Instrumentation and Measurement of a Power Distribution System Laboratory for Meter Placement and Network Reconfiguration Studies

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***Abstract*—At Drexel University, instrumentation and measurement of the Reconfigurable Distribution Automation and Control Laboratory include hardware and software instruments which together form an automated measurement and control system. This system contains special features that were included to enable meter placement and network reconfiguration studies. This paper presents an outline of the measurement and control system for the general laboratory and then focuses on the capabilities purposely added for the meter placement and network reconfiguration studies.**

***Index Terms*—Control system, energy management system, instrumentation, laboratory, measurement, meter placement, network reconfiguration, power distribution systems.**

I. INTRODUCTION

INSTALLATION of metering and monitoring systems in electric power distribution networks has been growing rapidly for several reasons. These reasons include the desire for automated meter readers and customer billing and the increasing need to maintain and improve reliability and energy efficiency, often through optimal control of distribution systems. In conjunction, the monitoring capabilities and automation level in power distribution systems has been significantly improved with advancements in digital signal processing and computer- and web-based technologies [1]–[4]. The integration of measurement capabilities is expected to continue. This will lead to the need for coordinated studies of instrumentation and measurement systems for power distribution systems under various conditions.

Two examples where an improved instrumentation and measurement system will have beneficial effects are the areas of network reconfiguration and meter placement. Network reconfiguration is the process of enabling topological changes of the network for improved energy efficiency and for maintaining reliability [5], [6]. Network topologies are often changed to perform, for example, load balancing and service restoration. Achievable configurations depend on the location and the control capabilities of network switches. As such, careful design of the distribution network is required to enable the reconfiguration of the network. Issues include the instrumentation for the monitoring and control of network switches, switch-placement studies, and the need for a flexible measurement system to enable appropriate meter placement for the various topologies.

In meter placement studies, the goal is usually to obtain an optimal monitoring system for the purposes of event observability and state and load estimation. Recently, algorithmic development of meter placement studies in power distribution systems has increased beyond the substation. In the study in [5]–[8], meter placement techniques were proposed for state estimation. For load estimation studies, the authors of [9] and [10] presented respective problem formulations and placed meters based on observability constraints and estimation accuracy. However, the above methods were typically based on networks with a given topological structure. As such, in the study in [11] and [12], integer-programming methods were used to maintain the observability of network states and parameters under contingencies and loss of measurements. A Genetic Algorithm was proposed for meter placement in [13] to obtain reliable estimates of system operating conditions under various network topologies. These studies show how diverse the area of meter placement is, where advancements in technologies related to instrumentation and measurement schemes will only benefit.

To evaluate meter placement techniques for different network topologies, hardware tests are desired in independent laboratories. At some universities, advanced measurement and monitoring systems have been created to investigate power-quality problems [14], [15]. In addition, distribution-automation laboratories have been developed to provide students with hands-on experience on distribution systems [16]–[20]. Network reconfiguration studies have been conducted at Drexel University through the Reconfigurable Distribution Automation and Control (RDAC) Laboratory [20]. In addition, it has been used to perform various operating and planning studies, including power flow [19]. However, the design of the measurement system itself for power-system studies has not been the focus in [14]–[20].

This paper proposes a flexible instrumentation and measurement system for power distribution system studies, which was designed for and integrated into the RDAC Laboratory. Initially addressed in [21], software and hardware instruments required to perform network reconfiguration were introduced,

