Diagnostic Tool for the Evaluation of Power Quality Events Related to Utility Capacitor Switching

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Abstract – **The Power Quality Diagnostic System is a complete system of tools designed to help engineers and technicians develop solutions for power quality problems. Individual modules perform the major functions and an investigation processor directs the user to modules required for a particular problem or investigation. The Capacitor Switching Simulator calculates voltage magnification at lower voltage buses and determines the probability of nuisance tripping of an adjustable-speed drive. The simulator also evaluates transients and mitigation options associated with capacitor switching on both transmission and distribution systems. This paper will present the modeling, simulation, and application aspects of the Capacitor Switching Simulator.**

Keywords: power quality, diagnostic tools, capacitor switching, voltage magnification, nuisance tripping.

I. INTRODUCTION

Power quality problems experienced by electric utility customers can be caused by events and conditions on the power system or within customer facilities. Even though many of the problems are related to wiring practices, grounding, and operating procedures within the customer facility, the utility is often called on to help solve these problems and, as a minimum, has the burden of showing that the problems are not caused by the supply system. In preparation for increased competition, utilities are reducing manpower to operate as efficiently as possible. Power quality investigations will continue to be very important, but there will also be significant emphasis on identifying and utilizing tools that improve the efficiency of the people performing the investigations. Tools that provide training, help automate investigations, and assist with reporting functions, will be in great demand.

A. The Power Quality Diagnostic System

The Power Quality Diagnostic System (PQDS) incorporates capabilities for collecting data from measurement equipment, processing the data, managing the database, automatically characterizing events using waveform recognition technology, maintaining libraries of example cases, analyzing problems using simulation tools to verify causes and develop possible technical solutions, analyzing the economics of problems and solutions to identify optimum solutions, and automatically writing reports to document the results.

The system is built in a modular fashion for expandability and flexibility. Individual modules are used for the major functions and a Power Quality Case Study Investigation Processor directs the user to the modules that are required for a particular problem or investigation. Both the Case Study Investigation Processor and the analysis modules use a variety of databases to store and retrieve the information needed to analyze and solve problems.

B. PQDS Modules

The system consists of the following modules in addition to the overall investigation processor.

- **Measurement Module:** This module integrates data collection from various types of monitoring equipment. It includes modules for putting the data in a standard format (PQDIF) and maintaining the data in a complete measurements database. Different modules can be used directly to automate all data collection and processing tasks.
- **Event Identification Module:** This module includes automated procedures for providing an initial assessment of the probable cause and impact of a power quality variation. The module incorporates advanced waveform recognition technology based on neural networks.
- **Economic Assessment Module:** This module evaluates the economics of different power quality improvement options using a system perspective. It interfaces with more extensive databases of power quality costs by customer and equipment type and databases of power quality solutions costs and effectiveness.
- **Analysis and Simulation Module:** This module includes a library of basic applications for analyzing specific PQ concerns and interfaces to more advanced analysis tools that may be required. These applications can analyze harmonics, capacitor switching, lightning surges, motor starting and voltage sag concerns.

B. PQDS Databases

The system requires a variety of different databases to provide full support for power quality investigations. The specific databases in the diagnostic system include the following:

- **Investigation Database:** This database contains the status of each step in the investigation, and it links to other databases. It also holds the "investigation templates" which will define the process of various types of investigations – site surveys, monitoring projects, etc.
- **Measurement Database:** This database contains the actual monitoring results for ongoing monitoring projects and specific investigations that require monitoring. This database consists of both raw measurement data and characterized data that can be the basis of statistical reports, summary reports, and system performance analysis.
- **PQ Case Study Database:** This database, which was developed prior to the diagnostic system, includes case studies, test data, and DPQ (Distribution Power Quality Project) summary reports. It provides the reference information needed to characterize a power quality problem, identify possible solutions, and document the case study with a report.
- **PQ Costs Database:** This is a summary database that can be developed from the overall case study database. It reflects typical costs of different PQ problems by customer type and equipment type. The Economic Assessment Module uses this database.
- **PQ Solutions Database:** Solutions to PQ problems can vary from protection at individual pieces of equipment to modifications on the overall power system. This database describes power conditioning equipment technologies, applications, and costs, and it can also be extracted from the overall case studies database. It is used directly by the Economic Assessment Module.

