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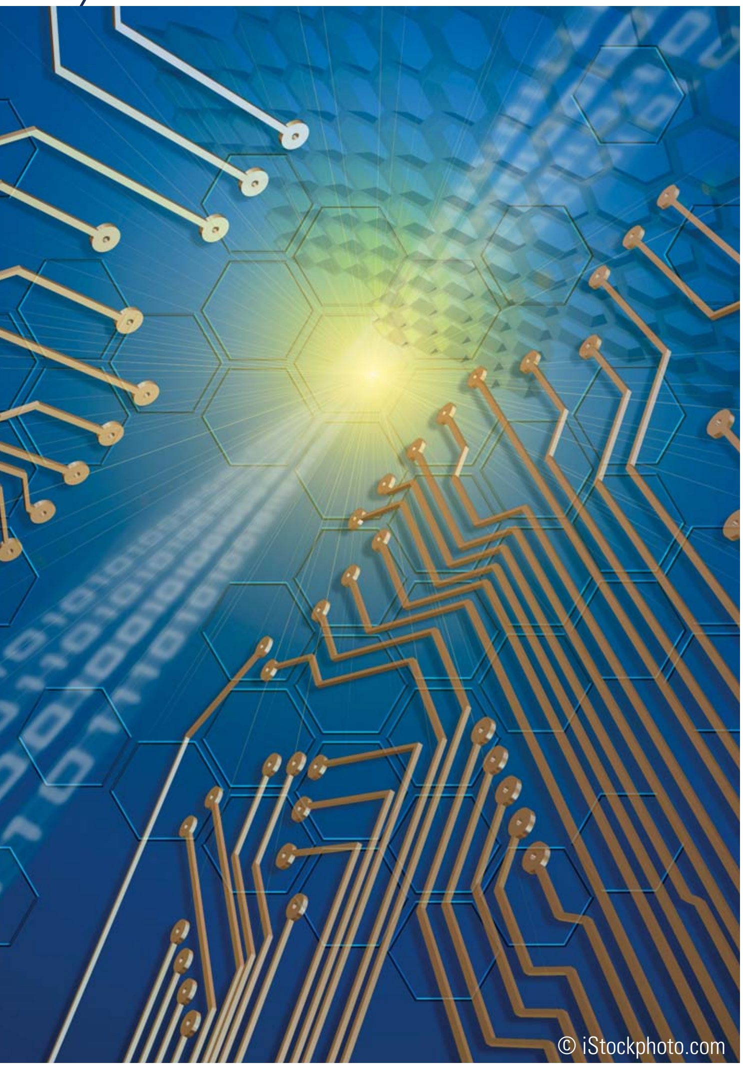
Instrumentation and Measurement of a Power Distribution System Laboratory for Meter Placement and Network Reconfiguration Studies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The monitoring and automation of power distribution systems has significantly improved with advancements in digital signal processing (DSP) and in computer and web-based technologies [1], [2]. Power distribution systems could realize benefits from an improved instrumentation and measurement (I&M) configuration for network reconfiguration and meter placement. Drexel University has developed the Reconfigurable Distribution Automation and Control (RDAC) laboratory; it has a power distribution system in which various meter placements and network reconfiguration techniques can be implemented and studied.

We designed a unique and flexible I&M system consisting of software and hardware instruments to perform network reconfiguration and meter placement studies; it can adapt to power system planning and operating scenarios. We tested this system in the RDAC laboratory and present our results here.

Background

Installation of metering and monitoring systems in electric power distribution networks has been growing rapidly. The main reasons for this growth include:

- the desire for automated meter readers and customer billing
- the increasing need to maintain and improve energy efficiency and reliability, often through optimal control of distribution systems.

Network reconfigurations change the topological structure of the power network. These changes can improve energy efficiency while maintaining reliability [3]. Network topologies are often changed to balance the load and to restore customer service. To do so requires careful design of

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- the monitoring and control capabilities of the network switches
- the location of switches
- the measurement system so that it is flexible.

In meter placement studies, the goal is optimal monitoring of the network to observe events, network reconfiguration, state or load estimation, and the impact of measurement loss in a real-life environment [4].

Network reconfigurations change the topological structure of the power network.

To evaluate meter placement techniques for different network topologies, hardware tests are performed in independent laboratories. Some universities have created advanced measurement and monitoring systems to investigate power quality problems [5], [6] and have developed distribution automation laboratories to provide students with hands-on experience in distribution systems [7], [8].

Our system addresses the following main measurement and control capabilities:

- Multiple, user-selected locations for three-phase measurement
- Simultaneous voltage and current measurements
- Root mean square (RMS), phase angle, and power calculations
- Control of system components, such as network switches, and devices used to create faults.

The measurement and control system changes network topologies by using actuation devices that are distributed throughout the system. The sensing and monitoring instruments capture both transient and steady-state behavior and sense unbalanced conditions across phases. The steady-state and transient events are observed by proper placement of metering devices. Multiple simultaneous measurement points are provided for redundancy. We can perform studies of different distribution systems and use the results to determine which control schemes give improved energy efficiency and reliability.

Our unique system comprises four remote terminal units (RTUs). Figure 1 shows the general architecture of the system. Each RTU consists of hardware and software instruments. The system must:

- Operate controllable network devices such as automatic switches
- Allow for both single-phase and three-phase switching
- Visualize actual distribution system setups.

The resulting design of the measurement and control system of the RDAC is described next.

