Visualizing Power System Operations in an Open Market

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The electric utility industry is undergoing a very turbulent period. In many parts of the world there is a myriad of rapid and deeply impacting changes that are resulting in a revamping of the way power systems operate and the way power industry players are structured. These changes have created an unprecedented need within both the unregulated and regulated sectors of the industry, including the regulatory agencies and legislative circles, to understand how power and transmission systems operate. This need has become particularly critical given the entry of many new players (independent power producers, financial traders, brokers/marketers, and public policy makers) into the industry. These people, many of whom lack technical training or experience, must become knowledgeable of the various aspects of system operations in general, and with system reliability and security in particular. The new players, as well as the existing ones, must understand sufficiently well how specific generation decisions and wheeling arrangements affect system operations, and subsequently the utility customers. The same holds for evaluating regulatory and legislative initiatives and the measures being proposed.

All players must understand how specific generation decisions, wheeling arrangements, and legislative initiatives affect system operations

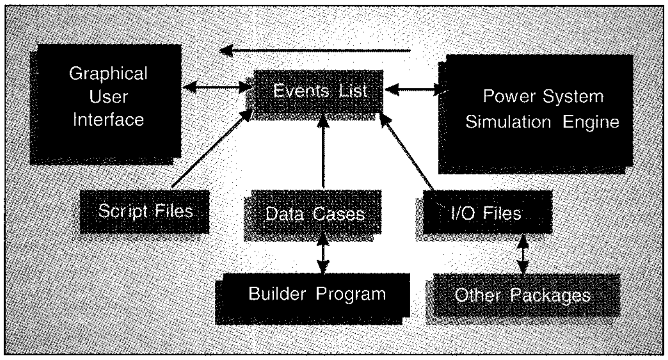

Figure 1. Modular structure and information flow

This article features PowerWorld, a comprehensive power system simulation package developed to help meet this need. The package differs from an operator training simulator (OTS), which is used in many energy management systems. The OTS is designed to replicate the behavior of a given power system, especially during emergencies, to provide the detailed training needed by those involved in the minute-to-minute operation of an actual system. The package featured in this article is designed for the many new players in the power industry who will never operate an actual system but who must have a basic understanding of its operations.

The package, which runs in the Microsoft Windows environment, is user friendly, interactive, and menu driven. It effectively uses visualization techniques to present the basics of power system operations and control simply, yet also with a level of detail to accurately model large-scale systems realistically and with the appropriate level of fidelity. The package has been demonstrated to policy makers, legislative analysts, small and large utilities, and regulatory decision makers both nationally and internationally. It has been found to be a very effective tool for communicating the many technical and economic impacts of third-party access.

Simulation Features

The basic objectives in the development of the simulation were to reproduce with good fidelity power system operations in the range of timeframes associated with many of the issues involved in open access transmission, to be easy to use, and to provide effective visualization capability suitable for presentations as well as individual studies.

The package simulates the operation of a multiarea power system over a specified period of time, typically from several hours to several days. The simulation runs at a rate proportional to actual time, but because of the need to reproduce some of the longer time frame transmission system concepts, this rate is usually consider-

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ISSN 0895-0156/97/$10.00©1997IEEE

