Next Generation Advanced Power Quality Instrument

Technical Report

Next Generation Advanced Power Quality Instrument

Information on Systems Hardware, Firmware, Customized Silicon System Chips and Software Design Specifications

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Final Report, November 2001

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REPORT SUMMARY

This report addresses the key needs and upfront requirements for implementing a next-generation advanced power quality instrument. The instrument has been defined in prior work, which includes a set of desired functional and design specifications. This report takes the process one step further and analyzes the present state of the art for implementing these desired specifications.

Background

With the advent of digital signal processing, it was only a matter of time before manufacturers of revenue meters would begin to replace the spinning disc with a completely solid-state meter. These new meters perform as well or better than the existing induction disc method while surviving outdoor temperature extremes, lightning, and surge protection requirements, as well as meeting other design and cost challenges. Gradually, as electronics have become less expensive, the digital revenue meter has matured. Some manufacturers are adding a few power quality-monitoring functions to these meters. Additionally, a few power quality monitors are able to perform basic revenue-metering functions. Only recently has it been feasible to combine these two functions into a single meter at a lower cost and overall better performance.

In 2000, EPRI launched the Power Quality Revenue Meter project to develop a state-of-the-art meter that combines the functionality of a revenue meter and a power quality meter into the same package. The functional and design specifications for the meter were written using input from a committee of meter manufacturers and expert users such as electric utility engineers. The desired functions were then ranked in order of importance.

The instrument package will ideally resemble that of a revenue meter and will be suited for installation in a standard meter base at commercial and industrial facilities. A secondary option is an even lower-cost “just PQ” meter that can replace the traditionally cost-prohibitive PQ investigation instrument of the 1990s. The design philosophy for both of these target markets is upward scalability to accommodate additional features and functions in the same instrument enclosure. One concept is that each meter may be shipped fully featured in hardware and processing capability. The overall cost might depend on how many features a customer wants. Appropriate functions would be enabled by software, allowing equipment users to tailor the device’s functionality to meet their needs or their customers’ needs. It also enables addition of new features with minimal cost by upgrading software, rather than upgrading hardware.

The selling price for a base instrument is targeted at a lower cost than existing designs, so to meet the low-cost target, some desired features written in the functional specification (such as transient

capture and accuracy) may not be included in the final product. Software-based expandability, low cost, and high accuracy are key design goals of the instrument.

Objectives

- To present the best of all available hardware technologies to facilitate the design process in a state-of-the-art report with latest chip technologies and silicon processes that will help to bring the design goals within the instrument's cost target.
- To address concerns of users of power quality instruments to guide the design process and resolve many of the shortcomings of present power quality monitors.

Approach

Information contained in this report is built on the collective knowledge of power quality engineers who have worked closely with meter manufacturers for many years or who have worked in electronics manufacturing environments. The report contains the summary contents of all interim reports issued in the earlier stages of this research project, including the report of June 2001 (EPRI 1005936). Additionally, new research has been conducted using the Internet, trade publications on instrumentation and power quality, and conversations directly with manufacturers of power quality meters and revenue meters.

Results

This report describes specifications and potential cost-reduction ideas for a multi-function revenue meter with a thoughtful and useful set of power quality-monitoring capabilities. The intent is for the meter to be priced such that it can be widely implemented in a utility, while being flexible enough to meet most power quality-monitoring needs of a typical electric utility. Changes taking place in the utility industry dictate a need for a flexible revenue meter. Data from such a meter can be used not only for billing but also to tailor new products for customers. The data also will be useful for power aggregators as they try to predict short-term demands.

EPRI Perspective

By providing utilities with the tools necessary for monitoring the quality of power delivered to their customers, they are better able to provide valuable services to those customers. EPRI can facilitate development of low-cost power quality monitoring systems that can be distributed in large numbers throughout a utility's service territory. The widespread availability of monitoring data over a larger region enables utilities to cost-effectively manage power quality problems on the network as well as at end-user facilities.

Keywords

Power quality	Monitoring	Revenue meter	Instrumentation
Metering	Digital Signal processing		

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1
INTRODUCTION

This report begins with a unique perspective on the features and capabilities that are desirable in a new power quality instrument. This chapter is written without the partiality that would be prevalent if written by a commercial manufacturer of metering equipment. It is written strictly from the combined experience of power quality (PQ) engineers on staff at EPRI PEAC, from surveys of utility PQ engineers, surveys of revenue meter manufacturers, and finally, from a long work history with other PQ engineers at electric utilities across the United States.

In the discussions in much of this document, it is assumed that the digital revenue meter has already evolved into a fairly mature product. At this point, we treat the revenue meter as a highly standardized piece of metrology. We also assume that its cost has been reduced through years of competition, mass production, and evolution. In other words, there is little need for discussing features of this part of the PQ revenue meter, and it can be treated as a completed block with a fixed price. Therefore, this document will be centered mostly on the PQ aspects of a new meter.

Monitoring in the Past

Digital power quality monitors during the 1980s and early to mid 1990s were very expensive, costing approximately $12,000 to $17,000. A typical monitor may have weighed approximately 25 lbs and would have physical dimensions similar to rack-mountable equipment or a bench-top oscilloscope. Typically, the instruments were not user friendly. Proficiency with some of these instruments required a fair amount of time investment.

Meters were fully functional as stand-alone equipment. That is, users could set them up for monitoring, control their operations, and perform data analysis completely by the use of buttons on the front panel. A typical meter had built-in display capability either in the form of a small screen or thermal paper printouts. The capability to connect to a computer for data extraction was an optional feature. Optional interfaces were standard serial or parallel ports. For those meters with data-export capabilities, the data would be saved in a proprietary format, making it impossible to read or analyze with any software other than the package written for the particular instrument. Data often contained an embedded logo of the meter manufacturer.

Monitoring in the Present

Recent trends in power quality monitoring include a progression of features such as mass-storage hard drives, extremely high-resolution A/D conversion, fast sampling rates, and on-board processing. The mass production of this type of hardware, thanks to a booming computer industry during the mid to late 1990s, has brought prices much lower than in the past, making PQ monitors much more capable and yet less expensive than their predecessors.

Many new manufacturers have entered the market with innovative meters. Monitors began to take on more unique shapes and sizes. Handheld power quality meters became a reality, although they remained fairly expensive. The capability to export data to a computer has become a necessity, and therefore nearly all PQ measurement instruments designed since the mid 1990s have data export capabilities. A typical communication scheme is a standard serial or parallel interface, while faster ports or remote connections are available as options. New data-storage options such as flash RAM cards have become available. A typical card may hold 1, 2, 4, or 8 megabytes of data.

One emerging trend is toward minimizing the number of buttons and controls on the meter itself. This has been accomplished either by “soft” buttons on the front panel, whose functions change depending upon the present mode, or by manipulation of the meter by computer connection. Having fewer fixed buttons reduces manufacturing costs and increases flexibility. A few meters take this trend one step further and require a full-time connection to a computer. All user controls are software buttons, and all processing and data storage are done by the connected computer. The meter itself is thereby reduced to a simple data-acquisition unit.

Software tools have become more useful, but data is still mostly proprietary. The Power Quality Data Interchange Format (PQDIF) standard is emerging, which is designed to make PQ data platform-independent.

Although these features represent state-of-the-art advancements in meter technology, and although prices have generally dropped, a power quality team of a typical electric utility cannot afford all of the meters that it needs to conduct widespread or long-term monitoring.

Monitoring in the Future

In the next five years, the trend will likely be toward cost and size reduction. Fully-featured PQ instruments will continue to be popular, but a new set of low-cost special-purpose meters may emerge. For example, a meter may be designed specifically to capture voltage sags. Such a meter may have only inputs for voltage and not current. It will not produce RMS trends or perform harmonic analysis. The processor, storage, and data-acquisition system can be minimized for this special purpose, making the meter affordable for utilities to purchase in larger quantities for the common task of monitoring voltage sags.

