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Power Quality Monitoring Data Mining for Power System Load Modeling

Technical Report

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PRODUCT DESCRIPTION

This report describes the potential for mining power quality (PQ) monitoring data to develop parameters that utilities can use in power system load modeling. The topics covered in this report include a brief overview of emerging load characteristics, PQ monitoring data characteristics and their applicability for use in load modeling, and methodology for using PQ data to evaluate parameters for static load modeling. The report also describes the concept of a *fast voltage collapse index* (FVCI) to identify potential weak locations in a power system with significant air-conditioning loads, and an algorithm to compute site-specific FVCI using RMS variation data available from a PQ monitoring system.

Results & Findings

While it is generally recognized that information technology (IT)-related loads, such as computers and electronic appliances, that utilize power electronics have increased over the last decade, motor loads are still the dominant load in any given power system. However, with the increasing proliferation of power electronics-based loads in many consumer electronics, the customer load composition during the next 10 to 20 years will certainly continue to change. The large installed base of PQ monitors throughout the electrical system, located in both customer premises and electrical substations, could become a useful source of data for developing parameters for power system load modeling.

The existing characteristics of PQ monitors, primarily based on event recording of high-resolution data for a short time period, are generally not appropriate for developing dynamic load models. However, utilities can use the existing PQ data to develop parameters for static load models. Furthermore, with only minor changes in the overall architecture required to capture data, utilities can configure the next generation of PQ instruments to allow development of dynamic load models. They can also use existing PQ monitors to extract information from RMS variation data to provide an indication of the relative post-fault transient recovery nature of the power system. The opportunity for using PQ monitoring data to fine tune load models enhances the overall value of such a system and opens the door for additional use of PQ data for system improvement.

Challenges & Objectives

The major difficulties in load modeling are due primarily to large numbers of load components, the accessibility of data set-ups for certain loads, the level of detail used to represent various load components, and considerable uncertainty in the utility community on how to “correctly” model loads. In addition, with the changing characteristics of customer loads, increasing utilization of transmission circuits, growing complexity of power flows in the deregulated environment, and lack of market incentives for generators to provide reactive compensation, it is of paramount importance to take a new look at load modeling and develop more accurate aggregate load models for bulk power system stability studies.

Applications, Values & Use

The next phase of the project involves integrating some of the load-modeling methods discussed in this report with a PQ monitoring software system in a trial implementation at a host utility site. An automated load-modeling system using data recorded and analyzed from PQ monitors located system-wide has potential as a powerful tool, not only for developing load models, but also to trend the changing system load characteristics. The development of an automated system as part of an existing PQ monitoring system will give power system planners greater confidence in their load models, and therefore provide a better representation of the overall system response during contingency situations.

EPRI Perspective

EPRI has been a pioneer in developing component-based load-modeling tools such as the EPRI LOADSYN program. EPRI is also conducting research in load modeling as part of both their transmission and substation and grid operations sectors. This work represents EPRI's effort in harnessing value from different data sources that exist in a power system. The value in any data lies in the information that managers can extract from it to make knowledgeable decisions. Mining existing power system data can facilitate this decision-making. This work and other concurrent work in load modeling signify EPRI’s effort to improve power system information through the intelligent processing of PQ data.

Approach

The research team first evaluated current and emerging trends in customer loads, and the significant changes that may occur in the future with the widespread proliferation of power electronics-based loads. They then analyzed the characteristics of commercially available PQ monitoring systems to identify their data characteristics and applicability in using the data for power system load modeling. The project team used actual data from a PQ monitor to illustrate the methodology for developing a static load model for an aggregate load. Finally, they reviewed the characteristics of RMS variation data from PQ monitors and postulated a simplified algorithm for a site-specific index to characterize voltage sags with long recovery time.

Keywords

Load modeling
Power quality monitor
ZIP model
Load
Power quality
Static model

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1
INTRODUCTION

Background

In any system stability study, it is necessary to model loads accurately. However, the modeling of load is always recognized as a difficult task to accomplish. While steady advancement has been made in modeling of other power system devices such as generators, stabilizers, exciters, transmission lines, etc., aggregate load modeling has still remained an "educated guess" in some cases and in other cases a legacy of following what has traditionally been done.

The major difficulties in load modeling are primarily due to large numbers of load components, the accessibility of data set-ups for certain loads, the level of details used to represent various load components, and considerable uncertainty in the utility community on how to model loads "correctly." What's more, with the changing characteristics of customer loads, increasing utilization of transmission circuits, increasing complexity of power flows in the deregulated environment, and lack of market incentives for generators to provide reactive compensation, it is becoming of paramount importance to take a fresh look at load modeling and come up with accurate aggregate load modeling for bulk power system stability studies.

Measurement-based load modeling gives a closer look at the real-time power system loads and their dynamic characteristics. Electrical system steady state and dynamic response is currently available from a number of data sources, with PQ monitors being the one most prevalent data-gathering instrument deployed by numerous utilities around the world.

Project Objective

Load modeling data based on research conducted in the 70s and 80s may no longer be adequate as we try to push power systems closer to their limits, particularly in the light of changing load characteristics and with the ongoing increase in non-linear digital loads. The main objective of this project was to:

- Identify the changing characteristics of customer load
- Identify the characteristics of PQ monitoring data and its applicability in evaluating system load models
- Develop methodologies for analyzing PQ data for estimating load characteristics at different locations
- Develop methodologies to derive aggregate load models from measured load response
- Conduct numerical simulations to show the feasibility of these algorithms

Organization of the Report

This report describes the potential of using power quality (PQ) monitoring data for developing the parameters that can be used in power system load modeling. The topics covered in this report include a brief overview of emerging load characteristics, PQ monitoring data characteristics and their applicability for use in load modeling. In addition, the report discusses a methodology for using PQ data for evaluating parameters for static load modeling. The report also describes the concept of a *fast voltage collapse index* (FVCI) for identifying potential weak locations in a power system with significant air-conditioning loads and describes an algorithm to compute site-specific FVCI using RMS variation data that is available from a PQ monitoring system.

The report is organized into 5 chapters, including this introductory chapter:

Chapter 2 provides an overview of emerging load characteristics, reviews the basic concepts of different types of load modeling and their application in power system stability studies, and illustrates the different methods for obtaining accurate parameters for load modeling.

Chapter 3 discusses the history of large-scale power quality monitoring systems. It identifies some desirable characteristics that a monitor should have in order to be applicable to capturing the data needed for load modeling. This chapter also reviews the specifications and configuration of seven power quality monitors and compares them to the desired characteristics. The chapter concludes with a discussion of the specifications for the “next-generation” power quality monitor (to include load modeling data capture).

Chapter 4 gives the procedure of a detailed static model that can be used to predict load behavior using PQ monitoring data. The procedure is implemented using an example of a static load model of an internet data center (IDC) facility with a large concentration of switch mode power supplies for information technology (IT) loads.

The final chapter, Chapter 5, describes the concept of a fast voltage collapse index (FVCI) for identifying potential weak locations in a power system with significant air-conditioning loads and describes an algorithm to compute site-specific FVCI using RMS variation data that is available from a PQ monitoring system.

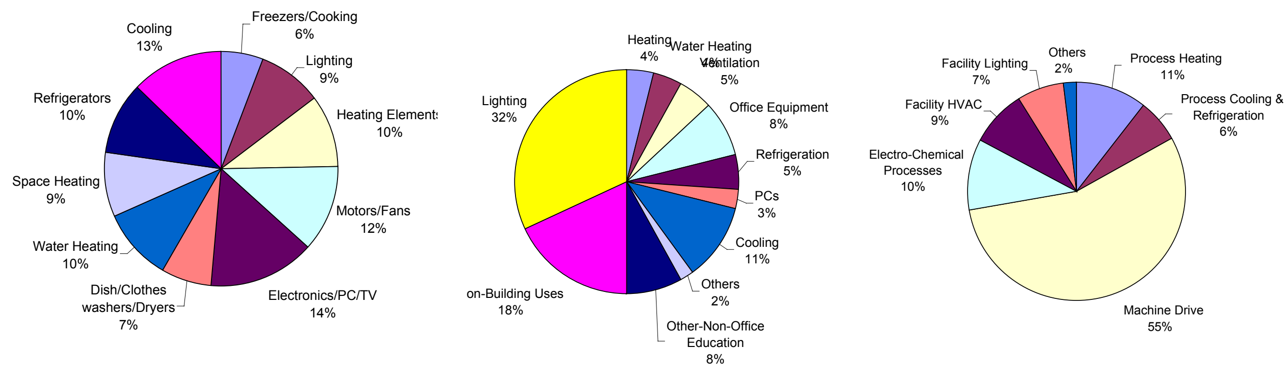
2
OVERVIEW OF LOAD CHARACTERISTICS AND LOAD MODELING

An interconnected power system operation hinges on real time balance of load and generation. During disturbances in a power system, the response of load to voltage and frequency deviation is one of the key factors that influence the overall power system response. As load characteristics change from traditional incandescent light bulbs to power electronics-based loads, and as the characteristics of motors change with the emergence of high-efficiency, low-inertia motor loads, it is critical to understand and model load response to ensure stable operation of the power system during different contingencies. This chapter provides an overview of emerging load characteristics, reviews the basic concepts of different types of load models and its application in power system stability studies, and illustrates the different methods for obtaining accurate parameters for load modeling. This chapter leads into the Chapter 3 discussion of power quality monitoring systems and their applicability in determining parameters for load model.

Customer Load Composition and Emerging Trends

While the characteristics of most of these elements are well understood by power system engineers, load modeling and the changes in load characteristics brought about by the evolution of the digital society have not been thoroughly analyzed in recent years.

Figure 2-1 shows the load composition of residential, commercial, and industrial users based on end-use load categories. While it is generally recognized that over the last decade the percent of loads utilizing power electronics have increased, especially in the form of information technology (IT) loads such as computers and electronic appliances, the dominant loads in existing power systems are still motor loads. However, the increasing proliferation of power electronics-based loads and potential changes in consumer electronics could result in significant changes in customer load composition in the next 10 to 20 years. Load research based on decade-old data of load composition may become quickly obsolete with rapid changes in the customer load profile. In the following sections we will focus on three particular emerging changes in load characteristics that have the potential to significantly influence overall power system load composition.



Residential sector　　Commercial sector　　Industrial sector

Figure 2-1
Breakdown of Electricity End-Use Load Consumption in Residential, Commercial and Industrial Sectors in U.S.[1]

Emergence of Variable Speed Drive Appliances

While use of electronic appliances in residential and commercial sectors has increased significantly in the last decade due to the widespread adaptation of information and communication technologies, the dominant loads in these sectors are still lighting and motor loads (Fig. 2-1). For example, in the residential sector air conditioning, refrigerators, dishwashers, and clothes washer/dryers still represent one-third of the total residential load.

With the decrease in cost of power electronics and emergence of embedded board-level power electronic systems for variable speed drive applications, it is only a matter of time before these motor-driven appliances are integrated with a power electronic front-ends for variable speed drive operation. Figure 2-2 shows the power electronics interface for a single-phase AC induction motor. Semiconductor companies such as Texas Instruments, Fairchild Semiconductors, Motorola, and ST Microelectronics are aggressively researching different motor drive technologies for the appliance market; the growth of power electronics is expected to move from the industrial and commercial Variable Frequency Drive (VFD) sector to the appliance market. Advancement in digital signal processing (DSP) and reduction in cost of DSP-based chips also is an enabling factor in developing low-cost, high-volume variable speed drive modules that can be integrated within an appliance. Figure 2-3 shows a 16A-rated IRAMX16UP60A “PlugNDrive” module designed for 750W to 1.2kW VSD applications that include in-room air conditioners, commercial refrigerators, and large-capacity washers.

[1] Residential/Commercial: *Annual Energy Outlook,* 2001, Department of Energy Industrial: *1998 Manufacturing Energy Consumption Survey*, Department of Energy

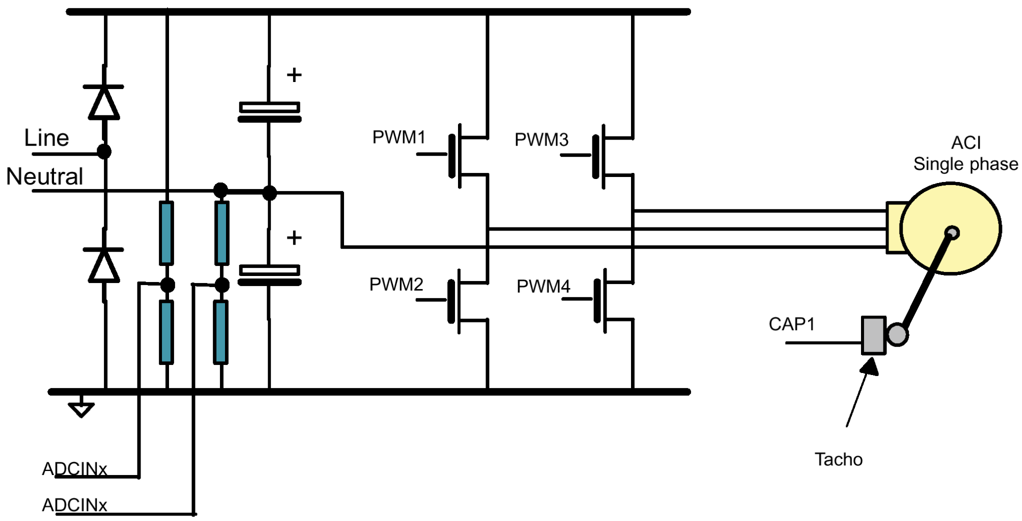


Figure 2-2
Single Phase AC Induction Motor Drives ***(Courtesy: Texas Instruments)***

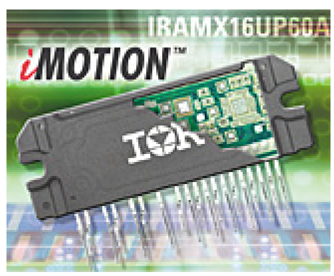


Figure 2-3
Single Module Power Output Stage of a Motor Drive for Appliances ***((Courtesy: iMotion))***

Figure 2-4
Commercially Available Variable Frequency Drive Integrated Appliances *(Courtesy: Maytag)*

Commercial models of such variable speed-driven appliances are already in the market, as shown in Figure 2-4. Decreases in cost and further improvement in variable speed motor drive technologies such as Brushless DC (BLDC) drives and Switched Reluctance Drives (SRD) will only increase the applications of these technologies. Figure 2-5 shows the characteristic input current waveform for single-phase and three-phase bridge rectifiers that are used for converting the incoming AC voltage to DC voltage. Clearly, widespread proliferation of variable speed driven appliances not only will change the steady state characteristics but also significantly impact the static and dynamic response of these types of loads during voltage and frequency deviations.

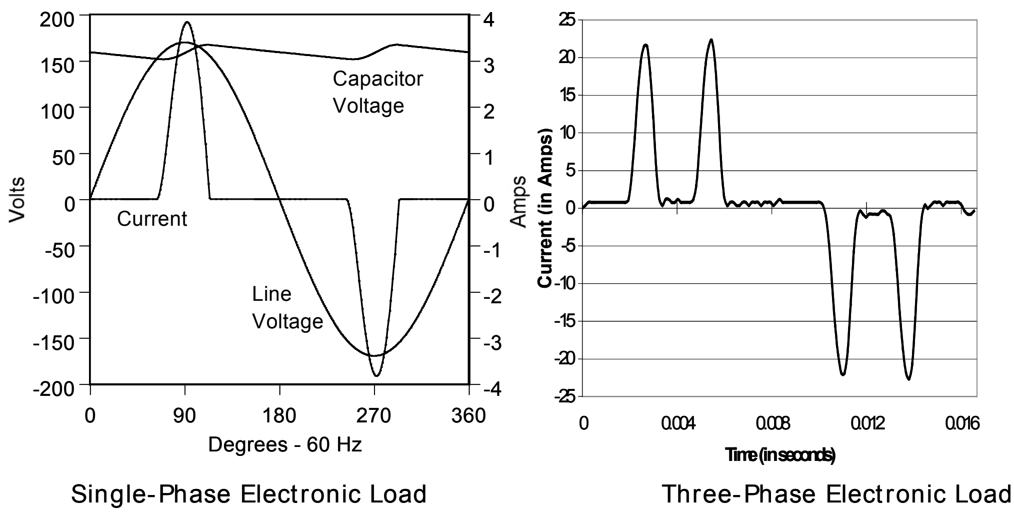


Figure 2-5
Characteristic Current Waveform for Single-Phase and Three-Phase Rectifier Front-End for Variable Speed Drives

Changing Characteristics of Display Panels for TVs and Monitors

TVs and computer monitors represent more than 10% of residential aggregate loads and also represent a significant component in the commercial sector. In the past few years, there has been a dramatic shift in the characteristics of these loads. Traditional Cathode Ray Tube (CRT)-based displays are being gradually replaced by different types of flat panel displays such as Plasma Display Panels (PDP) and Liquid Crystal Displays (LCDs). While the initial prognosis of this technology change was increased energy efficiency and reduced power consumption for TVs and other displays, in reality these new technologies are resulting in a trend of consumers purchasing larger screen sizes. According to forecasts for leading industry research firms, approximately 3 million large screen (>40 inch) TVs will be sold in 2003, and this trend will increase in the future.

Efficiency of these new technologies may also be a factor. Plasma Display Panels (PDPs) are, in fact, much less efficient than traditional CRT-based TVs. For example, a 40-in. plasma display consumes about 300 W, but its peak brightness is only a third that of a cathode-ray tube consuming half that power. Most of the current models of plasma TV have power consumption in the range of 300W-500W. This can be an order of magnitude more than the traditional small screen CRTs that are widely used in residences today. An overall five- to six-fold increase in power level of TVs in the residential sector will have a profound impact on the overall residential load characteristics, especially during prime time, when TV loads constitute a large portion of the overall residential load.

Decrease in Reactive Support from Large Industrial Synchronous Motors

In the past, industries needing high horsepower motors with controllable speed, such as steel rolling mills and large surface mining equipment, opted for synchronous AC motors driving DC generators (See Figure 2-6). The DC generators in turn provided power to DC motors whose speed could be easily controlled. This system had some disadvantages as well as some distinct advantages. The disadvantages were primarily related to the maintenance required by both the synchronous machines and DC machines. The primary advantage was in the ability to use the synchronous machine to correct facility power factor.

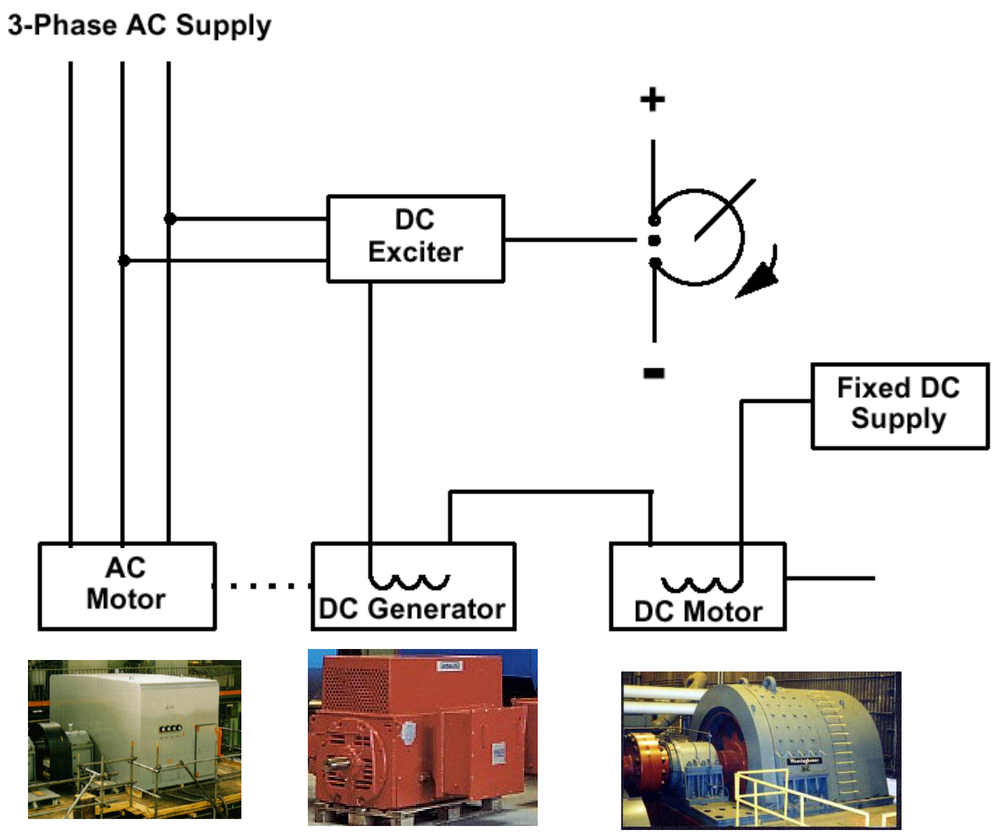


Figure 2-6
Traditional Synchronous Motor-DC Generator-DC Motor System for Speed Control

Advances in semiconductor-based drive technology led to the conversion of some of these systems to one of two topologies: medium-voltage DC drives with DC motors (See Figure 2-7), or medium-voltage AC drives with AC motors (See Figure 2-8). Medium-voltage DC drives are the preferred system when an existing facility is being upgraded; the synchronous machine and DC generator are simply replaced with a large (or multiple) DC drive(s). In this way, there is no need to replace all of the existing motors. The DC option eliminates the maintenance related to the synchronous machine and the DC generator, but does nothing to reduce the maintenance requirements of the DC motors. The AC drive option is more likely to be used when a new piece of equipment or production line is being designed and built. The AC option reduces the overall maintenance requirements compared to a solution using DC motors.

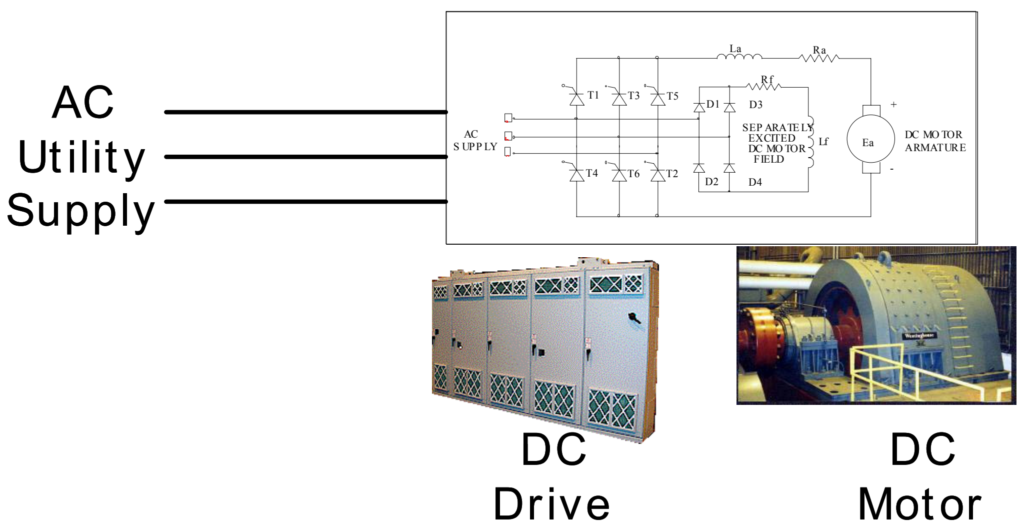


Figure 2-7
Replacing MG Sets with DC Drives

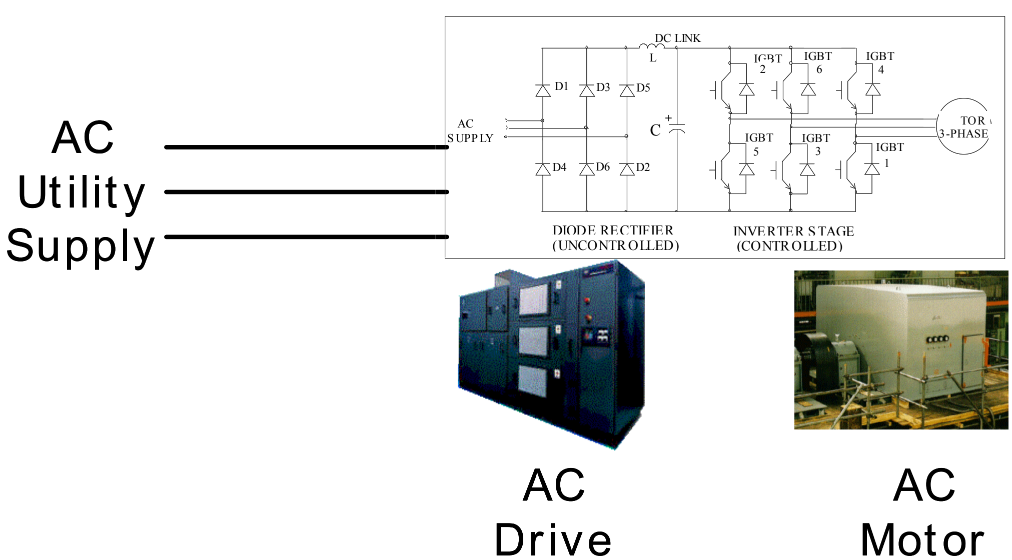


Figure 2-8
Replacing MG Sets with AC Drives

The trend to replace synchronous machines with either DC or AC drives has an impact on the var requirements of customers and the utilities serving them. Neither DC nor AC drives provide var support and both complicate var correction due to the harmonics they produce. In one large electric utility, a steel mill opted to replace a large (4000 hp) synchronous machine/DC generator set with a properly sized DC drive. Calculations and billing data showed that a significant amount of power factor correction would be required. The customer's AE firm designed and installed a large, switched capacitor bank on their medium-voltage bus. When the capacitor bank was energized during operation of the DC drive, it failed. Harmonics produced by the drive were causing an overload on the capacitor bank due to resonance. The bank was redesigned as a passive harmonic filter and continues to operate successfully today.

