IOP Publishing

New Technologies for Smart Grid Operation

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Chapter 6

The use of the utility communication network for monitoring power quality problems

6.1 Introduction

Recent advances in communication, digital electronics and computer technology have made remote monitoring of the electric utility distribution network possible. Numerous utility applications, such as automatic meter reading (AMR), demand response type projects and some distribution control functions, are already being implemented by many utilities and more added-value functions are being looked into or have already reached the pilot project stage. One of the most recent issues raised by the electric power industry is that of power quality monitoring. Power quality is one of the important issues that falls under the broad category of power delivery reliability.

The nature of power quality problems can be defined in terms of their detrimental impact on customers' appliances and devices and also on the supply network and energy monitoring devices. This chapter concentrates on the ability to locate power quality problems that are affecting customers and revenue metering as well as the ability to locate the culprits of harmonic pollution, which may or may not affect a broader segment of the network.

Without a good and reliable communication network, it is practically impossible to monitor each customer site for problems related to power quality because of the sheer number of sites to monitor in a timely fashion. As an example, the very stringent requirements imposed on the communication system for AMR opens the door for other applications. In particular, the recent trend of requiring synchronized time-stamped interval revenue meter reading makes the system more powerful for time correlation of events or conditions occurring in the power delivery network. Devices capable of monitoring power quality problems installed at strategic locations throughout the network and linked to the communication infrastructure will provide an invaluable amount of information that can be used to remedy situations

doi:10.1088/978-0-7503-1158-8ch6

that affect the quality of power delivery. Voltage swell and sag data from many sites, not merely evaluated statistically on an individual site basis but also correlated by time for all the sites being monitored, will be more valuable to the electric utility for setting up strategies to minimize their detrimental effects.

Other types of power quality problems are related to distortions of the 60 Hz voltage and current waveform. Numerous papers have been written on the effects of harmonics on losses in electric power networks and major appliances. Many sensitive digital electronic devices are also affected by distorted voltages. Digital clocks, relying on the 60 Hz voltage zero-crossings for their proper operation, are also affected by recurring transient spikes on the voltage waveform. Other malfunctions are caused by memory contamination of these devices due to burst transient phenomena.

The degree of severity of the voltage distortions can be such that many customers' devices are affected simultaneously due to a main culprit. Monitoring the problems at the point of common coupling quite often produces results which point to the source of the problem. A more commonly occurring power quality problem, caused by locally generated harmonics and only affecting devices in its immediate vicinity, is more difficult to locate.

Revenue meters are also prone to being affected by locally generated distorted voltages and currents. It is difficult to quantify the cumulative loss of revenue due to harmonic pollution. This chapter is an attempt to explain and discuss the main issues related to the detrimental effects of severely distorted voltages and currents on revenue meters and how the existing communication system already used for remote metering can be used to quickly determine the sites affected by harmonic pollution.

In addition, there is the question of which metric can be used to quantify distortion and what data should a power quality monitoring device generate, time-stamp and make available for data gathering using the communication network.

6.2 The root causes of power quality problems

When power quality problems arise at metering sites, meter reading accuracy may be compromised. Loads can cause fluctuating voltages at the point of connection to the network which will be different from the source voltage. This voltage can also be distorted by some types of loads at the point of connection. The energy consumption is generally also monitored at the same point of connection.

One of the categories pertaining to voltages in the area of power quality issues is voltage stability. Large steady state loads that cause network overloading and are subject to frequent switching in and out during short intervals, the loss of voltage due to re-closer operations, etc, cause voltage dips or swells that may have undesirable effects for the electric users. To determine the causes of these voltage problems, one assumes that the voltage at the point of use maintains its sinusoidal wave shape and frequency except during a short period after a switching action. The current standards and recommendations already address these situations.

