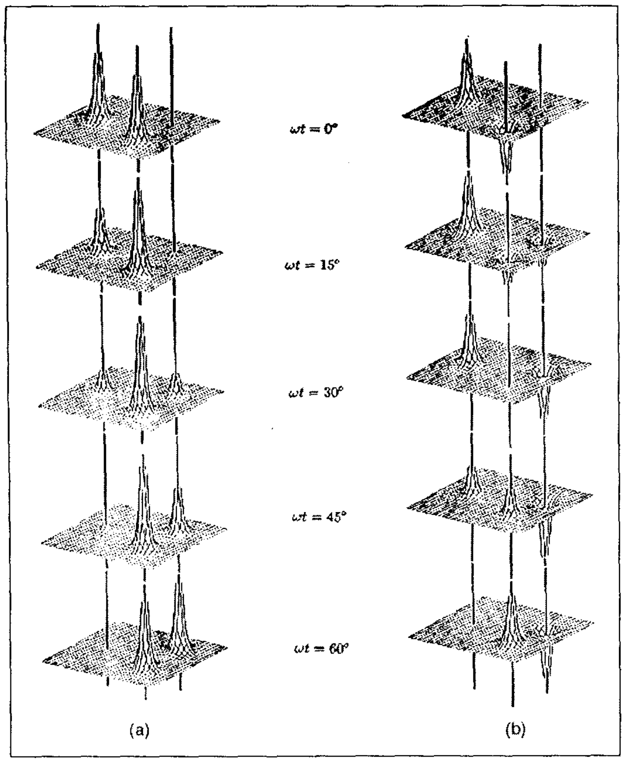

Figure 2. Poynting vector envelopes for the ideal system sketched in Figure 1: (a) unity power factor, (b) zero power factor

tributions. Such conditions reveal that the interactions of E and H caused by voltages and currents of different frequencies yield oscillations of energy with no net energy transfer to the load due to the axial component. Physically there is no difference between the PV caused by the 60 Hz reactive current and the 60 Hz voltage and the PV caused by a harmonic current and the 60 Hz or any harmonic voltage. In all these situations, we deal with nonactive PV components; they sustain parasitic oscillations of energy that cause additional losses in the supplying conductors and electromagnetic interference but no useful transfer of energy to the load.

Conclusions: The electric energy delivered to end users is transported by the electromagnetic field produced in the space that surrounds the conductors. The useful electromagnetic field is produced by the 60 Hz components of the voltage and current, namely their positive sequences. All other components, the 60 Hz negative and zero-sequence voltage and currents, the harmonics, subharmonics and interharmonics, produce electric and magnetic fields that support energy that oscillates between the sources and loads, or between different loads, without benefit to the end user or the energy producers (except when filters meant to confine the flow of nonactive energy are installed). Electromagnetic fields that sustain the flow of nonactive energy are electromagnetic pollution, the actual cause of power quality problems.

The complete picture of the energy flow and the effects of different components of the apparent power can be understood by studying the flow of the PV in the space surrounding the supplying lines. For polyphase systems, lumped circuits models do not reveal the actual physical mechanisms that sustain the flow of energy. Such models may lead to wrong apparent power resolutions and the misleading linking of 60 Hz active power with harmonic active power or, 60 Hz reactive power with other nonactive powers.

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A Power Quality Monitoring System: A Case Study in DSP-Based Solutions for Electric Power Industry

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Introduction: Electric power quality has captured increasing attention in power engineering in recent years. The term power quality refers to a wide variety of electromagnetic phenomena that characterizes the voltage and current at a given time and location on a power system. Very broadly, power quality is concerned with maintaining the near sinusoidal waveform of power distribution bus voltages at rated voltage magnitude and frequency [1].

Power quality testing is necessary to characterize electromagnetic phenomena at a particular location in an electric power circuit. The results of a power quality study can be used to diagnose power quality problems that affect an existing facility, to evaluate measures to improve power quality, to refine power quality modeling techniques, or to predict future performance of load equipment.

