

## Integrating a Power Systems Laboratory into a Client/Server Based Computing Environment

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### 1. Abstract

The primary goal of the project is to develop a set of experiments which will allow students to examine power systems in a realistic manner. Drexel University's *Interconnected Power Systems Laboratory (IPSL)* provides an interchangeable real-life power system network and a computer interface to the system in order to provide control and data capturing. The computer interface utilizes **client/server** and industry standard networking technology to help students visualize power system phenomena as seen by the system operator via an Energy Management System (EMS). This new laboratory will become an important piece of the new Drexel University curriculum, which emphasizes computer-aided design and hands-on laboratory experience coupled with longitudinal courses. A fault analysis experiment has already been designed on the IPSL and will be discussed as an example.

### 2. Introduction

The new Drexel Curriculum is a redesign of the methods of teaching electrical engineering fundamentals and applications in a way that will meet the needs of the students and industry in the 21st Century. The curriculum revision will produce a set of modern courses emphasizing computer-aided design and **hands-on** laboratory experience coupled with longitudinal courses. The motivation for changing the curriculum comes from the faculty, who have been using the same curriculum for at least fifteen years, and also from the students, who have expressed a desire for a more applications-oriented and hands-on experience.

These new courses will put engineering problems up front (design, experimentation, and analysis), provide basic science and math background as needed, use team work, build communication skills, and put engineering in a social context. In terms of content distribution, courses will combine compatible sets of topics from different "traditional" areas of electrical and computer engineering. Courses such as these, which break down the conventional "barriers" between disciplines, may provide the students a clearer sense and more realistic picture of what the future holds for electrical engineers. It is not expected that all courses can be constructed in this manner.

*The Interconnected Power Systems Laboratory* has been designed to meet the demands of this new Drexel curriculum. It is hoped that the modernization of the power systems laboratory at Drexel University will counteract the declining interest in the power systems curriculum. The newly designed *Interconnected Power Systems Laboratory* reduces the various steps involved in laboratory setup and data gathering and provides more time for the students to appreciate the theory and concepts behind the experiment.



The IPSL was designed to provide students with a hands-on learning experience about the attributes and implications involved in the management and control of a small electric power system. The general objectives of this laboratory are:

- . Provide a set of experiments on the interaction of the various system components in a real-life power system operating environment.
- Experimental Model validation platform.
- . Provide for exploration of relatively new areas in power systems: semiconductor control, programmable relays, flexible AC transmission systems (FACTS), among others.

The developed IPSL experiments incorporate the emerging technologies of **client/server** and industry standard networking. Client/server technology, in the context of this paper, refers to using multiple slave server computers to provide information to a master client computer. Industry standard networking refers to the EPRI Utility Communication Architecture (UCA) component called MMS (Manufacturing Message Specification), an ISO protocol devoted to interconnecting manufacturing and industrial heterogeneous devices on a network. Using these technologies along with readily available computer hardware and modem software programming techniques, a customized graphics intensive laboratory environment was created. This environment enhances the students' perception of electrical power systems and their performance by graphically modeling the active control elements of the power system on a color computer screen.

In recent years, there have been a number of papers written on the development of educational electric machinery laboratories geared towards the use of computers. For example, Case Western Reserve University has set up a facility for computer control of electrical drives and machines[ 1]. Similar facilities have been set up at the University of Missouri-Rolla[2], Ohio State University[3], and New Mexico State University[4]. Concordia University has implemented a computer-aided power electronics laboratory[5], while Auburn[6] has implemented computer controlled protective relays systems laboratory. The above projects show that most of the educational laboratory development in the area of power and energy has been in the computerization of one of its main components: *electric machinery, power electronics, power electronics and high voltage*. In addition, there have been quite a few papers[7-9] that have stressed the necessity of incorporating realistic power system laboratories in undergraduate curricula. While a power systems educational laboratory built at Chalmers University in Sweden[ 10] relies solely upon power systems modeled in software, most designers, such as those at the University of Houston[ 11] incorporate both software models and actual real power system components.

The marked difference between Houston's facility and Drexel University's IPSL is: (i) Drexel's power system consists of the interconnection of components (such as generators, motors, transformers) that the students have learned in previous courses; (ii) It can be easily reconfigured to a two bus, three bus, etc. power system; (iii) It is inexpensive since it uses components readily available in the lab.