Switching generates transient voltages that may cause problems for equipment and devices. Recurrent transients, burst transients caused by power electronic switching devices, arc furnaces, arc welding, etc, occur quite often in the electric network and cause voltage and current distortions. Numerous studies on the hazards and detrimental effects of harmonics on the electric network, equipment, etc, have been published. Other sources of power quality problems are high impedance faults, surface discharges on polluted insulators, bad contacts, etc.

In addition to affecting appliances and metering devices, there is also the possibility that the quality of power can cause communication problems. Power line communication (PLC) technologies are especially vulnerable. Communication signals are contaminated by burst harmonics. Recurring transients sometimes cause damage to the memory or the electronic hardware of the communication devices. A great deal of effort and money have been spent to make communication systems reliable and less sensitive to power quality problems. Severe communication impairments can be used as alerts that power quality problems are occurring on the communication channel being used. New generation electric meters—digital electronic based meters—are purported to have the ability to measure kVAh, kWh, power factor, demand, etc. This leads to the possibility to more comprehensive and novel billing strategies. The existing standards require that these meters guarantee a certain degree of accuracy when calibrated with clean sinusoidal voltage and current waveforms. Intuitively it is clear that a 'clean' ac electric power source comprises a sinusoidal voltage that maintains a constant amplitude and frequency under various loading conditions. However, this assertion deviates from reality since the source and the power delivery network have impedances which may produce phase differences and decreased voltage amplitudes at different locations on the network.

Studies are available on the effects of distorted voltage and currents on electric revenue meters and kVAh metering. However, the lack of a good definition of what distortion means can become a problem. An industry accepted form of standardized distortion recognized by the various testing laboratories has yet to be defined. In this chapter, an attempt is made to clarify and describe the main issues and to recommend certain steps needed to consolidate future efforts in order to arrive at testing standards that are logical and that are possible to implement.

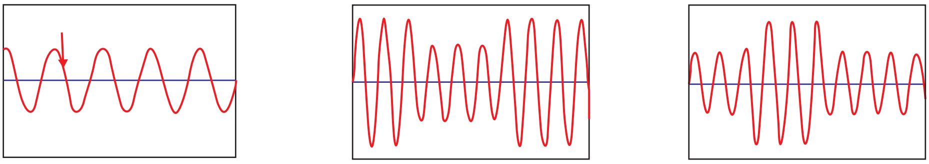
6.3 Descriptions of some types of waveform distortions

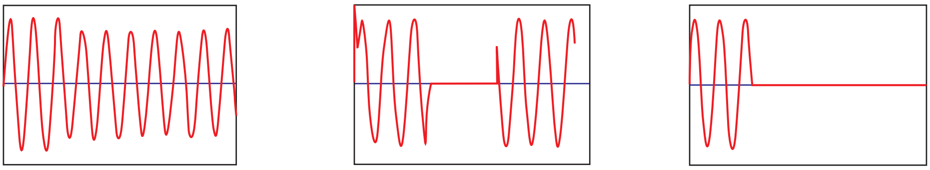
Transients. A transient is a subcycle overvoltage wave in an electric circuit generating a disturbance of the power voltage waveform (figure 6.1(*a*)).

Impulsive. The duration can range between less than 50 nanoseconds and over 1 millisecond and can reach magnitudes of several per unit depending on the disturbing source and on the voltage withstanding characteristics of the system.

Oscillatory. The duration is between 0.3 and 50 milliseconds in a 60 Hz system. Its frequency ranges between less than 5 kHz and 5 MHz and the magnitude can reach up to 8.0 unit^{-1}.

Short duration variations (sag and swell). Sag is a momentary under-voltage at fundamental frequency lasting from half a cycle to one minute, as seen in figure 6.1(*b*). Swell is a momentary overvoltage at fundamental frequency of similar duration to a sag. See figure 6.1(*c*).