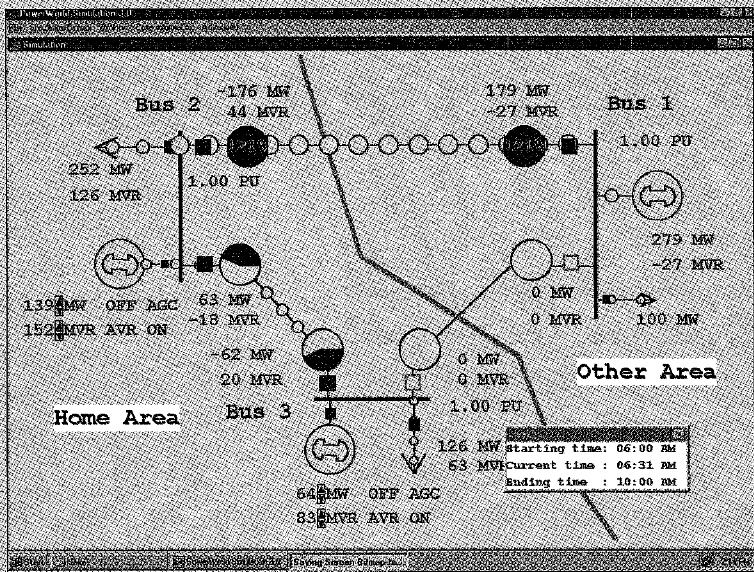

Figure 2. Three bus system one-line diagram

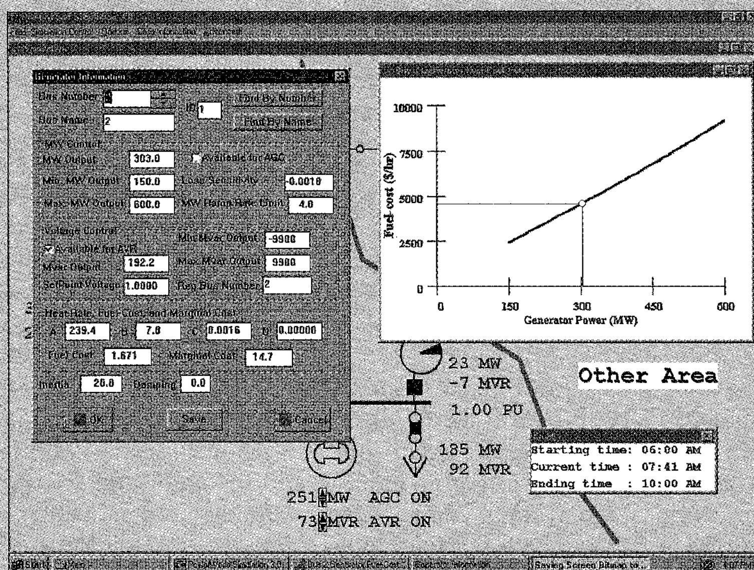

Figure 3. Dialog box for the generator at bus 2 for the system of Figure 2

ably faster than actual time. The simulation reproduces the various continuous and/or discrete events that affect a power system such as continuous load variations and sudden loss of a transmission line. A user-friendly graphical user interface (GUI) allows easy interaction with the system. The GUI enables the user to obtain an intuitive feel for system operations by understanding:

- Basic concepts of real and reactive power flows in an interconnected power system
- Power flow effects of system control actions, such as changing generator megawatt (MW) output or a voltage setpoint
- Power flow effects of modifying a tap of a load top changing (LTC) transformer or an angle of a phase shifting transformer
- Central ideas of a control area including the notions of area control error (ACE) and automatic generation control (AGC)
- Economic dispatch of a set of generating sources
- Power transactions between adjacent and nonadjacent control areas
- Implementation of wheeling
- Nature and role of ancillary services.

The highly flexible package uses a modular structure. Figure 1 shows a representation of the information flow between the main modules of the package. The modular structure allows the addition of new modules and external programs in a straightforward manner.

System Displays

The main interaction between the user and the simulation is through the GUI. The GUI presents novice users with the information they need, and provides easy access for advanced users to additional detailed information. Thus the GUI is instrumental in allowing users to gain an intuitive feel of power system operation, rather than just learning how to use the package. The majority of illustrations in this article reproduce various system displays.