It has been planned to implement several experiments on the IPSL system. These experiments include: (i) Fault Analysis; (ii) Load Flow Analysis; (iii) Power System Stability; (iv) Economic Dispatch; and finally (v) Motor Drive Studies.

A fault analysis experiment was the first experiment to be implemented on the IPSL system. The purpose of the fault analysis experiment is to provide students with valuable experience related to the characteristics of the different kinds of short circuit fault conditions. This experience includes:

- . How faults are created.
- The magnitude of the fault currents that are produced during different types of faults that occur on a power system network.
- . The characteristics of the voltages and currents produced from fault conditions over a duration of time.
- . How faults are cleared.

It is the aim of the authors to show how the IPSL is used to teach students how to analyze real-life power system networks and show them the modern tools that are available to Energy Management System operators. This laboratory will provide a more realistic picture of what the future holds for electrical power engineers. The following discusses the problems that had to be resolved and the approach to the solution of these problems in order to accomplish this goal. Section 4 presents the set-up and results of a fault experiment on a two bus (two generator, single line) power system. The conclusion of the paper is in Section 5.

### 3. Problem Formulation and Methodology

The main objective of the project was to design interactive laboratory experiments that would provide students with an opportunity to examine power systems in a realistic manner. It was desired to provide students with the experience of visualizing power system phenomena in terms of the Energy Management System (EMS) equipment. In order to realize this objective, it was necessary to provide a real-life power system network and a computer interface to the system in order to provide control and data capturing. The power system that was designed is shown in Figure 1. This particular power system configuration can be broken up or rearranged to meet the needs of the particular experiment to be performed. The power system network consists of two synchronous generators, a motor, a transformer, protective relaying, and three transmission lines (using lumped parameter equipment for resistances, capacitances, and inductances). The computer interface to this system consists of several computers serving as Remote Terminal Units (RTUs) and one computer serving as the EMS central computer (The Master Station). Signal conditioning hardware provides a safe interface between the computers and the power system. This type of setup leads to many kinds of hardware and software design problems, which will be discussed separately in the sections that follow.

#### 3.1 Hardware

The four main problems involved in the hardware design of the Interconnected Power Systems Laboratory are:

- 1) The creation of a realistic power system network.
- 2) Signal conditioning hardware needed to provide a safe interface between the power system and the Remote Terminal Unit (RTU) computers.
- 3) Finding suitable off the shelf data acquisition (DAQ) hardware to digitize signal conditioned waveforms in the RTUS.
- 4) Setting up a Local Area Network (LAN) connecting the RTUS and the master station.



### 3.1.1 Realistic Power System Network

The power system that was designed for the IPSL is shown in Figure 1. The power system network consists of two synchronous generators, a motor, a transformer, protective relaying, and three transmission lines. This configuration is flexible enough to perform the experiments listed above and simple enough for student to analyze and model. This system has to be able to handle fault currents that the students will be creating for some of the experiments. Based on the synchronous generator ratings, maximum fault currents may reach as high as 20 amperes. Laboratory floor space is also an issue in the design.