The Automated Measurement And Control System

The RDAC is a 43.2-kW, 208-V, three-phase, 36-bus, scaled-down distribution system. It has four identical stations, each of which is a 9-bus distribution feeder with four three-phase normally-closed sectionalizing switches, up to four three-phase normally-open tie switches, and multi-phase loads. See Figure 2 for a top-view of the 9-bus distribution feeder box, which illustrates both the power hardware and embedded sensor and measurement network.

The measurement and control system on each RDAC station is capable of automatically measuring three-phase and neutral voltages and currents at up to four user-selected buses for a total of 32 signals per station. The system can also remotely operate

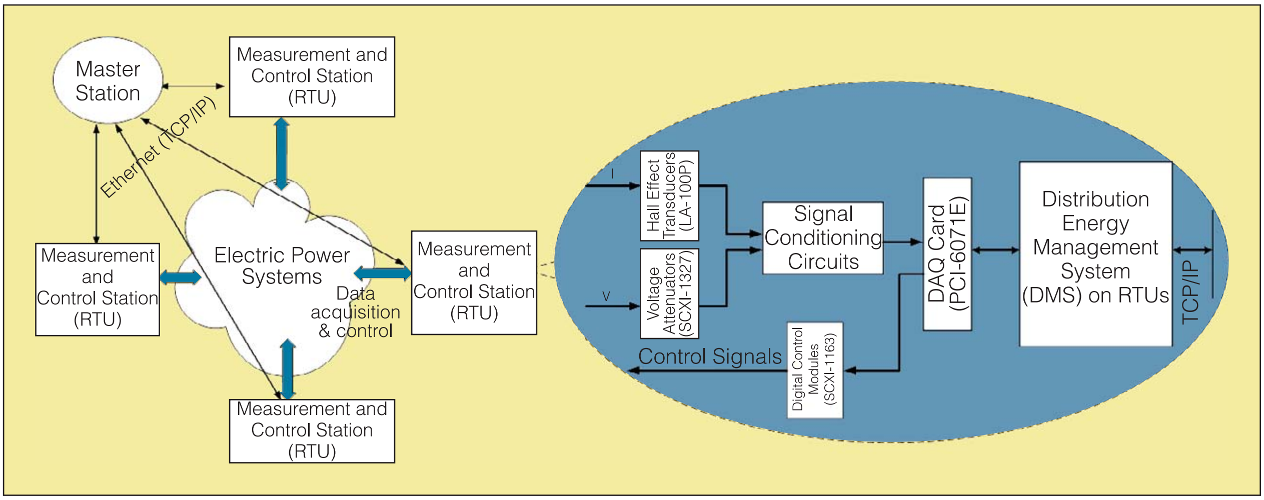


Fig. 1. System architecture of the measurement and control system.

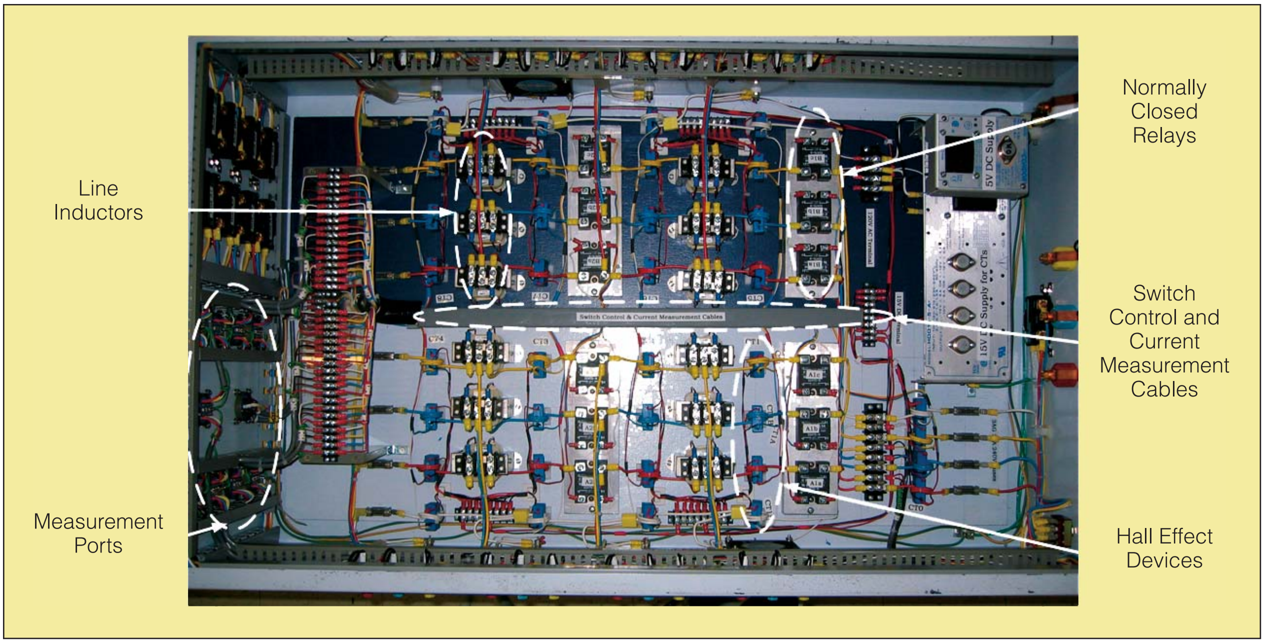


Fig. 2. Top-view of the Reconfigurable Distribution Automation and Control (RDAC) 9-bus distribution feeder box, showing power hardware and measurement hardware.

digital relays, which provides the capabilities of reconfiguring system structure, switching capacitors on or off, and creating various types of faults. The measurement and control hardware is operated by the Distribution Energy Management System (DEMS), a software platform that runs on the RTU.