Future monitors will be PQDIF-compliant, making them more versatile. Software functions will become more sophisticated and more useful. Manufacturers will continue to provide better communication options using data compression and faster data transfer rates.

Ideally, power quality monitors will be inexpensive so that large customers such as electric utilities will be able to afford a large number of monitors. Presently, a utility that buys five monitors at $15,000 each is not able to leave a monitor at a customer facility for an extended period of time, nor is the utility able to simultaneously monitor at very many locations. In the near future, a utility should be able to purchase 150 monitors (at $500 each) for the same investment.

Customer Needs

Available PQ monitoring products do not always fulfill customer needs. Today's customers have more monitors from which to choose, but inevitably they will find that necessary features are spread among multiple monitors, and that no single monitor fulfills the present needs. For example, customers faced with a decision to purchase monitors may be forced to sacrifice ease of use in order to get a meter that will perform all of the needed functions. In summary, customers need reliability, portability, low cost, and ease of use. Meter manufacturers are working toward meeting these design goals in a single unit.

Problems with Power Quality Monitors

EPRI PEAC Corporation informally interviewed utility power quality engineers to gain further insight into the most and least desirable characteristics of today's power quality measurement instruments. The comments were consistent with those heard for many years on the subject. Typically, those who depend on power quality monitoring equipment on a daily or weekly basis have these complaints:

- Reliability – For a variety of reasons, whether it is a crashed hard disk, full memory, thresholds set incorrectly, CPU lockup, or other problems, a monitoring session can produce incomplete data or no data at all. It is costly and embarrassing to learn at the end of a monitoring period that no data has been captured. However, the solution, which is frequent tending of the meter at short intervals during the monitoring period, is also costly.
- Interface to PC – Whether a monitor connects to a PC via modem, serial port, or even Ethernet, communication has been a weak point for many monitors. The connection in some cases is difficult to establish. In other cases, communication is lost during a download session. Both rank highly as causes of user frustration.
- Classification of events – Each meter has its own non-standard rules for classifying events. For example, in a former EPRI project on power-line monitors [System Compatibility Research Project: Task 21 Powerline Monitors] multiple meters by different manufacturers were subjected simultaneously to a two-cycle (33 ms) voltage sag to 90% of nominal voltage. In this example, the monitors accurately reported the magnitude of the event, but the reported durations were anywhere between 16 and 83 ms.
- Proprietary data format – Until PQDIF was developed, all meter manufacturers had their own proprietary data-storage formats and their own software for reading data. Although meter manufacturers are conforming to the PQDIF standard, it is still not a completely bug-free platform-independent format. Data should be easy to extract and to save in a format readable by any spreadsheet software.
- Confusing software – Many users have complained about software that is confusing to operate. The result is often lost data due to incorrect threshold settings or basic meter settings that can be easily forgotten, such as enabling a hidden save-to-disk feature. Users often waste time searching for functions that are hidden or difficult to access.
- Data presentation – In many software packages, users waste time making up for inadequacies of software. Many users spend a significant amount of time interpreting waveforms that are not presented clearly. For example, simple vertical or horizontal scaling of data should be done so that users do not have cumbersome fractional units per division.

Although the comments above are not listed in any official order, they are generally in the order of importance beginning with the most costly problem.

Suggested Improvements

Below are some suggestions for improving power quality monitors. Again, these are provided by power quality engineers who rely heavily on monitoring equipment. The list addresses some of the concerns shown in the previous section, but also introduces some additional ideas for future improvements.

Solid-State Data Storage

Hard disks are vulnerable to wear, vibrations, shock, moisture, and other environmental factors because they are mechanical devices. Solid-state storage (Flash memory) is much more immune to the environment. It is also becoming smaller and less expensive compared to years past, but cannot compare to a hard disk in terms of capacity or read/write speed. In applications where a large amount of data storage is not needed, RAM is a much better option than a hard disk. In order to minimize the data-storage requirements, filtering of important versus unimportant data becomes an important consideration. Also important are data-compression techniques.

Self-Diagnostics

Power quality monitors are complex and multi-functional devices. In the event of failure of one particular component (for example, a monitor's built-in modem), the user cannot readily determine the reason for the trouble. Time is often wasted while checking and double-checking connections, wires, or other potential weak links before the user realizes that there has been a failure of a meter function. Self-diagnostics are recommended for basic functions such as modem (or other communication hardware), data-acquisition channels, memory, display, and other peripheral functions.

PLC (Power-Line Carrier)

PLC is a communications method where signals are transmitted and received using power lines as a transmission medium. This method has the distinct advantage of permitting the use of an existing infrastructure instead of adding copper wires or fiber-optic cable. It is particularly useful where the cost of the hardware is a disadvantage or where it is impractical to run a telephone line, such as in very remote locations. Possibly the reason that this communication option has not been given much consideration is because of some known disadvantages, including the inability to pass the signals through transformers. Another disadvantage is the relatively slow data transfer rate compared to other, more common media. While the known disadvantages seem to rule out this option, the lower costs and the potential for not needing a fast or constant communication with the monitor may make this technology a viable option. Some further exploration is needed in this area.

Clock Synchronization

Inexpensive meters have independent timekeeping or in some cases, no clock at all. Typical internal clocks are free-running and may drift by several seconds during a daily monitoring period. A permanently installed meter needs a higher standard of timekeeping for the purposes of data correlation with other meters on the same circuit, correlations with customer equipment upset, and reporting of information for database storage or requirements of regulatory commissions. There are several ways to achieve this. The most cost-effective method may be by periodic synchronization signals from the central monitoring station to each installed meter using the same communication scheme that is used to transmit data. Another option is periodic synchronization of each meter against a GPS clock. However, a GPS receiver is very expensive.

Intelligent Software

Digital power quality meters operate by sampling voltage and current waveforms at a rate that is sufficient to analyze the signals or portray a transient event. While it is the philosophy of some meters to store everything, very large amounts of data can become overwhelming to users and is not useful if it cannot be presented in a meaningful way. Filtering the extraneous data from the useful information can be an arduous task. At the other extreme, monitors that have very little capacity to store data often do a quick analysis on sampled waveforms, store a description of the event, and then throw away the raw data. In the latter case, if a meter’s assessment is not adequate or accurate, information is permanently lost. Intelligent software is needed to find the most relevant and meaningful balance of data storage and information storage.

Power quality standards can help to determine which events should be stored. For example, the ITIC (Information Technology Industry Council) curve is a voltage-versus-time envelope defining an area in which most information technology equipment will operate, as shown in Figure 1-1. At a minimum, events falling outside the ITIC curve should be recorded.