The most important part of the GUI is the one-line diagram window. Figure 2 reproduces the one-line diagram for a three-bus, two-area system. Graphical symbols are used to represent standard power system equipment, such as buses, generators, capacitors, transformers and transmission lines. Multi-colored symbols and numbers are used to display values of various variables. For example, numeric values are used to show the bus voltages and loads, while pie charts are used to show the percentage line loading. In addition, background text and graphical displays may be placed on the one-line diagram. For example, in Figure 2, two operating areas are indicated, with the magenta line showing their boundary. The circles on the transmission lines, loads and generators are animated, and their movement indicates flows with their size and direction representing the magnitude and direction of the power flow.

In simulation mode, all windows are continuously updated with bitmap copies providing a "smooth" animation. The display update rate depends upon the computer's speed, the size of the simulation case, and the number of windows shown. Using a PC with a Pentium processor and 1024-by-768 display resolution, an update rate of several times per second is typical, even with rather large systems. Panning and zooming capability are provided, which allows the user to simulate a system of virtually any size of interest.

The user controls the simulation by clicking the mouse on different components on the one-line diagram. For example, the status of circuit breakers can be changed by positioning the cursor on the device, and clicking the left mouse button. Because of the fast display update rate, the new flows appear almost instantaneously. Likewise, the real or reactive output of a generator can be changed by placing the cursor on the up/down arrows by the generator's MW or Mvar fields and clicking the left mouse button. By trying different control actions, users can strengthen their intuitive feel for the system and its operation.

More detailed system information requires one or more additional mouse clicks. For example, Figure 3 reproduces the dialog box for the generator at bus 2, along with a graph showing its fuel cost curve. Such dialog boxes with detailed information are available for virtually every network element. Such boxes are a convenient means to view and modify any of the parameters associated with an element.

The simulation provides visualization capabilities suitable for presentations and individual studies

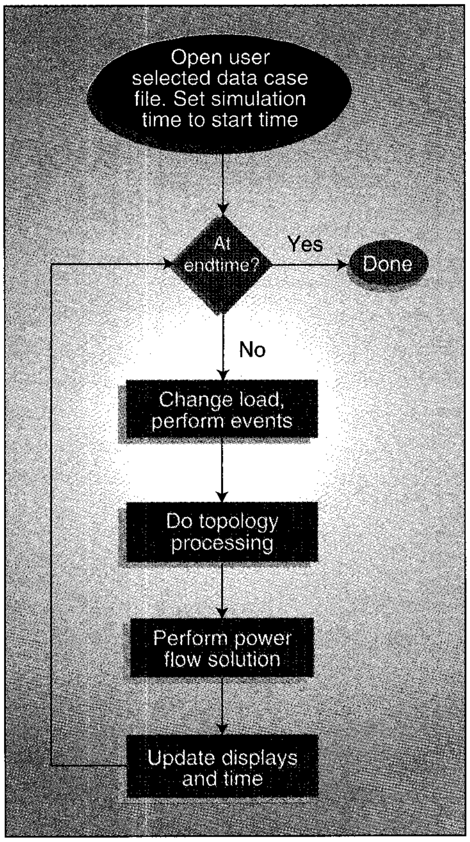

Figure 4. Simulation solution cycle

Simulation Engine

At the heart of the simulation package is a computationally efficient simulation engine that emulates the behavior of the power system. For the time intervals and phenomena of interest, a constant frequency model of the power system is used. In this way, the actual behavior of the power system is replicated through repeated power flow solutions. The basic simulation solution cycle is as shown in Figure 4. The data case file includes the power flow, economics, and load variation information; the package then reads the one-line diagram information from separate disk files. Once started, the simulation runs at a user specified scaling multiple of real-time. At any time point in the simulation, the user can pause or restart the simulation.

For each time step in the simulation, a number of adjustments are made to the system. These include changing the loads at each bus according to a piecewise linear model, enacting any scheduled or user requested events, checking for transmission line thermal limit violations, and, optionally, introducing random events. All transmission lines are assumed to have thermal loading limits, with the line capable of indefinite operation for any loading below this value. However, for loadings above this limit, the line temperature starts to increase. Line heating is approximated by integrating over time the square of the line current. As time progresses, if the user does not take corrective actions to reduce the line's flow to a value below its thermal limit, the line is automatically removed from service. Random events, such as loss of transmission lines and/or transformers, may also be activated at the user's option.

