

The Development of a Comprehensive Power Distribution System Curriculum

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Abstract: The restructuring of the electric utilities and the rapid installation of new automated components has created the need for engineers with formal knowledge about power distribution automation and control. In response, at Drexel, we have developed a power distribution systems curriculum centered around a *Reconfigurable Distribution Automation and Control* laboratory, RDAC. This paper will present (i) new developments in the hardware design and layout of a RDAC [1] and (ii) the current steps being taken to integrate RDAC into the existing curriculum.

I. Introduction

The security, the maintenance and the improved reliability of electric power distribution systems (<115kV) has recently experienced increased scrutiny for multiple reasons. As such, power distribution companies, automotive companies, architectural engineering firms, ship builders, pharmaceuticals, etc., are increasingly concerned with their energy systems and are re-evaluating (i) the current status, (ii) the monitoring and control systems, and (iii) the operating and planning techniques of their power distribution systems.

To address this trend, the topic of power distribution systems has been addressed at several universities in terms of classes and software laboratories, with a smaller number of universities addressing hardware laboratories [1-6]. Also, recent textbooks have been created to satisfy demand for power system studies focused on the lower power, lower voltage systems [7]. Frequently, power distribution systems encompass many interconnected electrical components servicing a large number of loads or end power users. While the number of components combined to form the system is numerous, the formal study of power distribution systems is complicated further because components can be of multiple-phasing and wiring.

At Drexel, a comprehensive curriculum in power distribution systems has been designed to expose all electrical and computer engineering students to three-phase power distribution systems. The main vehicle for experimental and classroom examples of power distribution systems will be through *Reconfigurable Distribution Automation and Control* (RDAC) laboratory modules. In addition, RDAC [1,2] will provide students with hands-on learning experiences in the analysis, operation and planning of electric power distribution systems.

RDAC consists of four modular stations that can combine to form a power distribution system with a total of 36 buses, 16 lines, 16 normally closed switches and a number of possible load connections. Thus, with a large number of interconnected components, special attention to the layouts of the hardware components (power source stations, distribution feeder boxes and transfer/load stations) and the entire RDAC laboratory was made in [1]. We note that each component is multi-phase and can be altered to be single, two or three-phase; and each scaled-down electrical component used to realize a power distribution system was subject to repeated hardware parameter testing and the checking of basic functions such as on/off characteristics for switches/relays [2].

Embedded within the distribution system is a supervisory control and data acquisition (SCADA) system which includes signal conditioning hardware, data acquisition equipment, and remote terminal units (RTUs) for local computations. RDAC will have four personal computers (PC) as remote terminal units (RTU's) and a master station. This set-up will allow up to 4 groups of students to acquire data and to perform network studies at one time. Four National Instrument's PCI-6071E data acquisition cards have been acquired to capture data and to provide control of network switches and capacitors.

Visual Basic software is currently under design to utilize the SCADA system and to allow students to view network voltages, currents, and power flow in a user friendly and realistic manner. In this paper, special attention on the hardware design of the embedded data acquisition system is included. In addition, efforts towards integrating the laboratory into existing power distribution courses are discussed. Specifically, the coordination of course objectives with the design of accompanying experiments will be discussed. This paper:

- introduces the design of educational experiments for upper-level courses
- discusses and displays the new RDAC hardware design and development since [1]
- highlights the effects of the experiment design on the RDAC hardware design.

II. Curriculum Overview

A comprehensive curriculum is targeted to expose all electrical and computer engineering students to power distribution systems through RDAC laboratory modules. Some targeted distribution system concepts are now listed for students at different levels:

- second-year material:
 - to understand differences between parallel and series connections of impedances
 - to experience examples of basic circuit theory in the context of distribution systems
- advanced material:
 - three-phase power flow analysis for unbalanced systems
 - network reconfiguration for load balancing or planned outages
 - service restoration after unplanned outages
 - capacitor placement for voltage regulations
- capstone/senior design and graduate level:
 - to enable students to design and test their own control schemes
 - to measure the effects of different automation and control schemes

For upper-level electrical engineering students a more formal education in unbalanced power systems through dedicated courses and laboratories is desired. Thus, a full academic year power distribution course sequence, for upper-level undergraduates and first-year graduate students, has been designed and has been offered three times in the last five years with an average enrollment of 15 students. Drexel operates on a quarter system, and a three-term course sequence has been developed. The first course focuses on the modeling and analysis of unbalanced distribution systems. The second course focuses on distribution application functions and the rigorous formulation and solution algorithms to practical problems such as network reconfiguration and capacitor placement and control. The third course focuses on service and power quality, and includes topics such as state estimation, service restoration and power quality. These distribution topics drive the hardware, software and data acquisition design of RDAC.

