Remote Hardware Power System Loading Studies over the World Wide Web

Andrew Golder *Student Member, IEEE* Karen Miu, *Member, IEEE* Chika Nwankpa *Member IEEE,* Stephen Carullo *Member IEEE*

***Abstract* — This work presents a remote data acquisition and control system that will allow students and researchers to perform an experiment using power systems hardware from any location with an active internet connection. There are four main components for this system: first, the power systems hardware necessary to perform the experiment; second, digital control and data acquisition hardware; third, a software system composed of a server and client module that communicate data and control signals over the internet; and fourth, a safety system to protect local hardware and software systems from damage. This paper will focus on the development of the software system which allows for remote access.**

***Index Terms*—Steady State Stability Studies, Remote Laboratory, Automation. Nondestructive Testing**

I. Introduction

The study of power systems under stressed loading conditions provides engineers with critical insight on system behavior. Specifically knowledge of the system behavior near steady-state stability limits can assist in the development of control schemes to avoid failures such as voltage collapse [1] [2]. Access to this important information is often limited as illustrated by the following examples:

- Shipboard power systems: Component failures and system events at sea provide a unique problem where resources are limited. Testing procedures not possible at sea could be simulated using networked power system hardware and software. This would provide valuable data used to make repairs at sea or speed debugging and repair at port.
- Terrestrial Power Systems: Many devices in the grid already utilize measurement and communication systems to provide remote control capabilities. Some examples are distributed generators, capacitors, and controllable loads. Loading studies on these systems may increase the risk of stability loss. By simulating grid systems using networked hardware and software tools, engineers can perform nondestructive tests that provide them with the measurements desired without risking damage to equipment.
- Universities/Laboratories: Development and maintenance of power systems hardware laboratories can be very time consuming and expensive. Therefore, power system experiments are often restricted to software simulations. However valuable experience is provided by hardware experiments.

Thus, for each of these applications, combining power systems hardware, simulation software and networking capabilities has the potential to increase the data and knowledge that help engineers learn and perform necessary tasks.

Early development of remote laboratories includes educational control engineering labs in 1996 [3]. Other applications such as telepathology workstations [4] where timing and speed are critical have followed. More recently advanced research applications such as Nuclear Magnetic Resonance Spectroscopy [5] have included the development of remote laboratories. In all cases the driving force behind development of the remote laboratory is either a shortage of equipment or a shortage of expertise. The internet provides an existing data link to almost any location, capable of connecting geographically distributed resources, human or machine.

The development presented here is unique in that the remotely controllable device is placed within a larger power system. Previous works such as [6] exist for remote control of power hardware components. In this work, control and data acquisition devices are placed within a power system. Thus testing will reveal the properties of the system as a whole.

This paper will describe the development of remote non-destructive power system loading experiments. The following topics are discussed:

- The hardware and software setup of the experiments. (Section II.)
- Detailed descriptions of the components required for remote capability. (Section II.)
- The software development with an emphasis on the network communications allowing for remote access. (Section III.)
- Results and analysis of example remote loading experiments. (Section IV.)

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Authors Andrew Golder, Karen Miu and Chika Nwankpa are with the Electrical and Computer Engineering Department, Drexel University, Philadelphia PA 19104, USA (email: asg29@drexel.edu, karen@cbis.ece.drexel.edu, chika@nwankpa.ece.drexel.edu). S. P. Carullo is with Raytheon Integrated Defense Systems, Tewksbury, MA 01876, USA (e-mail: Stephen_Carullo@raytheon.com)