Following these adjustments, topology processing may need to be performed to take into account changes in bus connectivity. Topology processing determines which buses are connected together through in-service transmission lines and transformers; this group is referred to as an island. Usually, the power system consists of a single island. However, during system emergencies, multiple islands may be created. The package allows the modeling of multiple islands, with an island marked as viable if it has sufficient generation reserves to match the total island load plus losses. Buses that are not connected to a viable island are marked as inactive, with their load and/or generation set to zero. Conversely, loads at buses that had been inactive but are not re-energized are immediately reset to their correct (time-dependent) values; generation is optionally either immediately set to its pre-outage value, ramped up to this value, or requested to remain at zero to simulate the tripping of a generator which cannot be immediately put back online.

Following topology processing, the power flow is solved using a full Newton-Raphson method. Sparsity techniques have been used to decrease both execution time and storage requirements. This allows the package to simulate systems with just about any number of buses. During the power flow solution longer timeframe dynamics are considered as time dependent constraints external to the main Newton-Raphson iteration, with the time period equal to the simulation time elapsed since the last time step. Examples include limiting the allowable change in generation to enforce ramp rate limits on generators, and limiting transformer tap changes according to transformer tap delays.

Area Control Modeling

The multiple changes in the industry underway are increasing both the number and the variety of transactions between various electricity business entities. In order to correctly model these interchanges, the control area concept must be explicitly modeled. Area control is implemented under what is known as automatic generation control (AGC), which keeps track of the load and ensures that the system frequency and the transactions underway are maintained at specified values. The key signal used is the area control error (ACE), which is a weighted sum of the deviations in frequency and transactions. For the constant frequency model, the ACE is simply the difference between the actual interchange and the specified amount. AGC is implemented by allocating the actions necessary to maintain the ACE within a specified bandwidth to the various generating plants using economic dispatch.