Thus, with these topics in mind, RDAC has been designed to be reconfigurable both in its physical construction and electrically, through computer and manually controlled devices. As completion of RDAC nears, new in-class examples include circuit representation of a nine bus distribution system with parameters obtained from [12]. This example corresponds to one RDAC lab station (1 source bus, 8 load buses, 4 lines and 4 switches.) In addition, the laboratory experiments being designed include: (i) network reconfiguration for load balancing, (ii) service restoration and (iii) capacitor placement studies. We will now discuss; how the desired experiments affected the hardware design of RDAC.

III. Laboratory Development

The general laboratory electrical configuration is now reviewed and a one-line diagram of RDAC is shown in Figure 1. The electric infrastructure will be normally operated in a radial manner at a frequency of 60Hz and a voltage level of 120V phase to neutral. It can also be reconfigured to operate as a DC system. Detailed descriptions of the physical layout and modularity of the laboratory and detailed descriptions of the components used can be found in [1] and [2] respectively.

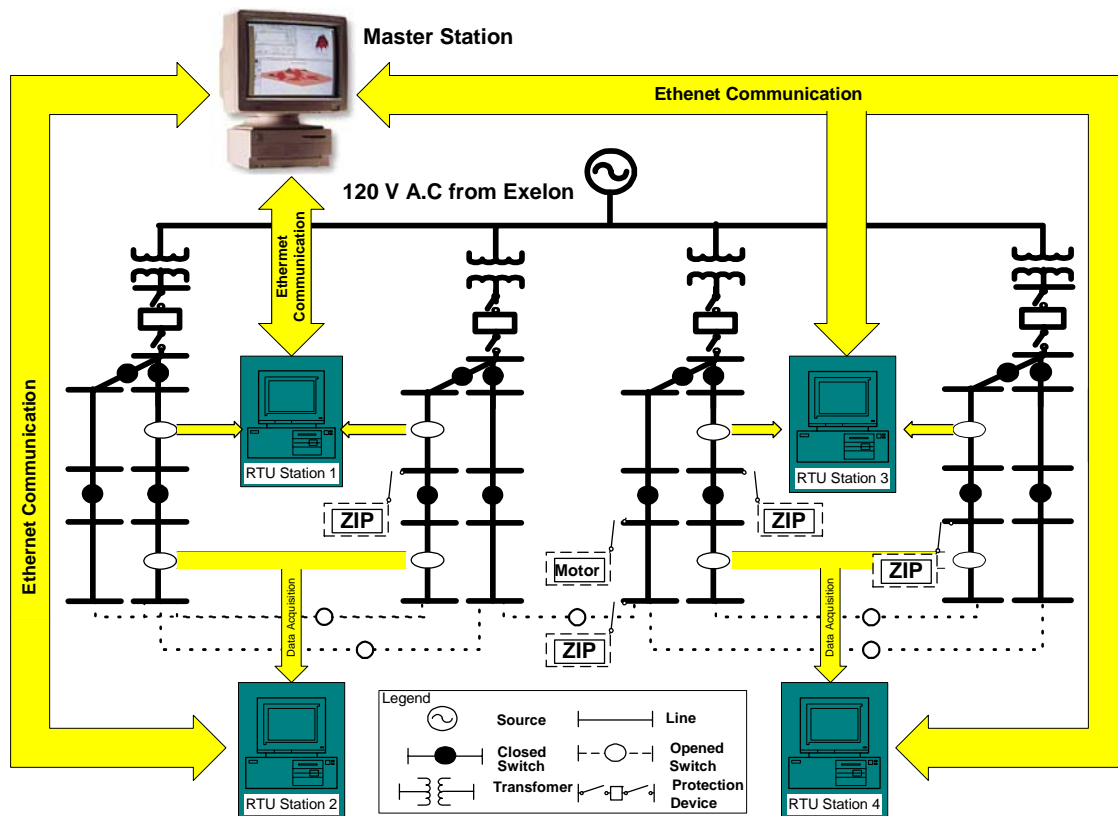


Figure 1. One-line diagram of the 7 kW three-phase RDAC laboratory in a typical setup

Please note, in this layout, four identical feeders each with one branching lateral can be identified. This resulted in the creation of 4 identical student laboratory stations each focusing on a radial 8 buses system. Within each laboratory station four main parts exist: (i) the power station, (ii) the distribution feeder box, (iii) the load station and (iv) a PC for data acquisition and computer control.

