A User-Friendly Simulation Program for Teaching Power System Operations

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Abstract

This paper describes a user-friendly power simulation program for teaching power system operations and control. The motivation for the development of the program is to provide students with a simple and useable tool for gaining an intuitive feel for power system operations. This Microsoft Windows™ based program simulates power system operation over a specified time period (of typically several hours to a day). Students dynamically interact with the simulated system through various windows, including a one-line display. The use of data files and option windows allows the program to simulate a wide variety of different power systems and operating problems. Efficient programming results in a modest program size of just 450k, allowing for easy distribution to students.

Introduction

As power systems become increasingly complex, there is a critical need to make available improved tools for training power system engineers and analysts. Traditionally this training has been provided primarily to student engineers, system operators, and practicing engineers. However, a worldwide trend towards increasingly more open transmission systems, the growing competition in electricity markets, the changing role of regulation, and the entry of new working professionals into the electricity business has created an unprecedented need to provide personnel without an extensive technical background with at least a basic understanding of power system operations. This is required in order to ensure that the interactions between business decisions and the technical/physical constraints of the power system are appropriately considered and understood. In particular, these people need an understanding of the effects of various power and energy transactions on system operation, and the constraints often imposed by the transmission system.

Over the years computer simulation programs have played an important role in providing students with a better understanding of power system operation. As a result of the rapid advances in computer hardware and software, computer-based power system educational tools have grown from very simple implementations, providing the user with little more than a stream of numerical output, to very detailed representations of the power system with an extensive graphical user interface (GUI). Examples of such programs include dispatcher training simulators (DTS) for operator instruction [1-4], along with a wide variety of different simulation programs targeted for university use [5-10].

The motivation for the development of the program described in this paper was to have a self-contained power system simulation program for instruction both of engineering undergraduates and of personnel with a nontechnical background involved in the electricity business. This required the use of a user-friendly GUI so the students could spend their time gaining an intuitive feel for operating an electrical system, rather than just learning how to use the program. Basic concepts needed to be presented simply, yet the program required sufficient detail to maintain the interest of and provide challenge to the advanced engineering student. The principal thrusts of the program include basic power flow in a network, how system controls (such as generator MW/voltage setpoint, LTC transformers, line outages, and power transactions) affect power flow, and area control concepts such as area control error (ACE), automatic generation control (AGC) and economic dispatch (ED).

Effective application of object-oriented programming (OOP) techniques using Borland Pascal [11] in a Microsoft Windows™ 3.1 environment produced a package which has modest system requirements. The program executable and associated data files are small enough to allow distribution on a single floppy disk. The size of the program executable is just 450k; the size of the data files is, of course, dependent upon the size of the simulated system. As an example, a 13 bus system requires about 30k. To run the program, the minimum recommended system requirements are a PC with a 486 or better processor, a VGA or better display adapter, a Windows-compatible mouse, and Windows 3.1. The program was developed for use in the Edison Electric Institute (EEI) Power Systems Planning and Operations School created and run by the University of Illinois at Urbana-Champaign (UIUC) and the University of California at Berkeley. The program is also used in the power system classes at UIUC.

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Program Features

In general, the program simulates the operation of an operating area in an interconnected power system over a given period of time (usually from several hours to a day). During

