Role of Laboratory Education in Power Engineering: Is the Virtual Laboratory Feasible? Part III

Virtual Power System Laboratories: Is the Technology Ready?

A. P. Sakis Meliopoulos
School of Electrical and Computer Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

George J. Cokkinides
Department of Electrical and Computer Engineering
University of South Carolina
Columbia, SC 29208

Abstract: IEEE PES sponsors a panel session in the summer power meeting in Seattle on laboratory education in power engineering. Six short papers and one full paper summarize the opinion of the panelists. This is the full paper.

The evolution of software engineering, multitasking environment, object-oriented programming and symbolically assisted simulation methods have enabled the creation of interactive simulation environments that come close to providing a virtual experience of the actual system. The initial attempts at utilizing this technology are impressive and yet the degree to which they achieve virtual status is questionable. This paper examines the pros and cons of the present status of this technology. We discuss the minimum requirements for a virtual environment. We present our approach and compare it to the general requirements of a virtual laboratory. We conclude that the technology exists today to generate a virtual power system laboratory. Yet much work remains to be done for claiming that we have achieve the objective of having a true virtual laboratory for power systems. At the same time, virtual environments have certain advantages that can not be achieved in a physical laboratory.

Introduction

Recent advances in software engineering have made it possible to develop dynamic system simulators that operate in a multitasking environment. The additional graphical user interface tools and hardware accelerated graphics algorithms make the final product an indispensable tools to the understanding of the operation of the system. Many products have been developed along these lines for power system engineering. Most of these are focused on simulating the system under sinusoidal steady state operation. Projecting the capabilities of the new technologies claims of replacing physical laboratories with a virtual environment have surfaced. A virtual laboratory should have the following properties:

1. Continuous simulation of the system under study.
2. Ability to "connect" new devices in the system under study while the simulation continues for the new system.
3. Ability to provide animation and visualization of any device in the system under study.

The above properties are fundamental for a virtual environment. The first property guarantees the continuous operation of the system under study in the same way as in a physical laboratory: once a system has been assembled, it will continue to operate. The second property guarantees the ability to connect and disconnect devices into the system without interrupting the simulation of the system. This property duplicates the capability of physical laboratories where one can connect a component to the physical system and observe the reaction immediately. For example connecting a motor to the mains of a system, etc. The third property guarantees the ability to view in some physical sense the response of the system, similar to a physical laboratory.

The minimal requirements of a virtual environment can be achieved with the present technology. This is easier said than done. For example, simulation methods that will accurately simulate all system responses require wideband models for all power system components. This task is quite difficult if one considers specific examples such as a power transformer. Nevertheless the technology exists to achieve all three requirements of a virtual environment. On the other hand, once a virtual environment has been developed, it can be of greater educational value than a physical laboratory. For example, in a physical laboratory we are limited as to what we can observe. Consider an electric motor. In a physical laboratory we can observe the acceleration of the motor, torque, speed, etc., but we cannot observe the inner workings of the motor, magnetic fields and their interaction, small rotor oscillations, etc. A virtual laboratory can provide this information with proper animations and visualizations, the operation of the system can be "frozen" for a while to study a specific condition, etc. In other words there are advantages and disadvantages to physical laboratories and virtual laboratories.

In the past few years, we have undertaken an effort to explore the development of a virtual environment. The central piece of this effort is a time domain simulator of dynamical systems in a multitasking environment. In this environment, visualization and animation objects have access to the

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instantaneous conditions of the components and the overall system. Thus the visualizer/animator can generate detailed 3D pictures/movies of the instant by instant operation of the component or the system.

This paper provides a brief overview of the new tool, the mathematical formulation of the simulator and the data flow between the time domain simulator and the visualizer/animator. The paper focuses on a number of important requirements for this type of interactive program to claim the status of virtual environment. We also provide examples of virtual laboratory exercises. We conclude with an assessment of the present status of the technology and we identify a few research issues that must be addressed to achieve a true virtual laboratory.

Description of the Virtual Power System Environment

The internal structure of the Virtual Power System environment is illustrated in Figure 1. This architecture was developed with consideration on the minimal representation of system components and the requirements of a virtual environment. In the background is the network solver that is a time domain simulation program. The network solver is based on the representation of each system component with its *algebraic companion form (ACF)* [1]. The ACF is developed from the integro-differential equations of a component by numerical integration. The ACFs of all components in a system are related via the connectivity constraints. Application of the connectivity constraints yields a quadratic network equation that is solved at the network solver.