Hardware Instruments: Data Acquisition and Control

We developed the hardware on each measurement and control station around a National Instrument (NI) SCXI signal conditioning and instrumentation system to enable the system to perform these tasks:

- Sensing three-phase, neutral voltage, and current signals at each measurement bus
- Monitoring up to 16 user-selected buses
- Signal attenuation, filtering, isolation, and suppression
- Capturing harmonic signals up to 1,000 Hz (i.e., up to the 15th harmonic at 60 Hz) to allow for capacitive load studies
- Operate controllable network devices such as automatic switches.

Figure 3(a) and (b) shows the SCXI rack composed of signal conditioning and digital boards and its connection to the distribution feeder box through cables made in-house. The measurement hardware on each station consists of voltage and current sensors, four signal conditioning boards, and a data acquisition (DAQ) card.

Future work includes the integration of a remote master station where the recorded data and control signal can be transferred through the Ethernet.

Voltage attenuators transform three-phase and neutral voltages from up to 250 V to levels acceptable to the DAQ card (<10V) at a 100:1 ratio. Three-phase and neutral currents are measured using 100 A Hall-effect current transducers. The attenuated voltage and current signals are then sent to eight-channel signal conditioning boards (SCBs). The signal conditioning circuit has four stages and provides the following functions:

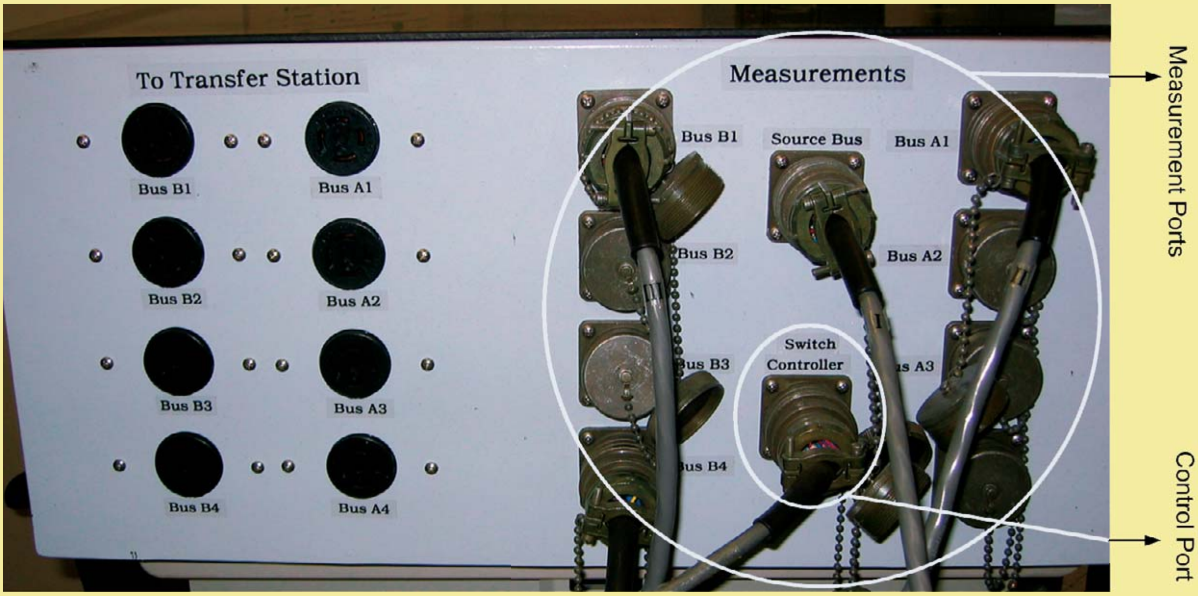
- attenuating signals
- suppressing voltage spikes
- preventing ground loops
- filtering out high-frequency noise above 1,000 Hz.

Figure 4 is a schematic of the signal conditioning circuit. Each RTU captures 32 filtered voltage and current signals using a DAQ card, which is also used in conjunction with two digital control modules to remotely operate 55 controllable switching devices. The switches are mimicked using normally open and normally closed digital relays.

Software Instruments: DEMS

We designed a DEMS to remotely monitor and control the above hardware and to enable subsequent performance evaluation of the power system. The DEMS was implemented on a PC using NI Component Works and Microsoft Visual Basic 6.0. It includes virtual measurement and control instruments and provides system control functions as well as data process and display capabilities. More specifically, it enables these tasks:

(a)



(b)

Fig. 3. (a) The SCXI rack signal conditioning and digital control boards connected to the distribution feeder box by in-house-made cables and (b) a side view of the distribution feeder box, showing measurement and control ports.

- Storing and displaying real-time voltage and current waveforms
- Calculating, storing, and displaying RMS and angles of voltages and currents, frequency, power factor, real and reactive power.

Figure 5 shows the functional schematic of the DEMS.

Figure 6(a) shows the measurement interface that links the hardware and software. It enables users to specify desired measurement locations (matching the hardware), which can be determined by meter placement studies. Figure 6(b) shows that the user is able to select the switch location to link power hardware and software control instruments for network configuration.