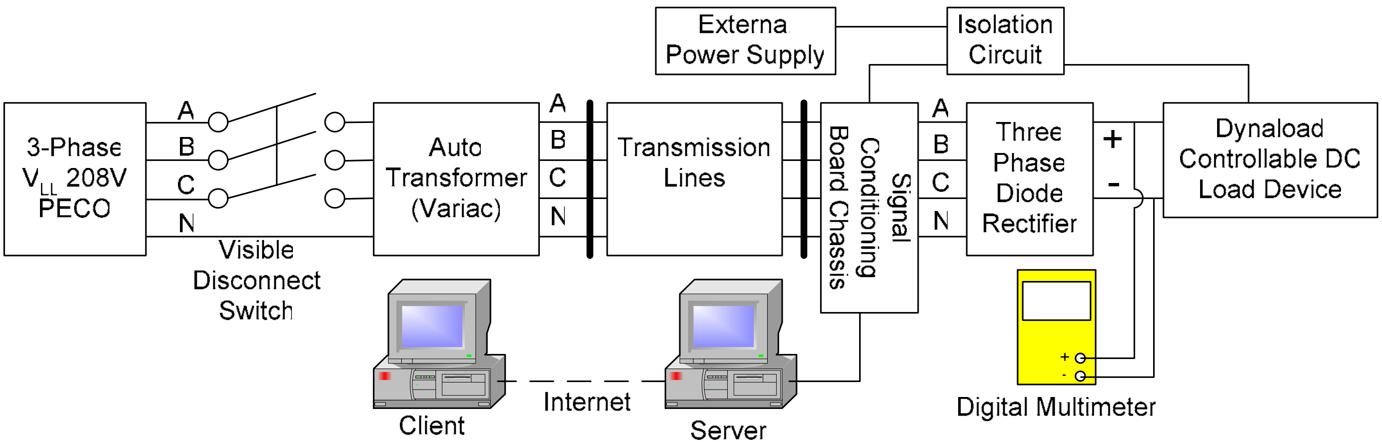

Figure 1. Power Systems Hardware Setup: a sample two bus hardware configuration used for testing is shown here.

II. Components and Setup

The remote laboratory experiment requires the integration of many components including power hardware, measurement hardware, data acquisition software, and networking software Descriptions of the individual hardware and software components utilized in the experiments follow.

A. Hardware

The remote power system loading experiments are available within Drexel Universities IPSL [8] laboratory. A range of hardware is available and several remote testing configurations such as those shown in Figures 1 and 2 are available. Hardware components required for a two bus system are now detailed.

- A balanced three-phase source.
- A disconnect switch containing a 50 amp breaker, used as a safety feature.
- An autotransformer used to safely increase the line voltage at the sending end of the transmission line to any point within the range 0 - 140V.
- A variable tap transmission line model using the Pi equivalent circuit.
- A chassis housing signal conditioning boards [8] used to filter measurements and relay input commands to the controllable load through the isolation circuit, which has an external supply for amplification.
- A three-phase diode rectifier to provide the Dynaload with the DC signal it requires, and a multimeter used to measure that signal.
- A Dynaload DLVP-130-110-1000 [7] controllable current device with digital control capability.

Dynaload parameters can be changed with digital control signals. For remote loading experiments, the load must be set to the appropriate operating range using manual controls. Then, digital control may be used to vary the load level. The Dynaload contains an internal circuit breaker which will open in the case of any operating constraint violation. The reset button for this breaker must be operated manually.

In addition to the two bus system shown, other power system configurations are available. Figure 2 displays examples of a 3-bus and a 5-bus system. The hardware and testing conditions have been carefully designed to allow each configuration to reach its maximum loading condition.

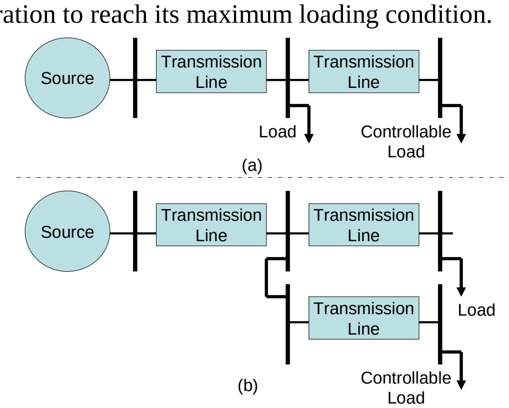

Figure 2. One line diagrams of a 3-bus and a 5-bus power system setup.

The Dynaload can be placed at any bus. All transmission lines have variable tap setting to simulate lines of varying length. The software system and its network architecture will be discussed next.