II. THE ANALYSIS AND SIMULATION MODULE

The Analysis and Simulation Module incorporates a two-tier approach to the study of power quality problems. The module includes a set of simplified and easy-to-use analytical applications for use in evaluating specific power quality problems. In addition, the module provides support for performing detailed simulations using the Electromagnetic Transients Program (EMTP) or harmonic analysis tools such as HarmFlo+ and SuperHarm. Figure 1 illustrates the opening window for the Analysis and Simulation Module.

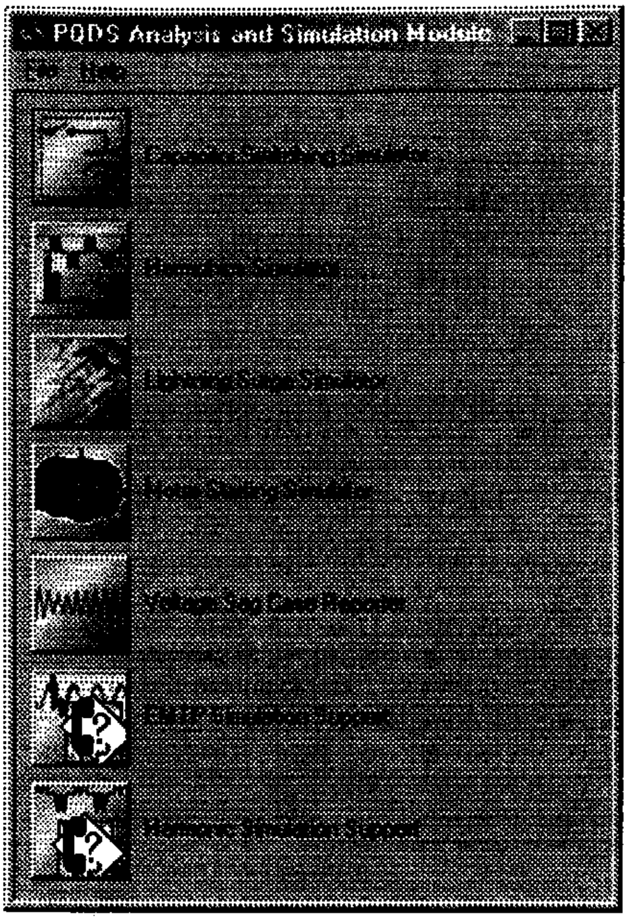

Fig. 1. Analysis and Simulation Module

The analysis applications offer a crucial advantage to users in that they require a minimal amount of system data for performing evaluations. The module's structure was designed to allow for the inclusion of additional analysis applications as demand for them arises. Currently, the Analysis and Simulation Module includes the following applications:

- Capacitor Switching Simulator
- Harmonics Simulator.
- Lightning Surge Simulator
- Motor Starting Simulator
- Voltage Sag Case Reporter
- EMTP Simulation Support
- Harmonic Simulation Support

III. THE CAPACITOR SWITCHING SIMULATOR

This simulator calculates voltage magnification at low voltage buses and helps determine the probability of nuisance tripping of an adjustable-speed drive. The simulator can evaluate transients associated with capacitor switching on both the utility transmission and distribution systems. Figure 2 illustrates the oneline-based visualization window.

