



ECE-22 Senior Design Final Report

"Integration and Analysis of Distributed Generation Resources in Micro-Grid Environments"

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1 Abstract

The main goal of a distribution management system is to ensure grid reliability. Two well-known methods of maintaining reliability are network reconfiguration and service restoration. One reason network reconfiguration is performed is to minimize the distribution system's real power loss as it serves demand. Network Reconfiguration (NR) is achieved through the actuation of sectionalizing and tie switches. Service restoration (SR) is performed to deliver power to customers that are experiencing a power outage which are caused by grid disturbances, such as faults. Over the course of the year, this project developed a set of algorithms: two that minimize real power loss in the distribution system by determining a near optimal network configuration, and two that maximize the amount of load restored in the event of a fault. The problems can be classified as non-linear, combinatorial, optimization problems, and they are subject to operating constraints such as voltage, current, power, and total harmonic distortion. The algorithms were coded in Visual Basic, and were then integrated into the existing software at Drexel's Reconfigurable Distribution and Automation Control laboratory (RDAC). The purpose of this is twofold. First, the algorithms served as the basis of lab modules that can be incorporated in the current power engineering curriculum. Second, as more single and poly-phase distributed generation resources are introduced into the power grid, complexities of NR and SR problems will increase, and thus algorithmic solutions will be needed by future students while performing network studies.

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3 Problem Description

In an electrical distribution system, loads are connected to buses which in turn are supplied by distribution lines and transformers. Within the distribution system, there are a number of switches—some of which are normally open, and others which are normally closed. The state of these switches defines the topology of the distribution network. Changing the state of the switches alters the topology, and thus can affect other quantities such as real power loss and the variation of voltage level. Changing the topology of the distribution system is known as network reconfiguration. This project will address the problem of finding the optimal switch configuration of a distribution system within the context of network reconfiguration under normal and emergency operating conditions. Normal operating conditions are defined as all loads being maintained in the network with sectionalizing switches closed and tie switches open. Emergency operating conditions are defined as one or more sectionalizing switches disabled in the network, causing a loss of power on one or more load busses. The disabled switch represents a fault. The problem is formulated as an optimization of a single cost function subject to various equality and inequality constraints.

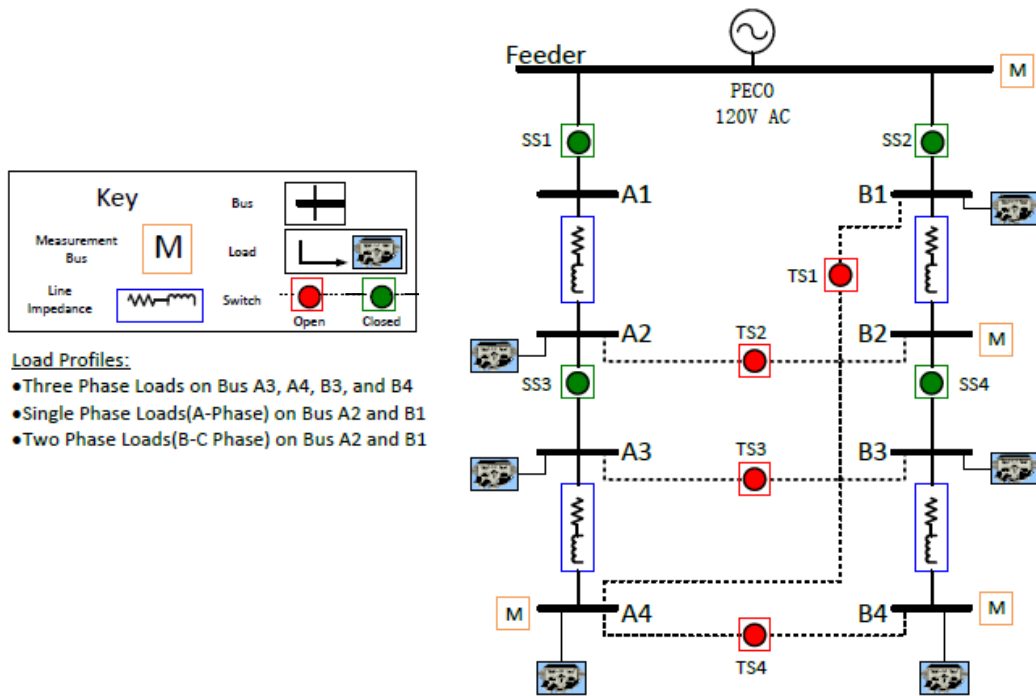


Figure 1. Example Power System Network to be used for cost minimization. Sectionalizing switches are normally closed, and tie switches are normally open.

Next the mathematical problem definition is discussed, notation follows in Table 1.

Table 1. Variables

Variable	Size	Description	Units
N_B	Scalar	Total number of buses	none
N_T	Scalar	Total number of XFMRs	none
N_{Br}	Scalar	Total number of branches	none
N_S	Scalar	Total number of switches	none
N_ϕ	Scalar	Total number of phases	none
P_k^{line}	Scalar	Real power loss in branch k	Watts
P_j^{XFMR}	Scalar	Real power loss in XFMR j	Watts
P_i^{bus}	Scalar	Real power delivered to bus i	Watts
P_i	Scalar	Injected real power at bus i	Watts
Q_i	Scalar	Injected reactive power at bus i	VAR
G_{io}	Scalar	Conductance between bus i and o	Siemens
B_{io}	Scalar	Suceptance between bus i and o	Siemens
u	Vector 1xn	State of the switches in the network	Binary
$ V_i $	Vector 4x1	3 phase voltage magnitude at bus i	Volts
ϕ_i	Vector 4x1	3 phase angle at bus i	Degrees
S	Matrix $u \times 2^n$	Search Space	Binary
X	Matrix $\Phi \times 2(i-1)$	State variable. Voltage magnitudes and phases at every bus except the slack bus	Degrees and Volts
$C_N(X, u)$	Scalar	Cost function for normal operating conditions	Dollars
$C_E(X, u)$	Scalar	Cost function for emergency operating conditions	Dollars

3.1.1 Formulation for Normal Operating Conditions

$$\underset{u \in \mathcal{S}}{\text{minimize}} C_N(\mathbf{X}, u) \quad \text{Eq. 1}$$

such that:

$$F(\mathbf{X}, u) = 0 \quad \text{Eq. 2}$$

$$G(\mathbf{X}, u) \leq 0 \quad \text{Eq. 3}$$

where \mathcal{S} is the set of all possible switch configurations, F is the set of non-linear power flow equations, and G is the set of constraint equations. The variable u is a set of ones and zeros representing the statuses (open or closed) of all the tie and sectionalizing switches in the given network. Thus the topology of a network is uniquely determined by a given u vector.

$$u = [x_1, x_n] \quad x_i = \{0,1\}; \quad 1 \leq i \leq N_S, \quad \text{Eq. 4}$$

There are 2^{N_S} unique u vectors for a system with N_S switches. The search space, \mathcal{S} 's rows are u vectors, and its columns are a list of the network's switches.

$$\mathbf{S} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_{2^{n-1}} \\ u_{2^n} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 1 & 1 & \dots & 1 & 0 \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \quad \text{Eq. 5}$$

To calculate the cost function, knowledge of the state of the system is needed. For a given load level, each u vector maps to a given state, denoted as \mathbf{X} . The state variable \mathbf{X} contains voltage magnitudes and phases at every bus in the system (except the slack bus). \mathbf{X} is a $(\Phi, 2(N_B-1))$ matrix where Φ is the number of phases and N_B is the number of buses.

$$\mathbf{X} = [|V_2|, \dots, |V_{N_B}|, \phi_2, \dots, \phi_{N_B}] \quad \text{Eq. 6}$$

The voltage magnitudes for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$|V_i| = [|V_i^A|, |V_i^B|, |V_i^C|, |V_i^N|]^T \quad \text{Eq. 7}$$

The voltage phase angles for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$\phi_i = [\phi_i^A, \phi_i^B, \phi_i^C, \phi_i^N]^T \quad \text{Eq. 8}$$

Under normal operating conditions, the cost function $C(\mathbf{X}, u)$ is defined as

$$C_N(\mathbf{X}, u) = \sum_{k=1}^{N_{Br}} P_k^{line}(\mathbf{X}, u) + \sum_{j=1}^{N_t} P_j^{transformer}(\mathbf{X}, u) \quad \text{Eq. 9}$$

Here, conversion factors, b_1 and b_2 , are scalars that are used to convert the real power losses measured in Watts to dollars. The factors are listed separately because different costs may be used for lines and transformers.

3.1.2 Equality Constraints

Unbalanced multi-phase power flow for each bus must be satisfied.

$$-P_i + \sum_{o=1}^{N_B} |V_i| |V_o| (G_{io} \cos(\theta_{io}) + B_{io} \sin(\theta_{io})) = 0 \quad \text{Eq. 10}$$

$$-Q_i + \sum_{o=1}^{N_B} |V_i| |V_o| (G_{io} \cos(\theta_{io}) - B_{io} \sin(\theta_{io})) = 0 \quad \text{Eq. 11}$$

3.1.3 Inequality Constraints

- Radial structure must be maintained.
- Current constraint

$$|I_k| \leq |I_k^{Max}|, \text{ for all branches } k \quad \text{Eq. 12}$$

- Voltage constraint

$$|V_i^{min}| \leq |V_i| \leq |V_i^{max}|, \text{ for all buses } i \quad \text{Eq. 13}$$

- Power constraint

$$|P_j + jQ_j| \leq |S_j^{max}|, \text{ for all XFMRs } j \quad \text{Eq. 14}$$

- Total Harmonic Distortion (THD)

$$THD_{voltage,i} \leq THD_{voltage,i}^{max} \text{ for all buses } i \quad \text{Eq. 15}$$

3.1.4 Formulation for Emergency Operating Conditions

Emergency operating conditions will occur in the case of a fault at a bus or line in the network resulting in a loss of service to loads.

$$\underset{u \in \mathcal{S}}{\text{maximize}} C_E(\mathbf{X}, u) \quad \text{Eq. 16}$$

C_E is the cost function for emergency operating conditions. The definition of the variables \mathbf{X} , \mathcal{S} and u are not changed from the preceding section.

Under emergency operating conditions, $C_E(\mathbf{X}, u)$ is the cost function measured in dollars.

$$C_E(\mathbf{X}, u) = \sum_{i=1}^{N_B} b_i P_i^{bus}(\mathbf{X}, u) \quad \text{Eq. 17}$$

P_i^{bus} is the real power delivered to the load at bus i in the network and it is a function of the state variable \mathbf{X} . The coefficient b_i is a conversion factor from Watts delivered to dollars. This coefficient is dependent upon the bus as the importance of restoring load to a customer depends upon said customer. In emergency operating conditions, the shedding of loads is authorized, as there are instances that the distribution system cannot handle all of load in the network.

4 Solution

In the fall term, the students

- Researched different problems associated with distribution systems
- Determined that with the increasing amount of distributed generation resources being incorporated into the grid, automated NR and SR will become increasingly vital the operation of the grid
- Determined that the number of power electronic devices present in distribution systems will likely increase due to their efficiencies, and while providing many benefits, will also be the source of new problems such as corrupted waveform due to harmonics.
- Researched the standard for THD: IEEE Standard 519-1992.
- Researched different algorithms to perform the automated NR and SR
- Formulated different metrics such as voltage level, THD, and amount of load restored
- Researched different power flow methods

The following was accomplished during the Winter Term:

- Researched how to actuate solid state relays (sectionalizing and tie switches)
- Development of the problem formulation.
- Code created for estimating the distribution system's
 - Real power loss
 - Reactive power loss
 - Total harmonic distortion
- Development of an algorithm that will perform an exhaustive search by:
 - Determining every possible network configuration.
 - Eliminating network configurations with loops (to maintain radial structure).
 - Estimating the real power loss for each valid network configuration.
 - Ensuring the equality constraint is met as well as hard inequality constraints.
- A GUI developed for:
 - Implementation of the algorithm.
 - Displaying all estimated and measured data to the user as well as the error between the two.

The following has been accomplished since the conclusion of the Winter Term:

- Power Flow code completed
 - Uses Gauss-Seidel Method and is parameterized for load level and network topology.
 - Compared code to MATPOWER to ensure accuracy.
- Exhaustive search algorithm completed for Network Reconfiguration
 - Conducts an exhaustive search of feasible network topologies and returns the optimal network configuration to minimize real power loss
- Expert system algorithm completed for Network Reconfiguration
 - Searches for smallest effective voltage drop between buses and looks to optimize the network using the smallest effective voltage drop.
- Exhaustive search completed for Service Restoration
 - Conducts an exhaustive search of feasible network topologies and returns the optimal network configuration to maximize power delivered to loads
- Heuristic algorithm completed for Service Restoration

- Minimizes the search space by eliminating topologies that will cause a switch's current capacity to be exceeded
- Developed and completed lab manuals for Network Reconfiguration and Service Restoration

4.1 Discussion of objective functions

As discussed previously, the solution of the problem is to determine the status of the switches (on or off) that optimize the given objective function. For network reconfiguration, the chosen objective function was real power loss. For service restoration, the chosen objective function was power delivered. These objective functions were chosen by the students and are not the only ones possible. For instance, in service restoration, another viable objective function could have been to maximize the number of loads restored, regardless of power consumption. For an example, to illustrate the difference between the two, consider the case where it is only possible to restore either an industrial plant consuming 10 kW, or 2 residential homes each consuming 1 kW. The first objective function would restore power to the plant because 10 kW is greater than 2 kW. The second objective function would restore power to the two homes because $2 > 1$. Even though the power delivered is less, the number of loads restored is greater. Obviously, the choice of the objective function has both economic and social consequences. An interesting service restoration scheme would use different objective functions based upon what day it is and the time of day. Thus, industrial plants would be supplied power during the working hours of the workweek, and residential homes would be provided power at nighttime and on the weekends.

4.2 Discussion of searches

Three different search methods were employed to determine the optimal switch configuration.

- Exhaustive
- Heuristic based
- Expert system based

Exhaustive searches were built for both network reconfiguration and service restoration. The exhaustive searches were performed on different loading levels because they determine the optimal solution. They are used for baseline performance metrics to be compared with developed algorithms.

The heuristic based search was developed for service restoration, and an expert system search was developed for network reconfiguration. An expert system focuses on emulating the decision-making ability of a human expert [1], while the heuristic based algorithm focuses on producing a sub-optimal solution in a faster manner than the exhaustive search. In the case of this project, an expert system is one that does not use the data obtained through running a power flow while the heuristic does. The searches were tested on different loading levels and evaluated based on the time of execution and accuracy of the determined solution. The solutions of the searches were also tested in the RDAC laboratory to gauge the accuracy of the model and qualitative performance

4.2.1 Network Reconfiguration Exhaustive Searches

As discussed in the problem formulation, the size of the search space is 256. This comes from the fact that there are 8 switches, and two possible switch states. However, by invoking the voltage and radial network constraints, the search space can be reduced to 70. This is based on the fact that if five or more switches are closed, there will be a loop in the network and the radial constraint is violated. If three or fewer switches are closed, there will be at least one bus without voltage violating the voltage constraint. Thus, the exhaustive search for network reconfiguration (and service restoration) is a practical exhaustive search; it ignores search elements that will fail the voltage and radial constraint. Of these 70 switches configurations, there are still many configurations with loops, so they were also

removed from the space before entering the power flow calculation. Once all the loops were removed from the space, the algorithm computes a power flow for each case, and based on the results of the power flow, computes the objective function. For network reconfiguration, the objective function is real power loss. The final action is to return the switch configuration with the lowest real power loss.

4.2.2 Network Reconfiguration – Exhaustive Search using MATPOWER

MATPOWER is a collection of MATLAB M-Files used for solving power flow as well as optimal power flow problems and it was selected so that conclusions regarding the effectiveness of the VB code could be made. Through MATPOWER, the power flow can be accomplished in three main steps: (1) Prepare the input data defining all of the relevant power system parameters, (2) Call the function `runpf` to run the simulation, and (3) View the results printed in the immediate window (or saved).