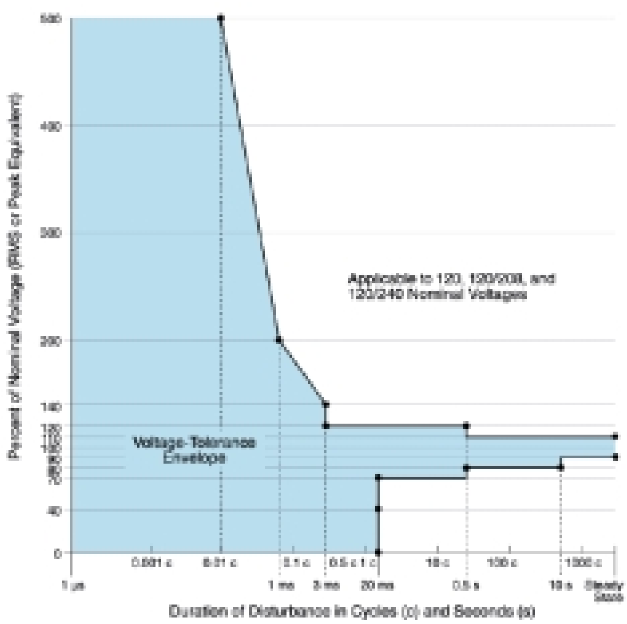

Figure 1-1
ITIC Curve (Formerly CBEMA, Computer and Business Equipment Manufacturers Association)

Value-Added Software

Software features such as power quality solution guides or intelligent data analyzers can help customers diagnose, predict, and resolve power quality issues. For example, EPRI's PQ-KAD (Power Quality Knowledge-Based Analysis and Decision System) offers real-time solutions to complex power quality problems. It synthesizes power quality and plant process monitoring and control system information with the overall financial impacts of power quality problems. Advanced analysis and decision-making methodologies are used to facilitate effective system tradeoff analysis. It understands the needs of energy providers and their customers, and can help engineers make more informed decisions about customer power quality solutions. Many other opportunities exist to enhance basic meter functionality with a software investment.

Wavelets

Wavelets are mathematical functions that divide data into different frequency components, much like the Fourier transform but with the added feature of time localization. This makes wavelets good for analyzing irregular waveforms containing discontinuities or sharp transients. Waveforms do not need to be periodic or symmetrical to be represented in wavelet form. Data stored as wavelets occupies less storage space, making it a useful data-compression technique.

Wavelet analysis is similar to Fourier in that it breaks down a signal into smaller parts; however, while Fourier breaks the signal down into a series of sine waves, the wavelet transform breaks down the signal into a series of wavelets. These wavelets are scaled and shifted versions of the original signal. Figure 1-2 shows a sine wave signal and a wavelet.

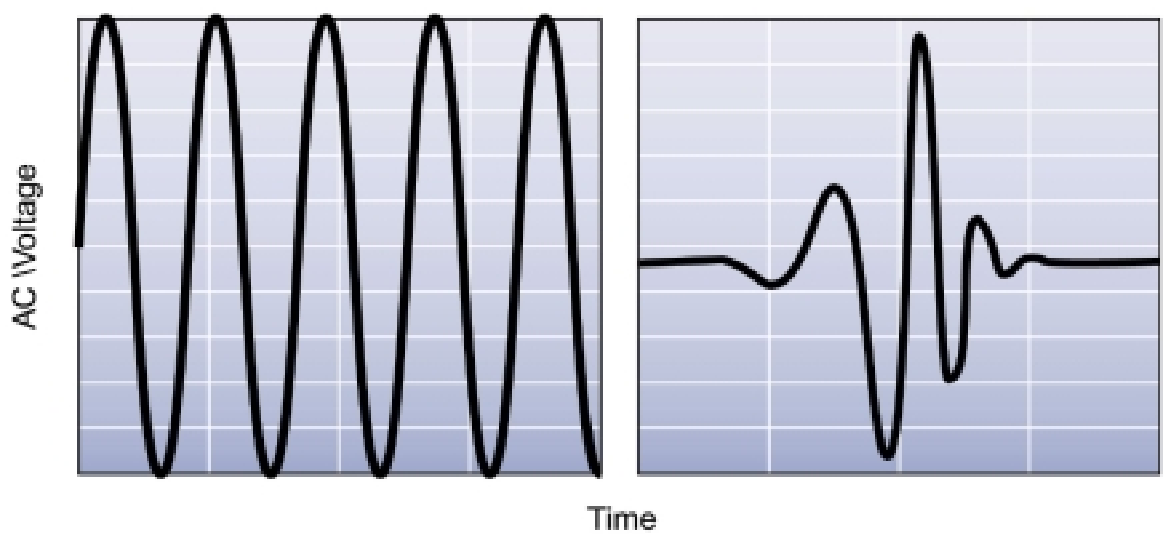

Figure 1-2
A Sinusoid (Left) and a Wavelet Used in Fast Fourier Transform and Wavelet Analysis

2
SUMMARY OF PRIOR WORK

A summary of prior work by EPRI to advance the PQ revenue meter is outlined in this chapter. This work was carried out during the year 2000 and is documented in EPRI TR 1000372, *Development of Meter Specifications.* The key activities were:

- Established a committee of expert users for discussion of desired meter features
- Created a Web-based forum for information exchange among committee members
- Performed a literature survey of existing monitor features and relevant information
- Surveyed manufacturers of revenue meters to assess their expectations for the revenue meter portion of the instrument
- Surveyed electric utility engineers for desired features and specifications
- Discussed the instrument with manufacturers of PQ meters to assess their level of interest in developing such an instrument
- Developed functional specifications based on input from the above sources
- Analyzed costs versus benefits of proposed meter features

Among the many types of electrical disturbances, this report identifies transients, voltage sags, voltage swells, voltage notches, harmonics, and voltage fluctuations as the greatest concerns to commercial and industrial customers. To measure these disturbances, the meter could be equipped with all the necessary hardware, which can then be activated on a feature-by-feature basis. This would afford the meter a great flexibility, enabling meter users to tailor functionality to meet their specific needs. The only additional hardware required would be a communications module, the type of which would depend upon the available mode of communication, such as modem, Ethernet, or cellular.

Surveys of Utilities and Manufacturers

EPRI PEAC Corporation conducted two surveys: one for utilities and one for manufacturers of revenue meters. A survey of power quality meters was also planned, but informal discussions with several manufacturers of power quality meters determined that their lack of interest in the project warranted no issuance of a formal survey.

Utilities indicated that the measurement of voltage sags was the highest priority, with the measurement of other electrical disturbances following (see Figure 2-1). Meter personnel tended to rate power quality features low, whereas power quality professionals rated them high. Most

(75%) supported the idea of specifying a single meter with "soft" upgrades to avoid expensive hardware change-outs. Half of the respondents indicated that the meter would have to be a "socket" type. Ideally, such a meter would be priced low enough to use widely throughout a distribution system ($500 for a base system).