Overview of Load Modeling

The essence of load modeling is to define through a set of algebraic equations the voltage dependency of the load. While frequency dependency of load is also important in some cases, the main focus of load modeling is to define the static and dynamic response of the load when subjected to a voltage variation. The term *load* often refers to an aggregate load of a feeder, substation, or major delivery point on a system. Load models must consider the proper modeling for individual load categories and also the composition of the overall load. Accurate models of the load components without understanding the load composition can still result in overall models that do not correctly represent the system response. For example, it is not only necessary to model induction motors accurately for static and dynamic response, but also to identify what percentage of the load is made up of induction motors as a function of the load profile, time of day, etc.

Static Load Model

Static load modeling reflects the behavior of the load without any time dependency of load response following a voltage or frequency change. In general static load models can be represented by the load real power (P) and reactive power (Q) as a function of voltage and frequency. Table 2-1 and Table 2-2 summarizes typical voltage and frequency-dependent characteristics of a number of load components and load classes (residential, commercial, industrial) based on testing conducted in the early 1980s [1,2,3,4].

Table 2-1
Static Characteristics of Load Components

Component	Power factor	∂P/∂V	∂Q/∂V	∂P/∂f	∂Q/∂f
Air conditioner					
3-phase central	0.90	0.088	2.5	0.98	-1.3
1-phase central	0.96	0.202	2.3	0.90	-2.7
Window type	0.82	0.468	2.5	0.56	-2.8
Water heaters,					
Range top, oven,	1.0	2.0	0	0	0
Deep fryer					
Dishwasher	0.99	1.8	3.6	0	-1.4
Clothes washer	0.65	0.08	1.6	3.0	1.8
Clothes dryer	0.99	2.0	3.2	0	-2.5
Refrigerator	0.8	0.77	2.5	0.53	-1.5
Television	0.8	2.0	5.1	0	-4.5
Incandescent lights	1.0	1.55	0	0	0
Fluorescent lights	0.9	0.96	7.4	1.0	-2.8
Industrial motors	0.88	0.07	0.5	2.5	1.2
Fan motors	0.87	0.08	1.6	2.9	1.7
Agricultural pumps	0.85	1.4	1.4	5.0	4.0
Arc furnace	0.70	2.3	1.6	-1.0	-1.0
Transformer (unloaded)	0.64	3.4	11.5	0	-11.8

Table 2-2
Static Characteristics of Load Classes

Load class	Power factor	∂P/∂V	∂Q/∂V	∂P/∂f	∂Q/∂f
Residential					
Summer	0.9	1.2	2.9	0.8	-2.2
Winter	0.99	1.5	3.2	1.0	-1.5
Commercial					
Summer	0.85	0.99	3.5	1.2	-1.6
Winter	0.9	1.3	3.1	1.5	-1.1
Industrial	0.85	0.18	6.0	2.6	1.6
Power Plant Auxiliaries	0.8	0.1	1.6	2.9	1.8

Constant P-Q Load Model

In classic load-modeling practice, most of the loads attached to the bus bars are regarded as PQ loads, meaning that their power consumption P and Q are constant. Most simulation packages treat constant PQ load as a constant impedance in time domain studies because the load impedance is essentially unchanged for the time scales of interest. However, the constant PQ load model has been found to be inadequate in representing system behavior during contingency conditions.

The PJM regional transmission organization (RTO) Operating Committee, in its July 1999 low voltage condition root cause analysis, identified inadequacy of the PQ load model in accurately representing system conditions during contingencies. Of the many root causes, root cause # 16 stated that:

> Root Cause 16. THE CONSTANT PQ LOAD MODEL HAD NOT RECENTLY BEEN VALIDATED
>
> *There are various types of load models that can be used in power flow analysis. Each type represents characteristics of "real-world" loads – resistive, reactive, motor load, etc. The model used in the EMS should represent the characteristics of the majority of system load. The accuracy of the Security Analysis (SA) calculation will depend on the how faithfully the majority of the load characteristics are modeled, especially during abnormally low voltage conditions, as occurred on July 6th and July 19th .*

The PJM recommendation to members was to reevaluate whether the constant PQ model continues to be an adequate representation of the present-day load characteristics of the PJM system.

ZIP Load Model

A refinement from the constant PQ load model is to represent loads as combinations of constant impedance (Z), constant current (I) and constant power (P) (ZIP model). While the ZIP model is a refinement over the constant PQ model, it still does not represent the dynamic behavior of the load. Moreover, a linear dependency of load with voltage and frequency, as described in Tables 2.1 and 2.2, may characterize the static model of a load better than a combination of constant impedance, constant current and constant power model.

Dynamic Load Model

The response of a power system following a disturbance spans several time periods. The initial response immediately following the disturbance may be adequately represented using a static load model. However, for predicting system response for a time spans greater than 10 seconds, the dynamic behavior of the load needs to be represented. The following sections, based on[5] , provide a qualitative explanation of load dynamic characteristics

Thermostatic Effects

Thermostatic effect represents the behavior of loads such as resistive space and water heaters that are controlled by a thermostat. Immediately following voltage depression, these loads behave as a constant impedance load, resulting in reduced power consumption. However, because of the thermostat set point, this reduced power consumption does not translate into reduced energy consumption and results in the loads running longer than they would have run without the voltage disturbance. The net effect of this could be a power level close to the pre-disturbance level over a period of time, which has been postulated at anywhere in the 10-30 minute range.

Voltage Control Devices

In many systems, voltage-regulating devices such as Load Tap Changers (LTCs) are set to maintain distribution or subtransmission voltages within a specified range. Depending on the equipment involved, this action occurs over a range of tens of seconds to a few minutes following a significant change in voltage. The LTC action to regulate downstream voltage may not always be a desired response during system contingencies. The voltage support provided by the LTCs can increase the real and reactive power requirements of the loads during conditions of depressed voltage on the overall supply system and may aggravate the overall problem.

This condition was also identified by PJM as one of the root causes of the July 1999 low-voltage conditions in the PJM system. The following root cause, related to Load Tap Changer Impact on system stability, was identified in the PJM report:

> Root Cause 22. THE EMERGENCY PROCEDURES DO NOT ADDRESS THE COORDINATION OF BLOCKING LTCs
>
> *The LTCs at some distribution substations were being used to maintain distribution voltage at the expense of the transmission voltage. PJM and members should evaluate the*

need to establish a procedure to block LTC operation in certain reactive deficient emergencies.

Induction Motors

Induction motors are a critical load component in any power system. Static load models do not adequately represent either the time dependency or the immediate response of a motor following a significantly reduced voltage condition. For example, a fault in the transmission system close to a major load delivery point could result in voltage sag down to 50% to 60% of nominal. Such a significant voltage drop could result in stalling of the air conditioning compressors downstream of the load delivery point. Adequately representing such low-voltage response could be critical in some cases, especially in predicting the fast voltage-collapse phenomenon further discussed in Chapter 5.

A contribution to the 2003 IEEE/CIGRE Quality and Security Symposium from Saudi Arabia[5] described an actual system voltage collapse that resulted because of the large amount of induction motor load (air conditioning) on the system. Figure 2-9 shows a simulated response compared to the actual system response during this voltage collapse. These simulations were performed after more detailed load model development to correctly represent the response of these loads during and following the initial voltage sag.

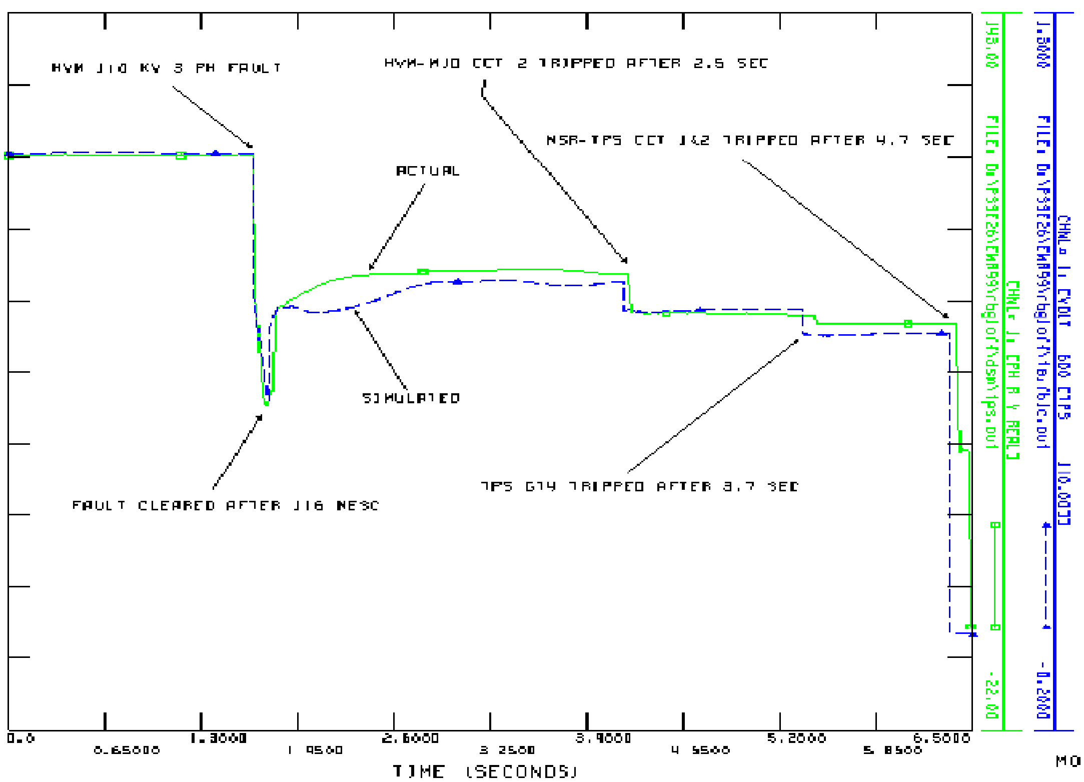


Figure 2-9
Example of System Voltage Collapse Caused by Induction Motor Loads [9]

Load-Modeling Parameter Evaluation Methods

There are several methods to identify load composition and load parameter models. These include:

1. **Component-based measurement**, which was developed by EPRI under several research projects beginning in 1976 [3, 5, 6, 7]. It involves building up the load model from information on its constituent parts as illustrated in Figure 2-10. The load supplied at a bulk power delivery point is categorized into load classes such as residential, commercial, industrial, agricultural, and mining. Each category of load class is represented in terms of load components such as lighting, air conditioning, space heating, water heating, and refrigeration.

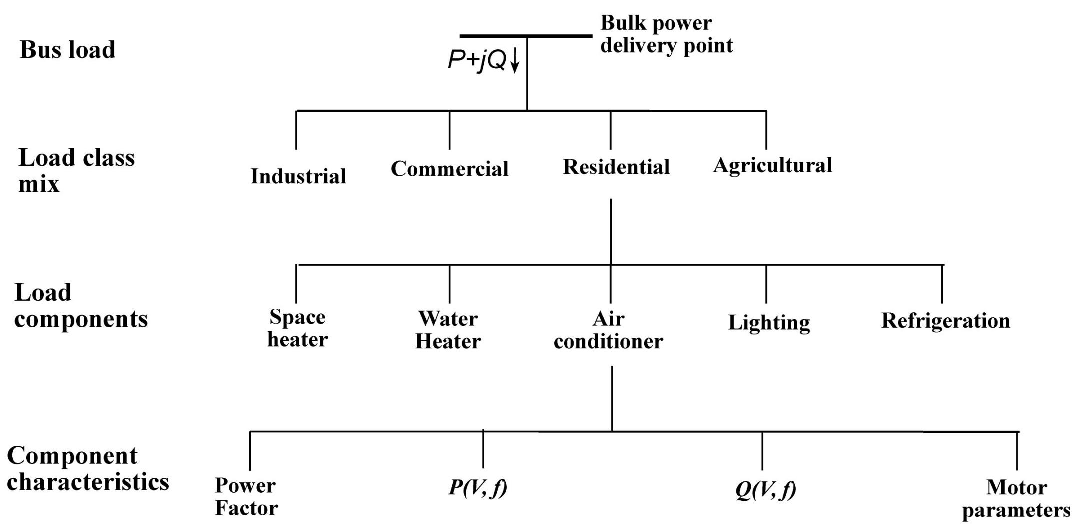


Figure 2-10
Components of a Load Model

2. **Parameter identification from controlled system tests** involves controlled testing to create a voltage deviation at a load delivery point and measuring the system response. In this approach, the load characteristics are measured at representative substation feeders at selected times of the day and season. These are then used to extrapolate the parameters of the load models throughout the system. Staged tests are sometimes conducted to derive load parameters, and in some cases load parameters can be determined from actual system transients. Field-testing is limited to step changes in voltage excursions within the allowable band since actual customers loads are connected downstream and cannot be subjected to variations that may potentially cause customer equipment to misoperate. In an actual environment, it is not feasible to subject customer loads to wide variations of step voltage changes that may occur in real-life situations. The load parameters derived from field-testing are valid mainly for steady state load characteristics and to derive small signal models.

3. **Parameter identification by measuring system response during normally occurring events** is another approach that can be implemented using existing monitoring instruments deployed by many utilities. These monitoring systems include Digital Fault Recorders

(DFRs), Phasor Measurement Units (PMUs) and Power Quality (PQ) monitors. This approach does not require elaborate test set-ups and if properly implemented could provide real time feedbacks of the changing characteristics of the load. The main focus of this report is to evaluate such measurement approaches using PQ monitors. The next chapter will review the hardware and data characterization methods used by PQ monitors and evaluate the applicability for identifying static and dynamic parameters for real time or near real time modeling of power system loads.

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8. T. Frantz, T. Gentile, S. Ihara, N. Simons, and M. Waldron, "Load Behavior Observed in LILCO and RG&E Systems," IEEE Trans., Vol. PAS-103, No. 4, pp. 819-831, April 1984.

9. I. Hamzah and J. Yasin, "Static Var Compensators Required to Solve the Problem of Delayed Voltage Recovery Following Faults in the Power System of the Saudi Electric Company – Western Region," CIGRE/IEEE Symposium on Quality and Security, Montreal, Canada, October, 2003.

3

USE OF POWER QUALITY MONITORS FOR LOAD MODELING

This chapter discusses the history of large-scale power quality monitoring systems and desirable characteristics that a monitor should have in order to capture the data needed for load modeling. It reviews the specifications and configuration of seven power quality monitors and compares them to the desired characteristics. The chapter concludes with a discussion of the specifications for the "next-generation" power quality monitor that will incorporate the functionality required to capture the data needed to perform load modeling.

Power Quality Monitoring Systems

A power quality monitoring system encompasses hardware, communications, and a data characterization software system that acquires continuous or event-triggered voltage and current samples to evaluate one or more PQ parameters as described by IEEE or IEC standards. Figure 3-1 shows the categories of PQ parameters based on the IEEE Std 1159-1995, "IEEE Recommended Practice for Monitoring Electric Power Quality."

Table 3-1 shows the types of measurement possible and the power quality phenomena that can be analyzed by a Dranetz-BMI 8010 PQNODE, one of the first-generation, complete PQ monitoring systems developed in the early 90s.

Categories			Typical Duration	Typical Spectral Content	Typical Voltage Magnitude	Method of Characterizing	Typical Causes	Example of Power Conditioning Solutions
Transients	Impulsive	Nanosecond	> 50 nanoseconds	5 ns rise		Peak Magnitude, Rise Time, Duration	Lightning, Electro-Static Discharge, Load Switching, Capacitor Switching	Surge Arresters, Filters, Isolation Transformers
		Microsecond	50 nanoseconds to 1 millisecond	1 μ rise				
		Millisecond	> 1 millisecond	0.1 ms rise				
	Oscillatory	Low Frequency	0.3 milliseconds to 50 milliseconds	< 5 kHz	0 to 4 pu	Waveforms, Peak Magnitude Frequency Components	Line/Cable Switching, Capacitor Switching, Load Switching	Surge Arresters, Filters, Isolation Transformers
		Medium Frequency	20 microseconds	5 to 500 kHz	0 to 8 pu			
		High Frequency	5 microseconds	0.5 to 5 MHz	0 to 4 pu			
Short Duration Variations	Instantaneous 0.5 cycles to 30 cycles	Sag			0.1 to 0.9 pu	RMS vs. Time, Magnitude, Duration	Remote System Faults	Ferroresonant Transformers, Energy Storage Technologies, UPS
	Momentary 30 cycles to 3 seconds	Swell			1.1 to 1.8 pu			
	Temporary 3 seconds to 1 minute	Interruption			< 0.1 pu	Duration	System Protection (Breakers, Fuses), Maintenance	Energy Storage Technologies, UPS, Backup Generators
Long Duration Variations	Undervoltages		> 1 minute		.08 to 0.9 pu	RMS vs. Time, Statistics	Motor Starting, Load Variations, Load Dropping	Voltage Regulators, Ferroresonant Transformers
	Overvoltages		> 1 minute		1.1 to 1.2 pu			
Voltage Unbalance			steady state		0.5 to 2%			
Waveform Distortion	DC Offset		steady state		0 to 0.1%			
	Harmonics		steady state	0 to 100th H	0 to 20%	Harmonic Spectrum, Total Harm. Distortion, Statistics	Nonlinear Loads, System Resonance	Filters (active or passive), Transformers (cancellation or zero sequence components)
	Interharmonics		steady state	0 to 6 kHz	0 to 2%			
	Notching		steady state					
	Noise		steady state	broad-band	0 to 1%			
Voltage Fluctuations			Intermittent	< 25 Hz	0.1 to 7%			
Power Frequency Variations			> 10 seconds			Variation Magnitude, Frequency of Occurrence, Mod. Frequency	Intermittent Loads, Motor Starting, Arc Furnaces	Static Var Systems

Figure 3-1
Power Quality Parameters as Defined by IEEE 1159-1995

Table 3-1
Overview of PQ Measurement Characteristics for the Dranetz-BMI 8010 PQNODE

Measurement type	Types of power quality phenomena which can be analyzed
RMS Variation	sags, swells, momentary interruptions, under- and overvoltages, beginning of sustained interruptions
Waveshape Fault	transients, beginning and end of faults
Impulse	high-frequency transients with above 5 kHz
Outage	sustained interruptions
Cold Load Pickup	inrush current at breaker recloser due to an outage
Steady-State Sample	regulation, voltage and current unbalance, power and power factor, harmonic distortion, voltage notching
Steady-State RMS Envelope	regulation, load cycles, frequency, monitor internal temperature, voltage and current rms variations

The installed base of power quality monitoring systems has increased significantly over the past ten years. Starting in the early 1990s, several utilities recognized the importance of moving beyond power quality monitoring in reaction to customer or system issues. These utility companies have installed (and continue to install) permanent power quality monitors at key locations on their transmission and distribution systems.

