of using a single quantity, like Pst, to characterize flicker is that it provides a basis for implementing contracts and describing flicker levels in a much simpler manner. Figure 11.19 illustrates the Pst levels measured at the PCC with an arc furnace over a 24-h period. The melt cycles when the furnace was operating can be clearly identified by the high Pst levels. Note that Pst levels greater than 1.0 are usually considered to be levels that might result in customers being aware of lights flickering.

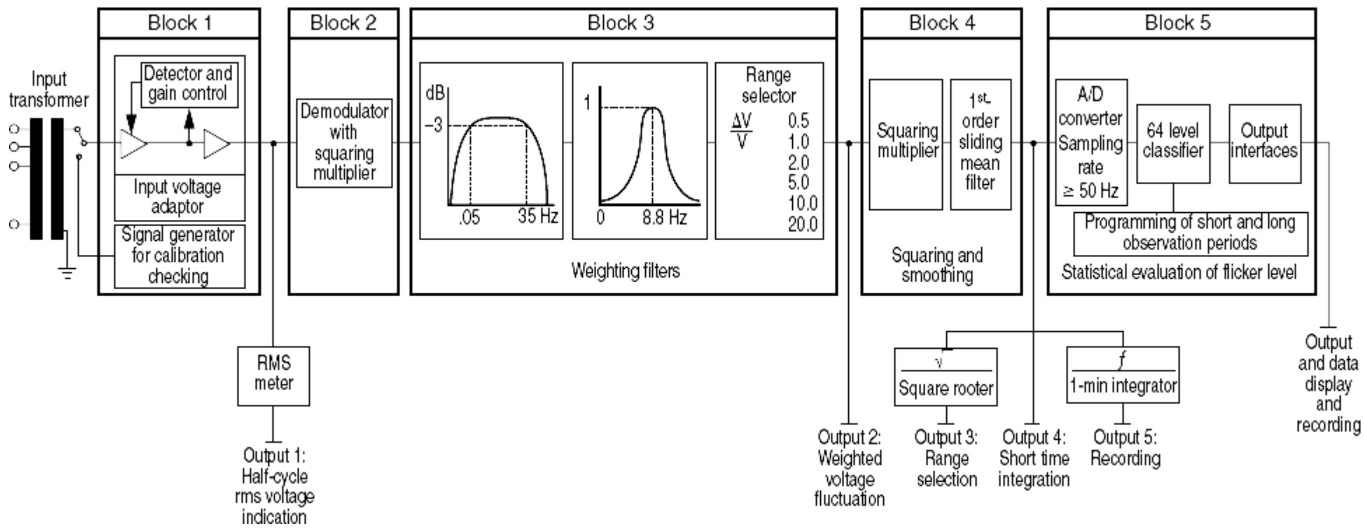


Figure 3.5 Diagram of the IEC flicker meter.

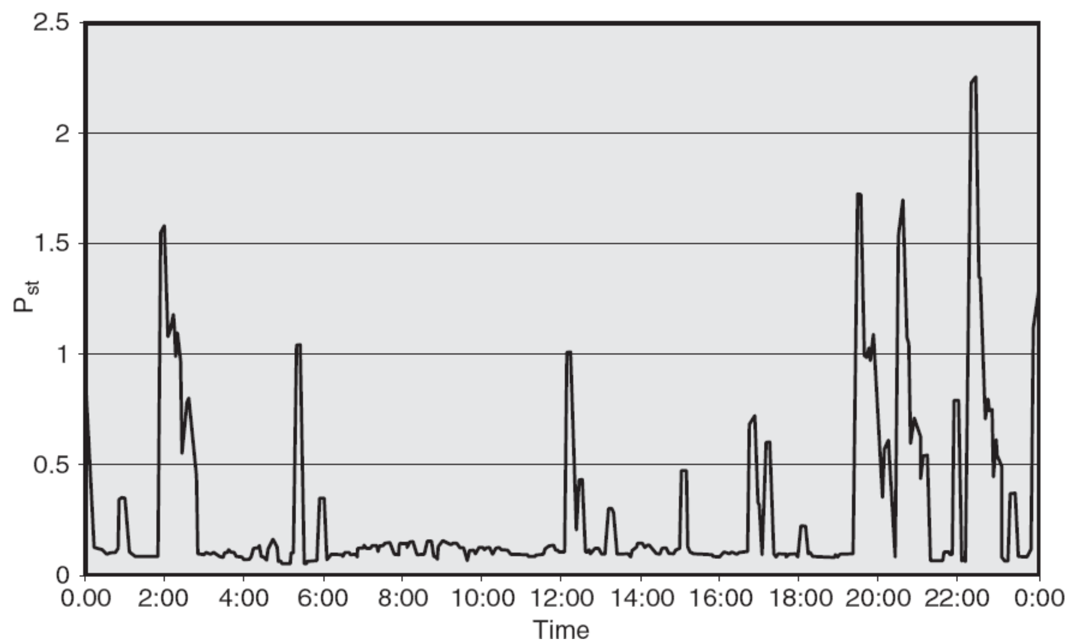


Figure 3.6 Flicker variations at the PCC with an arc furnace characterized by the Pst levels for a 24-h period (March 1, 2001) (note that there is one Pst value every 10 min).