The input data, also known as a base case contains the system MVA base, bus data (injections), generator data, and branch data. Because the u vectors represent different network topologies, another MATLAB function was created to take the branch data and u as an input and the output is the modified branch data which can then be used for the power flow. Both VB code and MATPOWER make the assumption that the system is balanced 3-phase. They also use a non-linear Gauss Seidel power flow algorithm with a tolerance of $1e-6$ and 1000 iterations. An l_2 -norm was used to measure vector difference, and it is defined as:

$$\|x\|_2 = \sqrt{\sum_i x_i^2}$$

A for loop was used to run a power flow for each U vector and the results were stored in a structure-array. On the Visual Basic side, the solutions were exported to a CSV so that a comparison could be made between the two. The following shortened table is a comparison of results obtained from MATPOWER and VB:

Table 2: Comparison of real power loss obtained through MATPOWER and VB

Setting	Pass Constraint?	Switch Configuration in Decimal Base	Real Power Loss, W		ERROR
			VB	MATPOWER	
0	true	240	13.60	13.60	0.00%
1	true	184	42.77	42.77	0.00%
2	true	180	29.37	29.37	0.01%
3	true	156	38.45	38.45	0.01%
5	true	226	24.52	24.51	0.02%
6	true	178	38.08	38.07	0.02%
7	true	170	35.95	35.95	0.00%
10	true	166	31.29	31.29	0.01%
11	true	150	43.05	43.04	0.03%
13	true	142	48.79	48.79	0.00%
16	true	225	25.87	25.87	0.01%
17	true	177	41.17	41.17	0.00%
18	true	169	38.03	38.03	0.01%
21	true	165	32.66	32.66	0.00%
22	true	149	44.28	44.28	0.01%
24	true	141	47.32	47.32	0.01%

There is a small deviation between the estimated real power losses calculated by VB and MATPOWER and that can be attributed to rounding error (see Table 2). Another key benchmarking metric is computation time; VB code finished executing more than 10 seconds before MATPOWER did. However it should be noted that although both VB and MATPOWER are compiled into p-code, they are much different. For example, MATPOWER collates and displays results after completing each power flow while VB does not display the tabulated results until the end - displaying information after each iteration slows down processing. One key advantage to MATLAB (MATPOWER) is that it contains toolboxes which in-effect help to speed up computations. So, while the VB code did seem to have an advantage in this case, MATLAB is the more attractive coding environment because it contains more useful engineering toolboxes. However, the RDAC laboratory uses VB thusly the project was coded in order to be integrated into the existing software.

4.2.3 Expert System Algorithm for Network Reconfiguration

An expert system is a computer system that emulates the decision making ability of a human expert [1]. The expert system for network reconfiguration in this project performed the decision-making based on the network topology and load levels. The expert system makes the following assumptions:

- Each unit of load in the network, draws one unit of current. Voltage drops through lines and switches are ignored.
- Line and switch impedance are constant.
- Network consumes less power loss with both SS1 and SS2 closed. This assumption was included based on the results from exhaustive search for network reconfiguration. Thus, the search only considers u vectors with the two feeder switches closed.

The metric, potential voltage drop, is evaluated by:

$$V_{potential\ drop} = \sum_{i=0}^{N_{Br}} I_i R_i$$

Where I_i is the current through branch i , and R_i is the equivalent resistance of branch i .

4.2.4 Exhaustive Search for Service Restoration

The exhaustive search for service restoration is considerably different than network reconfiguration. The main difference is the size of the search space. In network reconfiguration, the search space was reduced to 70 by invoking the voltage and radial network constraints. However, in service restoration, the minimum voltage constraint is dropped. Thus, the search space must contain all u vectors with less than 5 switches closed (radial constraint still applies). To illustrate why the minimum voltage is dropped, consider the following circuit.

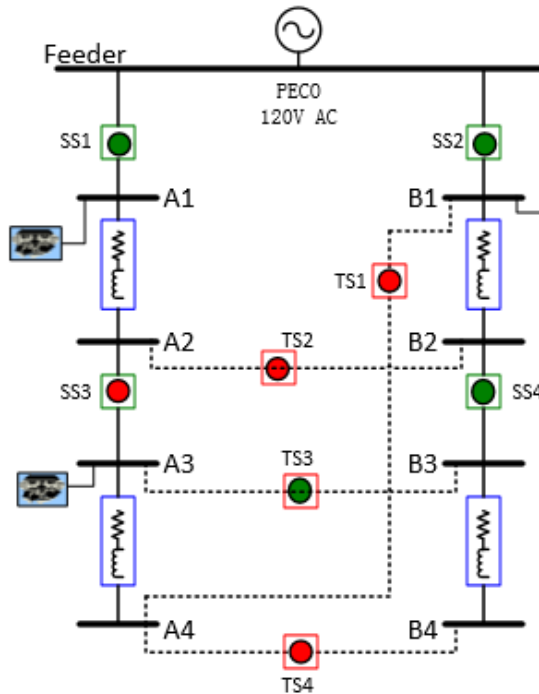


Figure 2. Hypothetical circuit to illustrate why the service restoration search space is larger than network reconfigurations.

First, consider a load level in which A1 and A3 are heavily loaded, and this load cannot be served by solely by SS1 or SS2. Initially, a valid configuration would be as shown above. The load at A1 is served by SS1, and the load at A3 is served by SS2 through TS3. SS3 is closed. However, if SS2 must be opened due to a fault, the entire load will have to be served by SS1. If the voltage constraint is adhered to, SS1 will be forced to pick up the load at A3, and will consequently fail due to over current. The result will be zero power delivered. However, if the load is dropped at A3, SS1 can simply serve the load at A1, and drop the load at A3. While it is not ideal, it maximizes the objective function while not violating any

constraints. Thus, the search space for service restoration must include all u vectors in which there are no more than four switches closed, as there may be load levels that maximize the objective function by only closing three, two, or only one switch.

4.2.5 Heuristic Algorithm for Service Restoration

The heuristic for service restoration seeks to reduce the search space by ignoring u vectors that will likely cause the current constraint to fail. The heuristic makes the following assumptions:

- A power flow has been performed on the base case (All sectionalizing switches are closed, and all tie switches are open), and there have been no constraint violations.
- All switches, both sectionalizing and tie, have the same current rating.
- The location of the fault is known. (and therefore which sectionalizing switch must be opened)
- The tie switch configuration is known.

With the results of the base case power flow, the algorithm calculates the amount of current through each switch, and normalizes it to the switches rating. Thus, the switch usage is denoted by Γ , and its value is given by

$$\Gamma_n = \frac{I_{base,n}}{I_{rated,n}}$$

where n is the switch number, I_{rated} is the switch's current rating, and I_{base} is the current flowing through the switch for the base case. The next step of the algorithm is to use this information, along with the fault switch location, to determine which u vectors to ignore. To understand, consider the following case. After the base case power flow, the following switch usages are computed.

Table 3. Example of Switch Current Capacities Calculated for SR Heuristic Algorithm.

Γ_1	0.7
Γ_2	0.6
Γ_3	0.3
Γ_4	0.4

Now, consider the possibilities available if SS1 must be opened due to a fault. The first action of the algorithm is to check if SS2 can handle the entire load SS1 was serving. If it can, the exhaustive search would be called, as there will not likely be any current failures. However, if SS2 cannot handle the entire load served by SS1, it attempts to maximize the load served by SS2 while not violating any constraints. Using the values of switch usages above, it would first check the sum of Γ_1 and Γ_2 . Since this value is above 1, it would then choose which load to serve, A1 and A2, or A3 and A4. It would realize that serving the load at A1 and A2 would yield a switch usage closest to 1 without going over. Thus, the load at A3 and A4 would be dropped. The search space would then be reduced by eliminating all u vectors that have a switch connected to A3 or A4 in a closed status. The code is implemented with a case statement and if/else statements.

4.3 Results

Each search was executed under different loading levels. Search efficiency was evaluated by first determining if the search achieved the global optimal, the time of execution, and the size of the search space. The scaling factors were not incorporated into the results, thus the metrics are in units of Watts, not dollars.

4.3.1 Network Reconfiguration Software Results

The network reconfiguration code was tested on the load levels described in Table 4. At any given time, the RDAC hardware can support up to four multiphase loads. Because of previously stated assumptions, the loads must be three phase balanced loads. That being said, load level 1 was chosen because the each leg of the feeder has a balanced load. Load level two was selected because it allows the user to see the effects of one bus being more heavily loaded than the other busses. The third case is an extreme case where only two buses out of the four buses are loaded. Each loading level has a different u vector corresponding to the optimal switch configuration.

Table 4: Loading Levels for NR Experiment.

Number of Bulbs per Phase on Each Bus					
Load Level 1		Load Level 2		Load Level 3	
Bus	Bulb #	Bus	Bulbs #	Bus	Bulbs #
A2	1	A2	1	A3	1
A4	1	A4	3	A4	1
B2	1	B3	1		
B4	1	B4	1		

Both exhaustive search and expert system were performed on each load level, and the results are displayed in Appendix B, in which optimal configuration is indicated.

The comparison of exhaustive search to expert system is displayed below in Table 5. The results illustrate that the expert system reduces the search time by approximately 90%. However, the search results of expert system are not all accurate due to its pre-defined search assumptions. In the assumption, we only considered the cases with both legs connected to feeder, however, in load level 3, the optimal case was picked out to be at "01111000" which contradicted the assumption.

Table 5. Comparison between Exhaustive Search and Expert System for NR Experiment

Load Level		Exhaustive Search	Expert System	Comment
1	Search Time	1.64	0.22	Reduced by 86.59%
	Optimal Config	11110000	11110000	Matching
2	Search Time	1.66	0.22	Reduced by 86.75%
	Optimal Config	11011000	11011000	Matching
3	Search Time	1.56	0.21	Reduced by 86.54%
	Optimal Config	1111000	01111000	Not Matching

4.3.2 Network Reconfiguration Hardware Results

The data collected in hardware experiment is stored below as Table 7 and Table 6; experiments were performed on three load levels for both base case and optimal case.

Table 6. Bus Voltage (volts) Measured of Base and Optimal Case for Three Loading Levels

Case	Bus #	A1	A2	A3	A4	B1	B2	B3	B4
Load Level 1	Base Case	119.40	119.20	118.50	118.40	119.20	119.10	118.40	118.30
	Optimal	119.40	119.20	118.50	118.40	119.20	119.10	118.40	118.30
Load Level 2	Base Case	119.20	119.00	118.20	118.10	119.20	119.20	118.40	118.40
	Optimal	119.40	119.20	118.30	118.40	119.30	119.20	118.40	118.50
Load Level 3	Base Case	119.80	119.90	119.00	118.90	118.20	118.00	115.50	115.50
	Optimal	116.00	116.00	118.70	118.80	119.50	119.60	117.00	117.10

Table 7. Feeder Bus Voltage (Volts) Measured for Three Loading Levels

Case	Feeder	Voltage	Current
Load Level 1	Magnitude	119.47	2.14
	Angle	0.00	-1.70
Load Level 2	Magnitude	119.52	3.52
	Angle	0.00	0.30
Load Level 3	Magnitude	119.98	0.93
	Angle	0.00	-7.10

Post-processing calculation were performed based on data from Table 7 and Table 6 to get power loss in actual hardware experiment, which was used in next section to compare with software results.

4.3.3 Comparison of Network Reconfiguration Software to Hardware Results

Table 8. Comparison of Hardware Results to Software in NR

Load Level	Case	SW P Loss, W	HW P Loss, W	% Error
1	Base Case	5.66	5.12	9.54%
	Optimal	5.66	5.12	9.54%
2	Base Case	17.90	12.45	30.45%
	Optimal	17.18	10.34	39.81%
3	Base Case	4.05	4.38	7.53%
	Optimal	3.55	3.68	3.53%

As shown in Table 8, the errors are relatively large, ranging from 3.53% to 39.81%. The possible sources of error consist of but not limited to: experimental error and calculation error.

4.3.4 Service Restoration Software Results

The service restoration code was tested on the following loading levels.

Table 9. Load levels for service restoration. Each load is a three phase balanced load. Each bulbs is a 200 ohm, constant impedance loads. Multiple bulbs at one bus are connected in parallel.

Load Level	A2	A4	B2	B4
	Number of Bulbs			
1	4	4	4	4
2	4	1	5	1
3	5	1	4	1
4	5	2	1	4
5	1	4	5	2

For each load level, a base case simulation was performed. Additionally, a switch was designated as the fault switch, and an exhaustive search, as well as a heuristic search was performed. One loading level would have two or more switches designated as the fault switch (not at the same time however).

Table 10. Software results for service restoration. The base case vector is 11110000.

Load Level	Fault Switch	U vector	Power Delivered, W	Time Elapsed, s	Number of search elements	Name of Search
1	N/A	Base	3278	N/A	N/A	N/A
	SS1	1001000	1656	3.19	33	SR exhaustive
	SS1	1010000	1638	0.35	2	B closed ties open
	SS2	10000100	1645	3.57	35	SR exhaustive
	SS2	10100000	1640	0.33	2	A closed ties open
	SS3	11001000	2502	5.4	51	SR exhaustive
	SS3	11010000	2484	2.4	18	SS2 Danger
	SS4	11001000	2502	6.16	50	SR exhaustive
	SS4	11001000	2502	3.3	18	SS1 Danger
2	N/A	Base	2305	N/A	N/A	N/A
	SS1	1001001	1459	3.2	33	SR exhaustive
	SS1	1001001	1459	0.97	7	Restore B4
	SS2	10100010	1252	3.54	35	SR exhaustive
	SS2	10100010	1252	0.87	6	Restore B4
3	N/A	Base	2305	N/A	N/A	N/A
	SS1	1001001	1257	3.23	33	SR exhaustive
	SS1	1001001	1257	0.98	7	Restore A4
	SS2	10100010	1453	3.58	35	SR exhaustive
	SS2	10100010	1453	0.85	6	Restore B4
4	N/A	Base	2487	N/A	N/A	N/A
	SS3	11011000	2495	5.37	51	SR exhaustive
	SS3	11011000	2495	5.37	51	SR exhaustive
	SS4	11001001	2481	5.17	50	SR exhaustive
	SS4	11001001	2481	2.3	18	SS1 Danger
5	N/A	Base	2487	N/A	N/A	N/A
	SS3	11010000	1667	5.39	51	SR exhaustive
	SS3	11010000	1667	2.4	18	SS2 Danger
	SS4	11100010	2471	5.18	50	SR exhaustive
	SS4	11100010	2471	5.18	50	SR exhaustive

4.3.5 Discussion of Service Restoration Software Results

The results of load level one illustrate a number of things. First, it exposes the poor locations for the tie switches. Of the four different fault switches chosen, the entire load was never recovered. A more optimal tie configuration would be the following:

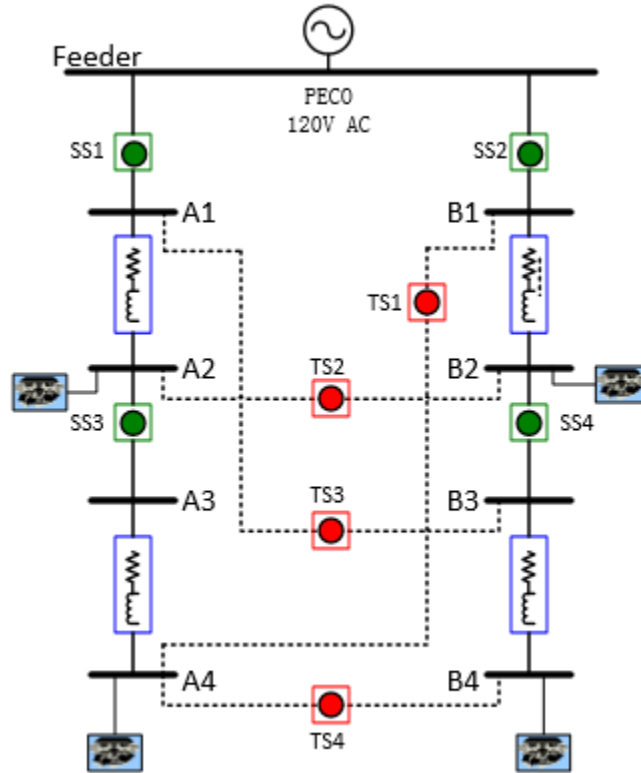


Figure 3. Modified tie switch configuration.

This tie switch arrangement would allow for the recovery of all load in the event of SS3 or SS4 opening. The load at A4 could be served through SS2 and TS1 with SS4 open. And the load at B4 could be served through SS1 and TS3, with SS3 open.

Another point worth noting for loading level one is that only in one case did the exhaustive search and heuristic match. While this may be interpreted as a failing of the heuristic, there are reasons in the data that ease this less than optimal solutions. Of the three cases in which the heuristic did not find the same switch configuration as the exhaustive search, the difference in the power delivered of the two switch configurations is on the order of 10 W, and is only due to voltage drops. The heuristic did restore the same load—the reduction of power delivered is due to lower voltage magnitudes at the load buses. The efficiency of the heuristic is evident—two of the search times were reduced approximately 90% and the other two times were reduced by over 50%. Of the remaining searches, the heuristic found the optimal configuration for every case while reducing the search time by 50 to 70 percent.

Load levels two and three illustrate another point. In both cases, SS1 or SS2 is opened, resulting in only one switch toughing the feeder. The full load was never recovered, due to the limited current capacity of the feeder switch. This begs the question if a switch's current rating should be related to its

electrical proximity to the feeder, as those switch have more loads downstream than other switches, and need to be able handle more current.

Load levels four and five illustrate that there will not always be enough information to perform the heuristic. When this happens, the exhaustive search is called instead.