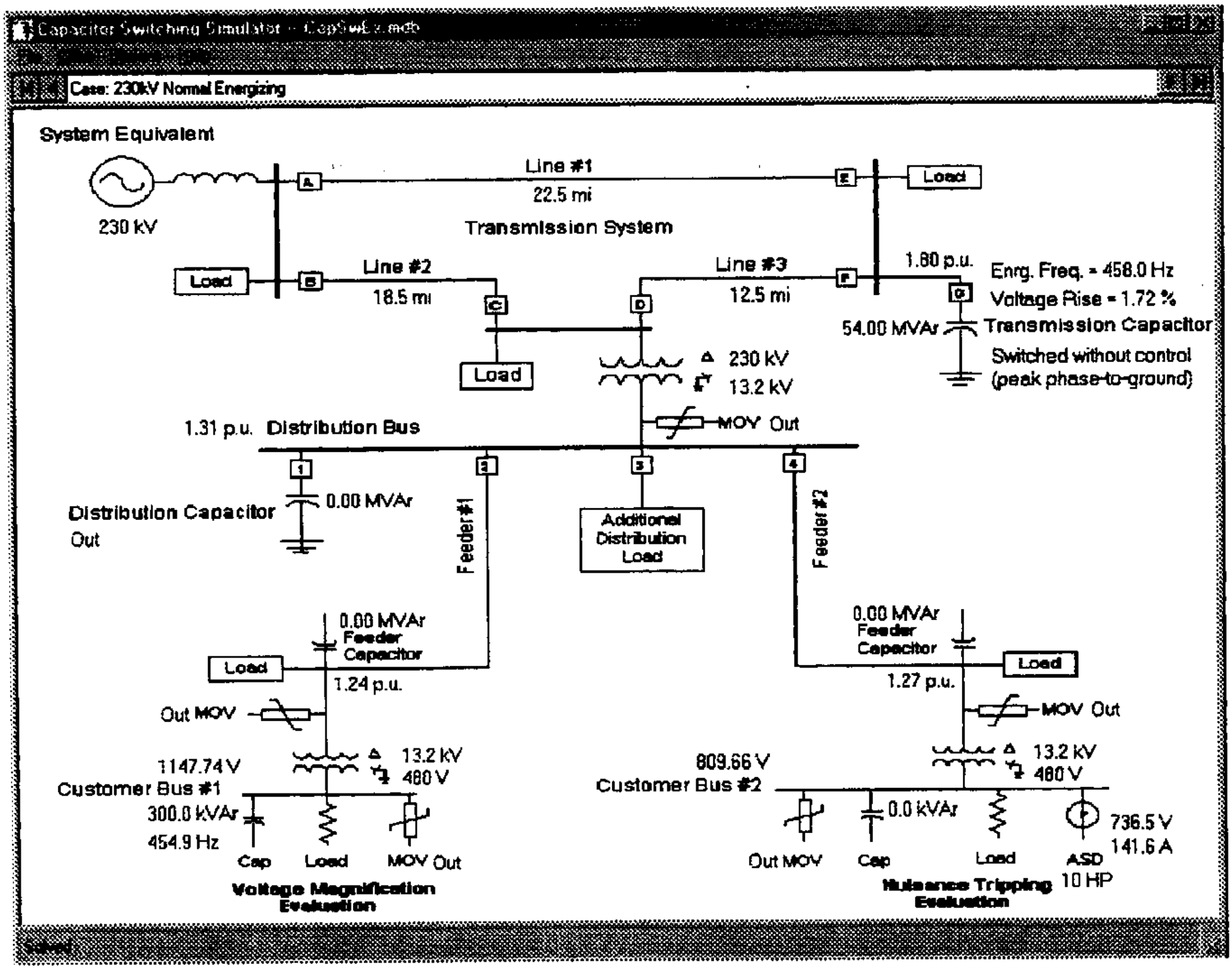

Fig. 2. One-line View of the Capacitor Switching Simulator

The Capacitor Switching Simulator provides the means to characterize the utility capacitor energizing transient using a time-domain simulation method. Mitigation options are available for user simulation and evaluation, and detailed reports provide simulation results and related information in a concise format.

A. Effect of Utility Capacitor Switching on Power Quality

The application of utility capacitor banks has long been accepted as a necessary step in the efficient design of utility power systems. Capacitor switching is generally considered a normal operation for a utility system and the transients associated with these operations are generally not a problem for utility equipment. These low frequency transients, however, can be magnified in a customer facility (if the customer has low voltage power factor correction capacitors) or result in nuisance tripping of power electronic based devices, such as adjustable-speed drives (ASDs). Capacitor energizing is just one of the many switching events that can cause transients on a utility system. However, due to their regularity and impact on power system equipment, they often receive special consideration.

