AC 2009-1464: AN ANALOG POWER SYSTEM EMULATOR AS A LABORATORY TOOL FOR TEACHING ELECTRIC POWER SYSTEMS

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An Analog Power System Emulator as a Laboratory Tool for Teaching Electric Power Systems

Abstract

Most power systems courses incorporate both software and hardware components into laboratories. Each of these technologies has strengths and weaknesses. In this paper, a novel analog power system emulator is presented as a unique laboratory tool for teaching power systems. Hardware laboratories are time consuming and expensive, but are all important to give students a hands on approach to education. In contrast, software laboratories require little setup, however, software packages can have steep learning curves and only approximately represent real system behavior. In addition, due to the non-linear nature of power systems, many software packages suffer from convergence errors. This can cause students great difficulty and frustration in learning. The analog emulator presented here provides favorable aspects of both hardware experimentation and software simulation. Through a simple graphical user interface, it is an easy to use system. However, at the core there is analog hardware emulating the power system behavior. The result is a powerful educational tool. The emulator consists of two main components: software and hardware. The hardware comprises the power system emulation, data acquisition, and control circuitry. The software interfaces with the hardware to allow for control, data acquisition, and subsequent analysis. The emulator, once constructed, requires no manual intervention. All aspects of emulation are directly controlled through the software interface. Moreover, the emulator never fails to converge to a solution and exhibits a low learning curve. The user can configure, control, and observe a virtual power system through the software interface. Changes can be made in real time while the emulator is running. The results will appear instantaneously to the user. Many experiments, such as power system design, stability analysis, power factor correction, etc., can be derived and even automated with this tool.

Introduction

Power engineering curricula contain laboratory exercises as a key component. Individual exercises typically incorporate either software or hardware, sometimes both in tandem. This paper presents an analog power system emulator as a new tool to enhance traditional hardware/software power system laboratories. This emulator exhibits some advantages when compared to conventional hardware/software tools.

Hardware laboratories are expensive and time consuming to operate as compared to software exercises. As a result, hardware laboratories are usually relegated to studying individual components, such as machines, transformers, power electronic converters, or an interconnection of only a few components. It is simply not feasible to perform hardware based power system analysis, on a large scale, in an educational laboratory. Consequently, software is utilized for system analysis exercises.

Power system simulation software can be classified as one of two types. Software packages are designed to perform either steady-state analyses (power flow solvers) or dynamic analyses (time domain solvers). PowerWorld[1] and MatPower[2] are examples of power flow solvers and

PSCad[3] is an example of a dynamic solver. Depending on the objectives of the laboratory a suitable software package is chosen.

Power system hardware laboratories commonly consist of small scale power system components and measurement equipment for recording data. A standard course in power systems will examine AC and DC machines, transformers, RLC components, and the interconnection of these devices. A three bus power system in hardware has been developed in the Center for Electric Power Engineering at Drexel University[4] and up to a six bus system at the United States Military Academy. These setups are expensive and time consuming to configure and operate, but allow students hands on approach at learning power system behavior. Analog emulation is a potential, cheaper, alternative for power system analysis laboratories.

Historically, analog emulators were quickly eclipsed by digital computers as the desirable power system analysis tool, for both academic and industrial purposes. The limiting factor with analog emulators was the time required for programming and data acquisition. Programming consists of connecting all the analog hardware, setting initial conditions on integrators, etc. In addition, oscilloscopes and meters were required to observe and record the results. This process is much like typical hardware laboratories today. However, with advances in electronics, a new robust analog power system emulator has been developed.[5] Once constructed, this emulator eliminates the need for manual programming. The obstacle of time consuming programming has been overcome. The result is a robust educational tool that provides many advantages when compared to traditional hardware/software tools.