The DEMS provides a 9-bus distribution system diagram that reflects the actual experimental setup on each RTU. A screen shot of the main graphical user interface (GUI) of a general three-phase experimental setup is displayed in Figure 7, showing the following system information:

- A 208-V alternating current (ac) source with a three-phase autotransformer servicing the system
- A 9-bus system with 12 color-coded distribution lines and the number of loads and their connection types to match the hardware setup
- Four three-phase closed switches (SW1 to SW4) represented using green circle icons

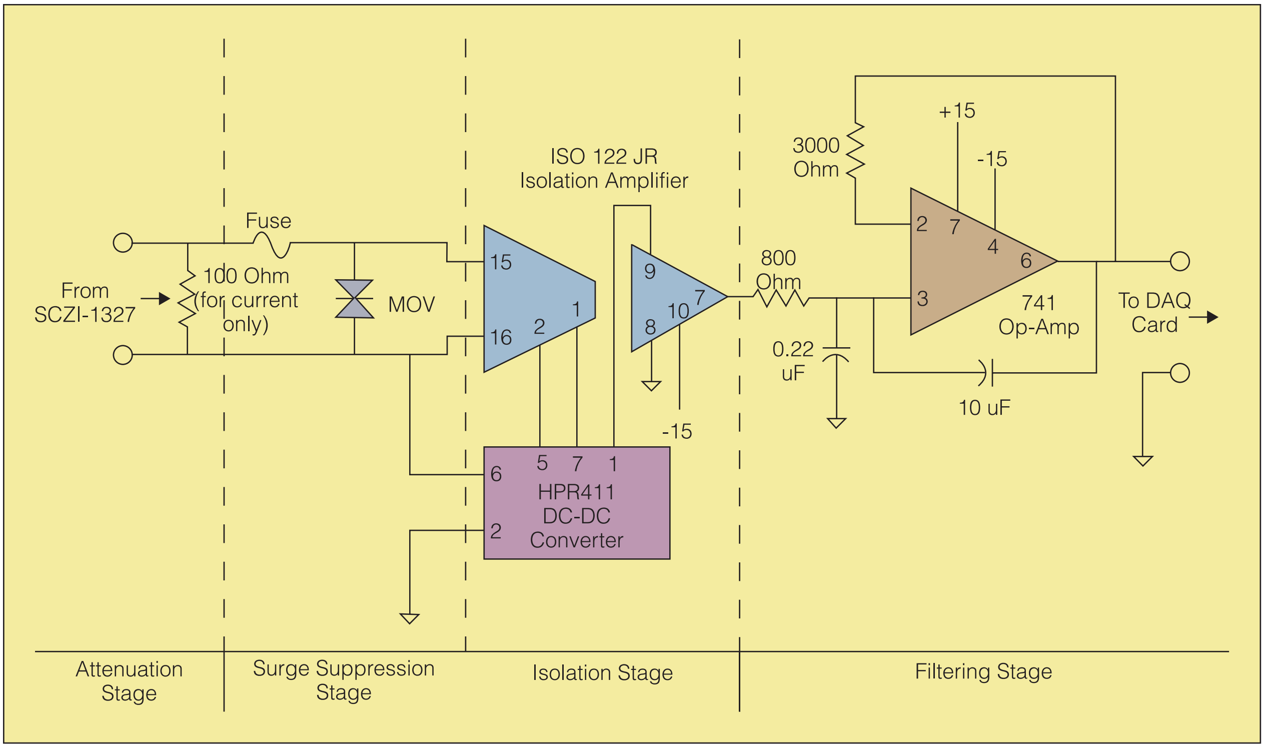


Fig. 4. Voltage and current signal conditioning circuits [9].

- Four single-phase meters at each bus (highlighted meters indicate selected measurement locations)
- RMS values and phase angles of voltages and currents in tabular form.

The DEMS is interactive. Users can view line impedance parameters by clicking on the distribution lines. The DEMS highlights the active measurement locations, and users can view measured data by clicking on individual meters. The measured signals and the calculated parameters can be displayed in:

- real-time oscillograph waveforms and phasors of voltages and currents (See Figure 8)
- real-time power waveforms
- numerical data of voltages, currents, and power.

The DEMS also enables users to record measured and calculated data into a data file for follow-up system analysis. For network reconfiguration studies, the DEMS has interactive control instruments to operate network switches. By double clicking on a switch icon, the users are able to remotely open or close any phase of a three-phase switch. Figure 9 shows the control instrument for operating a normally open tie switch.

Application Example of the Measurement and Control System in RDAC

The I&M system in RDAC provides flexibility for users to select between one to four three-phase and neutral measurements at different locations in the 9-bus system. Generally, one measurement is taken on the Feeder Bus and treated as the reference. Then, the total possible number of meter locations is 93. As such, users can test different meter placement schemes for various purposes.

We now use the network in Figure 7 to show the application of the I&M system for a network reconfiguration experiment. Three measurements are placed on the Feeder Bus, Bus A2, and Bus B1. We find that the current entering Feeder A is approximately 4.9 A, whereas the current entering Feeder B is less than 1.23 A. To balance the loads in this particular network, a new network reconfiguration is shown in Figure 10. To reconfigure the network in Figure 7, the following switch operations were performed:

- Open the three-phase sectionalizing switch SW2 between Bus A2 and Bus A3
- Close the three-phase tie switch 3-P Tie1, connecting Bus A3 to Bus B2.

The measurements show that the currents entering the two feeders are now more balanced: 2.96 A through Bus A2 and 3.13 A through Bus B1. It can be seen that both the meters on Bus A2 and Bus B1 can detect the network reconfiguration event by capturing the changes of the line currents.

On the other hand, the current meter placement scheme (Feeder Bus, Bus A2, and Bus B1) might be inappropriate when the objective is to estimate the loads in the system. Assuming the loads may vary with time, then note that:

- The loads on Bus A2 and A4 in Figure 7 cannot be determined using the three meters
- The loads on Bus A4 and Bus B4 in Figure 10 cannot be determined after the reconfiguration.