From a functional standpoint, PQ monitoring involves the following general functions:

- Periodic sampling of steady state voltage and current waveform (Figure 3-2)
- Trending of steady state voltage and current (Figure 3-3)
- Trigger-based waveform capture (Figure 3-4)

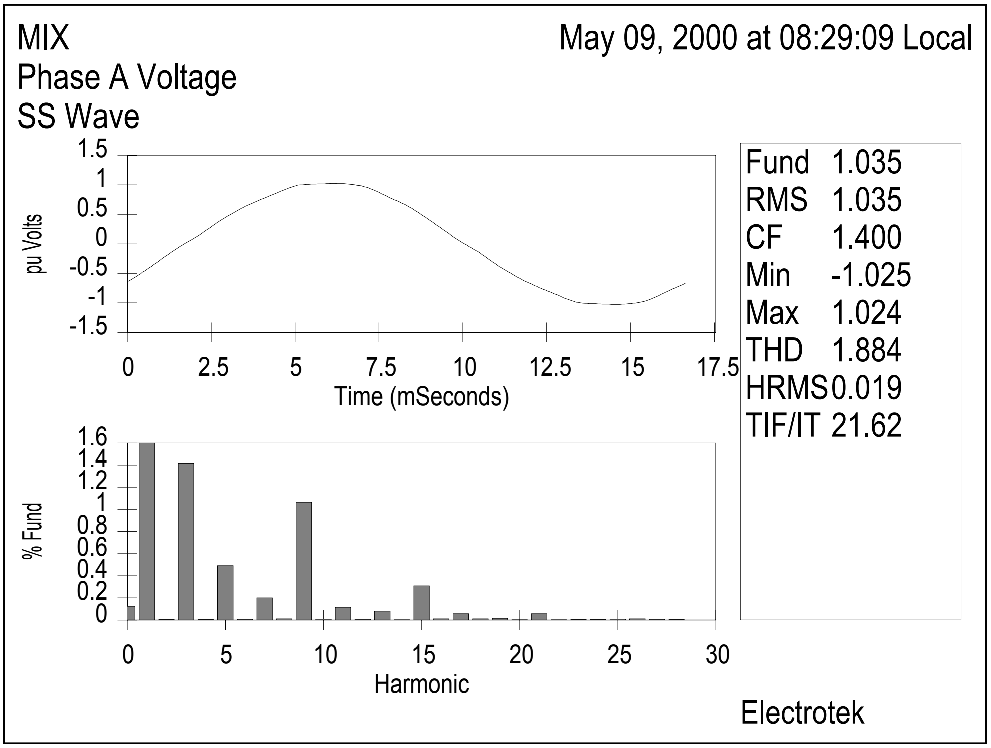


Figure 3-2
Periodic Sampling of Steady State Voltage and Current Waveform from a Dranetz BMI PQNODE 8010

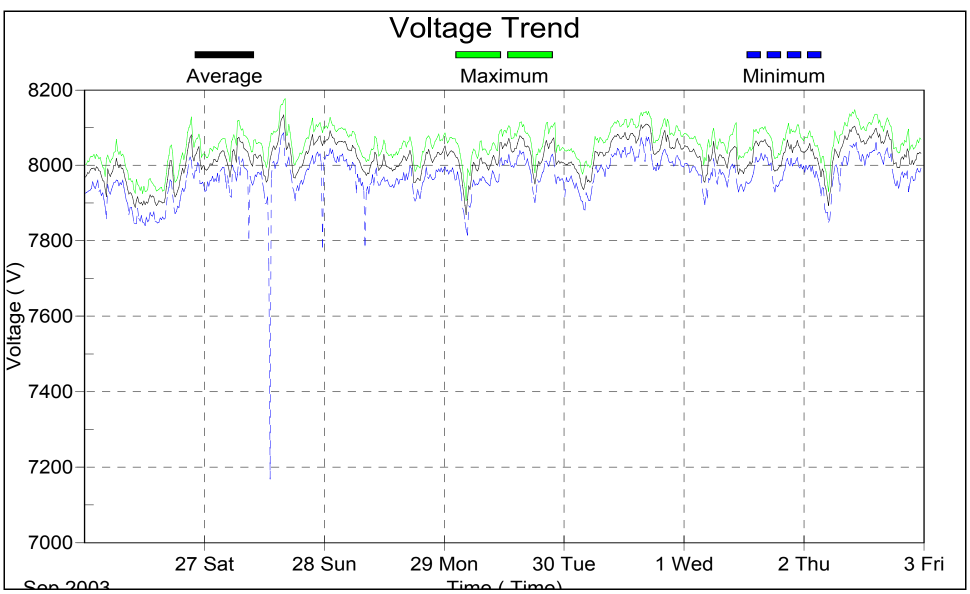


Figure 3-3
Voltage Trend Recorded by a Dranetz-BMI 7100

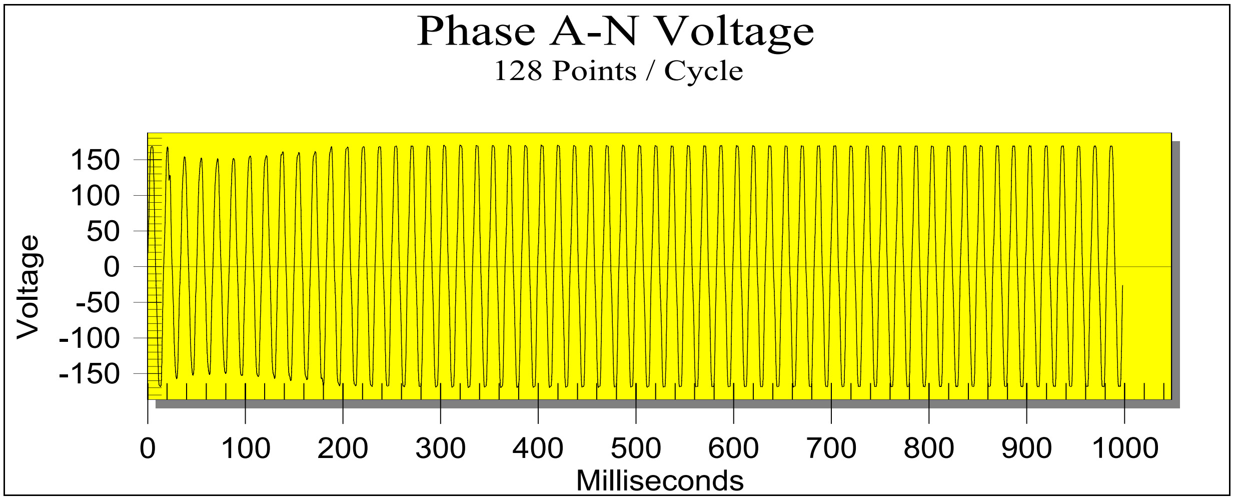


Figure 3-4
Waveform of a Voltage Sag Recorded by a Square D PowerLogic CM4000T

Data gathered by power quality monitors is useful in trending various PQ parameters and for diagnosing and eventually solving power quality problems. In order to evaluate whether the data capture and data characterization method for PQ monitors lends itself to identifying load-modeling parameters, the basic requirements of data for load modeling need to be identified.

The next section lists some basic requirements that monitors should meet in order to provide the data required in developing load models.

Monitor Requirements to Support Load Modeling

As discussed in the previous chapter, data for load modeling may be acquired from controlled field testing such as a regulator tap change or by capturing data from naturally occurring system events such as a fault in the power system that results in a voltage sag. For the purpose of field testing, any portable test equipment that can acquire the necessary voltage and current data for the period of testing will suffice. It is not necessary to use a PQ monitoring instrument for this purpose.

However, for measuring system response during naturally occurring events, the test instrument has to be connected for a long period of time. System-side PQ monitors that are already permanently installed in the system could provide a useful platform for collecting such data. In order for the data to be useful for load modeling, the record length of the data during and following a system event should be large enough for the time scale of interest. For static load models, the data should be at least 10 seconds long. For dynamic load models, the record length should be longer than 10 seconds; thermostatic effects could require a record length of 30 minutes. One important thing to note is that this requirement does not mean that the waveform data at the sampling rate used by the monitor (typically 128 samples per cycle) needs to be recorded. The data that is needed for the entire record length are primarily rms values of voltage, current, active and reactive power at a sample rate of 20 Hz. Since frequency dependency of load response is also a useful parameter for load modeling, any frequency variation during the monitoring period should be recorded as well.

In addition to this requirement, it is also beneficial for PQ monitors to have a continuous recording capability. This data can be used for detecting any possible oscillation that may be representative of a power system stability problem. The emphasis again is not on waveform data, but on rms data. For such continuous recording capability, a scan rate of a few Hz is sufficient to detect primary modes of power system oscillations.

Generally power oscillations can be divided into three different categories:

1. Local plant mode oscillations or inter-machine oscillations with a frequency range of 0.7 – 2 Hz

2. Inter-area oscillations, where groups of generators are swinging against each other in the frequency range of 0.4 – 0.7 Hz

3. Large sub-systems oscillating against each other, where the swinging frequency usually is in the order of 0.1 – 0.3 Hz[1].

If we look at these phenomena together, we can arrive at a reasonable set of requirements that a monitor should meet in order to gather data to support load modeling. The minimum requirements can be listed as:

Table 3-2
Minimum Requirements of a Monitor for Load Modeling

Capture of RMS (root-mean-square) voltage
Capture of RMS current
Capture of real power*
Capture of reactive power*
Capture of fundamental frequency
Exception-based recording up to 20 seconds after voltage recovery within pre-disturbance threshold at a 20 Hz scan rate
Continuous recording at a 2-20 Hz scan rate

*Optional if voltage and current phasors are recorded

Capturing of RMS voltage and current entails recording the RMS magnitude and phase angle of the three-phase voltage and current quantities. Capturing the real and reactive power is optional depending on whether the monitor is capable of recording the phase angle of the three-phase voltage and current quantities. Fundamental frequency capture is also required for modeling of loads which have or are assumed to have some frequency dependence.

The quantities listed in Table 3-2 should be recorded in two manners: 1) continuous and 2) exception-based. Continuous recording is necessary to capture long-term load characteristics such as the effects of long-term voltage variations in response to load levels. Since this occurs over such a long time frame, the scan rate that is required is much slower. A slow scan rate of 2

Hz is a reasonable compromise between system events that would result in a load change (such as automatic gain control operations) and onboard storage requirements.

Exception-based recording, as mentioned previously, is a trigger or alarm-based recording mechanism. Events such as voltage deviations, current deviations, or frequency deviations trigger the monitor to record data covering the event. Since this is not a continuous operation, the scan rate of data capture can be higher.

Load-Modeling Capabilities of Commercially Available Monitors

Seven commercially available power quality monitors are reviewed in this section for their applicability to load modeling, based on the requirements listed in the previous section. The review of the monitors is based on published information alone and does not include capabilities of the monitors that are not known in the public domain. Therefore, the manufacturers should be contacted directly for unpublished features which may more appropriately meet the requirements as listed in the previous section.

Arbiter 1133A Power Sentinel

The Arbiter 1133A Power Sentinel is an intelligent electronic device (IED) which provides measurement of electrical power quality and revenue data. Its capabilities include:

- Revenue Metering
- Power Quality Monitoring
- System Control and Metering
- Time Synchronization
- Data and Event Logging
- Data Communications

The Power Sentinel CSV (PSCSV) software allows communication, configuration, and control of the 1133A. With the PSCSV software one can either view broadcast data as it arrives or download data which has been stored in memory. It also allows the export of the recorded data in either CSV or the IEEE Std. 1159.3 format known as the PQDIF format.

Unless otherwise indicated the following capabilities refer to the 16 MB model using Ethernet connection.

Continuous Recording Capabilities

In broadcast mode (while connected with the software), the 1133A can send voltage and current phasors as well as frequency at a rate of 20 samples per second to the PSCSV software via an Ethernet connection. A sample phasor plot as displayed in PSCSV is shown in Figure 3-5.

Additionally, the data can be streamed to a text file for later analysis. Please note that the data values shown are from a demo unit with varying ratios on the voltage and current channels.

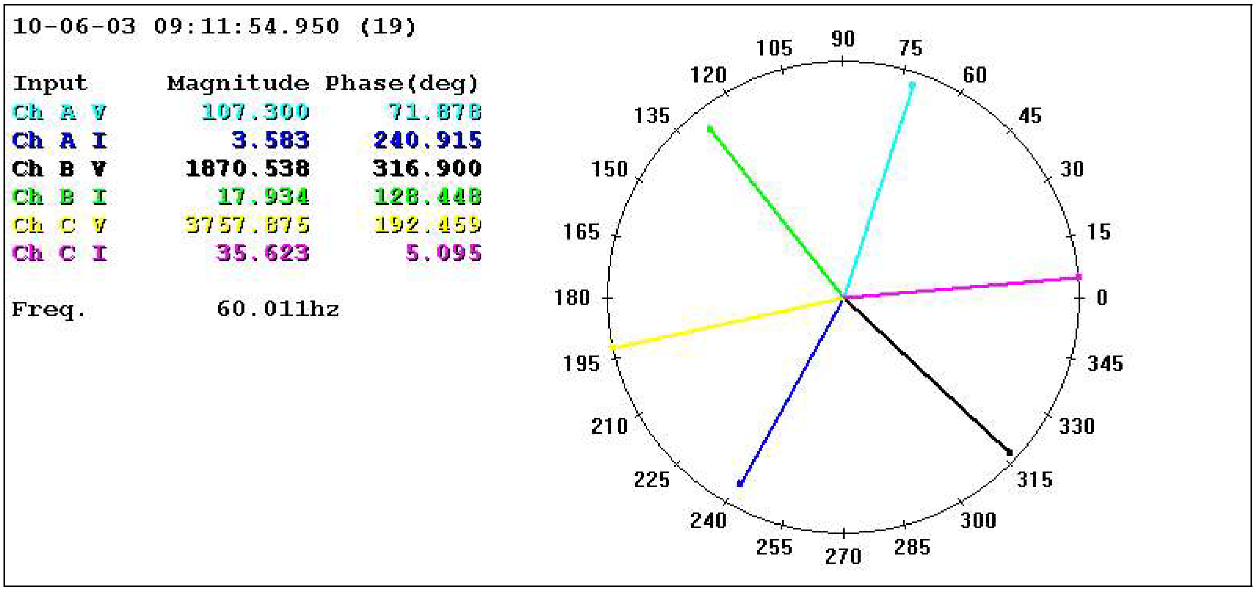


Figure 3-5
Phasor Diagram from Power Sentinel 1133A and PSCSV Software

While not the 1133A does not directly register real and reactive power, they can be calculated from the current and voltage phasors. In this respect, the Power Sentinel 1133A exceeds the continuous capture method. However, the PSCSV must be connected to the 1133A in order to record this data, as it is not stored ‘permanently’ in onboard memory.

Onboard storage of continuous data is via the scheduled parameters setup. Energy, voltage, frequency variation, flicker, and harmonics are some of the parameters which can be recorded into flash memory via a schedule. The shortest interval between these samples is 1 minute. In this configuration the 1133A, does not meet continuous recording requirements for using onboard memory.

Exception-Based Recording Capabilities

The following signal functions are available to be used as user-defined triggers in the 1133A (Figure 3-6). The quantities are updated at the rates shown.

Table 6-2. Signal Functions Available for Triggering

ID#	Function	Update Rate	Channels Available
0	Off	N/A	N/A
1	Voltage	20/sec	A, C, B, Average[1]
2	Current	20/sec	A, C, B, Average[2]
3	Active Power (Watts)	20/sec	A, C, B, Total[3]
4	Reactive Power (VARs)	20/sec	A, C, B, Total[3]
5	Apparent Power (VA)	20/sec	A, C, B, Total[3]
6	Power Factor (PF)	20/sec	A, C, B, Total[3]
7	Sequence Voltage Components	20/sec	Zero, Pos., Neg.
8	Sequence Current Components	20/sec	Zero, Pos., Neg.
9	Phase Balance Ratio, derived from sequence components	20/sec	Zero/pos., Neg./Pos. for both voltage & Current
10	Frequency and Time	20/sec	Frequency, ΔF, df/dt, ΔT
11	THD, Voltage	1/sec	A, C, B, max (A, C, B)[1]
12	THD, Current	1/sec	A, C, B, max (A, C, B)[2]
13	Harmonic V_{RMS}	1/sec	A, C, B, max (A, C, B)[1]
14	Harmonic I_{RMS}	1/sec	A, C, B, max (A, C, B)[2]
15	K-Factor, voltage	1/sec	A, C, B, max (A, C, B)[1]
16	K-Factor, current	1/sec	A, C, B, max (A, C, B)[2]
17	Flicker, instantaneous, voltage	1/sec	A, C, B, max (A, C, B)[1]
18	Flicker, PST, voltage	1/sec	A, C, B, max (A, C, B)[1]
19	Flicker, instantaneous, current	1/sec	A, C, B, max (A, C, B)[2]
20	Flicker, PST, current	1/sec	A, C, B, max (A, C, B)[2]
21-25	Reserved	TBD	TBD
26-31	Transient detector channels 0 - 5	20/sec	Bound, rate/change, osc.

[1] Average or maximum of 3 voltage channels in 3Φ4W3E and 3Φ3W2E input mode, 1 channel in 1Φ2W1E mode, and 2 channels in other modes. In 3Φ3W2E mode, the voltage V_{AC} is derived internally by point-by-point calculation after A/D conversion. The voltage V_B, synthesized internally in 3Φ4W2½E mode, does not correspond to an actual physical quantity and is not included in the analysis, although measurements can be made on the synthesized signal.

[2] Average or maximum of 3 current channels in 3Φ modes, 1 channel in 1Φ2W3E mode, and 2 channels in other modes. In 3Φ3W2E mode, the current I_B is derived internally by point-by-point calculation after A/D conversion.

[3] Total of 3 elements in 3Φ4W3E and 3Φ4W2½E modes, 1 element in 1Φ2W1E mode, and 2 elements in other modes.

Figure 3-6
Signal Functions Available for Triggering in the 1133A

For each channel, there is a limit that may be set by the user as well as a reference value that may be used by the trigger logic. The limit function logic may be set to any of four modes: 1) x > limit; 2) x < limit; 3) |x| >limit; or 4) |x – ref| > limit. In addition, each trigger channel may be made dependent on the results of another channel. It may be set so that the channel requires the other trigger to be either active or inactive before proceeding with its own comparison. Comparisons are made at the 20 per second rate for all channels, even for input signals, which change more slowly [2]. The 1133A also includes special logic for detecting oscillatory transients.

Once a user-set trigger condition has been met, the monitor will record (to flash memory) basic data, phasors, harmonic data, harmonic summary data, or waveforms. Basic data consists of one or more of the quantities shown in Figure 3-7, stored into memory at a rate of 1 per second.

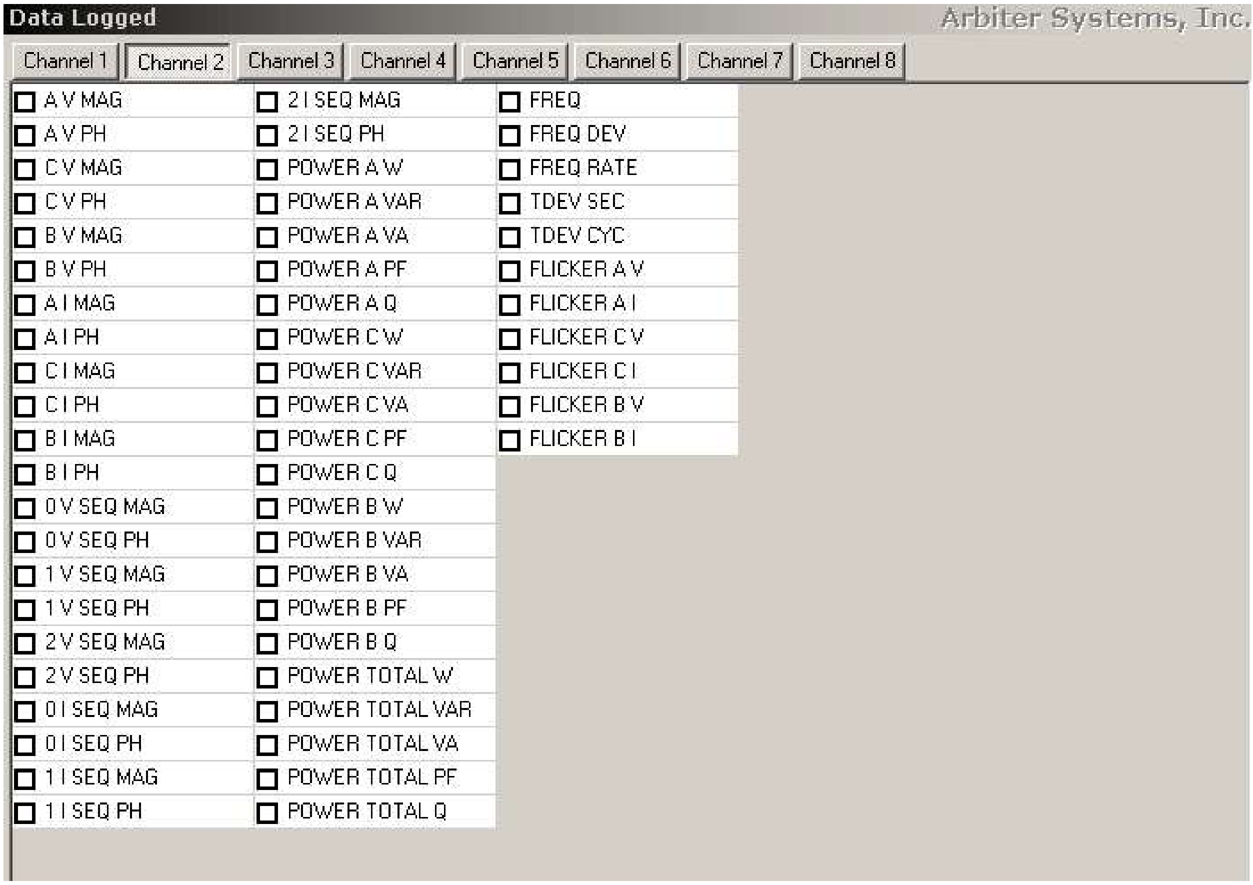


Figure 3-7
Basic Quantities to be Logged on an Event by the 1133A

Phasors recorded by the instrument are recorded 20 times per second into available onboard memory. It can record greater than 20 seconds in duration of an event after it has been triggered in this mode. The PSCSV software user's manual indicates a maximum log time of 65,535 seconds and a maximum post-fault log time of 65,535 seconds. It is unknown if these are practical limits, given the device's 16 MB of memory.

Waveforms can also be stored by the 1133A apparently at a rate of 600 per second, according to the manufacturer's technical support, but this could not be verified; it is recommended that the manufacturer be contacted for more information. The unit can record up to 6 seconds of pre-fault data, 65,535 seconds of log time data, and a maximum post-fault log time of 65,535 seconds. The practical limits of the 1133A's onboard memory are unknown.

Dranetz-BMI 7100 PQNode

The Dranetz-BMI 7100 PQNode is an eight-channel power quality monitoring instrument which provides single or three-phase voltage and current monitoring. It has three independent operating modes for characterization of power quality, power flow, and power harmonics of the AC power system.

The Power Evaluation System (PES) software is used for configuration of the monitor, switching between operating modes, and for retrieval of data from the instrument. PES is used to define one or more sites (a specification of data that should be gathered by an instrument and the rate at which it should be gathered), upload the site definitions to the instrument, download data from the instrument periodically, and analyze the downloaded data.

The current firmware version of the 7100 is at level H and the current version of the PES software is at level L1.

Continuous Recording Capabilities

In power quality mode, there are two published methods for obtaining power quality data on a somewhat continuous basis. The first method is to use the RMS summary setup to record current and voltage on a timed interval. The shortest timed interval which can be configured is a 1 minute interval, as shown in Figure 3-8.

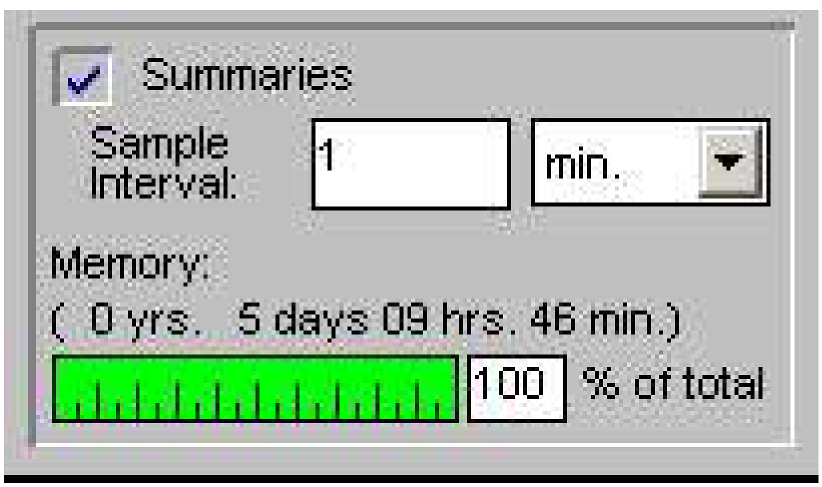


Figure 3-8
RMS Summary Configuration Screen in PES Software

RMS voltages and currents are calculated for every cycle and the minimum and maximum and their average values are recorded for each minute in this configuration. Figure 3-9 is a strip chart of voltages as recorded by this method.

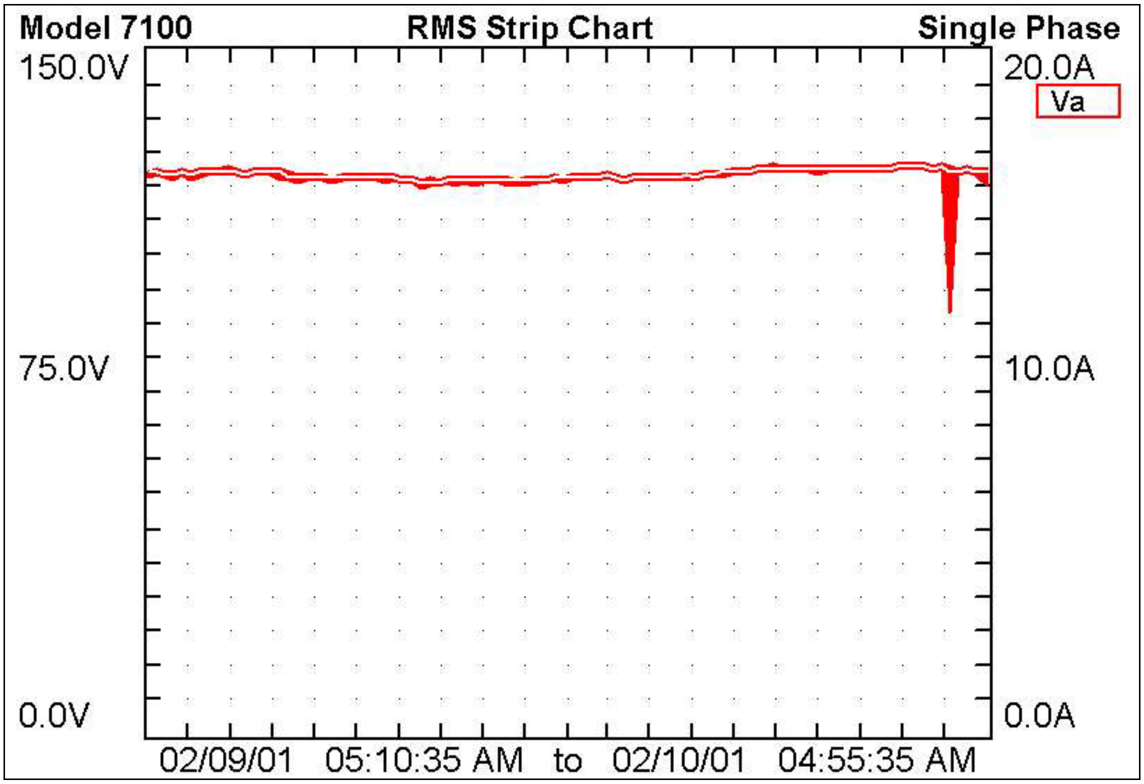


Figure 3-9
RMS Strip Chart as Displayed by PES Software

Unfortunately, the RMS strip chart does not meet the requirement of monitoring continuously at 2 hertz because the cycle-by-cycle data is not kept. It also does not meet the requirement of capturing real and reactive power or frequency data. Rather, it is summarized by three data points on a per minute basis. Another approach might be to use snapshot configuration as shown in Figure 3-10.

