Assessing Power Quality Levels from a Limited Set of Monitoring Data: Functional Description

Technical Report

Assessing Power Quality Levels from a Limited Set of Monitoring Data: Functional Description

1005928

Final Report, November 2001

EPRI Project Manager
S. Bhatt

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com

ORGANIZATION(S) THAT PREPARED THIS DOCUMENT

EPRI PEAC Corporation

ORDERING INFORMATION

Requests for copies of this report should be directed to the EPRI Distribution Center, 207 Coggins Drive, P.O. Box 23205, Pleasant Hill, CA 94523, (800) 313-3774.

CITATIONS

This report was prepared by

EPRI PEAC Corporation
942 Corridor Park Boulevard
Knoxville, TN 37932

Principal Investigator
A. Maitra

Investigators
A. Mansoor
R. Langley
T. Cooke

This report describes research sponsored by EPRI.

The report is a corporate document that should be cited in the literature in the following manner:

Assessing Power Quality Levels from a Limited Set of Monitoring Data: Functional Description, EPRI, Palo Alto, CA: 2001. 1005928.

REPORT SUMMARY

This report describes the concept of a unified tool that integrates the functionality of power quality assessment from a limited set of data with dynamic load modeling.

Background

Characterization of power quality levels on power systems becomes increasingly important with the increase in the sensitivity of power electronic and digital automation systems to momentary interruptions, voltage sags, transients, and harmonics. Characterizing power quality levels on electrical systems on both sides of the meter and determining response of sensitive loads to power quality variations helps both the energy company and its customers in effectively resolving power quality problems. It is cost-prohibitive and time-consuming to measure the power quality level at different locations over an extended period to determine power quality characteristics. Therefore, innovative alternatives are needed to arrive at meaningful and reliable measurements through the intelligent assessment of power quality levels from a limited set of monitoring data. In addition, dynamic load modeling is required to evaluate the response of loads to power quality variations at the point of load connection.

Objectives

- To evaluate at a customer facility the feasibility of predicting the quantity and severity of voltage sags based on monitoring data at the substation level.
- To develop the framework for a unified software tool that will combine the functionality of a power quality assessment and dynamic load response at the point of load connection inside the facility.

Approach

The project team first evaluated different algorithms and techniques for voltage-sag estimation from one measurement point to a downstream location. Based on this evaluation, a simplified algorithm using the magnitude and phase angle of voltage and current at the measurement location was implemented in a Visual Basic program. The algorithms were verified using field data and through Electromagnetic Transient Program (EMTP) simulation. In addition, the project team developed the concept of a "unified" software program that integrates the sag-transformation module with dynamic load response to evaluate the impact of voltage sags on different critical loads. As part of this evaluation, the team reviewed a modeling technique for motors, variable-frequency drives, and sensitive single-phase control loads that can be implemented within the framework of a unified modeling tool

Results

The ability to transform voltage sags from a substation monitor location inside a customer facility at the point of load connection will allow accurate modeling of the dynamic response of the load to voltage sags. For single-phase critical loads, such as programmable logic controllers, a simplified voltage-sag tolerance envelop is sufficient to predict the response of the load. However, for three-phase loads, such as adjustable-speed drives and induction motors, a dynamic model is required to predict the response of the load to voltage sags estimated at the point where the load is connected. In some cases, information on phase angle during voltage sags will be needed to evaluate the response of some loads such as DC drives. The ability to predict load response from measured voltage sags at the substation level provides a useful tool for evaluating different mitigation options at the load level.

EPRI Perspective

By providing utilities with tools that will allow assessing power quality levels inside a customer facility by monitoring data at the substation level, EPRI is enabling utilities to better use their existing power quality monitoring systems. The methodology and proof of concept presented in this report will ultimately lead to a unified tool that will be used to predict power quality levels and response of sensitive loads inside a customer facility from the substation feeder. Because of their understanding of the power quality characteristics of the electric service, electric utilities are in a unique position to help customers understand the impact of power quality on sensitive loads and develop appropriate immunity specifications for critical process equipment.

A companion EPRI report titled, *Assessing Power Quality Levels from a Limited Set of Monitoring Data: Proof of Concept for Sag Transformation Modeling* (1005929), describes the proof of concept for a voltage-sag transformation method and the verification of the method using field data and EMTP simulation.

Keywords

Power quality
Voltage sag
ASD
Load modeling
Sag transformation

CONTENTS

LIST OF FIGURES

LIST OF TABLES

1 INTRODUCTION

Electric power utilities and related consulting firms are steadily improving the software programs used in the power industry today. There is a growing need to develop an all-in-one software-based diagnostic solution engine that will allow utilities and other users of power quality monitoring to easily: (1) predict power quality parameters and (2) evaluate the vulnerability of sensitive end-use devices as it relates to voltage sags inside a customer facility from the pre-existing, state-of-the-art power quality monitoring systems at the substation. Successful development of such a tool will provide participating utilities, end-users, and manufacturing designers with a complete software package that leverages existing stochastic prediction approaches (short circuit models) as well as a limited number of power quality monitors to estimate voltage sag performance at every distribution and transmission location in an electrical network.

The proposed software product will take advantage of the voltage sag transformation module that is described in the companion report, *Assessing Power Quality Levels from a Limited Set of Monitoring Data: Proof of Concept for Sag Transformation Modeling, EPRI, Palo Alto, CA: 2001. 1005928.* It will be integrated with static (in the form of voltage sag tolerance curves) and dynamic load modeling tools that are required to evaluate the response of voltage sags on different critical loads. In general, the tool would have the following functional capabilities:

- Ability to estimate voltage sag parameters at every distribution and transmission location in an electrical network from only a limited number of pre-existing monitors.
- Ability to calculate and graphically plot synthesized levels of power quality measurements, such as voltage sag measurements, with the end-use device voltage sag sensitivity curves including CBEMA curves.
- Capability to maintain a database library of commercially available device sensitivity curves of critical, single-phase loads, such as PLCs, ASDs, relays, contactors, etc., that have been developed through system compatibility tests at EPRI's Power Electronics Applications Center.
- Ability to maintain what might be called a global library of sag tolerance curves for different categories of process equipment as well as different manufacturing brands that will allow the user to identify the exact process equipment that is being used.
- Capability to generate single-phase and three-phase dynamic models, thereby providing a full functionality to analyze modern digital controllers such as adjustable speed drives, induction motors, DC drives, etc.

This two-way approach capability to incorporate static as well as dynamic modeling of critical loads from a limited set of monitoring data will provide utilities with a "unified" software package to implement cost-effective mitigation techniques in a more timely fashion. Proof of concepts and functional capabilities required for developing such a user-friendly, integrated, unified, simulation software package will be discussed in the next chapter.

A Shift From a Mechanical To a Digital Process Control

In the past, most of the electromagnetic-based industrial process equipment was fairly tolerant to voltage disturbances such as sags, momentary interruptions, harmonics, spikes, and transients. Due to the type of equipment being mechanical in nature, electrical energy was converted to mechanical energy and motors essentially were connected directly to the mains. However, with the drive toward higher production costs, increased energy efficiency, and reliability in today's highly competitive market, modern industrial and large commercial facilities are incorporating a vast array of semiconductor-based electronic devices. Power electronics is being extensively used in AC and DC drives, process controllers, power supplies, machine tools, computers, and programmable logic controllers. Examples of industrial and commercial facilities that typically employ sensitive power electronic-based equipment include: pulp and paper, plastics, petrochemical, mining, textiles, machining, rubber, semiconductor, etc. However, even well maintained and reliable power electronic devices turn out to be very sensitive to power quality variations.

Characterizing Voltage Sags for Utility/Customer Interface

One of the most common power quality-related concerns for utility customers with sensitive process equipment is the voltage sag or momentary interruption. Voltage sags are highly random events caused by fault conditions and are likely to cause power electronic components to trip, malfunction, or adversely affect production. Faults over a wide area in a power system network can affect customers that use sensitive power electronic devices as a part of their process control. Industrial facilities supplied at distribution voltages can be impacted by faults either at their own feeders, on parallel feeders, or on transmission networks. Figure 1-1 illustrates the breakdown of utility fault events that cause sensitive equipment to malfunction for a typical process industry customer connected at the distribution level [1].

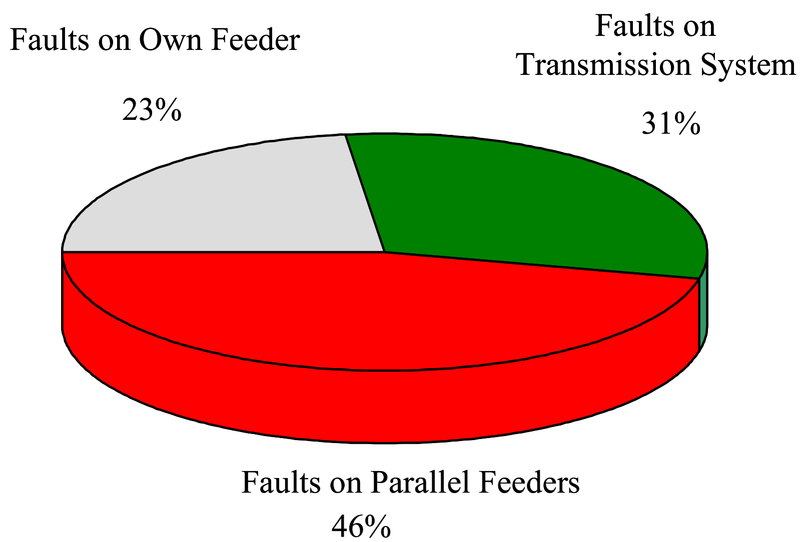


Figure 1-1
Equipment Disruption Statistics for an Industrial Facility

Controls of power electronic devices can be just as sensitive to minor power system voltage sags (lasting 4-5 cycles) as they are to complete electrical breakdowns. Voltage sags are much more frequent than momentary interruptions and are more likely to cause the controls of an electrical appliance to trip multiple times over its lifetime. In addition, if automatic circuit re-closure is used by the utility, Permanent faults can cuase the voltage sag condition to occur .

A one-line diagram of a power system network obtained from the *EPRI Power Quality Diagnostic System, Capacitor Switching Simulator, version 1.0,* is shown in Figure 1-2. This is used to illustrate remarkably different voltage sag characteristics throughout a power system due to a three-phase fault placed on the transmission level (denoted by '**X**'). The fault is cleared within five cycles. All capacitors were considered off-line for this simulation.

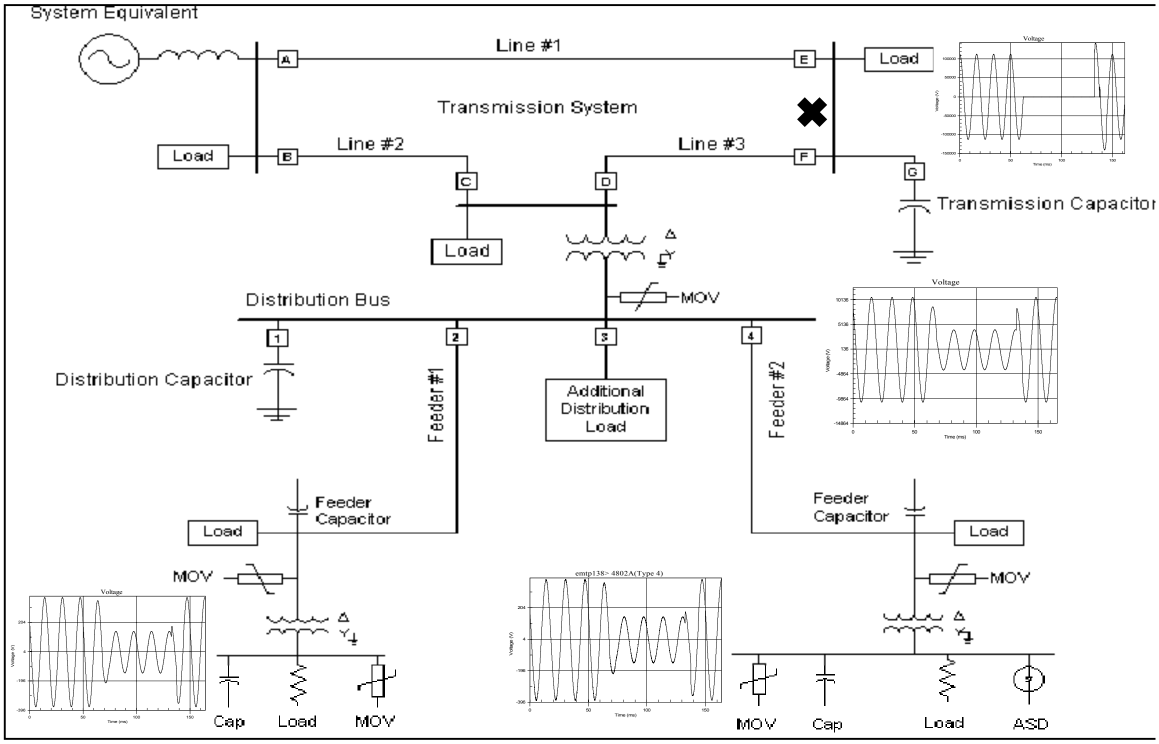


Figure 1-2
One-Line Diagram of a Power System

It is clear from Figure 1-2 that while the fault is on the transmission system, the entire power system, including the two customers located on the distribution system, experienced voltage sags. Even though customers normally would not experience an interruption for a fault condition at the transmission level, customers located hundreds of miles from a fault location can still experience voltage sags that might be sufficient to cause their sensitive equipment to trip.

