UNIT-III POWER QUALITY MONITORING
Monitoring considerations - monitoring and diagnostic techniques for various power quality problems - modeling of power quality (harmonics and voltage sag) problems by mathematical simulation tools - power line disturbance analyzer – quality measurement equipment - harmonic / spectrum analyzer - flicker meters - disturbance analyzer. Applications of expert systems for power quality monitoring

➢ Monitoring considerations

- ❖ 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 monitoring objectives often determine the choice of monitoring equipment, triggering thresholds, methods for data acquisition and storage, and analysis and interpretation requirements.
- ❖ Several common objectives of power quality monitoring are summarized here.
  - Monitoring to characterize system performance.
  - Monitoring to characterize specific problems.
  - Monitoring as part of an enhanced power quality service.
  - Monitoring as part of predictive or just-in-time maintenance.
- ❖ **Objectives of power quality measurements (Needs for power quality measurement)**
  - Preventive and predictive maintenance.
  - Determining the need for mitigation equipment.
  - Ensuring equipment performance.
  - Sensitivity assessment of process equipment to disturbances.

➢ Monitoring and diagnostic techniques for various power quality problems

Monitoring as part of a facility 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.
- ❖ Power quality monitoring, along with infrared scans and visual inspections, is an important part of the overall survey.
- ❖ 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.

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

switching, power electronic equipment operation, arcing equipment, etc.)

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

Determining what to monitor

- Power quality encompasses a wide variety of conditions on the power system.
- Important disturbances can range from very high frequency impulses caused by lightning strokes or current chopping during circuit interruptions to long-term overvoltages caused by a regulator tap switching problem.
- The range of conditions that must be characterized creates challenges both in terms of the monitoring equipment performance specifications and in the data-collection requirements

Choosing monitoring locations

- The monitoring experience gained from the EPRI DPQ project1 provides an excellent example of how to choose monitoring locations.
- The primary objective of the DPQ project was to characterize power quality on the U.S. electric utility distribution feeders.
- Actual feeder monitoring began in June 1992 and was completed in September 1995. Twenty four different utilities participated in the data-collection effort with almost 300 measurement sites.
- Monitoring for the project was designed to provide a statistically valid set of data of the various phenomena related to power quality.

Options for permanent power quality monitoring equipment

Permanent power quality monitoring systems should take advantage of the wide variety of equipment that may have the capability to record power quality information. Some of the categories of equipment that can be

1. *Digital fault recorders (DFRs)*
2. *Smart relays and other IEDs.*
3. *Voltage recorders.*
4. *In-plant power monitors.*
5. *Special-purpose power quality monitors.*
6. *Revenue meters.*

Computer Tools for Transients Analysis

- There are two fundamental issues that need to be considered in developing a system model for harmonic simulation studies.
- The first issue is the extent of the system model to be included in the simulation.
- Secondly, one must decide whether the model should be represented as a single-phase equivalent or a full three-phase model
- The most widely used computer programs for transients analysis of power systems are the Electromagnetic Transients Program, commonly known as EMTP, and its derivatives such as the Alternate Transients Program (ATP).
- EMTP was originally developed by Hermann W. Dommel at the Bonneville Power Administration (BPA) in the late 1960s and has been continuously upgraded since.
- One of the reasons this program is popular is its low cost due to some versions being in the public domain. Some power system analysts use computer programs developed more for the analysis of electronic circuits, such as the wellknown SPICE program and its

derivatives.

