Setup of RDAC – a Reconfigurable Distribution Automation and Control Laboratory

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Abstract: This paper outlines the setup of RDAC, a reconfigurable distribution automation and control laboratory for undergraduate and graduate electrical engineering education at Drexel University. The physical design of the electrical hardware of a 7kW, three-phase distribution system is described. The paper also details component testing and the analysis of test results that directly affect the system design. Experiments were performed, also, to determine parameters of the network equipment, such as distribution lines, resistive loads, and induction motors.

Keywords: distribution systems, hardware laboratory, power engineering education, distribution automation

I. INTRODUCTION

Traditional power system engineering programs have focused on the generation and transmission system level [1][2][3] of electric utilities. However, several factors have highlighted the need for electrical engineers with exposure to formal education in distribution power systems before they enter the workforce. Industries, including the power distribution companies, automotive companies, architectural engineering firms, pharmaceuticals, etc., are concerned with and hire engineers for the operation and planning of lower power, lower voltage distribution systems.

To fill this need, a power distribution system curriculum is under development at Drexel University. The curriculum is targeted to expose all electrical and computer engineering students to power distribution systems through laboratory modules and to provide more formal education to upper-level electrical engineering students through full courses and laboratories. The power distribution system curriculum will center around RDAC. The laboratory will provide students with hands-on learning experiences in the analysis, operation and planning of electric power distribution systems.

Other universities have developed power distribution laboratories ranging from software to hardware. Among them, software distribution laboratories in [4][5] have focused on distribution system planning. At the University of Florida, a hardware laboratory was established for power quality and energy studies [6]. In Taiwan, a distribution automation laboratory was created for wider types of studies [7]**.**

At Drexel, an interconnected power system laboratory (IPSL) has been incorporated into the existing ECE curriculum [8][9]. IPSL has successfully combined four existing generation and transmission system laboratories into an interconnected three-bus power system with real-time data acquisition. The power distribution system focus of RDAC will complement the generation and transmission oriented laboratories.

The distribution laboratory will incorporate a three-phase radial distribution network. A SCADA system will be developed with facilities such as signal conditioning hardware, data acquisition equipment, and remote terminal units (RTUs). It will allow students to view network voltages, currents, and power flow in a user friendly and realistic manner.

A set of new interactive laboratory experiments will be designed for students from second year to senior level. For second year and third-year students, experiments will illustrate basic circuit theory and complex power concepts in the context of a distribution network. Senior students will perform experiments in three-phase power flow analysis, network reconfiguration for load balancing, service restoration and capacitor placement for voltage regulation. Graduate students can investigate distribution system state estimation, load estimation, power quality issues and transients.

This paper presents the setup process of the electrical system in the distribution laboratory. Appropriate equipment is selected to model realistic equipment characteristics. The equipment must be tested for reliability and appropriate behavior under different operating conditions. However, the parameters of these equipments can vary with the environment. Therefore, a series of tests should be performed to determine the parameters of the equipment.

The paper is organized as follows: in Section II, the physical setup of the distribution laboratory is presented. The design of the hardware is given in Section III. The tests for the distribution lines, resistive loads, and induction motors are discussed in detail in Section IV and the test results are analyzed.