As a result of repeated tripping of sensitive equipment, the end result can be translated into thousands of dollars in loss due to equipment restarting, production line shutdowns, damaged or lower quality products, delay in delivery, and reduced customer satisfaction. Costs associated with a voltage sag incident can easily vary from tens of thousands of dollars at a plastic plant to millions of dollars at a semiconductor manufacturing facility. Also, it is worthy to note that not all voltage sag incidents will trip sensitive equipment.

What Are We Doing To Understand This Problem? - Utility Initiatives

With increased sensitivity and the industry’s dependency on sophisticated process control equipment in manufacturing, the first task involves an ability to access and quantify voltage sag levels throughout electrical systems. Utilities are realizing that they should not only understand the levels of service quality they provide, but also must be able to ascertain whether these levels are appropriate. These reasons are certainly becoming more and more prevalent as the utilities are contracting with customers to provide premium power services over an extended period of time. The basic intent is to limit the number of disturbances supplied to customers that might result in a probable loss in production.

Therefore, direct monitoring of transmission as well as distribution systems, seems to be the preferred approach for benchmarking power quality levels that many utilities are performing for their industrial and commercial customers. Furthermore, due to the seasonal variations of many significant quality disruptions, data must be collected over an extended period of time. Although this period is dependent on several factors, the process of benchmarking voltage sag levels generally requires 2-3 years [2]. The point at which monitoring must take place is also a key to evaluate successfully the sensitivity effects of a voltage sag problem to process equipment [3].

In an attempt to assess the quality of service provided by energy companies on distribution feeders, many utility companies are beginning to install power quality monitoring equipment to collect data for their individual customers. In 1989, EPRI embarked on a power quality-monitoring program (EPRI DPQ Project) that monitored power quality levels on some 276 locations on 100 distribution feeders across the United States for approximately 2 years. As might be expected, this effort resulted in 30 gigabytes of power quality data. In 1996, EPRI completed the Reliability Benchmarking Methodology (RBM) project that provided power quality indices to allow power quality to be described in a systematic manner in terms of various disturbances that affect sensitive end-use equipment [4,5].

However, considerably less effort has been directed at benchmarking power quality levels at the transmission level due to the relative proximity to the end-user, additional costs of monitoring at that level, and the transmission events are included indirectly in distribution assessments. With the unbundling of the traditionally vertically integrated utility into generation, transmission, and distribution, along with the practice of serving large influential customers from the transmission level, increases the need for assessing the performance of the two levels separately. For some years now, stochastic based prediction approaches [3, 4] are typically used to characterize voltage sag levels on transmission levels. More generally, short- circuit simulations are performed using historical data from utilities to generate a vulnerability contour (Area of Vulnerability [AOV]), which is then used to evaluate the system's sensitivity to voltage sags.

A Need To Develop an "Intelligent" Voltage Sag Estimation Algorithm

Developing cost-effective mitigation methods and better define premium power quality contracts, electric utilities and equipment designers need an "intelligent" assessment tool that will accurately predict the response of sensitive process equipment to voltage sags inside a customer's facility from limited sets of monitoring data. Moreover, it is labor intensive and cost prohibitive to maintain a data-gathering infrastructure that will monitor power quality characteristics at different locations over an extended period of time. Procurement and installation of a single power quality monitor can cost tens of thousands of dollars. These costs allow for monitoring only a small subset of a utility's electrical power network.

Therefore, innovative alternatives are needed to quantify and assess power quality levels from pre-existing, state-of-the-art power quality monitoring systems at the substation. With the availability of distribution level power quality monitors currently installed at substations of distribution systems nationwide, it would be beneficial from an economic and engineering standpoint to develop intelligent fault analysis techniques and algorithms that can:

- Distinguish between transmission- and distribution-level events (upstream and downstream incidents) captured by the distribution-level power quality monitors at the substation
- Use appropriate iterative techniques that use monitoring results from pre-existing monitors at the distribution substation as input to estimate the type of fault and fault impedance
- Transform voltage sag levels from a substation monitor location to locations inside a customer facility at the point of load connection

It is important to note that the proposed sag transformation [6] is based on a simplified algorithm that uses voltage and current magnitude and phase angles from pre-existing monitors at the distribution substation as input and estimates voltage sag levels at every distribution and transmission location in an electrical network, including the locations inside a customer facility. In short, the voltage sag transformation technique expands the monitoring system to include all the buses (points of interest) in the system without actually having monitors at all buses. Moreover, this assessment is not based on stochastic prediction approaches and the results of these techniques can be used easily to evaluate vulnerability of end-use devices as it relates to voltage sags at points were it matters the most, the customer.

Proof of this concept of one such sag transformation technique and its verification using field data and Electro Magnetic Transient Program (EMTP) is proposed in the companion report, *Assessing Power Quality Levels from a Limited Set of Monitoring Data: Proof of Concept for Sag Transformation Modeling, EPRI, Palo Alto, CA: 2001. 1005928.*

A Need To Develop an “All-in-One” Compatibility-Based Software Tool

The next step is to be able to accurately predict load responses to voltage sags. However, an ability to predict the compatibility profile of different types of process equipment (e.g., PLCs, ASDs, relays, contactors, etc.) in a plant to analyze voltage sag concerns is not a simple task. Different categories of end-use equipment and different brands of this equipment within a category can have significantly different sensitivities to voltage sags. This makes it difficult to define a single standard for the sensitivity of all types of modern process equipment. However, it is important for utility personnel, who are providing mitigation techniques to voltage sag-related problems for an industrial facility understand that their cost-effective solutions be based on the expected sensitivity of a customer-specific, end-use equipment.

Sensitivity Standards

Some of the earlier and more recent voltage tolerance-based susceptibility curves for end-use equipment include CBEMA (Computer Business Equipment Manufacturer’s Association), ITIC (Information Technology Industry Council), and SEMI (Semiconductor Equipment and Materials International). While these new ITIC and SEMI curves serve as a benchmark for equipment susceptibility, they do not necessarily address the wide range of equipment such as ASDs, DC drives, PLCs, relays, and contactors that are used typically in process industries and are often the most sensitive element impacted by voltage sags. In general, meeting these requirements alone does not guarantee that critical loads will be unaffected by voltage sag events.

Representative Process Equipment's Immunity Curves

To assess the sensitivity of other process equipment, EPRI PEAC has over the past several years, conducted numerous projects broadly classified as System Compatibility Research to characterize the sensitivity of equipment commonly used by industrial, commercial, and residential customers. While the range of equipment tested does not include every manufacturer brand, model, and type of equipment available, it does represent a sufficiently broad cross-section that allows some general inferences to be made. A reference to these sag tolerance curves can be obtained in *IEEE P1346 Recommended Practice For Evaluating Electric Power System Compatibility With Electronic Process Equipment*, and are not shown here for the sake of brevity.

Process Level Characterization

It is also important to recognize that any typical industrial and commercial facility can be divided into several process levels or steps. Consider a simple tree structure of a typical industrial process, as illustrated in Figure 1-3. This type of hierarchical structure divides an industrial process into the following levels:

- Main Level - where a specific product is being manufactured or processed
- Section Level - where a specific task is performed
- Sub-Process Level - where a task inside a section is performed
- Device Level - where actual components (PLCs, ASDs, relays, contactors, etc.) are required to perform the task

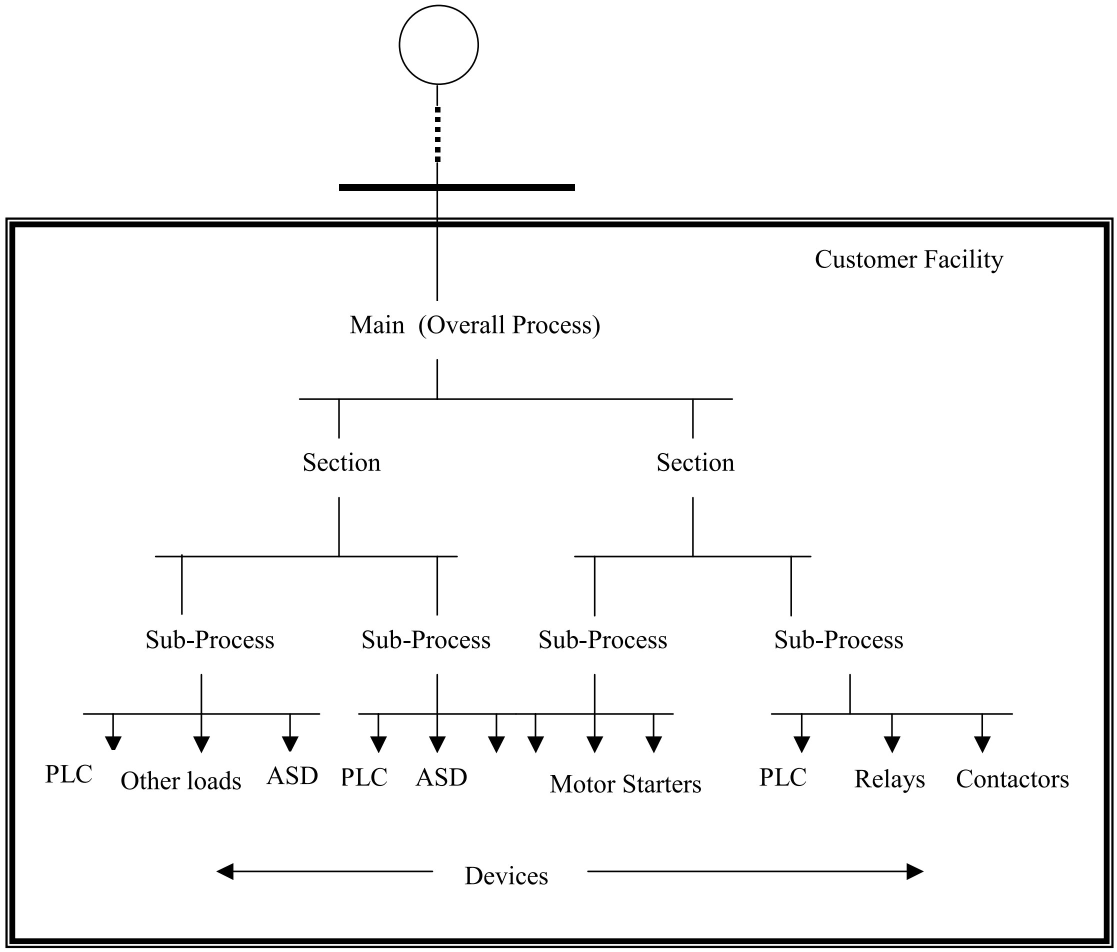


Figure 1-3
Process Hierarchy of a Typical Industrial Process

At first glance, an ability to identify sensitive pieces of equipment from an overall process might be particularly difficult. Therefore, understanding the basic layout of an overall process and how individual process levels impact production quality is critical.

A general-purpose diagnostic software tool that can analyze susceptibility of every process, section, sub-process, and device based on voltage sag data that is transformed inside a customer's facility and the compatibility levels of each device, will have to be developed. An ability to develop and maintain individual database libraries comprising several HTML documents that discuss specific industrial process devices, voltage sag tolerance curves for different categories of process equipment as well as different manufacturing brands, ride-through options, and solutions for devices, all inside the framework of one software, is a key. In short, this software-driven database tool should have similar functionalities as the Industrial Voltage Sag Investigator (IVSI) that was proposed by EPRI in 1999 [7].

With IVSI, users follow a systematic approach to investigate a customer's voltage sag problem. The software package serves as an excellent diagnostic tool allowing utilities and end-users to:

1. Follow a systematic scenario-based approach to solve customer's voltage sag problems

2. Document customer and process specific information in separate database libraries

3. Identify process equipment that is sensitive to voltage sags

4. Review information resources that discuss descriptions, susceptibilities, ride-through options, and specific ride-through solutions for industrial equipment

5. Analyze the economic impact of sensitive equipment

6. Print customized reports for each customer that highlights process- and customer-specific information, susceptible process equipment, and solutions and ride-through options

These functionalities are inherent in IVSI's three application modules (Interview Module, Analysis Module, and Solution Module).