(*a*) Transient (*b*) Sag (*c*) Swell


(*d*) Undervoltage (*e*) Momentary interruption (*f*) Long term interruption

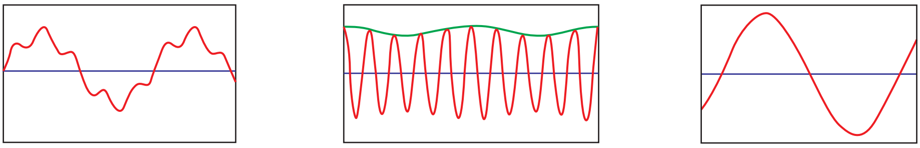

(*g*) Steady state voltage distortion (*h*) Flicker (*i*) Noise

Figure 6.1. Some types of common waveform distortions.

Instantaneous swell or sag. The duration is between 0.5 and 30 cycles with magnitudes ranging between 0.1 and 1.8 unit^{-1}.
Momentary swell or sag. The duration is between 30 cycles and 3.0 s with magnitudes ranging between 0.1 and 1.4 unit^{-1}.
Temporary swell or sag. The duration is between 3.0 s and 1.0 min with magnitudes ranging between 0.1 and 1.2 unit^{-1}.
Long duration variations:

Overvoltage. The duration is longer than 1.0 min with magnitudes ranging between 1.0 and 1.2 min.

Undervoltage. The duration is longer than 1.0 min with magnitudes ranging between 0.80 and 0.9 unit^{-1}, as illustrated in figure 6.1(*d*).

Interruptions. An interruption is the complete loss of voltage for a period of time.
Instantaneous. The duration is between 0.5 and 30 cycles.
Momentary. The duration is between 30 cycles and 3.0 s. See figure 6.1(*e*).
Temporary. The duration is between 3.0 s and 1.0 min.
Long term. The duration is longer than 1.0 min. See figure 6.1(*f*).
Distortion. A waveform distortion is any deviation from the nominal sine wave of the ac line voltage or current. The spectrum ranges between 0.0 Hz and the 100th harmonic, the harmonic strength ranges between 0.0% and 20.0% for the voltage and for the current the strength ranges between 0.0% and 100.0%. An example of a severe voltage distortion produced by a non-linear load with high 5th harmonic current is shown in figure 6.1(*g*).

Flicker (voltage fluctuations). Flicker is a variation of the input voltage as illustrated in figure 6.1(*h*), sufficient in duration to allow visual observation of a change in electric light source intensity. It is intermittent and its magnitude ranges between 0.1% and 7.0 %.

Noise. Electric noise is unwanted electric signals, see figure 6.1(*i*), which may produce undesirable effects in the circuits of the control systems in which they occur. They are random and can be very short and intermittent or continuous, with magnitudes reaching up to 1% unit^{-1} of the fundamental voltage.

These definitions are fine, but the question remains: what does one do with them? A fundamental need is to understand the sources of the distortions, to characterize them and to decide how to use the information. In order to identify these distortions, a method for processing the distorted waveform using a remote device is needed. The result of the processing is the piece of information that will be communicated to the central computer. Would total harmonic distortion (THD) meet the criteria?

There are cases where a large non-linear load is served by a sinusoidal voltage source. The distorted current creates non-sinusoidal voltage drops. Adjacent neighboring electric customers suffer from the distorted voltage. Sometimes the non-linear load is small enough not to cause spillover to adjacent customers and yet is severe enough to cause local problems. This case is the most difficult to detect.

When the load varies with time, the distortion is not constant with time. What one measures today may not be a reflection of tomorrow's measurements.

6.4 Problematic considerations

Many of the published results of investigations on the effects of voltage distortions on electric metering devices have been primarily concerned with the difficulties in defining and measuring the energy entity 'kVA' under harmonic distortion conditions. Distinctions have to be made between distorted voltages serving linear loads and voltage distortion caused by non-linear loads. Issues of unbalanced loading on three-phase systems are also problematic.