- ❖ Although the programs just discussed continue to be used extensively, there are now many other capable programs available.
- ❖ Nearly all the tools for power systems solve the problem in the time domain, re-creating the waveform point by point.
- ❖ A few programs solve in the frequency domain and use the Fourier transform to convert to the time domain.
- ❖ Unfortunately, this essentially restricts the addressable problems to linear circuits.
- ❖ Time-domain solution is required to model nonlinear elements such as surge arresters and transformer magnetizing characteristics.
- ❖ The penalty for this extra capability is longer solution times, which with modern computers becomes less of a problem each day.
- ❖ It takes considerably more modeling expertise to perform electromagnetic transients studies than to perform more common power system analyses such as of the power flow or of a short circuit.
- ❖ Therefore, this task is usually relegated to a few specialists within the utility organization or to consultants.
- ❖ While transients programs for electronic circuit analysis may formulate the problem in any number of ways, power systems analysts almost uniformly favor some type of nodal admittance formulation.
- ❖ For one thing, the system admittance matrix is sparse allowing the use of very fast and efficient sparsity techniques for solving large problems.
- ❖ Also, the nodal admittance formulation reflects how most power engineers view the power system, with series and shunt elements connected to buses where the voltage is measured with respect to a single reference.
- ❖ To obtain conductances for elements described by differential equations, transients programs discretize the equations with an appropriatenumerical integration formula.
- ❖ The simple trapezoidal rule method appears to be the most commonly used, but there are also a variety of Runge-Kutta and other formulations used.
- ❖ Nonlinearities are handled by iterative solution methods.
- ❖ Some programs include the nonlinearities in the general formulation, while others, such as those that follow the EMTP methodology, separate the linear and nonlinear portions of the circuit to achieve faster solutions. This impairs the ability of the program to solve some classes of nonlinear problems but is not usually a significant constraint for most power system problems.

➢ **Disturbance analyzers / power line disturbance analyzer**

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 undervoltages. 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 undervoltage 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 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. However, a simple conventional disturbance monitor can be valuable for initial checks at a problem location.

➢ Smart power quality monitors / quality measurement equipment

All power quality measurement instruments previously described are designed to collect power quality data. Some instruments can send the data over a telecommunication line to a central processing location for analysis and interpretation. However, one common feature among these instruments is that they do not possess the capability to locally analyze, interpret, and determine what is happening in the power system. They simply record and transmit data for post processing. Since the conclusion of the EPRI DPQ project in Fall 1995, it was realized that these monitors, along with the monitoring practice previously described, were inadequate. An emerging trend in power quality monitoring practice is to collect the data, turn them into useful information, and disseminate it to users. All these processes take place within the instrument itself. Thus, a new breed of power quality monitor was developed with integrated intelligent systems to meet this new challenge. This type of power quality monitor is an intelligent power quality monitor where information is directly created within the instrument and immediately available to the users. A smart power quality monitor allows engineers to take necessary or appropriate actions in a timely manner. Thus, instead of acting in a reactive fashion, engineers will act in a proactive fashion.

One such smart power quality monitor was developed by Electrotek Concepts, Dranetz-BMI, EPRI, and the Tennessee Valley Authority (TVA). The system features on-the-spot data analysis with rapid information dissemination via Internet technology, e-mails, pagers, and faxes. The system consists of data acquisition, data aggregation, communication, Web-based visualization, and enterprise management components.

The data acquisition component (DataNode) is designed to measure the actual power system voltages, currents, and other quantities. The data aggregation, communication, Web-based visualization, and enterprise management components are performed by a mission-specific computer system called the InfoNode. The communication between the data acquisition device and the InfoNode is accomplished through serial RS-232/485/422 or Ethernet communications using industry standard protocols (UCA MMS and Modbus). One or more data acquisition devices, or DataNodes, can be connected to an InfoNode. The InfoNode has its own firmware that governs the overall functionality of the monitoring system. It acts as a special-purpose database manager and Web server. Various special-purpose intelligent systems are implemented within this computer system. Since it is a Web server, any user with Internet connectivity can access the data and its analysis results stored in its memory system. The monitoring system supports the standard file transfer protocol (FTP). Therefore, a database can be manually archived via FTP by simply copying the database to any personal computer with connectivity to the mission-specific computer system via network or modem. Proprietary software can be used to archive data from a group of Info Nodes.

➢ Power Quality Measurement Equipment

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, there are other instruments that can be used to help solve power quality problems by measuring ambient conditions:

- Infrared meters can be very valuable in detecting loose connections and 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.
- 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 measure the strength of electric fields for electrostatic coupling concerns.
- 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

Spectrum analyzers and harmonic Analyzers

Instruments in the disturbance analyzer category have very limited harmonic analysis capabilities. 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:

1. 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 several hand-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.

2. 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 designed specifically 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.

3. 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.

- **Combination disturbance and harmonic analyzers:** The most recent instruments combine harmonic sampling and energy monitoring functions with complete disturbance monitoring functions as well. The output is graphically based, and the data are remotely gathered over phone lines into a central database. Statistical analysis can then be performed on the data. The data are also available for input and manipulation into other programs such as spreadsheets and other graphical output processors.