First and foremost, the emulator requires minimal setup time for experimentation. No further connections or manual configuration are required once the emulator is constructed. The student operates the emulator via a graphical user interface. Configuration, control, and data acquisition are handled remotely via software. Through this software, emulation hardware can be programmed for specific exercises. This is very similar to field programmable gate arrays (FPGA) or synthesis of hardware through VHDL programming. From a student's perspective, the interface appears similar to other power system software packages. However, behind this software package is robust power system emulation hardware. This hardware models power system dynamics and emulates system behavior faster than real time. As a result, it provides transient response of the system, steady-state solutions, and stability analysis instantaneously to the user. Once configured, the hardware runs constantly and behaves similar to a power system. The student can adjust parameters and make changes to the hardware during operation and observe the response of the system. It is analogous to operating a small scale power system. Table 1 enumerates and compares the performance of an analog emulator as a laboratory tool to traditional technologies.

Table 1. Comparison of Software, Hardware, and Analog Emulation as Laboratory Tools

	Software Packages	**Hardware Experiments**	**Analog Emulation**
Setup Time	Low	High	Low
Operating Time	Moderate	Moderate to High	Low
Analysis Capabilities	Dependant upon Package	Transient and Steady-State	Transient and Steady-State
Learning Curve	Moderate	High	Moderate to Low
Cost	Low	High	Moderate

The analog emulator exhibits some distinct advantages. Namely, the learning curve is not that high and setup/operation time is quite low. The learning curve is restricted to the students familiarizing themselves with the graphical user interface. In addition, the capabilities of the emulator are quite robust. Transient and steady-state analyses can be performed through the same interface and hardware. In contrast, hardware experiments require much setup and operation time. The learning curve is relatively high due to the experimental setup and measurement equipment. Software packages exhibit a low setup time but have moderate operating time, mainly due to simulation errors such as convergence problems. Moreover, capabilities are dependent upon which software package is used. Students are often required to learn multiple different software packages depending on what is covered in the curriculum. However, one distinct advantage of software packages is cost. The cost of software packages, as compared to hardware, is quite low. Educational versions of software can be obtained at heavily discounted prices, or in some cases free of charge. Analog emulation requires both hardware and software components. The resulting cost is lower than traditional power systems hardware laboratories, but it is more expensive than most software packages. In summary, the capabilities, ease of use, and moderate cost of an analog emulator make it a desirable educational tool.

The next section provides an overview of the power system emulator and user interface. The following section details the teaching methodology for this technology. The paper is ended with an illustrated laboratory example and conclusion.

Analog Power System Emulator

The analog power system emulator, shown in Figure 1, consists of numerous components. A high level overview of the emulator is provided here. There is a digital Computer with a keyboard and mouse for the software interface. Data acquisition and control hardware consists of analog-to-digital converters, digital-to-analog converters, and multiplexors. This hardware enables an interface between the digital computer and the analog hardware. Lastly, there is analog hardware that emulates the power system behavior. More specifically, the components of this emulator are as follows:

- National Instruments PXI chassis (PXI-1050)
- Digital computer with Intel processor (specify details)
- 2x National instruments DAQ cards (PXI-6071E)
- 3x National Instruments analog output cards (PXI-6703)
- National Instrument SCXI chassis (SCXI-1101)
- 2x National Instruments counter/time cards (PXI-6602)
- Keyboard, mouse, and monitor
- Analog emulation printed circuit boards

The National Instruments (NI) PXI chassis houses the digital computer and all the associated hardware for emulation. The chassis contains seven PXI slots. Two slots are dedicated to data acquisition cards (PXI-6071E) for acquiring data from the emulator. Another two slots are dedicated to counter time cards (PXI-6602) for digital control signals to the emulator. The last three slots house three analog output cards (PXI-6703) for analog control signals. Through LabVIEW software these cards, and hence the emulator, can be controlled directly through the software interface. The PXI chassis also contains four SCXI slots and associated power supplies. These slots contain the analog emulation circuit boards. In addition, there is a twelve slot SCXI chassis for expansion of the analog emulator to a larger system. With respect to the pricing equipment setup as shown in Figure 1, based on the National Instrument pricing structure at the time, the total cost amounted to approximately $20k. The majority of this cost is found in the parts that make up the PXI setup that includes the chassis controller with embedded Windows XP environment (NI PXI-8196) along with the necessary high resolution analog output cards (NI PXI-6704) and multi-function data acquisition card (NI PXI-6071E).