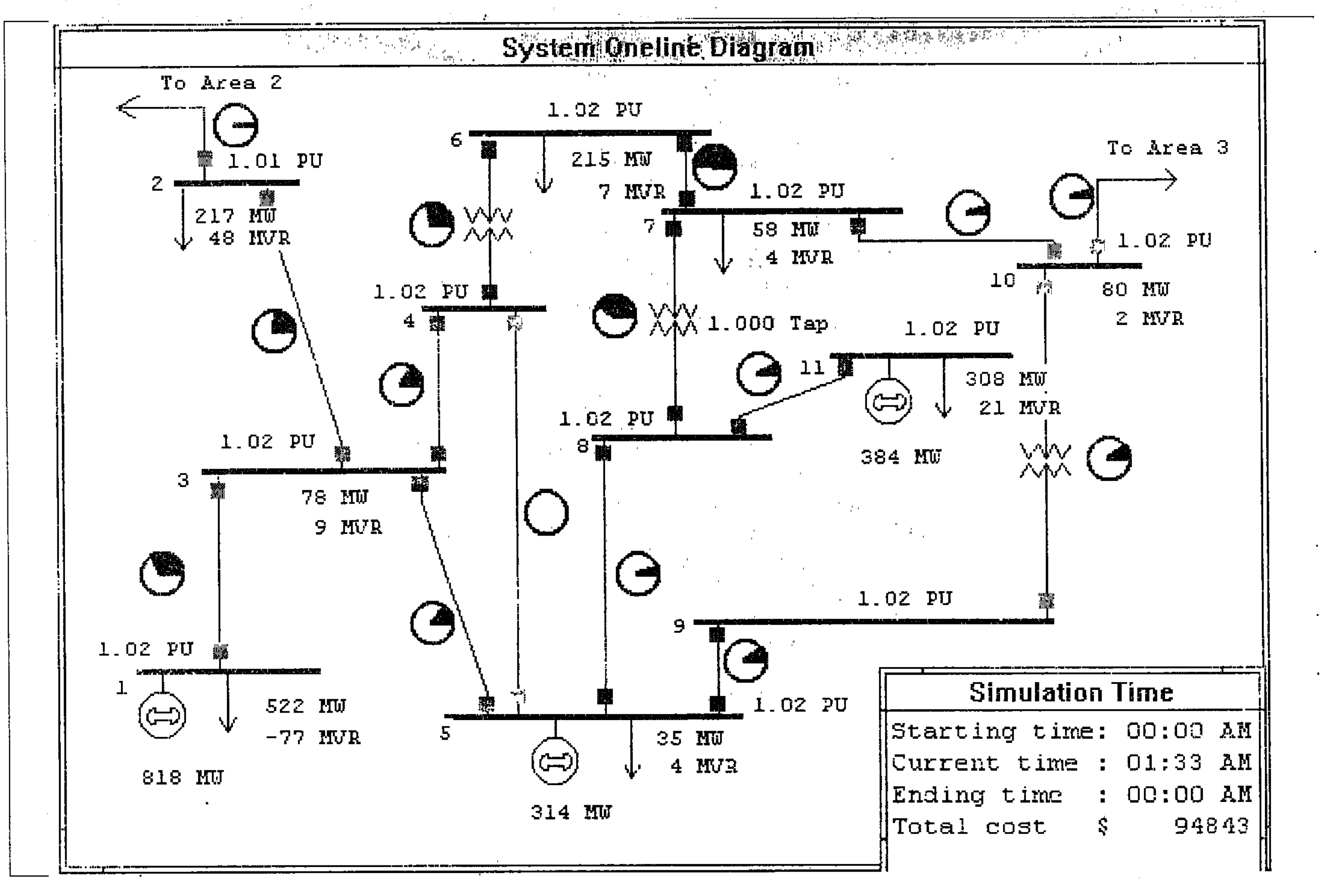

Figure 1: One-Line Diagram of a Sample Thirteen Bus System

the course of the simulation the loads will usually change automatically, and, optionally, different types of random events can occur (such as equipment outages). The student operates the system primarily by using a dynamic one-line diagram to change system controls including generator MW outputs, LTC transformer tap positions or circuit breaker status. As an example, Figure 1 shows the one-line diagram for a thirteen bus system. Other windows allow the student to interchange power from other (external) areas, to further monitor the system, and to change various options. The student is responsible for operating the system at minimum cost while maintaining correct area interchange, and ensuring that system voltages and flows are within their limits. Different data cases can be used to simulate different systems. A student can start operating just a two bus system and then work up to increasingly larger systems.

Simulation Solution Cycle

Because of the emphasis on longer time frame transmission system concepts, the key component of the simulation is the power flow solution. The basic steps of the simulation are the following:

1. Read simulation case and one-line diagram information from disk files, set simulation time to start time and perform initial power flow solution.
2. While simulation time <= end time Do
   a. Change load, perform any scheduled events and, on an optional basis, introduce stochastic events.
   b. Check for limit violations and outage any lines that have reached their maximum thermal limits.
   c. Perform network topology processing.
   d. Set scheduled transactions and do area control calculations, including (optionally) ED.
   e. Perform power flow solution.
   f. Update simulation displays, clock, and total cost.
3. Stop the simulation.

To begin a simulation the mouse is used to select a case from disk with a file dialog box. The one-line diagram and simulation time windows are then displayed along with a menu bar. At any time during the simulation, the student can interact with the case (such as by changing controls or setting up MW transactions) through the various windows.