Need For Dynamic Modeling

One major drawback in the present version of IVSI is the tool does not have the functionality to perform dynamic modeling of three-phase process equipment. It must be re-emphasized that voltages experienced during a voltage sag condition depend on the equipment conditions. For single-phase critical loads such programmable logic controllers (PLCs) and computers, a simplified voltage sag compatibility envelope might be sufficient to predict the response of the PLC. However, for three-phase critical loads such as adjustable speed drives (ASDs), induction motors, and DC drives, a dynamic load model is required to predict accurately their responses to voltage sags at the point where they are connected in the customer's facility.

2
CONCEPT PLANNING FOR UNFIED SAG TRANSFORMATION AND DYNMAIC LOAD MODELING TOOL

Consumer satisfaction is considered to be a prime rule of any trade. When a customer complains about the power that is supplied, the utility has to go to great lengths to solve the problem. Moreover, voltage disturbances, especially voltage sags, can be utility generated or can be caused by connection of certain equipment at the site of the problem. When the utility is presented with such a problem, the usual practice is to monitor the voltages and currents at the customer location. As stated earlier, it is cost prohibitive and time consuming to measure the power quality levels at different locations over an extended period of time. The aim is to develop a user-friendly, integrated simulation engine that is cost effective and could accomplish almost all functions of the individual testing equipment at different locations. The software product will take advantage of the voltage sag transformation module and the present Industrial Voltage Sag Investigator (IVSI) software package created by EPRI and integrate it with dynamic load modeling capability for three-phase critical loads such as adjustable speed drives (ASDs), induction motors, and DC drives.

A Need To Develop An Improved IVSI Software Tool

The primary objective of this “unified” software tool is to provide assessments and solutions to voltage sag problems for industrial and commercial customers. As a part of the overall goal for providing added functionality, this product will have built-in capabilities to interact with other EPRI software such as Industrial Design Guide, EPRI PQ Database (that will provide case studies for specific industries), and EPRI PQDS (Power Quality Diagnostic System). The PQDS software already has the scalability to read in EMTP data files, which can be used to determine the dynamic responses of critical loads. In particular, providing such an interactive environment as a front end will allow users to review existing information on specific process industries and voltage sag case studies to understand the customer, the customer’s process, and customer’s problems more clearly.

A Demo Version of the “Unified” Software Tool

Although this software eventually will be a stand-alone, complete software package, the intent is to demonstrate the overall conceptual framework of this proposed solution engine through a demo presentation. The numerous functional as well as optional capabilities (for example; to upload the system that the user wants to evaluate, the user can either draw his one-line electrical network; or he can obtain generic industry-specific templates of one-line diagrams; or he can download the case study networks from the PQDS database library) that this tool could later utilize for entering these inputs are obviously not depicted in this demo. A step-by-step approach that will be required to integrate the three most important application modules, namely,

- Voltage Sag Transformation Module
- Static Load Sensitivity Module (present IVSI software)
- Dynamic Response Related Load Module

are demonstrated in Figures 2-1 through 2-18. Furthermore, the type parameters that will be required as inputs to these individual modules are discussed. Overall objectives of this interactive package are demonstrated in Figure 2-1.

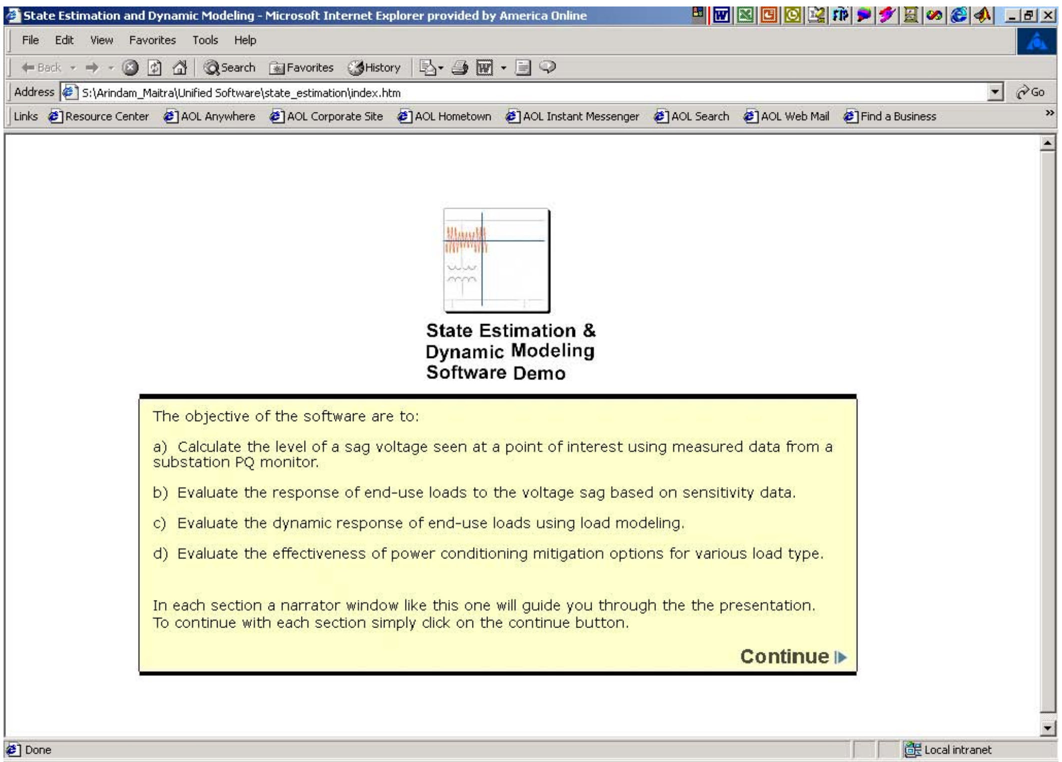


Figure 2-1
Example Screen of a Unified Software Tool

STEP 1: Acquire Information about the System

A one-line diagram of a typical power system distribution network is shown in Figure 2-2. This model was obtained from the EPRI Power Quality Diagnostic System (PQDS) for the Capacitor Switching Simulator.

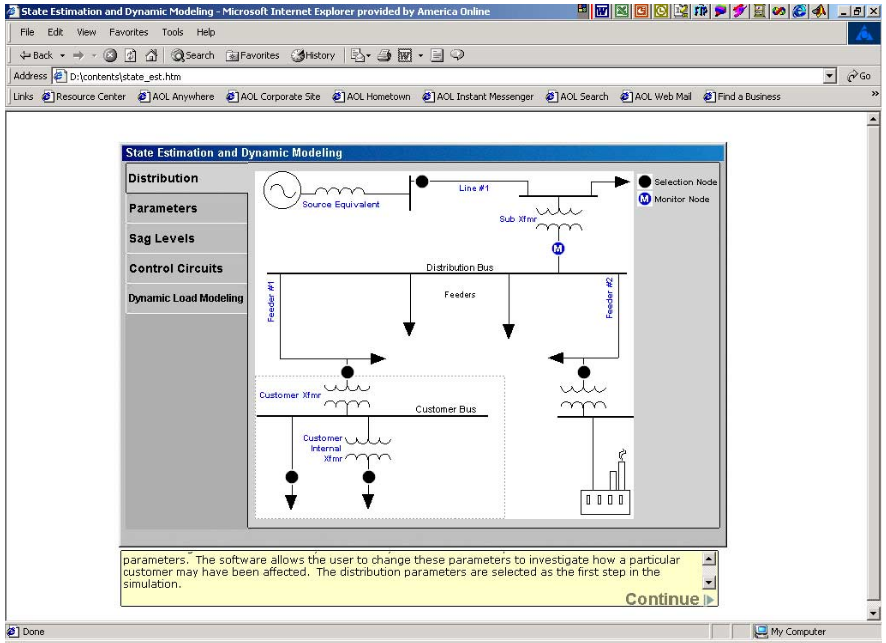


Figure 2-2
Example Screen of a Power System Network

Distribution parameters are selected as the first step in the diagnostic analysis. The software will allow the user to enter different system parameters (shown in Figures 2-3 through 2-6), which are required as inputs to the Voltage Sag Transformation Module.

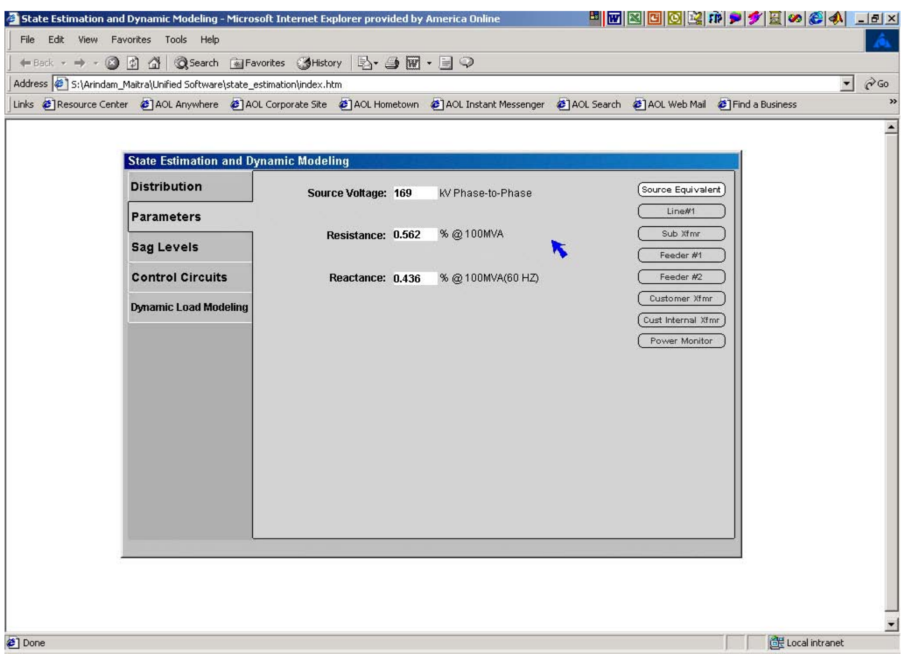


Figure 2-3
Example Screen of Input Parameters – Equivalent Impedance of the Source

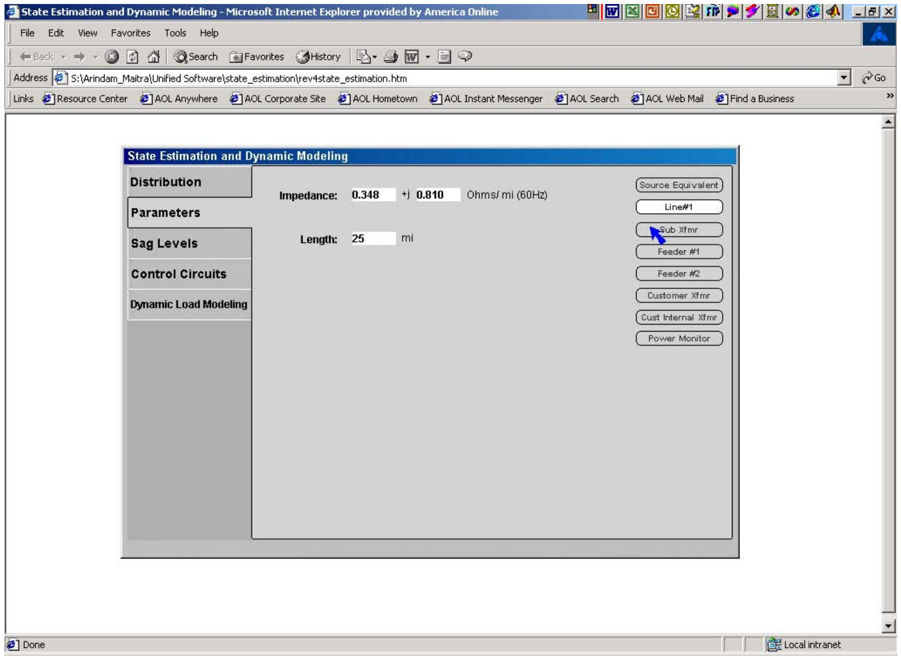


Figure 2-4
Example Screen of Input Parameters – Typical Transmission Line Parameters