Power quality engineers are primarily concerned with rms voltage variations and steady-state deviation from the ideal power frequency sinusoid. Therefore, the testing system must be designed to monitor short-duration variations, long-duration variations and waveform distortion. Continuous monitoring is required to adequately characterize waveform distortion and rms voltage variations. Real-time data analysis should be used in conjunction with continuous monitoring in order to reduce storage requirements. This makes extended data acquisition and therefore long-term power quality studies feasible. Real-time analysis also provides rapid insight into results as data is collected.

It is desirable that results be available both in numeric and graphical form. Ideally, all the necessary analysis and presentation functions should be included in the presentation software; but this is not possible. So, results must be available for export to other computer analysis tools, such as spreadsheets, statistical analysis programs, databases and graphics packages.

The monitoring system must be easily reconfigurable and adaptable so as to accommodate custom testing. The monitoring unit must be portable so that the power quality engineer can carry it along for field tests. It is also desirable that the monitoring system work in conjunction with the engineer's laptop or notebook computer. This enables easy storage and retrieval of results, and seamless use of results in further study and in design of power quality improvement strategies.

The purpose of this study is to develop and implement a power quality monitoring system that will enable power quality engineers to conduct diagnostic testing in the field. The study does not deal with the selection and use of transducers that are required to obtain acceptable voltage and current signals for power quality testing. We will limit our concerns to the implementation of hardware and software required to process the analog signals received. A real-time monitoring system that can be used to perform automated power quality testing is described. The system is centered on a digital signal processor (DSP) interfaced to a personal computer (PC). The block diagram of the system is shown in Figure 1. The test signal is input to the system through the A/D board. The signal is analyzed in real-time in the DSP, and the results are transferred to the PC through the communication interface. The PC presents the results and interacts with the user. This system can be used to perform onsite power quality studies.

Power Quality Phenomena: The IEEE Standard 1159-1995 has established definitions for various power quality phenomena found in electric distribution systems. In this study, attention is limited to short-duration variations, long-duration variations, and waveform distortion, as these power quality phenomena occur frequently within customer premises and are therefore of particular interest to power quality engineers.

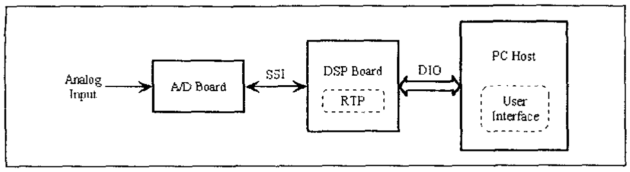

Figure 1. Power quality testing system

Short-Duration Variations: Short-duration voltage variations are almost always caused by fault conditions, the energization of large loads that require high starting currents, or intermittent loose connections in power wiring. Depending on the fault location and the system conditions, the fault can cause either temporary voltage rises (swells) or voltage drops (sags), or a complete loss of voltage (interruptions). Each type of variation can be designated as instantaneous, momentary, or temporary, depending on its duration.

Long-Duration Variations: Long-duration rms variations are deviations outside the normal tolerance in the ac voltage for a period exceeding 1 minute. Overvoltage and undervoltage are the standard terms employed for a long-duration voltage increase and decrease, respectively. Long-duration variations result from addition or removal of system load or reactive compensation, and can be controlled by improving the voltage regulation characteristics of the system. An interruption involves complete loss of voltage for 30 cycles or longer. Interruptions are caused by faults.

Waveform Distortion: Waveform distortion is defined as a steady-state deviation from an ideal sine wave of power frequency, principally characterized by the spectral content of the deviation.

Power Quality Testing Equipment: The first step in addressing the concern for power quality is to identify and understand the actual power quality problems at the customers' premises. The wide range of power quality concerns imposes special requirements for monitoring equipment, and creates a need for sophisticated software to analyze the data recorded. Conventional monitoring systems focus on steady-state voltages and currents, and therefore fall short of accommodating the full spectrum of power quality variations that impact customer equipment. Therefore, there is an imminent need for a power quality measurement system that can be used to perform quick and reliable power quality surveys. Programmable digital signal processor (DSP) based real-time power quality measurement is emerging as an important area in power quality monitoring [2].