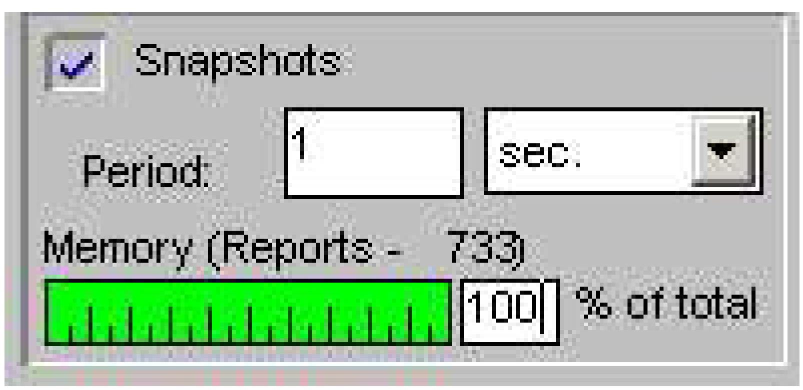


Figure 3-10
PES Snapshot Configuration Screen

The snapshot configuration also does not meet the 2 hertz requirement for onboard data collection, although it does capture waveforms for all channels at a 1 hertz interval.

Exception-Based Recording Capabilities

In exception-based recording mode, the 7100 is a voltage-triggered device. It can trigger on RMS, waveshape, and impulse voltage deviations. RMS voltage deviation memory configuration allows the user to set the number of cycles over which the calculation is to occur as well as the number of cycles required to start and end the event. The data recorded by this method are the magnitude of the voltage and current channels that are active. An example RMS sag disturbance is shown in Figure 3-11 for a single-phase configuration. The recorded data does not include the magnitude of real and reactive power or the fundamental frequency, but does meet the other requirements for exception-based recording.

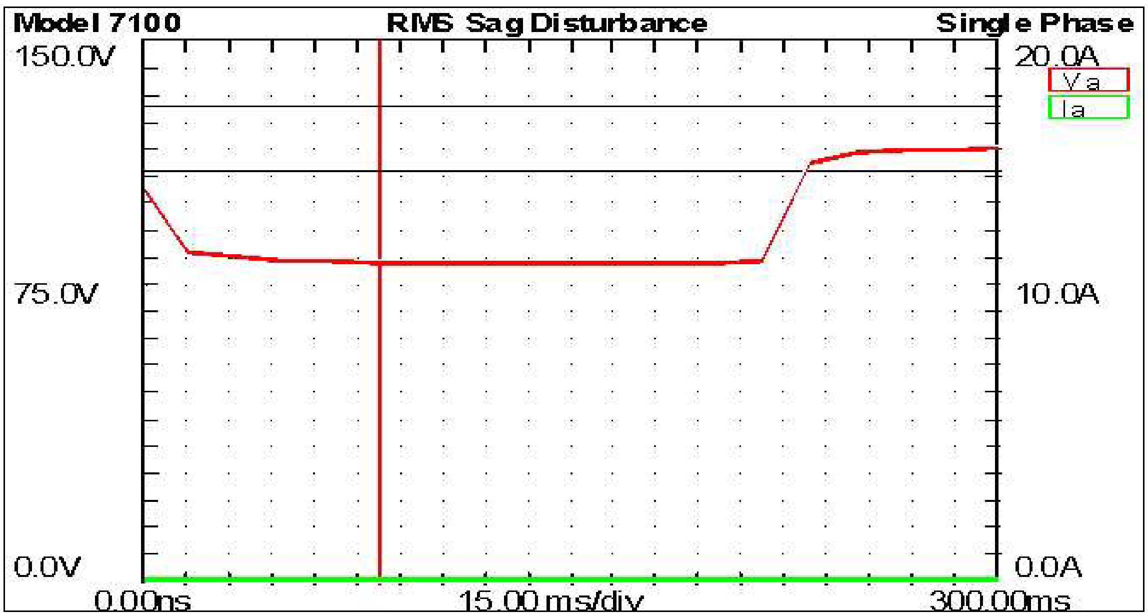


Figure 3-11
Dranetz-BMI 7100 RMS Sag Disturbance Capture

The instrument records waveshape disturbances if the waveshape limits are exceeded as configured in the threshold setup screen in the PES software (Figure 3-12). The user may calculate the desired quantities such as frequency and real and reactive power from the waveforms for this 16-cycle period. The 7100 will not capture an event up to 20 seconds in duration under this configuration. Impulse measurements are similar in that up to 16 cycles of data can be recorded based on the trigger threshold being exceeded.

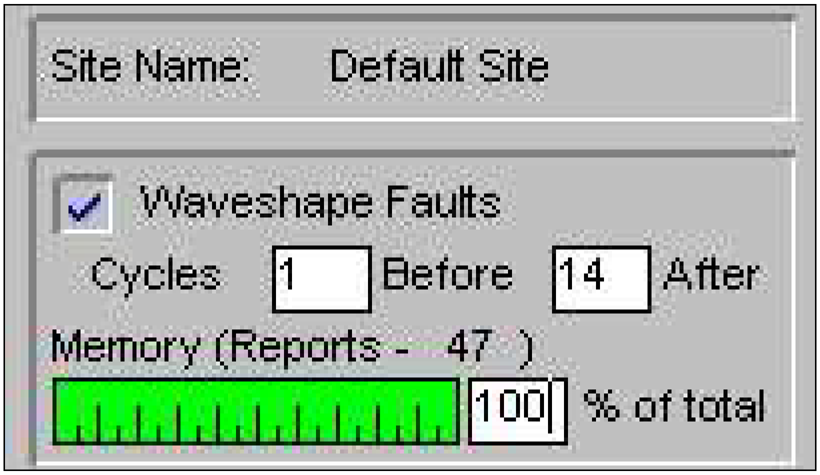


Figure 3-12
Waveshape Memory Configuration in PES for Dranetz-BMI 7100

Dranetz-BMI 8010 PQNode

The 8010 PQNode is a power quality instrument which is capable of simultaneous data gathering across eight independent channels. Voltage is sampled at 256 samples/cycle and current is sampled at 128 samples/cycle. Voltage impulses are also detected and recorded. PQNode Application and System Software is used to communicate with, configure, and download from the 8010 PQNode. PES Software can also be used with the 8010 PQNode.

Continuous Recording Capabilities

The configuration screen for sampled data is shown in Figure 3-13. Waveform samples are used to calculate trends in power, power factor, and various harmonic quantities. Steady-state samples are used to calculate trends in volt and current RMS magnitudes for each cycle (these are reported as minimum, average, and maximum values for each interval). Also RMS quantities can be sampled periodically for a certain number of cycles.

From the screen in Figure 3-13, one can see that the minimum interval between samples is 1 minute. This holds true for sampled waveforms, sampled steady-state quantities, and for periodically sampled RMS. Therefore, the monitor does not meet the 2 hertz scan rate requirements for continuous recording.

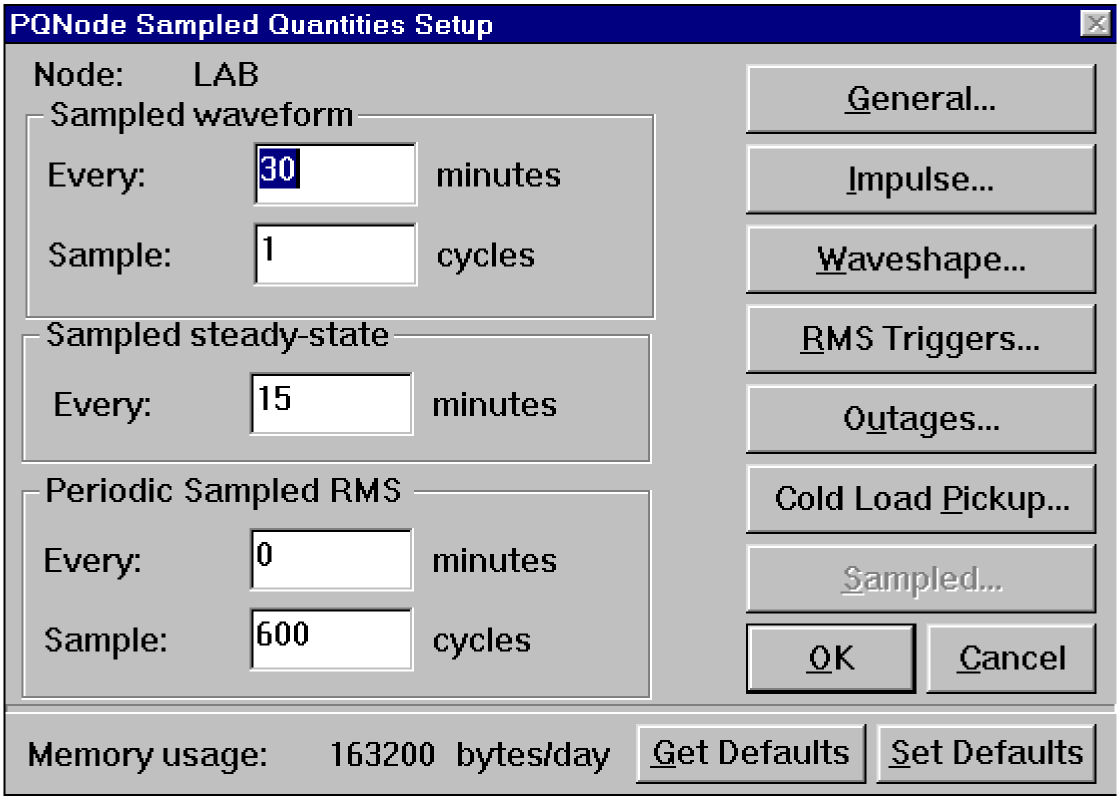


Figure 3-13
PASS Sampled Data Setup Screen for 8010 PQNode

Exception-Based Recording Capabilities

The monitor has two sets of triggers (not including impulse, which we will neglect for this discussion) that can trigger on voltage deviations. The first set of triggers are the waveshape fault triggers, which are configured via the screen in Figure 3-14.

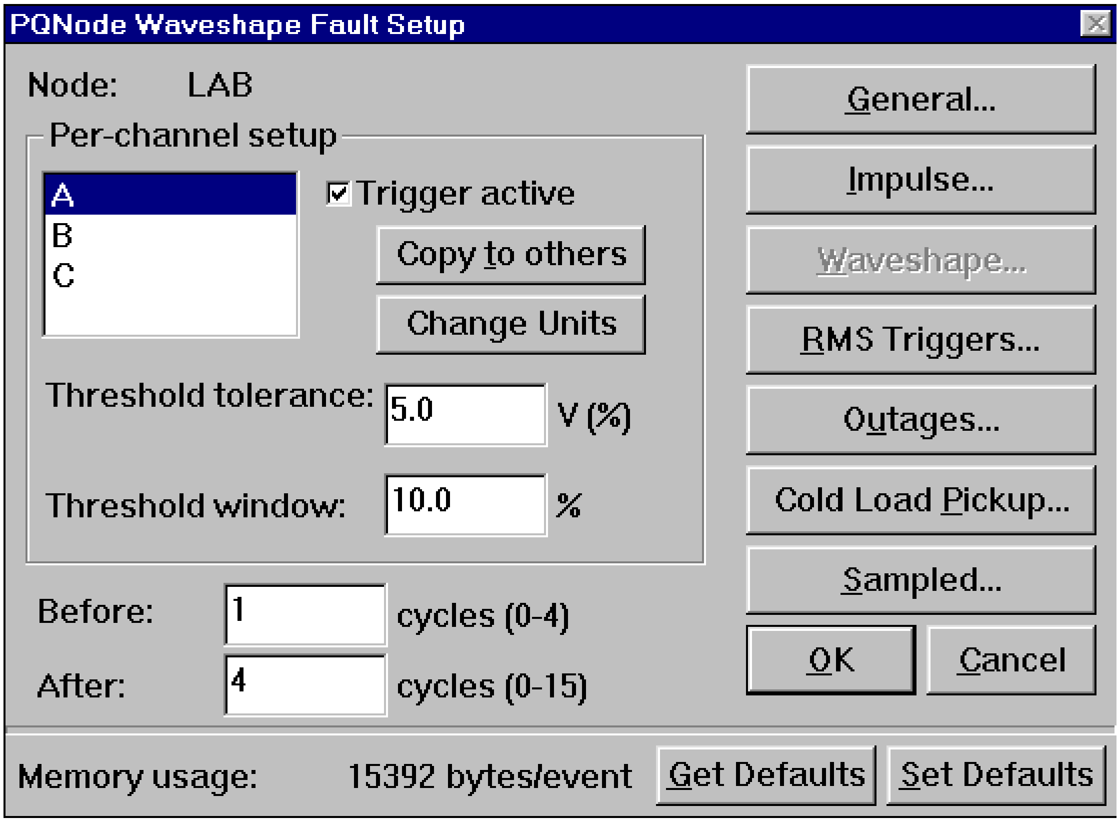


Figure 3-14
Waveshape Fault Configuration Screen in PASS

If the samples of the present cycle compared to those of the previous cycle differ by more than the threshold tolerance for a length of time exceeding the fraction of the power frequency cycle specified by the threshold window value, then a waveshape fault (or disturbance) is recorded. The duration of the event that gets recorded is up to 4 cycles before the cycle in which the disturbance was registered, plus up 15 cycles after the event. This does not meet the requirements as listed.

The second set of triggers are the RMS voltage triggers. The basic configuration screen in PASS for this set of triggers is shown in Figure 3-15. To trigger an RMS variation, the measured quantity (voltage) must exceed the high or low threshold values by an amount greater than the hysteresis value for a period at least as long as the cycles to trigger value. The disturbance will not end when the measured quantity again crosses the threshold value. It must remain greater than the hysteresis value away from the threshold for a minimum of a certain number of cycles[3].

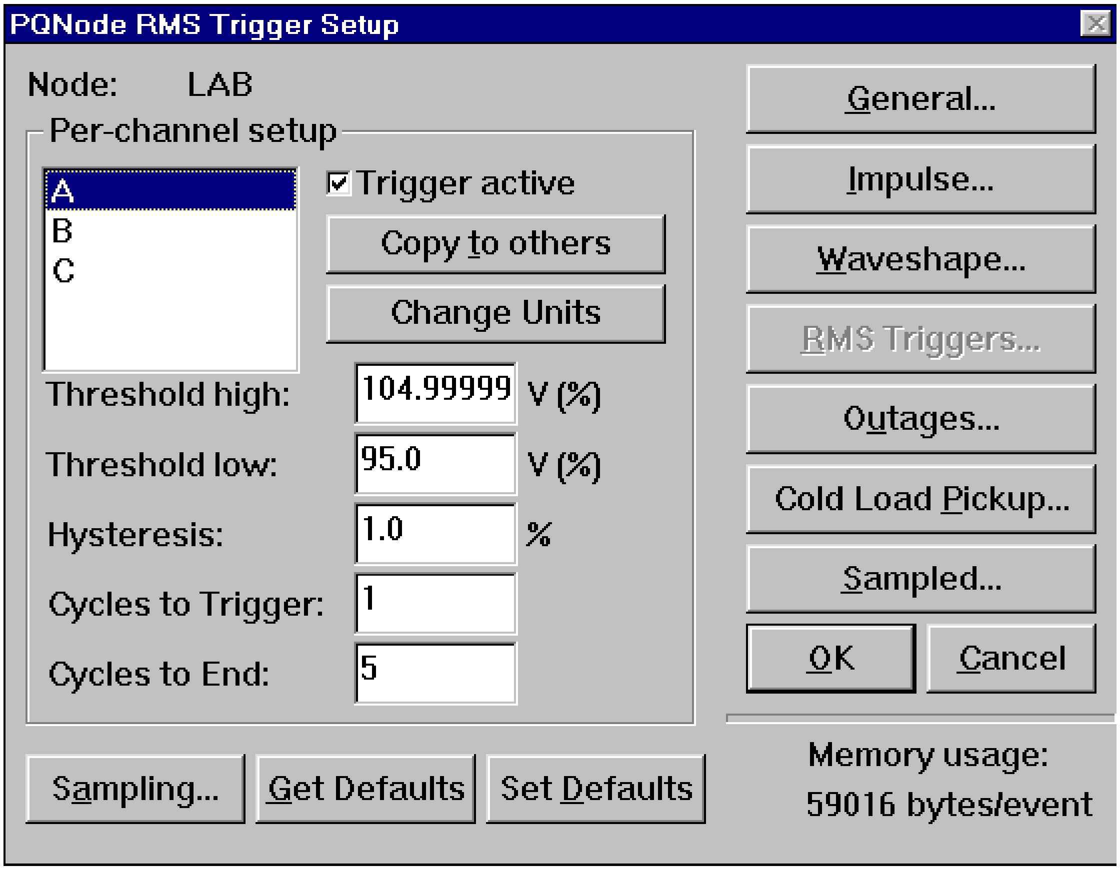


Figure 3-15
PASS Basic Setup Screen for RMS Triggers

When an RMS trigger has been activated, the 8010 PQNode will enter one of three recording modes. It will sample RMS data according to the configuration entered into the screen shown in Figure 3-16. Initially it will start storing RMS data at a rate of once per cycle and it will continue storing instantaneous RMS data for the number of cycles after the trigger, specified by the *After* parameter, or until the disturbance ends – whichever occurs first. It will also save the number of cycles before the trigger specified by the *Before* field[3]. As can be seen from Figure 3-16, this would be up to 255 cycles after the event.

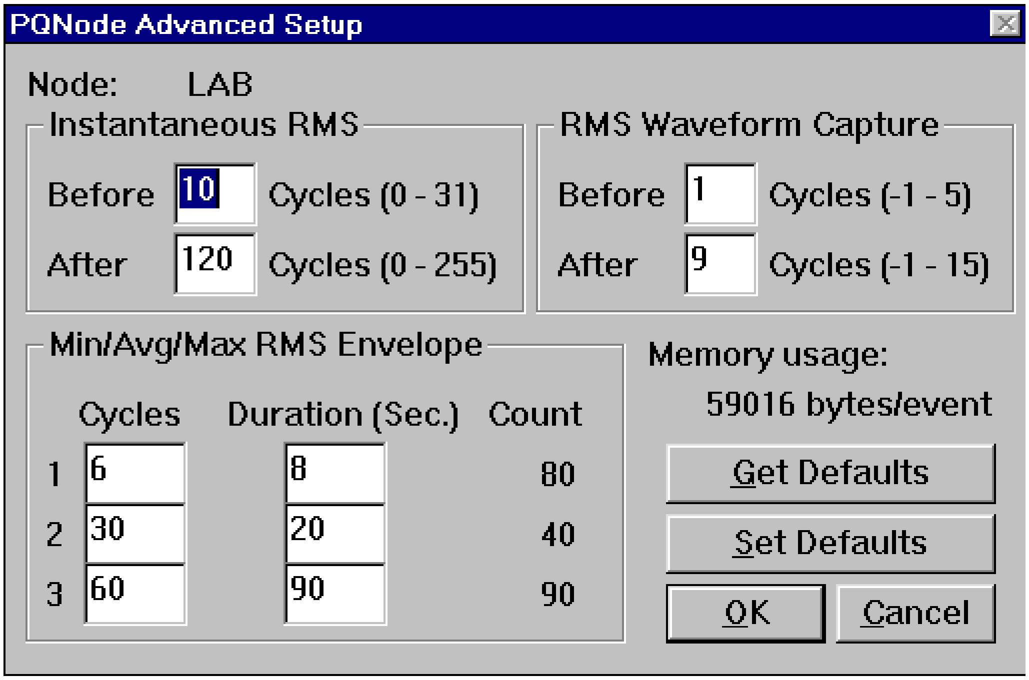


Figure 3-16
PASS Advanced Configuration Screen for RMS Trigger Data Capture

If the disturbance has not ended after the number of cycles specified by *After*, the PQNode shifts to minimum/average/maximum recording. It continues to compute the RMS value once per cycle, but will store only the minimum, average, and maximum values computed over the number of cycles specified in the *Cycles* box of Figure 3-16. This mode of recording lasts for the number of seconds specified in the *Duration* box.[3]. Up to three minimum/average/maximum periods can be specified.

Beyond the RMS level recording, waveforms can be recorded for up to 7 cycles before and up to 15 cycles after the trigger. Also, please note that there is a size constraint on all of the above parameters to not exceed 62,000 bytes total.

While this does easily meet the duration requirements, it only records RMS voltage and current for the longer durations (magnitude only, not phasor information). It is possible to calculate frequency and real and reactive powers from the waveform data, but for a shorter duration.

Dranetz-BMI Signature System

A typical Signature System is built from several DataNodes, plus one or more InfoNodes equipped with a selection of Answer Modules. DataNodes gather readings from circuits and processes. InfoNodes gather DataNode data, convert the data to information, and manage and communicate the information[4]. Voltage and current are sampled at 128 samples/cycle (maximum of 384 samples/cycle with dual peak detectors for transient-capable models). Setup, communication, and download of data is performed via Java code and uses a standard web browser.

Continuous Recording Capabilities

"Journalled" parameters, such as voltage, current, real and reactive power, frequency, and so forth, are checked once per second. Voltage and current minimum/average/maximum numbers are based on cycle by cycle values, while the power values are based on per second values. The journalled parameters can be stored at intervals as short as 1 per minute (minimum, average, and maximum values). Configuration of the interval is via the screen shown in Figure 3-17. A sample output screen is shown in Figure 3-18 for minimum, average, and maximum frequency as recorded at the EPRI PEAC laboratory. The interval scan rate does not meet the requirements as listed.

Steady State Trending	
Time between periodic samples (min)	5
Demand Interval (min)	15
Demand Sub Interval (min)	5

Figure 3-17
Steady-State Trending Setup in DataNode 5520

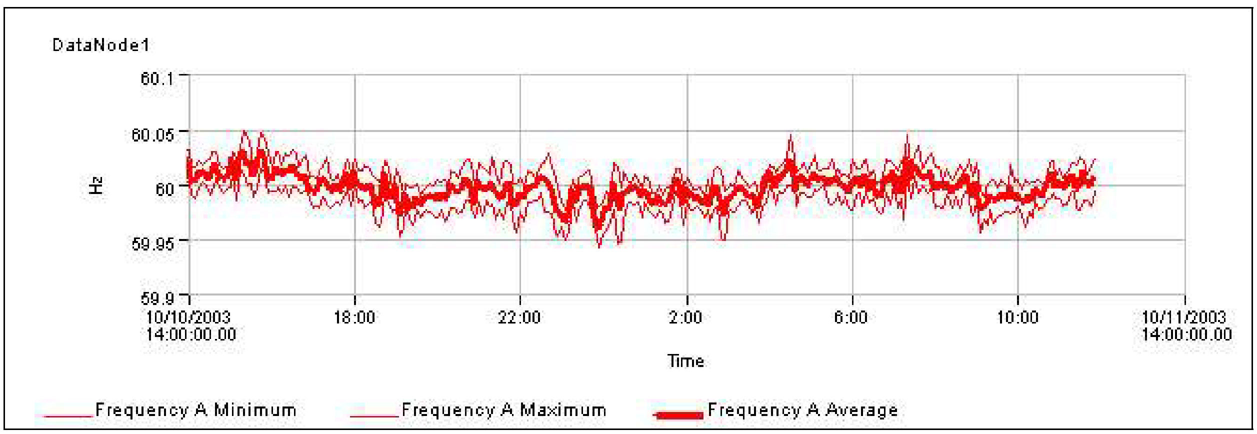


Figure 3-18
Example Frequency Plot at EPRI PEAC Laboratory as Recorded by Signature System

Exception-Based Recording Capabilities

Voltage and current thresholds can be used to trigger 16 cycle pre/post/fault cycles of waveforms for every channel per event. If a high or low limit crossing is detected for longer than the programmed minimum number of cycles to begin an event, then an event is begun. The first cycle and channel which were out of limits are labeled as the trigger cycle and trigger channel, respectively.