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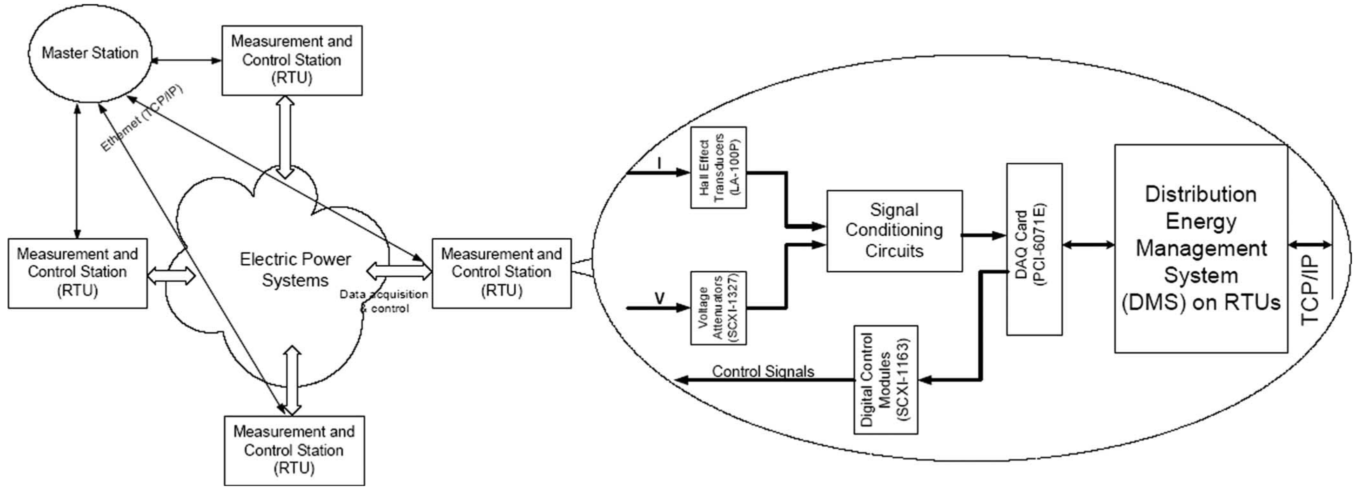


Fig. 1. System architecture of the measurement and control system.

and subsequent measurement instruments were presented. This paper expands on the study in [21] by

1) directly addressing the design and operation of measurement systems via meter placement;
2) introducing software and hardware instruments required to perform meter placement;
3) describing more in depth software and hardware instruments required to perform network reconfiguration;
4) further discussing a unique instrumentation and measurement system which can adapt for a variety of power-system planning and operating scenarios;
5) demonstrating application of the system to test various meter placement schemes under different network configurations.

We note that the purpose of this paper and the laboratory is not to promote one meter placement technique over another, nor one network reconfiguration technique over another. Rather, the subsequent laboratory allows for the testing of different techniques and, consequently, is an effective research and educational tool. This paper will present an overview of the measurement and control system for the general laboratory and then will focus on capabilities purposely added for meter placement and network reconfiguration.

II. PROPOSED APPROACH

At Drexel University, an automated measurement and control system has been designed and constructed for distribution system analysis. It is applied to the RDAC Laboratory, which is a 43.2-kW, 208-V, three-phase, 36-bus scaled-down distribution system [18]. This measurement and control system, which includes hardware and software instruments, is composed of four remote-terminal units (RTUs). The general architecture of the system is shown in Fig. 1. Each RTU consists of 1) hardware instruments: data acquisition (DAQ) and control circuits based on a National Instruments (NI) SCXI signal conditioning and instrumentation system [22], and 2) software instruments: a distribution energy management system (DEMS) with a graphical user interface (GUI) developed using NI Component Works [23] and Microsoft Visual Basic 6.0 [24].

In order to evaluate the power-system performance and to perform meter placement and network reconfiguration studies, the following main measurement and control capabilities need to be addressed:

1) multiple user-selected three-phase measurement locations;
2) simultaneous voltage and current measurements;
3) rms, phase angle, and power calculations;
4) control of system components, such as network switches, and devices used to create faults.

To perform electric power network reconfiguration studies, the measurement and control system needs to adapt to different network topologies. Thus, actuation devices must be adequately distributed to create different network configurations. Sensing and monitoring resources must be sufficient for these different topologies and should capture both transient and steady-state behavior, as well as sense unbalanced conditions across phases. Thus, the placement of metering devices should also allow for both state and event observability. Hence, multiple simultaneous measurement points are needed to provide redundancy.

Studies of different distribution systems can be performed. The data and subsequent results can be applied to determine network reconfiguration-control schemes for improved energy efficiency and reliability. Then, hardware instruments can be actuated to realize the configuration of the network and the desired placement of the meters.