4.3.6 Comparison of service restoration software to hardware

In the RDAC laboratory, the students tested the base case and optimal switch configuration for each loading level and fault switch. The power delivered was calculated by measuring the RMS voltage at each load bus with a fluke power meter.

$$Power\ delivered = \sum_{i=1}^{n_{load_bus}} \frac{|V_{i,RMS}|^2}{R_i}$$

N_{load_bus} is the total number of load buses. R_i is the effective resistance at load bus i , and $V_{i,RMS}$ is the effective voltage at bus i . The feeder voltage was measured with the data acquisition equipment of the RDAC.

Table 11. Results of the hardware testing, and comparison to software results.

Load Level	Fault Switch	U vector	Software Power Delivered, W	Hardware Power Delivered, W	Hardware feeder voltage, Vrms	Error, %
1	N/A	Base	3278	3367	119.59	2.72%
	SS1	01001000	1656	1702	120.30	2.78%
	SS2	10000100	1645	1699	120.18	3.32%
	SS3	11001000	2502	2556	119.97	2.15%
	SS4	11001000	2502	2553	120.07	2.03%
2	N/A	Base	2305	2286	118.35	0.82%
	SS1	01001001	1459	1449	118.35	0.71%
	SS2	10100010	1252	1248	118.83	0.29%
3	N/A	Base	2305	2353	120.03	2.06%
	SS1	01001001	1257	1287	120.62	2.45%
	SS2	10100010	1453	1498	120.43	3.10%
4	N/A	Base	2487	2544	120.01	2.31%
	SS3	11011000	2495	2549	120.06	2.18%
	SS4	11001001	2481	2533	120.01	2.13%
5	N/A	Base	2487	2559	120.19	2.91%
	SS3	11010000	1667	1734	120.74	4.05%
	SS4	11100010	2471	2582	120.90	4.51%

There are two main sources of error.

- Feeder voltage
- Resistance of lines and switches

As seen in Table 11, the feeder voltage ranges from 118 to 121 Vrms. This is due to the fact that the feeder is set by an analog auto transformer, and an exact 120 Vrms is not always possible. This differs from in software simulation as the feeder voltage was always set to exactly 120 Vms.

Another source of error is the assumption that the lines and switches are constant impedance. Both the line and the switch impedances are functions of temperature, especially the switches, as they are semiconductor based. In the software, the switches were assumed to have a constant resistance of 0.4 ohms. This assumption is likely to be valid for only a small range of current. This is due to the semiconductor nature of the switches. As the current in them increases, their temperature rises, elevating more free carriers to the conduction band. This explains the trend in the data in which the hardware power delivered is always greater for comparable feeder voltages. The switch resistance is actually lower, resulting in fewer drops through the switches, and slightly higher load bus voltages. Future work would include testing of the switch impedance for different values for current. This data could be implemented into the model to improve accuracy.

5 Budget

Table 12. Industrial budget for this project.

Electrical Engineers Salaries	Weekly Hours	Payrate	Nine Month Total
Evan Greer	40	\$50/Hr.	\$72,000.00
Michael Black	40	\$50/Hr.	\$72,000.00
Yi Li	40	\$50/Hr.	\$72,000.00
Michael Caro	40	\$50/Hr.	\$72,000.00
Consulting Fees	Weekly Hours	Payrate	Nine Month Total
Dr. Karen Miu	2	\$150/Hr.	\$10,800.00
Dr. Chika Nwankpa	1	\$150/Hr.	\$5,400.00
Nicole Segal	2	\$100/Hr.	\$7,200.00
Labor Budget			\$311,400.00
Facility Fees	Duration	Rate	Nine Month Total
Drexel Power Lab	15 hours/week	\$50/Hr.	\$27,000.00
Supply Costs	Quantity	Per Unit	Nine Month Total
Microsoft Office 2010	3	\$75/License	\$225.00
Visual Basic License	1	\$30000/License	\$30,000.00
Office Supplies	1	\$1,000	\$1,000.00
Facility/Supplies Budget			\$58,225.00
Net Total			\$369,625.00
Overhead 35%			\$129,369.00
Total			\$498,994.00

6 Gantt Chart

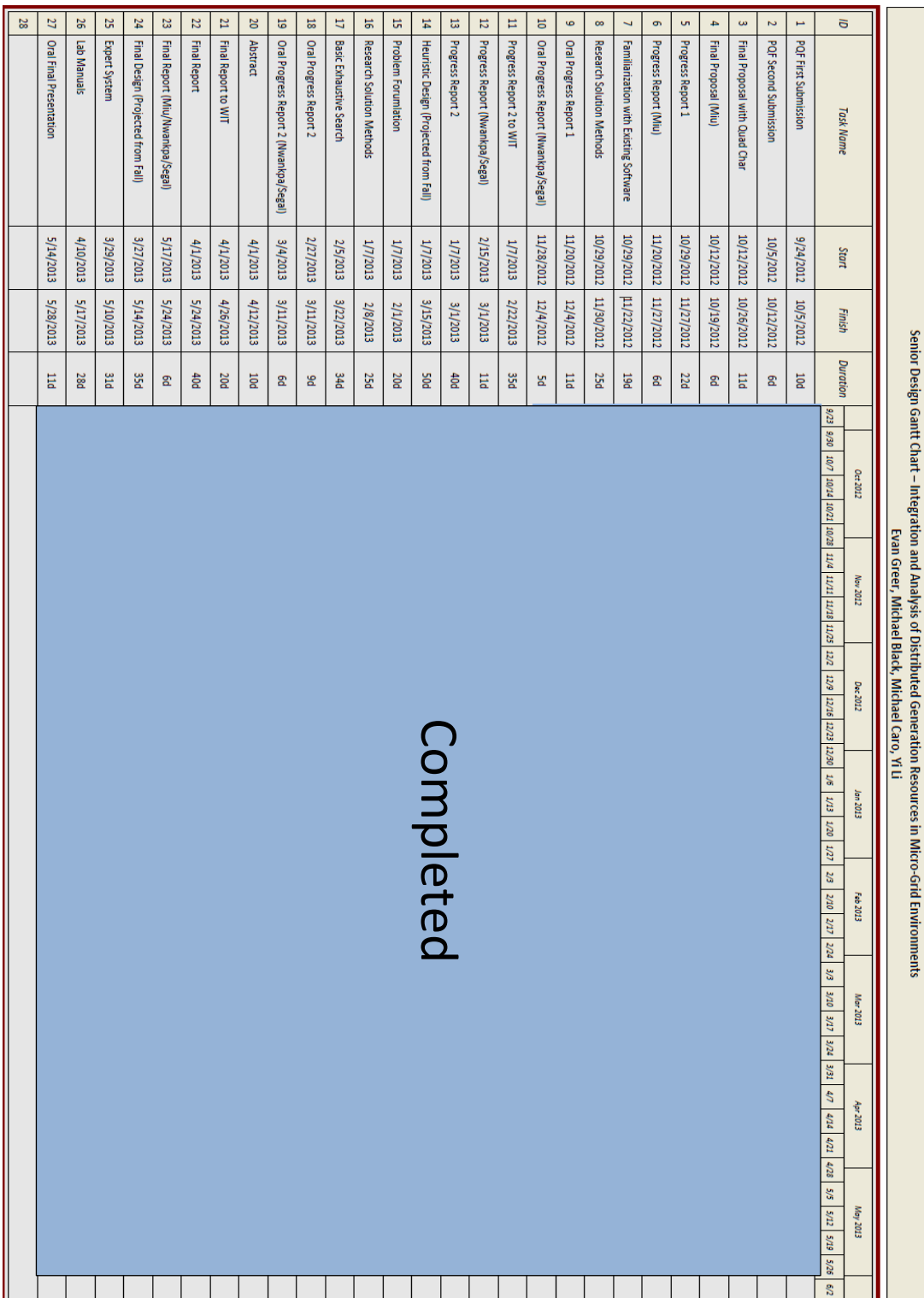


Figure 4. Revised gantt chart.

7 Societal, Environmental and Ethical Impacts

The aim of this project is to implement an optimization algorithm for a given distribution network in Visual Basic. The algorithm performs NR and SR for loss minimization. The algorithms will be crucial as the complexity of the network continues to grow. Contributions to society and industry that can be realized by implementation of this project are as follows:

- Reduction of real power loss. This is more beneficial when considering the losses in the transmission and generation systems.
- Reduction of black out time. These benefits are obvious, especially considering the past Super Bowl.

Aside from the overall effects on society as a whole, electrical engineering students at Drexel will be able to participate in laboratory experiments which will acquaint them with the fundamental concepts of network reconfiguration and service restoration. By doing so it will reinforce their understanding of various power flow methods and how total harmonic distortion affects the network. Understanding these concepts will make them more knowledgeable engineers and also help to prepare them for a position in the power industry.

8 Summary

The goal of this project was to gain an understanding of Network Reconfiguration and Service Restoration and how these processes will need to adjust to changes in distribution networks. Distribution networks face changes such as increased use of smart meters, increased multi and poly-phase distributed generation resources, and the increased presence of micro-grids. These changes lead to questions on how the existing networks will be able to respond and what is the best way to mitigate any negative effects. Ways in which distribution networks can adapt to the persistent changes is research into automation and algorithmic means of analyzing the network. This project developed algorithms to determine optimal switch configuration in these conditions in the hopes of automating NR and SR. As discussed, the optimization will be with respect to minimum real power loss in normal conditions and service restoration in emergency conditions. Thus far, an exhaustive search method and a heuristic algorithm have been developed and implemented for both conditions. The data collected from implementing these different algorithms allowed for the creation of two laboratories and accompanying manuals, one for NR and one for SR, that can be incorporated into the existing power engineering curriculum.

9 Reference

[1]. Jackson, Peter (1998), *Introduction To Expert Systems* (3 ed.), Addison Wesley, p. 2, [ISBN 978-0-201-87686-4](https://www.amazon.com/Introduction-Expert-Systems-Peter-Jackson/dp/0201876864)

10 Appendix A

Design Constraints Summary

Team Number: ECE-22

Project Title: Integration and Analysis of Distributed Generation Resources in Micro-Grid Environments

1) Summary of the Design Aspects of the project:

This project developed a set of algorithms to optimally reconfigure distribution networks in order to achieve either minimum real power loss in the case of network reconfiguration or maximize real power delivered in the case of service restoration.

2) Summarize how Realistic Constraints that were evaluated for the project, including:

Economic:

The minimization of real power loss in distribution leads to more energy and cost efficient networks while a heuristic approach to maximizing power restored in the case of outages returns power to customers quicker.

Manufacturability:

This constraint was not considered.

Sustainability:

This constraint was not considered.

Environmental:

Through minimizing losses in a network the distribution grid can become more energy efficient leading to less waste and less CO2 emissions.

Ethical, health and safety:

Safety constraints such as voltage, current and power ratings were adhered to. Each of these constraints were developed through the ratings of the equipment in the RDAC laboratory.

Social:

Residents are now adding more poly and multi-phase sources to their homes which leads to a higher awareness of these sources. In turn, more residents want to add generation sources to their own homes. The effects of these additional sources need to be researched.

Political:

This constraint was not considered

3) Cite list of Standards/Regulations that were used or evaluated for the project (use IEEE Reference-style):

IEEE-519 for THD regulations

11 Appendix B

11.1 Exhaustive Search for NR

Exhaustive Switch Configuration Search Algorithm:

- 1) Start the Min Loss Estimator Module.
 - 2) Initialize a result table with the following in columns:
 1. Switch Status of SS and TS (u vectors)
 2. Estimated Real Power Loss
 3. Estimated Reactive Power Loss
 - 3) Also initialize a display table with the following in columns
 1. Switch Status of SS and TS for base and best case configurations
 2. Estimated Min Loss
 3. Actual Loss
 4. Error Percentage
 5. THD.
 - 4) Store V and I at the 4 given measurement locations.
 - 5) For the base case, post process data to obtain
 1. Total real power losses (PL)
 2. Total reactive power losses(QL)
 3. Proximity to constraints (V, I and S Constraints)
 4. Total harmonic distortion (THD)
 - 6) Check for Violations of V, I, S, & THD.
 1. All limits are defined during initialization as in assumption.
 2. If violations exist, flash warning to user. Else go to next step.
 - 7) Save base switch configuration and power loss to first row of result table.
 - 8) Locate and count all sectionalizing switches (SS). Set n_{ss} to counted number.
 - 9) Locate and count all tie switches (TS). Set n_{ts} to counted number.
 - 10) 1. Perform power loss calculation with for loop below:
For $i = 2$ to $2^{(n_{ss} + n_{ts})}$
 - i. Load ith row of S as current switch configuration
 - ii. Check for valid switch configuration using predefined function for checking loops.
 1. If violated: go to next iteration
 2. If not, go to next step
 - iii. Calculate new V&I at each bus
 1. Check for Violations of V, I, S, & THD If violated: go to next iteration
 2. If no, go to next step
 - iv. Real power loss estimation
 1. Calculate real power loss and THD for current switch configuration
 2. Store calculated real power loss, THD and switch configuration correspondingly in to result table
- End
2. With the table above, choose the minimal real power loss, save it to display along with its THD and switch pair locations (determined from the switch configuration vector u).
- 11) Tells user to apply above switch pair(Settings to yield off-line Ploss) and reconfigure network

1. Record V and I at the 4 given measurement locations
 2. Calculate the V, I, P, Q and load at buses based on new configuration
 3. Post Process to obtain the actual power loss and save it to display table
- 12) Calculate the percentage error of estimated/actual real power loss and save it to display table.

11.2 Exhaustive Search Data for NR

Table B1: Exhaustive Search Results for NR Experiment Load Level 1 with optimal configuration at Setting 0

Setting	Switch Config	P loss, W	Q loss, var	Constraint
0	11110000	5.66	4.89	true
1	11011000	5.96	3.01	true
2	10111000	16.43	14.29	true
3	01111000	10.15	3.15	true
4	10110100	11.55	8.84	true
5	01110100	11.87	8.65	true
6	10011100	13.57	8.88	true
7	01011100	9.49	4.95	true
8	11100010	7.91	5.92	true
9	11010010	8.07	5.82	true
10	10110010	14.77	8.91	true
11	01110010	15.09	8.72	true
12	11001010	6.91	2.13	true
13	10101010	14.14	10.69	true
14	01101010	12.18	3.21	true
16	10100110	11.55	8.84	true
17	01100110	15.09	8.71	true
18	10010110	14.76	8.9	true
19	01010110	11.87	8.65	true
20	10001110	15.32	10.69	true
21	01001110	10.14	3.15	true
22	11100001	8.22	6.83	true
23	11010001	8.3	6.75	true
24	10110001	15.88	12.51	true
25	01110001	16.05	12.34	true
26	11001001	6.64	1.2	true
27	10101001	14.72	12.5	true
28	01101001	11.63	1.38	true
30	10100101	11.85	9.75	true
31	01100101	15.38	9.61	true
32	10010101	14.99	9.81	true
33	01010101	12.1	9.57	true
34	10001101	15.06	9.79	true
35	01001101	9.88	2.22	true

Table B2: Exhaustive Search Results for NR Experiment Load Level 2 with optimal configuration at setting 1

Setting	Switch Config	P loss, W	Q loss, var	Constraint
0	11110000	17.9	14.51	true
1	11011000	17.18	3.43	true
2	10111000	36.64	30.88	true
3	01111000	24.53	3.69	true
4	10110100	27.81	22.1	true
5	01110100	33.16	21.67	true
6	10011100	35.91	22.1	true
7	01011100	22.3	5.4	true
8	11100010	32.47	22.12	true
9	11010010	29.64	17.11	true
10	10110010	32.47	22.12	true
11	01110010	42.34	21.74	true
12	11001010	23.57	3.65	true
13	10101010	32.47	22.13	true
14	01101010	32.95	5.74	true
16	10100110	32.47	22.12	true
17	01100110	46.81	21.77	true
18	10010110	43.74	22.14	true
19	01010110	35.46	21.68	true
20	10001110	44.49	30.73	true
21	01001110	28.07	3.8	true
22	11100001	34.62	29.18	true
23	11010001	30.18	19.81	true
24	10110001	34.62	29.18	true
25	01110001	44.01	28.77	true
26	11001001	23.02	1.85	true
27	10101001	34.62	29.18	true
28	01101001	31.87	2.17	true
30	10100101	34.62	29.18	true
31	01100101	48.85	28.65	true
32	10010101	44.25	24.77	true
33	01010101	36	24.37	true
34	10001101	43.98	29.02	true
35	01001101	27.52	2	true

Table B3: Exhaustive Search Results for NR Experiment Load Level 3 with optimal configuration at setting 3

Setting	Switch Config	P loss, W	Q loss, var	Constraint
0	11110000	4.05	2.5	true
1	11011000	3.55	0.6	true