DSPs are the processors of choice in real-time monitoring systems. Their special architecture and high performance make it possible to implement a wide variety of nontrivial control and measurement algorithms. DSP designs are optimized to handle real-time applications with high bandwidth requirements. In the following, we will illuminate the features native to DSPs that facilitate high throughput.

DSP Architecture: DSPs are built with Harvard architecture. This configuration employs separate program and data memories and associated data and address buses. The benefit of this arrangement is increased speed, because instructions and data can move in parallel instead of sequentially. DSPs, like many advanced microprocessors, use pipelining to operate on several instructions simultaneously. Several other architectural features, such as hard-wired logic, scaling, saturation, and large word length, enhance the performance of DSPs in real-time environments.

Special DSP Instructions: DSPs resemble reduced instruction set computers (RISC), in that a small set of frequently used instructions are optimized for numerical processing. DSP instruction sets efficiently handle mathematical operations common to many algorithms that are repeatedly executed in time-critical loops. Each step in the computation involves a multiplication and addition. The multiply-and-accumulate (MAC) instruction in DSPs performs this in a single instruction cycle. The MAC instruction is also highly effective in matrix multiplication and fast Fourier transform (FFT) algorithms. MAC is the one instruction that most distinguishes DSPs from other micros.

Real-Time Systems: Real-time systems respond to specific events within specified time. The correctness of a real-time system depends not only on the logical results of the computation, but also on the time at which the results are produced. The time at which output is produced is important, because the input corresponds to a real-time event in the physical world, and the output has to relate to the same movement. There is a distinction between hard real-time systems and soft real-time systems. In *hard real-time systems,* it is absolutely imperative that responses occur within the specified time. *Soft real-time systems* are those in which response times are important but the system will still function correctly if deadlines are missed occasionally. The power quality testing system is a hard real-time system.

All real-time events can be divided into two fundamental categories: aperiodic and periodic. *Aperiodic* events occur at random intervals and are characterized as requests which must be responded to in a timely manner. For each request, there is a defined algorithm that produces a valid response. These algorithms are called request-response (RR) algorithms. The key implementation issues of aperiodic event processing are twofold. First, a valid request must never be missed. Second, a valid response must be generated within a specified response time. Typical examples of aperiodic event processing are: keyboard input, display output, master-slave communications, and alarm inputs.

Periodic events occur at repeated intervals and are characterized as a sequence of actions which must be repeatedly executed at a specific time interval. This sequence may be for a specified number of intervals or may be indefinite. Periodic event processing is exemplified by most data-acquisition systems. The sequence of actions for these types of systems take the general form of input-compute-output (ICO) algorithms.

In aperiodic and periodic event processing, much of the total time available is spent waiting for the next event to occur. This idle time could be used to service other real-time events. Thus, multitasking environments are desirable.

The two fundamental techniques that allow real-time event processing are polling and interrupt-driven. A mixture of the two methods yields an optimal solution which retains the advantages of both, while minimizing their disadvantages.

Real-Time Processing Kernel: Real-time processing requires a fast multitasking operating system. The elaborate memory management, I/O processing, and resource sharing capabilities found in conventional operating systems are not desired because the overhead associated with these capabilities adversely affects real-time performance. In this study, the basic environment for processing is provided by the real-time processing (RTP) kernel implemented on the DSP. The kernel supports multi-tasking to handle the tasks associated with data