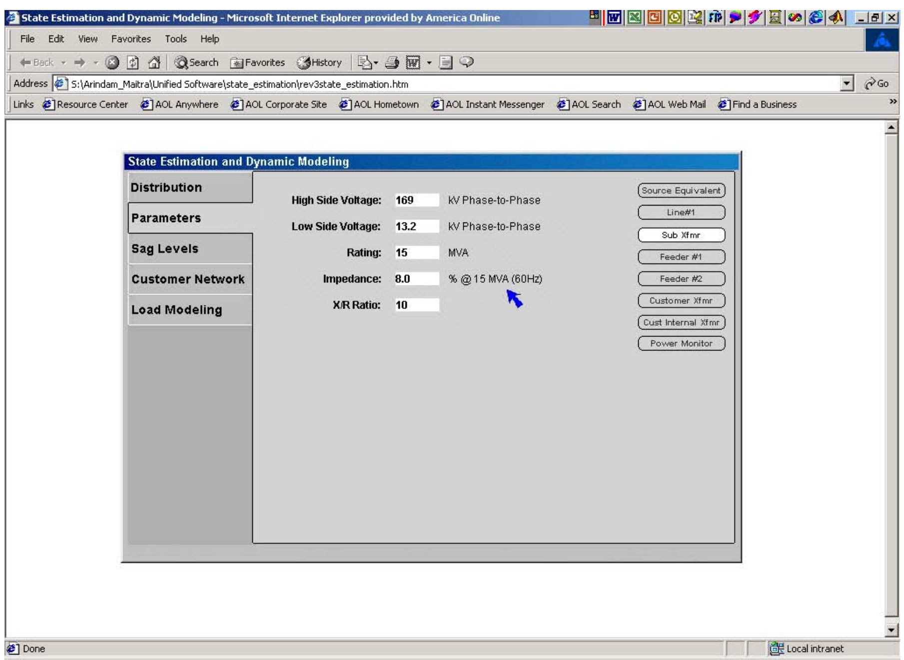


Figure 2-5
Example Screen of Input Parameters – Typical Transformer Parameters

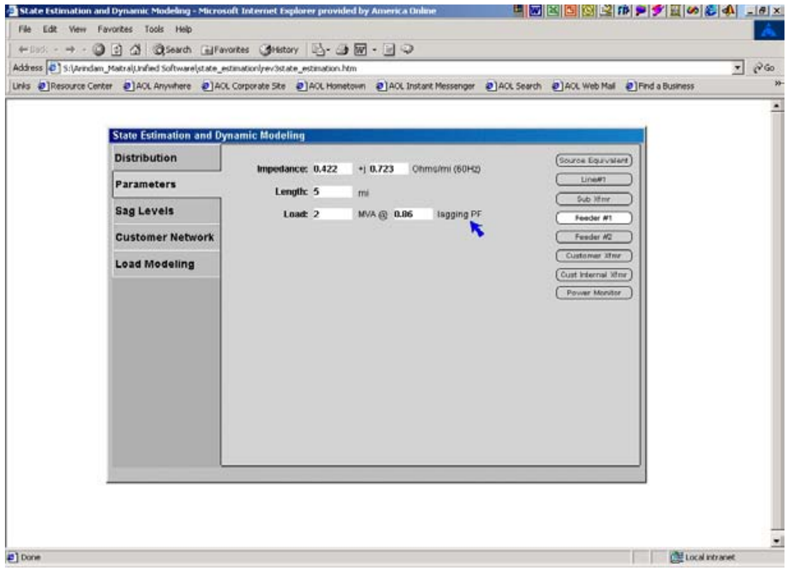


Figure 2-6
Example Screen of Input Parameters – Typical Feeder Parameters

STEP 2: Acquire PQ Data at the Distribution Substation

A PQ monitor, as shown in Figure 2-1, is located at the distribution substation. Figure 2-7 illustrates a case when this monitor captures a voltage disturbance scenario. Numerical values of line-to-neutral voltage (expressed in % of nominal) and current magnitudes and phase angle of all the three phases at the substation bus will be used as the inputs to the Voltage Sag Transformation Module.

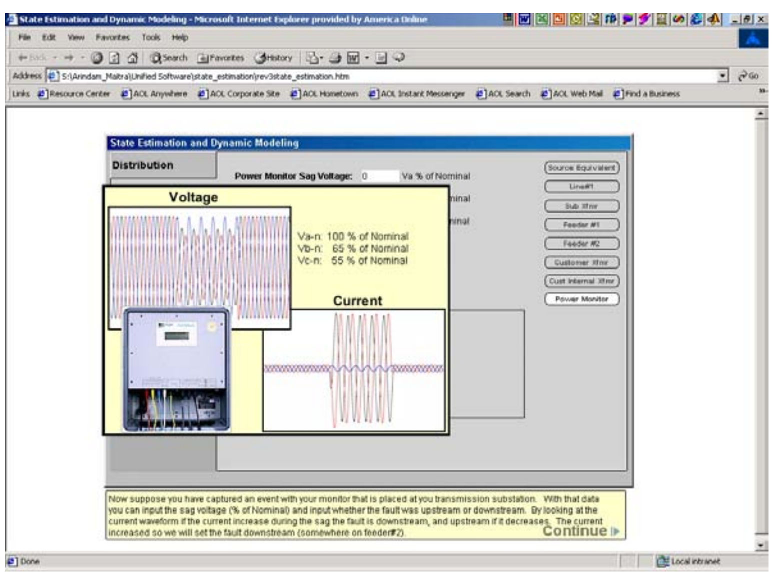


Figure 2-7
Example Screen of a Voltage Sag Event Captured at the Distribution Substation

STEP 3: Differentiate Between Upstream and Downstream Events (an optional capability)

To use the already installed distribution level power quality monitors effectively, techniques to differentiate between faults at the transmission level and faults at the distribution level (upstream and downstream events with respect to the location of the monitor) can be provided as an additional feature to the software. It is important to note that this differentiation would not be used as inputs to the Voltage Sag Transformation Module. It is an optional feature that provides the user added information regarding the fault location.

At present, this determination is made from the measured substation current [3]. From Figure 2-7 it is clearly seen that the current recorded at the substation monitor increased during the fault, indicating that the fault was somewhere downstream of the meter. Had the fault been upstream (somewhere in the transmission level), the fault current would not have been measured at the substation monitor. The result of this differentiation for the power network shown in Figure 2-1 is illustrated in Figure 2-8. It was known beforehand, as shown in Figure 2-9, that the fault was on Feeder #2.

Needless to say, at this point it will not be possible to quantify the exact fault location downstream of the meter. In short, the fault could have happened on either one of the two feeders (Feeder #1 and Feeder #2) shown in Figure 2-1. It can, however, be speculated that an ability to ascertain the exact fault location be obtained from the pre-existing distribution feeder monitors located on individual feeders. An educated guess can also be made from prior knowledge of the fault impedance, relay operation times, and other information.

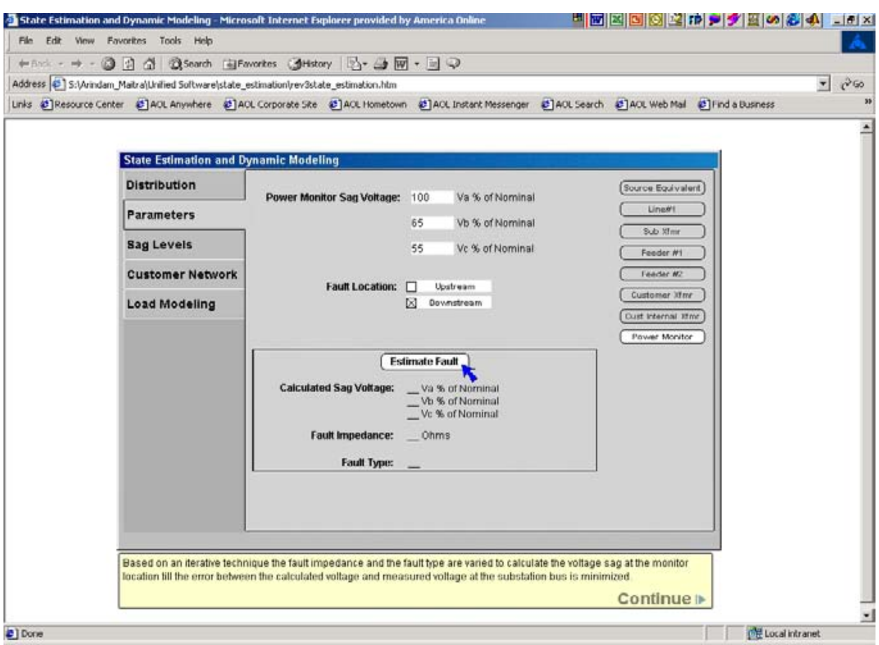


Figure 2-8
Example Screen that Infers Between Downstream and Upstream Incidents

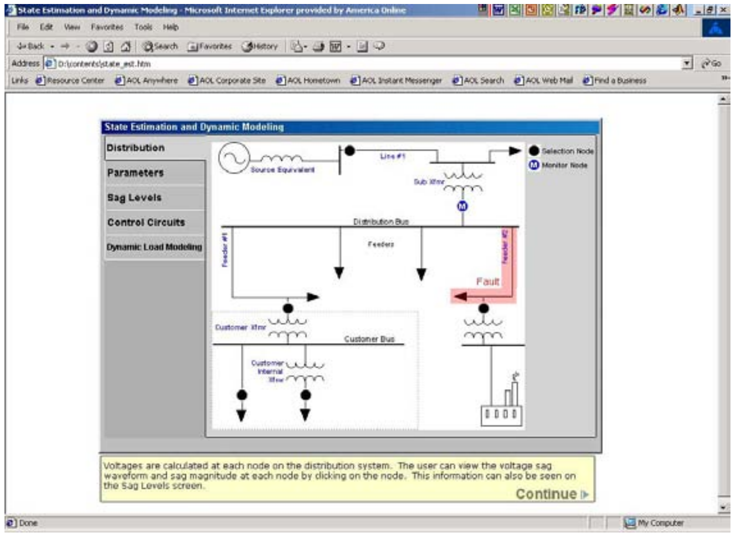


Figure 2-9
Example Screen Depicting Fault Location

STEP 4: An Iterative Technique to Evaluate Fault Type/Fault Impedance (an optional capability)

An iterative technique like a "weighted least squares" approach [3,4] can be used to estimate the fault impedance and fault type. This estimator is designed to predict voltage sag at the monitor location by varying the fault type and fault impedance until the error between the predicted voltage and the measured voltage at the substation bus is minimized. Again, this is not a mission-critical step for the overall process, but should be treated as add-on capability. The result for this step is shown in Figure 2-10.

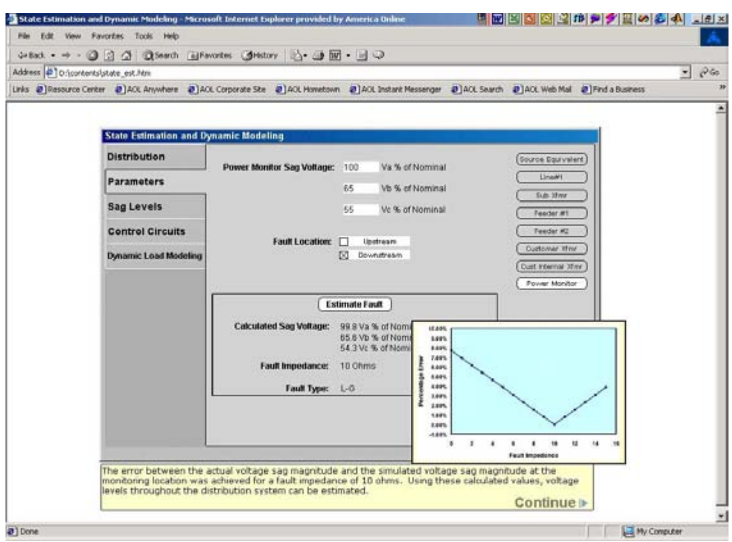


Figure 2-10
Example Screen Depicting Fault Impedance and Fault Type

STEP 5: Voltage Sag Transformation

Figure 2-11 depicts the voltage sag levels called by the Voltage Sag Transformation Module at various locations in the network. Once the sag levels have been determined, the user can continue to the customer's network to evaluate the sensitivity of individual loads to voltage sag. The present IVSI module can be called for a more detailed assessment of the voltage sag susceptibility evaluation of industrial process equipment.