All of the distortions used to check metering calibrations are due to steady state harmonics. Measurement results indicate that under conditions of distortion due to steady state harmonics, kWh measurements do not cause appreciable loss of metering accuracy. The problem is with kVAh measurements because it is not clear how one should define kVA under distorted conditions of the voltage and current waveforms.

One major aspect that has been absent in all previous investigations is the case when the distortion contains non-integer harmonics. The complexity increases dramatically when the relationship between the source voltage and the load current is non-linear. A non-steady state dc component in the load current adds to the complexity of the problem.

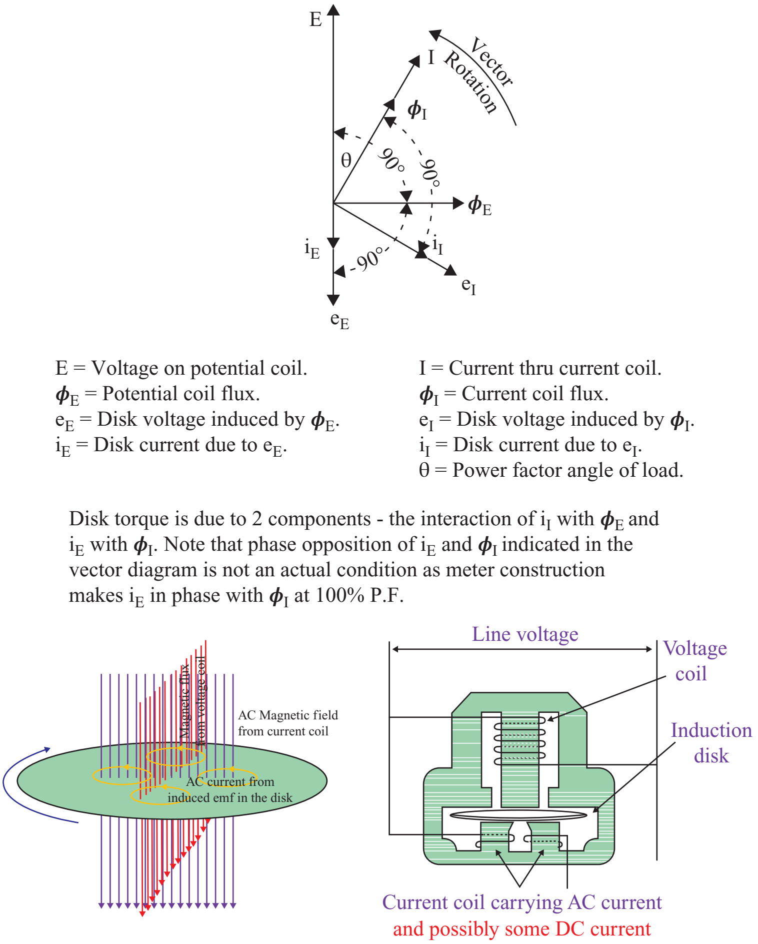
Several important questions can be raised in this case:

1. What are the effects on electromechanical meters that use a Ferraris disk?
2. What are the effects on electronic meters?
3. Which components or parts of the meter are involved in metering inaccuracies?

4. Do concepts such as kVA, power factor and reactive power still make sense if these items are used for electric energy metering and billing?
5. Does filtering affect actual energy consumption?
6. Can the distortion be categorized in several classes that can be used for calibration purposes?
7. What types of remedies can be applied to the sources of distortion?

6.4.1 Causes of inaccuracies

To appreciate the problem that we mentioned above, let us take a fairly simple example for purposes of illustration. A simple induction disk electric meter operates on the following principles. An ac passing through the current coil of the meter generates an alternating magnetic field that crosses the rotating disk perpendicularly, see figure 6.2(*a*). The induced electromotive force (EMF) in the metallic disk causes



E = Voltage on potential coil.
ϕ_E = Potential coil flux.
e_E = Disk voltage induced by ϕ_E.
i_E = Disk current due to e_E.