B. Software

The software systems for this application perform data acquisition and control functions, manage and display data, and communicate these signals over the internet. The system is composed of server and client side modules. To interconnect the server and client the software set-up uses the Data Socket Server which is an independent software module created by National Instruments. It provides a vehicle for data exchange over a network without the difficulty of low level TCP Programming [9]. As seen in Figure 3, each module connects to the Data Socket Server which stores data values and handles communication protocols. Further discussion of the software development follows in Section III after a description of the security features.

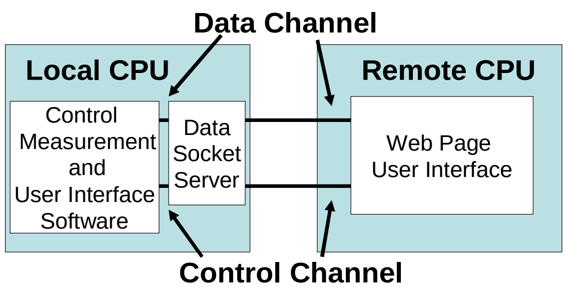

Figure 3. The network architecture for Data Socket communication.

C. Security

The following hardware and software security systems provide protection for local equipment:

- The website providing control of local systems is password protected.
- Remote users must have an approved IP address to send control inputs.
- The hardware has overvoltage, overcurrent, power, and temperature protection schemes to trip vulnerable equipment out of the circuit before damage can occur.

III. Software Development

Goals of the software development are a safe and reliable system providing measurements, controls, and communication tools to remote users.

A. Server Side Module

The server is responsible for a number of tasks including data acquisition and processing, measurement display, networking functions, hardware control, and communication between local and remote users. The server user interface (UI) is shown in Figure 4. The main functions of this module are as follows:

- Data Acquisition (DAQ) and Processing: Sampled data points from a DAQ card are converted to RMS measurements. Real-time measurements include three-phase magnitudes and angles for voltages and currents, as well as three-phase real and imaginary power. All calculations are performed by the server module.
- Measurement Display: User prompted data is output in tabular and graphical format. These data points include the Dynaload control voltage, three-phase real power consumption, line-to-line voltage magnitude, and calculated equivalent resistance of the load. Real-time measurements for voltage, current, and power are updated and displayed automatically.
- Networking Functions: User interface elements manage connections to the Data Socket Server, and display connection status. Logged measurements are concatenated to a single vector and written to the Data Socket Server. When prompted, control inputs are read from the Data Socket Server.