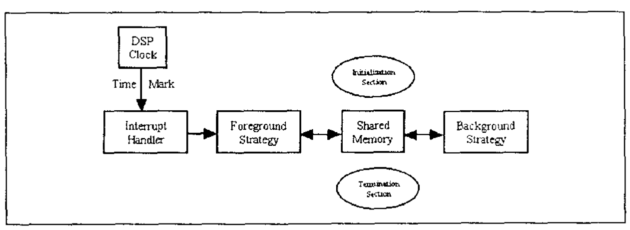

Figure 2. Real-time processing kernel

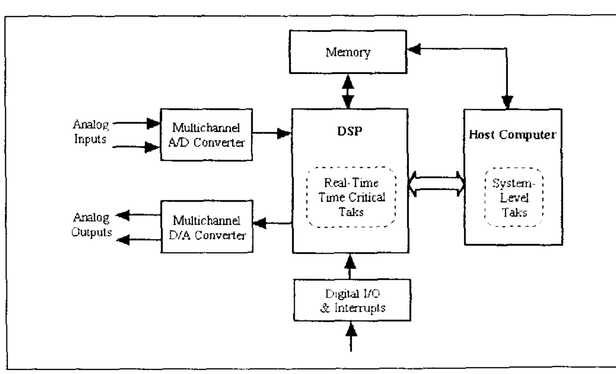

Figure 3. Dual-processor system architecture

collection, data analysis and communication. Figure 2 shows the principal elements of RTP.

The initialization section is responsible for initializing the timer, installing the interrupt handler, and setting up the foreground process. The interrupt handler is responsible for creating the multitasking environment. The tasks specific to the interrupt handler are separated out into the foreground strategy routine. This routine interacts with shared memory to set the appropriate run flags, and executes tasks scheduled to run in the foreground. The background strategy embodies the notion of the polled environment. It interacts with shared memory, and executes tasks scheduled to run in the background. The termination section resets the timer, uninstalls the interrupt handler, and destroys the processes.

System Architecture: The goal in system design is to synthesize a system architecture that will accommodate the needs of the application at hand. The objectives of this study dictate several requirements. The primary concern is to have enough processing power to meet the computational requirements of the real-time tasks associated with power quality monitoring. The system must be easy to implement, flexible, and cost-effective; and it should have a good user-interface.

The dual-processor architecture meets these requirements. This architecture is based on a DSP interfaced to a host computer, as shown in Figure 3. Real-time tasks are delegated to run on the optimized hardware of the DSP, while system level requirements, such as user interface, are implemented on the host computer. In this application, the host computer is a personal computer. In actual field tests, the host will be the power quality engineer's laptop (or notebook) computer.

Software Development for the DSP: DSPs deliver high performance provided the software running on the processor facilitates such performance. Programming with DSPs presents some unique issues because of the specialized architecture of the DSPs and the nature of applications. Using a high-level language (HLL) like C can cut development effort substantially. However, HLL compilers for DSPs do not produce efficient code. Assembly language produces efficient code, but it is difficult to write large applications in assembly.

In real-time applications, the best approach is to use a judicious mixture of HLL and assembly. HLL code is used for initialization and non-real-time code. Time-critical tasks are coded in assembly. RTP was developed using this approach. The framework for the power quality testing application was developed using C, and the real-time data-collection, data-analysis, and communication tasks were coded in assembly.

Windows has been accepted as the environment of choice for application development in PCs. It provides a multitasking, graphics-based windowing environment. The processing environment in the PC was developed in Windows 3.1 using the Microsoft Foundation Class (MFC) library. Windows is not inherently a real-time operating system, but it provides a plethora of functions that, if judiciously invoked, can be used to create a Windows based real-time application.

Windows are useful in reducing spectral leakage when using the FFT for spectral analysis. The Hann window is recommended for power quality testing, because this window is particularly effective when the input signal is a sine wave or a combination of sine waves [3].

Windows programs are designed to respond to messages from the Windows kernel. The message loop receives messages from the kernel and invokes the corresponding message handlers. The message loop in this application primarily has two responsibilities; to respond to menu selections by the user and to handle the update message posted by the idle-loop processing routine. Real-time results are available through dialog boxes such as the power quality indices dialog box shown in Figure 4.

The update message handler is incorporated into the main window. On recognizing an update message, the following operations are performed.

- Results from the DSP are scaled to compensate for factors introduced when applying the Hann window and computing FFT.
- Power quality indices are computed.
- A smoothing filter is applied to the real-time result, producing the final output.
- The display is periodically updated.

Test Results: The power quality testing system was first calibrated to meet the accuracy requirements. Then, tests were performed to determine the attenuation capabilities. Output spectra, for sine and square wave inputs at different frequencies, were observed and compared with corresponding theoretical spectra. Finally, measurement errors for different power quality indices were determined.