System One-Line Diagram

The one-line diagram is the most important part of the graphical user interface (GUI). The one-line representation, like all of the other windows in the program, has been designed using object-oriented techniques. The advantages of this approach include flexibility to allow the user to interact with all objects on the screen, small source and executable files, extensibility and reusability of existing code, and a user-friendly GUI. When the program is running the one-line is

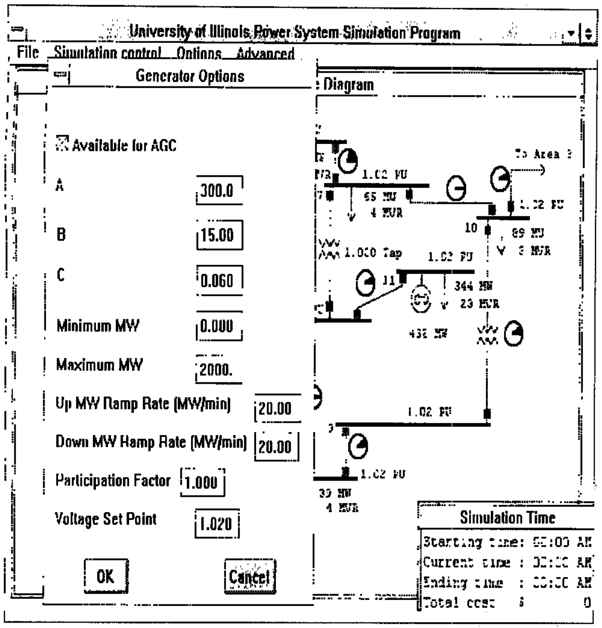

Figure 2: Sample Generator Dialog Box

continually updated with bitmap copies used to provide a "smooth" animation. The display update rate depends upon the computer's speed and size of the simulation, with several times per second typical with a relatively fast PC, a small system (less than 20 buses) and 1024 by 768 display resolution.

The one-line uses graphical symbols to represent system equipment such as buses, generators, loads, transmission lines and transformers. A combination of numeric values and graphical symbols are used to show system values. For example in Figure 1 numeric values are used to show bus voltage magnitudes, and load/generation real and reactive power values. However, graphical pie charts are used to show percentage line loading. As the line loading increases, the pie becomes increasingly full; for flows above the transmission line's limit the pie changes color from blue to red, with the percentage value then shown in the interior of the pie. Additionally, the rotor position changes to indicate the voltage angle at generators. Options are provided to show the voltage magnitudes in either per unit or actual kV, and to "declutter" the display by removing different classes of values (such as all line flows).

The user can control the simulation by clicking the mouse on different components on the one-line. For example circuit breakers can be opened by positioning the cursor on the circuit breaker symbol and clicking the right mouse button, while they are closed by clicking with the left button. Because of the fast display update rate, the new flows appear almost instantaneously. Similarly, the MW output of the generators is increased by positioning the cursor on the generator MW value and clicking with the left button (or with the right button to decrease the value). Transformer taps, generator set point voltages, and capacitance values can also be modified in a similar manner. By double clicking with the left button on the actual device symbol the user can view and sometimes modify different parameters associated with the device. For example, Figure 2 shows the dialog box obtained by double clicking on the generator symbol. All values in this dialog box can then be changed by the user. If desired, the user can also use the double border of the one-line window to change its size or position on the screen.

The OOP techniques of inheritance and polymorphism are effective in succinctly providing this display functionality. In OOP the object hierarchy defines the relationships between various objects, with descendant objects inheriting access to all its ancestor's code and data. Polymorphism is giving an action one name that is shared up and down an object hierarchy, with each object in the hierarchy implementing the action in a way appropriate to itself [11]. For example, polymorphism permits clicking the left mouse button on the breaker to open the device, while the same action on the generator MW value increases the generator's MW output. Figure 3 shows the program's object hierarchy. The object hierarchy can be easily modified to permit the incorporation of additional objects.

System Data Files

Each power system case has two associated data files. The first file contains the one-line diagram information. The one-line displays are currently built off-line using a separate Windows-based program. With this program the one-line diagram designer uses the mouse to position objects (such as a line pie chart) on the new representation and then uses a dialog box to enter the values of various parameters associated with the object (such as for the line pie chart the desired size, and the "from" bus, the "to" bus and the circuit number of the line flow associated with the pie chart). The program then stores this information in a non-ASCII format in a file. The time required to build the one-line diagram depends upon the system size and complexity. For reference purposes, the one-line diagram shown in Figure 1 required about an hour to build.