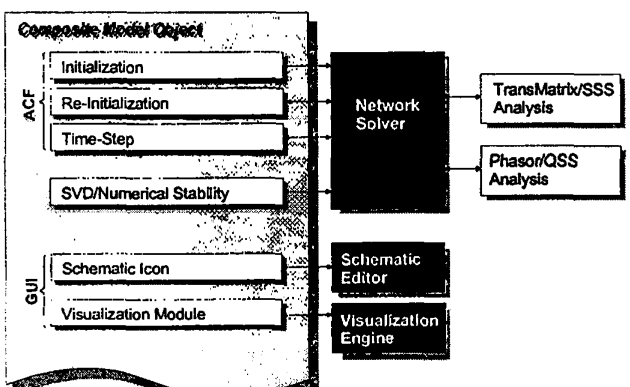


Figure 1. The Virtual Test Bed Architecture

The network solver is continuously executed providing the simultaneous solution of the entire system and determines the state of each component of the system. This information is passed back to the individual devices for animation and visualization of a specific component or groups of components. The Virtual Test Bed has been developed in a multitasking environment, thus allowing parameter changes and immediate system response observations.

The paper discusses a number of power system virtual laboratory exercises. Each exercise uses visualization and animation to enhance the pedadological value of the exercise to the students. Specific examples are:

1. Synchronous machine dynamics and internal fluxes.
2. Distance and Mho relay operation.
3. Induction motor start-up and voltage dynamics.
4. Small signal stability tracking.

Each exercise can be demonstrated on a single PC. Description of these exercises is given below.

Virtual Laboratory Exercise 1: Synchronous Machine Dynamics

Figure 2 illustrates the basics of a virtual laboratory exercise to study the dynamics of a synchronous machine. The simulation engine provides continuously the state of the generator at discrete time steps, i.e. ...t-2h, t-h, t. At the present time t, the state of the generator is known, x(t). From the state one can compute all the currents and voltages of the generator model. The magnetic fluxes of the generator can be also computed as well as the electromagnetic torque. Figure 2 is a snapshot of this information.

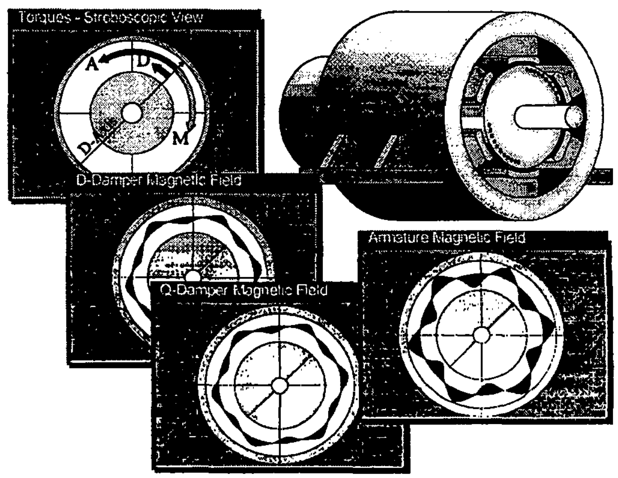
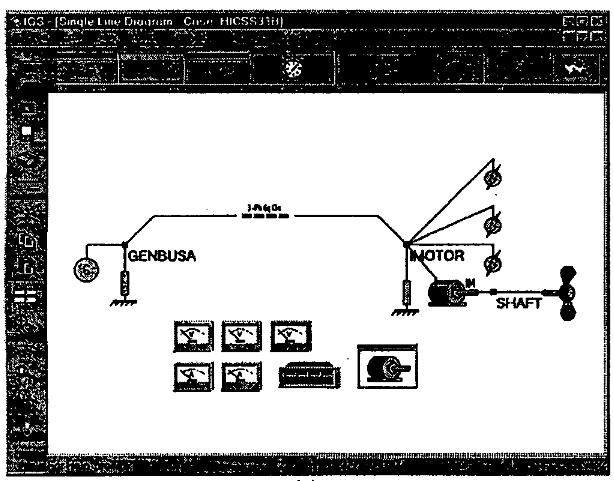