I = Current thru current coil.
ϕ_I = Current coil flux.
e_I = Disk voltage induced by ϕ_I.
i_I = Disk current due to e_I.
θ = Power factor angle of load.

Disk torque is due to 2 components - the interaction of i_I with ϕ_E and i_E with ϕ_I. Note that phase opposition of i_E and ϕ_I indicated in the vector diagram is not an actual condition as meter construction makes i_E in phase with ϕ_I at 100% P.F.

Figure 6.2. Diagram showing the direction of rotation of the induction disk.

an ac to flow in the disk, which reacts with the magnetic flux generated by the voltage coil, figure 6.2. The sum of all the elemental Lorentz forces generates a net mechanical torque which rotates the disk.

(a) *Retardation torques.* If in addition to the ac a dc is also present in the current coil, a dc flux is also generated and superimposed on the ac magnetic flux. The disk rotation generates an EMF due to motion in the disk. This EMF causes current flow in the disk and retardation torques.

(b) *Harmonic torques.* Additional torques can also be produced by steady state harmonic currents from non-linear loads on the customer side and these can be in the same or in the opposite direction to the fundamental frequency torque, depending on whether the harmonic currents are positive- or negative-sequence. Slowing down the disk rotation essentially means a loss of revenue. Likewise, continuing positive-sequence currents can impose accelerating torques on the disk that may affect customers' metering. These findings have been identified by several investigators and reported in the literature. Moreover, studies conducted by Louisiana State University indicated that a loss of accuracy of as much as 8% is possible when both the voltage and currents contain harmonics.

(c) *Transducers.* Electronic meters are coupled to the power line through transducers. The most common types of coupling devices are potential and current transformers. These transformers have a certain degree of accuracy guaranteed when subjected to 60/50 Hz voltages and currents. When subjected to distorted voltages or currents, it is not clear whether the voltage and current ratios and inherent transformer phase shifts are still within the certified range of accuracy for pure sinusoidal conditions. A dc component in the voltage or current may cause core saturation. High frequency harmonics are transferred through capacitive coupling. The skin effect increases the winding impedances. High voltage spikes may affect the contents of memory devices or the display used in the electronic meter.

6.4.2 Examples of extreme waveform distortion

Some examples of extreme distortion on voltage and current waveforms are shown in figures 6.3–6.6. The voltage of figure 6.3 was taken at the service box of a three-phase supply serving a pump motor with a variable speed drive. The line-to-line voltage was 480 V and measurements at the medium voltage level did not indicate any cause for concern of damaging spillover to other customers.

The voltage depicted in figure 6.4 was captured at the installation of another variable speed drive. The distortion is completely different to that depicted in figure 6.3.

Figure 6.5 depicts the unfiltered current to a six-phase power rectifier serving a 100 kW TV transmitter load. The smoothing filter capacitors were never installed for some unknown reason.

In figure 6.6 a load current rich in the third harmonic from a small industrial plant is shown.