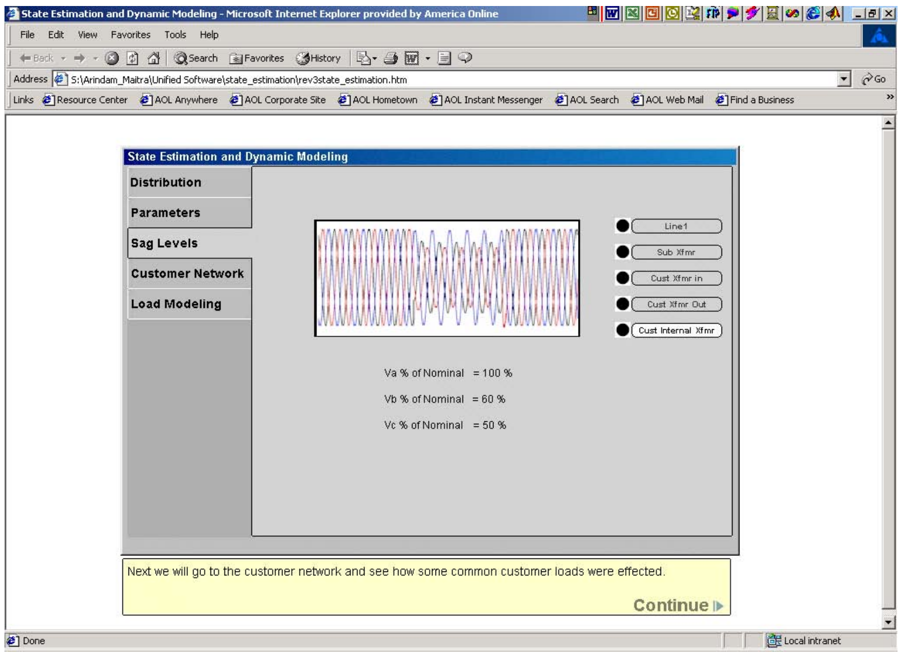


Figure 2-11
Example Screen Depicting Estimates of Voltage Sag Performance Throughout the Network

STEP 6: Static Modeling – Ability to Ascertain Load Susceptibility

An example of a customer's network control circuit is shown in Figure 2-12. The user has the ability to select brand (manufacturer's model number) of contactor and PLC that is pertinent to his process from the equipment database list. The databases will serve as a running library and will have the functionality to be updated when a new brand is available.

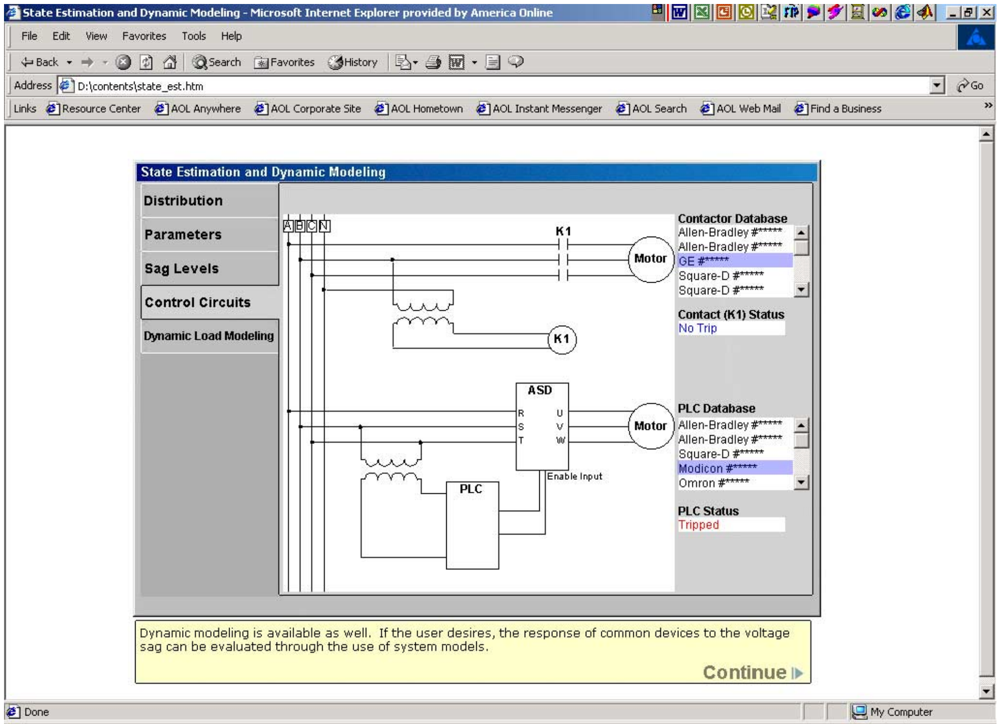


Figure 2-12
Example Screen Illustrating Compatibility Level Testing for Contactors and PLCs

STEP 7: Dynamic Modeling – Ability to Ascertain Load Response

Figures 2-13 through 2-16 illustrate an instance of dynamic modeling. In this case, the response of ASD to voltage sags is analyzed. The inputs required to construct dynamic models of the ASD are also illustrated.

Figure 2-14 depicts that the speed of the motor drops to zero. This could be attributed to the fact that the ASD "tripped" as a result of voltage sag. Moreover, the PLC could have tripped causing the ASD to shut down. Therefore, the PLC susceptibility curves should be constructed to ascertain sensitivity to voltage sags. As a ride-through enhancement, a constant voltage transformer (CVT) could replace the standard transformer. A CVT model would then have to be constructed and the simulation would have to be run again to evaluate the response of the ASD to voltage sag. Figure 2-15 and Figure 2-16 demonstrate the updated response. The speed of the ASD was maintained during the voltage sag incident when the PLC was connected via a CVT. This postulates that the PLC was the "weak" link in the process.

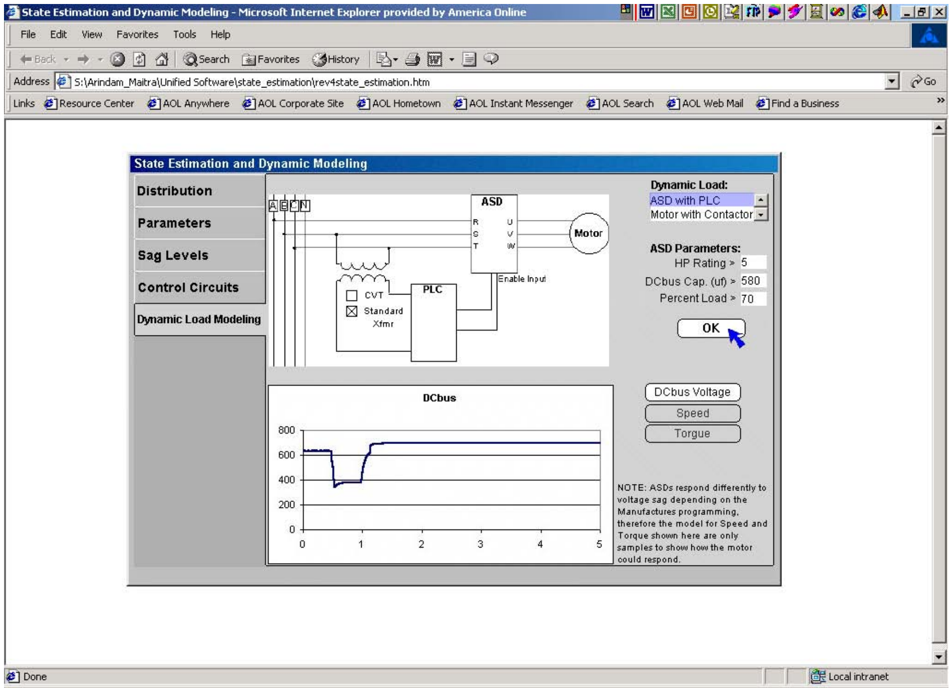


Figure 2-13
Example Screen Illustrating Variations in DC Voltage (ASD) with the PLC Connected through a Standard Transformer during a Voltage Sag Event

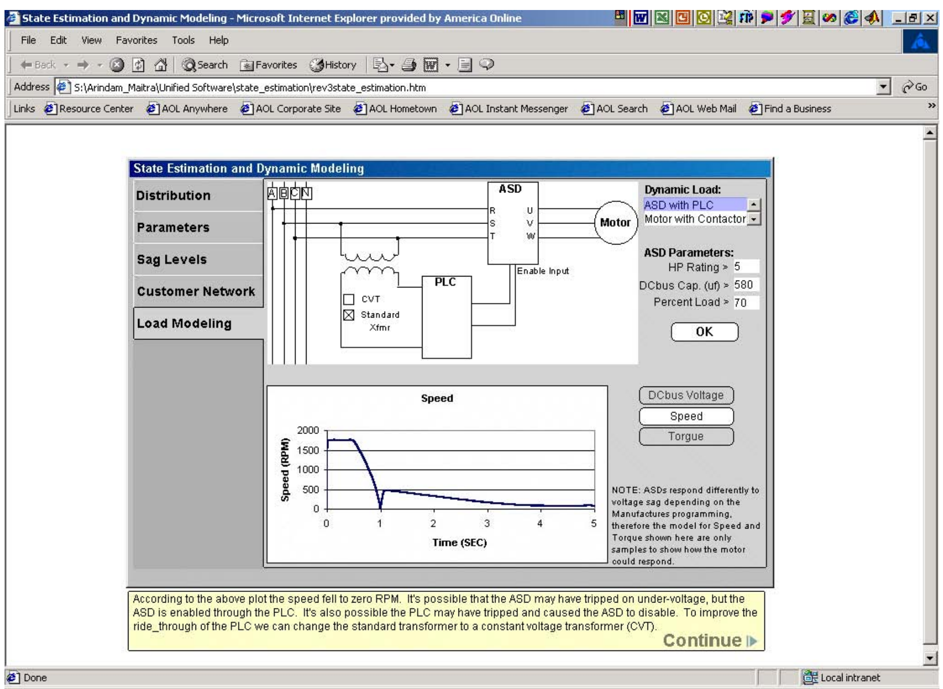


Figure 2-14
Example Screen Illustrating Variations in Motor Speed with the PLC Connected through a Standard Transformer during a Voltage Sag Event

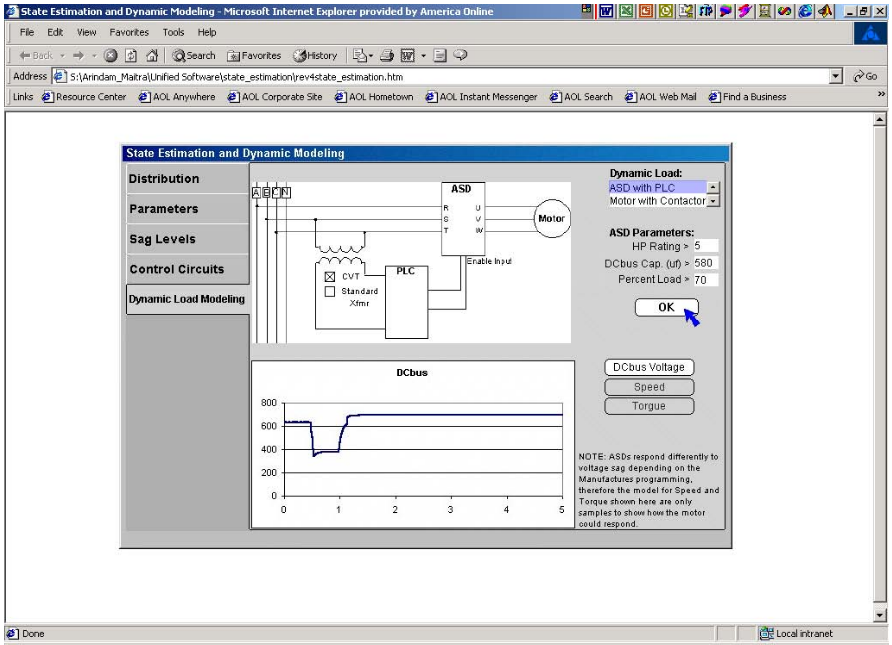


Figure 2-15
Example Screen Illustrating Variations in DC Voltage (ASD) with the PLC Connected through a CVT during a Voltage Sag Event

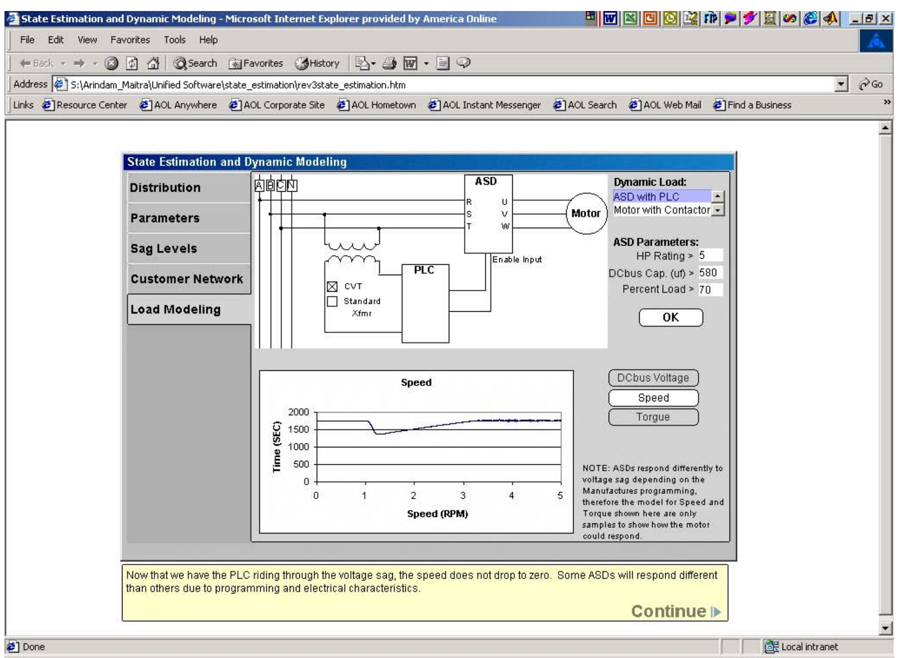


Figure 2-16
Example Screen Illustrating Variations in Motor Speed with the PLC Connected through a CVT during a Voltage Sag Event

Figure 2-17 depicts an instance when the contactor drops out causing the speed of the induction machine to go to zero. No ride-through capability was provided in this model. The inputs required to construct the dynamic model of an induction machine are also illustrated. With a ride-through capability installed, the motor speed change will be minimal indicating the motor starter did not "trip." Simulation results with ride-through capabilities installed to the motor is depicted in Figure 2-18.