The above needs to identify several desired characteristics of the measurement and control system of RDAC. For its measurement capability, the system must perform a series of tasks, including the following:

1) sensing three-phase and neutral voltage and current signals at each measurement bus;
2) monitoring up to 16 user-selected buses;
3) signal attenuation, filtering, isolation, and suppression;
4) capturing harmonic signals up to 1000 Hz (i.e., up to the 15th harmonic at 60 Hz) to allow for capacitive load studies;
5) storing and displaying real-time voltage and current waveforms;

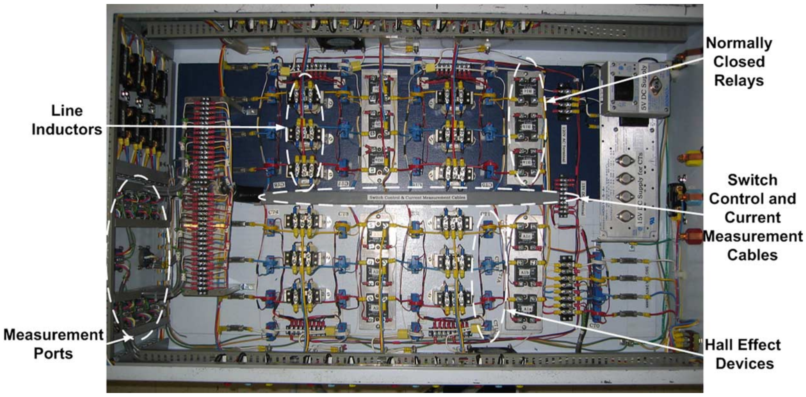


Fig. 2. Top-view of RDAC nine-bus distribution feeder box, showing power hardware and measurement hardware.

6) calculating, storing, and displaying rms and angles of voltages and currents, frequency, power factor, and real and reactive power.

In addition, for its control capability, the system needs to perform a series of tasks that includes

1) operating controllable network devices such as automatic switches;
2) allowing for both single- and three-phase switching;
3) visualizing actual distribution system setups.

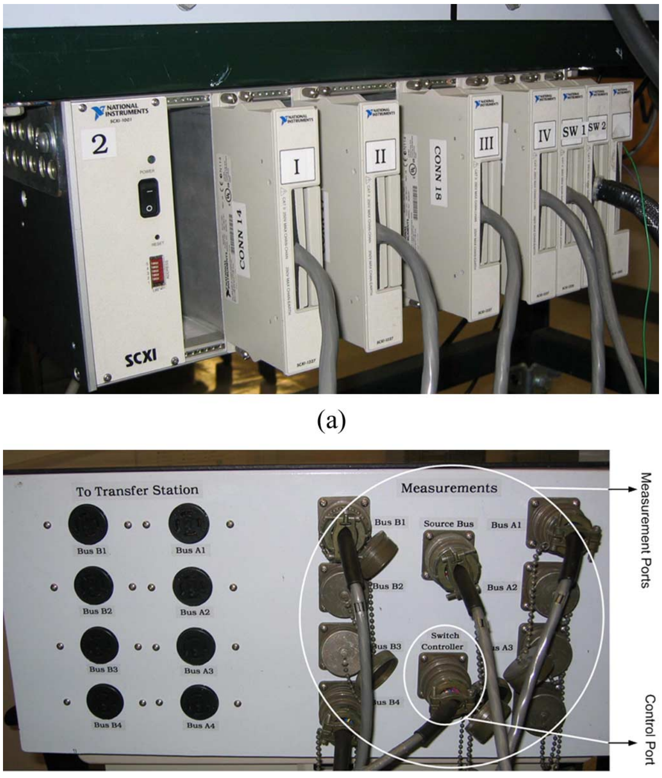
The resulting design of RDAC's measurement and control system is presented in the next section. A description of its applications is also discussed.