B. The Capacitor Energizing Transient

Energizing a utility shunt capacitor bank from a predominantly inductive source results in an oscillatory transient that can approach twice the normal system peak voltage (V_{pk}). Because capacitor voltage cannot change instantaneously, energization of a capacitor bank results in an immediate drop in system voltage toward zero, followed by an oscillating transient voltage superimposed on the fundamental frequency (e.g. 60 Hz) waveform. The peak voltage magnitude depends on the instantaneous system voltage at the instant of energization, and can reach 2.0 times the normal system voltage (V_{pk} – in per-unit - pu) under worst-case conditions. The voltage surge is at the same frequency as the inrush current (I_{pk}) and rapidly decays to the system voltage.

For a practical capacitor energization without trapped charge, system losses, loads, and other system capacitances cause the transient magnitude to be less than the theoretical 2.0 pu. Typical magnitude levels range from 1.2 to 1.8 pu and typical transient frequencies generally fall in the range from 300 to 1000 Hz. Figure 3 illustrates an example (measured) distribution system capacitor energizing transient.

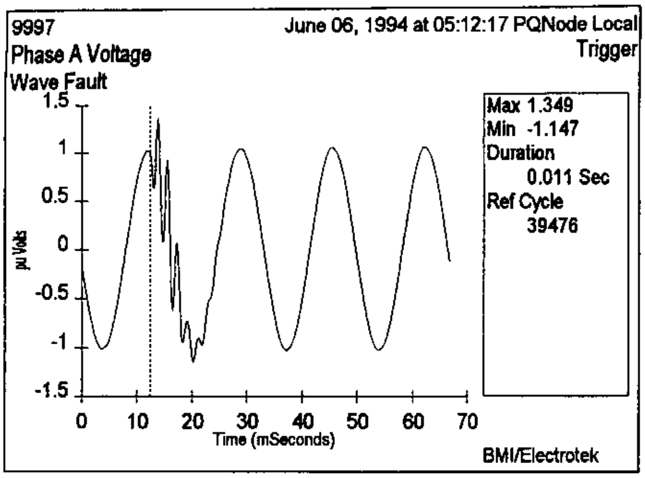

Fig. 3. Typical Distribution Bus Voltage during Capacitor Energizing

C. Evaluations Using the Capacitor Switching Simulator

The solution engine utilizes a time domain method similar to the Electromagnetic Transients Program (EMTP). Extensive data validation is completed to assure accurate and reasonable simulation results. Utility transmission and distribution capacitor energizing transients are simulated via a user-defined switching sequence and mitigation selection. Sample data cases provide typical system and equipment parameters in each of the available voltage classes.

The potential for voltage magnification and nuisance tripping is evaluated at two low voltage buses (refer to Figure 2). Modeling capabilities (Figure 4) include the following:

- variable source strength and transmission line lengths
- variable T&D system load levels
- variable transmission capacitor bank rating and switching preference
- variable distribution capacitor bank rating and switching preference
- variable feeder lengths, loading and capacitors
- variable secondary configurations (including load and compensation levels)
- distribution and customer MOV arrester status
- variable adjustable-speed drive parameters

Transmission and distribution capacitor switching options include the following:

- normal energizing (switched without control at system peak voltage)
- energizing with a pre-insertion device (user-defined value)
- energizing with synchronous closing control (user-defined timing error)
- energizing with user-specified switching times