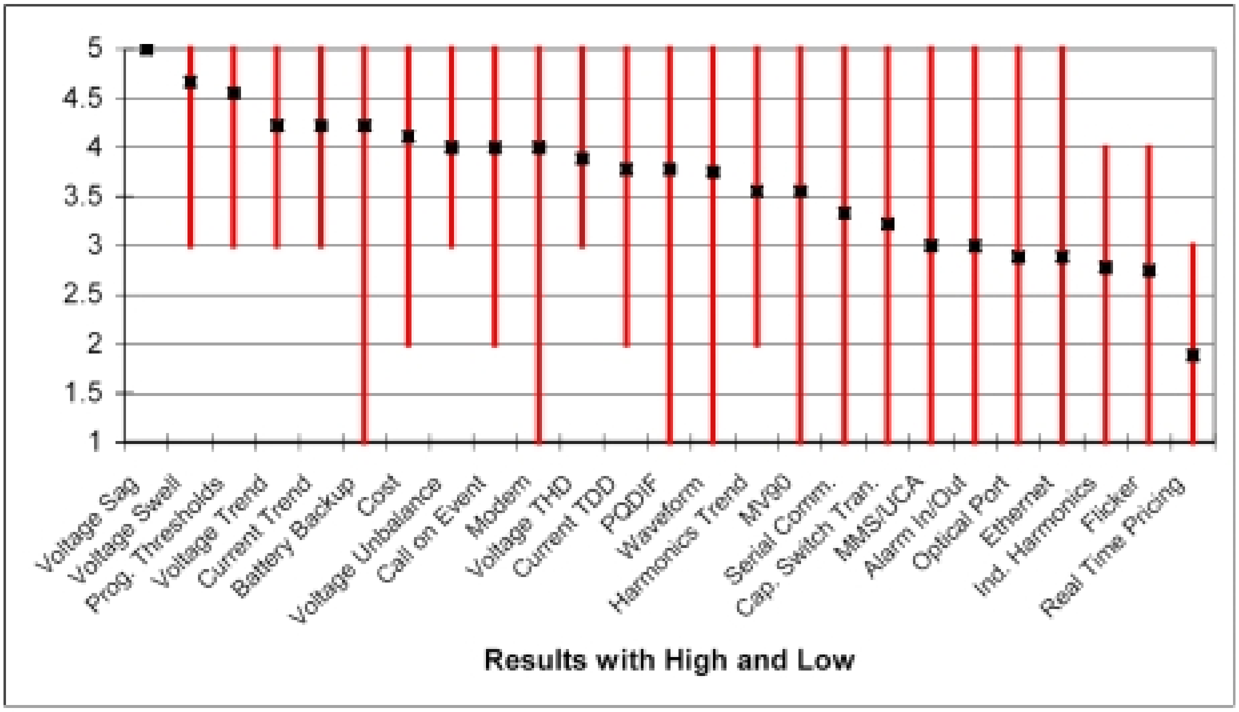

Figure 2-1
Ranking of the Importance of Electrical Disturbances by Electric Utilities
(Higher Numbers Mean More Importance)

Manufacturers of revenue meters indicated that they were concerned about the increased production costs of adding power quality measurement features. For example, the calculation of flicker would require expensive hardware that would increase the cost of the meter beyond the target price, and the capture of waveforms would require increasing the amount of memory. Power supplies were another concern of the revenue-meter manufacturers, who predicted an additional cost of between $30 and $60 for an adequate power supply for the various hardware features.

Functional and Design Specifications

Expert users and manufacturers of metering equipment generated a list of desirable features and specifications that they thought should be developed into the next generation of advanced power quality instrument. They prioritized the list of features and specifications based on benefit and usefulness, but the list is not necessarily all-inclusive. Furthermore, in order to meet the cost objectives, some of these specifications may not be feasible in the final product.

Revenue Meter Functions

Revenue metering is the most important function of a power quality revenue meter. A power quality revenue meter must be able to measure the quantities required for billing under the various tariffs in effect. The continuing interest in distributed generation makes four-quadrant metering important. The meter should be able to measure power flow into and out of customer facilities. Specifically, the following features were considered most important by the panel of expert users:

- 0.2% accuracy on kWh and kW
- Standard meter functions such as demand kW and kWh (delivered and received)
- Four-quadrant metering
- Four-channel recording
- Multi-level password protection
- Alpha display
- Battery-backed operation (15 seconds for the meter, 35 days for the data)
- Compliance with MV90
- Compensated metering (transformer loss)
- Alarm inputs and outputs (minimum of four, selectable for input or output)
- Real-time pricing capability
- A-base, socket, and panel models available

Power Quality Metering Functions

The meter should measure the most common electrical disturbances that cause problems with process equipment and commercial operations. A meter that measures all disturbances is too costly. Therefore, capabilities must be chosen with cost/benefit in mind. The meter needs to have an overall cost that does not impede its widespread installation in a distribution system. It should measure and monitor the most notoriously problematic events, such as voltage sags, swells, overvoltages, undervoltages, voltage and current unbalance, voltage and current distortion, and momentary voltage interruptions. Specifically, the following were considered to be the most important capabilities by the panel of expert users:

- Logging of voltage sags in table form (magnitude and duration with 0.5-cycle resolution, time stamp)
- Logging of voltage swells in table form (magnitude and duration with 0.5-cycle resolution, time stamp)
- Programmable thresholds for voltage limits
- Waveform capture on event (voltage and current at 128 samples per cycle)

- Voltage unbalance measurement
- Voltage trending (minimum, average, and maximum during the billing interval)
- Current trending (minimum, average, and maximum during the billing interval)
- Capture of capacitor-switching transients (300 to 900 Hz)
- Call home on event
- Logging of voltage THD events with programmable threshold
- PQDIF data export from the interface software
- Alarm inputs and outputs (minimum of four, selectable for input or output)
- Logging of current TDD events with programmable threshold (total demand distortion as defined by IEEE Std. 519-1992)
- Harmonic trending (V_{THD} and I_{TDD})
- Individual harmonic trending

Communications

The envisioned power quality revenue meter will have an interchangeable module for advanced communication options. These options will enable the meter to be used for data transmission to the electric utility or wires company. Plug-and-play options include modem, Ethernet, and cellular communication. Below is a list of communication features voted as most useful by the panel of expert users:

- Standard optical port and serial (RS232) communications port
- Optional modem, Ethernet, and RS485 ports
- MMS/UCA, Modbus, and DNP3 as options

Interface Software Specifications

- PQDIF data export option
- Compliance with MV90
- Compliance with ODBC (Open Database Connectivity)
- Compatible with Windows 95/98, NT4.0, and 2000
- Includes a full version for translation and a version for data access and programming
- Automated polling of meters via telephone or Ethernet

A possible scenario is that the meter would function as a basic revenue meter out of the box. Advanced functions, the cost of which would be added to the price of the basic unit, would be activated by using the interface software. This flexibility would enable equipment users to tailor the functionality of the device to meet their needs. It also enables the addition of new features in the future by upgrading software, rather than upgrading hardware. Therefore, the signal-processing and data-processing subsystems would need to be state-of-the-art to allow for the addition of new features in the future. A modular power quality revenue meter would have three main functions: revenue metering, power quality monitoring, and communication.

Cost/Benefit Analysis

A cost/benefit analysis yielded specifications for a revenue meter that would measure steady-state voltage, voltage sags, voltage swells, voltage unbalance, transients, and distortion. The meter would also be able to capture waveforms. The cost of the base unit is estimated to be around $500, and the cost of the fully featured unit would be around $1,500. With a base cost of approximately $500, it would be feasible to install this meter at many, if not all, sites of commercial and industrial customers. The power quality and advanced revenue features can then be added on to those customers who warrant the additional expense or those that have a power quality complaint. The majority of power quality events affecting customers are voltage sags. The proposed meter could cost-effectively monitor voltage sags on an entire system.

Interim Report

A report was issued in June, 2001 (EPRI 1005936), which served as an update for project sponsors. It contained ideas for potential new features that would be useful in a new meter design. The report also compared present technologies of power quality instruments by price category. Additionally, it listed available technologies of necessary components such as memory and batteries. The contents of the interim report are included in appropriate sections of this final report.

3
STATE OF THE ART IN POWER QUALITY METERS

Semiconductors continue to become smaller, denser, and more affordable. For the world of electronics, this means that functions that were cost-prohibitive and even inconceivable several years ago can now be built into electronic equipment. For example, when the first VHS home movie cameras were introduced, their functions were limited to recording and playing back cassettes. Modern camcorders now include such features as retractable color video screens, digital special effects, wireless remote control, built-in audio, removable non-volatile memory, long-range zoom, image stabilization, and infrared night-vision. All of these features come in addition to the standard videocassette functions, but in a much smaller package than the first generation of camcorders. As a bonus, the price for a full-featured camcorder today is actually lower than the first generation of camcorders. A similar trend can be seen in nearly all portable electronic appliances.

Today, there are very few low-priced (less than $1,000) power quality monitors. The current generation of monitors has only basic features. The majority of meters that have been manufactured in recent years fall into the midrange ($1,000 to $6,000) or high-end ($6,000 – $15,000) categories. Meter manufacturers are beginning to answer the call for affordable monitoring. In recent years, the reduction in the cost of microprocessors and digital signal processors (DSPs) has enabled the development of monitoring equipment with limited power quality functionality at a relatively low cost. As this trend continues in the cost of semiconductor devices, more capabilities will become available. This concept is further illustrated in the following paragraphs.