III. AUTOMATED MEASUREMENT AND CONTROL SYSTEM

A set of hardware and software instruments was developed for RDAC. As alluded to in the previous section, RDAC consists of four identical stations, each of which is a nine-bus distribution feeder with four three-phase normally closed sectionalizing switches, up to four three-phase normally open tie switches, and multiphase loads (see Fig. 2 for a top view of the nine-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 digital relays, which provides capabilities of reconfiguring system structure, switching capacitors ON/OFF, and creating various types of faults. The measurement and control hardware is operated by the DEMS, which is a software platform that runs on the RTU. Details of the hardware and software instruments used for the flexible and automated measurement and control system are now discussed.

A. Hardware Instruments: DAQ and Control

The hardware on each measurement and control station was developed around an NI SCXI signal conditioning and instrumentation system to allow the system to perform tasks one through four, seven, and eight in the proposed approach section [see Fig. 3(a) and (b)].



(a)

(b)

Fig. 3. (a) SCXI Rack—SCBs and digital-control boards, connected to the distribution feeder box by in-house-made cables. (b) Side-view of the distribution feeder box, showing measurement and control ports.

The measurement hardware on each station consists of voltage and current sensors, four signal-conditioning boards (SCBs), and a DAQ card.

NI SCXI-1327 voltage attenuators [25] transform three-phase and neutral voltages from up to 250 V to levels acceptable to the DAQ card ($<$ 10 V) at 100 : 1 ratio. These voltage attenuators have a typical gain error of ±0.035%, a maximum gain error of ±0.08%, and an offset error of ±0.51-mV/gain respect to input (RTI) (with respect to the input). Three-phase and neutral currents are measured using 100-A Liaisons Electroniques-Mécaniques (LEM) LA-100P hall-effect current transducers [26], which have a 2000 : 1 ratio and a 0.45%

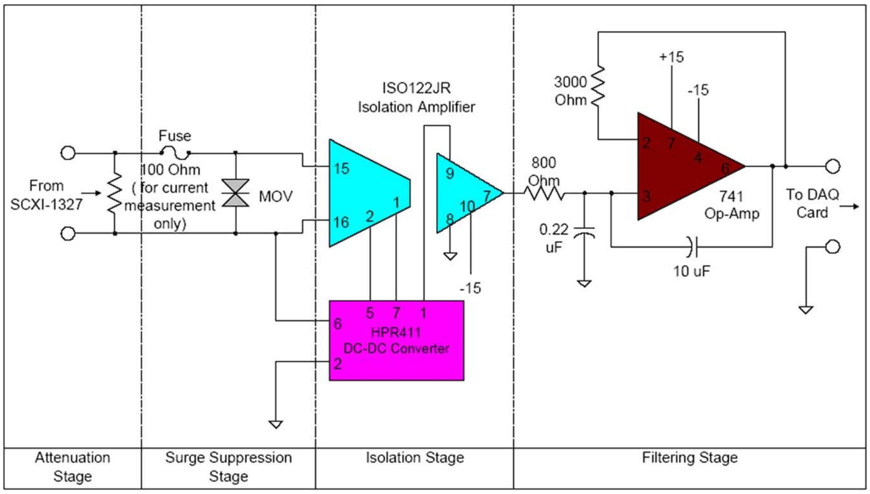


Fig. 4. Voltage and current signal-conditioning circuits [30].

accuracy. The attenuated voltage and current signals are then sent to eight channel SCBs. The signal-conditioning circuit has four stages and provides the following functions: 1) attenuating signals, 2) suppressing voltage spikes, 3) preventing ground loops, and 4) filtering high-frequency noise over 1000 Hz. A schematic of the signal-conditioning circuit is shown in Fig. 4. Repetitive testing was performed to establish the SCBs' output-to-input ratios. The average ratio for the four voltage channels was found to be 0.985, while the ratio for the four current channels was determined to be 1.002. Each RTU is programmed to capture 32 filtered voltage and current signals using a 12-b 1.25-MHz NI PCI-6071E DAQ card [27].