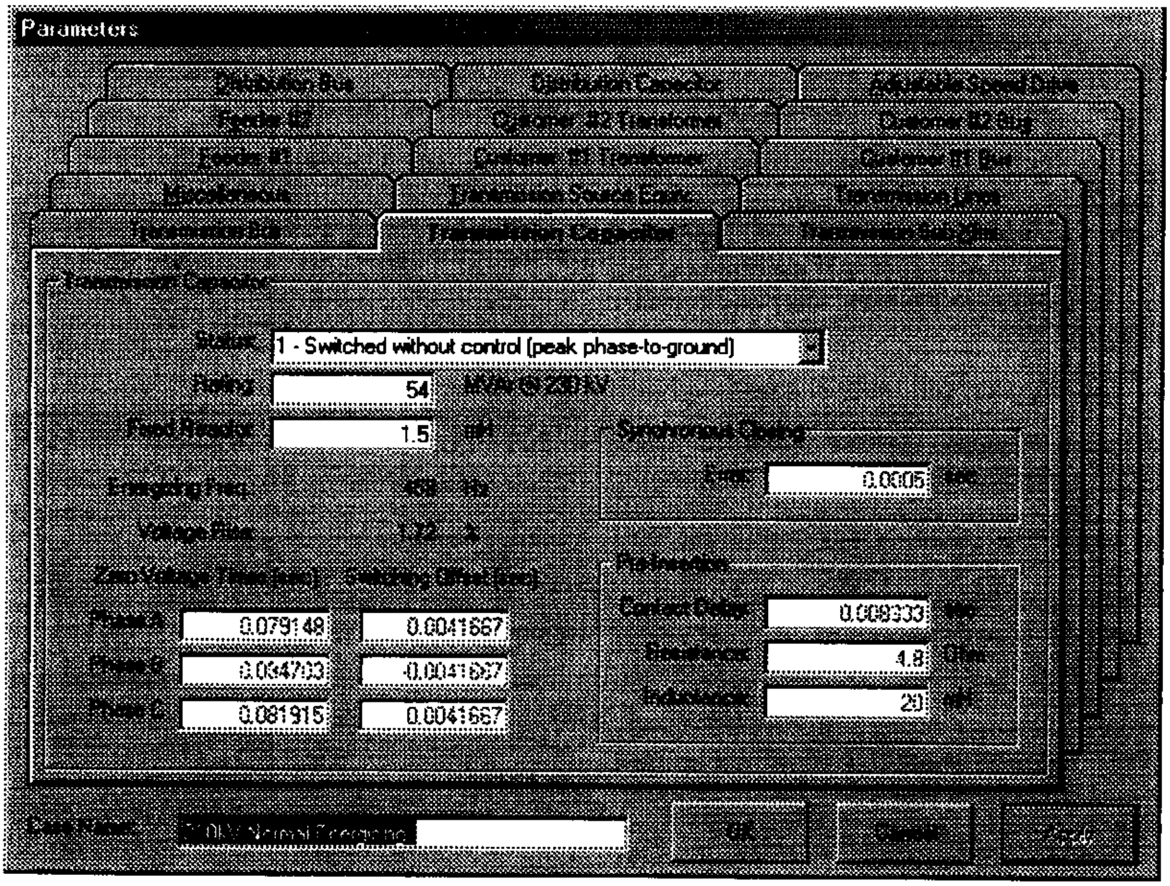

Fig. 4. Setting Capacitor Switching Simulator (Transmission Capacitor) Parameters

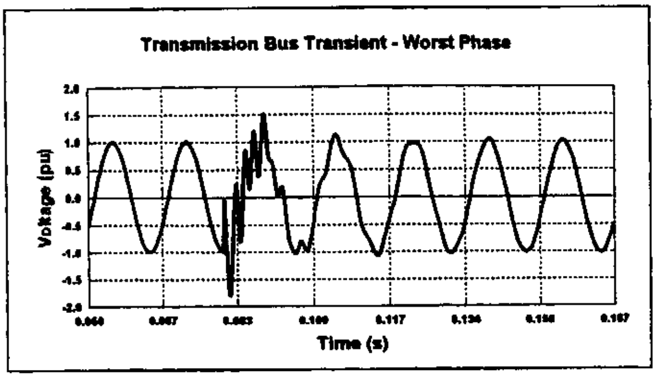

Fig. 5. Example Simulation Results – Waveform Data

Power quality mitigation options include the following:

- energizing the capacitor bank using a pre-insertion device
- energizing the capacitor bank using synchronous closing control
- distribution and customer MOV arresters
- harmonic filters (reduce voltage magnification [2])
- ac choke (on the ASD)

Output options for the Capacitor Switching Simulator include tabular data for transient overvoltages and arrester duties and graphical waveforms illustrating worst-case quantities. Figure 5 illustrates an example simulation waveform for energization of a transmission capacitor bank without any overvoltage control selected.