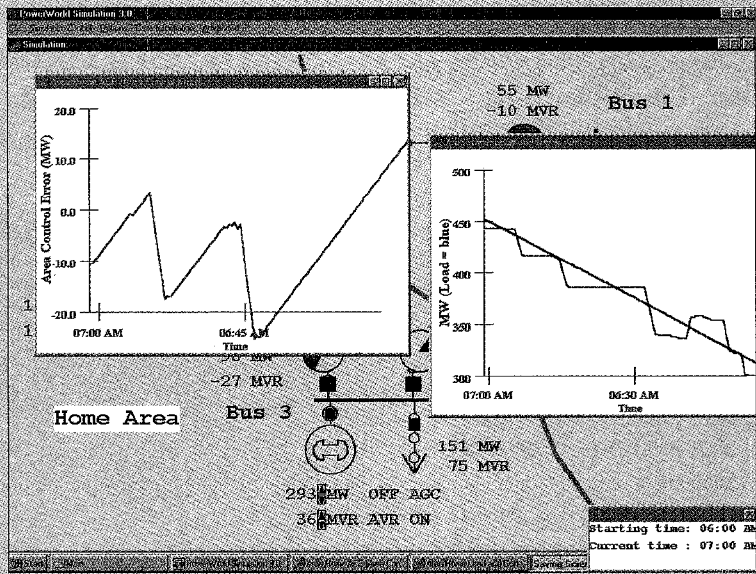

Figure 5. ACE and load/generation strip-chart windows

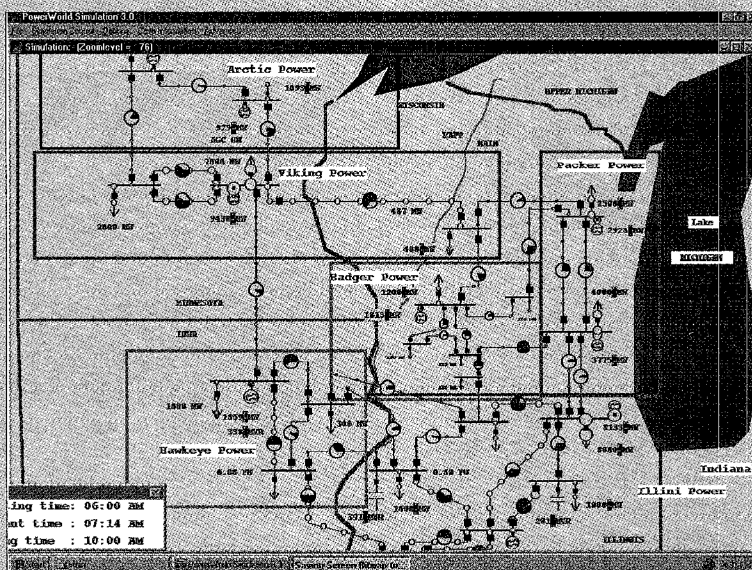

Figure 6. Twenty-one bus, six-area system

The relationship between generation, load and the ACE can be illustrated by using the ACE and the load/generation strip-chart windows to obtain time plots of the data. These windows are updated at each time step, with new data appearing on the left and scrolling to the right, providing the user with instantaneous feedback of the effects of changing load or generation on the ACE. These windows can easily be resized, moved, or rescaled. Figure 5 shows these charts for the three-bus system of Figure 2.

Under manual control, driving ACE to zero or within an acceptable bandwidth is not an easy task, particularly as the size of the network increases. A user can easily verify this by trying to operate the simulation using manual control of the generators. When an area is placed on AGC, the package uses an economic dispatch (ED) algorithm to dispatch the generation. This algorithm uses the generator fuel-cost curves and takes into account generator minimum/maximum MW limits as well as area losses. Changes in generation from one time step to the next may be (optionally) limited to take into account the maximum up and down ramp rates.

Transactions Model

When areas are operating on AGC control, the package can be used to demonstrate the benefits of scheduled power transactions between areas, along with some of the often undesirable consequences. Primarily two types of displays are used to accomplish this: the one-line diagram and the area transactions display. In its simplest form, a power transaction is when one area sells a specific amount of power for a specific time period at a specific price to another area. In actual practice, there can be an almost infinite variety of different types of power transactions. In the current version of the package, the user can either buy a fixed block of power from another area over a specified time period, or the user can sell a fixed block of power to another area over a specified time period. The user may enter into any number of individual transactions over the course of the simulation, even buying low from one area and then turning around and selling high to another.

Consider the 21-bus, six-area system shown in Figure 6. While the numbers in the figure are small, in an actual simulation the user could use the zooming capability to focus on any particular region, so as to view the actual flow in any network element.

The area transactions display, shown in Figure 7, supplements this information by showing a summary of the actual power flow between areas and the scheduled power flow. When transactions are scheduled, the display shows clearly the loop flows in the system, which is flow that does not move along the contract path. By clicking on DEAL/WHEEL the user can set up multiple transactions between different areas. Contiguous areas may transact directly, and noncontiguous areas must obtain a wheeling contract before transacting. The areas wheeling the power of a transaction on the contract path are compensated based upon the amount of energy they wheeled and using the area specified wheeling charge expressed in dollars per MWh.

Figure 8 shows the same system, except with a 200-MW transaction between Arctic Power and Illini Power, with the contract path negotiated to be through the Viking Power and Badger Power areas. A comparison of the displays of Figures 7 and 8 shows that the majority of the transaction did not flow along the contract path. Figure 8 also shows the area information display, which can be used to obtain detailed information about an area, including hourly operating cost. By using these displays, the user can quickly gain an appreciation for the impact transactions can have on system operations, and obtain a much better understanding of concepts such as wheeling and loop flow.