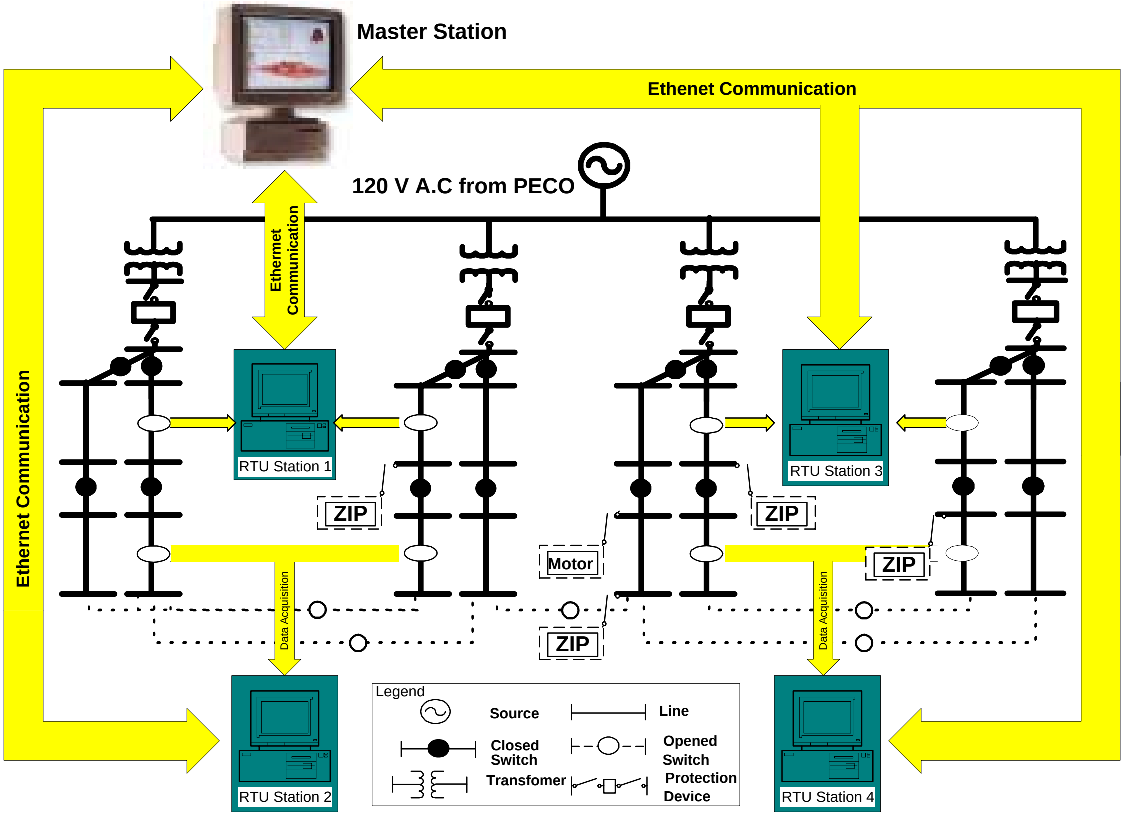

Figure 1. One-line diagram of the 7 kW three-phase power distribution laboratory in typical setup

II. LABORATORY OVERVIEW

The electric infrastructure of RDAC will be multi-phased and normally operated in a radial manner. It can be reconfigured conveniently for different experiments. A single line diagram of a general configuration of RDAC is shown in Figure 1.

The system will normally be operated at a frequency of 60Hz and a voltage level of 120V phase to neutral. It consists of the following:

- 1 source providing power for typical loading conditions, up to 7kW with four feeders connected;
- 4 1:1 variable three-phase auto transformers;
- 4 three-phase over-current circuit breakers with maximum current of 30A, which correspond to the protection devices in Figure 1;
- 4 feeders with one lateral on each feeder, and 16 three-phase lines represented by 48 inductors with maximum 20A current rating each;
- 48 normally opened and 48 normally closed digital relays are used to model 16 three-phase sectionalizing switches and 16 three-phase tie switches. Each relay can be controlled individually;
- ZIP loads with various compositions, including individual constant impedance, constant current, and constant power loads. They can be connected in a balanced/unbalanced fashion.

Each feeder will be enclosed in a distribution feeder box mounted on a cart with casters. This built-in mobility will allow flexible setups; for example, any two feeders can be connected in series to form one long feeder with two laterals. Tie switches in the network can join any two buses between the feeders through a transfer panel.

The whole network will be monitored and controlled by a SCADA system, which consists of four personal computers (PC) as remote terminal units (RTU’s) and a master station. The system will allow for up to 4 groups of students to acquire data and perform network studies. Four National Instrument’s PCI-6071E data acquisition cards (DAQ) will be installed in the PCs to capture data, which will be transferred through an Ethernet between the RTUs and the master station. Care must be taken to design the appropriate number of measurements and sampling rates required for each experiment. This remains as future work.