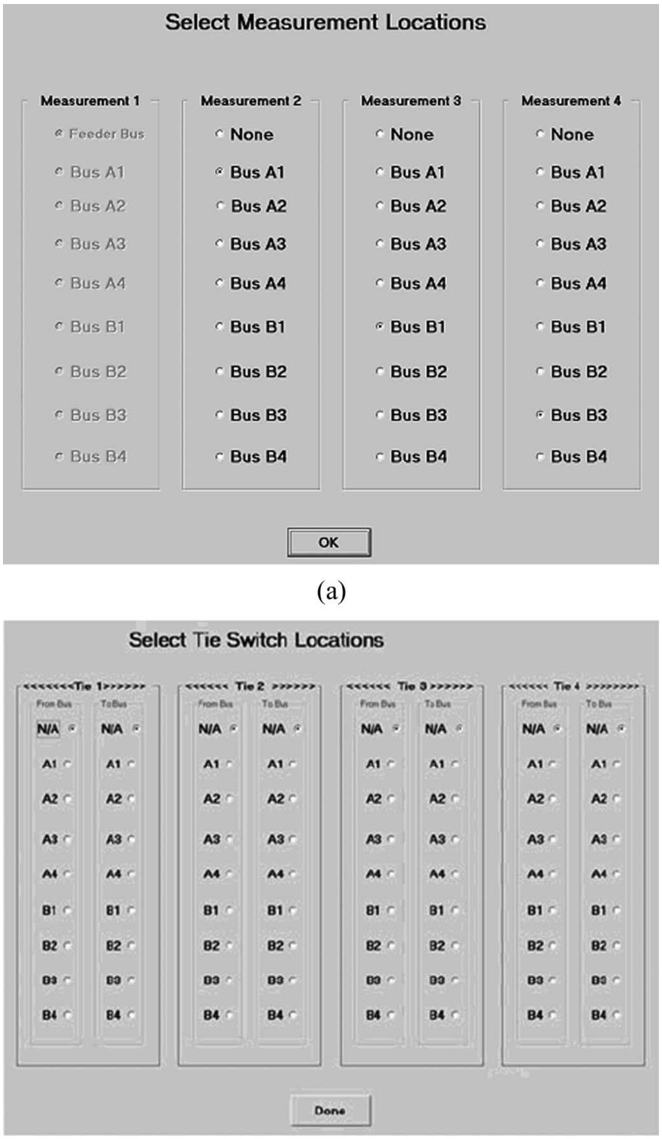
Each RTU also uses its DAQ card and two NI SCXI-1163 digital-control modules [28] to remotely operate 55 controllable switching devices, which are mimicked using Crydom D2475 and D2475B [29], normally open and normally closed digital relays, respectively.

B. Software Instruments: DEMS

A DEMS was designed to remotely monitor and control the above hardware and to enable performance evaluation of the power system. The DEMS was implemented on a PC using NI Component Works and Microsoft Visual Basic 6.0. The DEMS includes virtual measurement and control instruments and provides system-control functions as well as data process and display capabilities. More specifically, it allows the accomplishment of tasks five through nine in the proposed approach section.

In order to link the measurement hardware and the software, a measurement interface was created, as shown in Fig. 5(a). It allows users to specify the locations of measurements placed in the hardware, which can be determined by meter placement studies. In order to link power hardware and software control instruments for network reconfiguration, the user is able to select and specify the desired switch location, as shown in Fig. 5(b).

The DEMS provides a nine-bus distribution system diagram that reflects the actual experimental setup on each RTU. A screen shot of the main GUI of a general three-phase



Select Measurement Locations

Measurement 1	Measurement 2	Measurement 3	Measurement 4
● Feeder Bus	○ None	○ None	○ None
○ Bus A1	● Bus A1	○ Bus A1	○ Bus A1
○ Bus A2	○ Bus A2	○ Bus A2	○ Bus A2
○ Bus A3	○ Bus A3	○ Bus A3	○ Bus A3
○ Bus A4	○ Bus A4	○ Bus A4	○ Bus A4
○ Bus B1	○ Bus B1	● Bus B1	○ Bus B1
○ Bus B2	○ Bus B2	○ Bus B2	○ Bus B2
○ Bus B3	○ Bus B3	○ Bus B3	● Bus B3
○ Bus B4	○ Bus B4	○ Bus B4	○ Bus B4