2	10111000	4.05	2.5	true
3	01111000	3.55	0.6	true
4	10110100	4.05	2.5	true
5	01110100	5.78	2.5	true
6	10011100	6.28	4.38	true
7	01011100	3.55	0.6	true
8	11100010	4.05	2.5	true
9	11010010	5.78	2.5	true
10	10110010	4.05	2.5	true
11	01110010	5.78	2.5	true
12	11001010	3.55	0.6	true
13	10101010	4.05	2.5	true
14	01101010	3.55	0.6	true
16	10100110	4.05	2.5	true
17	01100110	5.78	2.5	true
18	10010110	7.33	2.6	true
19	01010110	5.78	2.5	true
20	10001110	6.28	4.38	true
21	01001110	3.55	0.6	true
22	11100001	4.05	2.5	true
23	11010001	6.28	4.35	true
24	10110001	4.05	2.5	true
25	01110001	6.28	4.35	true
26	11001001	3.55	0.6	true
27	10101001	4.05	2.5	true
28	01101001	3.55	0.6	true
30	10100101	4.05	2.5	true
31	01100101	5.78	2.5	true
32	10010101	7.82	4.43	true
33	01010101	6.28	4.35	true
34	10001101	6.28	4.38	true
35	01001101	3.55	0.6	true

11.3 Expert System for NR

Expert System

' Assumption 1: network consumes less power loss with both SS1 and SS2 closed.(makes no ED at bus larger than 4)

' Assumption 2: number of components*loading conditions on bus represented by 'electronic distance'

' Assumption 3: Minimum electronic distance gives optimal switch configuration

Public Sub ED_Click()

'Reset Table to show ED

RT.TextMatrix(0, 0) = "Switch Setting"

RT.TextMatrix(0, 1) = "SS Configuration"

RT.TextMatrix(0, 2) = "TS Configuration"

```
RT.TextMatrix(0, 3) = "Estimated Metric"  
'RT.TextMatrix(0, 3) = "Estimated Real Power Loss"  
RT.ColWidth(0) = 1000  
RT.ColWidth(1) = 2000  
RT.ColWidth(2) = 2000  
RT.ColWidth(3) = 2000
```

```
Dim FullSS() As Integer  
Dim CaroSS() As Variant  
Dim reducedSS() As Integer  
Dim U() As Integer  
Dim uh() As Integer  
Dim Uvector(0 To nbus - 2) As Variant  
Dim strAdd As String  
Dim lb(1 To 8) As Integer  
Dim ED As Double  
Dim branchED(0 To 11) As Integer  
Dim i, k, n, m As Integer  
Dim j As Integer ' configuration index
```

```
'branch Info
```

```
' branch #1 = feeder-A1  
' branch #2 = A1-A2  
' branch #3 = A2-A3  
' branch #4 = A3-A4  
' branch #5 = feeder-B1  
' branch #6 = B1-B2  
' branch #7 = B2-B3  
' branch #8 = B3-B4  
' branch #9 = A4-B1 TS1  
' branch #10 = A2-B2 TS2  
' branch #11 = A3-B3 TS3  
' branch #12 = A4-B4 TS4
```

```
'Resistance Bus
```

```
Dim rLine(0 To 11) As Double
```

```
rLine(0) = 0.4 'SS1  
rLine(1) = 0.121  
rLine(2) = 0.4 'SS2  
rLine(3) = 0.141  
rLine(4) = 0.4 'SS3  
rLine(5) = 0.141  
rLine(6) = 0.4 'SS4  
rLine(7) = 0.122  
rLine(8) = 0.4 'TS1  
rLine(9) = 0.4 'TS2  
rLine(10) = 0.4 'TS3  
rLine(11) = 0.4 'TS4
```

```

'feed in number of light bulbs on each bus phase a
ll() = loadlevel()
For i = 1 To 8
lb(i) = ll(i).a
Next i

'feed in U matrix
FullSS = makeSS(8)
reducedSS = makereducedSS(FullSS(), 4)
U = reducedSS()
modCaroLoop.initializeAll
CaroSS = modCaroLoop.CaroMakeSS(U)
j = 0

For i = 0 To (UBound(CaroSS) - 1)
'Apply assumption 1
If (CaroSS(i, 0) + CaroSS(i, 1) = 2) Then
'Debug.Print CaroSS(i, 0); CaroSS(i, 1); CaroSS(i, 2); CaroSS(i, 3); CaroSS(i, 4); CaroSS(i, 5); CaroSS(i, 6);
CaroSS(i, 7)
'Initiate ED for each branch
For m = 0 To 11
branchED(m) = 0
Next m

If CaroSS(i, 2) = 0 Then 'SS3 open
branchED(0) = lb(1) + lb(2)
branchED(1) = lb(2)

If CaroSS(i, 3) = 0 Then 'SS4 is also open --> TS1 has to be closed
branchED(5) = lb(6)

'Case 1: SS3 and SS4 Open, TS1 and TS3 Closed
If CaroSS(i, 6) = 1 And CaroSS(i, 4) = 1 Then
branchED(7) = lb(8)
branchED(10) = lb(7) + branchED(7)
branchED(3) = branchED(10) + lb(3)
branchED(8) = branchED(3) + lb(4)
End If

'Case 2: SS3 and SS4 Open, TS1 and TS4 Closed
If CaroSS(i, 7) = 1 And CaroSS(i, 4) = 1 Then
branchED(7) = lb(7)
branchED(3) = lb(3)
branchED(11) = branchED(7) + lb(8)
branchED(8) = branchED(11) + branchED(3) + lb(4)
End If
branchED(4) = branchED(8) + branchED(5) + lb(5)

```

Else 'SS4 is closed

'Case 3: SS1 Open, TS4 Closed

If CarOSS(i, 7) = 1 Then

branchED(3) = lb(3)

branchED(11) = branchED(3) + lb(4)

branchED(7) = branchED(11) + lb(8)

branchED(6) = branchED(7) + lb(7)

branchED(5) = branchED(6) + lb(6)

branchED(4) = branchED(5) + lb(5)

End If

'Case 4: SS3 Open, TS3 Closed

If CarOSS(i, 6) = 1 Then

branchED(7) = lb(8)

branchED(3) = lb(4)

branchED(10) = branchED(3) + branchED(7)

branchED(6) = branchED(7) + branchED(10) + lb(7)

branchED(5) = branchED(6) + lb(6)

branchED(4) = branchED(5) + lb(5)

End If

'Case 5: SS3 Open, TS1 Closed

If CarOSS(i, 4) = 1 Then 'TS1 is closed

branchED(3) = lb(3)

branchED(7) = lb(8)

branchED(8) = branchED(3) + lb(4)

branchED(6) = branchED(7) + lb(7)

branchED(5) = branchED(6) + lb(6)

branchED(4) = branchED(5) + branchED(8) + lb(5)

End If

End If

Else 'CarOSS(i,2)=1

'Case 6: SS4 Open, TS3 Closed

If CarOSS(i, 3) = 0 Then

branchED(5) = lb(6)

branchED(4) = branchED(5) + lb(5)

If CarOSS(i, 6) = 1 Then

branchED(7) = lb(8)

branchED(10) = branchED(7) + lb(7)

branchED(3) = lb(4)

branchED(2) = branchED(3) + branchED(10) + lb(3)

End If

'Case 7: SS4 Open, TS4 Closed


```

If CarOSS(j, 7) = 1 Then
branchED(7) = lb(7)
branchED(11) = branchED(7) + lb(8)
branchED(3) = branchED(11) + lb(4)
branchED(2) = branchED(3) + lb(3)
End If

```

```

branchED(1) = branchED(2) + lb(2)
branchED(0) = branchED(1) + lb(1)

```

```

Else

```

```

'Case 8: SS4 SS3 all Closed -->base case

```

```

branchED(3) = lb(4)
branchED(2) = branchED(3) + lb(3)
branchED(1) = branchED(2) + lb(2)
branchED(0) = branchED(1) + lb(1)
branchED(7) = lb(8)
branchED(6) = branchED(7) + lb(7)
branchED(5) = branchED(6) + lb(6)
branchED(4) = branchED(5) + lb(5)
End If
End If

```

```

'sum all branches to get total electric distance

```

```

ED = 0
For k = 0 To 11
ED = ED + branchED(k) * rLine(k)
Next k

```

```

'Fill in Tables

```

```

RT.TextMatrix(j + 1, 0) = j
RT.TextMatrix(j + 1, 3) = ED

```

```

For n = 0 To 7

```

```

    Uvector(n) = CarOSS(i, n)
    strAdd = Uvector(n)
    'Debug.Print strAdd
    If (n < 4) Then
        RT.TextMatrix(j + 1, 1) = RT.TextMatrix(j + 1, 1) + strAdd
    Else
        RT.TextMatrix(j + 1, 2) = RT.TextMatrix(j + 1, 2) + strAdd
    End If
Next n

```

```

j = j + 1

```

```

End If

```

```

Next i

```

End Sub

11.4 Expert System Data for NR

Table B4: Expert System Results for NR Experiment Load Level 1 with optimal configuration at setting 1

Setting	SS Config	TS Config	Estimated Metric, V	Constraint
0	1111	0000	3.187	TRUE
1	1101	1000	2.925	TRUE
2	1110	0010	3.567	TRUE
3	1101	0011	4.928	TRUE
4	1100	1010	3.325	TRUE
5	1110	0001	3.586	TRUE
6	1101	0001	3.588	TRUE
7	1100	1001	3.062	TRUE

Table B5: Expert System Results for NR Experiment Load Level 2 with optimal configuration at setting 1

Setting	SS Config	TS Config	Estimated Metric, V	Constraint
0	1111	0000	5.711	TRUE
1	1101	1000	4.925	TRUE
2	1110	0010	6.471	TRUE
3	1101	0011	8.312	TRUE
4	1100	1010	5.725	TRUE
5	1110	0001	6.753	TRUE
6	1101	0001	6.914	TRUE
7	1100	1001	5.443	TRUE

Table 13: Expert System Results for NR Experiment Load Level 3 with optimal configuration at setting 3

Setting	SS Config	TS Config	Estimated Metric, V	Constraint
0	1111	0000	1.983	TRUE
1	1101	1000	1.741	TRUE
2	1110	0010	1.983	TRUE
3	1101	0011	1.482	TRUE
4	1100	1010	1.741	TRUE
5	1110	0001	1.983	TRUE
6	1101	0001	3.067	TRUE
7	1100	1001	1.741	TRUE

12 Appendix C

12.1 Network Reconfiguration Metric UI

The User Interface for Network Reconfiguration Offline Form is as Figure C1.

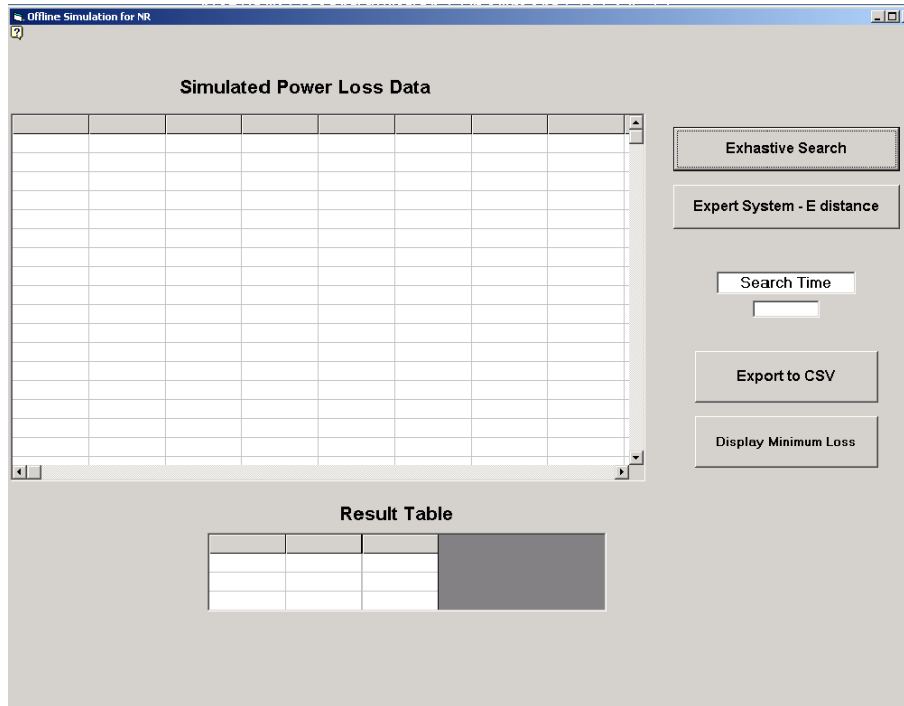


Figure C1. The NR Metric Form in Visual Basic

As shown in Figure C1, the table named “Simulated Power Loss Data” stores and displays offline real and reactive power loss calculation, which is realized with above exhaustive search algorithm or expert system algorithm. Display of the table is coded to be controlled by user’s click of command button named “Exhaustive Search” or “Expert System” for corresponding search algorithm.

The table named “Result Table” is coded to be controlled by user’s click of command button named “Display Minimum Loss” and display the minimum switch configuration.

The Textbox named “Search Time” is coded to display the execution time of the switch algorithm.

12.2 Service Restoration Metric UI

The User Interface for Service Reconfiguration Offline Form is as Figure C2.

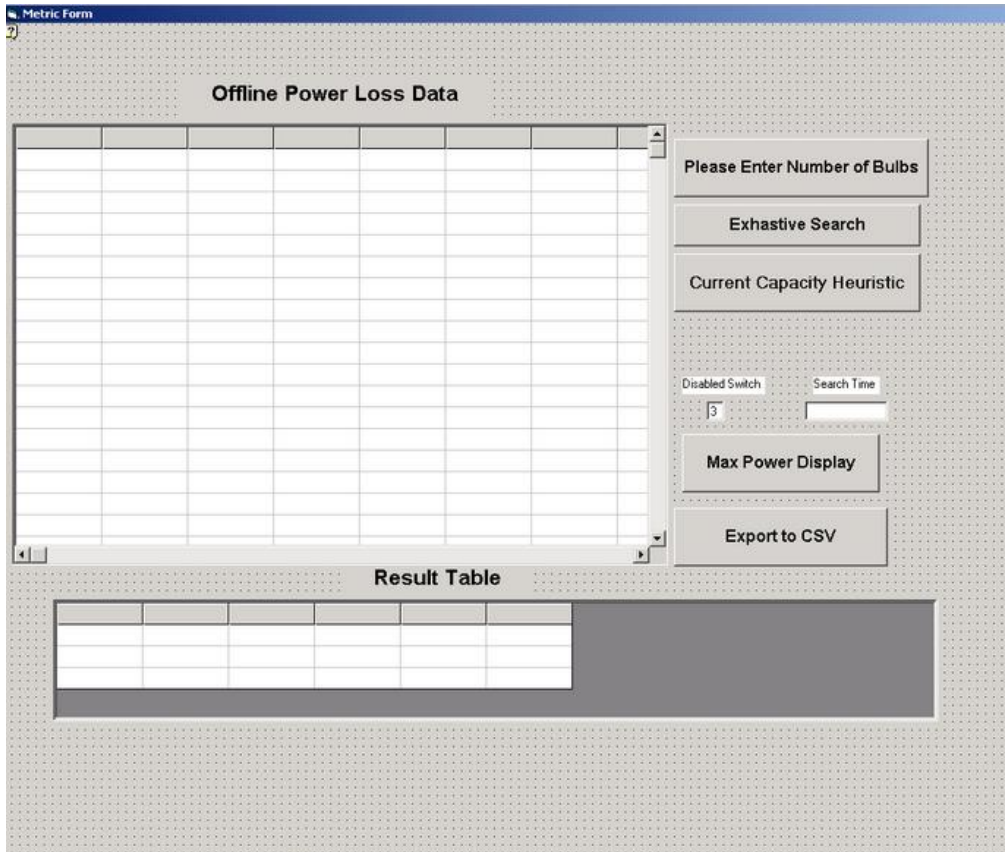


Figure C2. Service Restoration GUI in VB

The “Exhaustive Search” button will complete the SR exhaustive search and update the larger of the tables. The “Current Capacity Heuristic” button will complete the SR heuristic algorithm and update the larger of the tables. For both, the “Max Power Display” button will display the switch configuration with the maximum power in the result table. In order to obtain the data, the user can click the “Export to CSV” button and then open the .csv file in Excel.