Low-Cost Meters *(<$1,000)*

With the exception of revenue meters with limited PQ functionality, the monitors in this cost range are voltage-only devices. However, the lack of current measurement is not always a hindrance to their use. Some of the devices available today offer only status lights to indicate the presence of events. This can somewhat limit their usefulness for diagnosing customer problems.

There are many instances where voltage-only monitoring with an inexpensive device is justified. The EPRI Distribution Power Quality Project verified that the majority (as many as 80%) of the events that a distribution customer experiences are voltage sags and momentary interruptions. Even the lowest-cost meters in this group are capable of detecting such events. Meters in this price range are particularly interesting to a utility if it is considering a widespread monitoring application to provide system benchmarking or notification about a power outage or power quality event. More expensive monitors, although having more features, are cost-prohibitive if widespread application is needed.

Existing Specifications

The low-cost meters can be subdivided into two groups: 1) revenue meters with limited power quality-monitoring functions and 2) power quality-only meters. Revenue meters are designed to first be a source of accurate data on energy usage for billing purposes. In recent years, some manufacturers of revenue meters have added a few power quality-monitoring features. This is possible through increased speed of DSPs and microprocessors. The traditional power quality meters are designed with a single purpose in mind: to monitor voltage quality at a specific location.

Accuracy

The voltage-accuracy specifications for this price range vary from 0.5% for revenue-grade meters to 2% for power quality meters.

Hardware Features

The types of features available in this price range include sag detection, swell detection, limited transient detection, and outage detection. One revenue meter also offers harmonic analysis for THD only. Some devices in this group can be upgraded with additional features, such as waveform capture, but that increases the cost beyond $1,000 per unit.

Software Features

The software interfaces of these meters vary. Some have no interface at all. Of the devices with software interfaces, the revenue meters are the most difficult to use. The software was designed to be used to program and read revenue quantities, with power quality added as an afterthought.

Communication Features

Some of these devices offer no communication. The rest offer communication via a serial port (infrared in one case). A few of the devices can be purchased with modems, but this may push the price over $1,000.

Future Specifications

The continued advances in digital signal processing and the subsequent reduction in price of these components promise the addition of many more features for devices in this price range. In the near future, these features are expected to be added without an increase in price:

- Modem or other remote communication
- Notify on event via pager, email, and so on
- Recording of voltage harmonics

- Voltage trending
- Transient detection
- Waveform capture of events

Midrange Meters and High-End Meters *($1,000 to $15,000)*

The midrange and the high-end meters tend to perform the same functions but have different levels of accuracy, sampling, filtering, storage, on-board capability, number of monitoring channels, and so on. For the purposes of this section, the midrange and high-end meters are grouped together primarily because the costs are coming down to the point where the high-end meters are now down around the midrange price and are expected to become even lower-priced.

Over the past ten years, there have been significant advances made in the power quality-monitoring arena. Manufacturers have found ways to incorporate many features into one device. In the early days of power quality monitoring, monitors fell into one of two categories:

1. Steady-state monitors
2. Disturbance monitors

In recent years, manufacturers have developed instruments that incorporate the features of both steady-state and disturbance monitors into one instrument. These devices, known as advanced power quality monitors, enable users to obtain data in both a hard (printed) and soft (electronic) format. Many of these devices come with proprietary software for performing post-processing and analysis. In fact, several devices have embedded algorithms in the hardware that are used to inform the user of the type of event that was recorded and the severity of that event.

The current application for the higher-end power quality instruments is to perform customer site monitoring to either trend the voltage quality or to actually diagnose specific events that have been causing process interruptions. The power quality team of a typical electric utility can afford only a few meters. They must stretch these few metering resources among hundreds of regional customers who need monitoring. The expense of the meter and the scarcity of the resources prohibit long-term measurements, which are often needed in order to perform a thorough study.

Existing Specifications

The specifications for monitors on the market today are highly advanced and technical. A majority of the high-end power quality monitors on the market today have the following minimum specifications:

- Sample rate of 128 points per cycle or greater for steady-state
- Transient-capture ability greater than 5 kHz
- Eight channels (four for voltage and four for current)

- Communication by modem or Ethernet
- Post-processing software for analysis
- Customized reporting features

Accuracy

The voltage-accuracy specifications for this price range vary from 0.5% for revenue-grade meters to 2% for power quality meters.

Hardware Features

The types of features available in this price range include sag detection, swell detection, transient detection, outage detection, harmonics, voltage monitoring, current monitoring, waveform capture, and, in some cases, DC channels and temperature. Most devices in this group can be upgraded with additional features for an additional cost.

Software Features

The software interfaces of these meters vary. Most have a reasonably good interface package and have advance software and analytical packages available.

Communication Features

Most of the devices in this price range offer nearly any conceivable communication function, including modem, parallel port, and serial port. Some of the more expensive units offer Ethernet connection.

Future Specifications

With the explosion of the Internet, manufacturers of power quality monitors have capitalized on the ability to view and transmit data via the World Wide Web (see Figure 3-1). Instruments have the ability to be set up via an Ethernet connection and a Web page. Data is made available via custom Web pages. This eliminates the need for users to install and be trained on custom software for the instrument. Many of these instruments have web pages embedded in the instrument itself. Others require servers to communicate with the instruments to allow for Web access to the data.

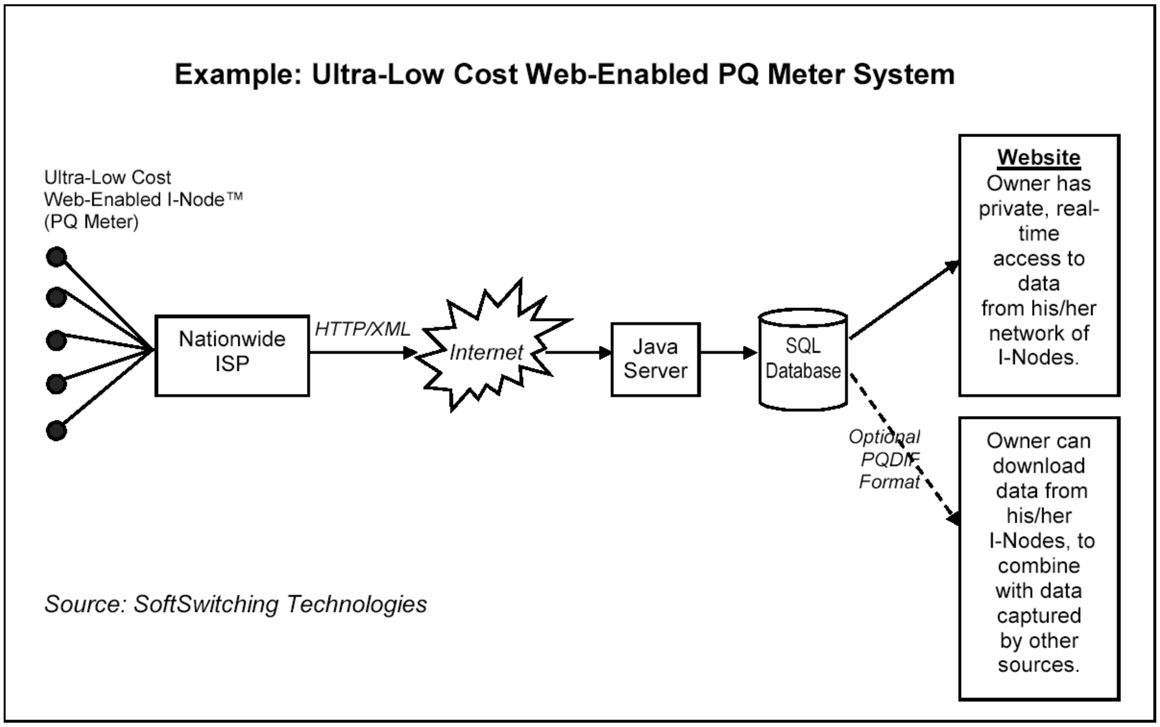

Figure 3-1
Example Low-Cost Web-Enabled Metering Technology

Figure 3-1 shows how the Internet and the trend to use Web-enabled metering for both revenue and power quality monitoring are driving costs lower. More and more Web-based meters are being introduced that can either act as servers themselves or can be connected to a server via the Internet and a Web host.