III. HARDWARE DESIGN

To create the network shown in Figure 1, it is necessary to specify all of the equipment listed in Section II. This section focuses on the selection of the power equipment for the electric distribution system, which includes distribution lines, switching devices, and loads.

Distribution lines are usually short with R/X ratios between 0.25 and 0.4. These lines are to be represented with series resistors and inductors. In RDAC, all the lines are assumed to have the same length. A 1000-meter actual distribution line was scaled down, and each phase represented by an inductor rated at 1mH. Each phase of a three-phase distribution line, will carry 5A under normal operating condition. Therefore, inductors with a maximum current rating of 20A are selected so that we can eventually perform network reconfiguration and we can have different network setups. Test results of the actual impedance of the inductors will be shown in Section 4. Considering the intrinsic resistance of the inductor, it was determined that no additional series resistors are required.

Current carrying digital relays D-2475 and D2475-B from CRYDOM were selected to model sectionalizing switches and tie switches because of their quick response and reliability. The maximum load current of the relays is 75A. It can handle up to 1000A surge current. These relays can also be used as circuit breakers, switching devices for remote controlled network capacitors, and loads.

Different types of loads exist in real distribution systems. In this laboratory, ZIP loads will be used. Static light bulbs, inductors, and capacitors have been selected as constant impedance loads. They can be connected in series and/or in parallel to create several different loading conditions. Constant current loads will be represented by current controlled converters. Induction motors operating in steady-state conditions will be constant power loads. Motor start-ups and transients can be used in the future if voltage dependent loads are required.

The following section presents the experimental test results of the several components discussed above.

IV. EQUIPMENT TEST

The equipment selected in Section III is required to be reliable and to show desired behavior under different operating conditions. The following tests have been performed to acquire the equipment parameters and characteristics:

(1) Distribution line tests for line impedances;
(2) Parameter tests for resistive loads ;
(3) Steady-state tests for the induction motors;
(4) Solid state relay tests;
(5) 3-phase auto-transformer test.

The digital solid state relays were tested using the SCADA system in IPSL. Results showed that the relays responded properly to the control signal from the RTUs. Other components, such as the breakers, the inductive loads, and the capacitive loads will be tested in future. The following subsections present results of the first three equipment tests.

IV. 1 Distribution Line Impedance Test

In total, 48 inductors are required to model 16 three-phase distribution lines and 1mH inductors acquired from PREM were tested. Since the current through each phase could vary from 1A (light load conditions) to 20A (network reconfiguration under heavy loading), which generates much heat in the inductor, it is desired to determine the impedance at different current levels. Also, it is necessary to know whether the R/X ratio approaches the desired R/X value.

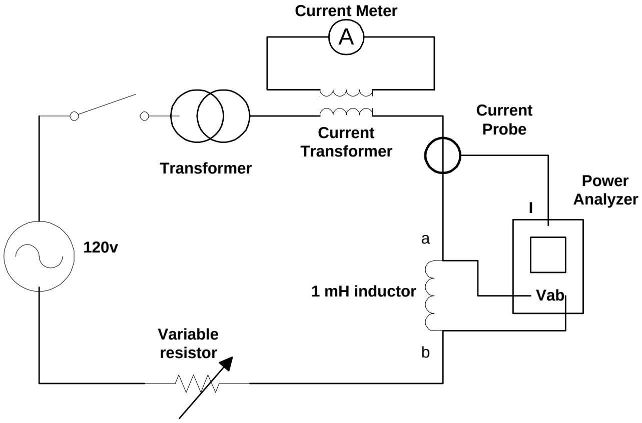

Figure 2. The test circuit for distribution line inductors

Each inductor was tested at 120V within the test circuit shown in Figure 2. Light bulbs were installed in the circuit as variable resistors to adjust the current flowing through the inductor. The current and the voltage across the inductor were measured by two Fluke 87-3 digital multi-meters. Their waveforms were sent to a Fluke 43 power analyzer. Power factor was obtained and used to calculate the impedance. Each inductor was tested at ten current levels. At each current level, four groups of data were measured. The average resistance and inductance values for a 1mH inductor was 0.149Ω and 1.117mH with standard deviation of 0.018Ω and 0.081mH respectively. The average R/X ratio over the different current levels was 0.355 with a standard deviation of 0.018.