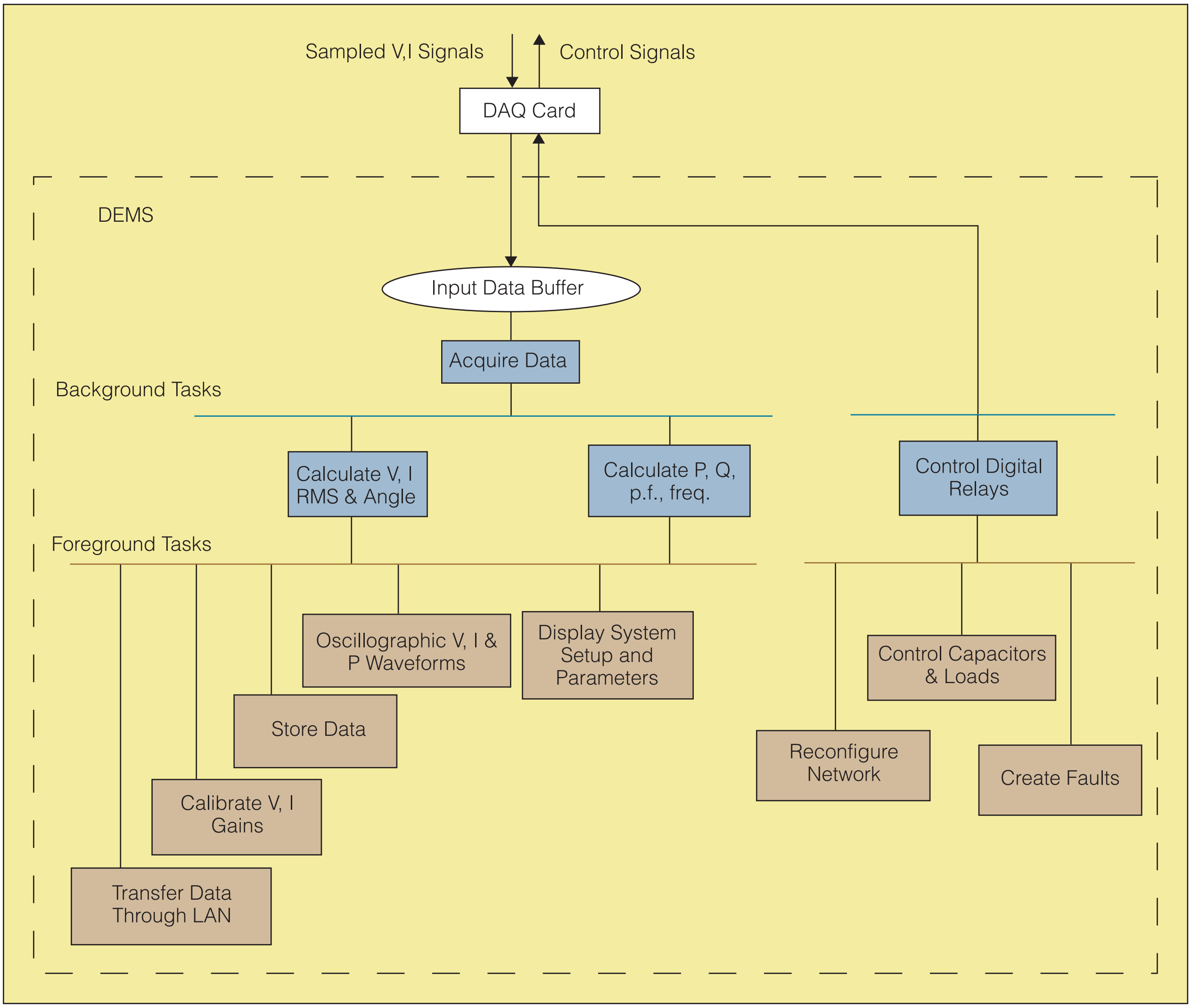


Fig. 5. The functional schematic of the Distribution Energy Management System.

Fig. 6. (a) Measurement selection window with feeder Bus, Bus A1, Bus B1, and Bus B3 selected. (b) The tie switch location selection window.