Functions versus Instrument Cost

One clear pattern with respect to monitoring is related to the cost-reduction techniques made possible by the utilization of commodity components. Table 3-1 shows how features are related to instrument price. The table shows an asterisk for current capability, two asterisks for near-term capability that will not raise the meter price, and three asterisks if it is a near-term capability but will likely raise the base meter price. Clearly, the higher-cost meters perform more functions and have more features at this time, but the table shows a trend toward the higher-cost meters moving into the mid range and the lower-cost meters actually having similar capabilities in the future as those found in today's midrange meters.

Table 3-1
Comparison of Functions for Meters in Three Price Categories

Feature or Function	Cost Range		
	< $1,000	$1,000-$6,000	$6,000-$15,000
Revenue Meter Functions			
0.2% accuracy on kWh and kW.	***	*/***	***
Standard meter functions such as demand kW and kWh (delivered and received).	***	*/***	*/***
Four-quadrant metering.	***	***	***
Four-channel recording.	**	*/***	*/***
Multi-level password protection.	**	*	*
Alpha display.	*	**	**
Battery-backed operation (15 seconds for the meter, 35 days for the data).	***	*	*
Compliance with MV90.	***	***	***
Compensated metering (transformer loss).	***	*	*/***
Alarm inputs and outputs (minimum of four, selectable for input or output).	*	*/***	***
Real-time pricing capability.	**	*/**	**
A-base, socket, and panel models available.	*	*	***
Power Quality Metering Functions			
Three Channel Voltage Metering	*/***	*/***	*
Three Channel Current Metering	***	*/***	*
Logging of voltage sags in table form (magnitude and duration with 0.5-cycle resolution, time stamp).	***	*	*
Logging of voltage swells in table form (magnitude and duration with 0.5-cycle resolution, time stamp).	***	*	*
Programmable thresholds for voltage limits.	*	*	*
Waveform capture on event (voltage and current at 128 samples per cycle).	*/**	*	*
Voltage unbalance measurement.	***	**	**
Voltage trending (minimum, average, and maximum during the billing interval).	**	*	*
Current trending (minimum, average, and maximum during the billing interval).	***	*	*
Capture of capacitor-switching transients (300 to 900 Hz).		*/***	*
Call home on event.	**	*/**	*/**
Logging of voltage THD events with programmable threshold.	***	*/**	*/**
PQDIF data export from the interface software	**	*/**	*/**
Alarm inputs and outputs (minimum of four, selectable for input or output).	*	*/***	*/***
Logging of current TDD events with programmable threshold (total demand distortion as defined by IEEE Std. 519-1992).	***	***	**
Harmonic trending (VTHD and ITDD).	***	*/**	*
Individual harmonic trending.	***	*/**	*
Communications			
Standard optical port and serial (RS232) communications port.	*	*	*
Optional modem, Ethernet, and RS485 ports.	***	*/**	*
MMS/UCA, Modbus, and DNP3 as options.	***	***	***
Interface Software Specifications			
PQDIF data export option.	**	*/**	*/**
Compliance with ODBC (Open Database Connectivity).	**	*/**	*/**
Compatible with Windows 95/98, NT4.0, and 2000.	*	*	*
Includes a full version for translation and a version for data access and programming.	**	*	*
Automated polling of meters via telephone or Ethernet.	***	*	*

* The meter currently performs this function
** The meter can perform the function in the future with no cost added
*** The meter can perform the function in the future with small cost adder

*/*** There is a range of performance from the different meters in that cost category

4
COMPONENT TECHNOLOGY TRENDS

Semiconductors

This chapter gives a brief summary of the evolution of semiconductor technologies and packaging. It provides information on today’s state of the art in the semiconductor market.

In the last few years, we have seen a new technology emerging. The micro-controller is driven by the increasing popularity of programmable devices that can be given any functionality, and be reconfigured quickly and inexpensively with total flexibility. A configurable micro-controller integrates peripheral components such as RAM and A/D converters. Traditionally, discrete components would be added to a circuit board to provide the functions that configurable micro-controllers internalize. Configurable micro-controllers thus reduce the size and cost of the electronics that can be used in meter technologies.

Technologies

Within the past decade, CMOS has become the technology of choice for a broad range of semiconductor products. CMOS is known for its low power consumption and higher speeds compared to other logic families such as standard TTL, LS, and ALS technologies. High-density DRAM (dynamic random access memory), high-speed processors, and low-power devices for mobile applications are key examples. Underlying this widespread appeal are the distinguishing advantages that CMOS provides: an exceptionally low power-delay product, the ability to accommodate millions of devices on a single chip, and flexible, custom design methodologies, which permit optimization as required for lowest cost, lowest power, or highest speed. Accompanying the versatility of CMOS is the economy of providing support for a single technology, rather than for a collection of several disparate ones. Because the CMOS logic family is able to cope with a wide range of voltages, it is well suited to lower supply voltages. Now CMOS is the platform for newer technologies such as high-density RAM, microprocessors, and other integrated circuits.

Logic Levels

Logic-level voltages have dropped in recent years to increase speed and decrease power consumption. In 1994, a 3.3-volt logic standard was introduced, not replacing 5-volt technologies, but working in concert with them. The progression has been toward lowering the voltage even further for higher performance, as shown in Figure 4-1. However, with lower voltage logic comes a need for better power supplies and better noise filtering simply because the signal-to-noise ratio is necessarily reduced.

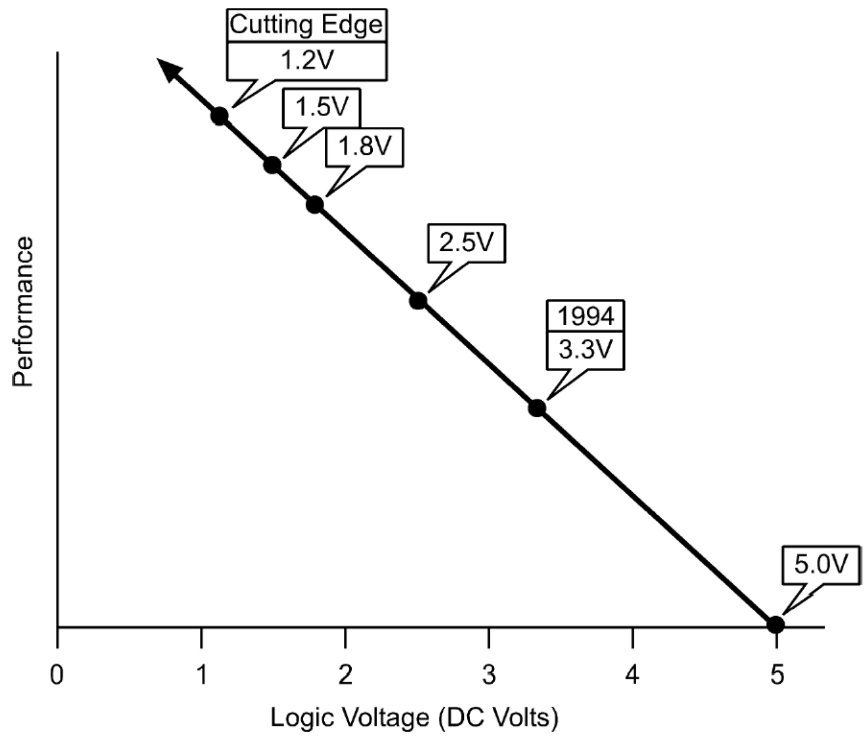

Figure 4-1
Logic-Level Voltage Trend

Reduced logic-level voltages offer the following advantages:

- The components in logic circuits use less power. These components, which spend about 95% of their on time in standby mode, draw less current at the reduced logic-voltage level. When these components are switching, the dynamic power consumption is less than that of components operating at a higher logic voltage. A lower power consumption affords a smaller power supply, lower temperatures, smaller circuit conductors, and increased reliability.
- Components are less susceptible to transients, which can cause false states of logic.
- Portable applications are smaller, requiring fewer, smaller batteries and shorter battery-recharge times.