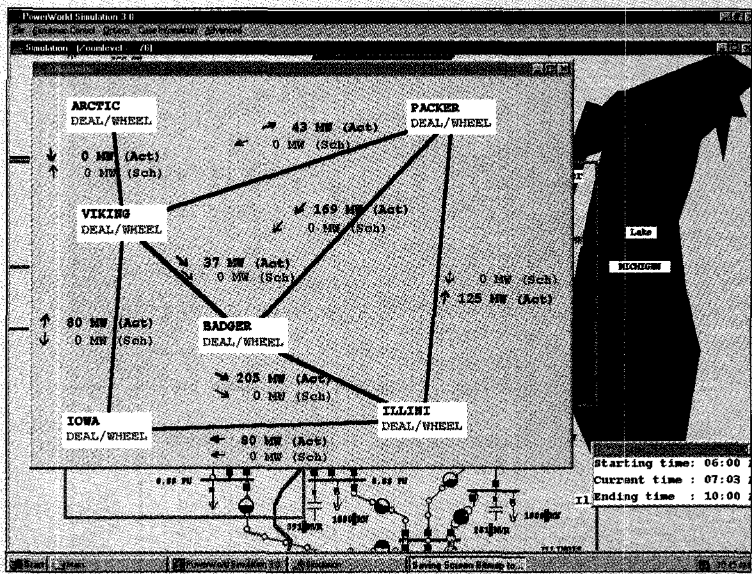

Figure 7. Area transactions display

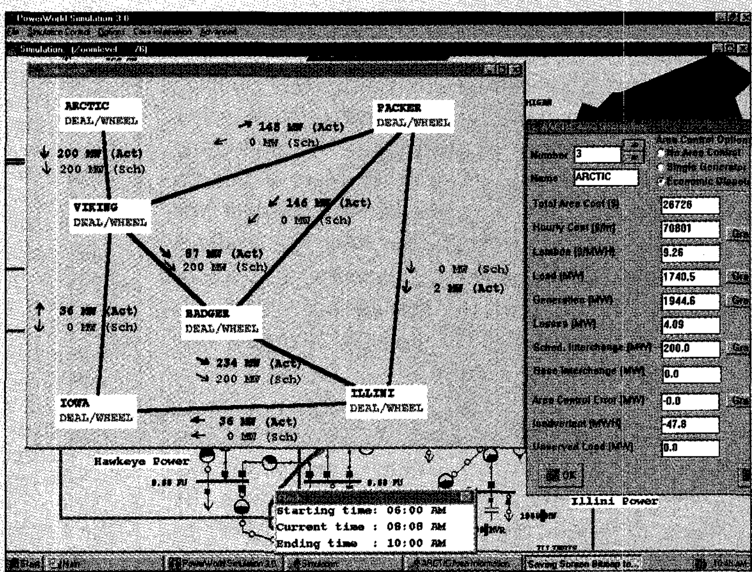

Figure 8. Area transactions display showing loop flow

Case Preparation

The simulation package also includes a *builder* module, which is used to construct new cases and to modify exist-

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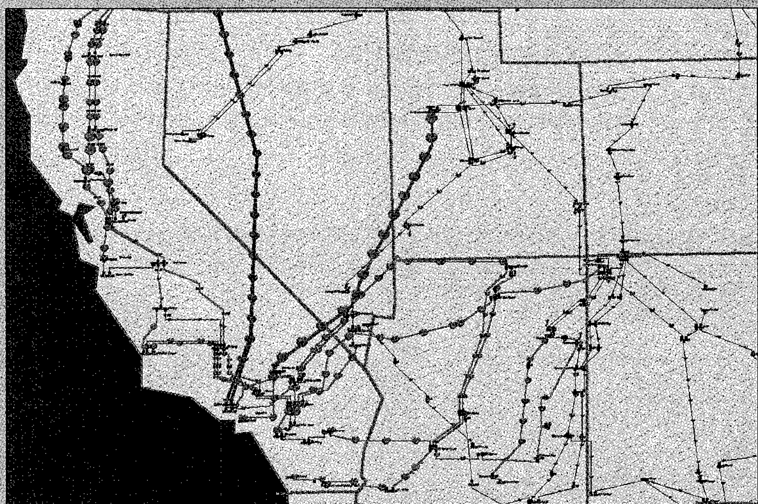