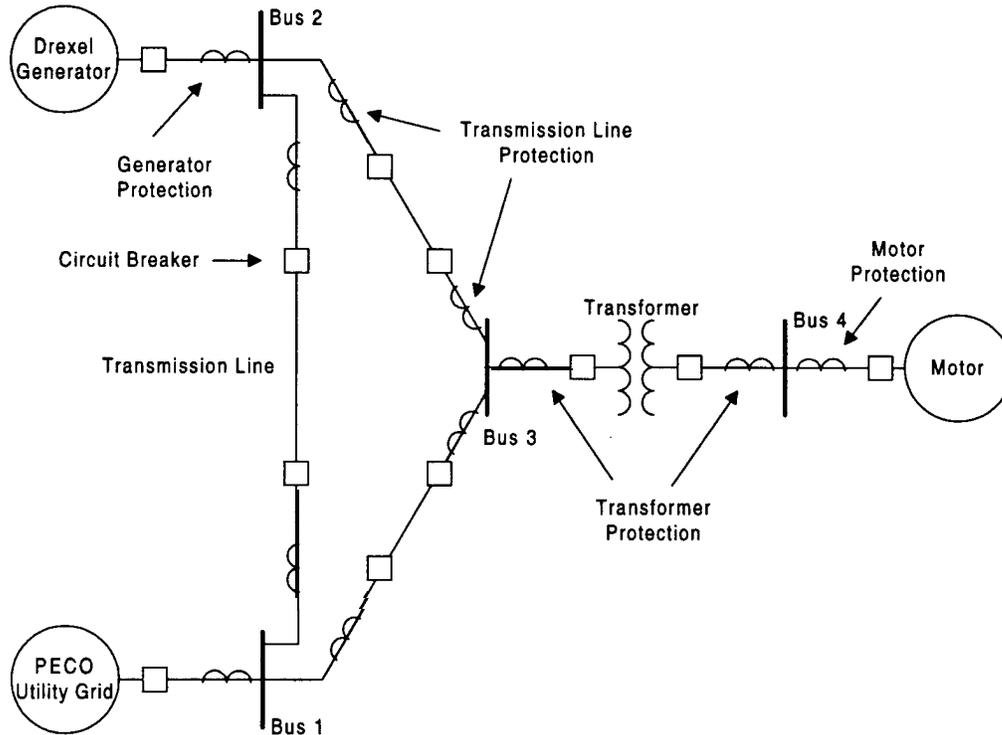


Figure 1: Power System Laboratory Setup

At the present time, this power system has not yet been completely built. The power system at the present time consists of two synchronous generators interconnected with a single transmission line. This setup is suitable only for the fault analysis experiment (which is the only experiment which has been completely designed). Lumped parameter equipment was used for resistances, capacitances, and inductances. A four position switch together with a fault creating circuit were incorporated into the setup in such a way that they allow the student to create a fault at 0%, 33%, 66%, or 100% of the line. Two electromechanical relays (rated at 115V, 30 A), placed at each of the generators, are used to clear the created faults.

### 3.1.2 Signal Conditioning Circuitry

Signal conditioning circuitry had to be designed to create a safe interface between the transmission lines and the data acquisition hardware. The signal conditioning circuitry had to be designed to perform four tasks: (i) attenuation to reduce the signals to levels acceptable to an electronic analog to digital converter; (ii) surge suppression to prevent voltage spikes from entering the PC; (iii) low pass filtering to reduce high frequency electrical noise; and (iv) isolation to prevent ground loops.

A schematic of the signal conditioning circuitry, that was developed to meet these requirements, is shown in Figures 2a and 2b. Separate circuits were designed for measuring voltages ( $V_a$ ,  $V_b$ ,  $V_c$ , and  $V_n$ ) and currents ( $I_s$ ,  $I_b$ ,  $I_c$ ,  $I_n$ ). Both circuits consist of four stages: (i) attenuation stage; (ii) surge suppression stage; (iii) isolation stage; and (iv) the low pass filter stage. The two circuits differ only in the attenuation stage.

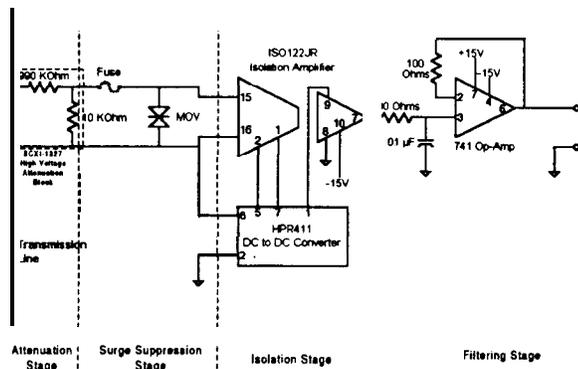


Figure 2a: Voltage Signal Conditioning

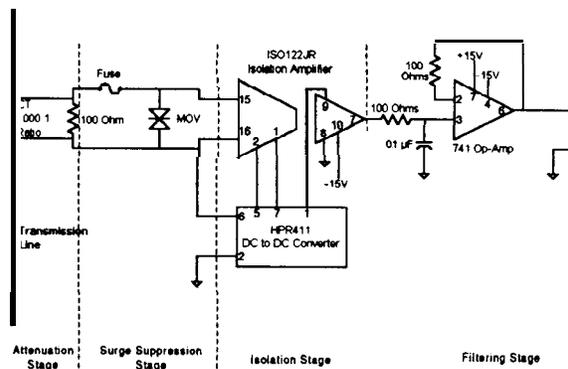


Figure 2b: Current Signal Conditioning [12]

### 3.1.3 Data Acquisition Hardware

Each RTU must be able to sample three phase voltage (plus neutral) and three phase current (plus neutral) waveforms at one point on the transmission line. This means that each RTU must sample eight signals. This required a DAQ board with at least eight input channels and a minimum sampling frequency of 14.4 KHz in order to obtain thirty samples per cycle per channel for 60Hz waveforms. A *National Instruments AT-MIO-16E-2* data acquisition card was chosen to perform this task. These boards were installed in each of the RTUS. Each card is capable of sampling sixteen channels, is 12-bit, and has a maximum sampling rate of 500 KHz. Since the project design calls for sampling eight signals per RTU, each signal can be sampled at a maximum rate of 62.5 KHz.