We note that when larger distribution networks are required for study, for example in senior design or graduate student projects, (ii) the distribution feeder boxes and (iv) the PC for data acquisition and computer control are mounted on rolling carts to allow for alternative connections. Also, in such a case, one data acquisition card will serve as the clock to obtain synchronized measurements throughout the lab and the RTU's and master station will communicate across an Ethernet.

A color coding scheme has been utilized throughout RDAC: red – phase A, blue – phase B, yellow – Phase C and white for neutral (shown as black in most subsequent figures) to ease the understanding of electrical connectivity of individual components. The following subsections reviews the design layouts for each part (i-iv) from [1] and presents the actual stations constructed.

III.A. Power Stations

Four individual 30A power stations service each laboratory station. Since distribution systems may have portions of the network that are single or two-phase, individual phases may be tapped when illustrating multi-phase concepts. In addition, some distribution systems are DC, for example certain shipboard power distribution systems, therefore, each power station can be fed by either an AC or DC source to allow flexibility in the types of distribution system being studied. Details of the power and voltage ratings can be found in [1]. The power station panel layout and the final constructed power station are shown in Figure 2a. and 2b.

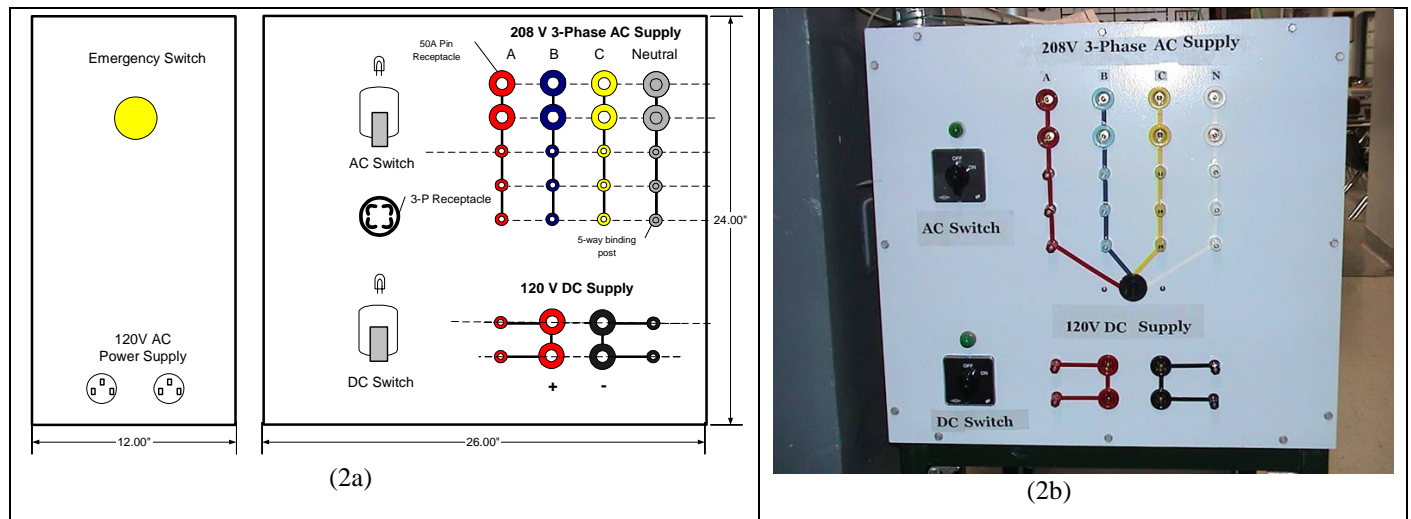


Figure 2a and 2b.. Power Station: (a) Design Layout [1] and (b) Constructed Station with 3-Phase 208V AC and 120V DC Power Supplies, three-phase and individual phase connections available

The power stations main purpose is to provide power to the subsequent distribution system although it may be used for other suitably rated laboratories. Within RDAC, the distribution feeder boxes and subsequent loads will be fed by direct connection to the power stations. In the next subsection, we discuss the construction of the distribution feeder boxes.