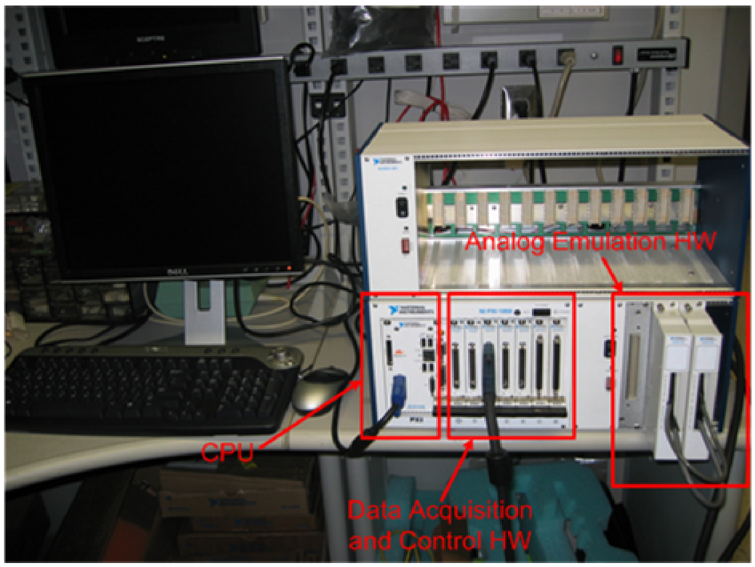

Figure 1. Power System Emulator

The analog emulation hardware contains analog models of power system components and some analog measurement/signal processing circuitry. The emulation method is based on a DC emulation approach to emulating AC power systems.[6] The power system model used in this emulator contains generators[7], transmission lines[8], transformers[9], and loads.[10] The generator model is a second order model based on the swing equation. The lines and transformers are steady-state impedance based models. The load model is a first order model based on induction machines. These models are represented in analog hardware across numerous printed circuit boards. These boards, shown in Figure 2, are designed to interface directly with the National Instruments SCXI chassis. A power system is constructed in analog hardware via the interconnection of these emulation devices, much like a real power system. The devices are hardwired together in the emulator. Different topologies and systems can subsequently be realized by turning devices on/off based on the desired configuration. Not included in this prototype, however planned for future versions, is the inclusion of switches to route components into different topologies. This would yield more flexibility in system configuration. A robust emulator, capable of realizing numerous power system configurations, would consist of many fundamental components (generators, lines, loads, etc.) interconnected by an array of switches. The states of the switches, and subsequently the power system topology, can be set via software. The current hardware design allows for remote operation of a three bus power system emulator.

Each component in the emulator has input signals to configure the devices. All model parameters, operation status (in service/out of service), and initial conditions for integrators can be controlled by external signals. Data acquisition is also handled via hardwired A/D converters and multiplexors. Operation is directly controlled through the software interface shown in Figure 3. This figure shows a three bus power system example. The system contains two generators, a load, and three transmission lines. The user can specify all parameters and initial conditions via the control boxes on the GUI. Clickable buttons allow for setting of initial conditions, creation of faults or other events, and turning the emulation on or off via analog integrators. Data acquired is also shown on the GUI in the gray boxes (numerical form) and via oscilloscope diagrams (waveforms). Data is acquired and updated constantly during operation of the emulator. Moreover, the software can be automated to run many cases quickly and acquire pertinent data.