One example of such an instrument: This instrument is designed for both utility and end-user applications, being mounted in a suitable enclosure for installation outdoors on utility poles. It monitors three-phase voltages and currents (plus neutrals) simultaneously, which is very important for diagnosing power quality problems. The instrument captures the raw data and saves the data in internal storage for remote downloading. Off-line analysis is performed with powerful software that can produce a variety of outputs. The top chart shows a typical result for a voltage sag. Both the rms variation for the first 0.8 s and the actual waveform for the first 175 ms are shown. The middle chart shows a typical wave fault capture from a capacitor-switching operation. The bottom chart demonstrates the capability to report harmonics of a distorted waveform. Both the actual waveform and the harmonic spectrum can be obtained.

Another device is shown in Fig. 11.15. This is a power quality monitoring system designed for key utility accounts. It monitors three-phase voltages and has the capability to capture disturbances and page power quality engineers. The engineers can then call in and hear a voice message describing the event. It has memory for more than 30 events. Thus, while only a few short years ago power quality monitoring was a rare feature to be found in instruments, it is becoming much more commonplace in commercially available equipment.

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. 11.16. 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.

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. 11.16, the system was said to have experienced flicker. A sample graph of rms voltage variations is shown in Fig. 11.17 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. 11.16, 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.

Fast Fourier transform. 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. 11.18. 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.

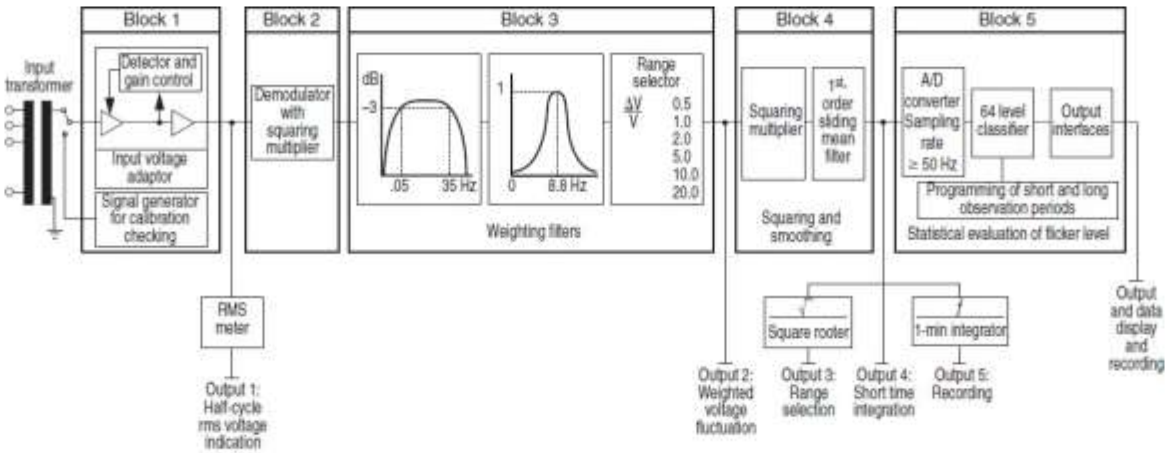


Figure 11.18 Diagram of the IEC flicker meter.

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.

➢ <u>Applications of expert systems for power quality monitoring</u>

Many advanced power quality monitoring systems are equipped with either off-line or on-line intelligent systems to evaluate disturbances and system conditions so as to make conclusions about the cause of the problem or even predict problems before they occur. The applications of intelligent systems or autonomous expert systems in monitoring instruments help engineers determine the system condition rapidly. This is especially important when restoring service following major disturbances. The implementation of intelligent systems within a monitoring instrument can significantly increase the value of a monitoring application since it can generate information rather than just collect data. The intelligent systems are packaged as individual autonomous expert system modules, where each module performs specific functions. Examples include an expert system module that analyzes capacitor switching transients and determines the relative location of the capacitor bank, and an expert system module to determine the relative location of the fault causing a voltage sag. Sections 11.5.1 and 11.5.2 describe the approach in designing an autonomous expert system for power quality data assessment, and give application examples.