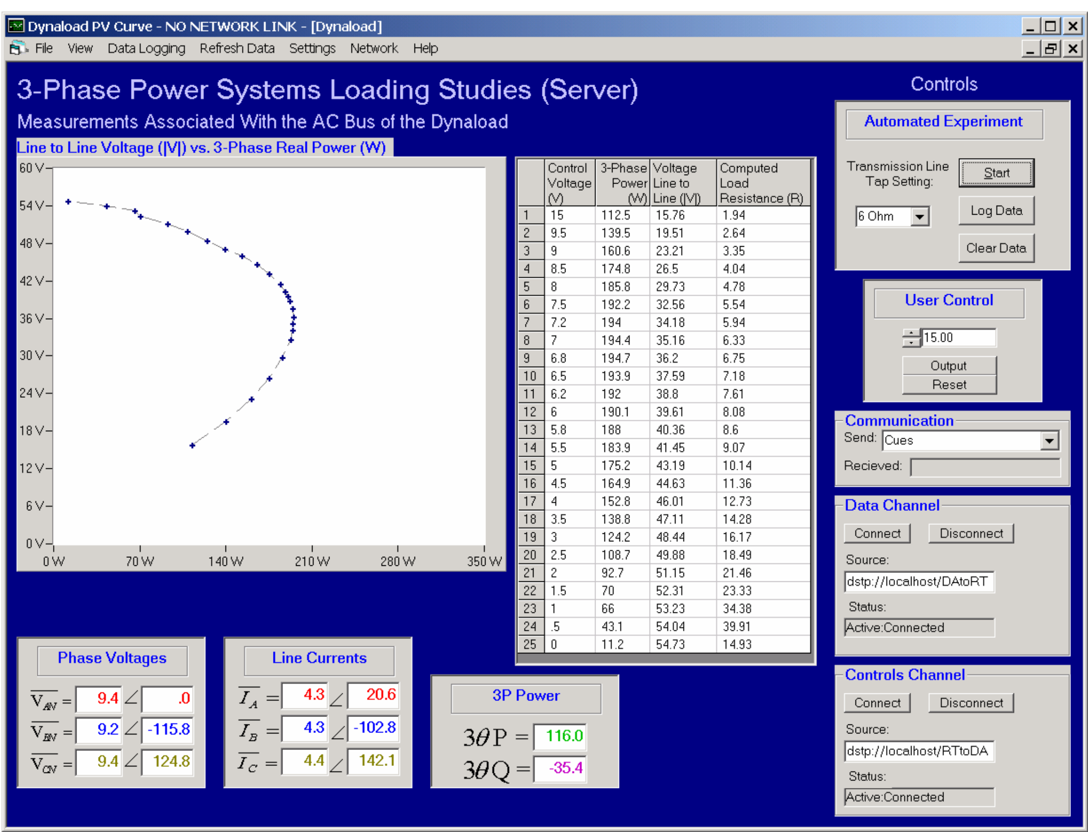

Figure 4. Server side user interface which performs local control of power systems hardware

- Hardware Control: Inputs and text displays are provided in the UI for local control. Local and remote inputs prompt digital control signals to be written to the DAQ card. These are then converted, amplified, and sent to the Dynaload using external electronics.
- Communication: A user interface provides a list of cues to be sent to the remote operator and displays cues received from the remote site.

B. Client Side Module

The client module was created as a website so that remote users do not need to obtain any software from the developer. It is built to mimic the operation of the server module; its user interface is shown in Figure 4. User interface modules for communication, control, and networking operate in the same manner as the server module. Functional differences of these systems include:

- Measurement Display: Real-time measurements are not provided to prevent bottlenecks on the network channels necessary for logged data.
- Networking Functions: Instead of measurements, control signals are written to the Data Socket Server, the measurement vector is read and divided into the appropriate arrays.

For the website to operate properly, the remote terminal must have Microsoft Visual Basic 6 (VB6) and Measurement Studio (National Instruments) for VB6 which contains Data Socket.

The webpage contains ActiveX controls which are Microsoft tools that provide graphic input and output displays and functions; they must be enabled in the custom security options of Microsoft Internet Explorer. The remote module is a shell user interface allowing remote users to perform the necessary experiments. All data processing and calculations are perfomed at the server side and the client UI simply displays data and communicates control signals.

C. Integrating Network Communications into the System

The Data Socket Server coordinates communication between the server and client modules. It works by creating data items which can be seen as a channel that transfers a single parameter or an array from one software module to another. The control channel item sends a coded integer from the client to the server to indicate control commands. The data channel item sends a single vector containing the logged measurements from the server to the client.

When creating a connection to the Data Socket Server a module must specify which channel it wishes to connect to and whether it will read or write to this channel. Therefore, for these loading experiments, two-way communications require two data channels. The software developed writes data to the appropriate channel. The Data Socket Server then stores the data and calls an event in any modules set to read that channel. Modules then read the data and store it in local memory for processing.