Figure 2. Analog Emulator PC Boards

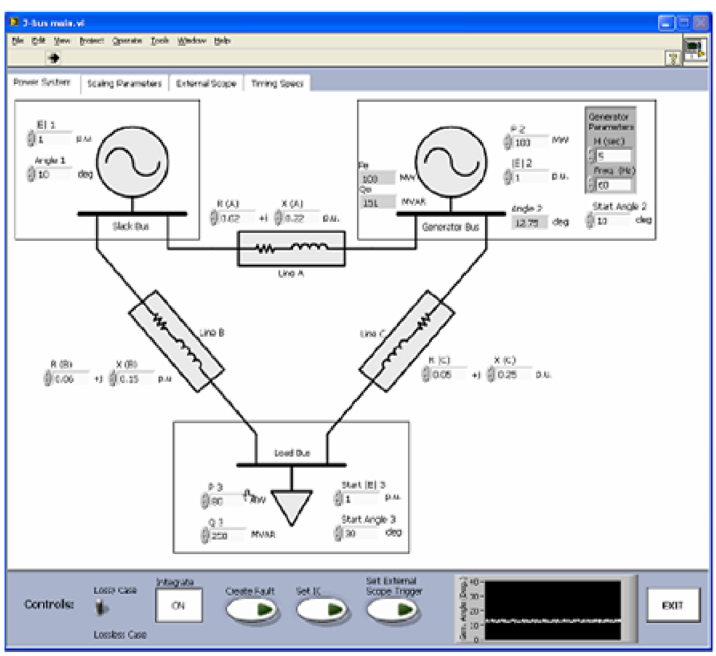

Figure 3. Analog Emulator Graphical User Interface

A power system emulator fits into the curriculums of the United States Military Academy and Drexel University in similar fashions. The emulator is geared particularly for power system courses. However, it is applicable to other topics in electrical engineering curriculums. Many concepts, such as analog and digital circuits, control, sensors, and data acquisition, which are prevalent in electrical engineering curriculums, are encapsulated in a laboratory based on an analog power system emulator. An overview of the EE curriculum at the United States Military Academy is shown in Table 2.

Table 2. United States Military Academy Electrical Engineering Curriculum

Sophomore	Junior		Senior	
2nd Semester	1st Semester	2nd Semester	1st Semester	2nd Semester
Intro to EE	Intro to Electronics	Electronic Design	EE System Design I	EE System Design II
Digital Logic	Signals and Systems	Electromagnetic Fields and Waves	Power Engineering	EE Seminar
Engineering Math	Computer Architecture	EE Depth courses/elective	EE Depth courses/elective	EE Depth courses/elective

Currently there is a senior level Power Engineering Course in the electrical engineering curriculum at the United States Military Academy. This course covers machines, transformers, transmission lines and system analysis. An analog power system emulator is planned to replace and/or enhance power flow software in the current laboratory structure. In addition, the emulator can be used for a small scale power system design project, specifically to emulate and evaluate the performance of potential designs. Beyond the scope of the power engineering course, the engineering concepts involved with the emulator are relevant to introductory electronics and electronic design courses. Concepts in these courses can be reinforced and showcased via an analog emulator application. Moreover, concepts of measurement, stochastic systems, A/D and D/A conversion, which are covered in engineering math and EE depth courses and electives, are all present in the emulator. Students will get hands on exposure of these concepts, which they have already seen in theory, by incorporating the emulator in a senior level course.

Table 3. Drexel University PES Curriculum

Year	Term	Drexel Curriculum for Engineering Students						
1	1 2 3	Mathematical & Physical Foundations of Engineering		Chemical & Biological Foundations of Eng.	Engineering Design and Laboratory		Liberal Studies	Seminar
2	4 5	Systems	Energy	Materials	Introductory Professional Courses	Evaluation & Presentation of Exp. Data		
3	6 7	Inter-disciplinary	Third and Fourth Year Professional Courses (8 Courses, 4 Credits Each)			L a b	Liberal Studies	
4	8 9	Inter-disciplinary				L a b	Liberal Studies	
5	10 11 12	Senior Design	ECE Technical Electives	Free Electives	Free Electives	L a b	Liberal Studies	

As seen in Table 3 above, at Drexel University, the ECE curriculum provides a certain level of flexibility in the selection of courses to fulfill B.Sc requirements. This table reflects the five year version which is taken by the majority of students. With respect to where the emulator fits, one finds a few options: a) as an experimental component module of the sequence of lab courses that run from Years 3-5; b) as an experimental module within one of two junior (Year 4) level power engineering courses called ECEP354 Energy Management Systems and c) as a experimental module within the second quarter of the three course sequence in Power Systems (ECEP401, 402 and 403) offered to all power engineering majors. The next section provides details on a teaching methodology for this power system emulator.