The second file is a text file that contains all the remaining information necessary to define the case. The actual power system information is defined in the beginning of this file using the IEEE common data format [12]. The remainder of the file then contains various simulation options and more detailed device modeling information. For example, to simulate the daily load variation, the real and reactive load at each bus is modeled as a piecewise linear function of time. Additionally, specific events such as removing/inserting lines can be

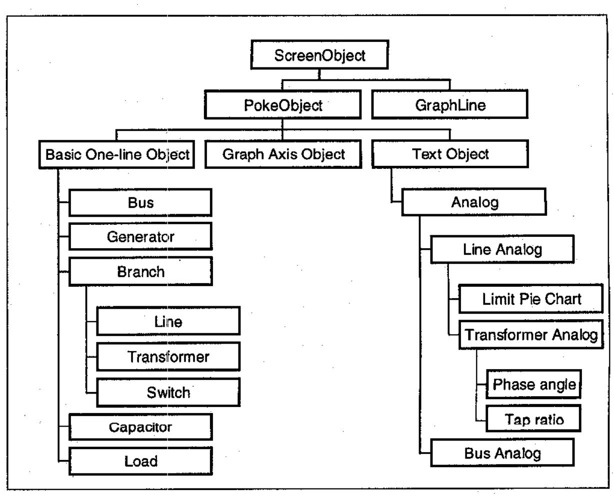

Figure 3: Program Object Hierarchy

scheduled in this file to occur at specific times during the simulation.

Automatic System Variation

For each time step in the simulation a number of adjustments are automatically made to the system. First, the real and reactive loads at each bus are changed according to their piecewise linear model. Second, any scheduled events are enacted. Third, the system is checked for limit violations. All transmission lines are assumed to have thermal loading limits, with the line being capable of indefinite operation for any loading at or 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. Eventually, if the line flow does not decrease to a value below its limit, the line is automatically removed from service. When this occurs the user experiences one of a number of different cost penalties. Additionally, as an option, the program permits the simulation of random events, such as a transmission line outage due to lightning. This capability is included to convey to students the critical role such unexpected events can have on power system operations. In the simulation the user specifies the frequency of these events by choosing an option of either "never", "sometimes", or "often". Whether a particular line is opened in a given time step depends on the selected option, the line outage probability, and the time step size.

Following these adjustments, topology processing may need to be performed to take into account any automatic line status changes, and any changes made by the user during the previous time step. Topology processing removes all buses that are not connected either directly or indirectly to the system slack. Load and generation at the removed buses are set to zero. Conversely, loads at buses that had been removed but are now reenergized are immediately reset to their correct (time-dependent) values; generation is optionally either immediately set to its pre-outage value, or ramped up to this

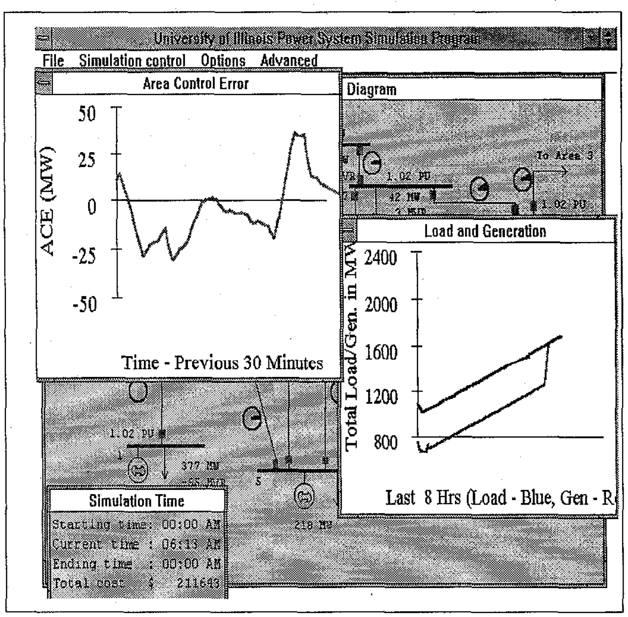

Figure 4: ACE and Load/Generation Strip Charts

value, or required to remain at zero (to simulate when a generator has tripped off-line and cannot be immediately put back on-line).