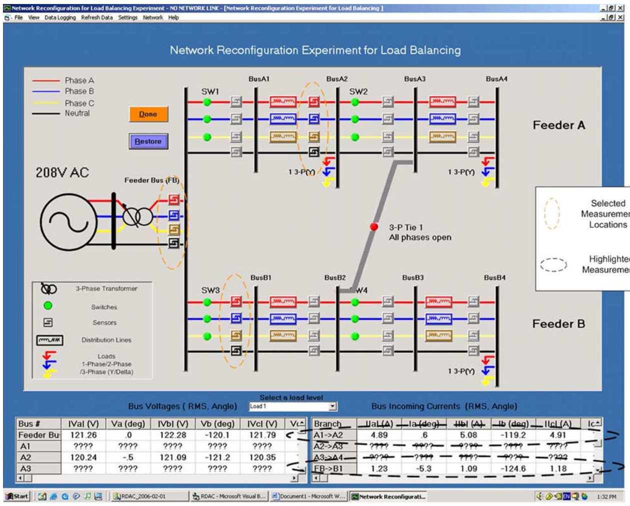
(a)

Select Tie Switch Locations

<<<<<<Tie 1>>>>>>		<<<<<< Tie 2 >>>>>>		<<<<<< Tie 3 >>>>>>		<<<<<< Tie 4 >>>>>>>	
From Bus	To Bus	From Bus	To Bus	From Bus	To Bus	From Bus	To Bus
N/A ●	N/A ●	N/A ●	N/A ●	N/A ●	N/A ●	N/A ●	N/A ●
A1 ○	A1 ○	A1 ○	A1 ○	A1 ○	A1 ○	A1 ○	A1 ○
A2 ○	A2 ○	A2 ○	A2 ○	A2 ○	A2 ○	A2 ○	A2 ○
A3 ○	A3 ○	A3 ○	A3 ○	A3 ○	A3 ○	A3 ○	A3 ○
A4 ○	A4 ○	A4 ○	A4 ○	A4 ○	A4 ○	A4 ○	A4 ○
B1 ○	B1 ○	B1 ○	B1 ○	B1 ○	B1 ○	B1 ○	B1 ○
B2 ○	B2 ○	B2 ○	B2 ○	B2 ○	B2 ○	B2 ○	B2 ○
B3 ○	B3 ○	B3 ○	B3 ○	B3 ○	B3 ○	B3 ○	B3 ○
B4 ○	B4 ○	B4 ○	B4 ○	B4 ○	B4 ○	B4 ○	B4 ○

(b)

Fig. 5. (a) Measurement selection window with Feeder Bus, Bus A1, Bus B1, and Bus B3 selected. (b) Tie-switch location-selection window.



Bus Voltages (RMS, Angle)

Bus #	|Va| (V)	Va (deg)	|Vb| (V)	Vb (deg)	|Vc| (V)	Vc
Feeder Bu	121.26	.0	122.28	-120.1	121.79	
A1	????	????	????	????	????	
A2	120.24	-.5	121.09	-121.2	120.35	
A3	????	????	????	????	????	

Bus Incoming Currents (RMS, Angle)

Branch	|Ia| (A)	Ia (deg)	|Ib| (A)	Ib (deg)	|Ic| (A)	Ic
A1->A2	4.89	.6	5.08	-119.2	4.91	
A2->A3	????	????	????	????	????	
A3->A4	????	????	????	????	????	
FB->B1	1.23	-5.3	1.09	-124.6	1.18	

Fig. 6. Screen shot of the DMS with selected measurement locations highlighted.

experimental setup is displayed in Fig. 6, showing the following system information:

1) a 208-V ac source with a three-phase autotransformer servicing the system;
2) a nine-bus system with 12 color-coded distribution lines and the number of loads and their connection types to match the hardware setup;
3) four three-phase closed switches (SW1–SW4) represented using green or lightly shaded circle icons;
4) four single-phase meters at each bus (highlighted meters indicate selected measurement locations);
5) 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 various forms: 1) real-time oscillographic waveforms and phasors of voltages and currents (Fig. 7), 2) real-time power waveforms, and 3) numerical data of voltages, currents, and power. The DEMS also allows 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. This allows them to create three-, two-, and single-phase system configurations. Fig. 8 shows the control instrument for operating a normally open tie switch.