Basic design of an expert system for monitoring applications

The development of an autonomous expert system calls for many approaches such as signal processing and rule-based techniques along with the knowledge-discovery approach commonly known as data mining. Before the expert system module is designed, the functionalities or objectives of the module must be clearly defined. In other words, the designers or developers of the expert system module must have a clear understanding about what knowledge they are trying to discover from volumes of raw measurement data. This is very important since they will ultimately determine the overall design of the expert system module. The process of turning raw measurement data into knowledge involves data selection and preparation, information extraction from selected data, information assimilation, and report presentation. These steps (illustrated in Fig. 11.30) are commonly known as knowledge discovery or data mining.

The first step in the knowledge discovery is to select appropriate measurement quantities and disregard other types of measurements that do not provide relevant information. In addition, during the data selection process preliminary analyses are usually carried out to ensure the quality of the measurement. For example, an expert system module is developed to retrieve a specific answer, and it requires measurements of instantaneous three-phase voltage and current waveforms to be available. The data-selection task is responsible for ensuring that all required phase voltage and current waveform data are available before proceeding to the next step. In some instances, it might be necessary to interpolate or extrapolate data in this step. Other preliminary examinations include checking any outlier magnitudes, missing data sequences, corrupted data, etc. Examination on data quality is important as the accuracy of the knowledge discovered is determined by the quality of data.

The second step attempts to represent the data and project them onto domains in which a solution is more favorable to discover. Signal-processing techniques and power system analysis are applied. An example of this step is to transform data into another domain where the information might be located. The Fourier transform is performed to uncover frequency information for steady-state signals, the wavelet transform is performed to find the temporal and frequency information for transient signals, and other transforms may be performed as well. Now that the data are already projected onto other spaces or domains, we are ready to extract the desired information. Techniques to extract the information vary from sophisticated ones, such as pattern recognition, neural networks, and machine learning, to simple ones, such as finding the maximum value in the transformed signal or counting the number of points in which the magnitude of a voltage waveform is above a predetermined threshold value. One example is looking for harmonic frequencies of a distorted waveform. In the second step the waveform is transformed using the Fourier transform, resulting in a frequency domain signal. A simple harmonic frequency extraction process might be accomplished by first computing the noise level in the frequency domain signal, and subsequently setting a threshold number to several fold that of the noise level. Any magnitude higher than the threshold number may indicate the presence of harmonic frequencies. The data mining step usually results in scattered pieces of information. These pieces of information are assimilated to form knowledge. In some instances assimilation of information is not readily possible since some pieces of information conflict with each other. If the conflicting information cannot be resolved, the quality of the answer provided might have limited use. The last step in the chain is interpretation of knowledge and report presentation.

Example applications of expert systems

One or more autonomous expert system modules can be implemented within an advanced power quality monitoring system. When a power quality event is captured, all modules will be invoked. Each module will attempt to discover the unique knowledge it is designed to look for. Once the unique knowledge is discovered, the knowledge will be available for users to inspect. The knowledge can be viewed on a standard browser, or sent as an e-mail, pager, or fax message. We present a few examples of autonomous expert systems.

Voltage sag direction module. Voltage sags are some of the most important disturbances on utility systems. They are usually caused by a remote fault somewhere on the power system; however, they can also be caused by a fault inside end-user facilities. Determining the location of the fault causing the voltage sag can be an important step toward preventing voltage sags in the future and assigning responsibility for addressing the problem. For instance, understanding the fault location is necessary for implementing contracts that include voltage sag performance specifications. The supplier would not be responsible for sags that are caused by faults within the customer facility. This is also important when trying to assess performance of the distribution system in comparison to the transmission system as the cause of voltage sag events that can impact customer operations. The fault locations can help identify future problems or locations where maintenance or system changes are required. An expert system to identify the fault location (at least upstream or downstream from the monitoring location) can help in all these cases. An autonomous expert system module called the voltage sag direction module is designed just for that purpose, i.e., to detect and identify a voltage sag event and subsequently determine the origin (upstream or downstream from the monitoring location) of the voltage sag event.

If a data acquisition node is installed at a customer PCC, the source of the voltage sag will be either on the utility or the customer side of the meter. If the monitoring point is at a distribution substation transformer, the source of the voltage sag will be either the distribution system or the transmission system.

The voltage sag direction module works by comparing current and voltage rms magnitudes both before and after the sag event. It tracks phase angle changes from prefault to postfault. By assembling information from the rms magnitude comparison and the phase angle behavior, the origin of the voltage sag event can be accurately determined.