The rate at which the input signal is sampled determines the highest harmonic in the signal that can be resolved. Power quality standards recommend a sampling rate sufficient to determine up to the 50th harmonic or better. However, most commercial instruments measure up to the 31st harmonic.

The testing system was calibrated to meet the accuracy requirements of class-A instruments. Since the requirements for measurement of voltage are more stringent, the system was calibrated to meet these requirements. A single-frequency signal of 1 V peak magnitude, corresponding to a harmonic in the operating frequency range of the system, was applied. The output at the applied frequency was adjusted using a calibration factor to read 1 V. This process was repeated for frequencies up to the 31st harmonic.

The system was tested for attenuation capabilities. The output spectra for different test signals were observed. The input signals were set to

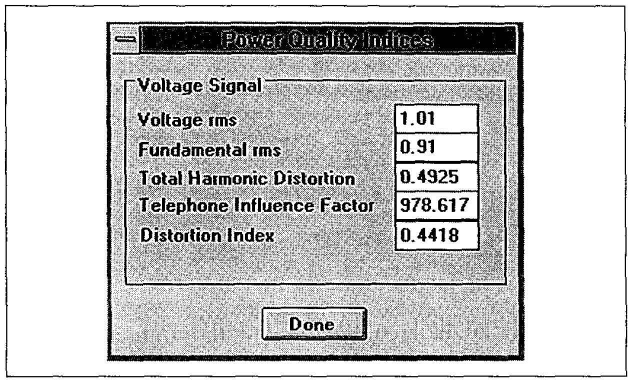

Figure 4. Power quality indices dialog

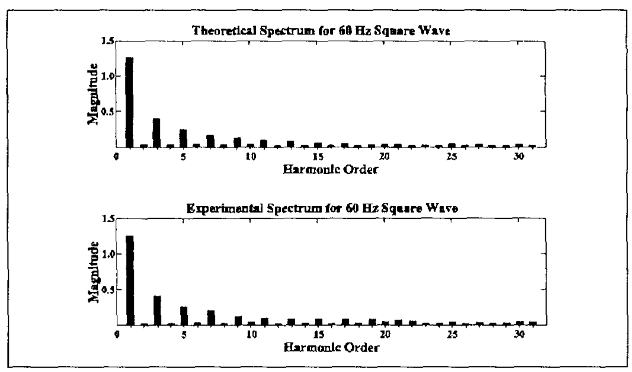

Figure 5. Spectrum for a 60 Hz square wave

Table 1. Magnitude spectrum for a 60 Hz square wave

Harmonic Order	Theoretical Magnitude (V)	Experimental Magnitude (V)
1	1.27	1.28
3	0.43	0.43
5	0.26	0.27
7	0.19	0.20
9	0.14	0.12
11	0.12	0.10
13	0.10	0.09
15	0.09	0.08

have 1 V peak amplitude. The signal generator is accurate up to 0.01 V in this range. So, only the first two decimal places in the output will be noted; the resolution of the testing system is 0.1 mV.

Figure 5 shows the spectrum for a 60 Hz square wave. Table 1 compares the theoretical and experimental magnitude spectra for this input signal up to the 15th harmonic. The results are quite accurate for the lower-order harmonics. However, as the order of the harmonic increases, the experimental magnitudes are less than the theoretical values. This can be explained by the fact that the fundamental frequency (61.04 Hz) corresponding to the sampling rate does not match the fundamental frequency of the input signal (60 Hz). Consequently, the FFT algorithm distributes the power at each harmonic frequency of the input signal among the available adjoining frequencies (corresponding to sampling frequency). The effect of such spreading is more noticeable at higher frequencies because the difference between the signal harmonic frequency and the corresponding harmonic frequency for the sampling rate is larger.

Figure 6 shows the spectrum for a 180 Hz square wave. The one significant feature in the experimental spectrum is that at higher frequencies, the spreading effect leads to poor attenuation of adjoining frequencies.