In Figure 3, the curves of the mean values of the reactance, the resistance, and the corresponding R/X ratio of a tested inductor are plotted with respect to the current at each loading condition. It can be seen that the inductance decreases with the increase of the current. The resistance also decreases, but more quickly. Thus, the R/X ratio reduces from 0.38 to 0.33, which satisfies the requirement for the R/X ratio.

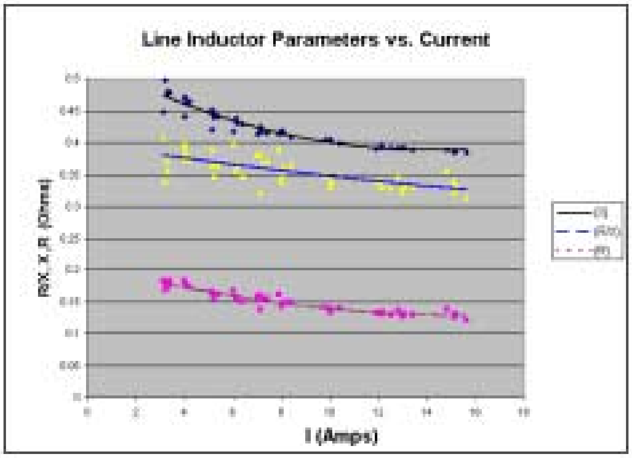

Figure 3. Test results of R, X, and R/X for one distribution line inductor under 10 loading conditions

Since both resistance and reactance are not constant, the inductor impedance can also be seen as a current dependent model. A second order polynomial function was found using the interpolation method to estimate the parameters. It can be expressed as (1)

$$Y = a \cdot I^2 + b \cdot I + c \qquad (1)$$

where:

Y represents the line parameters

I represents the current.

a, b, c represent coefficients of the polynomial function

Considering the error in the test, the actual values of R, X, and R/X can be represented by the value calculated using Equation (1) and an deviation

$$Y^{'} = Y \pm \sigma \qquad (2)$$

where:

$Y^{'\,'}$ represents the actual value of the line parameters

Y represents the predicted line parameters

σ represents the deviation.

The deviation σ can be estimated using the average absolute deviations of the parameters at different current levels:

$$\sigma = \left(\frac{1}{n} \sum_{i=1}^{n} \sigma_i^2 \right)^{1/2} \qquad (3)$$

where:

n represents the # of current levels

σ_i^2 represents the i^{th} absolute deviations deviation

The coefficients of the polynomial functions of the three parameters are provided in Table 1. The deviation values for the R, X, and R/X are also given. It shows that the R/X ratio can be represented as a straight line.

Table 1. Coefficients of the current dependent polynomial function for line inductor R, X, and R/X

Parameter	*a*	*b*	*c*	σ (Ohms)
R (Ohms)	0.0003	- 0.0102	0.2082	0.0064
X (Ohms)	0.0007	- 0.0204	0.5303	0.0064
R/X	1E-04	- 0.0061	0.3984	0.0184

After testing the inductor impedances at other current levels, it was found that the polynomial function could represent the impedance very well.

Note:

- It is planned for students to perform hardware experiments and then validate these experiments using software simulations. Thus, any simulation package used for this purpose must include the polynomial expression for how the line parameters change with respect to current.

IV. 2 Resistive Load Parameter Test

80 W 120 V carbon filament light bulbs were selected as resistive loads in RDAC because of their good resistance characteristics. Experiments were performed at different current levels to determine whether they exhibit constant impedance behavior. Considering the planned voltage levels in RDAC, the maximum voltage added on the light bulbs was limited to 120 V.