IV. APPLICATION OF THE MEASUREMENT AND CONTROL SYSTEM IN RDAC

The instrumentation and measurement system in RDAC allows users to perform meter placement studies for various purposes, such as detection of network reconfiguration, load estimation, and impact of a loss of measurements, in a real-life environment. It provides flexibility for users to select between one to four three-phase and neutral measurements at different locations in the nine-bus system. Generally, one measurement is taken on the Feeder Bus and treated as the reference. Then, the total number of possible meter locations is $1 + C_1^8 + C_2^8 + C_3^8 = 93$, where C is the combination. As such, users can test different meter placement schemes for various purposes.

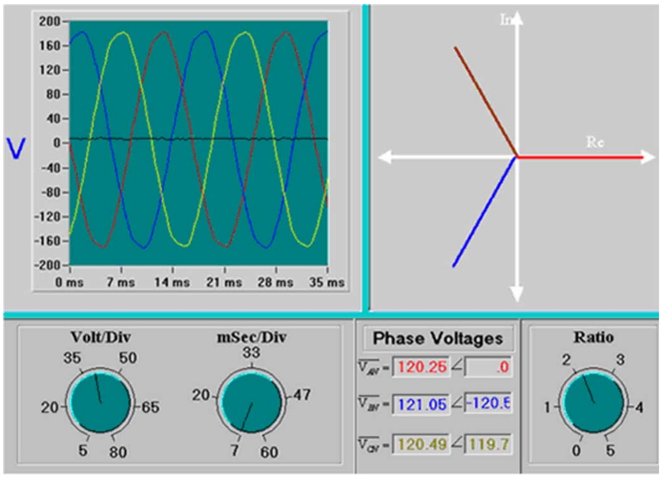


Fig. 7. Measurement instrument: oscilloscope view and the phasor diagram of three-phase ac voltages.

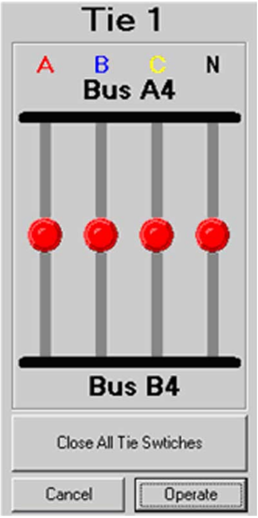
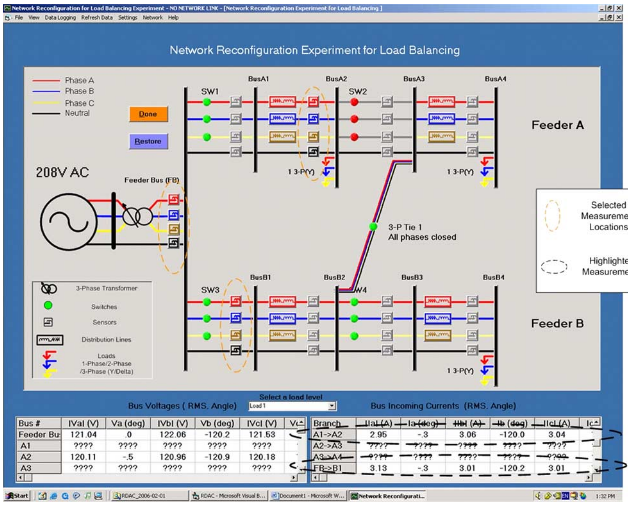


Fig. 8. Control instrument. Network tie-switch operation.