Figure 2. Visualization and Animation of the Operation of a Synchronous Generator

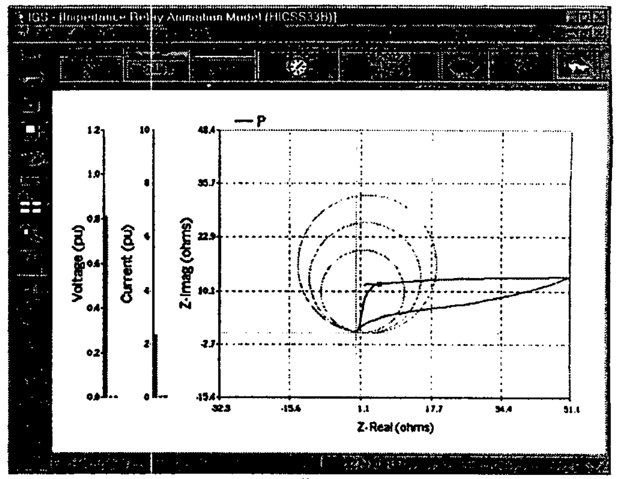
Note that the magnetic fluxes due to various currents in the generator can be reproduced as a function of the location in the air gap. The flux due to the armature current is displayed in the first window. The flux produced by the damper winding D is displayed in the second window. The flux produced by the damper winding Q is displayed in the third window. Finally the torque generated by the interaction of the armature and field currents is displayed in the forth window together with the torque due to the damper windings D and Q and the position of the direct axis of the generator. Figure 2 is a snapshot. In an actual simulation, Figure 2 evolves as the state of the system evolves. For example under normal operating conditions, the armature flux rotates with synchronous speed. The fluxes due to damper winding currents are zero and the armature-field torque is constant while the damper winding torque is zero. In case of a fault anywhere in the system, the picture changes and the user can observe the evolution of the magnetic fields and the electromagnetic torque.

Virtual Laboratory Exercise 2: Distance and Mho Relay Operation

Figure 3 illustrates the basics of another visualization and animation example. The figure illustrates a simple test system consisting of a generator, a transmission line, a motor and a motor load (fan). A modified distance relay (mho relay) is applied on the transmission line. The virtual laboratory exercise is concerned with the visualization of the modified impedance relay. The operation of this relay is based on the apparent impedance that the relay 'sees' and the trajectory of this impedance.



(a)



(b)

Figure 3. Virtual Laboratory Exercise with Relays
(a) Example Test System
(b) Animation of a Modified Impedance Relay

The visualization of this relay provides what the relay 'sees' during a disturbance in the system. The relay monitors the three phase voltages and currents at the point of its application. The animation model retrieves the information that the relay monitors from the simulator at each time step. Subsequently, it computes the phasors of the voltages and currents. Part of the visualization displays these phasors (see left part of the visualizer). From this information, the positive sequence voltage and current are constructed and displayed. The apparent impedance is also computed and displayed. As the system state evolves so do the pictures of the visualization providing a pictorial view of the operation of this relay. This animation of the impedance trajectory is superimposed on the relay characteristics and settings. Figure 3b illustrates the recorded impedance trajectory for a three phase fault at the terminals of the motor. The impedance trajectory is superimposed on the trip characteristics of this relay.

Virtual Laboratory Exercise 3: Induction Motor Start-up and Voltage Dynamics

Figure 4 illustrates another virtual laboratory exercise that involves induction motor start-up and voltage dynamics. The simulated system consists of a 15 MVA 13.8 kV three phase induction motor fed by a three phase source via a 100 meter cable. In addition to the speed, torque and voltage versus time plots, two animation objects are included which show different aspects of the motor operation.

The first animation object (top right window of Figure 4) shows the location of the rotor and the air gap magnetic field (red area). The window is updated at every step of the simulation, thus showing the relative rotation speeds of the rotor and magnetic field, as the rotor accelerates. Also the changing magnetic field magnitude can be observed during the motor acceleration. Furthermore, effects of motor current transients and phase asymmetries on the air-gap magnetic field can be visualized.