In total, seven possible load levels, ranging from 5-60 light bulbs in parallel, were tested. Experiments showed that the reactance of the bulbs is equal to zero. The average resistances of seven groups of light bulbs are plotted with respect to the current in Figure 4. The legend indicates the number of the bulbs represented by each curve. Interpolation and extrapolation methods were applied to obtain resistance at other current levels.

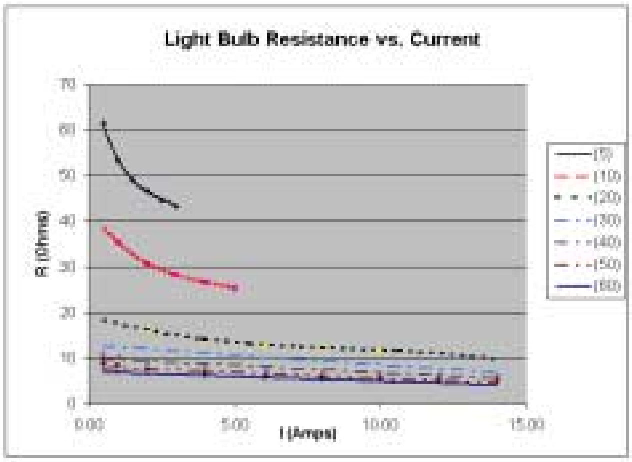

Figure 4. Resistance characteristics of carbon filament light bulbs with respect to the current

From the curves, it can be seen that the resistance does not vary significantly and can be considered as constant resistance when more than 20 bulbs are connected in parallel. Thus, for this laboratory, constant resistance loads will be realized by placing 30 or more light bulbs in parallel. The mean and the standard deviation of the resistance are calculated for each group of light bulbs and given in Table 2.

Table 2. Mean and standard deviation of the resistance for 30, 40, 50, and 60 light bulbs connected in parallel.

# of Bulbs	30	40	50	60
Mean (Ohms)	10.04	7.89	6.51	5.67
STDV (Ohms)	2.28	1.73	1.34	1.08

Notes:

- Figure 4 shows that the resistances of the light bulbs reduce quickly with the increase of the current when only 5 or 10 parallel bulbs were tested. Thus, if voltage dependent loads are desired, a smaller numbers of parallel bulbs can be used.
- capacitor banks and inductors will be used for constant reactance loads and they will undergo similar testing and analysis procedures.

IV. 3 Induction Motor Test

Since a significant portion of the loads in distribution systems are motors, it is desired to study the behavior of motors in the distribution laboratory. Four 200V, 3-phase, 60Hz, wye-connected, 5hp induction motors manufactured by Westinghouse were tested at Drexel University. To determine the parameters of the induction motors, a steady state transformer model was used[10], as shown in Figure 5.

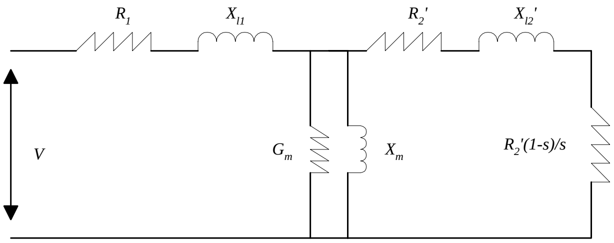

Figure 5. Per-phase equivalent circuit of an induction motor

Where:

R_1 represents the stator resistance.

X_{l1} represents the stator leakage reactance.

X_m represent the magnetizing reactance.

R_2' represents the standstill rotor resistance referred to the stator.

X_{l2}' represents the standstill rotor leakage reactance.

G_m represent the magnetizing conductance.

Four experiments were conducted on the induction motors. The no load test, DC test, and blocked rotor test [10] were repeated 10 times to determine equivalent series resistance, and reactance, magnetizing impedance and core resistance. Load characteristic experiments were also performed to evaluate efficiency [11].