The network shown in Fig. 6 is used to show the application of the instrumentation and measurement system for a network reconfiguration experiment. Three measurements are placed on the Feeder Bus, Bus A2, and Bus B1. It is found that the current entering Feeder A is approximately 4.9 A, while 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 Fig. 9. To reconfigure the network in Fig. 6, the following switch operations were performed

1) Open the three-phase sectionalizing switch SW2 between Bus A2 and Bus A3.
2) Close the three-phase tie-switch three-P Tie 1, 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



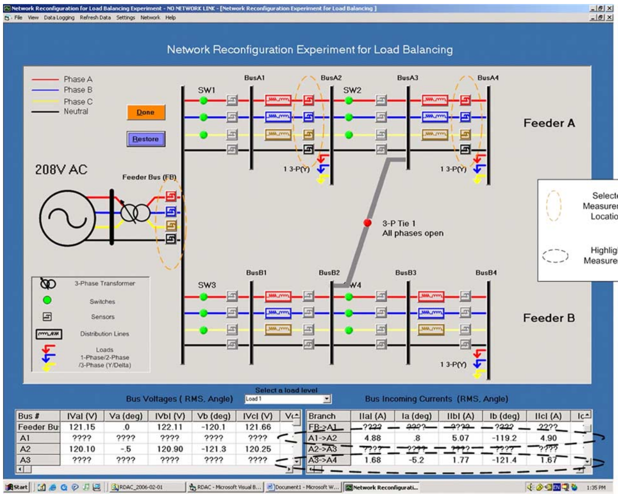
Bus Voltages (RMS, Angle)

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

Bus Incoming Currents (RMS, Angle)

Branch	|Ia| (A)	Ia (deg)	|Ib| (A)	Ib (deg)	|Ic| (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. 9. Screen shot of the DMS after network reconfiguration with SW2 open and three-P Tie 1 closed.



Bus Voltages (RMS, Angle)

Bus #	|Va| (V)	Va (deg)	|Vb| (V)	Vb (deg)	|Vc| (V)
Feeder Bu	121.15	.0	122.11	-120.1	121.66
A1	????	????	????	????	????
A2	120.10	-.5	120.90	-121.3	120.25
A3	????	????	????	????	????

Bus Incoming Currents (RMS, Angle)

Branch	|Ia| (A)	Ia (deg)	|Ib| (A)	Ib (deg)	|Ic| (A)
FB->A1	????	????	????	????	????
A1->A2	4.88	.8	5.07	-119.2	4.90
A2->A3	????	????	????	????	????
A3->A4	1.68	-5.2	1.77	-121.4	1.67

Fig. 10. Screen shot of the DMS with selected measurement locations highlighted for load estimation.

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 that the loads may vary with time, it is noted that we have the following: 1) The loads on Bus A2 and A4 in Fig. 6 cannot be determined using the three meters, and 2) the loads on Bus A4 and Bus B4 in Fig. 9 cannot be determined after the reconfiguration.

A more appropriate meter placement for this particular load estimation case, using three meters, is provided in Fig. 10. 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 Fig. 10 can be determined by subtracting the current measured on Bus A2 by the current measured on Bus A4. It is approximately equal to $4.88 - 1.68 = 3.2$ A on phase A.

The impact of the loss of measurements on system monitoring and operation can also be studied in RDAC. For the network reconfiguration example in Fig. 6, both the meters on Bus A2 and Bus B1 capture the changes in the network structure Fig. 9. Thus, this meter placement can detect network reconfiguration even if one of the three meters does not function. For the load estimation in Fig. 10, 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 the 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.

It is noted that the proposed instrumentation and measurement has been utilized in several educational experiments. These experiments are performed within a three-course sequence at Drexel University, focusing on the distribution system analysis. Laboratory modules have been utilized for undergraduate, graduate, and professional training and education. In addition, the laboratory facility provides a test bed for research in the planning and operation of electric power and energy systems.

V. CONCLUSION

Several hardware and software instruments have been specifically designed and implemented to allow for meter placement and network reconfiguration studies. The instruments provide measurement and control capabilities for distribution systems of different configurations. The hardware and software instruments have been combined with measurement instruments to form the unique and flexible instrumentation and measurement system of the RDAC Laboratory at Drexel University. Instrumentation and measurement capabilities of the laboratory include the following: monitoring up to 16 user-selected locations, recording and displaying real-time measured voltage, current, and power waveforms, and remotely operating controllable devices, such as digital relays, to reconfigure the network structure. These characteristics enable event and state estimation. The resulting laboratory can be applied to study meter placement and network reconfiguration and can be utilized for research, as well as 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, allowing for larger system studies and remote-laboratory operation.

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