The second animation object (bottom-left window) illustrates the motor dynamics using a dynamically updated torque-speed plot. This plot includes the electrical torque (red trace) the motor mechanical load torque (blue trace) as well as a cursor (vertical white line) indicating the present motor operating point. To the left of the torque-speed plot, the RMS values of the motor terminal voltages and currents are shown using bar graphs. Note that the electrical torque speed curve of the motor is a function of the RMS voltage at the motor terminals. During the motor start-up, the motor draws a large current (5.5 pu in this example) which causes the motor terminal voltage to drop below the nominal value (0.7 pu in this example). This animation object dynamically updates the motor electrical torque-speed curve as it is affected by the changing motor terminal voltage, as well as the motor operating point cursor. The motor electrical torque-speed curve is computed as follows.

During the simulation, the RMS values of the phase voltages are continuously calculated over a sliding time window using a recursive Fourier transform method. The sliding time window width is user-selected (typically one power frequency cycle (16.66 ms)) and ends on the latest calculated waveform sample. Using the phase voltage RMS values, the motor electrical toque versus speed is computed as follows:

$$T = \frac{pR_r(V_a + V_b + V_c)}{2\omega(1-s)\left(\left(\frac{R_r + R_s}{1-s}\right)^2 + (X_r + X_s)^2\right)}$$

where: s is the motor speed in pu.,
R_r, X_r are the rotor resistance and reactance
R_s, X_s are the stator resistance and reactance
p is the number of poles
ω is the power frequency.

The distance between the operating point cursor intersections with the electrical and mechanical load torque curves is equal to the accelerating torque. When the system reaches steady state, the operating point cursor overlaps with the intersection between the electrical and mechanical torque curves. Furthermore, the relative shape of the electrical and mechanical torque curves determines the stability characteristics of the system. Thus this animation object illustrates the voltage sensitivity of systems containing induction motor loads.

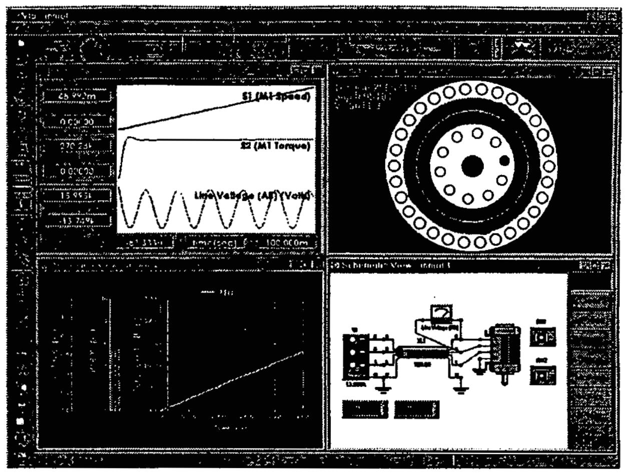


Figure 4. Animation of Induction Motor Operation

Virtual Laboratory Exercise 4: Small Signal Stability Tracking

Another important visual laboratory exercise is the tracking of the small signal stability of dynamical systems. This is achieved by providing displays of the eigenvalue map in real time. Specifically, the VTB computes the system transition matrix over a user specified time interval. Subsequently, the eigenvalues of the transition matrix are computed and displayed. The process is illustrated in Figure 5. A concise description of the computational algorithm for the transition matrix is presented in the Appendix.

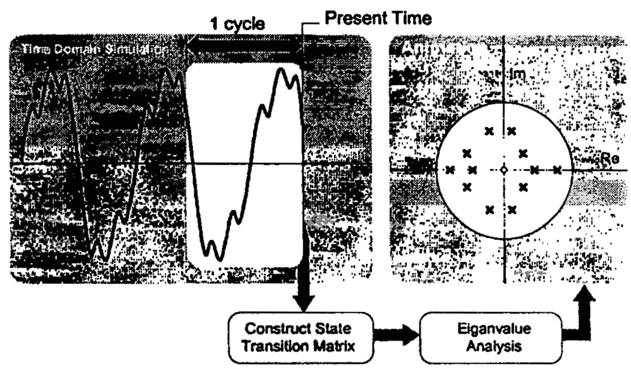


Figure 5. Illustration of Small Signal Stability Tracking

The proposed method has been applied to a power system with generators, loads and motors. A program-generated screen is illustrated in Figure 6. The simulated system is displayed in the lower left window in single line diagram form. It contains four three phase buses labeled 10 20, 30 and 40, connected via three phase transmission lines. Three phase generators are connected at busses 10, 30 and 40. Y-connected balanced loads are connected at buses 10 and 20.