The simulation uses a full Newton-Raphson power flow solution. Sparsity techniques have been used to decrease both execution time and storage requirements. In order to maximize the region of convergence of the algorithm, the optimal multiplier technique [13] is used. However since the user is free to modify the system from the one-line diagram, it is certainly possible to stress the system beyond its point of maximum loadability. If this were to occur in actual operation, the system would probably experience a voltage collapse induced blackout. In the simulation anytime the power flow fails to converge, it is assumed that such a situation occurs. A message is displayed on the screen indicating that a blackout has occurred, the windows dim to a dark gray, and the simulation pauses.

Generator Models and Area Control

An important use of the program is to familiarize students with the requirements for area control, and the mechanisms of energy interchange between different operating regions. For an actual operating area, the area control error (ACE) is defined as a weighted sum of the difference between the actual and scheduled real power flow out of a control area, and the frequency error. The simulation assumes that the actual frequency is always equal to the scheduled frequency, so the ACE reduces to the difference between the actual interchange and the scheduled interchange. The user may select the Options menu to open "strip-chart recorder" windows that show either the ACE or the load/generation as a function of time. These windows are updated at each time step, with new data appearing on the left. These windows can also be resized and/or moved. The vertical (horizontal) scales can also be changed by double clicking on the vertical (horizontal) axis. As an example, Figure 4 shows the ACE over the most recent 30 minutes and the load/generation since the beginning of the simulation for the 13 bus system. In the load/generation window the upper curve is the load while the lower one is the generation; for this case the two curves differ primarily due to the presence of several scheduled transactions.

To keep the ACE close to zero, the user has three options for area control. First, the area can be controlled manually by clicking on the generator MW field to manually vary generation. By using the ACE strip-chart, the student gets instantaneous feedback of the effect of the generation change on the ACE. Second, the area can be placed on an automatic control where the ACE is allocated to the area generators according to specified participation factors. The third option is to use an economic dispatch (ED) routine to determine the generation dispatch. For both types of automatic control the change in generation can be (optionally) limited to take into account maximum up and down ramp rates (specified in MW/minute). Unit minimum/maximum MW limits are also enforced, and the generator options dialog (shown in Figure 2) can be used to take a particular unit off automatic generation control. For all cost calculations, the generator fuel-cost curves are represented by a quadratic cost function.

One of the most important benefits of interconnected operations is the ability for areas to undertake energy transactions. With increasingly more open transmission regimes, many more people involved in the electricity business will need at least a basic familiarity with how these transactions are implemented, and their potential impacts upon the transmission network. While in actual operations there can be an almost infinite variety of different types of power transactions, for simplicity the program currently only allows two generic types. One can either buy or sell a fixed block of power from or to another area at a fixed price. Such transactions are normally initiated as a result of economy, but can also be used to alleviate transmission system limit violations.

Power transactions are initiated using the Power Transactions window shown in Figure 5. The window first shows the incremental cost for the user's area, along with buy and sell quotes for a specified block of power (in \$/MWh). The buy quote is determined by dividing the generation cost decrease due to proposed purchase by the MW purchase amount, while the sell quote is the generation cost increase divided by the sale amount.

Next the window shows the buy and sell prices for the other areas in the system calculated using a similar algorithm. Note that if an area does not have sufficient generation to do the anticipated transaction, then that transaction cannot occur and no quote is available. For example, this is the case for the Figure 5 system where buying power from area 3 would push that area's generators past their upper limits. The actual transaction price is then calculated to be the average between one area's purchase price and the other's sale price if the transaction is economical, or the actual purchase/sale price of the other area if it is not. For convenience, the total cost savings for each possible transaction are also shown in the window.

A transaction is initiated with an area by double clicking on its buy/sell price. All transactions begin to take effect immediately, ramping to their full value over a ramp time (set by default to 10 minutes). The bottom of the window shows all of the currently active transactions.