There is some compatibility among different voltage levels enabling the possibility to mix voltage levels within a design, as shown in Table 4-1.

Table 4-1
Application Example of Mixed Logic Voltage Levels

Application	Logic-Level Voltage (DC Volts)		
	2.5	**3.3**	**5.0**
CPU	X		
SRAM	X	X	
DRAM		X	
Graphics		X	
PCMCIA		X	X
LAN Controller		X	X
IDE Controller			X
Audio			X
I/O Expansion Bus			X

Package Types

Today, there are more packaging options for semiconductors than in years past. Formerly, most integrated circuits came in one package style: DIP (dual inline package). The package is much larger than the actual semiconductor component, but is oversized so that it can be easily installed by humans. With miniaturization, more space-saving packages have arisen in recent years. These packages are too small and the pins are too close together for installation by human hands. Instead, they are soldered to circuit boards by machines using a wave-soldering technique. Newer package styles are:

- A PLCC (plastic leaded chip carrier) contains a small IC with pins on all four sides. It can be surface-mounted to a circuit board, but typically is installed in a special socket. It may be inserted into the socket manually, but requires a special tool to extract.
- A SOIC (small outline integrated circuit) contains a small IC with leads on only two sides. It resembles a miniaturized DIP. Sockets are available, but SOIC packages are typically wave soldered directly to the circuit board.
- A TSOP (thin small outline package) is one of the smallest packages available. It is soldered directly to the circuit board. They are typically used where circuit board space is at a premium. For this reason, the TSOP package would be the most likely choice for the major IC components used in a PQ revenue meter.

Memory

System operation dictates what types of memory to use in a new design. The main considerations are speed, density, board real estate, support circuitry, and cost. Often, several types of memory technologies are employed to facilitate program storage, primary storage, and secondary storage.

In DRAM, each bit (1 or 0) is stored as a charge on a capacitor. This charge is controlled by a transistor, acting as a switch that can change the contents of the capacitor. The charge must be refreshed thousands of times per second or it will discharge. DRAM is inexpensive and is primarily used as main memory in computers because it is designed for fast and frequent read and write operations. It is also inexpensive so that it can be purchased in multi-megabyte modules.

SRAM (static random access memory) uses a circuit technique whereby the electron flow is directed to one side or the other. It is approximately five times faster than DRAM but is much more expensive. It is commonly used as computer cache, where its speed advantage can be used.

FLASH memory is a type of EEPROM (electrically erasable programmable read only memory). It functions more like a hard drive than as memory. It does not need a battery to retain information. It is best suited as removable or sometimes fixed media in small handheld electronic devices such as digital cameras and MP3 players.

Table 4-2 describes the types of memory by speed, memory density, power consumption, and cost.

Table 4-2
Memory Types and Their Characteristics

Memory Type	Speed	Density (Memory Capacity per Unit Size)	Power Consumption	Cost
FLASH	Slow	High	Moderate	Moderate
DRAM	Moderate	Moderate	High	Inexpensive
SRAM	Fast	Low	Low	Expensive

Energy Storage

The proposed PQ revenue meter will be powered from the voltage phases that it is monitoring. As long as voltage is present, meter functions will continue normally. If power is lost, some type of energy storage is needed to support the memory until normal power returns. Most processing functions will not be needed during the downtime. Additionally, many processors are able to enter a low-power mode. Therefore, the energy-storage needs for this application are very small. Factors such as cost, ease of use, and cycle life all play a role in determining the optimal backup energy source for a given application. Additionally, the energy-storage unit to be chosen for the PQ revenue meter must be resistant to outdoor temperature and humidity extremes.

Rechargeable Batteries

Nickel cadmium (Ni-Cad) batteries are by far the most widely used rechargeable battery type. However, battery experts consider lithium-ion batteries a significant advancement in the world of electrochemical energy storage. Table 4-3 shows a comparison of the present storage technologies that are commonly used as backup power sources for electronic equipment.

Table 4-3
Comparison of Back-up Storage Types

Storage Type	Features
Nickel-Cadmium	• Fairly long cycle life (300 to 500 cycles to 80% of rated capacity). • Not environmentally friendly. • Memory effect. • Very long shelf life (5 years). • Near constant voltage output until near end of charge.
Nickel-Metal Hydride	• Drop-in replacement for nickel-cadmium; about 30 to 40% longer run-time per cycle. • Limited product line compared to packaging options of Ni-Cad. • Does not store well (self discharge to half within two months). • No memory effect. • Environmentally safer than Ni-Cad. • 40% greater density than Ni-Cad for a longer runtime per cycle.
Lithium-Ion	• Latest technology; very long cycle life (1,000 cycles not uncommon). • Requires electronics management of charge and discharge in packs. • Expensive. • Environmentally safe. • Twice the energy density of Ni-Cad. • Up to 500 cycles before any drop in capacity. • Higher voltage than typical batteries (4.2 V).
Rechargeable Alkaline	• Limited niche use; cheap, high capacity, but very short cycle life (25 cycles to 50% capacity). • Short life (25 cycles). • Non-toxic. • Long charge retention (stays charged when not in use). • No memory effect. • Low cost.
Ultracapacitor	• Offers some advantages over batteries.

Ultracapacitors in Place of Batteries

Batteries have a limited number of charge/discharge cycles, but the more significant advancement is in the hybrid asymmetrical ultracapacitor storage technology. The development of ultracapacitors suitable for medium- and high-power applications has raised much excitement and speculation throughout many industries. The promise of high power and a large amount of energy storage, coupled with a high cycle life and wide temperature range, has given product designers a new capability to manage the power and energy used within their products. However, with this new capability come many questions. For example, how does an ultracapacitor compare to batteries in terms of energy density, power density, and cost? What applications, previously not possible, are now options with the use of ultracapacitors?

While traditional capacitors are rated in fractions of a farad, ultracapacitors are rated in farads or even thousands of farads. And, the energy density is not fractions of a joule but thousands of joules. Ultracapacitors are devices that store electrical energy as charge separation in porous electrodes with very high surface areas. They are true capacitors in that energy is stored via charge separation at the electrode/electrolyte interface, and they can withstand a very large number of charge/discharge cycles without degradation. They are also similar to batteries in many respects, including the use of liquid electrolytes and the practice of configuring various-sized cells into arrays to meet the power, energy, and voltage requirements of a wide range of applications. Some advantages of the ultracapacitor include:

- Wide range of operating voltage, compared to a battery, which has a narrow voltage range
- Remaining energy can be predicted using a simple measure of voltage
- Ability to deliver pulses of energy without degradation
- Fast charging
- Many charge/discharge cycles

5
SOFTWARE CONSIDERATIONS

There are basically two levels of software: firmware and user interface software. Firmware is necessary to control the basic functions of the microprocessor, which in turn controls the data-acquisition hardware, memory, and other functions that are not directly controllable by the end user. Firmware resides on a chip inside the electronic device. In contrast, the user interface software resides on the user’s computer. It is the graphical interface that provides the familiar functionality and control. It acts as a translator between the human user and the firmware.