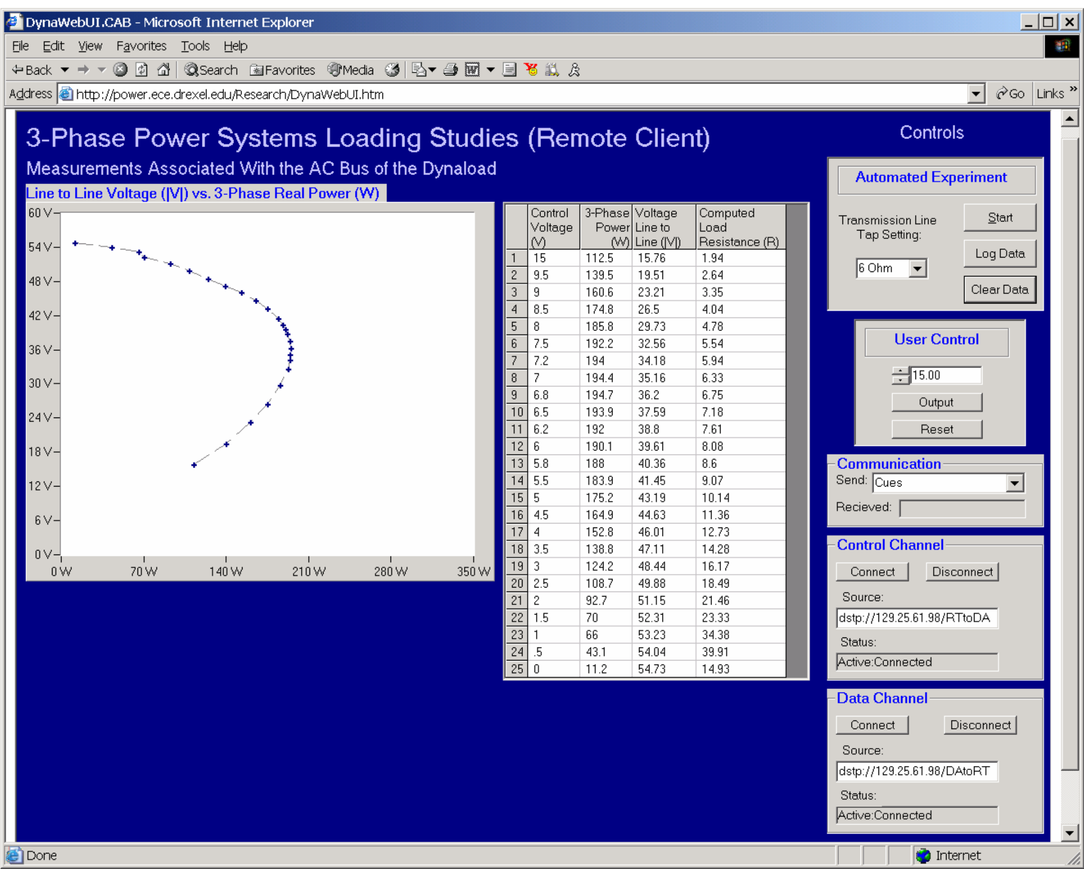

Figure 4. Remote User Interface, viewed as a webpage, this module displays data and relays commands to the server module.

For a remote module to be given write permissions to the Data Socket Server, its IP address must be added to the permitted writers list on the Data Socket Server Manager housed on the server. This ensures that unauthorized users are not able to send control signals to the local devices.

D. Experiment Control

Two control schemes are implemented which provide users with a varying level of involvement in the operation of hardware:

Automated: The remote operator begins the experiment by simply pressing the Start button. An internal vector stored on the local machine provides the Dynaload with a sequence of control inputs. For example, the control vector can cover the full range of the Dynaload and concentrate its points around the maximum loading point. When the experiment has completed its cycle and displayed all data, the user may simply press Clear Data and run the automated experiment again or explore the system with more freedom using the user controlled mode described below. Remote users can also provide a local operator with their own control vector to be stored in memory and used for the automated experiment.

User Controlled: For remote user controlled operation an input field is provided in the UI for the user to specify the desired control input. Display of the control variable along with the measurement points provides a reference by which to seek the desired result. Inputs may be entered at any speed and with any change from the previous value. This gives a maximum amount of control however it may also increases the chances of a protection trip in the Dynaload, requiring it to be reset by a local operator.

E. Experimental Procedure

Procedures have been written for an educational laboratory experiment. A shorter operation manual has been written for experienced power systems engineers to use this system. Both write ups have been implemented and tested. The remote testing has been performed on 2-bus and 3-bus systems. Results are presented in the following section.

V. Results and Analysis

The development has been successful in providing a laboratory for remote data acquisition and control of power system loading experiments. Measurements are available to users in tabular format, which allows for further numerical analysis if desired, and in graphical form which shows the shape of the PV curve. Many hardware configurations are available; in this section, results obtained from various two-bus and three-bus poser systems are presented.