In addition, the voltage sag direction module is equipped with algorithms to assess the quality of the knowledge or answer discovered. If the answer is deemed accurate, it will be sent as an output; otherwise, it will be neglected and no answer will be provided. In this way, inaccurate or false knowledge can be minimized. Inaccurate knowledge can be due to a number of factors, primarily to missing data and unresolved conflicting characteristics. Outputs of the voltage sag direction module can be displayed on a computer screen using Web browser software, displayed in printed paper format, sent to a pager, or sent as an e-mail. Figure 11.31 shows an output of a voltage sag direction expert system module. The first column indicates the event time, the second column indicates the monitor identification, the third column indicates event types, the fourth column indicates the triggered channel, and finally the fifth column indicates the characteristics of the event and outputs of the answer module.

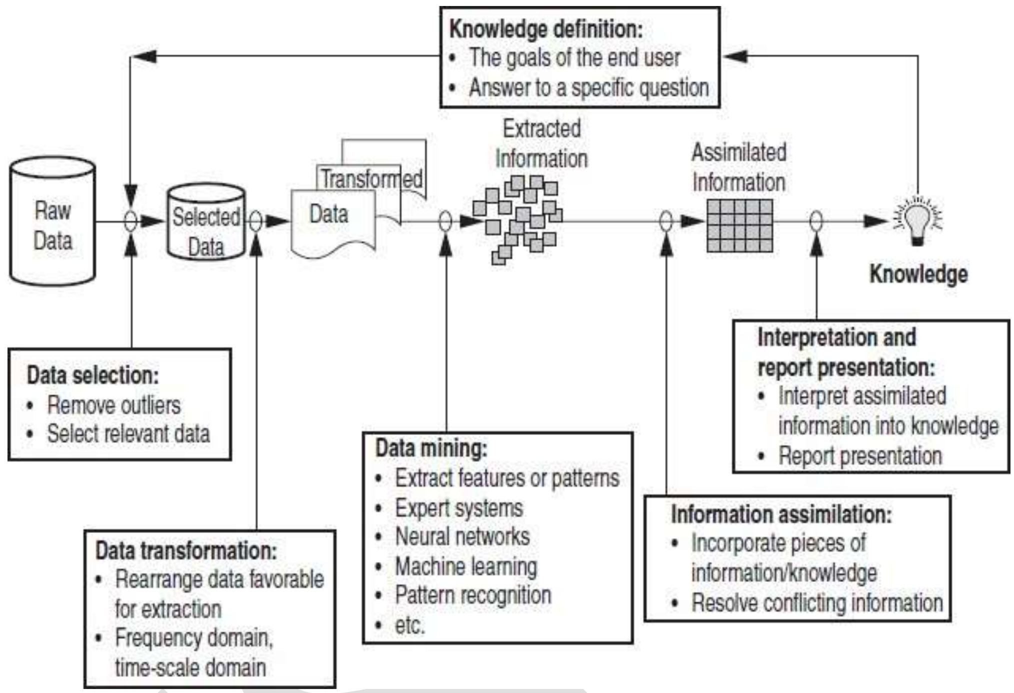
Radial fault locator module. Radial distribution feeders are susceptible to various short-circuit events such as symmetrical faults (three-phase) and unsymmetrical faults, including single-line-to-ground, double line-to-ground, and line-to-line faults. These system faults arise from various conditions ranging from natural causes such as severe weather conditions and animal contacts to human intervention and errors, including equipment failure. Quickly identifying the source and location of faults is the key to cost-efficient system restoration. The current practice to locate the faults is to send a lineperson to patrol the suspected feeders. While this is a proven method, it is certainly not a cost effective way to restore power. An expert system module called the radial fault locator is developed to estimate the distance to a fault location from the location where the measurements were made. The unique feature of this module is that it only requires a set of three-phase voltages and currents from a single measurement location with the sequence impedance data of the primary distribution feeder. The module works by first identifying a permanent fault event based on the ground fault and phase fault pickup current threshold. Users can enter these values in the answer module setup window shown in Fig. 11.33. Once a permanent fault event is identified, the distance to fault estimation is carried out based on the apparent impedance approach.13 Estimates of the distance to the fault are then displayed in a computer screen with the Web browser illustrated in Fig. 11.34 or sent to a lineperson via a pager. The lineperson can quickly pinpoint the fault location. This example illustrates the emerging trend in smart power quality monitoring, i.e., collect power quality data and extract and formulate information for users to perform necessary actions.