The number of RMS and waveform cycles to be saved before (pre-) and after (post-) the start and the end of the event can be individually programmed. For waveforms, the maximum total cycles is 16 {# start cycles = 0 to 16, # end cycles = 0 to 16, not to exceed 16- # of start cycles}. For RMS recordings, the maximum of event start cycles is 240 {# pre-event start = 0 to 8, # post end start = 0 to 240, not to exceed 240 - # pre}. If the event lasts longer than 240 cycles, then the unit goes into a reduced sampling rate to conserve memory. The post-event end RMS cycles can be programmed to 0-16.

If the voltage goes from out of limits to within limits (that is, below the *hi* limit minus the hysteresis) and above the *lo* limit plus the hysteresis) for at least the programmable *minimum_ required_event_end_cycles* number of cycles, then the RMS event recording is terminated. The first cycle (of the last phase) which was back in limits is the fault recovery cycle.

In addition, RMS variations can have three stages of averaging or chart rates, which is particularly useful for long duration events to save memory in exchange for reduced resolution. This is accomplished by programming the number of cycles to be consolidated for the min/max/avg values {1-10000}, as well as for how long to use this rate {1-100000 seconds}. This mode begins if the RMS value remains out of limits for longer than the post-start event number of RMS cycles that were programmed [5].

While this does easily meet the duration requirements, it only records RMS voltage and current for the longer durations (magnitude only, not phasor information). It is possible to calculate frequency and real and reactive powers from the waveform data but for a shorter duration.

Power Measurements ION 7600

The ION 7600 provides revenue-accurate, true RMS measurements of voltage, current, power, and energy and is complemented by I/O capabilities, logging, and power quality measurement and compliance verification functions. Maximum resolution of waveform recording is 256 samples/cycle. The ION Enterprise software is used to communicate with, control, download from, and display data for the ION 7600.

Continuous Recording Capabilities

The ION 7600 is capable of monitoring at a 2 hertz scan rate. It can be set up using the Designer software that is part of the ION Enterprise package. Figure 3-19 is an example of a setup screen in Designer to accomplish this. In this example, the periodic timer is set for 0.5 seconds and the requested data is stored in data recorder 9. The one-shot timer is set for the duration of monitoring that is required. For truly continuous monitoring this block and the external pulse block would be eliminated. The unit is capable of meeting the requirements for continuous monitoring.

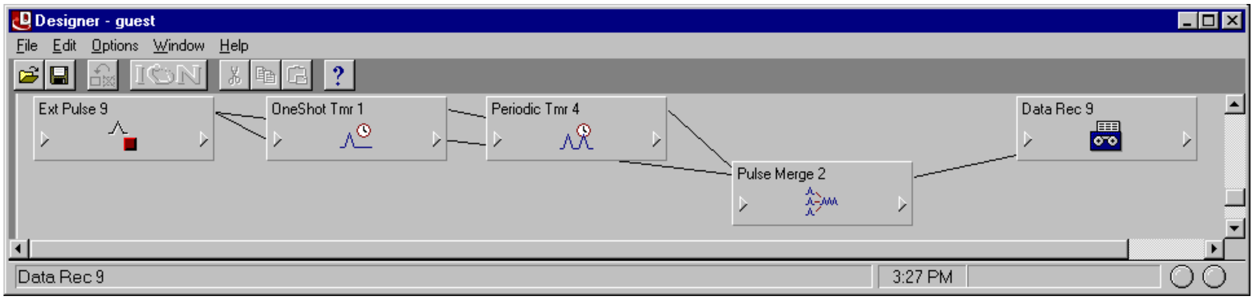


Figure 3-19
Designer Configuration Screen to Set Up Continuous Recording Capabilities

Exception-Based Recording Capabilities

The same configuration shown in Figure 3-19 could be used to record an event on an exception basis. Referring to the diagram, external pulse 9 simulates the event that triggers the alarm. The one-shot timer would be set for 20 seconds and the periodic timer would be set to 1/20th of a second. Data would be stored in the data recorder 9. As well as continuous monitoring requirements, the unit is capable of meeting the requirements for exception-based monitoring.

AVO International PA-9

The AVO International PA-9 is a portable, nine-channel analyzer capable of performing functions on four AC/DC voltages and five current inputs[6]. The analyzer samples at a rate of 256 samples/cycle (per channel). The PA-9 Plus portable analyzer is the latest revision of the PA-9, but it is not discussed here. The avo-pa9W software package is used to communicate with, display information from, configure, and download from the PA-9.

Continuous Recording Capabilities

With the power option installed, the meter is capable of recording real and reactive power as well as the RMS quantities of voltage and current at rates as short as once per cycle. This can be configured on the screen shown in Figure 3-20. A corresponding setup parameter, not shown in the figure, is the response time. The response time determines how many samples will be used in calculating RMS voltage and current values. This value can be set from 1 to 60 cycles. The meter does not directly store frequency through either of these screens. It can however output the frequency to the readings screen. The meter does not meet the continuous recording requirements since it does not store frequency.

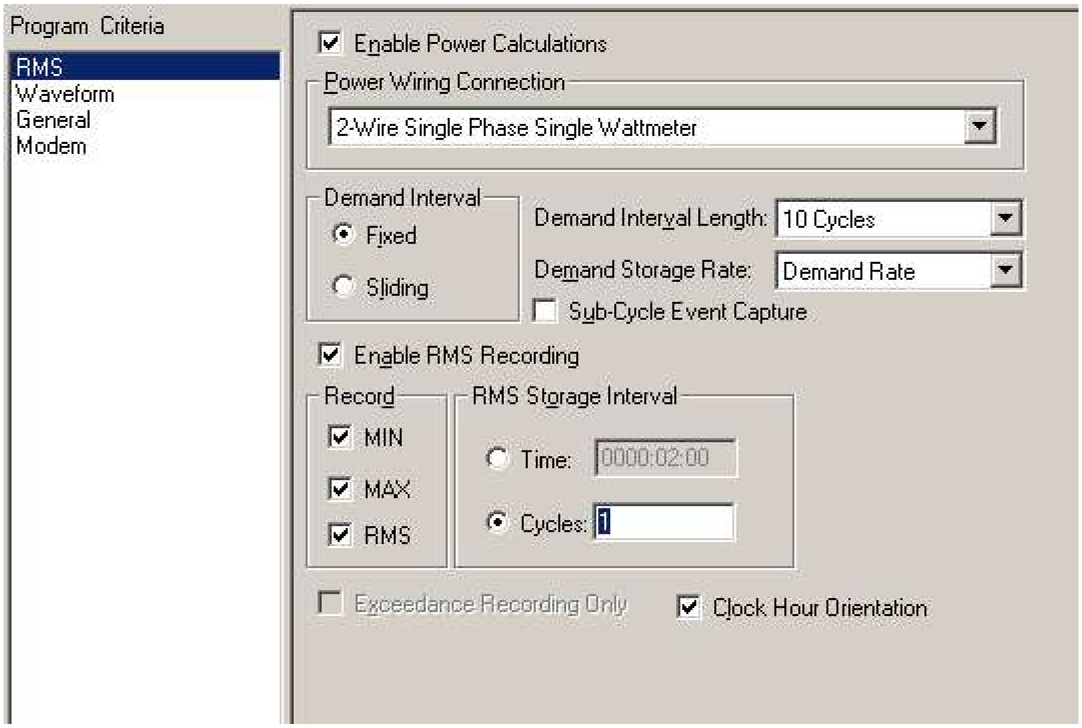


Figure 3-20
Configuration of the RMS and Power Calculations for the PA-9

Exception-Based Recording Capabilities

Waveform capture for exception-based events is set up via the screen shown in Figure 3-21. Here the user can select the capture rate, number of pre-trigger cycles, number of post-trigger cycles, and the expected number of waveform events. The number of pre-trigger cycles can be set at 2 while the number of post-trigger cycles can be set at up to 99 cycles. The meter does not meet the exception-based monitoring requirements.

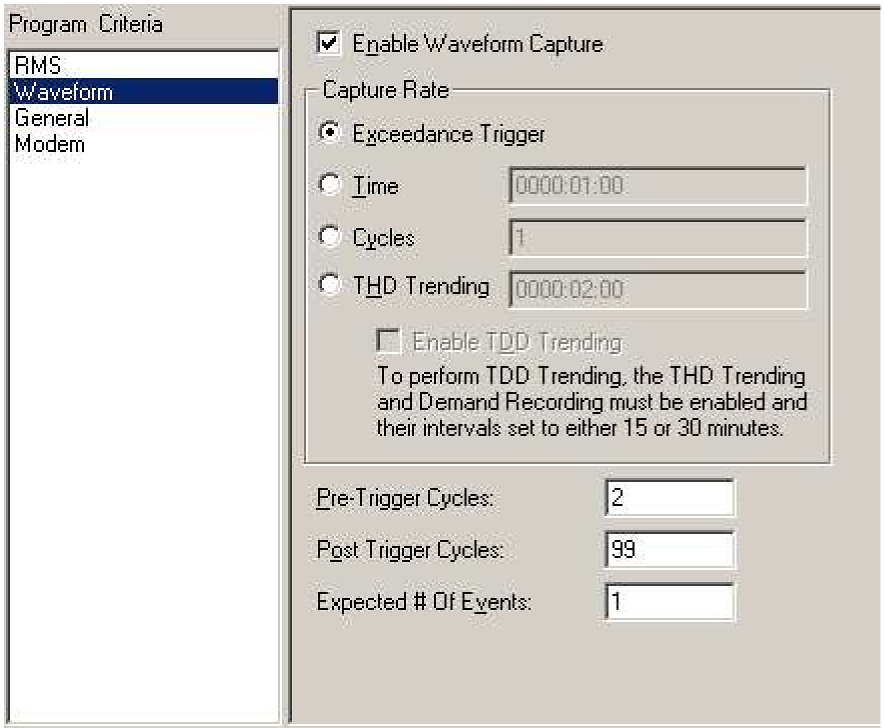


Figure 3-21
Waveform Configuration Screen

Square D PowerLogic CM 4000

The CM4000 is a permanently mounted power quality monitor that has been developed by Square D PowerLogic. The circuit monitor measures currents and voltages and reports in real time the rms values for all three phases, neutral, and ground current. In addition, the circuit monitor calculates power factor, real power, and reactive power, plus other quantities. Although it can be controlled through a display, it is controlled primarily through the System Manager Software (SMS) which is at revision 3.3.2.2 as of the writing of this document.

Continuous Recording Capabilities

Using the SMS software, the monitor can be configured to measure a large number of quantities (some of the more common ones are shown in Figure 3-22) at 1-second intervals into onboard memory. A complete list of the quantities which can be logged can be found in the CM4000 Reference Manual.

Current Per-Phase Neutral[1] Ground[1] 3-Phase Average Apparent rms % Unbalance
Voltage Line-to-Line, Per-Phase Line-to-Line, 3-Phase Average Line-to-Neutral, Per-Phase[1] Neutral to Ground[1] Line-to-Neutral, 3-Phase Average % Unbalance
Real Power Per-Phase[1] 3-Phase Total
Reactive Power Per-Phase[1] 3-Phase Total
Apparent Power Per-Phase[1] 3-Phase Total
Power Factor (True) Per-Phase[1] 3-Phase Total
Power Factor (Displacement) Per-Phase [1] 3-Phase Total
Frequency 45–67 Hz 350–450 Hz
Temperature (Internal Ambient)
[1] Wye systems only.

Figure 3-22
Common Quantities Recorded Into Onboard Memory of CM4000

The onboard log setup screen is shown in Figure 3-23. The process for setting up onboard data files to log quantities is as follows: First the user must choose the data log that the desired quantities are to be logged to. Next the user should choose a logging interval (the minimum logging interval is 1 second). The user should then choose the quantities that should be logged by choosing creating or selecting a log template. Next, the user should choose the number of records to be allocated to the data log and they should choose the memory should be configured as fill and hold or whether the memory should be in FIFO mode. Finally, the user should enable the data log and update the monitor with the configuration.

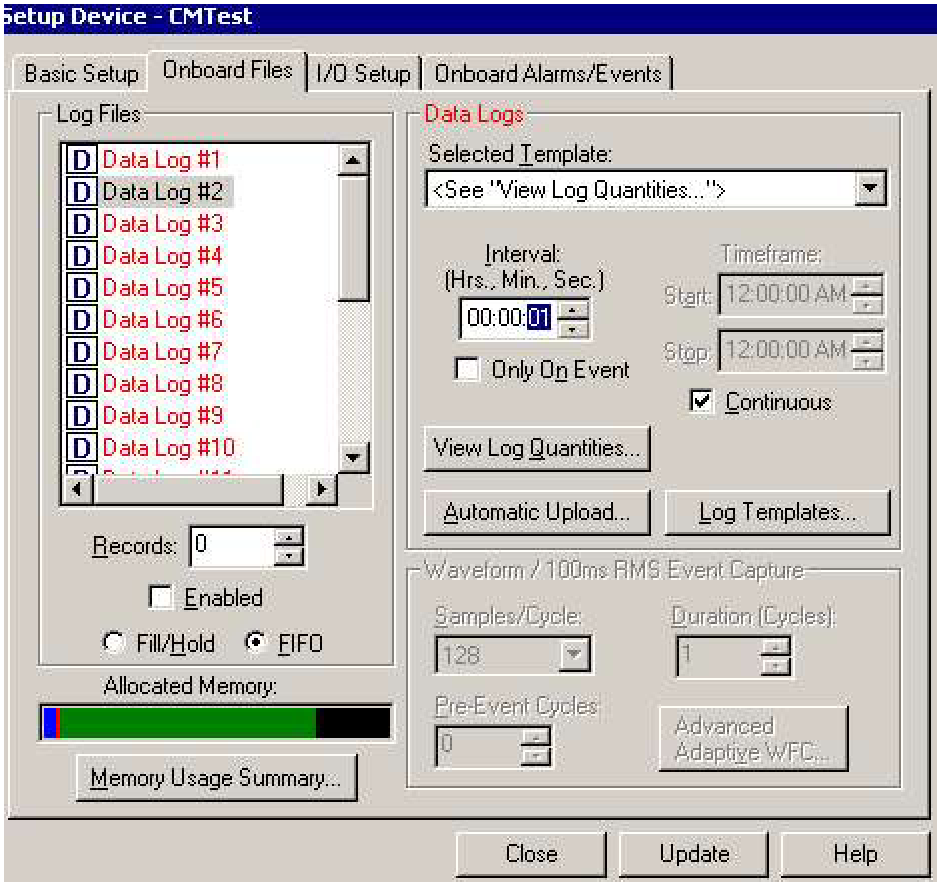


Figure 3-23
SMS3000 Onboard File Setup Screen

It is possible, according to the documentation, to perform real-time measurements at a rate of once every 100 ms of the quantities below (see Figure 3-24) over an active Modbus TCP connection. However, it does not make frequency values available at that rate. The meter does not meet the continuous recording requirements, although it can measure the required quantities at a rate of once per second.

Real-Time Readings
Current Per-Phase Neutral[1] Ground[1] 3-Phase Average Apparent rms
Voltage Line-to-Line, Per-Phase Line-to-Line, 3-Phase Average Line-to-Neutral, Per-Phase[1] Neutral to Ground[1] Line-to-Neutral, 3-Phase Average[1]
Real Power Per-Phase[1] 3-Phase Total
Reactive Power Per-Phase[1] 3-Phase Total
Apparent Power Per-Phase[1] 3-Phase Total
Power Factor 3-Phase Total
[1] Wye systems only.

Figure 3-24
CM4000 Real-Time 100 ms Readings

Exception-Based Recording Capabilities

The CM4000 has seven classes of onboard alarms (or onboard events) which can be configured to record certain data once the alarm conditions have been met. Those classes of alarms are:

- Boolean
- Digital
- Disturbance
- High-speed
- Standard
- Transient
- Waveshape

All of the alarms can be configured to record data logs, some waveforms, and the 100 ms RMS recorder. We will focus on disturbance alarms for the remainder of this section, but most points apply to the other alarm classes.

Disturbance alarms are configured in the SMS 3000 software using the onboard alarm setup tab in the configuration dialog box. An example dialog is shown for voltage sag alarms on phase A to B. The setup is somewhat like a relay in that there are pickup and dropout points (with some intentional delay, if desired). In the sample dialog box shown, the pickup set point for the alarm to become active is 187 volts (out of 208 line-line). The dropout point is 192 volts, and this would be the point at which the alarm becomes inactive again. The user can also specify a delay (in cycles) for the pickup or dropout points, which means that the voltage values have to exceed the levels entered for a certain number of cycles.

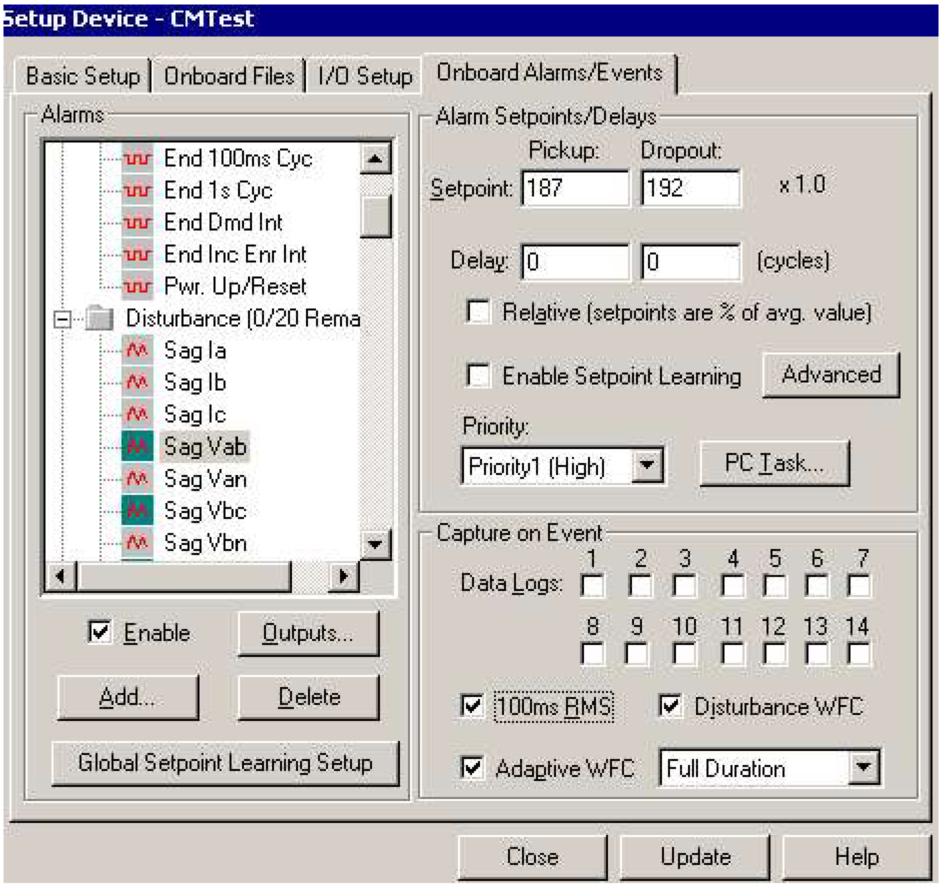


Figure 3-25
SMS3000 Voltage Sag Setup Dialog Box for Phase A-B

Once an alarm is active disturbance waveforms, adaptive waveforms, 100 ms RMS recordings, or data logs can be captured on the alarm condition. Disturbance waveform captures are well suited for short duration events, but the maximum duration that can be captured is 915 cycles at a rate of 16 samples/cycle, which is about 15.25 seconds (at 60 hertz).

The adaptive waveform capture is used to record longer events than can be recorded by the disturbance waveform capture method. Table 8-2 from the CM4000 Reference Manual is reproduced here (Figure 3-26) to give an indication of the duration of event(s) that can be captured based on the number of samples per cycle.

Samples per Cycle (Resolution)	Max. Duration (with per-phase current and voltage channels)
16	110 seconds
32	55 seconds
64	27 seconds
128	13 seconds
256	6 seconds
512	3 seconds

Figure 3-26
CM4000 Resolutions for Adaptive Waveform Captures

The CM4000 exceeds the required scan rate of 20 hertz. The best resolution for around 20 seconds is 64 samples per cycle for a total duration of 27 seconds. As mentioned previously, the 100 ms RMS recording mode does not record frequency so it is not useful for this purpose.

The monitor has two sets of triggers (not including impulse, which we will neglect for this discussion) that can trigger on voltage deviations. The first set of triggers are the waveshape fault triggers, which are configured via the screen in Figure 3-25.

Conclusion

From the preceding discussion of the load-modeling capabilities of six commercially available power quality monitors, it is evident that they are not well suited for continuous load-modeling data gathering. Some of the monitors can only perform continuous monitoring of the required parameters at a rate of 1 per second, while others can only perform the required monitoring at a rate of once per minute. From an exception-based standpoint, some of the monitors have difficulty recording the required data at the 20 hertz scan rate for the entire 20-second duration.

It should be noted, however, that the storage requirements for the required quantities are fairly low in comparison to the requirements to store waveform data. By means of comparison, a power quality monitor might have the capability to store 10 waveforms on-board, consisting of 60 cycles of 128 samples per cycle. Neglecting compression, this would require 7680 units of memory and would correspond to 10 seconds in time. For the same 7680 units of memory the monitor could store the five quantities listed in Table 3-2 (assuming each quantity consumed 1 unit of memory each) covering a period of 512 seconds in time (at a 20 hertz scan rate). With the memory available in today's monitors and compression techniques available, the amount of data that can be stored is significantly higher than in this example.

The next generation of power quality monitors should be configurable in such a manner as to allow data collection for load modeling. The availability of powerful microprocessors and inexpensive memory makes the issue of load-modeling capabilities in power quality monitors more of a marketing issue than a technical issue. It should be noted that most power quality monitors could be adapted to perform load-modeling data acquisition with only a change in firmware.

In order for a power quality monitor to be used as a device that collects and stores the information for PQ load modeling, it should have the minimum set of data capturing requirements shown in Table 3-3.

Table 3-3
Minimum Set of Requirements for Future Power Quality Monitors to Support Load Modeling

Capture of RMS (root-mean-square) voltage
Capture of RMS current
Capture of real power*
Capture of reactive power*
Capture of fundamental frequency
Exception-based recording up to 20 seconds after voltage recovery within pre disturbance threshold at a 20 Hz scan rate
Continuous recording at a 2-20 Hz scan rate

References

1. "Thesis for the Degree of Doctor of Philosophy: Protection Strategies to Mitigate Major Power System Breakdowns", Mattias Jonsson, p.5.

2. "Arbiter Systems Model 1133A Power Sentinel Operation Manual", May 2003, Arbiter Systems, p. 64.

3. "PQNode Software Online Help", Electrotek Concepts, 1999.

4. "Series 5500 InfoNode User's Guide", Revision C, Dranetz-BMI, December 2002.

5. "Series 5500 DataNode User's Guide", Revision B, Dranetz-BMI, February 2002.

6. "ION 7500 7500/7600 User's Guide", Power Measurement, May 2003.

7. "Instruction Manual PA-9 User and Software Manual", Revision K, AVO International, May 2002.