Several experiments have been performed with the remote client located at Iowa State University, and the server module and power systems hardware located at Drexel University. Results of experiments performed using the two bus system of Figure 1 are located in Table 1. Three transmission line tap settings representing lines of different lengths were used. As can be seen from these measurements, the equivalent load impedance which corresponds to maximum power transfer is close to the impedance of the transmission line, illustrating impedance matching. For these experiments graphic representations of line to line voltage magnitude vs. three-phase real power to the load are shown in Figures 5, 6, and 7. An experiment was also performed on the three-bus system shown in Figure 2a. Graphical representation of voltage magnitude vs. three-phase real power to the load for this experiment is shown in Figure 8.

The system developed here for remote loading experiments is an example of what can be accomplished with custom and commercially available hardware and software systems. They effectively utilize the internet as a data channel for power system measurements and control signals.

Table 1. Data and Calculations for the two-bus system shown in Figure 1

Tap Setting	Line Impedence	Line Reactance	Maximum Loading Conditions							Voltage Regulation
			Sending End Voltage (Bus 1, Phase A)	Receiving End Voltage (Bus 2, Phase A)	Voltage Drop Across the Line (Phase A)	Load Current (Phase A)	3-Phase Power to the Load	3-Phase Line Loss	Equivalent Load Resistance (Phase A)	
R (Ohms)	R (Ohms)	X (Ohms)	|V| (Volts), θ (Degrees)	|V| (Volts), θ (Degrees)	|V| (Volts), θ (Degrees)	| I | (Amps), θ (Degrees)	P (Watts), Q (Vars)	P (Watts), Q (Vars)	R (Ohms)	%
12	1.3	12.96	35.19, 37.62	22.5, 0	22.14, 75.96	1.7, -8.3	111.4,19.6	3.757, 37.45	12.85	43.1
6	0.72	6.5	31.6, 40.97	20.9, 0	20.93, 81.87	3.2, -1.8	198.3, 12.3	7.37, 66.56	6.45	50.2
3	0.39	3.25	29.53, 43.23	19.8, 0	20.30, 85.16	6.2, 2	370, 1.3	15, 124.93	3.23	61

Line to Line Voltage |V| vs. 3-Phase Real Power W

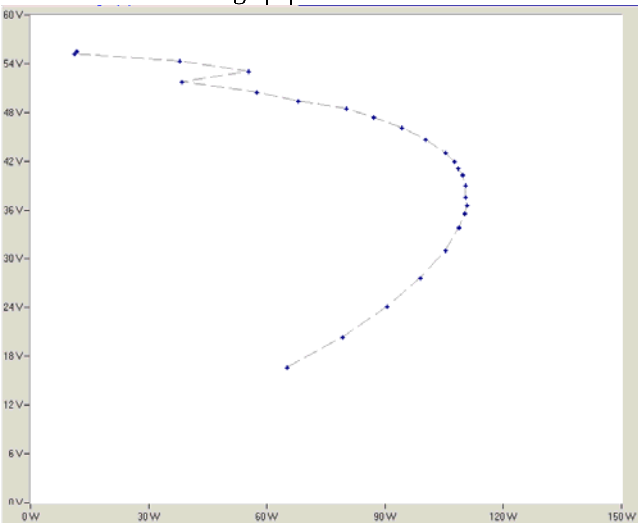

Figure 5. Two-bus system. 12 ohm line tap setting.

Line to Line Voltage |V| vs. 3-Phase Real Power W

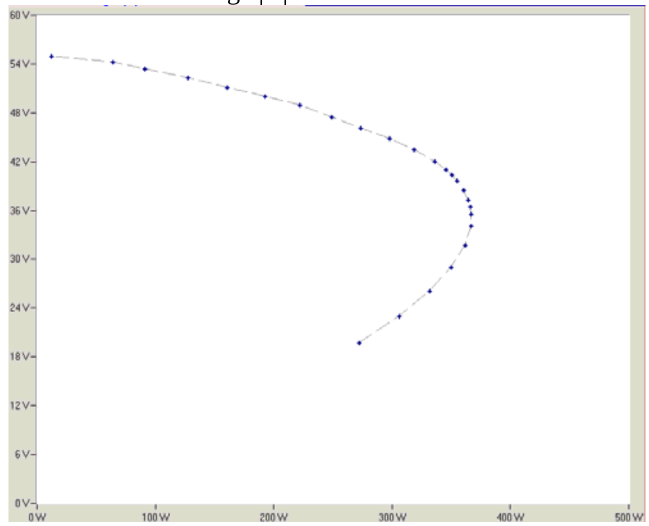

Figure 7. Two-bus system. 3 ohm line tap setting.