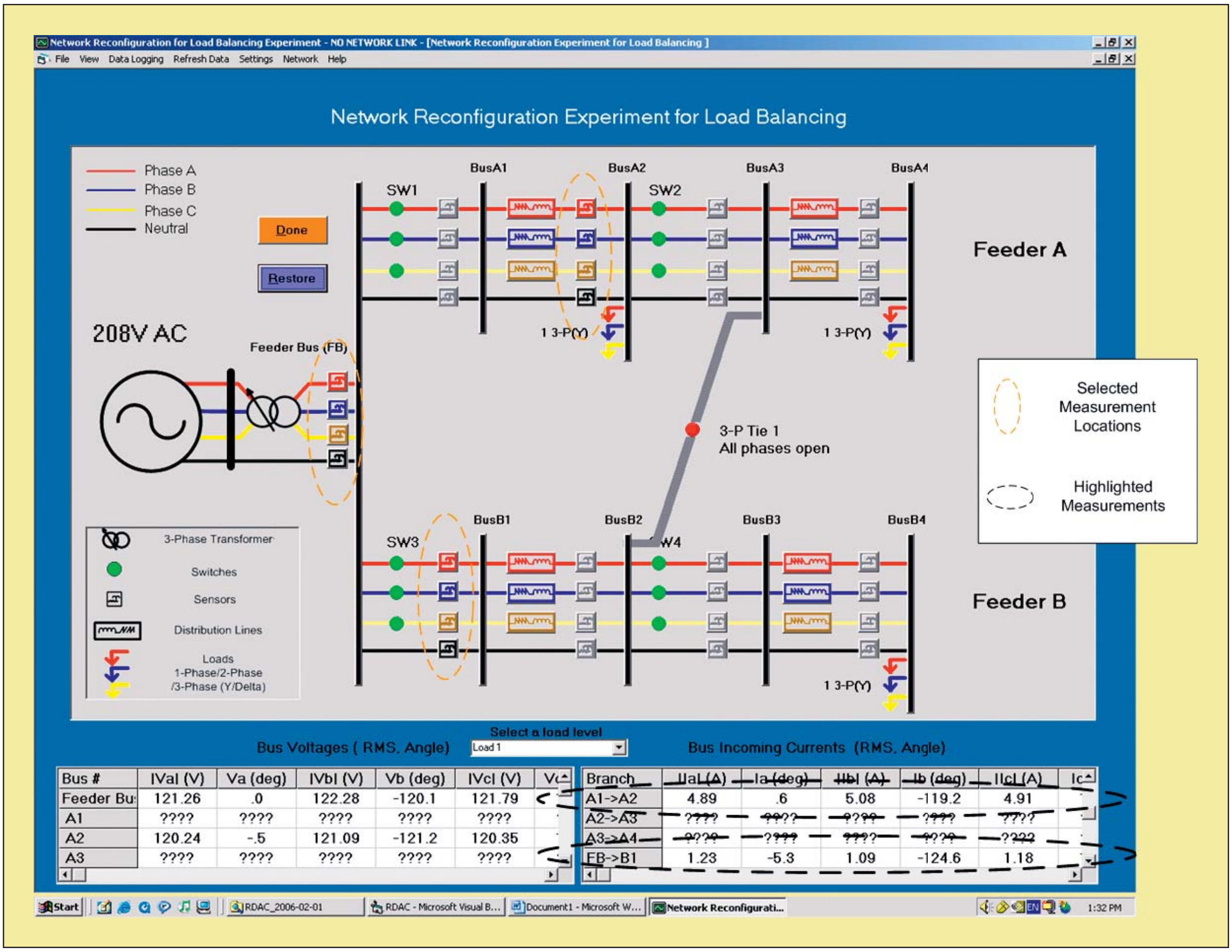


Fig. 7. Screen shot of the DEMS with selected measurement locations highlighted, before network reconfiguration.

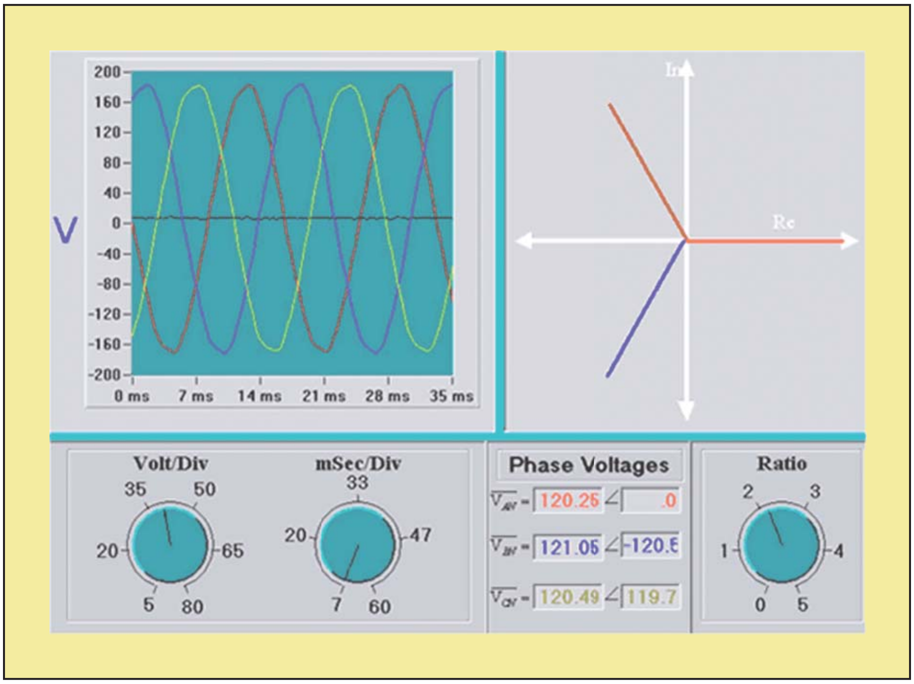


Fig. 8. Measurement instrument: oscilloscope view and the phasor diagram of three-phase ac voltages.

Figure 11 provides a more appropriate meter placement for this particular load estimation case using three meters. The meters are placed on the Feeder Bus, Bus A2, and Bus A4, respectively. Using the three meters, all of the loads can be estimated before and after network reconfiguration (for example, the load on Bus A2 in Figure 11 can be determined by subtracting the current measured on Bus A2 by the current measured on Bus A4).

The impact of the loss of measurements on system monitoring and operation can also be studied in RDAC. For the network reconfiguration example in Figure 7, both the meters on Bus A2 and Bus B1 capture the changes in the network structure represented in Figure 10. Thus, this meter placement can detect network reconfiguration even if one of the three meters does not function. For the load estimation in Figure 11, the meter setup will not be able to estimate the loads if one of the three meters does not function. For instance, the load on Bus B4 is unknown if the meter on the Feeder bus does not function. Thus, this meter placement scheme with three meters might not be sufficient when loss of measurements is considered and more meters should be installed, e.g., one meter on Bus B2.