Teaching Methodology

A number of experiments may be developed based on the emulator. At Drexel University these experiments in turn can be integrated into one of the three options discussed in the previous section. This in essence entails coursework ranging from 3rd year or pre-junior students to 5th year electrical and computer engineering and possibly graduate students. In addition, the laboratories can be frequently used for demonstration purposes for outreach and open house events. To provide students with experience on various power system phenomena and interactions, a set of experiments can be designed to include the: (i) Single-Phase AC Power Experiment; (ii) Three-Phase AC Power Experiment; (iii) Fault Analysis Experiment; (iv) Transmission Line Parameters Experiment and (v) Transient Stability Analysis Experiment. Please note that experiments (i) and (ii) can be performed by all electrical and computer engineering students. In regards to the United States Military Academy, the aforementioned experiments encompass most topics covered in the senior level power engineering course.

To provide students with experience on various power system operating and planning functions, the instructor will first lead a discussion on present day computational methods. This will set the stage for the use of the emulator showcasing its multiple advantages including its relative ease of use based on its low learning curve. The accompanying experiments will sometimes be accompanied by software-based studies for the purposes of verification and validation. Please note that all experiments will be conducted in a safe and controllable environment at all times based on identical safety procedures used in all other hardware-based laboratories offered at Drexel University and the United States Military Academy. The next section presents a power flow experiment using an analog emulator.

Example

In this section, the authors demonstrate two examples showing how the emulator may be utilized for educational purposes. More specifically, these exercises are to perform load flow and contingency analysis on a 3-bus power system. All examples are emulated in hardware 2500 times faster than real time. As shown in Figure 3, the test system consists of two generators (slack bus, PV bus) and one constant power load (PQ bus). The load flow example is presented first.

Load Flow

When performing load flow, the students will configure and operate the emulator for numerous predetermined cases. For this example five cases, listed in Table 4, are examined.

Table 4: Test Power System Case Parameters

Case	|V2| (pu)	P2 (MW)	P3 (MW)	Q3 (MVAR)	Z12 (pu)	Z13 (pu)	Z23 (pu)
1	1	-75**	50	37.5	0.02+j0.20	0.02+j0.20	0.04+j0.40
2	1	-125**	75	56.25	0.02+j0.20	0.04+j0.40	0.02+j0.20
3	1	-75**	100	75	0.04+j0.40	0.02+j0.20	0.02+j0.20
4	1	-125**	125	93.75	0.02+j0.20	0.02+j0.20	0.04+j0.40
5	1	-75**	125	93.75	0.02+j0.20	0.04+j0.40	0.02+j0.20

*** Note that generated power is denoted as a negative value, load demand is denoted as positive.*

A configuration file is provided which initializes all parameters for the three bus system. To acquire the load flow solution for each case, a student is required only to apply and relax the system's initial condition. This is done via controls located within the graphical user interface. The student is not required to have access to the emulation hardware.

For all results, the authors utilize solutions yielded via digital simulation performed in Matlab 7.1 as a reference. It is the authors' expectation that emulation, as described in previous sections, may be utilized as an alternative to simulation as well as allows students to perform load flow analysis accurately, quickly, and with minimal effort. This is supported by the data presented in Figures 4 and 5.

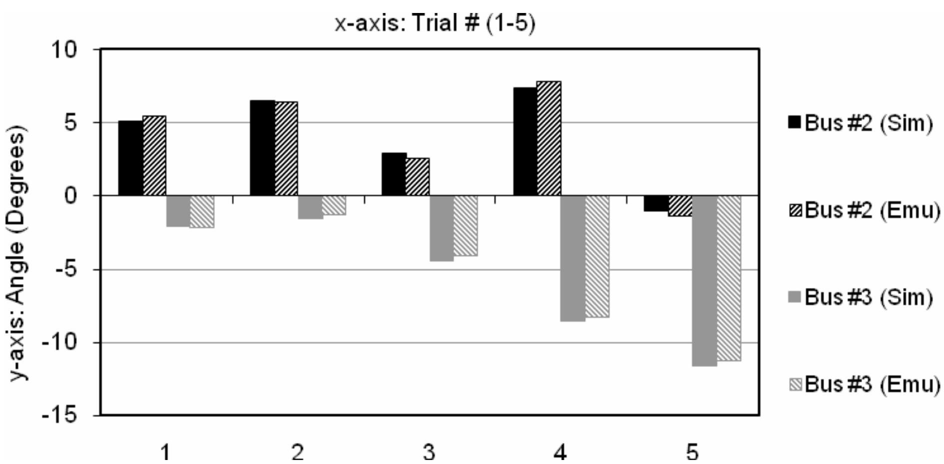

Figure 4: Comparison of Simulated (Solid) and Emulated (Striped) Load Flow Results for Voltage Angle at Buses #2 (Black) and #3 (Grey)