Line to Line Voltage |V| vs. 3-Phase Real Power W

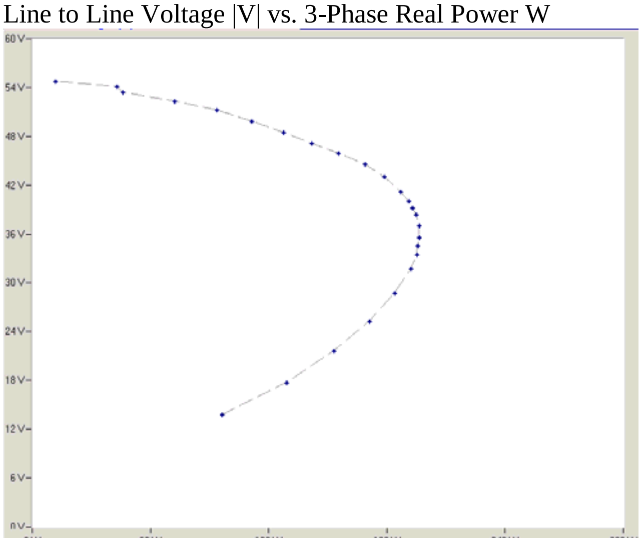

Figure 6. Two-bus system. 6 ohm line tap setting.

Line to Line Voltage |V| vs. 3-Phase Real Power W

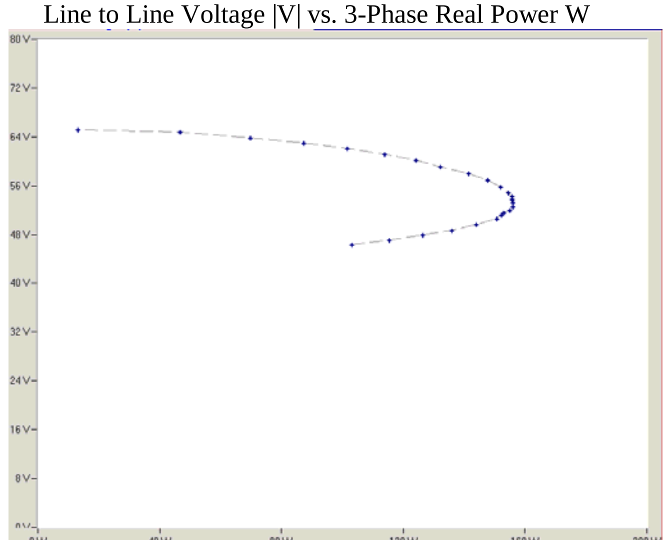

Figure 8. Three-bus system of Figure 2a. Both transmission lines are set to the 3 ohm line tap setting.

VI. Conclusion

This paper has presented the development of a software system for remote operation of power system loading studies. Software was developed utilizing commercially available software platforms and networking technologies to help provide rapid prototyping. The remote software system contains the same capability as the local module for data acquisition and control of system hardware and provides communication tools to aid collaboration for manual local procedures. Remote users are thus able to perform the experiment and collect data as if they were at the hardware location. Intervention at the server side is required only if the hardware safety features are activated.

Descriptions of hardware setup, software setup and software development have been provided. Detailed procedures for remote experiments have been written and tested. Results for sample hardware configurations are given to demonstrate the educational value of the experiments.

This experiment is the first step in creating a more extensive remote power systems laboratory. It has been developed to demonstrate the networking tools, communication systems, protection schemes, and data systems necessary to make such a system effective. Using these tools it would be possible to connect more digitally controllable devices for remote access. With remote measurements and control available, multiple components and software simulations could be virtually connected using the internet in order to study larger power systems.

Acknowledgment

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