4
DEVELOPING STATIC LOAD MODELS USING PQ MEASUREMENT DATA

This chapter gives the procedure of a detailed static model that can be used to predict load behavior using PQ monitoring data. The procedure is implemented using an example of a static load model of an internet data center (IDC) facility with a large concentration of switch mode power supplies for information technology (IT) loads.

Basic Load-Modeling Concepts

Load

Load modeling is an essential element in power system stability studies. In the realm of bulk power system studies, the term *load* can have several meanings in terms of power system engineering, including:

- A device, connected to a power system that consumes power
- The total power (active and/or reactive) consumed by all devices connected to a power system
- A portion of the system that is not explicitly represented in a system model, but rather is treated as if it were a single power-consuming device connected to a bus in the system model
- Equivalent representation of the aggregate effect of many individual load devices
- The power output of a generator or generating plant

Where the meaning is not clear from the context, the terms *load device*, *system load*, *bus load*, and *generator (*or *plant) load* may be used to clarify the intent. Note that the first four definitions are relevant to IDC load modeling, as an IDC can be considered as a device or a group of devices connected to a power system or a bus load.

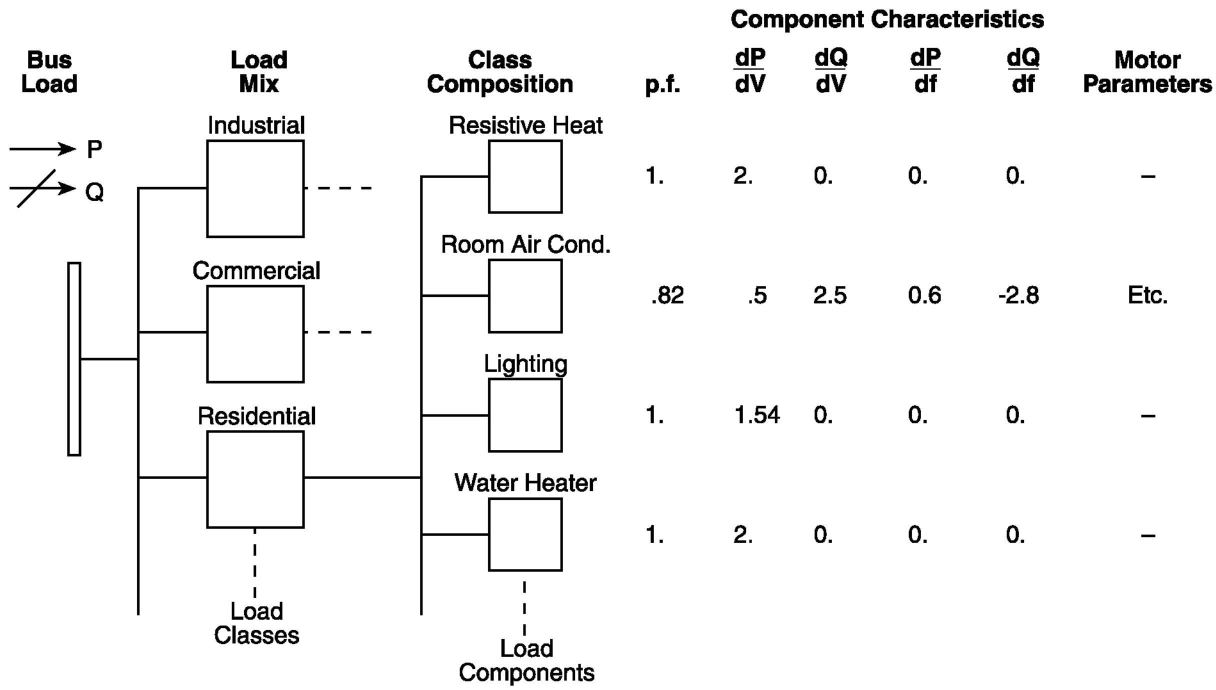


Figure 4-1
Terminology in Load Modeling [1]

Load Component

A load component is the aggregate equivalent of all devices or similar types. For example, in an IDC, computer servers and HVAC (heating, ventilation and air-conditioning systems) are the load components.

Load Class

A load class is a category of load, such as residential, commercial, or industrial. For load-modeling purposes, it is useful to group loads into several classes, where each class has similar load composition and characteristics. IDCs could themselves be a load class.

Load Composition

The fractional composition of the load by load components. This term may be applied to the bus load or to a specific load class.

Load Class Mix

The fractional composition of the bus load by load classes. As an example, composition for an IDC could be 40-50% computer serves, 40-50% HVAC loads, and 10-15% lighting loads.

Load Characteristics

A set of parameters, such as power factor, variation of P with V, etc. that characterizes the behavior of a specified load. This term may be applied to a specific load device, a load component, a load class, or the total bus load.

Different Types of Load Models Used for Bulk System Studies

Different types of load models are explained in the literature [1, 2, 3, 4]. Generally, the load is represented by some combination of static and dynamic models to approximate the voltage (and frequency) sensitivity of the aggregate load. There are various types of load models that are being used in power system stability and voltage collapse analysis. One approach is to measure the voltage and frequency sensitivity of the combined load and to fit the measured results to a polynomial or exponential equation. Another approach uses generic models for a particular type of load such as motors, UPSs, switch-mode power supplies, resistive heating, etc. Using this approach, the portion of the load that is believed to belong to each category is represented by the appropriate generic model. The accuracy of a given model will depend on how accurately the load characteristics are modeled and how accurately the load composition is specified, especially for simulations representing abnormally high or low voltage or frequency. This section defines the commonly used load models used in power system studies [1,2].

Static Load Model

A static load model expresses the characteristics (active and reactive powers) of the load at any instant of time as algebraic functions of the bus voltage magnitude and frequency at that instant. Static load models are used both for essentially static load components (such as resistive and lighting loads) and as an approximation for dynamic load components (such as motor-driven loads).

Dynamic Load Model

A dynamic load model expresses the active and reactive powers at any instant of time as functions of the voltage magnitude and frequency at past instants of time and, usually, including the present instant. Difference or differential equations can be used to represent such models.

Constant Impedance Load Model

A constant impedance load model is a static load model where the power varies directly with the square of the voltage magnitude. It may also be called a constant admittance model.

Constant Current Load Model

A constant current load model is a static load model where the power varies directly with voltage magnitude.

Constant Power Load Model

A constant power load model is a static load model where the power does not vary with changes in voltage magnitude. It may also be called a constant MVA load model. Because constant MVA devices, such as motors and electronic devices, do not maintain this characteristic below some voltage (typically 80-90%), many load models provide for changing constant MVA (and other static models) to constant impedance or tripping the load below a specified voltage.

Polynomial Load Model

A static load model represents the power relationship to voltage magnitude as a polynomial equation. This is usually in the form as shown in Equation 4-1 and Equation 4-2.

$$P = P_0\left[a_1\left(V/V_0\right)^2 + a_2\left(V/V_0\right) + a_3\right]$$ **Eq. 4-1**

$$Q = Q_0\left[a_4\left(V/V_0\right)^2 + a_5\left(V/V_0\right) + a_6\right]$$ **Eq. 4-2**

The parameters of this model are the coefficients (a_1 to a_6) and the power factor of the load. This model is sometimes referred to as the "ZIP" model, because it consists of constant impedance (Z), constant current (I) and constant power (P) terms. If this or other models are used for representing a specific load device, V_0 should be the rated voltage of the device, and P_0 and Q_0 is the power consumed at rated voltage. However, when using these models for representing a busload, $V_{0,}$ P_0 and Q_0 are normally taken as the values at the initial system operating condition for the study. Polynomials of voltage deviation from rated (V) are also sometimes used.

Exponential Load Model

A static load model represents the power relationship to voltage as an exponential equation. This is usually in the form as shown in Equation 4-3 and Equation 4-4:

$$P = P_0\left(V/V_0\right)^{np}$$ **Eq. 4-3**

$$Q = Q_0\left(V/V_0\right)^{nq}$$ **Eq. 4-4**

Two or more terms with different exponent are sometimes included in each equation. The parameters of this model are the exponents, np and nq, and the power factor of the load. Note that by setting these exponents to 0, 1, or 2, the load can be represented by constant power, constant current, or constant impedance models, respectively. Other exponents can be used to represent the aggregate effect of different types of load components. Exponents greater than 2 or less than 0 may be appropriate for some types of loads.

Frequency-Dependant Load Model

A static load model that includes frequency dependence is commonly called a frequency-dependent load model. Multiplying either a polynomial or exponential load model by a factor as shown in Equation 4-5 represents this:

$$[1 + a_f (f - f_0)] \qquad \text{Eq. 4-5}$$

where f is the frequency of the bus voltage, f_0 is the rated frequency, and a_f is the frequency sensitivity parameter of the model.

The frequency of the bus voltage is not an inherent variable in fundamental-frequency network analysis and is not used in many dynamic performance analysis programs.

Commercial load modeling and stability programs use their own load models. EPRI LOADSYN and EPRI ETMSP are the examples of static load models used in LOADSYN and ETMSP software packages, respectively. The PSS/E stability program from Power Technologies, Inc. (PTI) uses a model called CLOAD to represent dynamic models of aggregations of large and small motors, non-linear models of discharge lighting, transformer saturation effects, constant MVA, and other static load characteristics.

Developing Static Load Models Using PQ Monitoring Data

Background

The example facility is a large Internet data center (IDC) company that is headquartered in the western United States. It serves hundreds of e-commerce customers locally, nationally, and internationally through a number of IDC facilities and services. The commercial electrical power grid by way of two separate distribution circuits from two different substations powers this IDC facility. Two 3000-kVA transformers (Y-Y) are used to power the facility. The service feeds are underground and traverse different paths in the ground.

Distributing Power to the Facility

For the first service, (Side A) the connected load was determined to be 2863 kVA and the demand to be 2284 kVA with a 1426-kVA backup power requirement. For the second service (Side B), a total of 2430.6 kVA was determined to be the connected load. Based on the demand for the first service and the known information for that transformer, 76 percent of its capacity was planned during the design phase. 24 percent of the capacity of the transformer is available for additional load. For the second service, which has a demand (and connected load because no demand was determined) of 2430 kVA, 81 percent of its capacity was planned during design. 19

percent of this transformer's capacity is available for additional load. More detailed information can be obtained in EPRI report titled *Case Studies on Internet Data Centers* (1005941).

Facility's Electrical System and Site Information

One-line diagram of these two services is shown in Figure 4-2.

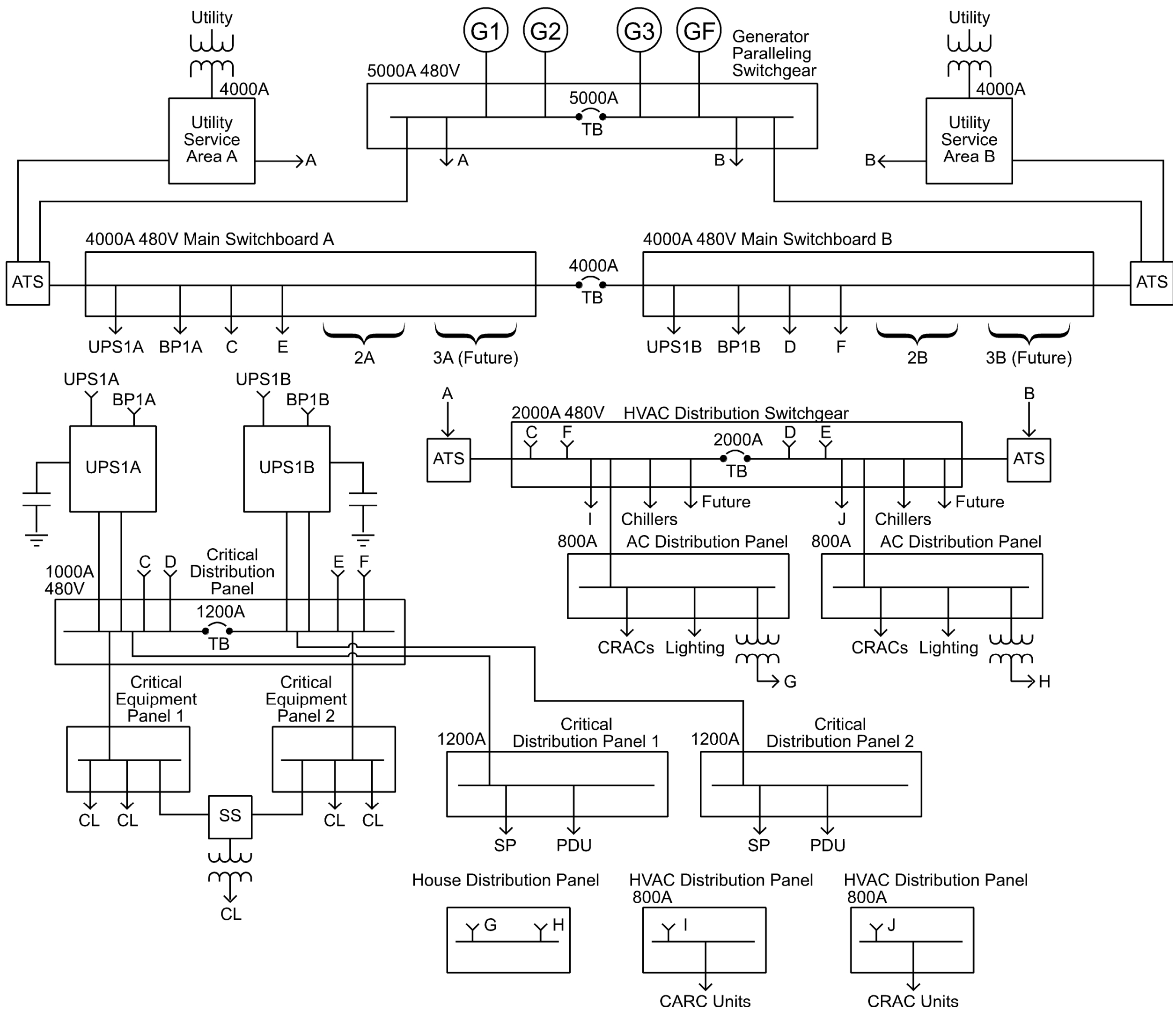
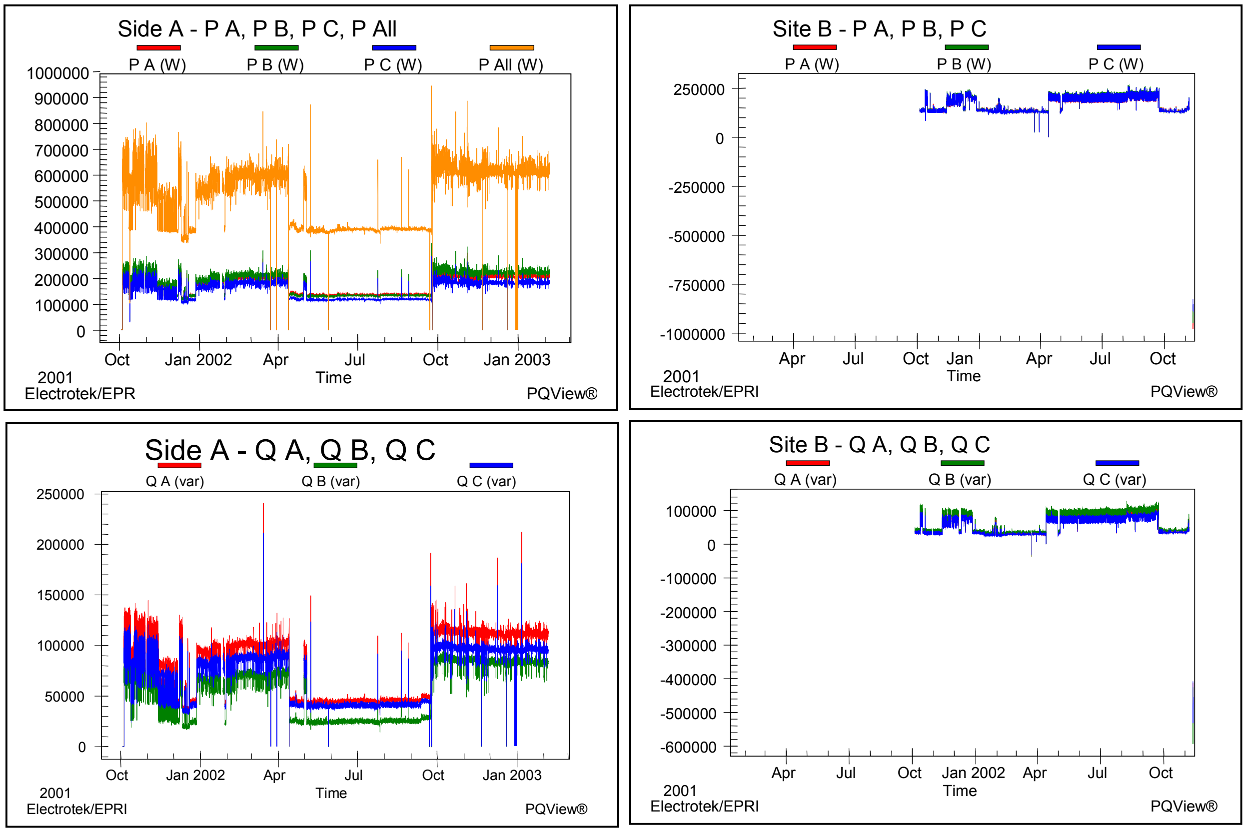


Figure 4-2
One-Line Electrical Diagram for the Internet Data Center

Sample Steady State Trends at Side A and Side B

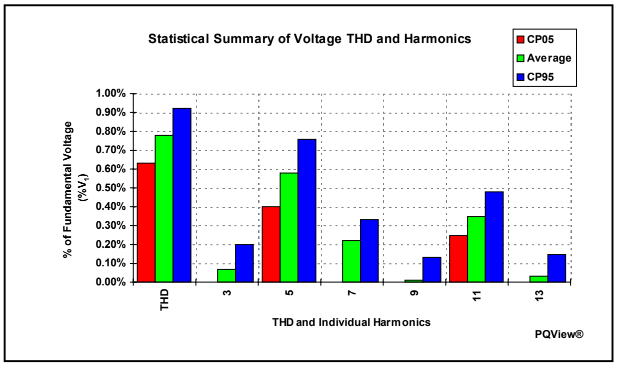
PQ monitors were installed at each utility service entrance to capture data for this case study. Steady state trends in real power and reactive power are shown in Figure 4-3 (Side A and Side B). Figure 4-4 provides the statistical summary of voltage and current THD as well as other harmonics for Side A and Side B.

Side A **Side B**

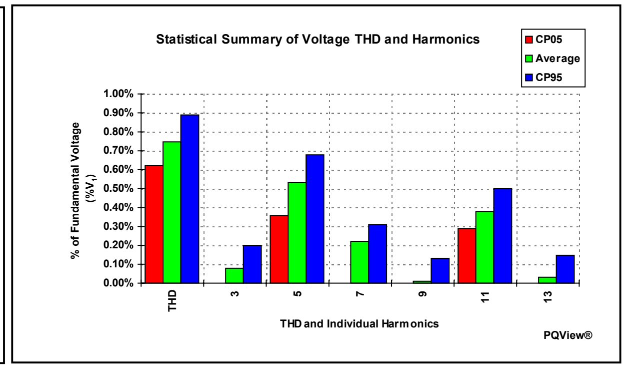


Side A **Side B**

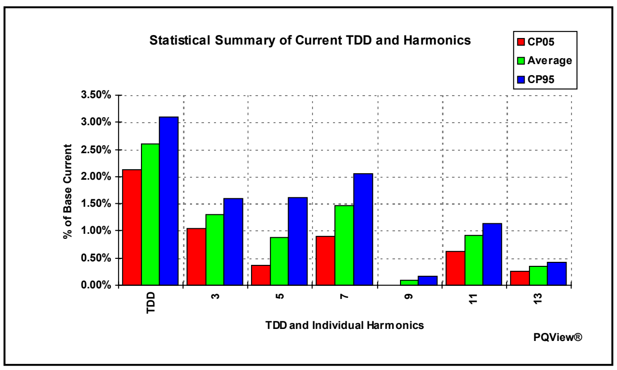
Figure 4-3
Steady-State Trends (P and Q) for Side A and Side B



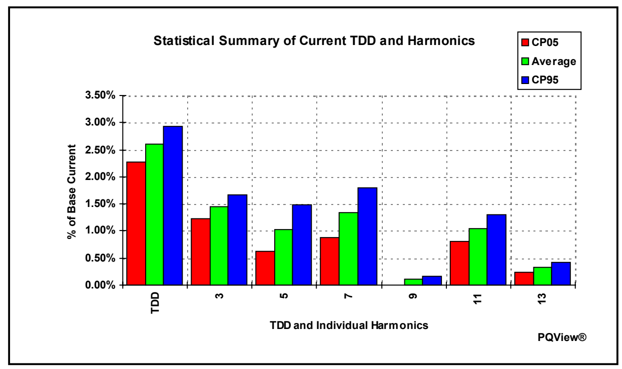
Side A



Side B



Side A



Side B

Figure 4-4
Summary of Voltage THD, Current THD, and Other Harmonics for Side A and Side B

From Fig. 4-4 we can say that the average value of voltage THD at side A is 0.79%. Additionally, 95% of the samples had a mean 3rd harmonic component of less than 0.2%. Also, the average value of voltage TDD at side A is 2.60%. Additionally, 95% of the samples had a mean 3rd harmonic component of less than 1.6%.

From Fig. 4-4 we can say that the average value of voltage THD at side B is 0.77%. Additionally, 95% of the samples had a mean 3rd harmonic component of less than 0.2%. Also, the average value of voltage TDD at side B is 2.60%. Additionally, 95% of the samples had a mean 3rd harmonic component of less than 1.7%. This indicates that harmonic-generating loads on Side B are highly similar to that on Side A.

Data Analysis Process

The basic process involved in static load modeling is to find variations in active and reactive powers with respect to variation in voltage. Sag disturbance data recorded by power quality monitors (located at the service entrance of the facility) were used to study variations in voltage and in real and reactive powers. In our case, variation in voltage was obtained from voltage sags occurring at the site. Two power quality monitors (one at Side A, the other at Side B) recorded variations in voltage and active and reactive powers before, during, and after a sag event. Sustained interruptions, momentary interruptions, and prolonged sags (typically below 70% and greater than 15 cycles) were not considered in the static load modeling. Such type of sags would require us to consider the dynamics of the rotating machines at the site and would need a completely different analysis.

Once the variations of voltage and powers for a number of sags are obtained, the next step is to extract fundamental (60Hz) component from the data. For the static model, only fundamental component is required. The fundamental component can be extracted using discrete Fourier transform (DFT) algorithm. This will also eliminate any noise present in the data. The complete static load-modeling process is pictorially represented in Figure 4-5.

Example waveforms of RMS voltage, RMS current, RMS powers (P and Q), and current wave shapes during voltage sag are shown in Figure 4-6. A popular method of viewing voltage and duration data is on a scatter plot, with each dot on the graph representing one measurement's magnitude and duration. This provides an estimate of the number of voltage sags outside the equipment voltage sag tolerance developed by the Information Technology Industry Council (ITIC)[2] as shown in Figure 4-7 and Figure 4-8.