The total simulation cost is modified to take into account the cost and/or income from each transaction. Additionally, the program keeps track of the inadvertent interchange error. This value is calculated by integrating the ACE over time and has

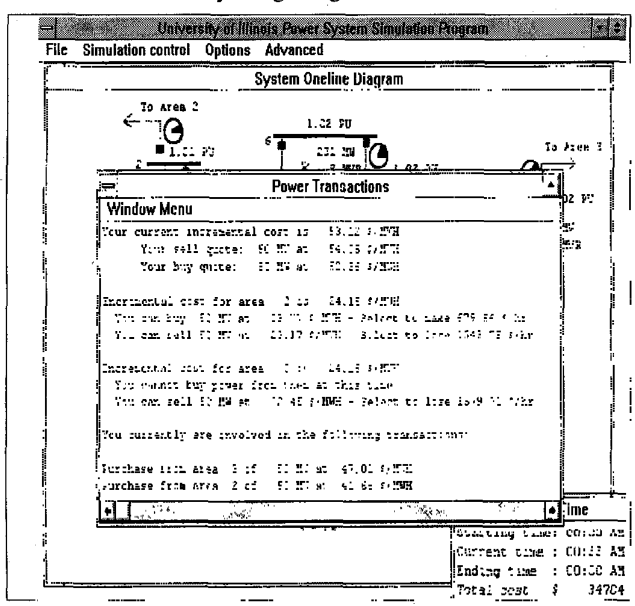

Figure 5: Power Transactions Window

units of MWh. At the end of the simulation a negative inadvertent error indicates that the user has (overall) undergenerated; the total simulation cost is therefore increased by the inadvertent multiplied by a high cost per MWh. At anytime during the simulation the inadvertent error, along with a number of other area values, can be viewed by displaying the area information window.

Limitations of the Simulation

The basic idea of the program is to simulate the evolution of load on a power system over a relatively long period of time. Therefore the program only models constant frequency operation, using the power flow "infinite bus" approach. As the load and other parameters change throughout the scheduled period, the program solves the power flow equations and displays the results. As such the program is a sequence of static simulations. The only dynamic aspects of the program are the enforcement of ramp rates on generation and real power transactions, the pre-programmed load variations, and the thermal overloading limits on transmission lines. Additionally, only two general types of MW transactions are allowed.

Using the Program as a Teaching Tool

The program may be used in many ways to teach the fundamentals of power system operations and control. Included with the program are a number of test systems ranging in size from two buses to thirteen buses. The program can be used by the instructor as a lecture tool to demonstrate phenomena such as load cycling during a time period, power flows on parallel lines, correlation between reactive power and voltage, economic dispatch, area control error, automatic generation control, wheeling, and the impact of contingencies on system operations.

As a lecture tool, the instructor may choose a simple system and begin the simulation. As the program executes, the instructor may display various quantities such as ACE, incremental costs, power transaction options, and other features. Generation units may be removed from participation in AGC and adjusted manually by the instructor in an attempt to maintain zero ACE as the load changes with time. The effects generators have on transmission line flows can also be demonstrated. The instructor could simulate line outages during the simulation to show the impact of lines out for maintenance or lost due to contingencies. If the random contingency events option is activated, the program would randomly remove lines, showing the effects stochastic events have on system operation. Intervention by the lecturer is sometimes required to provide manual generation rescheduling to remove any resultant overloads.

Outside of the classroom (or for assignments), the students can use the program to gain a more intuitive feel for power system operations and control. If the students run the test systems without taking any action, there will be a total cost associated with the load scheduled cycle. They could first simply observe the automatic operation of the system to get a physical feeling for the interaction between loads, generation, line flows, bus voltages, and the power system economics. Then, rather than being passive observers, the students may be challenged to improve the economic outcome of the simulation. Using one of the test systems with a given load cycle, the students could be tasked to operate the system to minimize cost. By undertaking power transactions, the students can take advantage of cheaper energy from neighbors. The student who goes through one load cycle with minimum cost would be the "winner". However, someone who tries to make too much money on transactions may find that overloads are encountered, and if the overloads are severe enough, they may result in line outages with potentially severe financial consequences or even total system collapse. Students quickly learn the need to minimize cost while maintaining system security and hence the need for applications such as optimal power flow. Also, the presence of stochastic events reinforces the need for the consideration of contingencies when operating a power system. An instructor could stimulate a classroom discussion on the importance of considering such events in system planning and operations, and thus the need for applications such as contingency planning.

Program Distribution

The program and user's guide are available for a nominal fee from the authors. The nominal fee is charged to cover the cost of duplicating and mailing.

Conclusion

This paper has described a user-friendly power system simulation program. The program is particularly effective in providing users with an intuitive feel for power system operations. The object-oriented design approach allows users great flexibility to dynamically interact with the simulation, while retaining a small size for the source and executable files. The use of data files and option windows allow users to simulate a wide variety of different operating conditions.