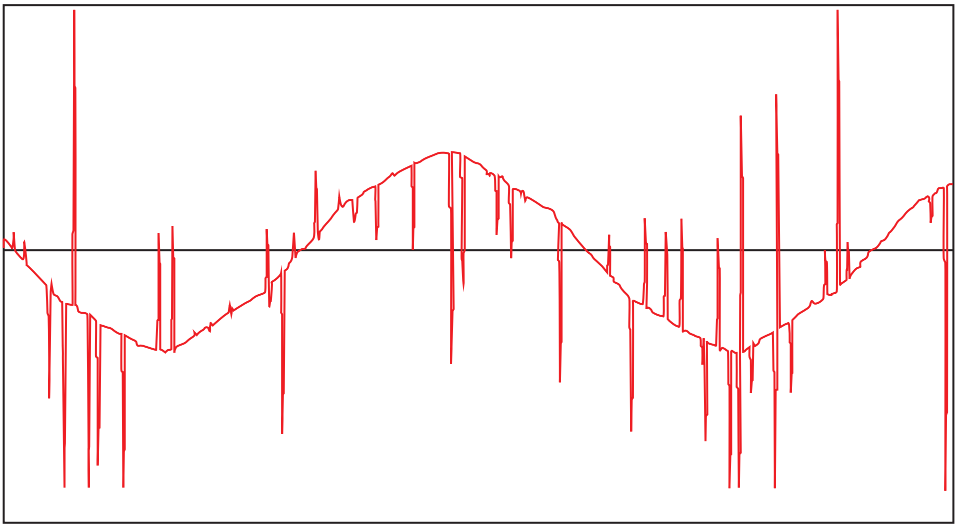


Figure 6.3. A severely distorted voltage waveform at a pump motor installation.

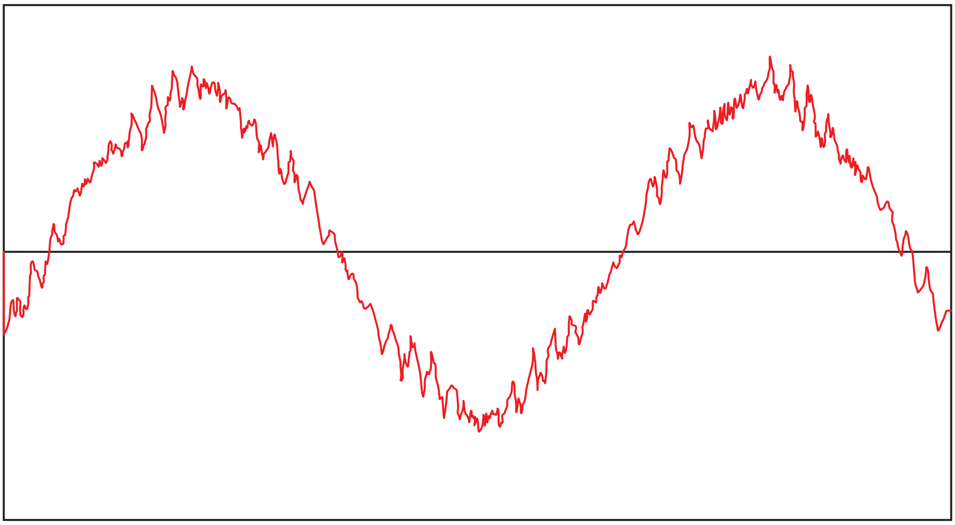


Figure 6.4. Another example of voltage distortion at a frequency drive installation.

Figures 6.3 and 6.4 do not exhibit steady state conditions and are difficult to characterize in terms of Fourier series and in essence represent a distorted periodic waveform as the superposition of a series of higher-order frequency components (harmonics) and a fundamental sinusoidal component. Figures 6.5 and 6.6 are more amenable to this kind of analytical representation.