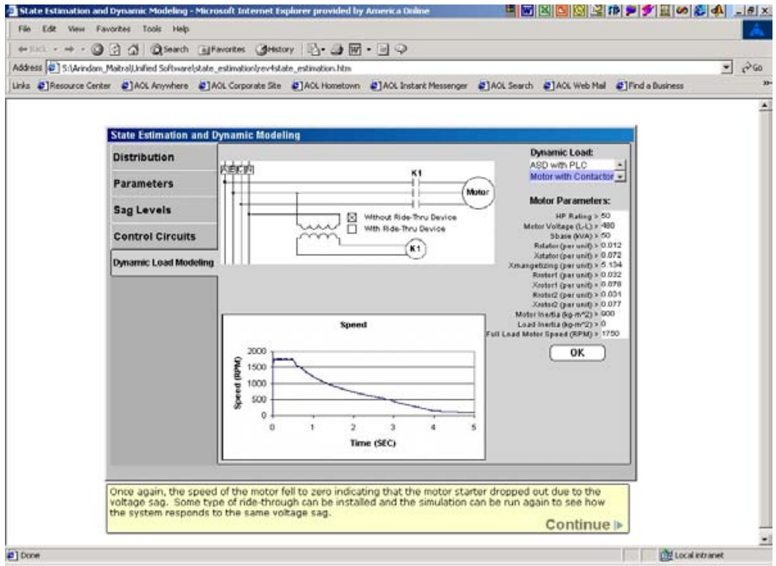


Figure 2-17
Example Screen Illustrating Variations in Motor Speed without any Ride-Through Capability Added

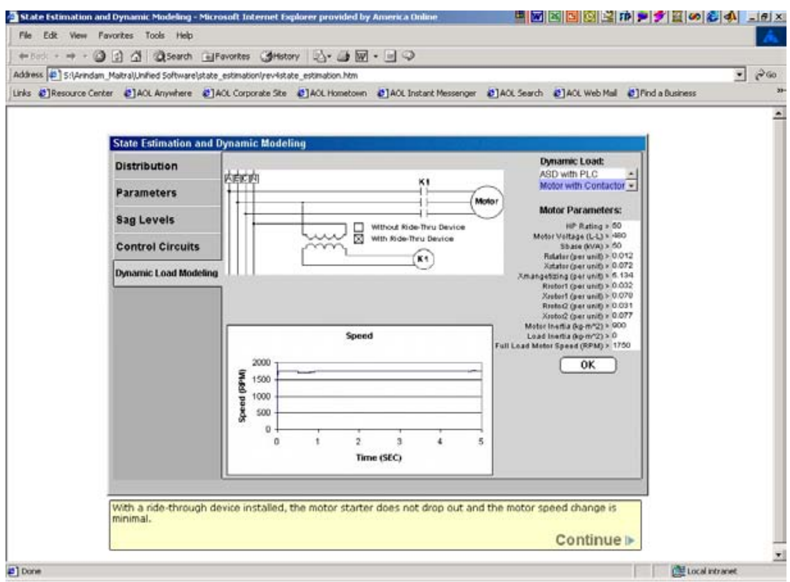


Figure 2-18
Example Screen Illustrating Variations in Motor Speed with Ride-Through Capability Added

In general, the software product will serve as a diagnostic tool that will fill in the need gap for detailed power quality simulation based on stochastic approaches and costly direct-measurement-based approaches. As stated earlier, a full-blown version of this proposed software could provide additional functional capability. Some of the numerous choices that a user could have are listed below.

- The tool could have the capability to create generic, industry-specific, one-line diagrams by calling database libraries that store general electrical power networks.
- The tool could also support user-defined data (system) transfer to the pre-existing one-line diagrams and the user could then revoke the simulation engine to re-calculate the results based on this update. This will allow maximum information retrieval with minimum user effort.
- The network could have the capability to import various network data files from PSS/E, ASPEN, CAPE, etc.
- The tool could allow users to perform “what-if” scenarios to evaluate different mitigation techniques. An illustration of this is depicted in Figures 2-15, 2-16, and 2-18 where the effect of adding a constant voltage transformer was evaluated.
- The tool could have the ability to calculate and graphically plot synthesized plots of power quality measurements such as voltage sag measurements with voltage sag sensitivity curves of the end-use device, including CBEMA curves.
- The tool could have the capability to maintain a database library of commercially available device sensitivity curves of critical single phase loads such as PLCs, ASDs, relays, contactors, etc., that have been developed through system compatibility tests at EPRI’s Power Electronics Applications Center.
- The tool could have the ability to maintain what might be called a global library of sag tolerance curves for different categories of process equipment as well as different manufacturing brands. This will allow the user to identify the exact process equipment that is being used.
- The tool could have the capability to generate single-phase as well as three-phase dynamic models thereby providing a full functionality to analyze modern digital controllers such as adjustable speed drives, induction motors, DC drives, etc.
- The tool could have the capability of integrating other EPRI software as the front-end module for better functionality.

3

LOAD MODELING

Load Modeling for Evaluating Voltage Sag Sensitivity

In its simplest form, load modeling for voltage-sag sensitivity can be implemented by overlaying sag points (magnitude on the Y axis and duration on the X axis) on the voltage tolerance envelop of the particular equipment. However, this simplified method neglects other characteristics of voltage sag, such as point of initiation, phase shift, and point of recovery—all of which may impact some load categories. Nevertheless, given the multitude of loads in a customer plant and a lack of accurate data on voltage sags at the point of load connection, a simplified load model is often sufficient to characterize the response of single-phase loads such as power supplies, computers, and programmable logic controllers (PLCs). This concept was utilized in the IVSI software to evaluate the sensitivity of equipment. Figure 3-1 shows this concept of evaluating sensitivity of equipment based on a rectangular voltage-tolerance envelops.

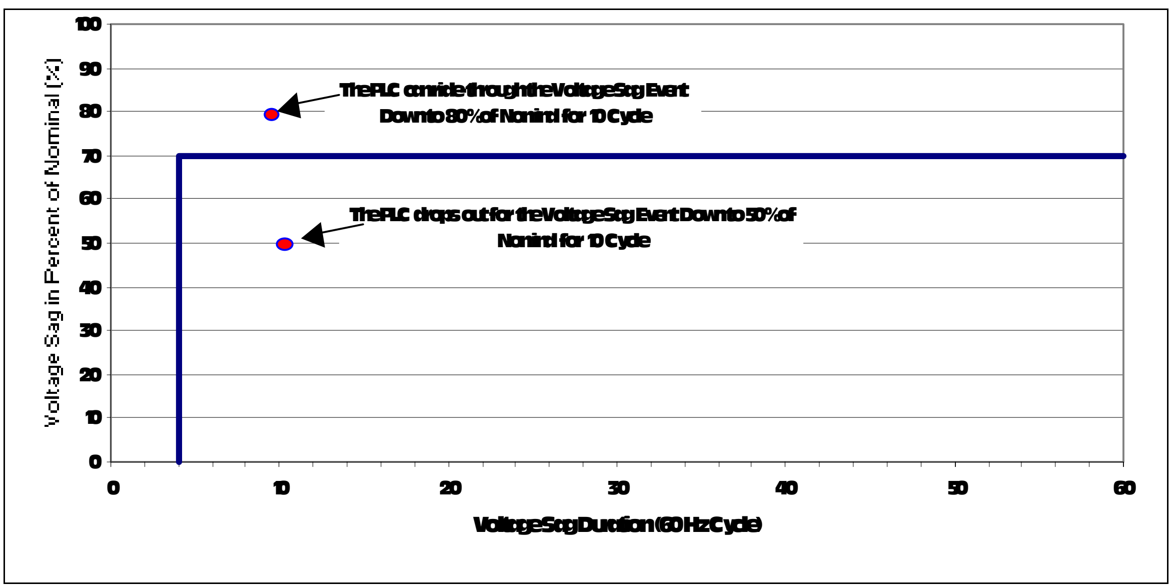


Figure 3-1
Static Model for Single-Phase Load for Evaluating Voltage-Sag Sensitivity

We will term this type of simplified load model as a static model. Although a static model for a single-phase load is easy to visualize and understand, for three-phase loads such as AC adjustable-speed drives (ASDs), a static model does not reveal how voltage sag on one, two, or three phases will impact the ASD. A static model of an ASD was developed later on in this chapter using a spreadsheet based approach to illustrate the importance of modeling three-phase loads for evaluating the sensitivity of these loads to voltage sags.

Voltage-Sag Sensitivity Model for Three-Phase AC Motor Drives

AC motor drives are among the most common power electronics-based industrial equipment. As shown in Figure 3-2, the typical AC drive has a three-stage topology; diode rectifier, DC link or bus (filtering), and a PWM (pulse width modulation) inverter. The drive normally supplies variable-frequency AC power to a three-phase induction motor. The AC drive has some energy storage in the DC link capacitor, and most use passive diodes on the "front end." AC drives are often touted as having better ride-through behavior than DC drives due to the energy storage.

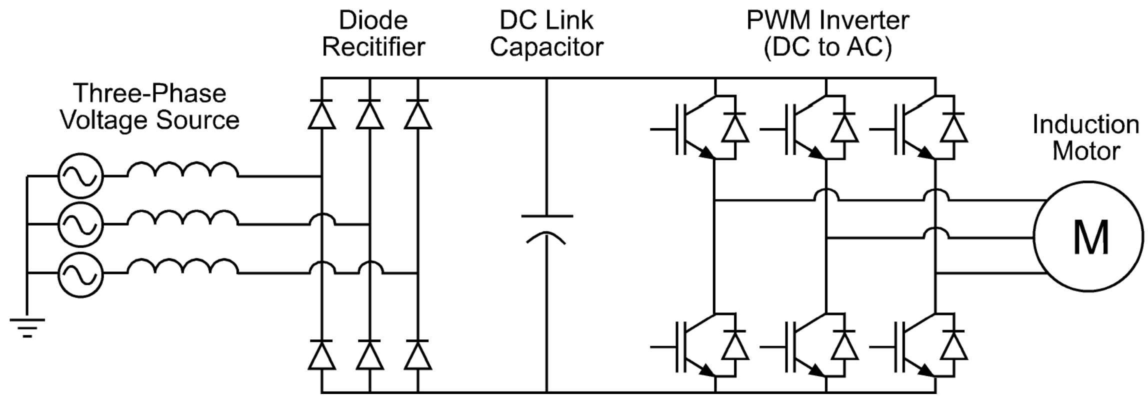


Figure 3-2
Simplified Schematic of AC Motor Drive

During normal operation, the diodes in the bridge rectifier are forward-biased symmetrically and in a uniform fashion from cycle to cycle. The current drawn by the rectifier section of an ASD typically has two pulses per half cycle, as shown in Figure 3-3. Each current pulse occurs for the short interval where the line voltage exceeds the voltage across the DC bus capacitor. Normally, the output voltage of the rectifier peaks six times per cycle, and the capacitor charges to the peak of the input line voltage, as shown in Figure 3-4. Between the six peaks, the diodes are not forward biased and the capacitor discharges slightly as energy is transferred from the capacitor through the inverter to the motor.