### 3.1.4 Local Area Network (LAN)

The project design calls for all of the RTU computers to pass near real-time data to the master station computer. This required the setup of an Ethernet LAN network. An Ethernet 10-baseT hub, twisted-pair networking cable, and crimp-on network jacks were used to create this LAN. Further networking considerations, concerning real-time data flow, will be discussed in section 3.2.3 of this paper.

## 3.2 Software

The three main problems involved in the software design of the project are:

- 1) The Master Station Laboratory Application.
- 2) The RTU DAQ Application.
- 3) Networking and Real-Time Data Flow Programming.

### 3.2.1 The Master Station Laboratory Application.

Master station laboratory applications have to be developed in order to provide students with: (i) the basic theory behind the experiment to be performed including equations, colorful diagrams and pictures, etc.; (ii) a **pre-lab** in which the students perform some preliminary calculations to give him/her a preview of the

type of results to expect; (iii) detailed instructions on how to perform the experiment; (iv) the control center from which to actively perform the experiment; and (v) data collection and presentation in the form of colorful graphs and tables. It is desired to present all of this information to the students in the most graphical, interactive, and educational way possible. The master station application must also include client-side network programming in order to receive data from the RTUS. This programming will be discussed separately in section 3.2.3 of this report. To date, only the Fault Analysis Experiment application has been completed.

*Microsoft's Visual Basic 3.0* was the computer language chosen to implement the master station programming. The *Visual Basic* programming system allows the programmer to create attractive and useful applications that fully exploit the Window's graphical user interface (GUI)[ 13]. *Visual Basic* makes the programmer more productive by providing appropriate tools for the different aspects of GUI development. A screenshot from the Master Station Fault Analysis Experiment application is shown in Figure 3. This application will be discussed further in section 4, *Examples and Discussion*.

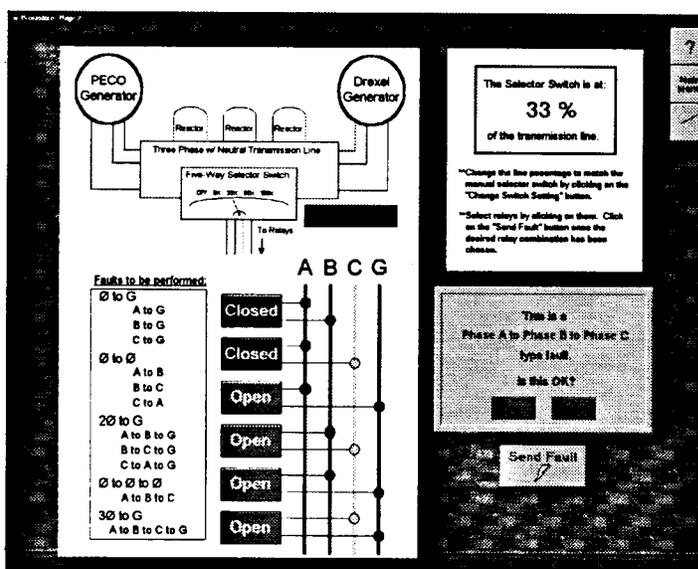


Figure 3: GUI Interface Used to Create Faults from the Master Station Application [12]

### 3.2.2 The RTU DAQ Application

The project design calls for a data acquisition application to run on each of the RTUs. This application must control the data acquisition board installed in the RTU. The application must provide for sampling eight signals ( $I_s$ ,  $I_b$ ,  $I_c$ ,  $I_n$ ,  $V_a$ ,  $V_b$ ,  $V_c$ , and  $V_n$ ). Some experiments may only call for sampling the voltage and current in one phase of a transmission line. The software should be flexible in these situations.

While collecting the sampled data, the RTU application must also: (i) display some **oscillographic** data from the sampled channels (the student should be able to select which channels to be displayed); (ii) calculate RMS voltage, RMS current, frequency, power, and power factor on a cycle per cycle basis; (iii) capture events, such as fault conditions; and (iv) package the processed data and send it over the network to the master station computer in near real-time. The network server-side programming will be discussed further in section 3.2.3.