III.B. Distribution Feeder Boxes

The power stations will provide power to distribution feeders consisting of several distribution lines and buses where loads can be connected [1,2]. Four, identical distribution feeders, each with one branching lateral has been built, please see Figure 1. The top view of the component layout for distribution feeders and a picture of the constructed box are presented in Figures 3a. and 3b. on the following page.

To enable experiments in distribution automation functions such as network reconfiguration for load balancing or loss reduction and service restoration techniques, each phase of a distribution switch in the feeder is emulated using a normally closed digital relay and is in place to allow for experiments demonstrating network reconfiguration techniques. Also, shunt connections to buses, for example loads and shunt capacitors, are allowed along the feeders and laterals through a connection to the transfer/load station. Finally, we note that three CT's are available at each bus and are part of the SCADA system. At each bus, 4 voltages (phase A, B, C

and neutral) and 4 currents can be sensed and communication wires are present to send the signals back to a signal conditioning board that is physically housed under the transfer stations.

Thus, the three-phase distribution feeder of Figure 3b consists of:

- electrical circuit elements – inductors and network switches/digital relays
- measurement devices and a DC power source for the measurement devices
- control signal wiring for remote control of digital relays
- fuses for overcurrent protection
- digital relays mounted on heat sinks

Each element will demonstrate to students the engineering and physical considerations that are involved in building and maintaining a power system and its associated monitoring and control system. Also, cable troughs are mounted along each edge of the distribution box to accommodate the electrical wiring connections to multiple measurement points and the communication system wiring for sensing and digital control signals for network switches.

Figure 3b also shows the external side views of the distribution feeder boxes. Again color coding is held consistent for all the receptacles and Figure 3b also displays:

- receptacles for receiving power from the power station
- three-phase power receptacles for connecting to the transfer station and subsequently loads and capacitors banks
- measurement receptacles to allow for connections to the signal conditioning chassis.
- cooling fans
- binding posts to allow for hand held metering

Finally, we would like to note that extensive effort has been spent in making the cables to interconnect the distribution feeder box, both electrically and for its sensing and communication needs to the power station and the transfer station which we now discuss.