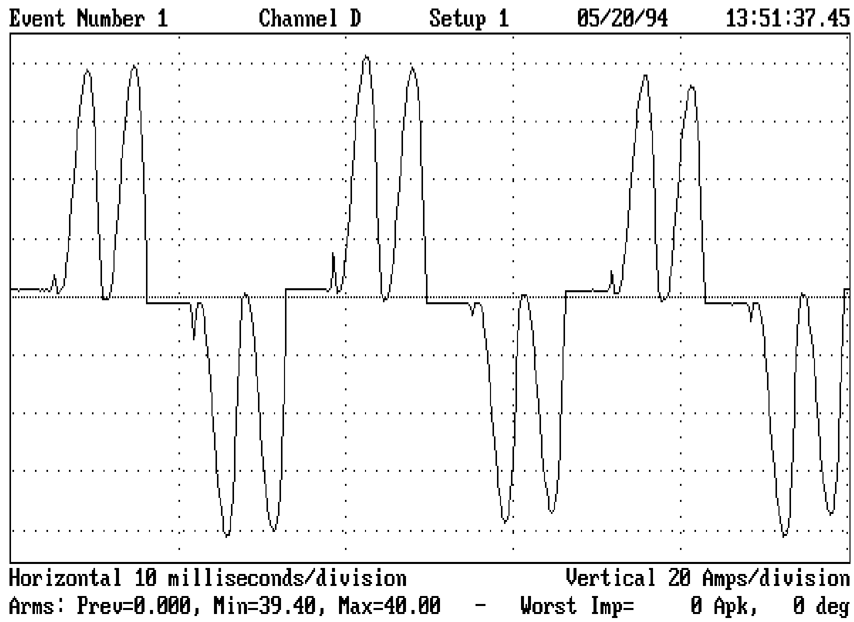


Figure 3-3
Input Line Current of AC Motor Drive during Normal Operation

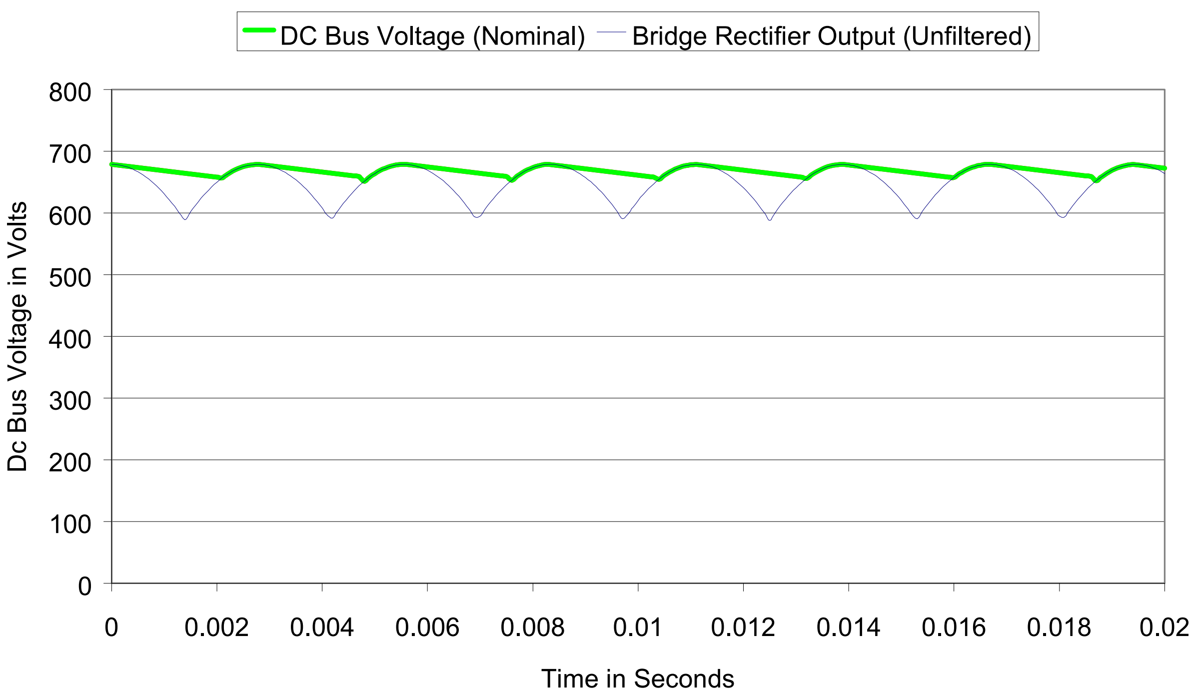


Figure 3-4
DC Bus Voltage during Normal Operation for an AC Motor Drive

During voltage sag, when voltage in one or more phases falls below the nominal voltage, the diodes are not forward biased in the normal symmetrical fashion. Instead, the peak voltage for one or more phases is often reduced below the nominal capacitor voltage. Hence, the diodes are not forward biased and no energy flows from the AC mains to the capacitor. The capacitor will continue to discharge until the next input voltage peak that is high enough to forward bias the diodes. During this discharge period, if the DC bus voltage falls below the under-voltage trip point of the AC Motor drive (typically 75 to 85% of the nominal DC bus voltage), a trip command is initiated. Depending on how the drive is programmed, it may trip or it may stop gating the inverter until the voltage returns to normal.

AC Motor Drive Model

The basic objective of a model of an AC motor drive is to evaluate the response of a three-phase bridge rectifier during voltage sags. For three-phase symmetrical voltage sags, determining the impact of DC voltage is trivial. This is because the DC bus voltage will simply follow the input AC voltage. For example, during a three-phase symmetrical voltage sag down to 60% of nominal voltage, the DC bus will also fall to 60% of nominal, which will trip the drive if 60% of nominal DC voltage is below the under-voltage trip point of the drive. However, for asymmetrical sags where all the three phase voltages are affected differently, determining how the DC bus voltage will be impacted is not as straightforward. To predict the DC bus voltage during asymmetrical sags, a simplified spreadsheet-based model for an AC motor drive was developed. Figure 3-5 shows the input screen for this simplified model.

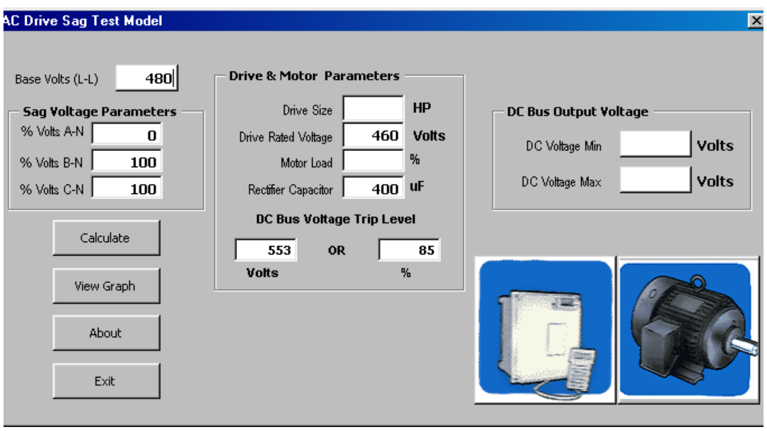


Figure 3-5
Input Screen for Simplified AC Drive Model

The following parameters are used as the input for modeling:

- Size of the AC motor drive in HP
- Rated input voltage (line-to-line)
- Percent loading
- Size of the DC bus capacitor in microfarads
- Under-voltage trip point

The inverter and motor section of the AC drive is modeled as a constant resistance that is calculated from the drive load. This simplified model is adequate to predict what the DC bus voltage will be during voltage sag. For the simplified model, the duration of the sag is neglected if the duration is sufficiently long enough for the DC bus voltage to reach the under-voltage trip point. This simplified assumption is valid if the duration of the voltage sag is several cycles or longer, which is usually the case.

The user inputs the sag depth for each phase (line-to-neutral voltage) and the drive parameters. The program calculates the DC bus under-voltage based on these input values. The simple example shown below illustrates the counterintuitive effect of asymmetrical voltage sags on AC drives.

Sample Cases with AC Drive Model

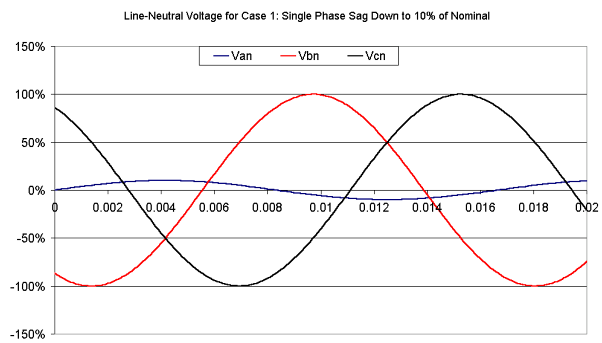
A 30-HP AC drive was modeled to evaluate the impact of three different voltage sags as shown below:

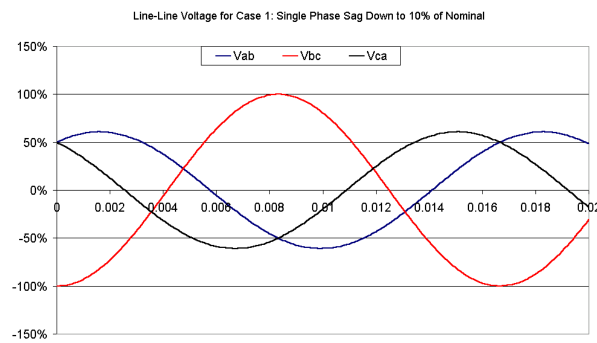
- Case 1: Single-phase sag down to 10% of nominal
- Case 2: Two-phase sag down to 65% of nominal
- Case 3: Three-phase sag down to 75% of nominal

The drive parameters are as follows:

- Drive Load: 60%
- DC Bus Capacitance: 2400 μF
- DC Bus Under-voltage Trip Point: 520 V

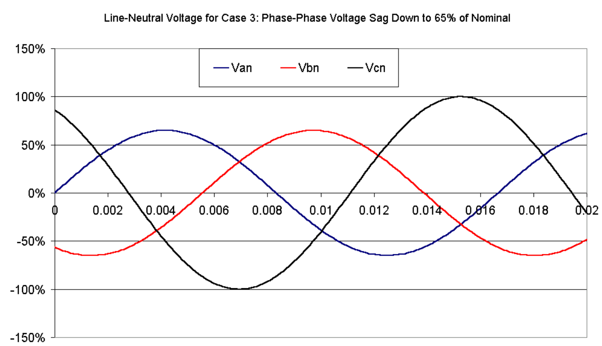
Figure 3-6 shows the line-to-neutral and line-to-line input for the three cases.

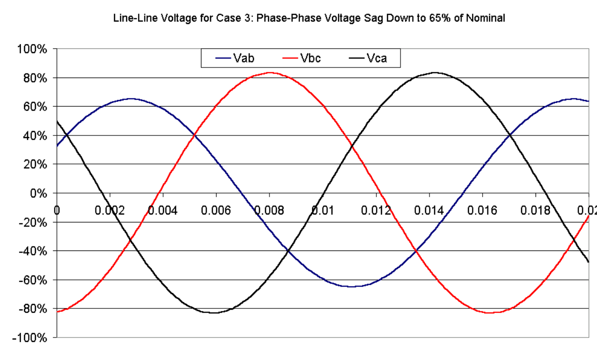




Line-to-Neutral **Line-to-Line**

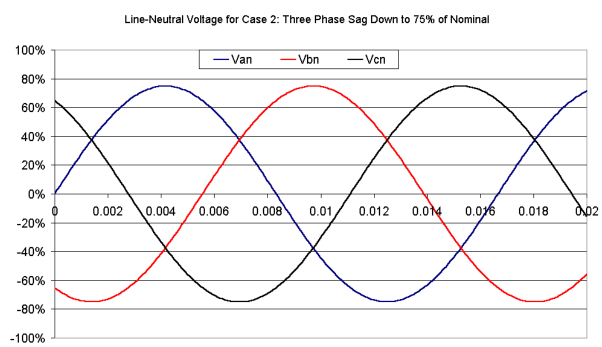
Case 1: Single-Phase Voltage Sag Down to 10% of Nominal Voltage

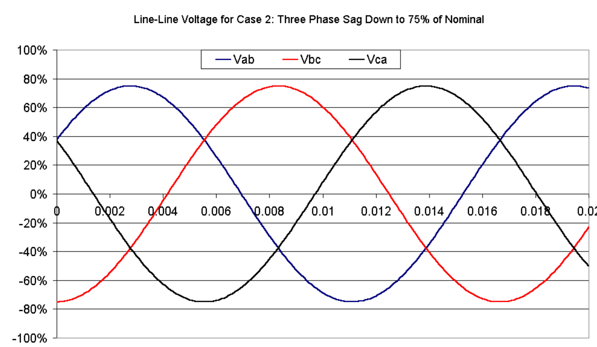




Line-to-Neutral **Line-to-Line**

Case 2: Two-Phase Voltage Sag Down to 65% of Nominal Voltage





Line-to-Neutral **Line-to-Line**

Case 3: Three-Phase Voltage Sag Down to 75% of Nominal Voltage

Figure 3-6
Line-to-Neutral and Line-to-Line Voltages for the Three Cases

Figure 3-7 shows the DC bus voltage during normal operation and during the three voltage-sag cases. Table 3-1 shows the DC bus voltage for the three cases.