*Microsoft Visual C++ 2.0* was the language used to create this RTU DAQ program. Microsoft *Visual C++* provides a very powerful and flexible development platform which includes many useful tools for GUI development. A screenshot from the RTU DAQ application is shown in Figure 4. This DAQ application provides the data collection, data processing, data display, and communications functions as stated above. Dynamic Link Libraries (DLLs) provided by National Instruments, make it possible for the RTU application to control the DAQ hardware directly. The oscillographic data is displayed on screen using the *LabOBJX Real-Time Chart* VBX tool.

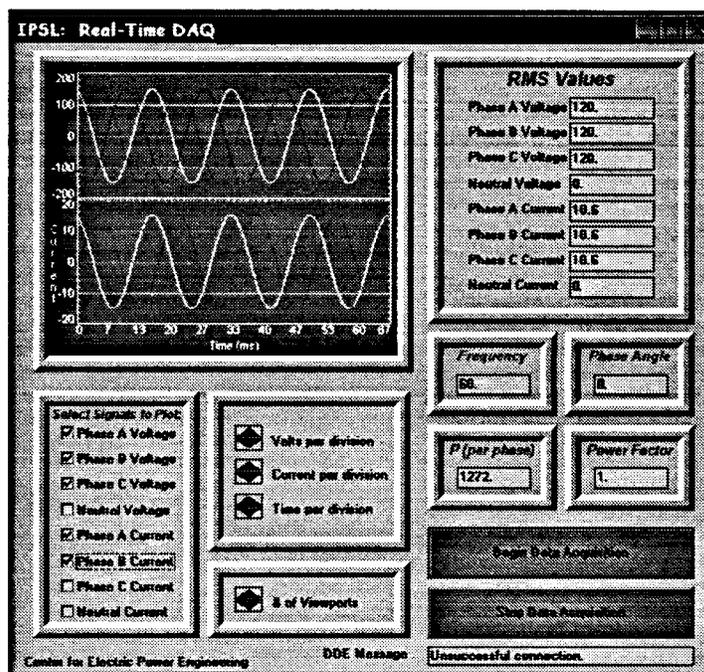


Figure 4: Graphical User Interface for RTU

### 3.2.3 Networking and Real-Time Data Flow Programming.

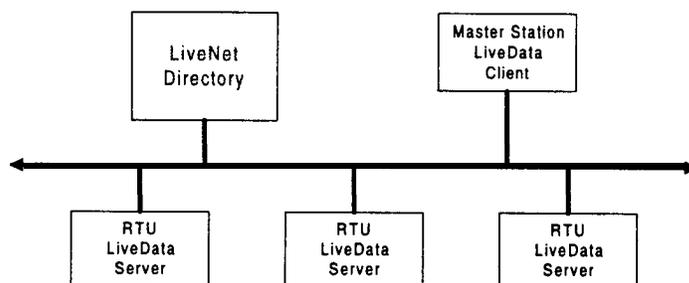
Data must be sent from each of the RTUS to the master station in near real-time. This calls for using a network protocol designed for real-time applications. This must be an open network protocol that will not change with every new release of client-server or **middleware** technology. It will also be more beneficial to use non-proprietary network protocols, preferably used by actual utilities.

The network protocol that was chosen to provide communication between the Master Station and the RTUS was the *LiveNet* network protocol purchased from *Cycle Software*. *LiveNet* is a group of software components that allow the user to create various kinds of corporate networks easily and quickly. *LiveNet* consists of four major components:

- 1) An Open Systems Interconnect (OSI) protocol stack.
- 2) The LiveNet Directory, a directory containing the names and addresses of every application that will be communicating on the network.
- 3) The LiveNet Router, which can connect up to four LANs and four WANS.
- 4) The LiveNet Directory Manager, a diagnostic tool with which the user can observe the functioning of the network [14].

Along with the Visual Basic Laboratory Experiment program, the *Cycle LiveData Client* program also runs on the Master Station. The LiveData Client program allows the user to gather real-time data from other LiveData clients and servers on the LiveNet network.