Firmware

Firmware is necessary when a microprocessor is used as a controller. It is a program that provides the basic meter command set for the microprocessor. The functions are written as software routines in a low-level programming language. The programming is likely to be done in-house by the meter manufacturer. This piece of software is compiled and stored in an EPROM (erasable programmable read-only memory) inside the meter and is typically not user-accessible. Firmware can be upgraded if necessary, but is done infrequently and usually for the purpose of fixing a bug or improving performance. In years past, to get a firmware upgrade, the user had to send the equipment back to the manufacturer, who would replace an EPROM chip. It is now possible for a user to download a firmware upgrade from the Internet and to send that code to the instrument via its communication link using a computer.

Figure 5-1 shows how the firmware (stored in EPROM) operates with basic hardware components in a microprocessor-based meter. The functions of the firmware are summarized in the following list:

- Set up and control the A/D (analog-to-digital) chip
- Control data flow
- Store data and index for retrieval
- Communicate with user interface software
- Perform event-capture routines
- Update LED or LCD display

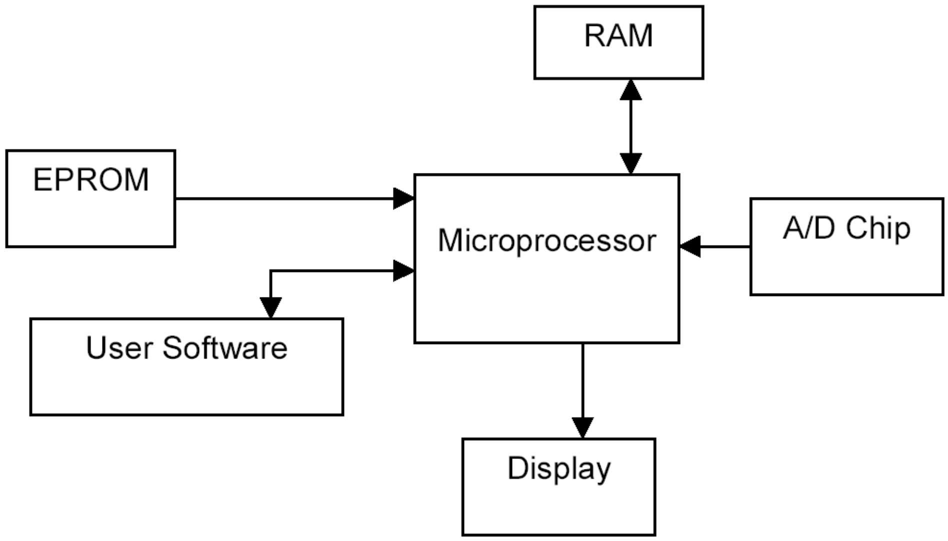

Figure 5-1
Block Diagram of a Basic Microprocessor-Based Meter

Firmware is a practically invisible, low-level instruction set for the meter hardware and is therefore not a feature-oriented element of the design process. The functional specifications of firmware are driven by the hardware that the firmware controls. The remainder of the discussion on software will focus on the user software, which is where the intelligent features and functionality reside.

User Software

The functions of the user interface software include setting up the meter for a particular site, extracting data, and presenting the data in useful formats. This software is often written in a high-level programming language such as C^{++}. It is then compiled to create an executable program to be installed on the user's computer. It may be written by the meter manufacturer, but is often written under contract by third-party software developers.

A key design goal of the software should be a user-friendly interface. In a graphical operating system such as Microsoft Windows®, users generally expect that modern software will conform to basic rules of the graphical user interface. As a minimum, it should have these features:

- *Familiar and intuitive to the user.* The software should be based on structures already put into place by the Windows operating system. The user should not have trouble finding commands and tools. Menus and icon-based toolbars are expected elements. Functions should be clearly labeled. Online help should be available.
- *Should allow user to easily set communication configurations for connection to the meter.* For example, serial communications require basic settings such as COM port, baud rate, stop bits, parity, and so on. The user should have clear feedback regarding the status of the connection—messages such as “connecting,” “logging on,” and “port not available”.

- Additionally, the software should initiate periodic checks to update the status of the connection. This informs the user if communication is lost during a session. It helps to answer the question, "Why am I not getting any more data?"
- *Easy to set up monitoring functions such as thresholds and enabling trends.* It is often easy for a user to forget to enable a feature that is hidden in menus. All metering capabilities that are enabled should be clearly visible. They should be set up for individual selection or de-selection.
- *Should present data in a useful format such as waveforms, tables, and trend lines.* It takes talent to turn data into information. Tables summarize events. Waveforms provide visual details of events. Data should be indexed and easy to find.
- *Self diagnostics*. The hardware should provide feedback to user about the status of monitor functions such as modem, data-acquisition channels, and amount of RAM available.

6 CONCLUSIONS

Increasingly, state utility commissions are setting quality and reliability standards for electric power distributors. A flexible, cost-effective revenue meter with power quality functions can provide the utility with the information needed to help influence the standards set by the commissions. Once limits are set, the same meters can provide the information necessary to measure the performance relative to the standards. In many cases, a utility that can prove that it is exceeding the requirements may be compensated with higher rates and/or profits.

There is a need for a dual instrument capable of both revenue metering and power quality monitoring. Additionally, user input gathered during this project gives EPRI a unique position to develop a meter that best fits customer needs. The rapid growth of the computer industry has brought down the prices of semiconductors and electronic parts. This development project can capitalize on the market situation and can meet the cost target for the instrument.

The first steps have already been taken. EPRI has developed functional specifications, cost/benefit analysis, and has accumulated lists of the professional opinions of meter users, manufacturers, and project sponsors. The next step is to identify and contact manufacturers of digital power-measurement instruments. Of particular interest are those who already have developed similar equipment or a significant portion of the target meter.

Another approach is for EPRI to develop a low-cost “just PQ” monitor without the revenue metering functions. Such a meter also meets the utility needs for affordable monitoring, and even reduces the cost further by isolating the PQ functionality. Again, the approach is the same. EPRI should identify and contact manufacturers of similar equipment and tailor the existing product to meet the functional and design specifications of this project.

One of the most significant development costs will be the software. Many of the features listed in this document and in prior documents are software features. The interface would necessarily include many unique features that are not already part of any existing PQ meter packages.

A
MANUFACTURER WEBSITES

Table A-1 is a listing of known manufacturers of power quality monitoring equipment and a group of generally useful links about monitoring hardware or technologies. The links to the web sites of each of the listed manufacturers is also supplied for convenience.

Table A-1
Web Sites for Manufacturers of Power Quality Monitoring Equipment

Corporation	Web Site
Fluke Corporation	www.fluke.com
Power Standards Lab	www.pqrelay.com
General Electric	www.geindustrial.com
Dranetz-BMI	http://www.dranetz-bmi.com/
Electro-Industries	http://www.electroind.com/
Power Measurements Limited	http://www.pml.com/
PowerTronics	http://www.powertronics.com/
Power Monitors Incorporated	http://www.powermonitors.com/
Reliable Power Meters	http://www.reliablemeters.com/
Square D Circuit Monitors	http://www.squared.com/us/internet/plogic.nsf
California ISO Website	http://www.caiso.com/
Allen Bradley	http://www.ab.com/PEMS

Target:
Power Quality Measure

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