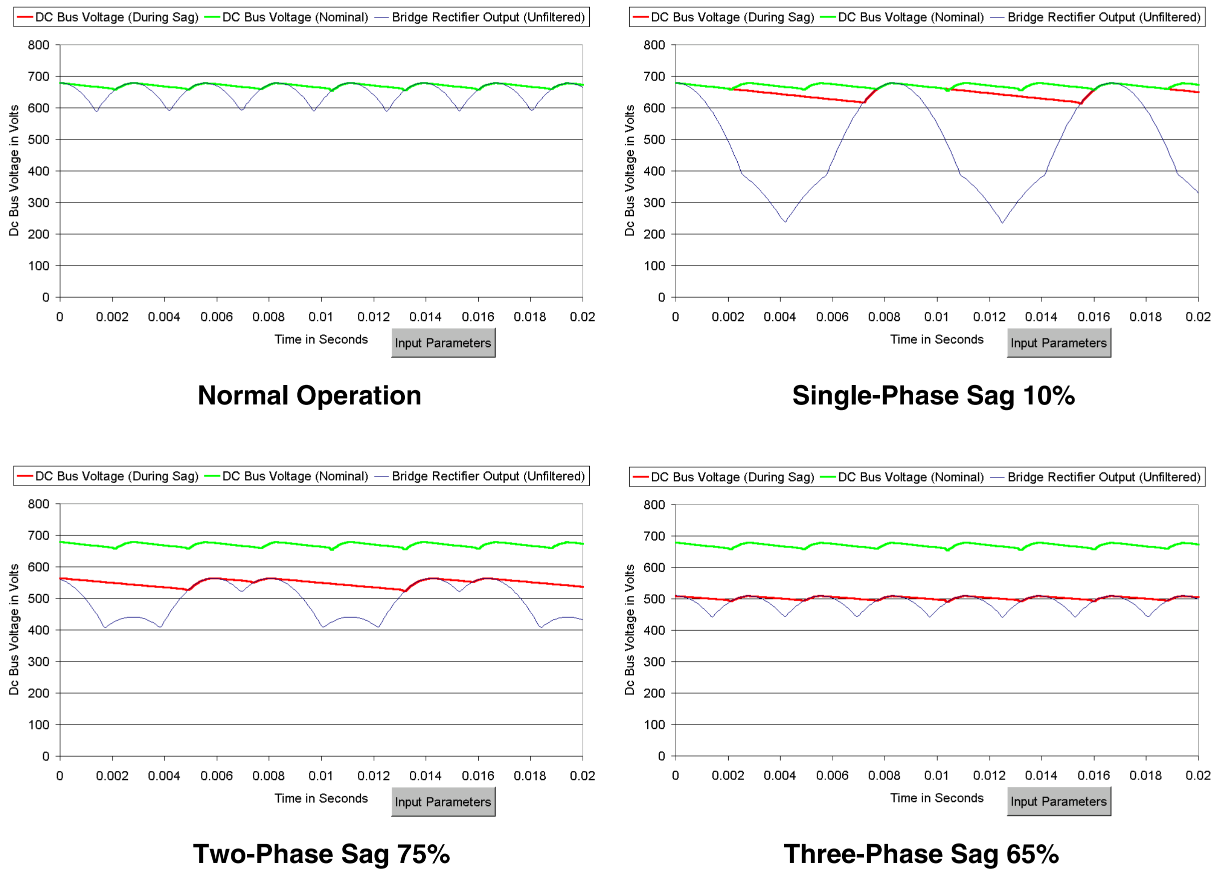


Figure 3-7
DC Bus Voltage during Normal Operation and the Three Cases of Voltage Sags

Table 3-1
Magnitude of Voltage Sag and DC Bus Voltage

	Line-to-Neutral Voltages					Line-to-Line Voltages					
	V_{an}	V_{bn}	V_{cn}	Min	Max	V_{ab}	V_{bc}	V_{ca}	Min	Max	DC Bus Voltage
Case 1	10%	100%	100%	10%	100%	58%	100%	58%	58%	100%	614 V
Case 2	65%	65%	100%	65%	100%	65%	83%	83%	65%	83%	524 V
Case 3	75%	75%	75%	75%	75%	75%	75%	75%	75%	75%	491 V

The table shows some unintuitive results. Based on the model, the drive trips only for case 3, which is the three-phase voltage sag down to 75% nominal, even though the single-phase and two-phase voltage sag appears to be more severe in terms of minimum voltage.

In almost all cases, three-phase voltage sags are represented in a two-dimensional voltage sag tolerance curve (see Figure 3-1) using the worst phase voltage as a representation of the event. Many power quality monitors will plot the worst phase voltage within a CBEMA/ITIC curve, as shown in Figure 3-8. Based on such a representation, the single-phase sag appears to be the most severe event, followed by the two-phase sag. The three-phase sag appears to be the least severe event. However, based on the AC drive model, the severity of the voltage sag as it relates to drive trips is completely the opposite, with the three-phase sag being the most severe, followed by the two-phase sag. The single-phase sag has the least effect on the drive. A careful evaluation of Table 3-1 reveals that the voltage-sag parameter that is directly correlated with the DC bus under-voltage is the maximum line-to-line voltage during the voltage sag.

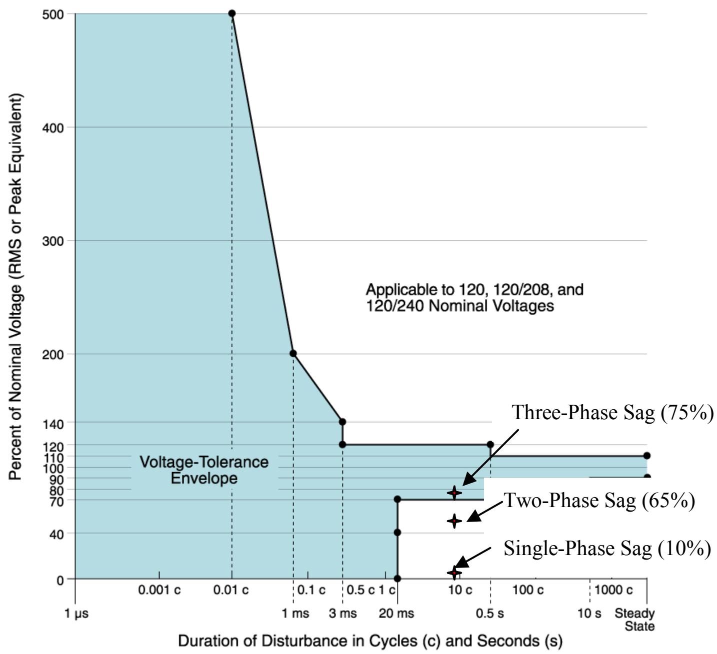


Figure 3-8
Voltage Sags Overlaid on the CBEMA/ITIC Curve

Dynamic Load Modeling for Voltage-Sag Evaluation

Single-phase control-circuit loads such as relays, contactors, and programmable logic controllers are often the most sensitive elements in a process. A static load model using a rectangular voltage-sag tolerance curve is a simplified method for determining the response of these loads to voltage sags. In the case of three-phase loads such as AC motor drives, a spreadsheet-based simplified model was developed and the results, as shown in the previous section, were able to predict the response of the AC drive to different types of voltage sag.

Directly connected induction motors, which represent the majority of customer loads, are, by themselves, not sensitive to voltage sags. Motor starters and other motor-control elements are usually the weakest links. Once these weak links are protected, the next step is to evaluate how the motor and its connected load will respond to voltage sags. When providing protection for motor-control circuits, end users often wonder whether the process will be able to tolerate the speed-torque variation of the motor during voltage sags. Protection of the motor itself is sometimes a cause for concern when contactors are held too long with a protection device or a high-speed bus transfer is used to reconnect the motor to an alternate source. Addressing these concerns requires a dynamic model for a motor and its connected load. In addition to induction motors, dynamic modeling of synchronous motors, AC motor drives, and DC motor drives are also useful in evaluating the impact of voltage sags with a variety of different customer load types.

One of the difficulties in dynamic load modeling is the lack of credible data representing the dynamics of the load. For example, in order to evaluate the impact of voltage sags on induction motors, it is not sufficient just to know the motor parameters for the model. An important part is to model the load dynamics accurately. Load inertia and load torque response are important parts of a dynamic load model.

A dynamic model for AC motor drives is also required to evaluate the impact of different solution strategies such as kinetic buffering, synchronous restart, and time delay. These ride-through solutions are often part of the drive programming parameter. For example, when the DC bus under-voltage of a drive reaches the under-voltage trip point during voltage sag, depending on the way a drive is programmed, its response could be different. In the simplest form, the drive will trip and will require a manual restart. However, a drive can also be programmed to stop gating the inverter after the DC bus under-voltage threshold has been reached and let the motor coast down until voltage recovers. When the voltage recovers, the drive can also be programmed to synchronously reconnect to a spinning motor, thereby minimizing the transients caused by such a reconnection. A dynamic model of an AC motor drive will allow the user to simulate such conditions in order to evaluate whether ride-through options will be feasible for the particular process that is driven by the AC motor drive.

4
FUTURE WORK

This report outlines the framework of a unified software tool that will combine the functionality of power quality assessment and dynamic load response at the point of load connection inside a customer facility. A companion EPRI report titled, *Assessing Power Quality Levels from a Limited Set of Monitoring Data: Proof of Concept for Sag Transformation Modeling* (1005929), describes the proof of concept for a voltage-sag transformation method and the verification of the method using field data and Electromagnetic Transient Program (EMTP) simulation.

The next steps will be to integrate these functionalities into the Power Quality Diagnostic System (PQDS) as a voltage-sag evaluation module. Key characteristics of this module will include:

- Capability to create generic industry-specific one-line diagrams by calling database libraries that store general electrical power networks.
- Support user-defined data (system) transfer to the pre-existing one-line diagrams and the user could revoke the voltage sag transformation module to re-calculate voltage sags at a customer's facility based on this update. This will allow maximum information retrieval with minimal user effort.
- Capability to import various network data files from PSS/E, ASPEN, CAPE, and so on.
- Allow users to perform "what if" scenarios to evaluating different mitigation techniques.
- Ability to calculate and graphically synthesize plots of power quality measurements such as voltage-sag measurements with the voltage sag sensitivity curves of the end-use device, including CBEMA curves.
- Capability to maintain a database library of sensitivity curves of commercially available single-phase loads critical to industrial processes such as PLCs, ASDs, relays, and contactors—for example, the database that has been developed through system compatibility tests at EPRI PEAC Corporation.
- Ability to maintain what might be called a global library of sag-tolerance curves for different categories of process equipment as well as different manufacturing brands will allow the user to identify the exact process equipment that is being used.
- Capability to generate single-phase as well as three-phase dynamic models, thereby providing a full functionality to analyze modern digital controllers such as adjustable-speed drives, induction motors, and DC drives.

A voltage-sag evaluation module will allow utilities to take the next step to the Industrial Voltage Sag Investigator (IVSI) by incorporating some basic functionality of voltage-sag transformation and three-phase static and dynamic load modeling for voltage-sag impact assessment.

5 REFERENCES

1. M. F. McGranaghan, D. R. Mueller, M. J. Samotyj, "Voltage Sags in Industrial Systems," *IEEE Transactions on Industry Applications*, Vol 29, No. 2, March/April 1993.

2. EPRI OIN-12114 Product Code: 100761, EPRI Reliability Benchmarking Application Guide for Utility/Customer PQ Indices, September 1999.

3. EPRI TR-1000408, Transmission Power Quality Benchmarking Methodology, December 2000.

4. EPRI TR-107938, Reliability Benchmarking Methodology, May 1997.

5. EPRI TR-106294-V2, An Assessment of Distribution System Power Quality; Volume 2: Statistical Summary Report, May 1996.

6. EPRI TR-1005929, Assessing Power Quality Levels from a Limited Set of Monitoring Data: Proof of Concept for Sag Transformation Modeling, December 2001.

7. EPRI TR-114115-CD, Industrial Voltage Sag Investigator (IVSI), December 1999.

Target:
Power Quality Measurements and Testing

About EPRI

EPRI creates science and technology solutions for the global energy and energy services industry. U.S. electric utilities established the Electric Power Research Institute in 1973 as a nonprofit research consortium for the benefit of utility members, their customers, and society. Now known simply as EPRI, the company provides a wide range of innovative products and services to more than 1000 energy-related organizations in 40 countries. EPRI's multidisciplinary team of scientists and engineers draws on a worldwide network of technical and business expertise to help solve today's toughest energy and environmental problems.

EPRI. Electrify the World

Printed on recycled paper in the United States of America

1005928

EPRI • 3412 Hillview Avenue, Palo Alto, California 94304 • PO Box 10412, Palo Alto, California 94303 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com