Conclusions

Several hardware and software instruments have been specifically designed and implemented to enable meter placement and network reconfiguration studies. The instruments provide measurement and control capabilities for distribution systems of different configurations. We have combined these hardware and software instruments with measurement instrumentation to form a unique and flexible I&M system at the RDAC at Drexel University. I&M capabilities of the laboratory include: monitoring up to 16 user-selected locations; recording and displaying real-time measured voltage, current, and power waveforms; and the remote operation of controllable devices such as digital relays to reconfigure the network struc-

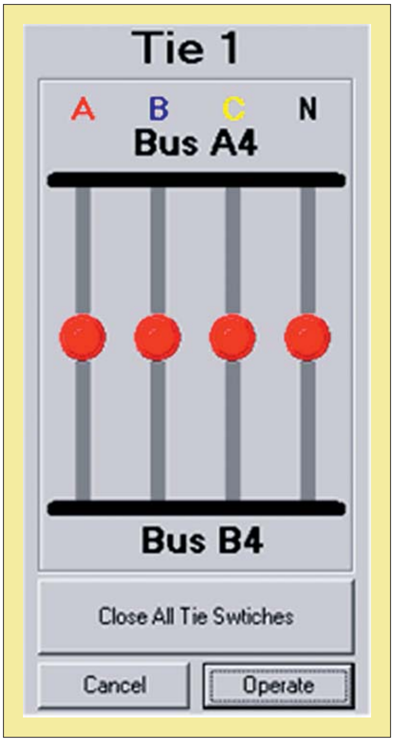
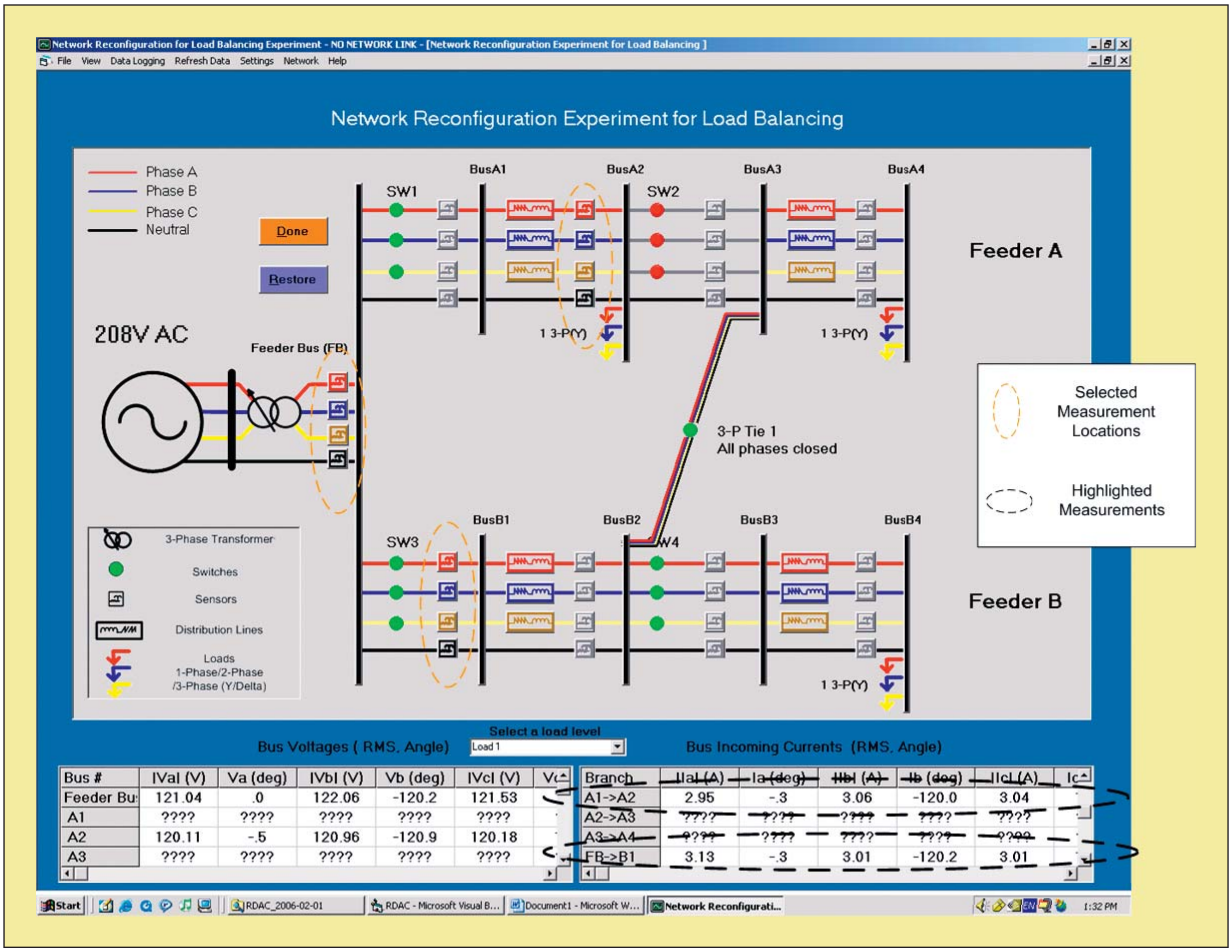


Fig. 9. Control instrument:network tie switch operation.