[2] http://www.itic.org/

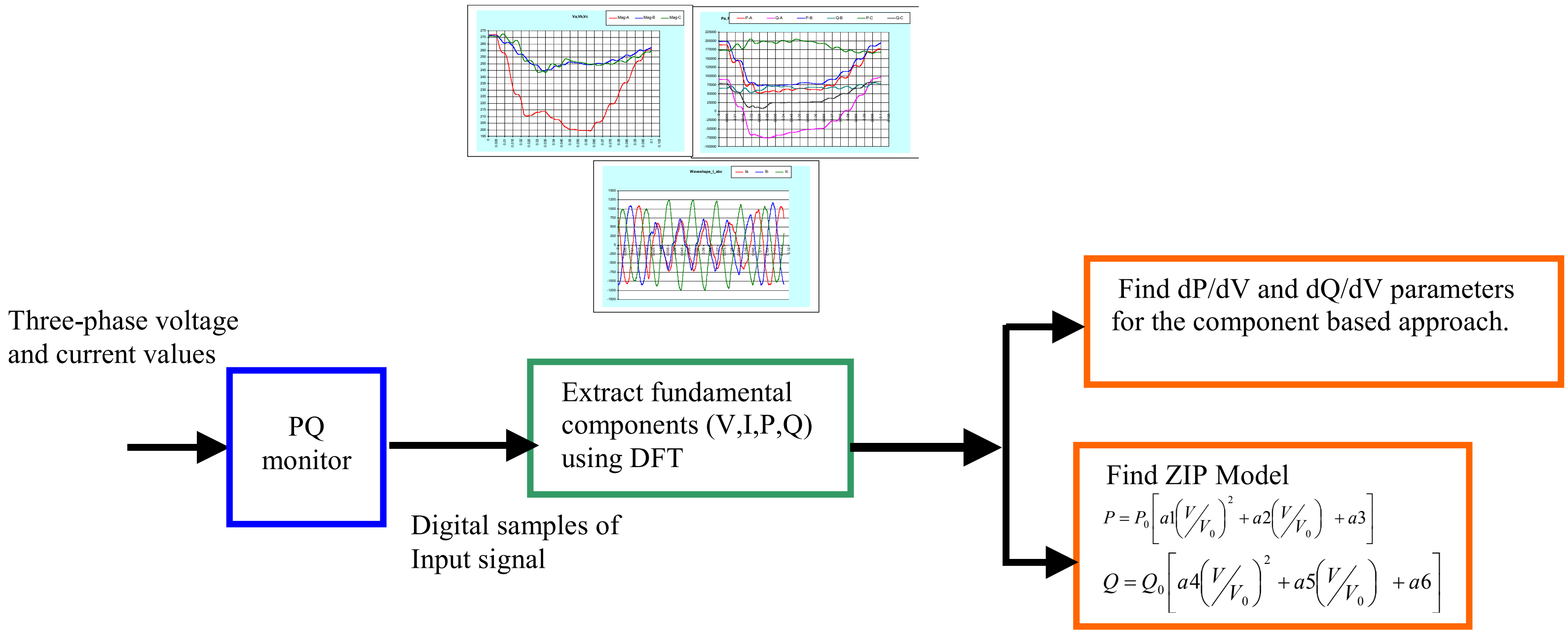


Figure 4-5
Steps Involved in Static Load Modeling

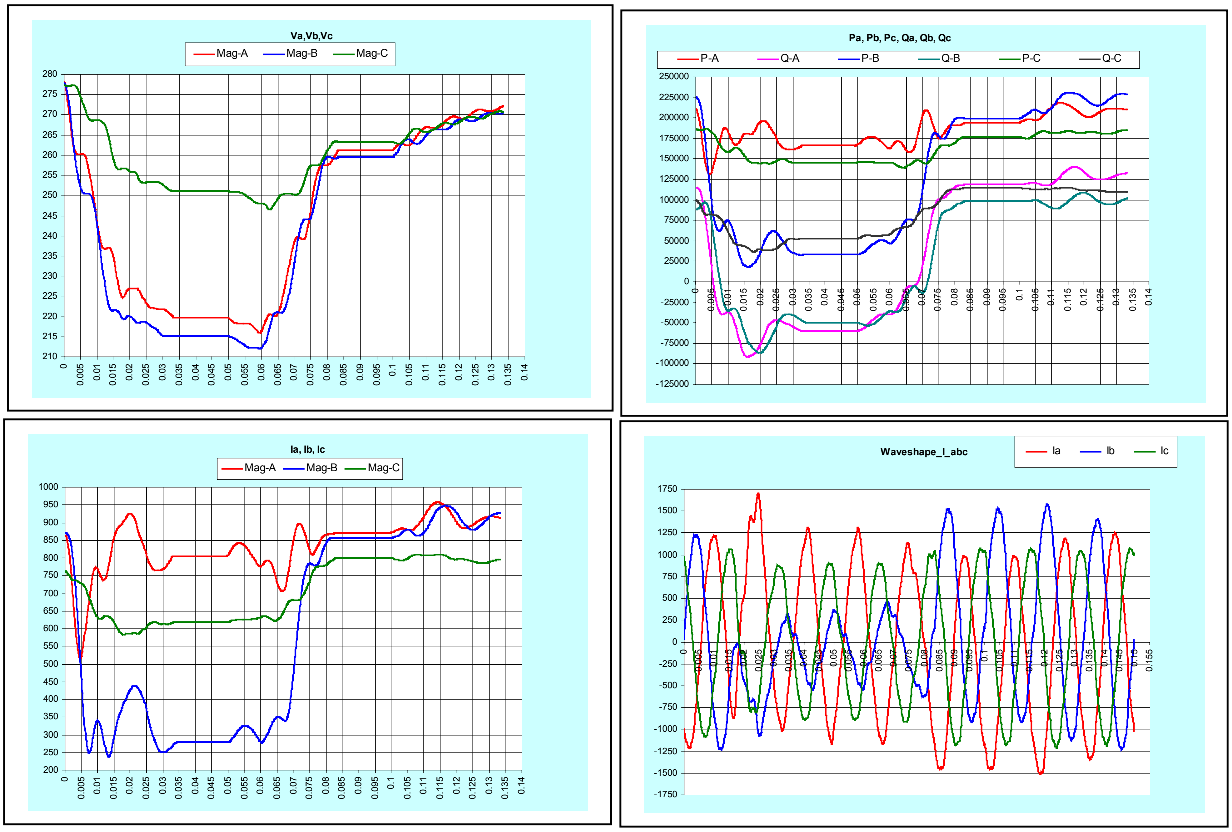


Figure 4-6
Sample Voltage Sag Data Extracted from a Sliding Window DFT Program

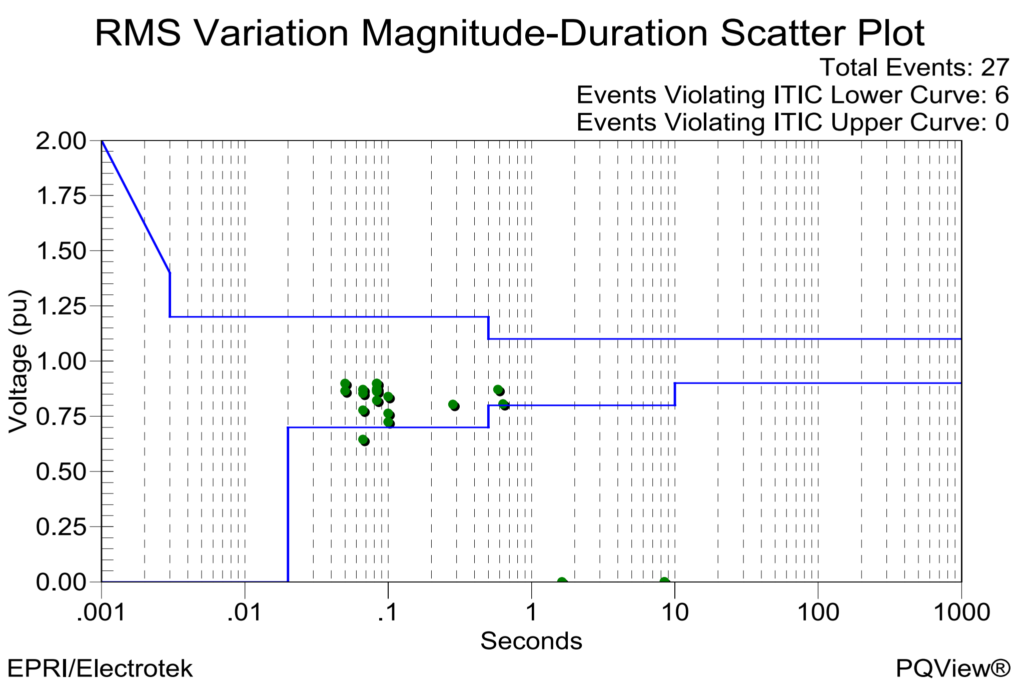


Figure 4-7
Voltage Sags Overlaid on the ITIC Curve (Side A)

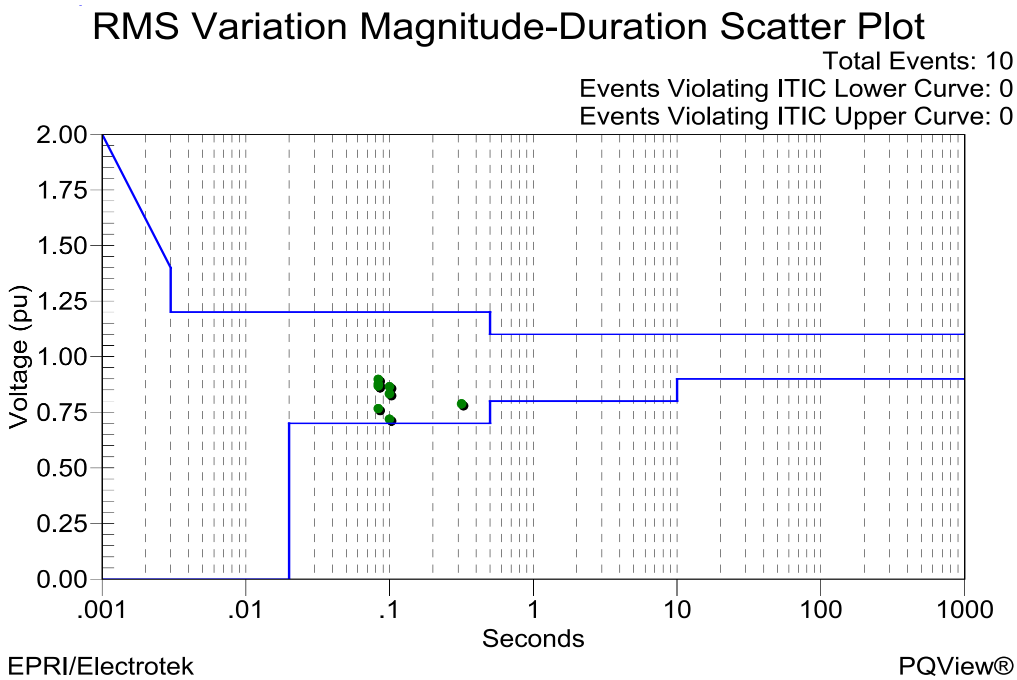


Figure 4-8
Voltage Sags Overlaid on the ITIC Curve (Side B)

Finding ΔP/ΔV and ΔQ/ΔV Parameters (Component-Based Approach)

Once the fundamental values are extracted from a DFT program, finding variations in powers with respect to voltage is a relatively straightforward process. The phase with the *maximum* deviation between pre-sag and during-sag voltages is chosen. For these two points, corresponding values of other two phases and powers are noted. The parameters are found as follows:

ΔV = Average pre-sag voltage of the three phases – Average during-sag voltage of the three phases (corresponding to the minimum voltage point selected)

ΔP = Average pre-sag real power of the three phases – Average during-sag real power of the three phases (corresponding to the minimum voltage point selected)

ΔQ = Average pre-sag reactive power of the three phases – Average during-sag reactive power of the three phases (corresponding to the minimum voltage point selected)

ΔV, ΔP and ΔQ were obtained for each of the sag events considered. The next step is to correlate ΔV with ΔP and ΔQ. This was done using simple linear regression. The linear relationship between change in real power due to change in voltage is shown in Figure 4-9. The corresponding relationship for reactive power is shown in Figure 4-10.

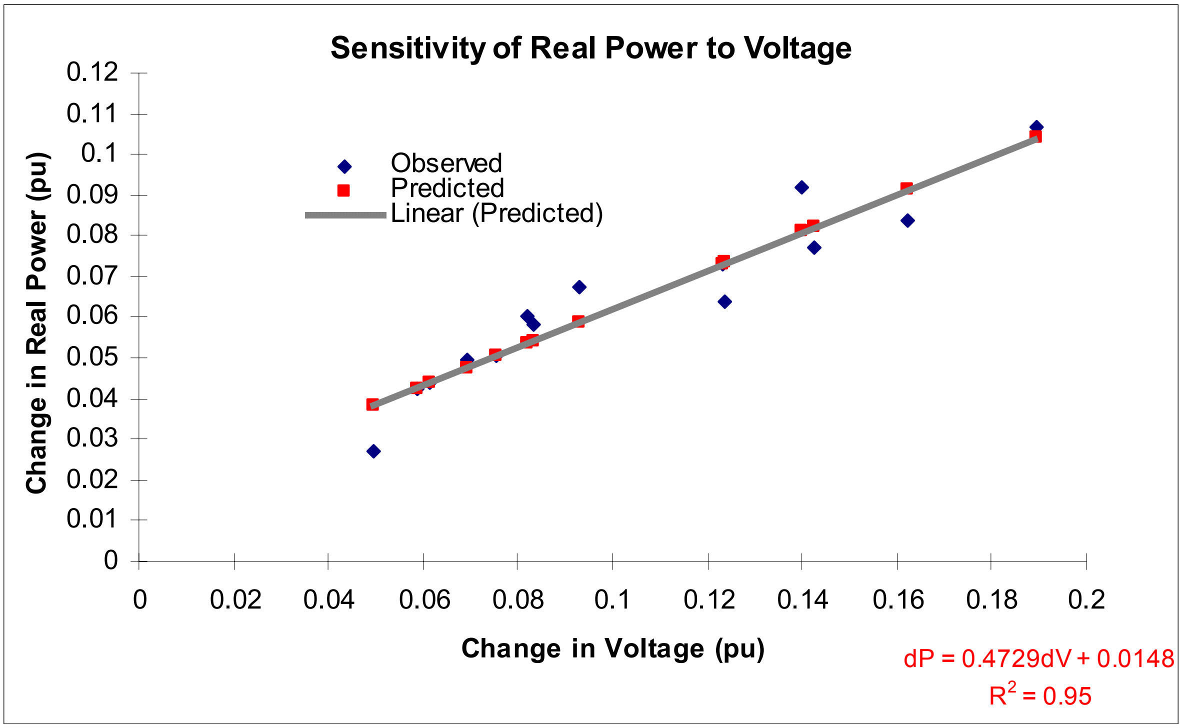


Figure 4-9
Sensitivity of Real Power to Voltage

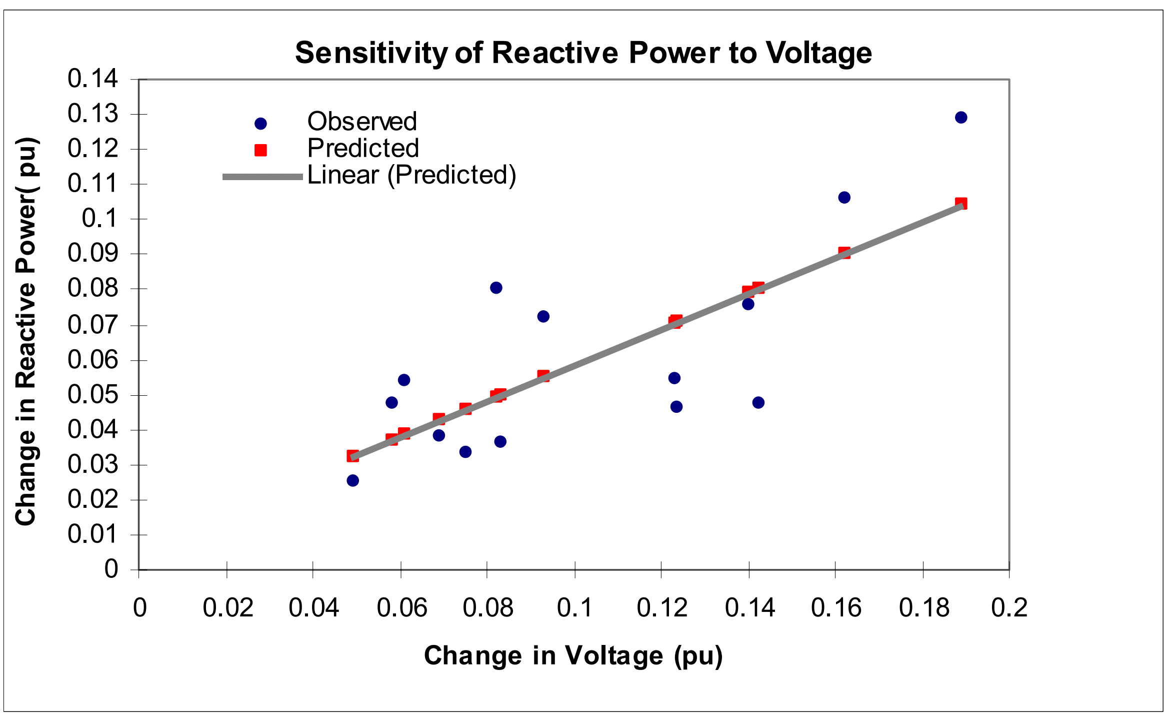


Figure 4-10
Sensitivity of Reactive Power to Voltage

The regression equations are shown in Equation 4-6 and Equation 4-7. Symbols V and V_0 represent the voltage level during the sag (average of the three phases in our case) and initial voltage level (average of the three phases in our case), respectively. Similarly, symbols P and P_0 represent power during the sag (average of the three phases in our case) and initial power (average of the three phases in our case), respectively. Similar nomenclature holds true for parameters Q and Q_0.

$$\begin{aligned} \Delta P = P_0 - P &= K_1 + K_2 (V_0 - V) \\ &= 0.014842 + 0.472856 (V_0 - V) \\ &= 0.014842 + 0.472856\, \Delta V \end{aligned}$$ **Eq. 4-6**

$$\begin{aligned} \Delta Q = Q_0 - Q &= K_3 + K_4 (V_0 - V) \\ &= 0.0069 + 0.51493 (V_0 - V) \\ &= 0.0069 + 0.51493\, \Delta V \end{aligned}$$ **Eq. 4-7**

From the equations, $\Delta P/\Delta V$ (slope of the line) in equation 4-6 is 0.472856 and $\Delta Q/\Delta V$ (slope of the line) in equation 4-7 is 0.51493. These two parameters are comparable to Kpv and Kqv parameters listed for different load classes in Table 3-1. Note that the parameters found are *specific* to the IDC under consideration. As all IDCs are different and utilities are still unsure of how each of them behaves, IDCs with their unique load composition represent a class by themselves. Continuing work will concentrate on validating and extending this approach for other IDCs sites as well. This will provide a better idea of these two parameters ($\Delta P/\Delta V$ and $\Delta Q/\Delta V$) that could then be representative of a "typical" IDC load.

Finding ZIP Parameters

Equation 4-6 and Equation 4-7 can be solved for P and Q as shown in Equation 4-8 and Equation 4-9.

$$P = (P_0 - K_1 - K_2 V_0) + K_2 V$$ **Eq. 4-8**

$$Q = (Q_0 - K_3 - K_4 V_0) + K_4 V$$ **Eq. 4-9**

The first term in Equation 4-8 is a constant and represents the portion of the initial real power that remains constant during the voltage excursion. The second term in Equation 4-8 is the real power term that is linearly dependent on voltage. Similarly, the first term in Equation 4-9 is a constant and represents the portion of the initial reactive power that remains constant during the voltage excursion. The second term in Equation 4-9 is the reactive power term that is linearly dependent on voltage.

The standard ZIP model is of the form as shown in Equation 4-10 and Equation 4-11. The parameters of the model are the coefficients α_1 to α_3 and α_4 to α_6, which define the proportion of each component.

$$\left(\frac{P}{P_0}\right) = \alpha_1\left(\frac{V}{V_0}\right)^2 + \alpha_2\left(\frac{V}{V_0}\right) + \alpha_3 \qquad \textbf{Eq. 4-10}$$

$$P = \alpha_1 P_0\left(\frac{V}{V_0}\right)^2 + \alpha_2 P_0\left(\frac{V}{V_0}\right) + \alpha_3 P_0 \qquad \textbf{Eq. 4-11}$$

The quadratic term (constant impedance) term in Equation 4-10 and Equation 4-11 can be neglected because the scatter plots of the data did not show a quadratic relation (see Figure 4-9 and Figure 4-10). Alternatively, a quadratic (nonlinear) regression analysis could have been used to fit the measured data (instead of Equation 4-10 and Equation 4-11) and one would have obtained a nearly zero coefficient for the $(V_0\text{-}V)^2$ (constant impedance) term.

Now the trick is to relate K_1 and K_2 from the regression Equation 4-10 to α_2 and α_3 in the ZIP model in Equation 4-11. Basic algebra gives this conversion, as shown in Equation 4-12. Similar expression can be derived for Q as shown in Equation 4-13.

$$P = \left(\frac{K_2 V_0}{P_0}\right)P_0\left(\frac{V}{V_0}\right) + \left(1 - \frac{K_1}{P_0} - \frac{K_2 V_0}{P_0}\right)P_0 \qquad \textbf{Eq. 4-12}$$

$$Q = \left(\frac{K_4 V_0}{Q_0}\right)Q_0\left(\frac{V}{V_0}\right) + \left(1 - \frac{K_3}{Q_0} - \frac{K_4 V_0}{Q_0}\right)Q_0 \qquad \textbf{Eq. 4-13}$$

If the voltage and power initial values are taken as base values and the entire equation normalized, the apparent dependence of the coefficients on the initial power level disappears. Of course, it is entirely appropriate for the coefficients to depend on initial power level because in effect the specific level of power during a voltage excursion depends on the initial power. As far as using these *initial condition dependent parameters* in a system study, the initial voltage and initial power would be available from the load flow solution, so it would be a simple matter to get the numerical values for the ZIP coefficients using the relations in Equation 4-12 and Equation 4-13.

Again, Equation 4-12 and Equation 4-13 do not have Z component of the model. They represent the IDC in terms of constant current and constant power terms. Also, the parameters obtained are specific to the site and cannot be generalized for all IDC load class.

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5
FAST VOLTAGE COLLAPSE INDEX

Introduction

Changing characteristics of customer loads, increasing utilization of transmission circuits and lack of market incentives for generators to provide reactive compensation are shedding a new light on short-term (a few seconds) voltage instability. Unlike traditional angle instability involving faults near generators, short-term voltage stability, also known as fast voltage collapse, may result from faults near load areas. Power system planning and operating engineers are often not aware of fast voltage collapse situations because of lack of analysis tools and difficulty in predicting load response in specific areas with a high concentration of motor loads.

A direct measurement based approach can help identify potential locations in a power system that may be more likely to suffer from the fast voltage collapse. This chapter describes the concept of a fast voltage collapse index (FVCI) that can be computed using data from system-wide power quality monitoring data. This index can be used as a tool for screening potential locations in a power system that may be more prone to a fast voltage collapse and candidates for using dynamic reactive compensation devices to safeguard against short-term voltage instability.

Voltage Stability and Voltage Collapse

Power system stability is usually subdivided into two broad classifications: 1) angle stability and 2) voltage stability. Rotor *angle stability* is the ability of interconnected synchronous machines of a power system to remain in synchronicity. *Voltage stability* is defined as the ability of a power system to maintain steady acceptable voltages at all buses in the system under normal operating conditions and after being subjected to a disturbance.

Voltage stability itself is divided into two subclasses. a) *Small-disturbance voltage stability* is concerned with a system's ability to control voltages following small perturbations such as incremental changes in load. b) *Large-disturbance voltage stability* is concerned with a system's ability to control voltages following large disturbances such as system faults, loss of generation, or circuit contingencies. *Voltage collapse* is the process by which the sequence of events accompanying voltage stability leads to a low unacceptable voltage profile in a significant portion of the power system [1].

Voltage collapse takes place on the following time scales, ranging from seconds to hours:

1. Electromechanical transient, such as generators, regulators, induction machines; and power electronics, such as SVC and HVDC, in the time range of seconds.

2. Discrete switching device, such as a load tap-changers and excitation limiters, acting at intervals of tens of seconds.

3. Load recovery processes spanning several minutes.

In voltage collapse, time scale 1 above is called the transient time scale. Time scales 2 and 3 above constitute the mid-term and long-term time scales, respectively, for voltage stability analysis. (Note that the long-term time scale presented here is sometimes referred to as mid-term)[2]. The fast voltage collapse index that will be discussed below focuses on the transient time scale, which is in the time range of seconds.