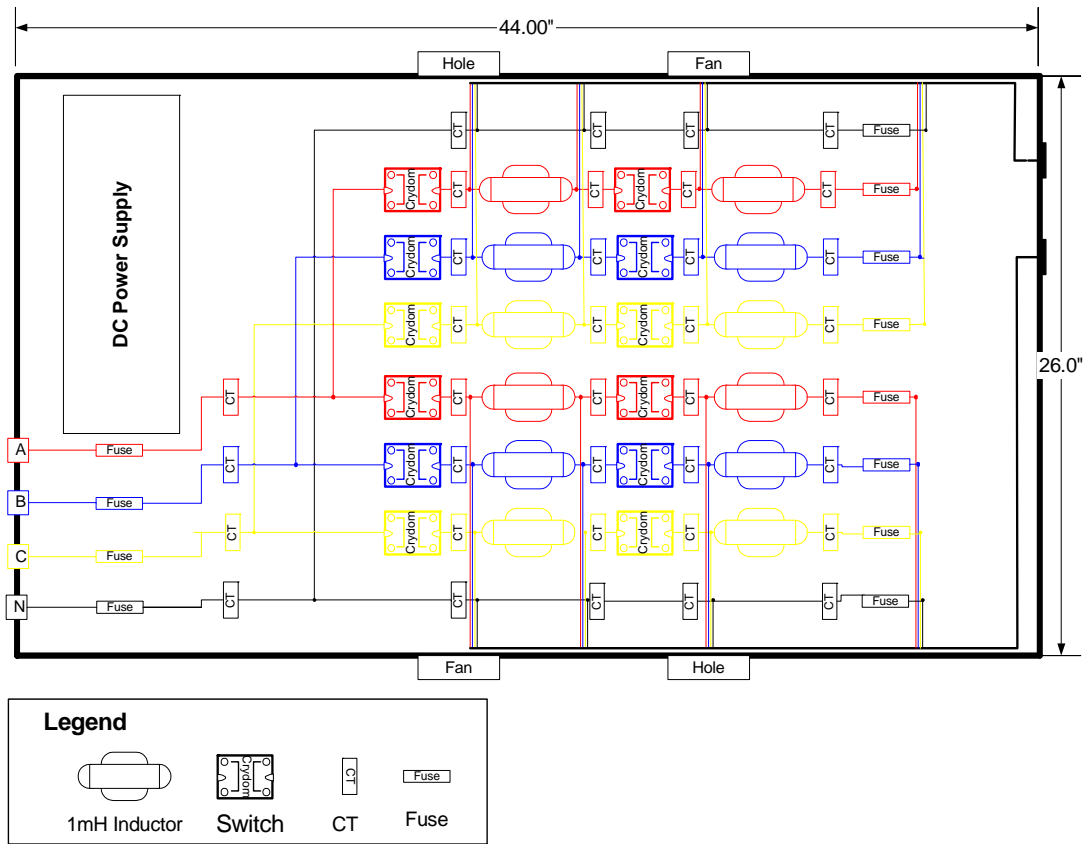


Figure 3a. Distribution Feeder Box Layout [1]: a 3-phase feeder with one branching lateral, color coded: red – phase A, blue – phase B, yellow – phase C and white for neutral (shown as black in the diagram.)

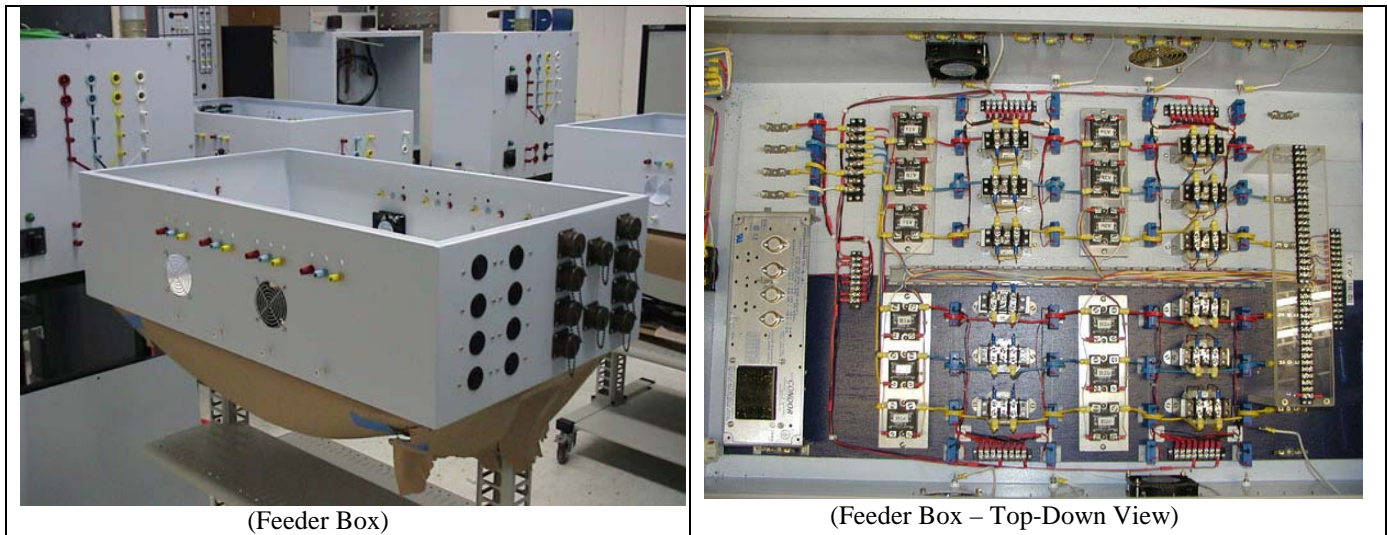


Figure 3b. Distribution Feeder Box: exterior housing unit (providing receptacles for hand-held meters, automated measurements and electrical transfer points to the transfer/load stations) and top-down view of the constructed feeder circuit from Figure 4a.

III.C. Transfer Stations

Each distribution feeder box connects to a corresponding transfer station. Since many of the desired educational experiments such as network reconfiguration and capacitor placement and control are realized within the transfer station, great care has been given towards its design. The initial layout [1] of a load station and the final constructed load station can be seen in Figures 4a. and 4b.