These figures demonstrate that the load flow solutions yielded via emulation and simulation match one another well, differing on average 1.56%. This percentage is with reference to the idea or simulated result. In addition, once the students obtain a load flow solution, the emulator is physically operating at that point. Subsequent analysis, such as line contingency and stability analysis can be performed at this time.

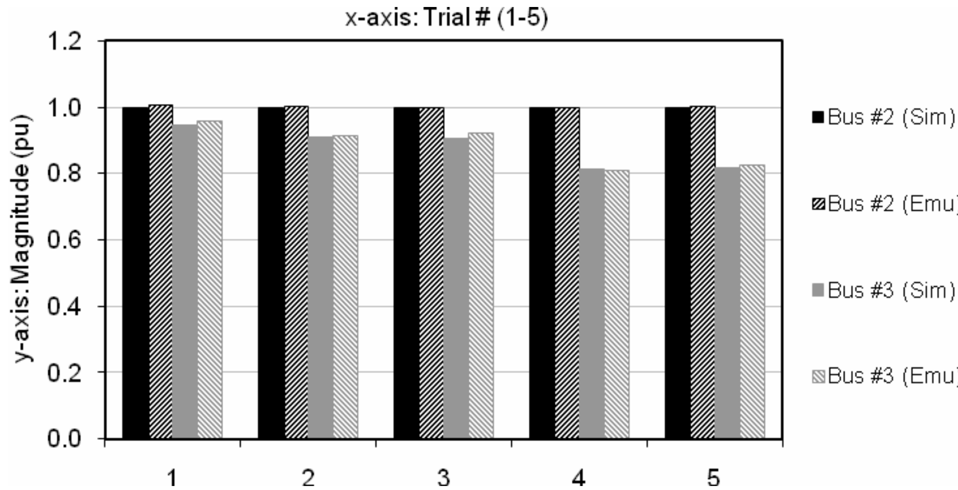

Figure 5: Comparison of Simulated (Solid) and Emulated (Striped) Load Flow Results for Voltage Magnitude at Buses #2 (Black) and #3 (Grey)

Contingency/Stability Analysis

When performing contingency and stability analysis, the students will configure and operate the emulator for given operating point, and then perturb the system. Observation of the system will yield stability information and the new operating point (if the system is stable). Line contingencies are examined in this example. This consists of four cases, including the base case, listed in Table 5. One transmission line is removed from the system for each of cases two through four. For example, the transmission line "Line 12", the line connecting buses one and two, is removed from the emulator. This is physically accomplished by clicking a button in the GUI which, subsequently, turns off the analog hardware emulating that transmission line. Data is then recorded and analyzed.

Table 5: Contingency/Stability Case Parameters and Configurations

Case	**|V2| (pu)**	**P2 (MW)**	**P3 (MW)**	**Q3 (MVAR)**	**Z12 (pu)**	**Z13 (pu)**	**Z23 (pu)**	**Contingency**
1	1	-100	150	50	0.02+j0.22	0.015+j0.15	0.019+j0.19	None
2	1	-100	150	50	0.02+j0.22	0.015+j0.15	0.019+j0.19	Line 12
3	1	-100	150	50	0.02+j0.22	0.015+j0.15	0.019+j0.19	Line 23
4	1	-100	150	50	0.02+j0.22	0.015+j0.15	0.019+j0.19	Line 13

For this example, the bust voltage at the load bus (bus 3) is monitored for voltage stability. Voltage angle and magnitude for all cases are enumerated in Figures 6 and 7 respectively. The system is stable for all cases and the emulated results track the simulation results closely. However, cases three and four are stressing the system. The resultant voltage magnitudes are very low. A more heavily loaded system can showcase instability for these contingencies.