Each of the RTUS run a LiveData server program. Voltage, current, frequency, power, and power factor calculations are passed near real-time to the RTU LiveData servers from the *Microsoft Visual C++* programs running on each of the RTUS. The LiveData Client program running on the Master Station is set up to poll the values passed to the RTU server programs every 1/2 of a second. The values are then sent to the Master Station Visual Basic program through an automatic dynamic data exchange (DDE) link. The Visual Basic program then can display these values to the user. Figure 5 shows the LiveNet network that was used in the project.



**Figure 5: Cycle LiveNet Network [12]**

### 3.3 Pedagogy

The laboratory is set up so a group of four or five students can perform the labs simultaneously. The master station provides the students with **prelab** calculations and questions, theory, instructions needed to perform the experiments, the control center for performing the experiments, and data collection from all points monitored on the power system. The RTU computers provide the students with near real-time **oscilloscopic** signal data as well as near real-time charts showing voltages, currents, frequency, power, and power factor from one point on the line. The students can take turns operating the master station (control center) and monitoring the data collected at the RTUS, so that they become familiar with all aspects of the laboratory setup.

The laboratory experiments are designed to reinforce the theory the students learn in class. The experiments will be designed to verify this theory. The students will be asked to make redundant measurements with oscilloscopes and meters for the purpose of error evaluation. The students will also be asked to perform software simulations (load flow, pspice, etc.) to verify data obtained during the experiments. The students can then use all these results to write a laboratory report.

## 4. Examples and Discussion

Presently, the Fault Analysis Experiment is the only completely designed experiment. The complete setup for this experiment, as shown in Figure 6, has been set up in **Drexel** University's Power Laboratory. The laboratory setup consists of the following:

- 1) A three-phase utility grid source (regulated to 110V).

- 2) A Drexel three-phase generator(110V, 5kVA).
- 3) A three-phase transmission line module (Total impedance of  $18\Omega/\text{phase}$ ).
- 4) Three signal conditioning modules (Each module is capable of handling eight input signals).
- 5) A five position fault location switch (Used to select which part of the line to create a fault).
- 6) A fault creation circuit.
- 7) Two electromechanical relays (rated at 115V and 30 A).
- 8) Four Data Acquisition Cards (National Instruments AT-MIO-16E-2).
- 9) A SEL-321: Directional Overcurrent Relay Fault Locator.
- 10) Two 90Mhz Pentium PC computers (One master station and one RTU), two 486DX PC computers (Two RTUs), and all laboratory software.
- 11) A 10 base T LAN and the Cycle Livenet protocol.

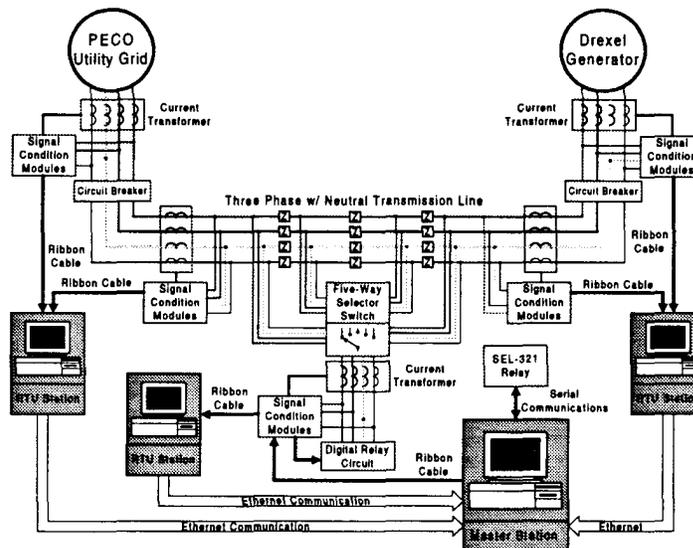


Figure 6: IPSL Setup for the Fault Analysis Experiment [12]

During the Fault Analysis Experiment, the students will have to create and identify many different kinds of short circuit faults. The master station application teaches students how to create faults by supplying them with interactive visual aids. One such visual aid can be seen back in Figure 3. This figure graphically illustrates how the fault creation circuit operates. The student can see how the digital relays, acting as breakers, are used to short the different phases of the transmission line together. The student can open or close these relays with the simple click of a mouse button.