Recent Fast Voltage Collapse Events

Several fast voltage collapse incidents and near-collapse events have occurred over the past two decades. A list of some of those events that have been discussed in the literature are shown in Table 5-1. An example of an actual voltage collapse in Saudi Arabia (SEC-WR) was provided in Chapter 2.

Table 5-1
Recent Voltage Collapse and Near Voltage Collapse Events

Date	Location	Time-Frame	Reference
5/17/1985	South Florida	4 seconds	[3]
5/17,5/20, 5/21/1986	Miles City Montana, dc link	1-2 seconds	[4]
7/19,7/22/1986	Miles City Montana, dc link	1-2 seconds	[4]
11/30/1986	SE Brazil, Paraguay	2 seconds	[5],[6]
8/22/1987	Memphis, Tennessee	10 seconds	[7]
5/3/1994	Florida	10 seconds	[12]
7/29/1995	Phoenix Area	20 seconds	[8]
7/2/1996	Idaho, Western US	20 seconds	[9]
8/5/1997	Southern California Edison	20-25 seconds	[10]
7/30/1999	Atlanta Area	15 seconds	[11]

One recent near-collapse event occurred in the Phoenix, Arizona area on Saturday, July 29, 1995. On that day, the system was operating normally, although at record demand levels for Saturday following all-time high demands on Friday, July 28, due to temperatures approaching 117 deg F.

At 15:04 MDT, one of the utility companies in the area closed a circuit switcher to insert a 30 Mvar capacitor bank. Six capacitors in that bank failed. Three 30 Mvar capacitor banks are fed through a single breaker, each capacitor with its own circuit switcher. The circuit switcher on the capacitor bank operated, but one phase failed to open. The breaker opened after 17 cycles, clearing the fault and interrupting the two capacitor banks already in service. Another utility also opened two capacitor banks (and disconnected two more banks by SCADA two minutes later). Several generating units tripped; the loss of their reactive support contributed to the low voltage conditions initiated by the fault and the loss of 206 Mvar of capacitors. About 1600 MW of load was lost. Figure 5-1 shows the voltage recovery at one monitoring site over a period of about 20 seconds.

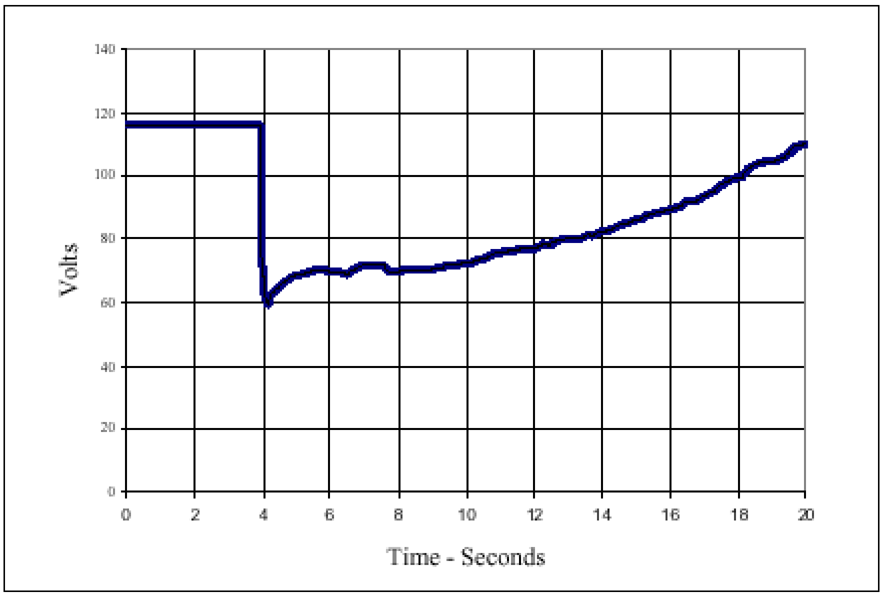

Figure 5-1
Voltage Recovery in the Phoenix Area on July 29, 1995

Several factors which contribute to the likely increase in the number of fast voltage collapse incidents in the future are a decrease in system operating margins due to de-regulation of the electric utility industry, the increase of low inertia compressor motor loads, increase in voltage insensitive electronic loads, and the increasing use of shunt capacitor banks for power factor correction [13]

Load Modeling and Fast Voltage Collapse

A number of analysis techniques have been developed in an effort to understand power system stability. Analysis techniques fall into steady state or dynamic approaches. Steady state analysis techniques generally look at the maximum capability of the power system and include modal analysis and continuation power flow analysis. Dynamic techniques use the overall system equations, comprising a set of first-order differential equations and a set of algebraic equations with a set of known initial conditions. The differential and algebraic equations are solved in the time domain by using suitable numerical integration methods and power flow analysis methods[1].

A critical component in both the steady state and dynamic analyses is the representation of the characteristics of loads connected to the system. The term *load* can have several meanings, including:

1. A device, connected to a power system that consumes power
2. The total power (active and/or reactive) consumed by all devices connected to a power system
3. A portion of the system that is not explicitly represented in a system model, but rather is treated as if it were a single power-consuming device connected to a bus in the system model
4. The power output of a generator or generating plant[16]

These loads are represented by one or more *load models*, which are a mathematical representation of the relationship between a bus voltage (magnitude and frequency) and the power (active and reactive) or current flowing into the bus load[16]. Load models are either static load models or dynamic load models. A static load model is a model that expresses the active and reactive powers at any instant of time as functions of the bus voltage magnitude and frequency at the same instant. Static load models are used both for essentially static load components (such as resistive and lighting loads), and as an approximation for dynamic load components (such as motor-driven loads)[16]. Dynamic load models, on the other hand, express the active and reactive powers at any instant of time as functions of the voltage magnitude and frequency at past instants of time and, usually, including the present instant[16] . For dynamic voltage stability analysis and voltage collapse analysis simple static load modeling is usually not sufficient. Studies at the Swedish State Power Board [17], Ontario Hydro[18], and B.C. Hydro[19] have shown the inadequacy of static load models in explaining voltage collapse and voltage stability issues.

Dynamic models, and load models in general, are developed using two basic approaches. One is to build a composite load model from knowledge of the mix of load classes served by a substation, the composition of each class and typical characteristics of each load component (sometimes referred to as the component-based approach)[16] The other approach is to directly measure the voltage and frequency sensitivity of load P and Q at representative substations and feeders[16]. By installing measurement and data acquisition devices at points where bus loads are to be represented this data can be gathered. These devices measure the appropriate parameters in response to intentional disturbances or naturally occurring events[16]. Some power quality monitors can perform these functions if configured properly.

While not directly a load-modeling technique, the following sections of this paper will discuss an index that can be calculated using readily available data from power quality monitors to gauge the relative voltage stability of a monitoring location. By looking at the rate of recovery of voltage following a disturbance and other parameters, we can provide an indication of those areas that are more prone to voltage collapse.

Fast Voltage Collapse Index – Definition and Algorithm

One of the basic power quality events captured by power quality monitors of various designs is the RMS voltage variation. An RMS voltage variation is defined as a variation in the voltage from a normal operating value[14]. A typical RMS voltage variation is shown in Figure 5-2, from the Distribution Power Quality Phase II project[20]. Note that the monitor records the waveform at the beginning of the event and an RMS trend for the entire event.

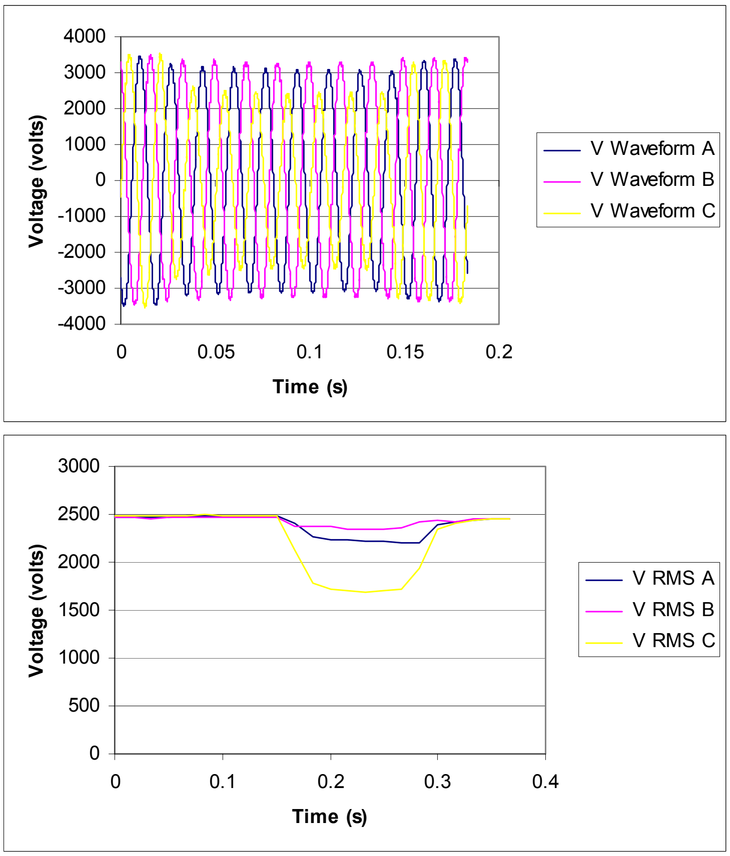

Figure 5-2
An RMS Variation Recorded During the DPQ Phase II Project

These RMS voltage variations are recorded by power quality monitors using triggers. A common setup that is used by the Dranetz-BMI 8010 PQNODE for RMS voltage variation events is shown in Figure 5-3. For this example monitor, an RMS voltage variation event is triggered when the voltage exceeds the variation threshold percentage for 1 cycle.

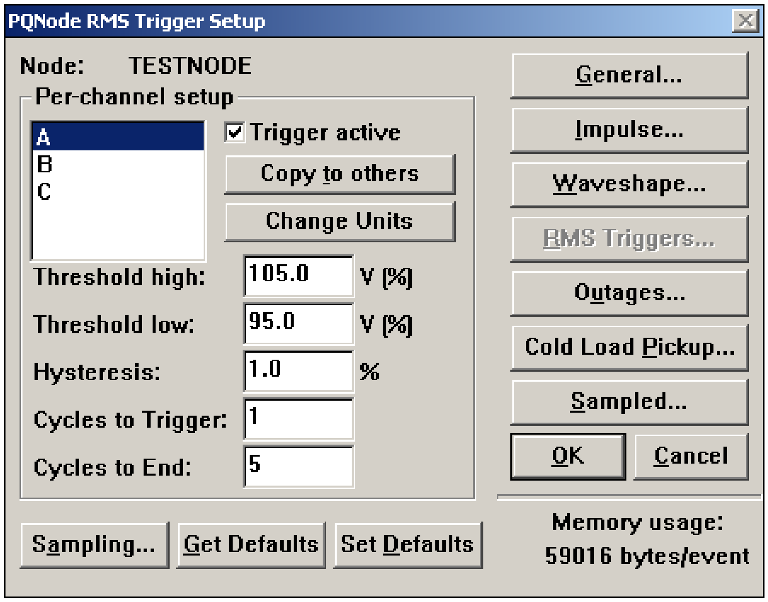

Figure 5-3
RMS Trigger Setup for a Dranetz-BMI 8010 PQNODE

Some power quality monitors record RMS trends during the event when a trigger threshold is exceeded, while others only record magnitude and duration information. In order to calculate the fast voltage collapse index, the monitor should meet the following criteria:

1. Be a triggerable instrument based on voltage thresholds.

2. Record at least an RMS trend during the event (waveforms can also be used).

3. Have at least one cycle resolution for each data point in the RMS trend.

The premise behind the fast voltage collapse index value is that weak locations in the system can be identified based on the rate of recovery of the voltage following disturbances such as faults. Locations that exhibit slow voltage recovery following faults are areas where the system strength relative to the load size and dynamics are questionable. This algorithm can be used as a preliminary means to identify those locations that appear to be more prone to voltage collapse for further study and for possible application of remedial measures.

Recently, a number of voltage sag characteristics have been defined in the EPRI report *Waveform Characteristic of Voltage Sags*. This report introduces a new *sag recovery time* parameter for use in developing the index. Sag recovery time is defined as the time required for the voltage to recover 10% of the difference between the sag recovery value (or end of the recorded event) and the minimum sag value to 96% of the pre-event voltage (or the end of the recorded event). In algorithmic form it is calculated as follows:

1. Generate an RMS trend from the waveform, if an RMS trend is not already available.

2. Calculate the pre-event RMS voltage from the RMS trend.

3. Calculate the minimum RMS voltage during the sag.

4. Determine the beginning (voltage drops below 95%) and end of the sag (voltage recovers to 96% of pre-event voltage). These values were chosen consistent with the values used in the EPRI report referenced above.

5. From the end of the event, move "backwards" in time to find the first voltage value that is equal to or less than:

$$(V_{recovery} - V_{minimum}) * 0.1 + V_{minimum} \quad \textbf{Eq. 5-1}$$

where

$V_{recovery}$ is the voltage at the end of the sag or at the end of the recorded event

$V_{minimum}$ is the minimum RMS voltage during the sag event.

6. Sag recovery time is then the time value of the end of the sag (or end of the recorded data) minus the time value found in Step 5.

An example should help illustrate. Consider the following RMS voltage trend recorded by a Dranetz-BMI PQPager (Figure 5-4).

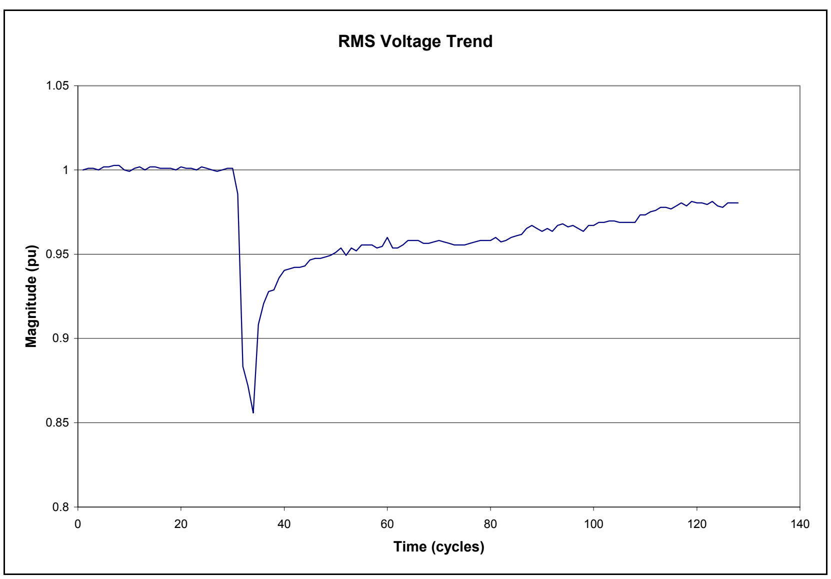

Figure 5-4
Example RMS Voltage Trend

The steps required to determine the sag recovery time for this example are shown as follows:

1. The PQPager records the RMS voltage variation as an RMS trend, so the first step can be skipped.

2. In this example, the pre-event voltage is 1 per-unit.

3. The minimum voltage is found to be 0.86 per-unit, or 86% of the pre-event voltage.

4. The fourth step is to determine the beginning and the end of the RMS variation itself. The beginning of the RMS variation is the point at which the voltage drops below 95% of the pre-event voltage, which is at 32 cycles. The end of the RMS variation is the point at which the voltage recovers to 96% of the pre-event voltage (or the end of the recorded event), which is at 85 cycles.

5. The fifth step determines the sag recovery time by moving "backwards" through the recorded event until the data point is found where the voltage is first equal to or less than:

$$(V_{recovery} - V_{minimum})*0.1 + V_{minimum} \qquad \textbf{Eq. 5-2}$$

or

$$(0.96 - 0.86)*0.1 + 0.86 = 0.87pu \qquad \textbf{Eq. 5-3}$$

The time stamp associated with this voltage is 34 cycles into the event.

6. The sag recovery time is 85 cycles minus 34 cycles, or 51 cycles.

The sag recovery time and the algorithm as applied to this event are illustrated in Figure 5-5.

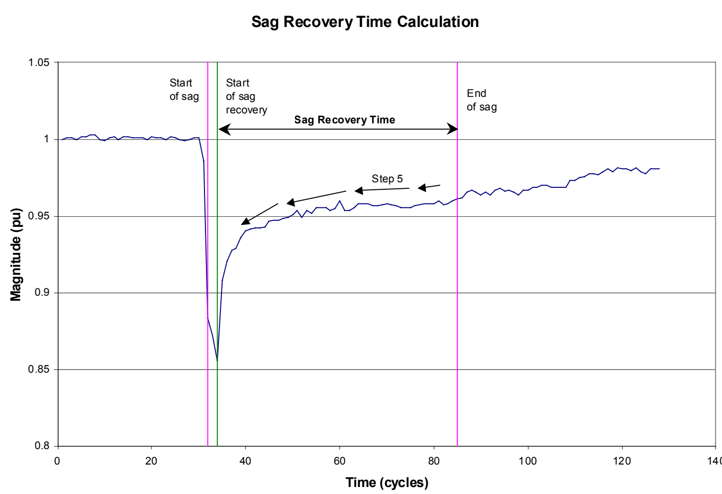

Figure 5-5
Sag Recovery Time Algorithm as Applied to the Example Event

A histogram of sag recovery times for approximately 100 events at the example PQPager site is shown in Figure 5-6.

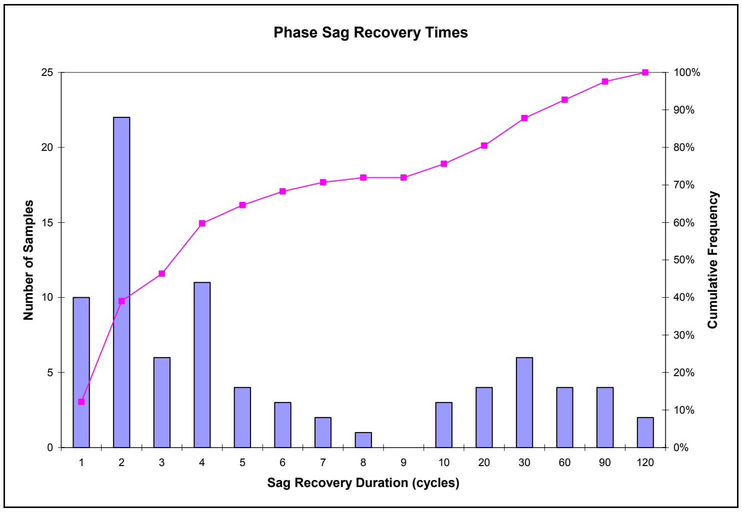

Figure 5-6
Sag Recovery Times for 100 Events at the Example Site

The sag recovery time value by itself is insufficient to adequately pinpoint areas prone to voltage collapse. In addition, it is not applicable if the fault clearing devices do not act promptly to clear the fault. If we look at an example location, which serves high-inertia rotating loads, we might expect different sag recovery times depending on the speed of the relaying in clearing a fault. For instance, if the fault were cleared in 10 cycles, the high-inertia loads wouldn't have much chance to decelerate, so the sag recovery time might be expected to be relatively short. On the other hand, if the relaying took significantly longer to clear, the rotating loads would have a chance to decelerate a greater amount. The system in this case would be required to re-accelerate the loads from a lower speed, possibly resulting in a longer sag recovery time. Obviously, it is not desirous to "flag" system issues just because the sag recovery time was longer. More detailed analysis is required to take into account the effects of different relaying times. The following paragraphs describe a means of normalization to take into account these effects.

The sag recovery time can be normalized by taking into account the duration of the rest of the event. Referring to the example RMS trend in Figure 5-4, a new quantity called *disturbance time* can be defined. It is the duration of the entire sag event minus the sag recovery time (disturbance time is the shaded region in Figure 5-7).

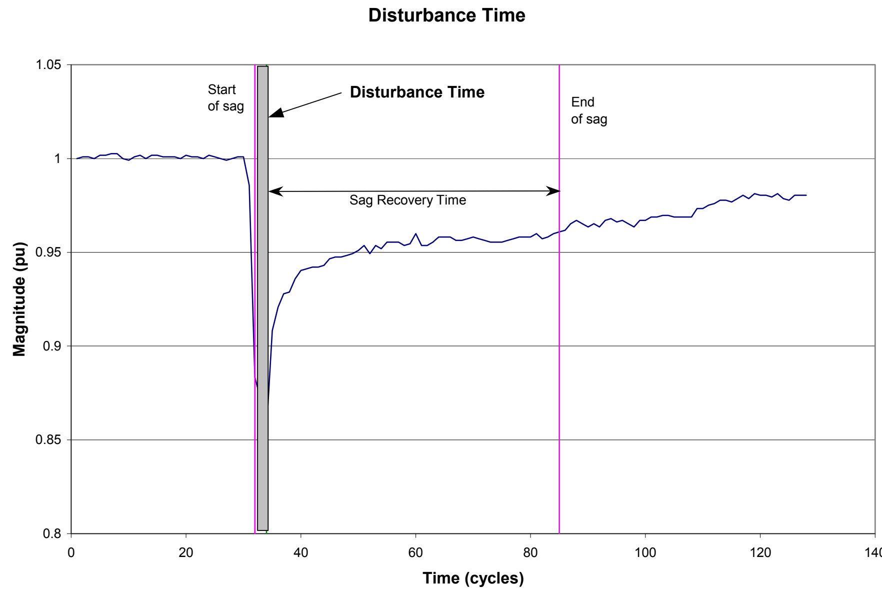

Figure 5-7
Disturbance Time Illustration

Roughly speaking, the disturbance time includes the initiation of the fault (or event causing the sag), the time required for the relays or other protection equipment to operate, and the time for the protection device to clear the fault. In equation form, the normalization, and the **definition of the fast voltage collapse index** is:

$$FVCI = \frac{sagre\mathrm{cov}erytime}{disturbancetime} \qquad \textbf{Eq. 5-4}$$

where

sagrecoverytime — is the time required for the voltage to recover 10% of the difference between the sag recovery value (or end of the recorded event) and the minimum sag value, to 96% of the pre-event voltage (or the end of the recorded event).

disturbancetime — is the duration of the entire sag minus the sag recoverytime.

Note: The disturbancetime parameter assumes a prompt clearing of the disturbance by protective device(s).

Again, referring back to the example RMS trend in Figure 5-4, the disturbance time is calculated as:

$$\overbrace{(85\text{ cycles} - 32\text{ cycles})}^{\text{Sag Duration}} - \overbrace{51\text{ cycles}}^{\text{Sag Recovery Time}} = 2\text{ cycles}$$

Eq. 5-5

The FVCI index value is found to be:

$$FVCI = \frac{sagrecoverytime}{disturbancetime} = \frac{51}{2} = 25.5$$

Eq. 5-6

The fast voltage collapse index value was tested on voltage sags from 5 sites from the EPRI Distribution Power Quality Phase II project[20]. A total of 1,106 sags were analyzed using the algorithm and equations listed above. It was expected that variations in load composition and system conditions might have an effect on the FVCI values that were calculated, so the 95th percentile values were chosen to be the point of comparison. The 95th percentile FVCI values for each of the sites are shown in Table 5-2. From this analysis we can surmise that Site 1 and Site 5 are more prone to voltage collapse due to their FVCI values. Therefore, in this grouping, these sites would warrant additional study.

Table 5-2
95th Percentile FVCI Values for Five Test Sites

Location	95th percentile
Site1	19.7
Site2	10
Site3	7.05
Site4	7
Site5	15

Conclusions

This chapter has briefly reviewed the phenomenon of voltage collapse and described some recent voltage collapse incidents. With the increasing utilization of utility resources in today's competitive environment, these incidents are likely to proliferate. Load modeling—and in particular dynamic loading—is critical to understanding and studying voltage stability and voltage collapse issues. Rather than directly ascertaining load parameters, a direct measurement-based approach has been proposed to provide a preliminary means to help identify potential locations in a power system that may be more likely to suffer from fast voltage collapse. The approach, called the fast voltage collapse index, looks at voltage sag recovery time versus disturbance time during the voltage sags. The fast voltage collapse index was calculated for five test sites to show its applicability.

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