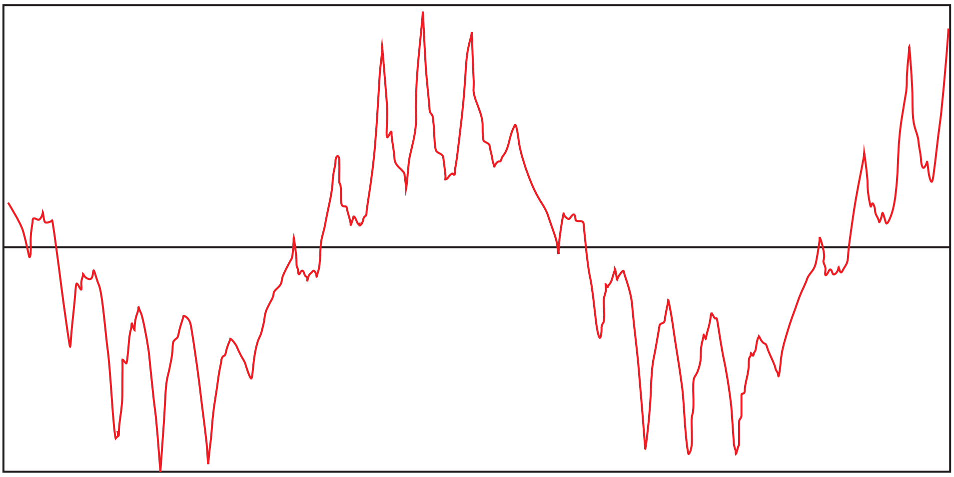


Figure 6.5. An unfiltered current to a six-phase power rectifier.

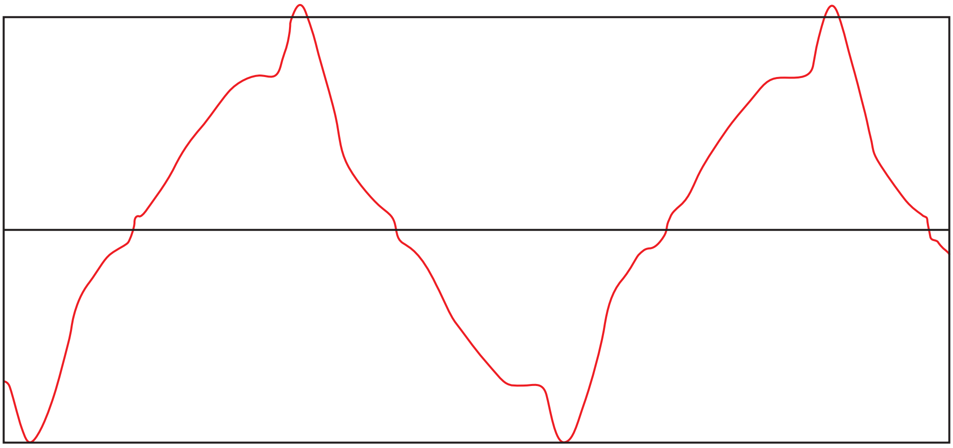


Figure 6.6. Significant third harmonic distortion in a current waveform.

6.5 Standards issues

The existing standard on power quality in the USA related to metering accuracy has been discussed by many professionals. Their concerns are primarily based on distortions due to integer harmonics of the 60 Hz waveform. However numerous field investigations have indicated that many distorted waveforms are rich in non-integer subharmonics and behave like steady state waves for certain intervals of time. A few such waveforms were shown in figures 6.3–6.6.

There are suggestions for introducing new rate structures based on kVA rather than on kW. These suggest penalizing the customer for a bad power factor. For a steady state sinusoidal voltage and current, kVA and kW are coupled by the concept of the power factor. The problem becomes extremely complex when both voltage and current are distorted. Under non-sinusoidal conditions and three-phase unbalanced conditions, engineers and scientists involved in the study of power entities have yet to agree what kVA means and whether there is even a correlation between real power and kVA.

At this moment it is not clear how much revenue is lost due to inaccurate meter registration due to severe waveform distortion within an electric utility. Locations or institutions performing calibration of electric energy meters under distorted voltage and current conditions are scarce and are not generally available or known. It is also not clear what *standard distortion* means and what a good measure of accuracy is.

The time has probably arrived to develop some generally accepted standards of distorted waveforms. For example, in the area of transient voltage testing, standard test waveforms such as the 1.2×50 μs voltage impulse wave and the 10×20 μs current impulse wave for testing the dielectric integrity of electric devices were adopted a long time ago. Yet these test waveforms are not necessarily replicas of the transient waveforms measured in the electric networks. However it has been proven repeatedly that withstand levels to transients as defined by these tests using the indicated waveforms provide a guaranteed level of survival against normally occurring damaging transients.