Capacitor-switching direction module. Capacitor-switching operations are the most common cause of transient events on the power system. When a capacitor bank is energized, it interacts with the system inductance, yielding oscillatory transients. The transient overvoltage in an uncontrolled switching is between 1.0 to 2.0 pu with typical overvoltages of 1.3 to 1.4 pu and frequencies of 250 to 1000 Hz. Transients due to energizing utility capacitor banks can propagate into customer facilities. Common problems associated with the switching transients include tripping off sensitive equipment such adjustable-speed drives and other electronically controlled loads. Some larger end-user facilities may also have capacitor banks to provide reactive power and voltage support as well.

When a sensitive load trips off due to capacitor-switching transients, it is important to know where the capacitor bank is, whether it is on the utility side or in the customer facility. A capacitor-switching direction expert system module is designed to detect and identify a capacitor switching event and determine the relative location of the capacitor bank from the point where measurements were collected. It only requires a set of three-phase voltages and currents to perform the tasks mentioned. This module is useful to determine the responsible parties, i.e., the utility or customer, and help engineers pinpoint the problematic capacitor bank.

The capacitor-switching transient direction module works as follows. When an event is captured, the module will extract the information and represent it in domains where detection and identification are more favorable. The domains where the information is represented are in the time-, frequency-, and time-scale (wavelet) domains. If the root cause of the event is due to a capacitor bank energization, the answer module will proceed to determine the most probable location of the capacitor bank.

There are only two possible locations with respect to the monitoring location, i.e., upstream or downstream. The expert system module works well with grounded, ungrounded, delta-configured, and wye- (or star-) configured capacitor banks. It also works well for back-to-back capacitor banks. The capacitor-switching transient direction module is equipped with algorithms to determine the quality of the information it discovers. Thus, the module may provide an undetermined answer. This answer is certainly better than an incorrect one. An example application of the answer module to analyze data capture from a data acquisition node installed at an office complex service entrance is shown in Fig. 11.35. The analysis results are shown in Fig. 11.36, which is a screen capture from a standard Web browser. Since the office complex has no capacitor banks, any capacitor-switching transients must originate from the utility side located upstream from the data acquisition node. The module correctly determines the relative location of the capacitor bank. Note that there are some instances where the expert system was not able to determine the relative location of the capacitor bank. From the time stamp of the events, it is clear that capacitor bank energizations occur at about 5:00 A.M. and 7:00 P.M. each day.



Capacitor-switching operation inspection module. As described, capacitor-switching transients are the most common cause of transient events on the power system and are results of capacitor bank energization operation. One common thing that can go wrong with a capacitor bank is for a fuse to blow. Some capacitor banks may not be operating properly for months before utility personnel notice the problem. Routine maintenance is usually performed by driving along the line and visually inspecting the capacitor bank. An autonomous expert system was developed for substation applications to analyze downstream transient data and determine if a capacitor- switching operation is performed successfully and display a warning message if the operation was not successful. With the large number of capacitor banks on most power systems, this expert system module can be a significant benefit to power systems engineers in identifying problems and correlating them with capacitor-switching events. Successful capacitor bank energization is characterized by a uniform increase of kvar on each phase whose total corresponds to the capacitor kvar size. For example, when a 1200-kvar capacitor bank is energized, reactive power of approximately 400 kvar should appear on each phase. The total kvar increase can be determined by computing kvar changes in individual phases from the current and voltage waveforms before and after the switching operation. This total computed kvar change is then compared to the actual or physical capacitor bank kvar supplied by a user. If the expected kvar was not realized, the capacitor bank or its switching device may be having some problems.

Figure 11.37 shows the application of the capacitor-switching operation inspector expert system in a commercial monitoring system. The monitoring location is at the substation;

thus, all capacitor banks along the feeders are downstream from the monitoring location. The first capacitor-switching event indicates that two phases of the capacitor are out of service. Either the fuses have blown or the switch is malfunctioning. The second event shows a successful capacitor-switching operation.