Figure 7 shows a screen shot from the master station application. This screen shows a three phase fault that was created and captured using the master station IPSL application (using the interface shown in Figure 3). As the figure shows, graphs for  $I_a$ ,  $I_b$ ,  $I_c$ ,  $I_n$ ,  $V_a$ ,  $V_b$ , and  $V_c$  are presented. The students can use these graphs to observe the magnitude of fault currents and voltages that are produced when different types of shorted fault conditions are created. The **prefault** data capturing allows the students to observe the state of the transmission line before the faults are created so they can compare the **prefault** and postfault waveforms and see exactly when the faults were created. The master station graphs also make it possible for the students to visualize almost the exact moment when the faults are cleared. Figure 7 shows a three phase fault that was cleared after three cycles. This figure also reminds the student of what percentage of the transmission line the fault was created.

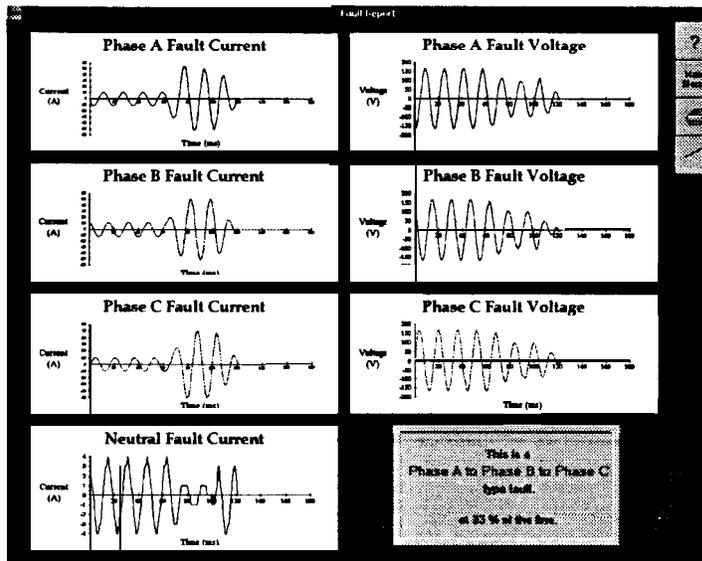


Figure 7: Fault Report Screen from Master Station Application [12]

## 5. Conclusion

The primary goal of the project is to develop a series of experiments which will allow students to examine power systems in a realistic manner. The Fault Analysis experiment is the first in a series of experiments to be implemented in Drexel University's Interconnected *Power Systems Laboratory*. The laboratory provides the students with hands-on experience of the limitations and methods of control of an energy management system.

The developed Interconnected Power Systems Laboratory incorporates the emerging technology of **client/server** real-time computing with power systems analysis. Using readily available computer hardware along with modern software programming techniques, a customized graphics intensive **laboratory** environment was created. This environment enhances the students' perception of power electrical systems and their performance by graphically modeling the active control elements of the power system on a color computer screen. The laboratory setup removes some of the steps involved in laboratory setup and data gathering and provides more time for the students to appreciate the theory and concepts behind the experiments.

The Interconnected Power Systems Laboratory was designed to put engineering problems up front (design, experimentation, and analysis), provide basic science and math background as needed, promote student team work, build communication skills among students, and put engineering in a social context. It is hoped that this **laboratory** will help break down the conventional "barriers" between power systems, data acquisition, and computer engineering courses and provide the students a clearer sense and more **realistic** picture of what the future holds for electrical power engineers. More specifically, it is desired that this laboratory setup will help students visualize power system phenomena in terms of the Energy Management System (EMS) equipment used by power system operators.

## 6. Acknowledgments

The authors would like to thank the National Science Foundation (Grant #: DUE-9452344) and Microsoft Curriculum Development Grant for providing funds for the project. The authors would also like to acknowledge financial support received from PECO energy and General Public Utilities (GPU). The authors would like to thank John Gillerman for his suggestions. In addition, equipment received from General Electric and Schweitzer Engineering Laboratories is also appreciated.

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## 8. Biographies

**S. P. Carullo** received his B.S. in electrical engineering from **Drexel** University in June 1995. He is currently pursuing a **M.S.** in electrical engineering at **Drexel** University while working as a research assistant in the Center for Electric Power Engineering. Mr. **Carullo** has worked at Sony Music Entertainment and the U.S. Coast Guard as a student design engineer.

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**R. Fischl** received the B. **S.E.E.** degree from City College of New York in 1955 and the **M.S.** and Ph.D. degrees from the University of Michigan, Ann Arbor, in 1958 and 1966, respectively, both in electrical engineering. In 1966 he joined the faculty of **Drexel** University where he is currently a Professor of Electrical Engineering. His research interests are in the areas of power systems and power electronics.