Acknowledgments

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DISCUSSION

D. M. VINOD KUMAR (Dept. of Elect. Engg., Regional Engineering College, Warangal):

Authors are complimented for their effort to provide a user-friendly simulation program for teaching power system operations. The simulation of basic power system operations are interesting. However, the training simulator is lacking some of the following aspects:

(1) Either teaching or utility point view the simulator should have the first basic one is power generation and control. This should have been incorporated with either thermal power generation or hydro power generation or nuclear power generation.

(2) Authors should have included "State estimation" program, because the output of the state estimator (bus voltage magnitudes and phase angles) are infeed to various energy management system functions. This provides the importance of filtering the real-time measurements.

(3) Authors should have incorporated static VAR compensators in the simulation program.

Discusser's point of view the above three are very important one either from the point of teaching or any utility operator's point of view. Hence, in future the authors may be incorporated in their simulation program.

Manuscript received March 1, 1995.

A. Bose and **R. Fairchild** (Washington State University, Pullman, WA): The authors have developed a PC based simple simulation program to teach power systems operation to university students and non-technical personnel. By handing out diskettes of the program during the presentation of the paper, they have made it possible for anybody to try out the simulation. This discussion is a result of being able to run the simulation in addition to reading the paper.

The power of desktop computation nowadays is such that real time simulations of large power systems can be run with significant dynamic detail. Many utilities are routinely training their operators using such simulators and several universities are also using them for research and teaching. The simulation described in the paper has the advantages of simplicity, maximum portability and minimum maintenance. The availability of such freeware (or at least 'cheapware') to students is also crucial for educational purposes and the choice of platform (MS Windows) allows for maximum dissemination. However, when compared to existing operator training simulators (OTS), this simulation appears to be more like a toy.

The obvious question then is the pedagogical usefulness of such simulations. If the same level of teaching can be achieved with simpler simulations, then it is obviously more cost effective. For example, certain concepts can be better explained with simple examples; but this may also leave a very wrong impression of the complexity of the real world problem. This simulation is supposed to show the concepts of power system control, economics and security but the simplifications may leave the impression, especially on non-technical policy setting personnel, that managing these aspects of a real power system is just a scaled up version of what is seen in this simulation rather than a much more complex undertaking. Is it better then to expose students to simple scenarios on more realistic simulators at the risk of some confusion or to simplified simulations at the risk of not getting across the complexity of the scenario? However, teaching effectiveness is difficult to measure, and so the availability of teaching tools with a choice of different levels of realism is probably the most desirable.

The simulation seems to do a very good job of running the power flow based scenarios with excellent handling of topology and control changes. The area control error is a bit misleading without the generation and frequency dynamics. The handling of power exchanges and their effect on the economics is particularly well done for demonstration purposes.

Although the user friendly graphics is presented in the paper as a major advantage, we found this to also be the most limiting. A power system can be easily entered or the existing ones modified by changing the data but there is no way for the user to generate or modify the graphics. Obviously, there must be a process used by the authors but this was not icluded on the diskette; this is an absolute minimum before the simulator is really usable by others. Actually, the authors volunteer to produce the graphics for others but it is obviously not realistic to expect that for every student wanting to try out a slightly different system. the authors would provide a graphics generation service. Without a simple way to create the graphics locally, however, this software cannot really be considered portable. Of course, the generation and modification of one-line diagrams brings up the desirability of many other features that people have struggled with for many years: can the graphics be generated automatically? what about pan, zoom and decluttering for systems that do not fit on one screen? etc.

The above discussion is not meant as criticisms but as suggestions for future improvements. The authors have provided a valuable tool to the educational community and we look forward to future versions.

Manuscript received March 2, 1995.

T.J. Overbye, P.W. Sauer, C.M. Marzinzik and G. Gross: We thank the discussers for their interest in the paper, for submitting comments and for providing us with an opportunity to clarify the scope and intended application of the POWERWORLD simulation package. We would like to first address the discussion by A. Bose and R. Fairchild. We agree with the discussers that the availability of teaching tools with different levels of realism is desirable. Hence a direct comparison of POWERWORLD with operator training simulators (OTS) is not only unfair but also ill advised. The two tools exist for quite different reasons. For an OTS the ability to replicate the behavior of a given system is paramount, with issues such as portability, data requirements and maintenance, ease of use, and cost of only secondary importance. In contrast, the purpose of the POWERWORLD simulation package is to provide users with a user-friendly environment in which they can gain at least a basic understanding of power system operations with maximum portability, minimum maintenance and excellent interactive capability.