Power Quality Indices: Power quality indices were observed for an input 1-V peak square wave at 60 Hz. The theoretical values of the indices were computed. Table 2 shows a comparison of the theoretical and experimental values. The error is less than 2 percent in all cases.

Test results show that the system meets the accuracy and attenuation requirements. Experimental spectra for test signals closely match the corresponding theoretical spectra. The errors in the power quality indices calculated for the test signals are well within the 5 percent tolerance. Some limitations should also be noted. An anti-aliasing low-pass filter, to eliminate frequencies outside the operating range of the instrument, was not used during testing because the test signals themselves were band-limited. Before using the instrument to conduct power quality surveys, it is essential to include an anti-aliasing filter. Since there is no strict synchronization between the sampling rate and the fundamental frequency of signal, higher frequency harmonics appear attenuated. This problem can be overcome by using a phase-locked loop (PLL) at the front-end.

Conclusions: In this project, a real-time power quality testing system was designed, implemented, and evaluated. The prototype can continuously monitor one input signal with a nominal full scale of 2 V p-p, a dynamic range of 4 V p-p, and a resolution of 0.1 mV. The system can determine up to the 31st harmonic of the power frequency and can compute important power quality indices. Results are available in real-time through a graphical user-interface. The system can be used to perform diagnostic power quality testing to evaluate waveform distortion, short-duration variations, and long-duration variations. Experimental results using standard test waveforms compare favorably with the theoretical values. Tests show that the measurement error is less than the maximum allowable error of 5%. The system also meets the attenuation requirements for time-domain instruments.

The dual-processor architecture used in this system is very versatile and can be employed in similar applications. The real-time processing kernel running on the DSP has proven to be very effective as a multitasking real-time operating system. It has been ported to other platforms and has been successfully used to develop other control and monitoring applications. The Microsoft Windows operating environment can be adapted to handle real-time processing, as demonstrated in this project.

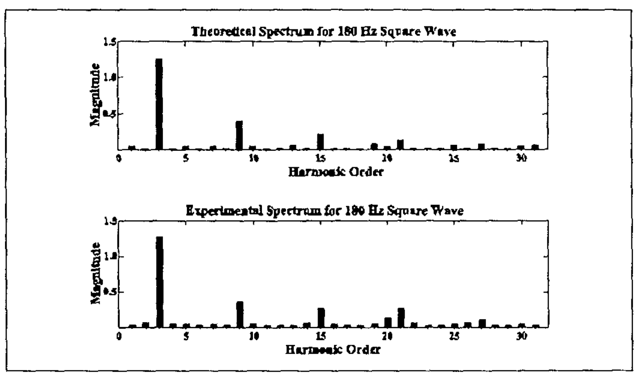

Figure 6. Spectrum for a 180 Hz square wave

Table 2. Power quality indices for a 60 Hz square wave			
Power Quality Index	**Theoretical Value**	**Experimental Value**	**Error Magnitude**
True rms	1.00 V	1.01 V	1.00%
Fundamental rms	0.90 V	0.91 V	1.11%
Total harmonic distortion	48.32%	49.25%	1.92%
Distortion index	43.52%	44.20%	1.56%

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Call for Nominations

PES established this award to annually recognize one engineer from the global industry who has made, in his or her engineering efforts, a remarkable achievement to enhance the quality and economy of electric power distribution.

Nominations are being solicited now through 31 December 1999 for the year 2000 award. The nominee may be from a public or investor owned utility, an equipment manufacturer, a research organization, or from a computer related organization, and must have been an IEEE PES member for 10 years. Contributions may have been in one or more of these examples: switching, voltage control/transformation, power quality/measurement, service reliability, surge protection, circuit protection, insulated conductors, conductor components, distribution automation, fault detection (monitoring and control), asset utilization, or communications. The selection committee considers all documented work of candidates that has resulted in substantial improvements to the effectiveness and utilization of electric power distribution.

The recipient is presented with a bronze plaque and receives a scholarship award in the amount of $4,000 to a university of his or her choice having an accredited degree program in electrical engineering. The next award will be presented at the 2000 PES Summer Meeting.

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