The induction motor parameters are provided in Table 2. In our experiments we will lump core losses with stator and rotor winding losses through R_1 and R_2', so G_m is not determined. Measurement device accuracy limits and cabling effects of the experimental setup contribute to discrepancies within tests. Therefore, the mean and the standard deviation of the induction motor parameters are calculated and displayed in Table 3.

Table 3. Mean and standard deviation of the equivalent parameters for induction motors 1-4 (Unit: Ω)

	R_1	X_{l1}	R_2'	X_{l2}'	X_m
Motor 1	0.403± 8e-3	0.740± 6.5e-3	0.511± 1.4e-2	0.740± 6.5e-3	12.258± 0.227
Motor 2	0.391± 4.8e-3	0.698± 6.0e-3	0.587± 1.2e-2	0.698± 6.0e-3	11.232± 0.192
Motor 3	0.483± 3.6e-3	0.733± 1.05e-2	0.579± 1.9e-2	0.733± 1.05e-2	11.819± 0.151
Motor 4	0.434± 6.4e-3	0.734± 1.5e-2	0.528± 1.2e-2	0.734± 1.5e-2	11.745± 0.21

To test for motor efficiency, each induction motor was coupled to a DC generator in CEPE. Light bulbs, tested in the previous section, were connected to the DC generator. The efficiency of the DC generator was assumed to be 85%. The efficiency of the motor was calculated using Equation (4)

$$\eta_{mot} = \frac{P_{out,mot}}{P_{in,mot}} = \frac{P_{bulb}/0.85}{P_{in,mot}} \tag{4}$$

where:

η_{mot}	represents the motor efficiency
$P_{in,\, mot}$	represents the input real power of the motor
$P_{out,\, mot}$	represents the output real power of the motor
P_{bulb}	represents the real power demand of the bulbs

Thus, using the efficiency and assuming the DC generator efficiency, different constant power loads can be realized by changing the load on the DC generator.

Figure 6 gives the efficiency of motor 1 at different load levels. Considering hysteresis, Curve 1 corresponds to the efficiency when the load current increases and Curve 2 corresponds to the efficiency when the load current decreases. As expected, motor efficiency is highest at the rated 15A. And, the maximum difference between curves due to hysteresis was approximately 2%.

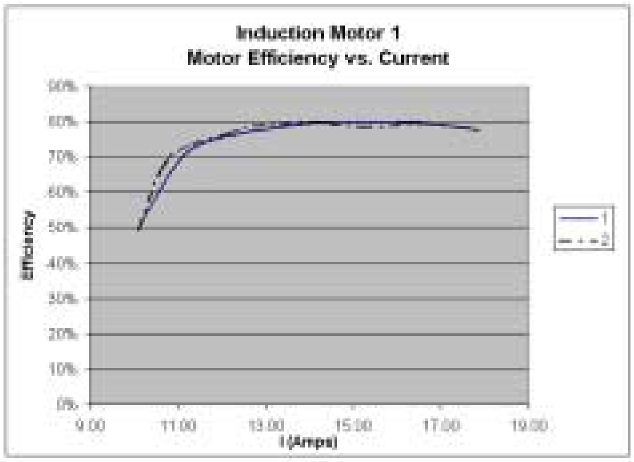

Figure 6. Efficiency of induction motor 1

V. CONCLUSIONS

In this paper, the setup of a reconfigurable distribution automation and control laboratory (RDAC) at Drexel University is introduced. The electric distribution system specifications and its flexible layout were designed to encompass characteristics of a real distribution system such as R/X ratios and reconfiguration capabilities.

Distribution components include lines, switches and loads are realized, for example, through inductors, digital relays, constant impedance devices such as carbon filament light bulbs and constant power loads such as motors operating in steady-state. Hardware testing of each component's behavior was performed under a range of conditions mimicking eventual use of RDAC. The hardware selected for the network is reliable and satisfied requirements for different experiments.

Completion of this laboratory will provide a hands-on environment for both power distribution system curriculum and research. Thus, ongoing work includes the design and development of its SCADA system.

VI. ACKNOWLEDGMENTS

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