The Transfer Station has several functions; the foremost is to make electrical connections of components, such as loads and capacitors, to the buses along a feeder, denoted Feeder A (feeder) and Feeder B (lateral). In addition, to support network reconfiguration experiments, transfer stations “To Other Stations” allow for normally open switches or tie switches (mounted on heat sinks on the right in Figure 4b) to interconnect buses which may be located on different distribution boxes; these are connected using the “To Other Stations” receptacles. Conduits and ceiling mounted cable troughs interconnect the four transfer stations in the lab to facilitate these reconfiguration needs.

In order to support capacitor placement and control schemes, 9 capacitor banks and associated digital relays are located on the lower right of the transfer station. The capacitors can be connected to any bus along the associated feeder by using the binding posts. Manual/toggle control of capacitors banks is available in addition to a computer controlled option for remote switching. We note that the same color-coding exists on the Transfer Stations and some of the other design features are as follows:

- 3-phase receptacles for easier connections and experiment setups
- single-phase receptacles to allow for single and two-phase load connections and capacitor connections
- 12 normally open digital relays used to emulate 4 three-phase tie switches
- light indicators to show whether or not power is flowing
- manual/toggle switch or computer controlled switches for capacitors
- 6 digital relays mounted on the side panel for creating single line to ground, double line-to-ground, line-to-line faults and three-phase to ground faults.
- hard wired connections to resistive loads [2]

Not shown are the side views of the Transfer Station which allow for easy access to fuse devices included for protection and 120V AC supplies for measurement devices and RTU’s. Also, mounted to the bottom of each load station, a signal conditioning board chassis will house voltage attenuators and signal conditioning boards which will receive the data acquired from the distribution feeder boxes. These signal conditioning boards will connect to the NI PCI-6071E data acquisition boards housed in the RTU’s. A total of thirty-two signals, corresponding to four measurement locations (which can be varied) along the distribution feeder are sent at any one time. For larger system studies which may be required by senior design and graduate projects, the on data acquisition board will be used as the clock for the other lab stations to allow for synchronous measurements.