13 Appendix D

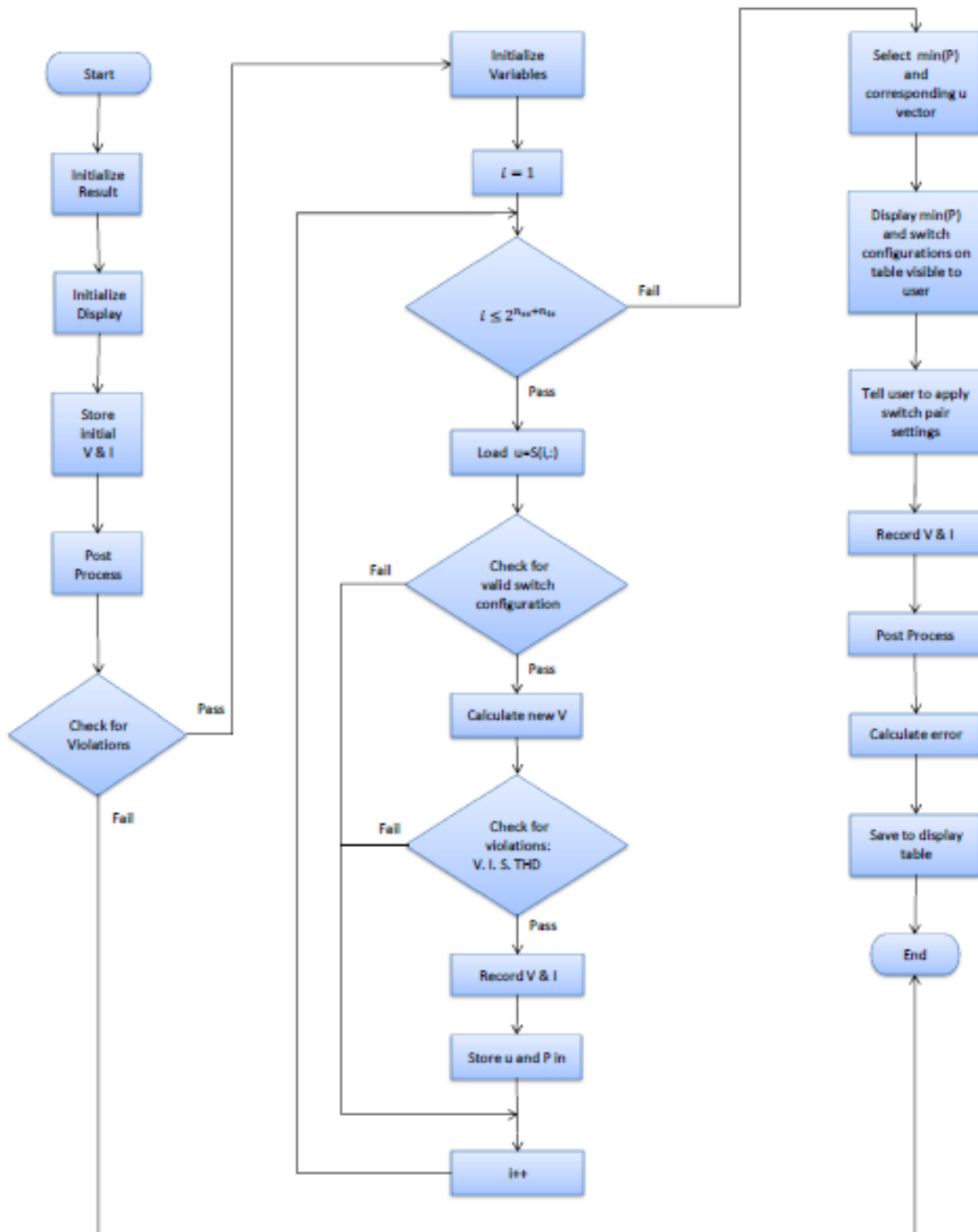


Figure D1. Flow chart illustrating the decision process for the exhaustive search.

14 Appendix E

14.1 Admittance Bus Building Algorithm

14.2 Gauss Seidel Power Flow

'Gauss Seidel Power Flow Module

'Sections: Declare data type;Initialize variables;Perform Power Flow

'April 18th, 2013

'Assumptions:

'1: Initial real power injection at each bus is 72W/bulb, initial reactive power injection at each bus is 0 VAR.

'2: Feeder bus(slack bus) voltage constant at 120 V with phase angle 0(phase A)

'3: Stop the iteration when $\max(\text{abs}(V(k+1)-V(k))/V(k)) < .0000001$

Option Explicit

'---Declare data type---

Public Type Rectangular

Real As Double

Imag As Double

End Type

Public Type MultiPhase

a As Double

B As Double

c As Double

End Type

Global Const nbus As Integer = 9

Public loadlevel(1 To nbus - 1) As MultiPhase

Public ll_22() As MultiPhase

'--- Initialize Variable---

Public Sub makeYbus()

Const nbus As Integer = 9

Dim Ybus(0 To nbus - 1, 0 To nbus - 1) As MultiPhase 'Admittance bus

Dim Gbus(0 To nbus - 1, 0 To nbus - 1) As MultiPhase

Dim Bbus(0 To nbus - 1, 0 To nbus - 1) As MultiPhase

Dim i, j As Integer

' ---make ybus for testing---

Dim rsw, xsw, rln, xln, gsw, bsw, gln, bln As Double

rsw = 0.4

xsw = 0.016

rln = 0.12

```
xln = 0.44
gsw = rsw / (rsw ^ 2 + xsw ^ 2)
bsw = -xsw / (rsw ^ 2 + xsw ^ 2)
gln = rln / (rln ^ 2 + xln ^ 2)
bln = -xln / (rln ^ 2 + xln ^ 2)
```

```
Gbus(0, 0).a = 2 * gsw
Bbus(0, 0).a = 2 * bsw
Gbus(1, 1).a = gsw + gln
Bbus(1, 1).a = bsw + bln
Gbus(2, 2).a = gsw + gln
Bbus(2, 2).a = bsw + bln
Gbus(3, 3).a = gsw + gln
Bbus(3, 3).a = bsw + bln
Gbus(4, 4).a = gln
Bbus(4, 4).a = bln
Gbus(5, 5).a = gsw + gln
Bbus(5, 5).a = bsw + bln
Gbus(6, 6).a = gsw + gln
Bbus(6, 6).a = bsw + bln
Gbus(7, 7).a = gsw + gln
Bbus(7, 7).a = bsw + bln
Gbus(8, 8).a = gln
Bbus(8, 8).a = bln
```

```
For i = 0 To 3
  If (i Mod 2 = 0) Then
    Gbus(i, i + 1).a = -gsw
    Bbus(i, i + 1).a = -bsw
  Else
    Gbus(i, i + 1).a = -gln
    Bbus(i, i + 1).a = -bln
  End If
Next i
```

```
For i = 5 To 7
  If (i Mod 2 = 0) Then
    Gbus(i, i + 1).a = -gsw
    Bbus(i, i + 1).a = -bsw
  Else
    Gbus(i, i + 1).a = -gln
    Bbus(i, i + 1).a = -bln
  End If
Next i
```

```
Gbus(0, 5).a = -gsw
Bbus(0, 5).a = -bsw
```

```

'Fill_22 in rest through symetry
For i = 0 To nbus - 1
    For j = 0 To nbus - 1
        Gbus(j, i).a = Gbus(i, j).a
        Bbus(j, i).a = Bbus(i, j).a
    Next j
Next i
'Copy data to phase b,c
For i = 0 To nbus - 1
    For j = 0 To nbus - 1
        Gbus(i, j).B = Gbus(i, j).a
        Gbus(i, j).c = Gbus(i, j).a
        Bbus(i, j).B = Bbus(i, j).a
        Bbus(i, j).c = Bbus(i, j).a
    Next j
Next i

'For i = 0 To nbus - 1
'For j = 0 To nbus - 1
'Debug.Print Bbus(i, j).c; ", ";
'Next j
'Next i
End Sub

'---Function that performs power flow---'
'---Input loadlevel,Gbus and Bbus---'
'---Output Vnode(bus#, magnitude/angle,phase)---'

Public Function Vnode(Il_22() As MultiPhase, Gbus() As MultiPhase, Bbus() As MultiPhase) As Variant

Dim i, j, k, count As Integer

Const nbus As Integer = 9
Dim Vmag(0 To nbus - 1) As MultiPhase 'Voltage magnitude
Dim Vangle(0 To nbus - 1) As MultiPhase 'Phase Angle

Dim VmagHist(0 To nbus - 1) As MultiPhase 'Historical voltage magnitude
Dim Vreal(0 To nbus - 1) As MultiPhase 'Real Part of Voltage
Dim Vimag(0 To nbus - 1) As MultiPhase 'Imag Part of Voltage
Dim Vnode1(0 To nbus - 1, 0 To 1, 0 To 2) As Double
'Output Nodal Voltage

Dim Pinj(0 To nbus - 1) As MultiPhase 'Real Power Injection
Dim Qinj(0 To nbus - 1) As MultiPhase 'Reactive Power Injection

Dim error, tol As Double 'Stopping Criteria

```


Dim gamma As MultiPhase
Dim RPT As MultiPhase
Dim IPT As MultiPhase
Dim RYT As MultiPhase
Dim IYT As MultiPhase
'gamma is the square of voltage magnitude
'RPT is the real part of S^*/V^* term in pf equation
'IPT is the imag part of S^*/V^* term in pf eq
'RYT is the real part of YV summation term in pf eq
'IYT is the imag part of YV summation term in pf eq

Dim RI As MultiPhase
Dim li As MultiPhase
Dim GI As MultiPhase
Dim BI As MultiPhase
'RI is the real part of current term in pf eq
'li is the imag part of current term in pf eq
'GI is the real part of Yii
'BI is the imag part of Yii

'Gload is the constant impdeacne load on bus(pure resistive light bulbs)
Dim Gload(0 To nbus - 1) As MultiPhase

'Taken from the user:ll_22(1 to nbus-1) is the load level(# of light bulbs)
'light bulbs connected in parallel

For i = 1 To nbus - 1

If ll_22(i).a = 0 Then
Gload(i).a = 0
Else
Gload(i).a = ll_22(i).a / 200
End If

If ll_22(i).B = 0 Then
Gload(i).B = 0
Else
Gload(i).B = ll_22(i).B / 200
End If

If ll_22(i).c = 0 Then
Gload(i).c = 0
Else
Gload(i).c = ll_22(i).c / 200
End If

Next i

```

For i = 0 To nbus - 1
'Initiate State Vector
Vmag(i).a = 120
Vmag(i).B = 120
Vmag(i).c = 120

Vangle(i).a = 0
Vangle(i).B = -120
Vangle(i).c = 120

Vreal(i).a = Vmag(i).a * Math.Cos(Vangle(i).a)
Vreal(i).B = Vmag(i).B * Math.Cos(Vangle(i).B)
Vreal(i).c = Vmag(i).c * Math.Cos(Vangle(i).c)

Vimag(i).a = Vmag(i).a * Math.Sin(Vangle(i).a)
Vimag(i).B = Vmag(i).B * Math.Sin(Vangle(i).B)
Vimag(i).c = Vmag(i).c * Math.Sin(Vangle(i).c)

Next i

'Initiate Power Injection
'Power injection is assumed to be constant for each load level
'For i = 1 To nbus - 1
'Pinj(i).a = -Vmag(i).a ^ 2 * Gload(i).a
'Pinj(i).B = -Vmag(i).B ^ 2 * Gload(i).B
'Pinj(i).c = -Vmag(i).c ^ 2 * Gload(i).c
'Debug.Print Pinj(i).a
'Next i

'Define initial count and starting error
count = 0
error = 100
tol = 0.000001

Do While (error > tol And count < 500)

'saving historical state vector
For i = 1 To nbus - 1
VmagHist(i).a = Vmag(i).a
VmagHist(i).B = Vmag(i).B
VmagHist(i).c = Vmag(i).c

Next i

'Updating power injection
'Assume light bulbs to be constant impedance load

```

```

For i = 1 To nbus - 1
Pinj(i).a = -Vmag(i).a ^ 2 * Gload(i).a
Pinj(i).B = -Vmag(i).B ^ 2 * Gload(i).B
Pinj(i).c = -Vmag(i).c ^ 2 * Gload(i).c
Next i

```

```

For i = 1 To nbus - 1

```

```

gamma.a = Vreal(i).a ^ 2 + Vimag(i).a ^ 2
gamma.B = Vreal(i).B ^ 2 + Vimag(i).B ^ 2
gamma.c = Vreal(i).c ^ 2 + Vimag(i).c ^ 2

```

```

'equation S*/V*

```

```

RPT.a = (Pinj(i).a * Vreal(i).a + Qinj(i).a * Vimag(i).a)
RPT.B = (Pinj(i).B * Vreal(i).B + Qinj(i).B * Vimag(i).B)
RPT.c = (Pinj(i).c * Vreal(i).c + Qinj(i).c * Vimag(i).c)

```

```

IPT.a = Pinj(i).a * Vimag(i).a - Qinj(i).a * Vreal(i).a
IPT.B = Pinj(i).B * Vimag(i).B - Qinj(i).B * Vreal(i).B
IPT.c = Pinj(i).c * Vimag(i).c - Qinj(i).c * Vreal(i).c

```

```

RYT.a = 0
RYT.B = 0
RYT.c = 0

```

```

IYT.a = 0
IYT.B = 0
IYT.c = 0

```

```

'equation of summing Yij*Vj

```

```

For j = 0 To nbus - 1

```

```

If (Not (j = i)) Then

```

```

    RYT.a = RYT.a + gamma.a * (Gbus(i, j).a * Vreal(j).a - Bbus(i, j).a * Vimag(j).a)
    RYT.B = RYT.B + gamma.B * (Gbus(i, j).B * Vreal(j).B - Bbus(i, j).B * Vimag(j).B)
    RYT.c = RYT.c + gamma.c * (Gbus(i, j).c * Vreal(j).c - Bbus(i, j).c * Vimag(j).c)

```

```

    IYT.a = IYT.a + gamma.a * (Gbus(i, j).a * Vimag(j).a + Bbus(i, j).a * Vreal(j).a)
    IYT.B = IYT.B + gamma.B * (Gbus(i, j).B * Vimag(j).B + Bbus(i, j).B * Vreal(j).B)
    IYT.c = IYT.c + gamma.c * (Gbus(i, j).c * Vimag(j).c + Bbus(i, j).c * Vreal(j).c)

```

```

End If

```

```

Next j

```

```

RI.a = RPT.a - RYT.a
RI.B = RPT.B - RYT.B
RI.c = RPT.c - RYT.c

```

```
li.a = IPT.a - IYT.a
li.B = IPT.B - IYT.B
li.c = IPT.c - IYT.c
```

```
Gl.a = Gbus(i, i).a
Gl.B = Gbus(i, i).B
Gl.c = Gbus(i, i).c
```

```
Bl.a = Bbus(i, i).a
Bl.B = Bbus(i, i).B
Bl.c = Bbus(i, i).c
```

```
Vreal(i).a = (Rl.a * Gl.a + li.a * Bl.a) / (gamma.a * (Gl.a ^ 2 + Bl.a ^ 2))
Vreal(i).B = (Rl.B * Gl.B + li.B * Bl.B) / (gamma.B * (Gl.B ^ 2 + Bl.B ^ 2))
Vreal(i).c = (Rl.c * Gl.c + li.c * Bl.c) / (gamma.c * (Gl.c ^ 2 + Bl.c ^ 2))
```

```
Vimag(i).a = (li.a * Gl.a - Rl.a * Bl.a) / (gamma.a * (Gl.a ^ 2 + Bl.a ^ 2))
Vimag(i).B = (li.B * Gl.B - Rl.B * Bl.B) / (gamma.B * (Gl.B ^ 2 + Bl.B ^ 2))
Vimag(i).c = (li.c * Gl.c - Rl.c * Bl.c) / (gamma.c * (Gl.c ^ 2 + Bl.c ^ 2))
```

```
'Voltage magnitude after each iteration
```

```
Vmag(i).a = Math.Sqrt(Vreal(i).a ^ 2 + Vimag(i).a ^ 2)
Vmag(i).B = Math.Sqrt(Vreal(i).B ^ 2 + Vimag(i).B ^ 2)
Vmag(i).c = Math.Sqrt(Vreal(i).c ^ 2 + Vimag(i).c ^ 2)
```

```
'Voltage angle after each iteration
```

```
Vangle(i).a = Math.Atn(Vimag(i).a / Vreal(i).a)
Vangle(i).B = Math.Atn(Vimag(i).B / Vreal(i).B)
Vangle(i).c = Math.Atn(Vimag(i).c / Vreal(i).c)
```

```
'Debug.Print Vreal(i).a
```

```
'update historical data to store abs(V(k)-V(k-1))/V(k)
```

```
VmagHist(i).a = Math.Abs(VmagHist(i).a - Vmag(i).a)
'Debug.Print Vmag(i).a; VmagHist(i).a
```

```
Next i
```

```
'checking stopping criteria
```

```
error = 0
For i = 1 To nbus - 1
error = error + (VmagHist(i).a) ^ 2
'Debug.Print error
Next i
error = Math.Sqrt(error)
```

```
count = count + 1
```

Loop

```
'Debug.Print "here is the "; count
```

```
For i = 0 To nbus - 1
```

```
Vnode1(i, 0, 0) = Vmag(i).a
```

```
Vnode1(i, 0, 1) = Vmag(i).B
```

```
Vnode1(i, 0, 2) = Vmag(i).c
```

```
Vnode1(i, 1, 0) = Vangle(i).a
```

```
Vnode1(i, 1, 1) = Vangle(i).B
```

```
Vnode1(i, 1, 2) = Vangle(i).c
```

```
Next i
```

```
Vnode = Vnode1
```

```
End Function
```

14.3 Constraint Check

14.4 Power Loss Calculation

Equations for real and reactive power loss calculation:

$$P = \sum_{nbr=1}^8 I_{nbr}^2 \times R_{nbr}$$

$$Q = \sum_{nbr=1}^8 I_{nbr}^2 \times X_{nbr}$$

Where

- The total number of the branches is 8
- nbr is the index for branch number in the network
- I_{nbr} is the current flow along the branch
- R_{nbr} is the resistance value of the branch
- X_{nbr} is the reactance value of the branch

Equation for obtaining current along each branch:

$$I = Y \times V$$

Where

- Y is a 8 by 8 admittance matrix for the network, which is updated at each network configuration
- I is a 1 by 8 matrix storing current along each branch, which is calculated for the purpose of power loss calculation
- V is a 1 by 8 matrix storing voltage at each nodal bus, which is calculated with a Gauss Seidel Power Flow.