D. Example Evaluation

The following example is used to illustrate the usage of the Capacitor Switching Simulator for evaluating the impact of energizing a 7.2 MVAr capacitor bank at the 13.2kV distribution substation, as illustrated in Figure 2. Figure 6 shows the resulting transient voltage waveform at the 13.2kV bus.

Primary power quality concerns evaluated in the example include voltage magnification (480V bus #1) and nuisance tripping of a 10 HP adjustable-speed drive (480V bus #2).

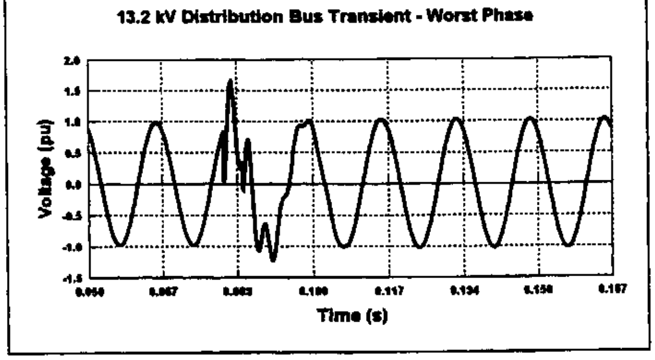

Fig. 6. 13.2kV Bus Voltage – Energize 7.2 MVAr Bank

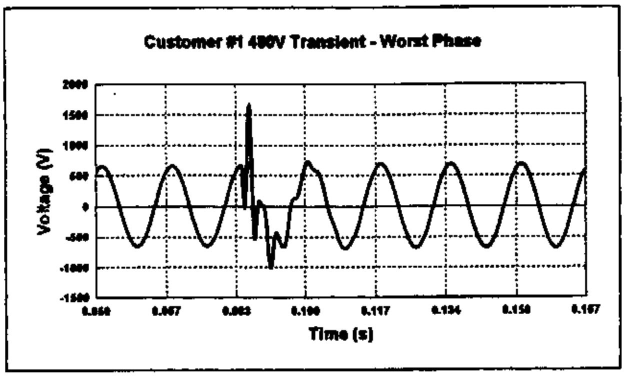

Fig. 7. 480V Bus #1 – Energize 7.2 MVAr Bank

Voltage magnification [2] occurs when the transient oscillation initiated by the energization of a utility (transmission or distribution) capacitor bank, excites a series resonance formed by the low voltage system. The result is a higher transient overvoltage at the lower voltage bus. Computer simulations and in-plant measurements have indicated that magnified transients between 2.0 and 4.0 per-unit are possible over a wide range of low voltage capacitor sizes. Typically, the transient overvoltages will simply damage low-energy protective devices (MOVs) or cause a nuisance trip of a power electronic device. Figure 7 shows the resulting transient voltage at the 480V bus with a 300kVAr power factor correction capacitor in service.

Nuisance tripping [1] refers to the undesired shutdown of an adjustable-speed drive (or other power electronic process device) due to the transient overvoltage on the device's dc bus (or ac control signal voltage). The nuisance tripping event consists of an overvoltage trip due to a dc bus overvoltage on voltage-source inverter drives (pulse-width modulated — PWM). Typically, for the protection of the dc capacitor and inverter components, the dc bus voltage is monitored and the drive tripped when it exceeds a preset level. This level is typically around 780 volts (for 480 volt applications), which is only 120% of the nominal dc voltage. It is important to note that nuisance tripping can occur even if the customer does not have power factor correction capacitors. Figure 8 shows the resulting transient voltage on the dc bus of a typical 10 HP adjustable-speed drive (diode-bridge front-end).