Lightning correlation module. The majority of voltage sags and outages in the United States are attributed to weather-related conditions such as thunderstorms. For example, TVA has approximately 17,000 mi of transmission lines where lightning accounts for as much as 45 percent of the faults on their system. The lightning correlation expert system module is designed to correlate lightning strikes with measured power quality events and make that information available in real time directly at the point of measurement. Armed with the correlation results, engineers can evaluate the cause and impact of voltage sags for a specific customer at a specific monitoring point as well as evaluate the impact on all customers for a given event. When the lightning correlation module detects a voltage sag or transient event, it queries a lightning database via the Internet. The lightning data are provided by the U.S. National Lightning Detection Network operated by Global Atmospherics, Inc. If the query returns a result set, the lightning correlation module will store this information in the monitoring system database along with the disturbance data for information dissemination. The lightning data include the event time of the strike, the latitude and longitude of strike location, the current magnitude, and number of strokes.

Future applications Industrial power quality monitoring applications

- Energy and demand profiling with identification of opportunities for energy savings and demand reduction
- Harmonics evaluations to identify transformer loading concerns, sources of harmonics, problems indicating misoperation of equipment (such as converters), and resonance concerns associated with power factor correction
- Voltage sag impacts evaluation to identify sensitive equipment and possible opportunities for process ride-through improvement
- Power factor correction evaluation to identify proper operation of capacitor banks, switching concerns, resonance concerns, and optimizing performance to minimize electric bills
- Motor starting evaluation to identify switching problems, inrush current concerns, and protection device operation
- Short-circuit protection evaluation to evaluate proper operation of protective devices based on short-circuit current characteristics, time-current curves, etc.

Power system performance assessment and benchmarking

- Trending and analysis of steady-state power quality parameters (voltage regulation, unbalance, flicker, harmonics) for performance trends, correlation with system conditions (capacitor banks, generation, loading, etc.), and identification of conditions that need attention
- Voltage sag characterizing and assessment to identify the cause of the voltage sags (transmission or distribution) and to characterize the events for classification and analysis (including aggregation of multiple events and identification of subevents for analysis with respect to protective device operations)

- Capacitor-switching characterization to identify the source of the transient (upline or downline), locate the capacitor bank, and characterize the events for database management and analysis
- Performance index calculations and reporting for system benchmarking purposes and for prioritizing of system maintenance and improvement investments

Applications for system maintenance, operations, and reliability

- Locating faults. This is one of the most important benefits of the monitoring systems. It can improve response time for repairing circuits dramatically and also identify problem conditions related to multiple faults over time in the same location.
- Capacitor bank performance assessment. Smart applications can identify fuse blowing, can failures, switch problems (restrikes, reignitions), and resonance concerns.
- Voltage regulator performance assessment to identify unusual operations, arcing problems, regulation problems, etc.
- Distributed generator performance assessment. Smart systems should identify interconnection issues, such as protective device coordination problems, harmonic injection concerns, islanding problems, etc.
- Incipient fault identifier. Research has shown that cable faults and arrester faults are often preceded by current discharges that occur weeks before the actual failure. This is an ideal expert system application for the monitoring system.
- Transformer loading assessment can evaluate transformer loss of life issues related to loading and can also include harmonic loading impacts in the calculations.
- Feeder breaker performance assessment can identify coordination problems, proper operation for short-circuit conditions, nuisance tripping, etc.

Power quality monitoring and the Internet

Many utilities have adopted power quality monitoring systems to continuously assess system performance and provide faster response to system problems. It is clear that intranet and Internet access to the information has been key to the success of these systems. An example of a completely Web based power quality monitoring system is the result of research initiated by TVA and EPRI (Fig. 11.40). Specifications for the system were developed with the help of all the members of the EPRI Power Quality Target group to support the variety of applications which must be supported by such a system. The result was a modular system with a completely open architecture so that it can be interfaced with a wide variety of platforms. After helping with the development of the system, TVA is deploying the Web-based monitoring systems at important customers and substations throughout their system. TVA distributors are also taking advantage of the system. It already had an extensive power quality monitoring system in place, and the new system is integrated with the existing monitoring system infrastructure at the central data management level (enterprise level), as illustrated in Fig. 11.41. This provides the capability to provide systemwide analysis of the power quality information.

The future of these systems involves integration with other data-collection devices in the substation and the facility. Standard interfaces like the Power Quality Data Interchange Format (PQDIF) and COMTRADE are used to share the information, and standard protocols like UCA are used for the communications. The intelligent applications described will be applied at both the substation level and at the enterprise level, as appropriate.