Figure 9. Southern portion of WSCC high voltage transmission system

ing cases. Builder allows users to create a power system case either from scratch graphically or by starting from an existing power flow case using the IEEE common format or PTI raw data format. When creating a new case, the user builds the case quite simply by selecting network elements from a menu and placing them on a one-line diagram; dialog boxes are then used to enter the various parameters. The user interface provides several features which make case construction and modification a simple and straightforward procedure. For example, the package has the ability to automatically link with the existing power system case information, saving users from having to re-enter this information. When users place a bus on the one-line diagram, they only need to specify the bus number; if the bus already exists in the case, the package will link to it. When drawing a line between buses, the user has to enter no information if the line already exists; the package will automatically determine the terminal bus numbers and link to the line data.

Large System Studies

The examples discussed in this article were specifically selected as small systems to effectively illustrate the way the package works. However, it has the ability to model cases of virtually any size. The one-line diagram needs to show only the portion of the system that is of interest and can be reasonably displayed on the monitor. The zooming function is useful for allowing the user to visualize regions of interest with greater clarity. For example, the one-line diagram in Figure 9 is based on the 6,400-bus North American Western Systems Coordinating Council (WSCC) system and displays only the high voltage transmission. The light green circles are used to indicate the magnitude and direction of power flow. During a simulation, in which their flow is animated, the power flow in the system is readily apparent. Note that the size, color and density of these circles can be easily changed. The information about the remainder of the system, including the lower voltage transmission, can be obtained either by zooming or from tabular displays. The ability to construct displays for areas of interest and the use of zooming/panning functions make the package extremely useful for actual large scale systems.

For Further Reading

T.J. Overbye, G. Gross, P.W. Sauer, "Understanding Third-Party Access Issues: A Simulation and Visualization Tool for Nontechnical Personnel," *Proceedings of the Power System Computation Conference*, Dresden, Germany, August 1996.

T.J. Overbye, P.W. Sauer, C.M. Marzinzik, G. Gross, "A User-Friendly Simulation Program for Teaching Power System Operations," *IEEE Transactions on Power Systems*, Volume 10, November 1995.

Biographies

Thomas J. Overbye received his BS, MS, and PhD degrees in electrical engineering from the University of Wisconsin-Madison in 1983, 1988, and 1991 respectively. He was employed with Madison Gas and Electric Company from 1983 to 1991. Currently he is an assistant professor of Electrical and Computer Engineering at the University of Illinois at Urbana-Champaign. In 1993, he was the recipient of the IEEE PES Walter Fee Outstanding Young Engineer Award.

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Mark J. Laufenberg is president of PowerWorld Corporation. He received his BS and MS degrees in electrical and computer engineering from the University of Illinois in Urbana-Champaign in 1992 and 1993, respectively. He was a co-op at the Jet Propulsion Laboratory in 1989 and 1990, interned at Pacific Gas & Electric Company in 1992, and interned at ECC/KEMA, Inc. in 1994.

Peter W. Sauer received the BSEE from the University of Missouri at Rolla, and MS and PhD degrees in electrical engineering from Purdue University in 1969, 1974, and 1977, respectively. He served in the U.S. Air Force from 1969-1973 as a facilities design engineer, and was the NSF Program Director in Power Systems in 1990-1991. He is currently a Grainger associate and a professor of electrical engineering at the University of Illinois at Urbana-Champaign. He is a registered professional engineer in Virginia and Illinois.