The same effort could be applied to arrive at some standard distortion of both voltage and current waveforms. Voltage and current waveforms are not independent of each other and using modern day data acquisition systems gathering these types of data is not difficult. References [10–12] described some of the techniques used to replicate distorted waveforms in a testing laboratory for meter calibrations.

6.6 The role of communications

With a communication infrastructure already in place, the question arises of what is the nature of the information needed to bring back to the dispatch center computer.

One possible method, pending the development of new meaningful metrics to measure power quality, is the use of a contiguous sequence of short time monitoring intervals ΔT. For each interval of ΔT the THD can be computed. For a contiguous number N of such intervals the maximum $\mathrm{THD}_{\mathrm{max}}$, the minimum $\mathrm{THD}_{\mathrm{min}}$ and the average $\mathrm{THD}_{\mathrm{avg}}$ can be computed. This method allows one to identify the degree of bursts occurring per unit time. If $\mathrm{THD}_{\mathrm{avg}}$ is very close in magnitude to $\mathrm{THD}_{\mathrm{max}}$ and $\mathrm{THD}_{\mathrm{min}}$ then this simply means that there are no minima or maxima. If $\mathrm{THD}_{\mathrm{avg}}$ is close to the magnitude of $\mathrm{THD}_{\mathrm{max}}$ then this simply means that there are more maxima then minima.

The interval $(N \times \Delta T)$ is time-stamped and the THD data are retrieved from the remote monitoring site using the communication system. ΔT can be as short as one or a few cycles of the 60 Hz wave and $(N \times \Delta T)$ can be as long as 15 or 30 min. To reduce the amount of communication bandwidth used, a number of consecutive intervals $(N \times \Delta T)$ can be stored in the memory of the monitoring device and retrieval of the stored data is performed on a daily schedule.

To take advantage of the communication network it is also possible to simplify the time correlation of the collected data by service territory. The following method can be used. All power quality monitoring devices connected to a distribution feeder or phase of a feeder can be assigned to a functional group address which can be communicated to by a single group command. The functional group data do not only provide time correlation, but also correlation by location served by the same supply or source.

The same technique can be applied to the monitored voltage. By time correlating the time-stamped collected data for a certain service territory, feeder or network section served by a distribution bus, one can decide whether the problem is local or widespread. The magnitudes of the monitored data also provide an indication of where the culprit of the harmonic pollution is located. Power line types of communication technologies are affected by severe power quality problems. Unusual degradation of the communication performance on a physical channel will serve as an alert of power quality degradation. Strategically placed advanced electronic meters capable of monitoring THD and voltages can be used to collect useful information. Also PLC impairments could be used as an alarm to pinpoint distribution network areas where power quality problems occur.

6.7 Conclusions

1. The effects of waveform distortion of the 60 Hz voltage and the current on metering devices and the lack of test standards have been discussed.
2. Loss of revenue due to inaccurate energy metering will offset the benefits gained by having an AMR system. Conversely, metering inaccuracies due to waveform distortion effects as described in this chapter can sometimes also affect customers’ devices.
3. A communication system for AMR, hardened to harmonic distortion, can be used to pinpoint localized power quality problems.
4. Some sophisticated electronic meters already exist, which have the capability to monitor THD. For the time being, they may be candidates for monitoring power quality problems by strategically scattering them throughout the distribution network.
5. For PLC systems, a sudden drastic drop in communication performance on certain physical communication channels can be used as an alert that a power quality problem exists on that part of the electric network.
6. There is definitely a need for a standardized distorted waveform that can be used for revenue meter calibration purposes and which can be replicated in testing laboratories. In addition, a metric has to be defined as a measure of metering accuracy when operating under distorted voltages and currents.
7. Consequently, as we improve our understanding of the effects of voltage distortion on meter accuracy, and in the search for answers to the above questions, we realize the great potential for using the communication system for AMR in conjunction with data acquisition equipment strategically positioned on the distribution network to better identify power quality problems.