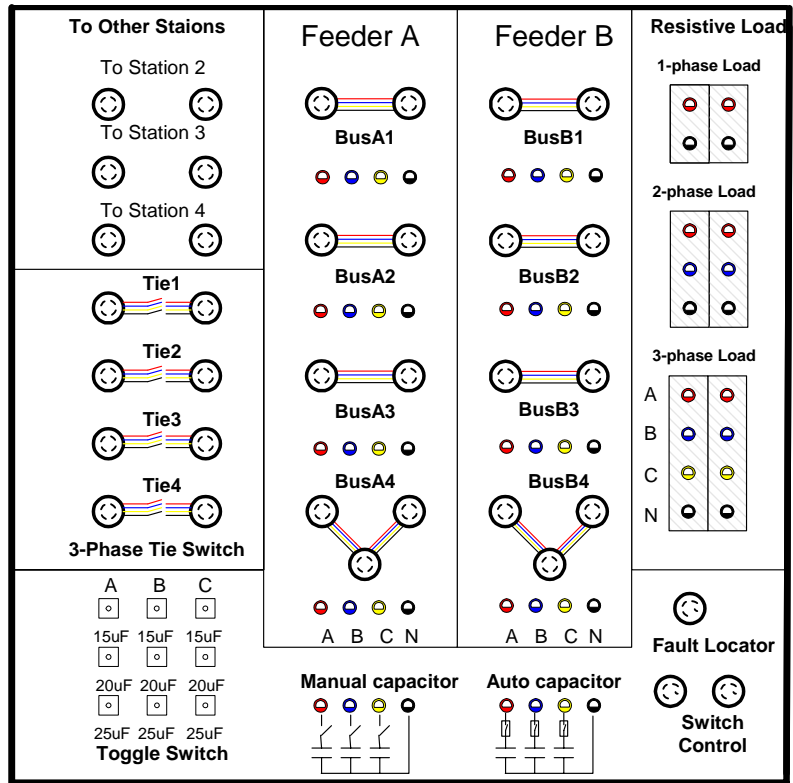
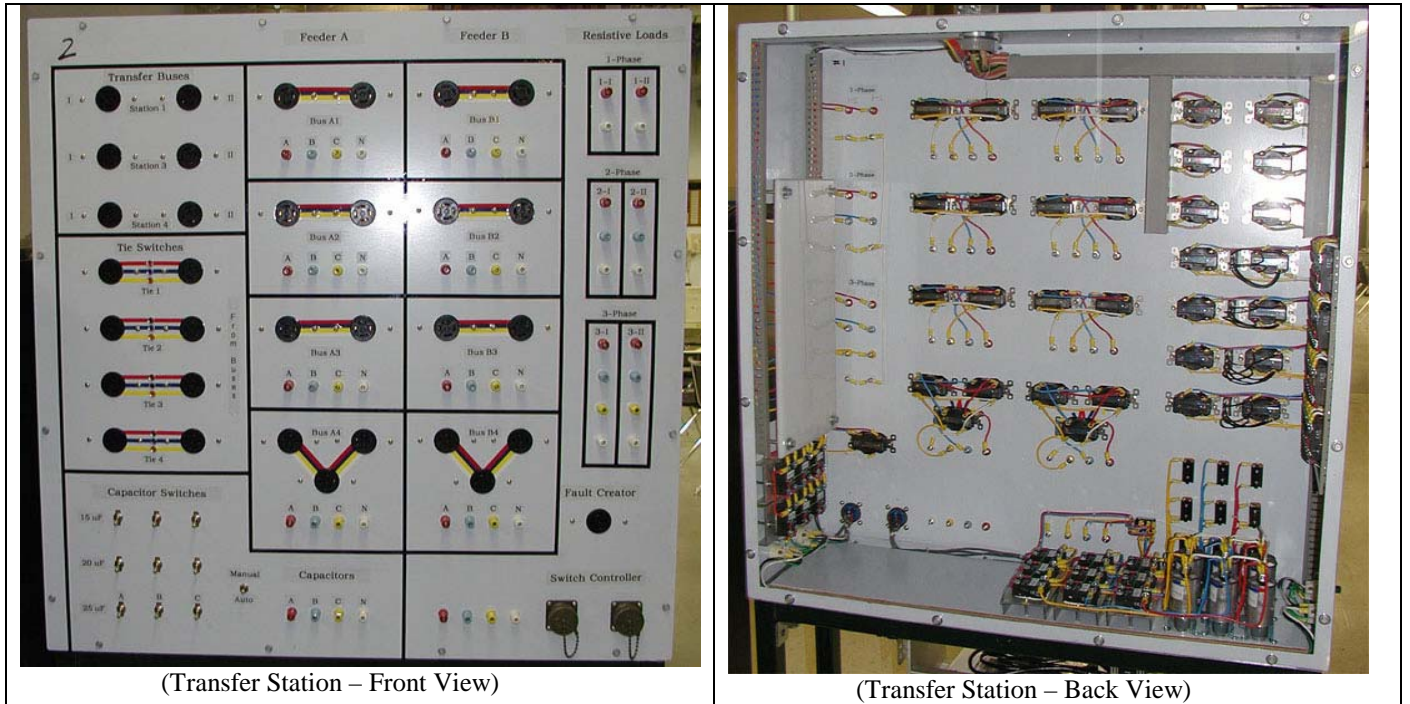


Figure 4a. Transfer Station Layout: with Bus Connections, Interconnections Between Different Feeders, Multi-Phase Capacitors, Resistive Loads and Fault Creating Devices



(Transfer Station – Front View)

(Transfer Station – Back View)

Figure 4b. Transfer Station from front and back views. Bus connections along feeders can be achieved through three-phase and individual phase connections. Capacitors in the lower right hand corner of the transfer station can be both manually and computer controlled through digital

relays. 12 digital relays on the right side of the box, mounted on heat sinks, are used for interconnected different distribution feeder boxes through their Transfer Stations. Six digital relays in the lower left corner are used to create various faults. Lexan backings have been installed so students can view the electrical connections of each component of the Transfer Station.

IV. Conclusions

This paper has documented the progress in the physical design and construction of the reconfigurable distribution automation and control laboratory (RDAC) Laboratory at Drexel University. This laboratory will be the center of a power distribution system curriculum geared towards students from the second year to the senior level and can be used in graduate level curriculum as well. In this paper, photographs of the constructed stations are included and a how the educational experiments affected the hardware design has been made.

V. Acknowledgements

This work was supported by NSF-DUE#9950775 and NSF-ECS#9984692.

VI. Bibliography

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VII. Biographies

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