Bus #	IVaI (V)	Va (deg)	IVbI (V)	Vb (deg)	IVcI (V)
Feeder Bu	121.04	.0	122.06	-120.2	121.53
A1	????	????	????	????	????
A2	120.11	-.5	120.96	-120.9	120.18
A3	????	????	????	????	????

Branch	IIaI (A)	Ia (deg)	IIbI (A)	Ib (deg)	IIcI (A)
A1->A2	2.95	-.3	3.06	-120.0	3.04
A2->A3	????	????	????	????	????
A3->A4	????	????	????	????	????
FB->B1	3.13	-.3	3.01	-120.2	3.01

Fig. 10. A screen shot of the DEMS after network reconfiguration with SW2 open and 3-P Tie 1 closed.

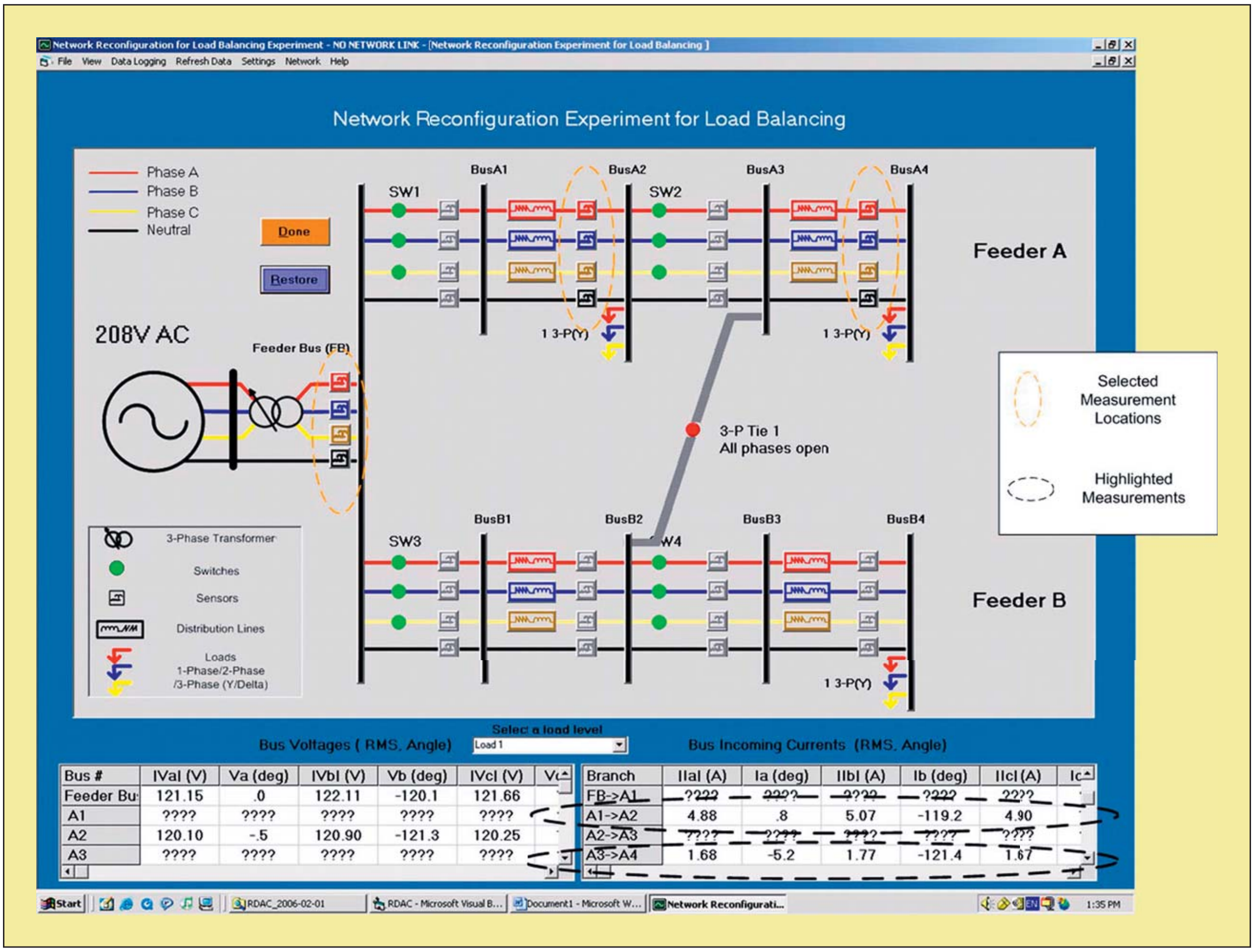


Fig. 11. A screen shot of the DEMS with selected measurement locations highlighted for load estimation.

ture. These characteristics enable event and state estimation. The laboratory can be applied to study meter placement and network reconfiguration and can also be used for educational purposes. Future work includes the integration of a remote master station where the recorded data and control signal can be transferred through the Ethernet. This would provide for larger system studies and remote laboratory operation.

This work was presented in [10].

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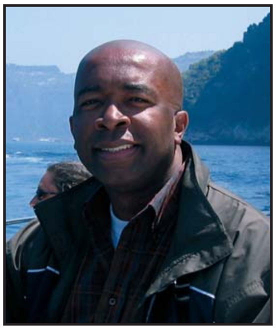

Chika O. Nwankpa (M'87) received the Magistr Diploma in electric power systems from Leningrad Polytechnical Institute, U.S.S.R., in 1986, and a Ph.D. degree in electrical and computer engineering from the Illinois Institute of Technology, Chicago, in 1990. He is currently a professor of electrical and computer engineering at Drexel University. His research interests include power systems, nonlinear systems, and stochastic systems.