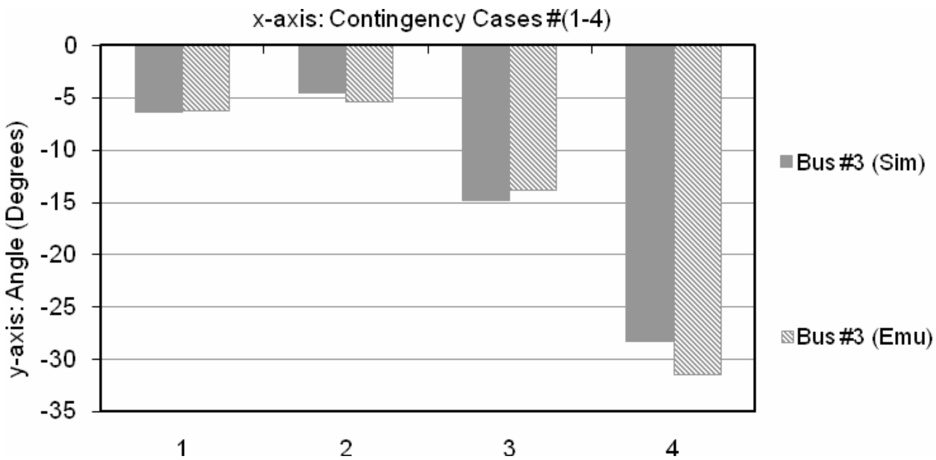

Figure 6: Comparison of Simulated (Solid) and Emulated (Striped) Contingency Results for Voltage Angle at Bus #3

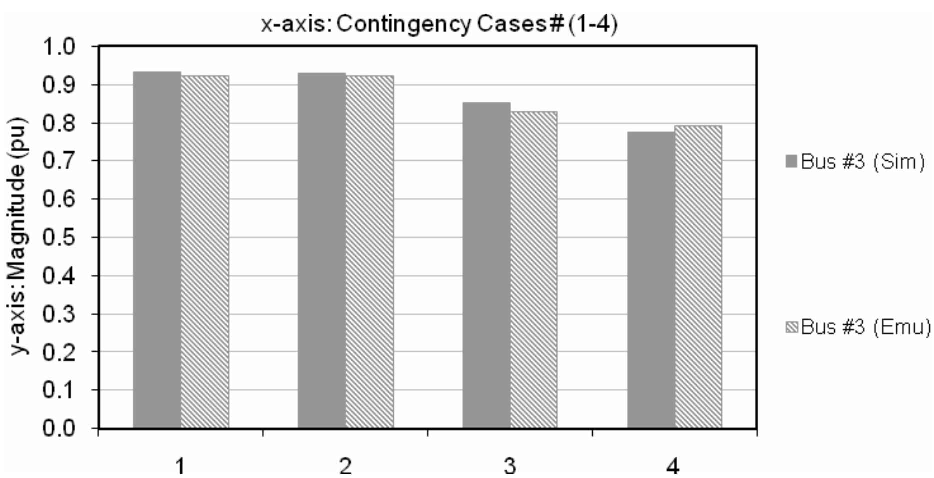

Figure 7: Comparison of Simulated (Solid) and Emulated (Striped) Contingency Results for Voltage Magnitude at Bus #3

Conclusion

This paper presented an application of a power system analog emulator as a laboratory tool. This analog emulator exhibits some favorable advantages as compared to traditional software/hardware tools. As a result, it will enhance existing power systems laboratories. The emulator is simple to use and setup like most software tools, while still containing hardware that behaves much like a real power system. Moreover, the emulator never fails to converge to a solution and exhibits a low learning curve. Students can configure, control, and observe a virtual power system directly through the software interface without changing any hardware connections. Changes to the emulator can be made while the emulator is running. The subsequent results appear instantaneously to the user. Many experiments, such as power system design, stability analysis, power factor correction, etc., can be derived and even automated with this tool. A formal assessment of learning with this analog emulator will be performed in the future.

Acknowledgements

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