The schematic diagram also contains three voltmeters and three current meters, as well as the stability animation object symbol (at the right of the schematic window). The meters monitor the voltage and current at bus 20.

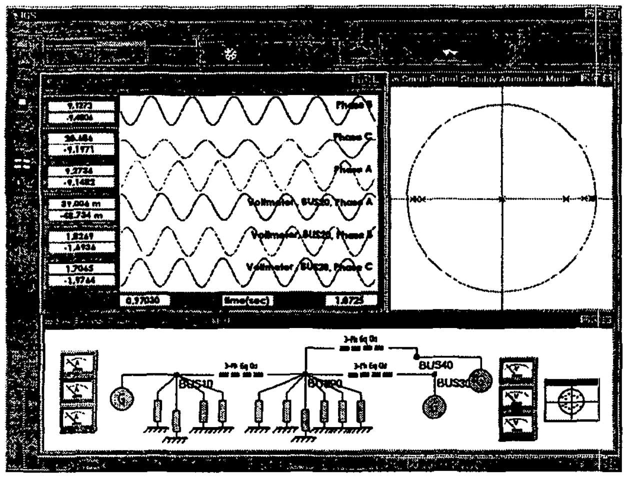


Figure 6. An Example Power System with Loads and Motors

The waveforms captured by the meters are displayed in the top left window of the screen image illustrated in Figure 6. The plot y-axis units are in kilovolts and kiloamperes. The computed system eigenvalues are displayed in the top right window. Note that all eigenvalues are within the unit-circle indicating a stable system. Both waveform and eigenvalue displays are continuously updated during the simulation, always indicating the present state of the system. For linear systems the eigenvalue map remains unchanged. For nonlinear systems the eigenvalue map changes with the operating point of the system providing instant feedback of the stability of the system.

Conclusions

The technology for development of virtual power system laboratories exists today. However, actual implementation of virtual laboratories are behind existing technologies. The reasons are: (a) need for better simulation methods that accurately capture all pertinent dynamics of power systems and (b) much work needs to be done to develop meaningful visualization modules of the plethora of different power system elements. We have discussed our recent work towards the development of a virtual environment. We have discussed specific examples of virtual laboratory exercises. From these examples, it is clear that virtual laboratories can be quite beneficial from the pedagogical point of view as they can provide visualizations of the system under study that are impossible in a physical laboratory. The presentation of the paper will include live demonstration of virtual laboratory exercises.

Acknowledgments

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Biographies

A. P. Sakis Meliopoulos (M '76, SM '83, F '93) was born in Katerini, Greece, in 1949. He received the M.E. and E.E. diploma from the National Technical University of Athens, Greece, in 1972; the M.S.E.E. and Ph.D. degrees from the Georgia Institute of Technology in 1974 and 1976, respectively. In 1971, he worked for Western Electric in Atlanta, Georgia. In 1976, he joined the Faculty of Electrical Engineering, Georgia Institute of Technology, where he is presently a professor. He is active in teaching and research in the general areas of modeling, analysis, and control of power systems. He has made significant contributions to power system grounding, harmonics, and reliability assessment of power systems. He is the author of the books, *Power Systems Grounding and Transients*, Marcel Dekker, June 1988, *Ligthning and Overvoltage Protection*, Section 27, Standard Handbook for Electrical Engineers, McGraw Hill, 1993, and the monograph, *Numerical Solution Methods of Algebraic Equations*, EPRI monograph series. Dr. Meliopoulos is a member of the Hellenic Society of Professional Engineering and the Sigma Xi.

George Cokkinides (M '85) was born in Athens, Greece, in 1955. He obtained the B.S., M.S., and Ph.D. degrees at the Georgia Institute of Technology in 1978, 1980, and 1985, respectively. From 1983 to 1985, he was a research engineering at the Georgia Tech Research Institute. Since 1985, he has been with the University of South Carolina where he is presently an Associate Professor of Electrical Engineering. His research interests include power system modeling and simulation, power electronics applications, power system harmonics, and measurement instrumentation. Dr. Cokkinides is a member of the IEEE/PES and the Sigma Xi.