15 Appendix F

Originally, THD was going to be a constraint because it was assumed that two different sources would be available, each with different harmonic content. As discussed later, it now appears the solar power source will not be ready for inclusion into the RDAC, so the only source available will from PECO. THD will still be monitored, and but it will not be acted on.

The amount of distortion in a waveform can be quantified by the metric *total harmonic distortion* (THD). The distortion component of a periodic waveform is given by

$$y_{dis}(t) = y_s(t) - y_{s1}(t) = \sum_{n \neq 1} y_{sn}(t)$$

where $y_s(t)$ is the waveform of interest, and $y_{sn}(t)$ is the nth Fourier component of that waveform **Error! Reference source not found.**1 can be expressed in terms of RMS values as well.

$$Y_{dis} = [Y_s^2 - Y_{s1}^2]^{\frac{1}{2}} = \sum_{n \neq 1} Y_{sn}^2$$

RMS values are used for the ease of calculation, and they are valid because, as stated in the assumptions, steady state has been assumed.

THD is defined as

$$\% THD_Y = 100 * \frac{Y_{dis}}{Y_{s1}}$$

As shown above, in order to calculate the THD of a waveform, the RMS magnitudes of the various harmonic components present in the waveform must be known. To determine the RMS magnitudes of the various harmonic components present in a discrete waveform, a discrete Fourier transform must be performed. This will be done using hardware and software that is already present in the RDAC—specifically, the National Instruments Measurement Studio. This package provides a function that can be called that will perform a DFT and will return the fundamental frequency of the waveform, as well as a vector of magnitudes of each harmonic present.

Considering there was previously no Visual Basic module in RDAC to calculate THD, the creation of this module allows for additional analysis of the state of the network. As discussed above, there is no method in place for controlling THD.

16 Appendix G

16.1 MATPOWER Base Case

```
function mpc = BaseCase_v2
% RDAC Power System

%% MATPOWER Case Format : Version 2
mpc.version = '2';

%%----- Power Flow Data -----%%
%% system MVA base
mpc.baseMVA = 120e-6;

%% bus data
% bus_i type Pd Qd Gs Bs area Vm Va baseKV zone Vmax Vmin
mpc.bus = [
1 3 0 0 0 0 1 1 0 .12 1 1.2 0.8; % PECO
2 1 0 0 0 0 1 1 0 .12 1 1.2 0.8; % A1
3 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % A2
4 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % A3
5 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % A4
6 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % B1
7 1 0 0 0 0 1 1 0 .12 1 1.2 0.8; % B2
8 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % B3
9 1 72e-6 0 0 0 1 1 0 .12 1 1.2 0.8; % B4
];

%% generator data
% bus Pg Qg Qmax Qmin Vg mBase status Pmax Pmin Pc1 Pc2 Qc1min Qc1max Qc2min Qc2max ramp_agc ramp_10 ramp_30 ramp_q
apf
mpc.gen = [
1 0 0 300 -300 1 120e-6 1 400 0 0 0 0 0 0 0 0 0 0
];

%% branch data
% fbus tbus r x b rateA rateB rateC ratio angle status angmin angmax
mpc.branch = [
1 2 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
2 3 0.121/120 0.449/120 0 250 300 350 0 0 1 -360 360;
3 4 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
4 5 0.141/120 0.44/120 0 250 300 350 0 0 1 -360 360;
1 6 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
6 7 0.141/120 0.438/120 0 250 300 350 0 0 1 -360 360;
7 8 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
8 9 0.122/120 0.442/120 0 250 300 350 0 0 1 -360 360;
5 6 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
3 7 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
4 8 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
5 9 0.4/120 0.016/120 0 250 300 350 0 0 1 -360 360;
];
```

16.2 MATLAB Run Script

```
% Michael Caro
clear; clc;

% Generate Binary sequence for all switch configurations
addpath(genpath('.')\')

for i = 0:255
    U(i+1,:) = binary2vector(i,8);
end

% Call basecase
[input.baseMVA, input.bus, input.gen, input.branch] = ...
    loadcase('BaseCase_v2.m');

num_success = 0;

for n = 1:256
    input.branch = branchDataMod(input.branch,U(n,:));
    input.YBus = makeYbus(input.baseMVA,input.bus,input.branch);

    mpopt = mpoption('PF_ALG',4, 'PF_TOL', 1e-6, 'PF_MAX_IT_GS', 1000);
    [output(n).MVABaseAns, output(n).busAns, output(n).genAns, ...
        output(n).branchAns, output(n).successAns, output(n).etAns] = ...
        Caro_runpf(input,mpopt);
    num_success = num_success + output(n).successAns;
    output(n).u = U(n,:);
    output(n).Ybus = input.YBus;
    output(n).RealPowerLoss = output(n).genAns(1,2)*1e6 -
sum(output(n).busAns(:,3)*1e6);;
    output(n).ReactivePowerLoss = output(n).genAns(1,3)*1e6 -
sum(output(n).busAns(:,4)*1e6);
end

savefile = 'output.mat'; save('PF_Output.mat', 'output');

disp(sprintf('There were %1.2f successfull combinations',num_success))
```

Appendix H



Evan Greer <evan.r.greer@gmail.com>

Drexel Writing Center: Appointment made successfully!

1 message

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Mon, May 6, 2013 at 11:35 AM

To: erg29@drexel.edu

Evan Greer,

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ECE-22 Senior Design Final Report

"Integration and Analysis of Distributed Generation Resources in Micro-Grid Environments"

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Abstract

The main goal of a distribution management system is to ensure grid reliability. Two well-known methods of maintaining reliability are network reconfiguration and service restoration. One reason network reconfiguration is performed is to minimize the distribution system's real power loss as it serves demand. Network Reconfiguration is achieved through the actuation of sectionalizing and tie switches. Service restoration is performed to deliver power to customers that are experiencing a power outage. Outages are caused by grid disturbances, such as faults. Over the course of the year, this project developed two algorithms: one that minimizes real power loss in the distribution system by determining a near optimal network configuration, and another that maximizes the amount of load restored in the event of a fault. (The problems can be classified as non-linear, combinatorial, optimization problems, and they are subject to operating constraints such as voltage, current, power, and total harmonic distortion.)

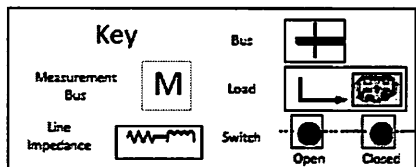
The algorithms were coded in Visual Basic and were then integrated into the existing software at Drexel's Reconfigurable Distribution and Automation Control laboratory (RDAC). The purpose of this is twofold. First, the algorithms served as the basis of lab modules that can be incorporated in the current power engineering curriculum. Second, as more single and poly-phase distributed generation resources are introduced into the power grid, complexities of NR and SR problems will increase, and thus algorithmic solutions will be needed by future students while performing network studies.

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1 Problem Description

In an electrical distribution system, loads are connected to buses which in turn are fed by distribution transformers. Within the distribution system, there are a number of switches—some of which are normally open, and others which are normally closed. The state of these switches defines the topology of the distribution network. Changing the state of the switches alters the topology, and thus can affect other quantities such as real power loss and the variation of voltage level. Changing the topology of the distribution system is known as network reconfiguration. This project will address the problem of finding the near optimal switch configuration of a distribution system within the context of network reconfiguration under normal and emergency operating conditions. Normal operating conditions are defined as all loads are maintained in the network with sectionalizing switches closed and tie switches open. Emergency operating conditions are defined as with one or more sectionalizing switches open in the network, loads on affected buses are lost and thus established fault conditions. The problem is formulated as an optimization of a single cost function subject to various equality and inequality constraints.



Load Profiles:

- Three Phase Loads on Bus A3, A4, B3, and B4
- Single Phase Loads(A-Phase) on Bus A2 and B1
- Two Phase Loads(B-C Phase) on Bus A2 and B1

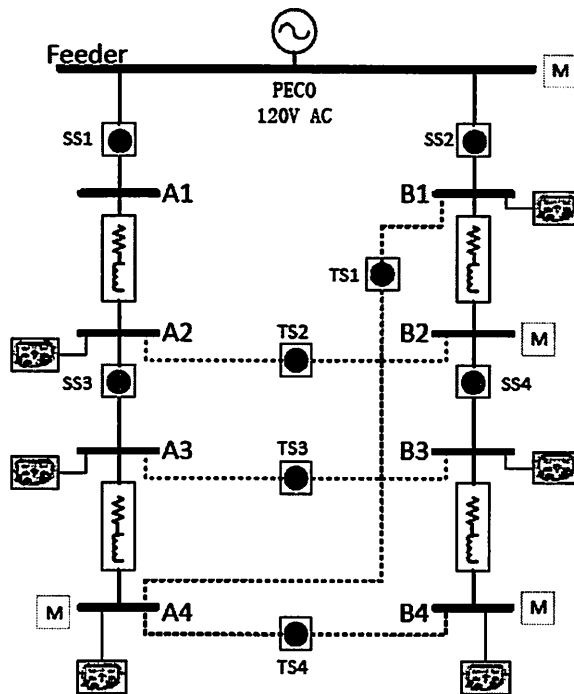


Figure 1. Example Power System Network to be used for cost minimization.

Table 1. Variables

Variable	Size	Description	Units
i	Scalar	Total number of buses	none
j	Scalar	Total number of XFMRs	none
k	Scalar	Total number of branches	none
n	Scalar	Total number of switches	none
Φ	Scalar	Total number of phases	none
b_1, b_2	Scalar	Conversion factor	\$/Watt
P_k^{line}	Scalar	Real power loss in branch k	Watts
P_j^{XFMR}	Scalar	Real power loss in XFMR j	Watts
$I_{s,0}$	Scalar	Source current magnitude before fault event	Amps
$I_{s,1}$	Scalar	Source current magnitude after fault event	Amps
P_i	Scalar	Injected real power at bus i	Watts
Q_i	Scalar	Injected reactive power at bus i	VAR
G_{io}	Scalar	Conductance between bus i and o	Siemens
B_{io}	Scalar	Suceptance between bus i and o	Siemens
u	Vector 1xn	State of the switches in the network	Binary
$ V_i $	Vector 4x1	3 phase voltage magnitude at bus i	Volts
ϕ_i	Vector 4x1	3 phase angle at bus i	Degrees
S	Matrix $u \times 2^n$	Search Space	Binary
X	Matrix $\Phi \times 2(i-1)$	State variable. Voltage magnitudes and phases at every bus.	Degrees and Volts
$C(X, u)$	Scalar	Cost function for normal operating conditions	Dollars
$\alpha(X, u)$	Scalar	Cost function for emergency operating conditions	Percent

1.1.1 Formulation for Normal Operating Conditions

$$\underset{u \in S}{\text{minimize}} C(X, u)$$

Equation 1.1.1.1

Where S is the set of all possible switch configurations such that:

$$F(\mathbf{X}, \mathbf{u}) = 0 \quad \text{Equation 1.1.1.2}$$

$$G(\mathbf{X}, \mathbf{u}) \leq 0 \quad \text{Equation 1.1.1.3}$$

F is the set of non-linear power flow equations. G is the set of constraint equations. The variable \mathbf{u} is a set of ones and zeros representing the statuses (open or closed) of all the tie and sectionalizing switches in the given network. Thus the topology of a network is uniquely determined by a given \mathbf{u} vector.

$$\mathbf{u} = [x_1, x_2, \dots, x_n] \quad x_i = \{0,1\}; \quad 1 < i \leq n, \text{ the number of switches} \quad \text{Equation 1.1.1.4}$$

There are 2^n unique \mathbf{u} vectors for a system with n switches. The search space, S 's rows are \mathbf{u} vectors, and its columns are a list of the network's switches.

$$S = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_{2^{n-1}} \\ u_{2^n} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 1 & 1 & \dots & 1 & 0 \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \quad \text{Equation 1.1.1.5}$$

To calculate the cost function, knowledge of the state of the system is needed. For a given load level, each \mathbf{u} vector maps to a given state, denoted as \mathbf{X} . The state variable \mathbf{X} contains voltage magnitudes and phases at every bus in the system (except the slack bus). \mathbf{X} is a Φ by $2(i-1)$ matrix where Φ is the number of phases, and i is the number of buses.

$$\mathbf{X} = [|V_2|, \dots, |V_i|, \phi_2, \dots, \phi_i] \quad \text{Equation 1.1.1.6}$$

The voltage magnitudes for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$|V_i| = [|V_i^A|, |V_i^B|, |V_i^C|, |V_i^N|]^T \quad \text{Equation 1.1.1.7}$$

The voltage phase angles for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$\phi_i = [\phi_i^A, \phi_i^B, \phi_i^C, \phi_i^N]^T \quad \text{Equation 1.1.1.8}$$

Under normal operating conditions, the cost function $C(\mathbf{X}, \mathbf{u})$ is defined as

$$C(\mathbf{X}, \mathbf{u}) = b_1 \sum_{k=1}^{N_L} P_k^{line}(\mathbf{X}, \mathbf{u}) + b_2 \sum_{j=1}^{N_t} P_j^{transformer}(\mathbf{X}, \mathbf{u}) \quad \text{Equation 1.1.1.9}$$

Here, conversion factors, b_1 and b_2 , are scalars that are used to convert the real power losses measured in Watts to dollars. The factors are listed separately because different costs may be used for lines and transformers.

1.1.2 Equality Constraints

Unbalanced multi-phase power flow for each bus must be satisfied.

$$-P_i + \sum_{o=1}^N |V_i||V_o|(G_{io} \cos(\theta_{io}) + B_{io} \sin(\theta_{io})) = 0 \quad \text{Equation 1.1.2.10}$$

$$-Q_i + \sum_{o=1}^N |V_i||V_o|(G_{io} \sin(\theta_{io}) - B_{io} \cos(\theta_{io})) = 0 \quad \text{Equation 1.112}$$

1.1.3 Inequality Constraints

1. Radial structure must be maintained.
2. Current constraint

$$|I_k| \leq |I_k^{Max}|, \text{ for all branches } k \quad \text{Equation 123.1}$$

3. Voltage constraint

$$|V_i^{min}| \leq |V_i| \leq |V_i^{max}|, \text{ for all buses } i \quad \text{Equation 13.2}$$

4. Power constraint

$$|P_j + jQ_j| \leq |S_j^{max}|, \text{ for all XFMRs } j \quad \text{Equation 143}$$

5. Total Harmonic Distortion (THD)

$$THD_{voltage,i} \leq THD_{voltage,i}^{max} \text{ for all buses } i \quad \text{Equation 154}$$

1.1.4 Formulation for Emergency Operating Conditions

As stated previously, emergency operating conditions will occur in the case of a fault at a bus or line location in the network resulting in a loss of service to loads.

$$\underset{u \in S}{\text{maximize}} \alpha(X, u) \quad \text{Equation 161}$$

Alpha is the cost function for emergency operating conditions. The definition of the variables X , S and u are not changed from the preceding section.

Under emergency operating conditions, $\alpha(X, u)$ is the cost function measured in dollars.

$$\alpha(X, u) = \frac{\sum I_{s,1}}{\sum I_{s,0}} * 100 \quad \text{Equation 172}$$

$I_{s,0}$ is the total source current before a fault. $I_{s,0}$ is a function of the state variable X . $I_{s,1}$ is the total source current after a fault. $I_{s,1}$ is also a function of X .

2 Progress toward a solution

In the fall term, the students

- Researched different problems associated with distribution systems
- Determined that with the increasing amount of distributed generation resources being incorporated into the grid, automated NR and SR will become increasingly vital the operation of the grid
 -
- Determined that the number of power electronic devices present in distribution systems will likely increase due to their efficiencies, and while providing many benefits, will also be the source of new problems such as corrupted waveform due to harmonics.
- Researched the standard for THD: IEEE Standard 519-1992.
- Researched different algorithms to perform the automated NR and SR
- Formulated different metrics such as voltage level, THD, and amount of load restored
- Researched different power flow methods

The following was accomplished during the Winter Term:

- Researched how to actuate solid state relays (sectionalizing and tie switches)
- Development of the problem formulation.