The discussion also raises important pedagogical and modeling issues. Due to the complexity of power systems, a good instructional tool should seek to present concepts as simply as possible. We developed POWERWORLD with a strong desire to provide a relatively simple construct. While in principle, a considerably more detailed model of the system could have been implemented, such a strategy would mask the important contribution of this tool, i.e., to explain in intuitive terms the basic principles of power system operation. Additional detail could come at the expense of getting across these basic concepts. We believe that the most important contribution of this package is to make available a tool that can explain the basic concepts without overburdening the explanation with an unnecessarily detailed representation.

The POWERWORLD package was developed with a view of exposing non-technical personnel to the intricacies of basic power flow concepts and the fundamentals of electric power operations. The driving force was the changing environment in which electric utilities operate and the sudden entry into the industry of workers unfamiliar with the physical difficulties and impediments to the flow of power. The detail of representation in the package was in line with this cadre of new employees. The software was never intended as a competitor to the operator training simulator, whose job is to train personnel involved in the minute-to-minute operation of a particular power system.

We believe that concepts such as power flow in a network, how system controls affect power flow, and even basic area control ideas such as power transactions between control areas can be adequately simulated using a constant frequency model (i.e., the power flow approach). In order for students to understand the complex issues involved in power systems, they must first understand these basic concepts. Therefore, rather than giving students the wrong impression about the nature of power system, the constant frequency assumption greatly helps student obtain a good grasp of their complexity.

We certainly agree with the discussers that more advanced students should be exposed to power system dynamics. In this vein, we have recently modified POWERWORLD to provide the option of using a simple uniform frequency model to expose students to concepts such as the effect frequency has on the ACE and generator speed-governing characteristics. Again, the intent is to give a feel for the operations of the system and not to train operators. Other simulations exist for those purposes, such as operator training simulators and transient/mid-term stability programs.

Concerning the generation of the one-line diagrams, the initial version of POWERWORLD did not include a module to construct the one-line diagrams. Such functionality has since been implemented. Using this auxiliary program a user can graphically create a new case by simply selecting various power system devices from a menu and then placing them on the one-line diagram; the program automatically creates all the necessary files. This process is illustrated in Figure A. This allows users to rapidly generate a wide variety of different systems. Users can also initialize a new case from

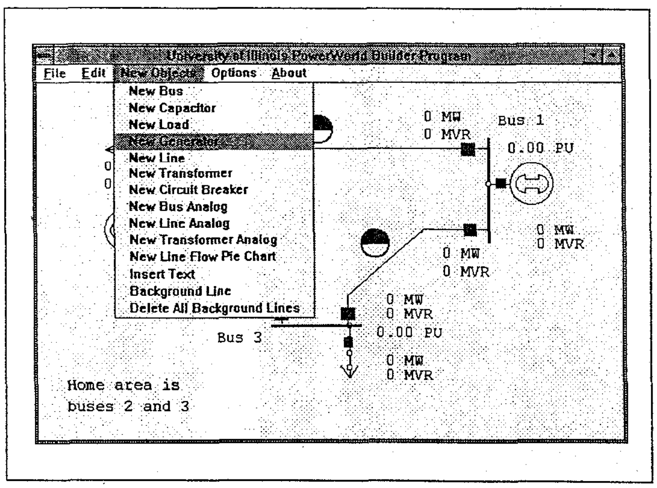

Figure A: Graphical Creation of a POWERWORLD Case an existing IEEE common format power flow file, using the auxiliary program to create the one-line diagram for this system, showing either a portion of the system or the complete system. Because POWERWORLD is intended primarily as a teaching tool, the one-line is currently restricted to just a single screen.

We thank the discussers for their kind comments concerning the handling of power exchanges and economics. We are enhancing this capability to permit POWERWORLD to be used as a more effective tool for illustrating the many issues involved in industry restructuring in the United States.

Concerning the comments of D.M. Vinod Kumar, we have augmented the generator models to permit the simulation of uniform frequency operation and are currently considering incorporating static var compensators into the program. Presently we have no plans to incorporate state estimation.

We have recently made the POWERWORLD package and associated user's guides available gratis electronically (with restrictions only on commercial usage). Current information on the location of this program can be obtained by contacting the first author at overbye@ece.uiuc.edu.

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