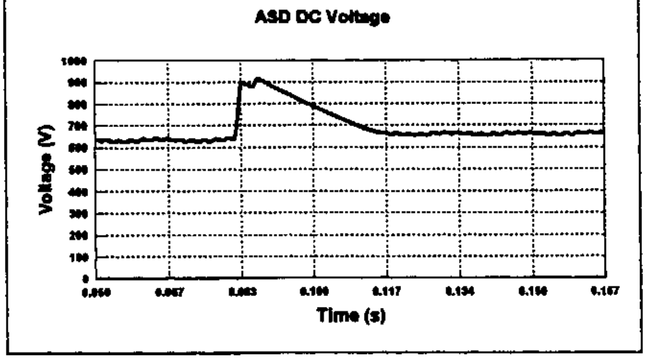

Fig. 8. 10 HP ASD dc Bus – Energize 7.2 MVAr Bank

Table. 1. Results Summary for Example Case

Case / Description	13.2kV Bus	480V Bus #1	ASD dc Bus
1. Energize 7.2 MVAr *with no control*	1.65 pu	2.44 pu	915 V
2. Energize 7.2 MVAr *using a 6.4Ω pre-insertion resistor*	1.15 pu	1.37 pu	721 V

The mitigation option selected for the example consists of 6.4Ω pre-insertion resistor on the 13.2kV capacitor switch. A pre-insertion impedance (resistor or inductor) provides a means for reducing the transient currents and voltages associated with the energization of a shunt capacitor bank. The impedance is "shorted-out" (bypassed) shortly after the initial transient dissipates, thereby producing a second transient event. The insertion transient typically lasts for less than one cycle of the system frequency. The performance of pre-insertion impedance is evaluated using both the insertion and bypass transient magnitudes, as well as the capability to dissipate the energy associated with the event, and repeat the event on a regular basis. The optimum resistor value for controlling capacitor energizing transients depends primarily on the capacitor size and the source strength. Table 1 summarizes the study results for the basecase and mitigation option.

IV. CONCLUSIONS

- The Power Quality Diagnostic System provides a number of benefits for electric utility engineers that deal with customer power quality problems. Primary benefits include reduced training, investigation, and reporting/documentation times.
- Investigation time for power quality problems is minimized by automatically collecting and processing measurement results, using analytical tools to verify the cause of disturbances, using a database of previous research to identify possible solutions, determining the optimum solution based on overall system economics, and then automatically generating a report.
- All power quality investigations are documented in a consistent manner and are available for future reference.
- Typical utility system capacitor energizing overvoltages range from 1.1 to 1.8 per-unit, last less than ½ cycle, and have a principle frequency of between 300 - 1000 Hz. In general, the more severe events are associated with the switching of larger substation banks. Also, the transient overvoltages associated with normal energizing are generally not a concern to the utility since peak magnitudes are just below arrester protective levels.

V. REFERENCES

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VI. BIOGRAPHIES

Lee King is a Power Systems Engineer at Electrotek Concepts, Inc., in Knoxville, Tennessee. He provides engineering and software support for power quality projects. Before joining Electrotek, Lee was a project manager at Advanced Control Systems, a power systems engineer at Harris Controls (now GE-Harris), and a cooperative education student at Alabama Power Company. Lee received a B.E.E. degree from Auburn University and an M.S.E.E. degree from the University of South Florida.

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Siddharth C. Bhatt, received the Ph.D degree in physics from Rensselaer Polytechnic Institute, Troy, NY, in 1972. He was a principal engineer in design, simulation, and computer products for 13 years with General Electric. He spent two years with Litton Industries in electronic warfare simulation and diagnostics systems. He is currently with EPRI managing various R&D projects involving power quality systems, power quality and load signature analysis, advanced power quality monitoring projects using advanced technologies such as wavelets, artificial neural networks, and expert systems.