- - Code created for estimating the distribution system's
 - Real power loss
 - Reactive power loss
 - Total harmonic distortion
 - Development of an algorithm that will perform an exhaustive search by:
 - Determining every possible network configuration.
 - Eliminating network configurations with loops (to maintain radial structure).
 - Estimating the real power loss for each valid network configuration.
 - Ensuring the equality constraint is met as well as hard inequality constraints.
 - A GUI developed for:
 - Implementation of the algorithm.
 - Displaying all estimated and measured data to the user as well as the error between the two.

The following has been accomplished since the conclusion of the Winter Term:

- Power Flow code completed
 - Uses Gauss-Seidel Method and is parameterized for load level and network topology
- Exhaustive search algorithm completed for Network Reconfiguration
 - Conducts an exhaustive search of feasible network topologies and returns the optimal network configuration to minimize real power loss
- Heuristic algorithm completed for Network Reconfiguration
 - Searches for smallest electrical distance between buses and looks to optimize the network using the shortest electrical distances.
- Exhaustive search completed for Service Restoration

- Conducts an exhaustive search of feasible network topologies and returns the optimal network reconfiguration to maximize load delivered
- Heuristic algorithm completed for Service Restoration
 - Utilizes two methods to minimize the search space
 - Searches for switches near their current capacity and limits operations that would increase current through the switch
 - Searches for smallest electrical distance between buses and looks to optimize the network using the shortest electrical distances
- Completed Lab Manuals for Network Reconfiguration and Service Restoration

2.1.1 Exhaustive Search for Network Reconfiguration

Power loss minimization is proposed to be accomplished with an exhaustive search in all possible switch settings for the purpose of network reconfiguration or service restoration. Mathematical theory, algorithm and visual basic code have been developed and discussed in Appendix A. The established visual basic interface is included and discussion in Appendix B.

2.1.2 Heuristic Algorithm for Network Reconfiguration

(Insert general information, specific information in the Appendix)

2.1.3 Exhaustive Search for Service Restoration

(Insert general information, specific information in the Appendix)

2.1.4 Heuristic Algorithm for Service Restoration

(Insert general information, specific information in the Appendix)

2.1.5 Calculation of THD (Potentially move to the Appendix)

Originally, THD was going to be a constraint because it was assumed that two different sources would be available, each with different harmonic content. As discussed later, it now appears the solar power source will not be ready for inclusion into the RDAC, so the only source available will from PECO. THD will still be monitored, and but it will not be acted on.

The amount of distortion in a waveform can be quantified by the metric *total harmonic distortion* (THD). The distortion component of a periodic waveform is given by

$$y_{dis}(t) = y_s(t) - y_{s1}(t) = \sum_{n \neq 1} y_{sn}(t) \quad \text{Equation 18}$$

where $y_s(t)$ is the waveform of interest, and $y_{sn}(t)$ is the nth Fourier component of that waveform. Equation 181 can be expressed in terms of RMS values as well.

$$Y_{dis} = [Y_s^2 - Y_{s1}^2]^{\frac{1}{2}} = \sum_{n \neq 1} Y_{sn}^2 \quad \text{Equation 2.192}$$

RMS values are used for the ease of calculation, and they are valid because, as stated in the assumptions, steady state has been assumed.

THD is defined as

$$\% THD_Y = 100 * \frac{Y_{dis}}{Y_{s1}} \quad \text{Equation 203}$$

As shown above, in order to calculate the THD of a waveform, the RMS magnitudes of the various harmonic components present in the waveform must be known. To determine the RMS magnitudes of the various harmonic components present in a discrete waveform, a discrete Fourier transform must be performed. This will be done using hardware and software that is already present in the RDAC—specifically, the National Instruments Measurement Studio. This package provides a function that can be called that will perform a DFT and will return the fundamental frequency of the waveform, as well as a vector of magnitudes of each harmonic present.

Considering there was previously no Visual Basic module in RDAC to calculate THD, the creation of this module allows for additional analysis of the state of the network. As discussed above, there is no method in place for controlling THD.

3 Budget

Table 2. Industrial budget for this project.

Electrical Engineers Salaries	Weekly Hours	Payrate	Nine Month Total
Evan Greer	40	\$50/Hr.	\$72,000.00
Michael Black	40	\$50/Hr.	\$72,000.00
Yi Li	40	\$50/Hr.	\$72,000.00
Michael Caro	40	\$50/Hr.	\$72,000.00
Consulting Fees	Weekly Hours	Payrate	Nine Month Total
Dr. Karen Miu	2	\$150/Hr.	\$10,800.00
Dr. Chika Nwankpa	1	\$150/Hr.	\$5,400.00
Nicole Segal	2	\$100/Hr.	\$7,200.00
Labor Budget			\$311,400.00
Facility Fees	Duration	Rate	Nine Month Total
Drexel Power Lab	15 hours/week	\$50/Hr.	\$27,000.00
Supply Costs	Quantity	Per Unit	Nine Month Total
Microsoft Office 2010	3	\$75/License	\$225.00
Visual Basic License	1	\$30000/License	\$30,000.00
Office Supplies	1	\$1,000	\$1,000.00
Facility/Supplies Budget			\$58,225.00
Net Total			\$369,625.00
Overhead 35%			\$129,369.00
Total			\$498,994.00

4 Gantt Chart

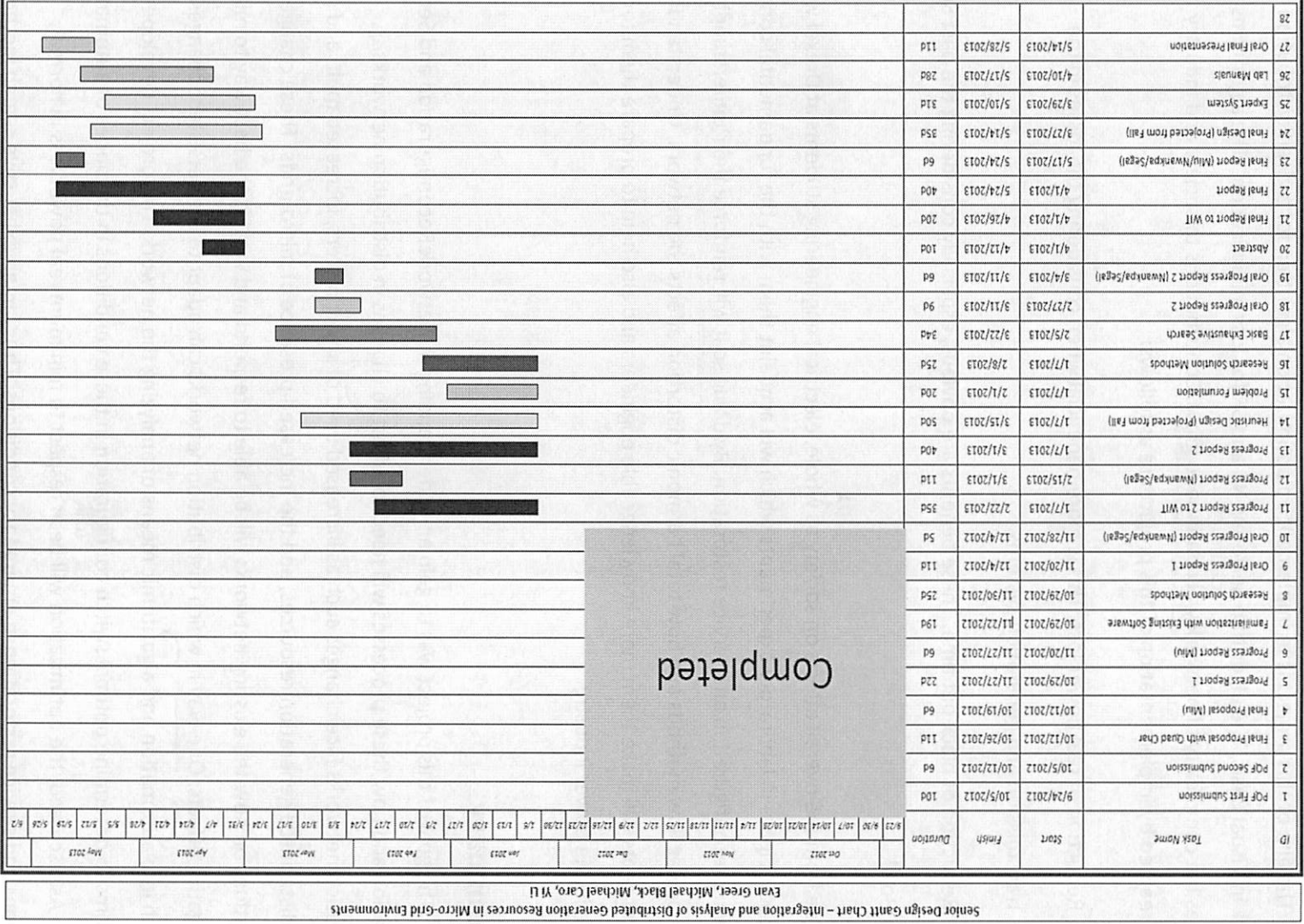


Figure 2. Revised gantt chart.

5 Societal, Environmental and Ethical Impacts

The aim of this project is to implement an optimization algorithm for a given distribution network in Visual Basic. The algorithm performs NR and SR for loss minimization. The algorithms will be crucial as the complexity of network ^{the} ~~will continue~~ ^{continues} to grow. Contributions to society and industry that can be realized by implementation of this project are as follows:

- Reduction of real power loss. This is more beneficial when considering the losses in the transmission and generation systems.
- Reduction of black out time. These benefits are obvious, especially considering the past Super Bowl.

Aside from the overall effects on society as ^a whole, electrical engineering students at Drexel will be able to participate in laboratory experiments which will acquaint them with the fundamental concepts of network reconfiguration and service restoration. By doing so it will reinforce their understanding of various power flow methods and how total harmonic distortion affects the network. Understanding these concepts will make them more knowledgeable engineers and also help to prepare them for a position in the power industry.

6 Summary

The goal of this project was to gain an understanding of Network Reconfiguration and Service Restoration and how these processes will need to adjust to changes in distribution networks. Distribution networks face changes such as increased ^{use} ~~used~~ of smart meters, increased multi and poly-phase distributed generation resources, and the increased presence of micro-grids. These changes lead to questions on how the existing networks will be able to respond and what is the best way to mitigate any negative effects. One way in which distribution networks can adapt to the persistent changes is research into automation and algorithmic means of analyzing the network. This project developed algorithms to determine optimal switch configuration in these conditions in the hopes of automating NR and SR. As discussed, the optimization will be ^{with} ~~in~~ respect to minimum real power loss in normal conditions and service restoration in emergency conditions. Thus far, an exhaustive search method and a heuristic algorithm have been developed and implemented for both conditions. The data collected

- from implementing these different algorithms allowed for the creation of two lab manuals, one for NR and one for SR, that can be incorporated into the existing power engineering curriculum.

7 Appendix A

Equations for real and reactive power loss calculation:

$$P = \sum_{nbr=1}^8 I_{nbr}^2 \times R_{nbr} \quad \text{Equation 21}$$

$$Q = \sum_{nbr=1}^8 I_{nbr}^2 \times X_{nbr} \quad \text{Equation 222}$$

Where

- The total number of the branches is 8
- nbr is the index for branch number in the network
- I_{nbr} is the current flow along the branch
- R_{nbr} is the resistance value of the branch
- X_{nbr} is the reactance value of the branch

Equation for obtaining current along each branch:

$$I = Y \times V \quad \text{Equation 233}$$

Where

- Y is a 8 by 8 admittance matrix for the network, which is updated at each network configuration
- I is a 1 by 8 matrix storing current along each branch, which is calculated for the purpose of power loss calculation
- V is a 1 by 8 matrix storing voltage at each nodal bus, which is calculated with a Gauss Seidel Power Flow.

Exhaustive Switch Configuration Search Algorithm:

- 1) Start the Min Loss Estimator Module.
- 2) Initialize a result table with the following in columns:
 1. Switch Status of SS and TS (u vectors)
 2. Estimated Real Power Loss
 3. Estimated Reactive Power Loss
- 3) Also initialize a display table with the following in columns
 1. Switch Status of SS and TS for base and best case configurations

Appendix I

Network Reconfiguration Experiment with Loss Optimization in Power RDAC

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Educational Objectives

The objective of this experiment is to gain hands-on experience on how to reduce real power losses using network reconfiguration.

Through this experiment user will learn to:

- a) Understand the need for network reconfiguration for load balancing and loss reduction in real life environment;
- b) Study how to schedule network reconfiguration for different loading conditions;
- c) Understand how to select and operate existing three- phase or single- phase switches to reconfigure network;
- d) Evaluate different network configurations with respect to loss minimization through offline minimum real power loss estimator incorporated in VB.

Introduction

In power distribution systems, loads may increase due to the installation of new customers and to the electricity demand shifts resulting from seasonal weather changes. Load increases not only cause higher power system losses but also may lead to overloads in electrical equipment, such as transformers and distribution lines, which may be dangerous and possibly reduce the equipment's lifespan. In order to reduce real power losses and relieve overload, network reconfiguration is performed.

Network reconfiguration is a process of changing the topological structure of distribution systems by opening and/or closing normally closed (sectionalizing) switches and normally open (tie) switches. It can considerably improve system operating conditions by transferring loads from more heavily loaded feeders to less heavily loaded ones. This transfer of loads is called load balancing. As a result, the real power losses might also be reduced. In addition, distribution systems are electrically unbalanced across phases (a, b, c), and it is known that unbalanced systems incur more losses than balanced systems. Hence network reconfiguration can also be performed to balance load across the three phases using single-phase switching. For the above reasons, electric power utilities plan for the installation of network switches and perform network reconfiguration to balance loads and reduce losses. Therefore, it is very important to gain practical experience as well as theoretical analysis skills on network reconfiguration, specifically planning and operation techniques.

Experimental Procedure

Warnings

The voltages and currents that are used during this lab may be much larger than you are used to working with in other Drexel laboratories. The voltage that will be used in this laboratory is 120 VAC Phase-to-Neutral (208 VAC Line-to-Line) voltage with currents as high as 10 amps (or higher if circuits are improperly connected!). Please take the proper precautions and use your head before touching any circuitry.

NEVER change any circuit connections while the power supply is turned on.

Please, wear goggles at all times in the laboratory!

In case of emergency, PUSH the Emergency Stop (Red button) on the power station.

It will shut down all the power on the four stations. DO NOT PULL the Emergency Stop.

Please, carefully follow the lab manual instructions step by step.

During this experiment, we will study and test network reconfiguration schemes in various networks and under different loading conditions with a combination of software (visual basic) and hardware activities.

Loads connected in the networks will be multi-phase loads in the forms of light bulbs; we note that these are “best” modeled as constant impedance (resistive) loads. During the experiment, we will vary:

- a) The numbers of light bulbs connected;
- b) The connection types of the load (single or multi-phase)
- c) The condition (open/close) of some sectionalizing as well as tie switches.

The location of sectionalizing and tie switches are fixed and will be provided.

We will be studying the distribution network shown below in Figure 1. The network can be configured as a 9-bus radial distribution system. It is supplied by 208VLL three-phase ac power from PECO Energy. For safety reasons, the power is fed to the 9-bus radial distribution system through a 1:1 autotransformer. The radial system has one feeder and one lateral with four three-phase lines. There are four three-phase sectionalizing switches embedded along the feeders, and four possible tie switches that can be connected between any two buses (with the exception of the feeder bus) through the transfer station for network reconfiguration (one shown in Figure 4). The switches are mimicked using 12 normally closed digital relays (a, b, c) for the four sectionalizing switches, and 16 normally open digital relays (for phases a, b, c, and neutral) for the four tie switches. At each bus, multi-phase resistive loads and three-phase capacitors can be connected as well as inductive loads. The RTU in the experiment is built on a PC with data acquisition, signal conditioning and digital control circuits.

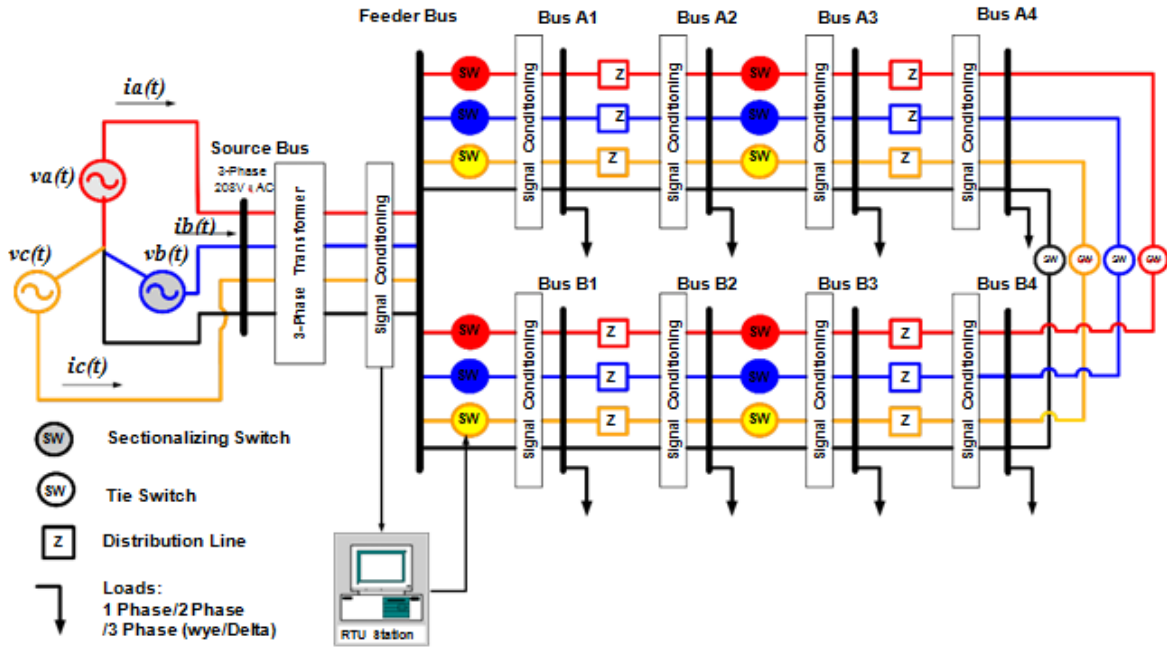


Figure 1. System Diagram for a Three-Phase Network Reconfiguration Experiment

The actual hardware setup of this experiment is shown in Figure 2. Before starting the lab please check the three-phase circuit (shown in Figure 2) at your station and be able to identify the following equipment/accessories:

- Remote Terminal Unit(RTU) computer with the experiment program running
- Power Station(120 Volts Sinusoidal Source)
- Three – Phase Auto Transformer
- Multi – Phase Distribution Line Feeder Box
- Transfer Station with 4 Tie Switches
- 1 Light Panel
- 1 PC Floppy Disk/USB Key Drive to save your experiment data

If you cannot identify any of the above equipment please ask your TA for assistance.

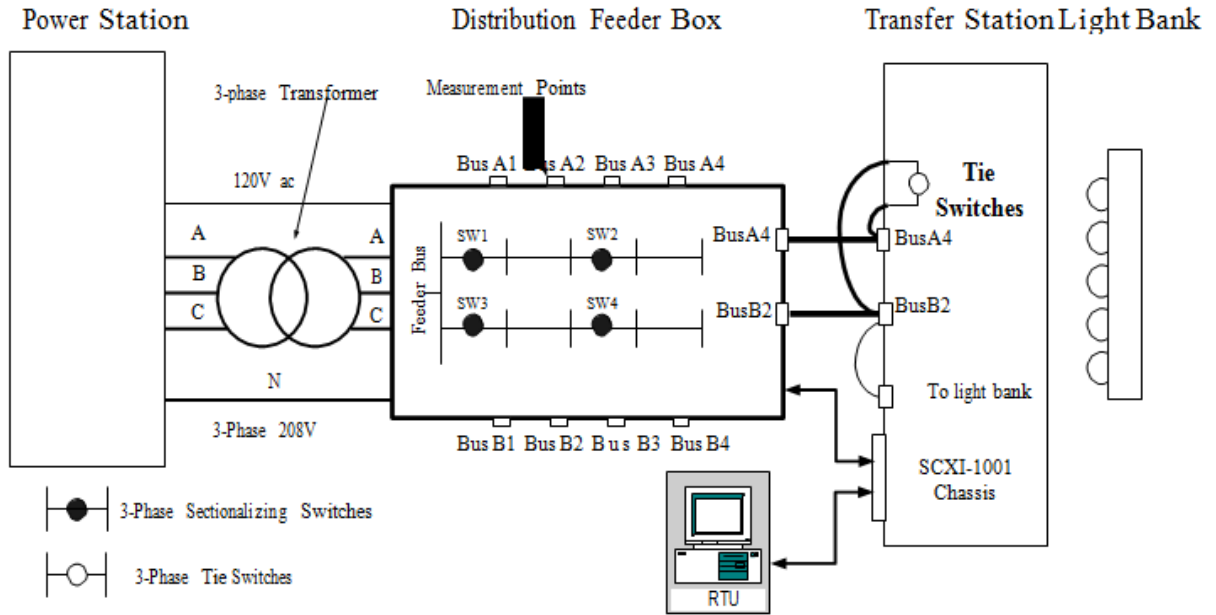


Figure 2. Example Hardware Setup for the Network Reconfiguration Experiment

Hardware Set-up

Step 0: Setup the circuit as shown in Figure 2. The details of the setup process can be seen in the Appendix. To save your time, the TAs might have already setup the hardware for the first part of the experiment, with the exception of the tie switches.

Step 1: Add the tie switches as indicated in Table 1 below.

Table 1. Tie Switch Locations for All Cases

Tie Switch	From Bus	To Bus
Tie 1	B1	A4
Tie 2	A2	B2
Tie 3	A3	B3
Tie 4	A4	B4

Step 2: The measurement connections are indicated in Table 2 below.

Table 2. Measurement Locations for Each Case

Measurement 1	Measurement 2	Measurement 3	Measurement 4
Feeder Bus	Bus A2	Bus B2	Bus B4

Experimental Procedure

Software Experiment

Step 1: Initialize the DMS Software

Step 1.a: Double click the RDAC icon on the desktop ;

Step 1.b: Select “Revised Network Reconfiguration” from the experiment list. Select the station number on which you are currently performing experiment (see Figure 3);

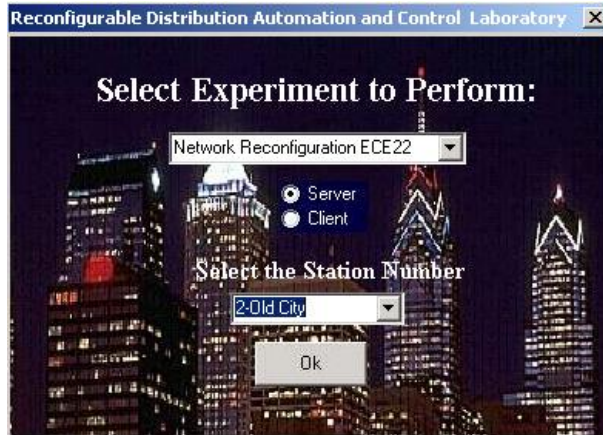


Figure 3. Station and Number Selection Screen

Step 1.c: On the load selection window, enter the number of loads on each bus, click on “Base Load” to get the initial load set up to be one load on each bus except bus A1 and B2; click on the “Restore All” button for restore and click on “save and continue” button for next step (see also Figure 4);

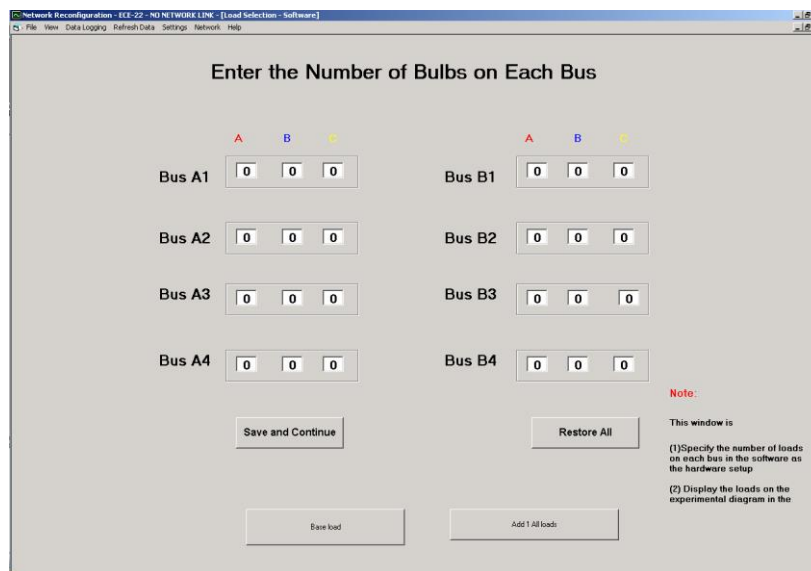


Figure 4. Load Number and Location Selection

Step 1.d: Select the measurement locations on the measurement selection window: Bus A4, Bus B2 and Bus B4 for measurement 2, 3 and 4 respectively for this part of the experiment. Note: measurement 1 is the reference and is already set as the Feeder Bus (see Figure 5);

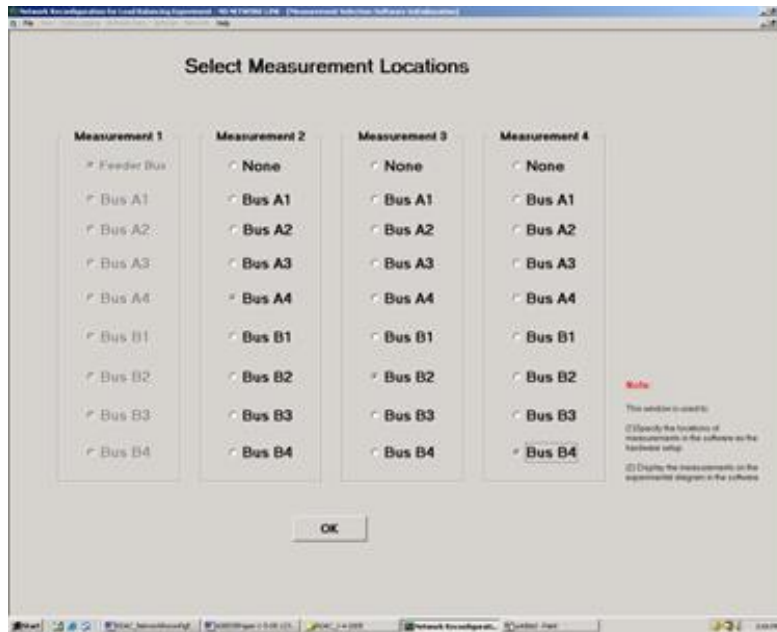


Figure 5. Measurement Bus Selection

Step 1.e: Select Tie Switch locations based on Figure 3, then press DONE (see Figure 6);

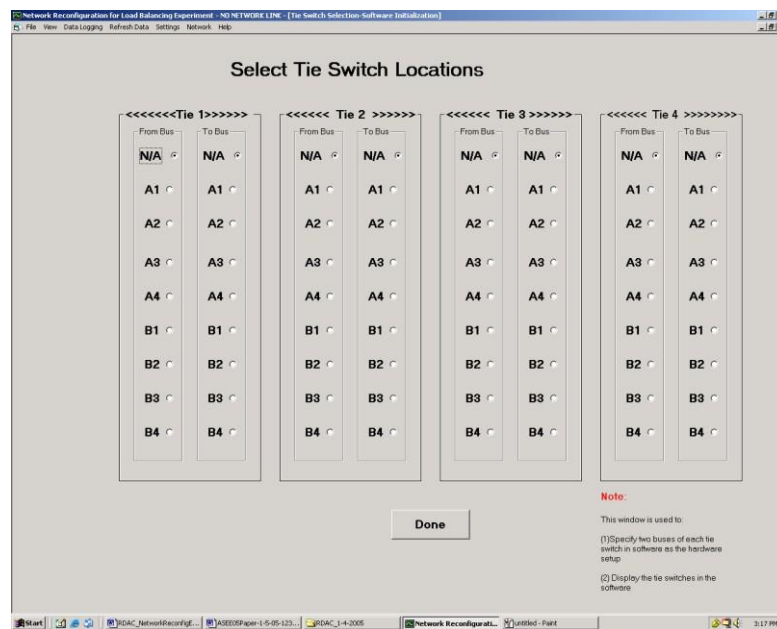


Figure 6. Tie Switch Location Selection

Step 1.f: The Network Reconfiguration Experiment program will be loaded in the DMS (see Figure 7).

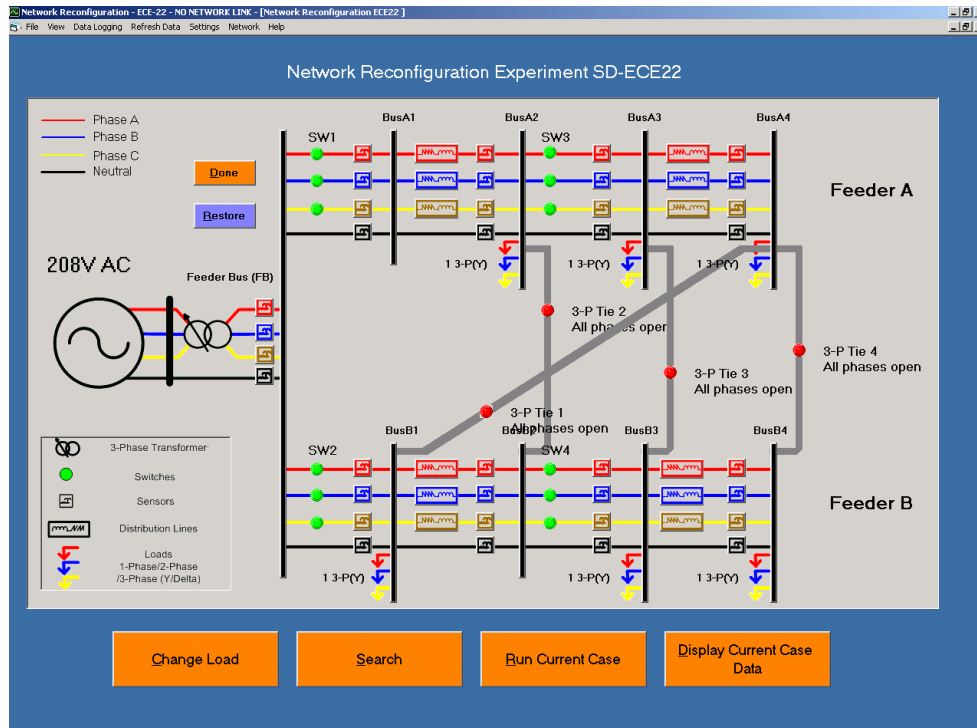


Figure 7. Network Reconfiguration Program Initialized

Step 2: Perform offline Metric Evaluation

Step 2.a: Click on the “Search” button on the main form; the metric main form will load up (see Figure 8);

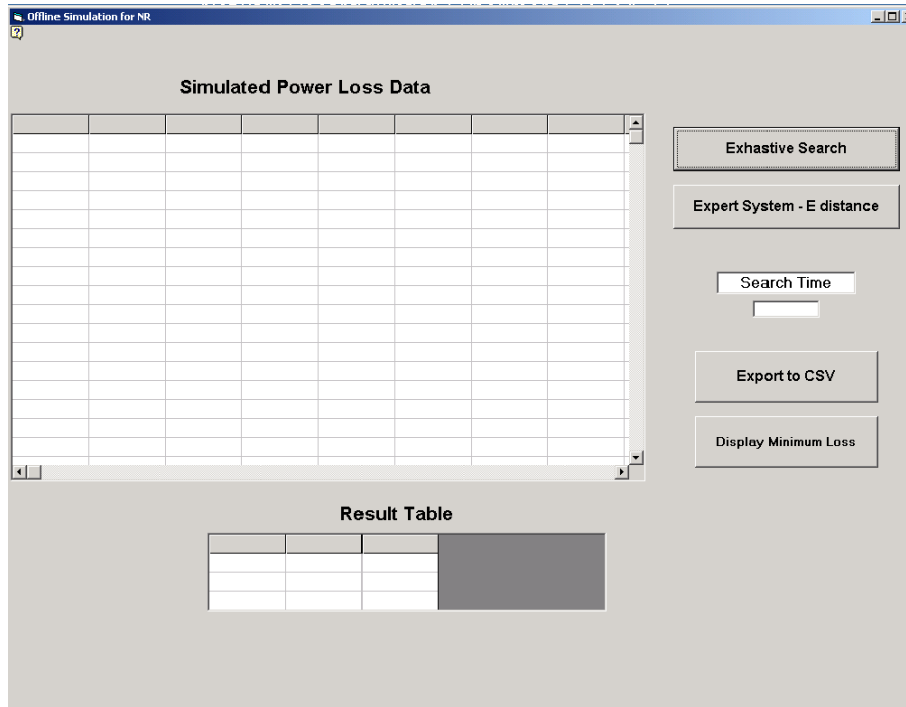


Figure 8. Metric Form User Interface

Step 2.b: Click on “Exhaustive Search” button, which performs loss estimation for each feasible switch configuration, data will be stored to “Simulated Power Loss Data” (see Figure 9);

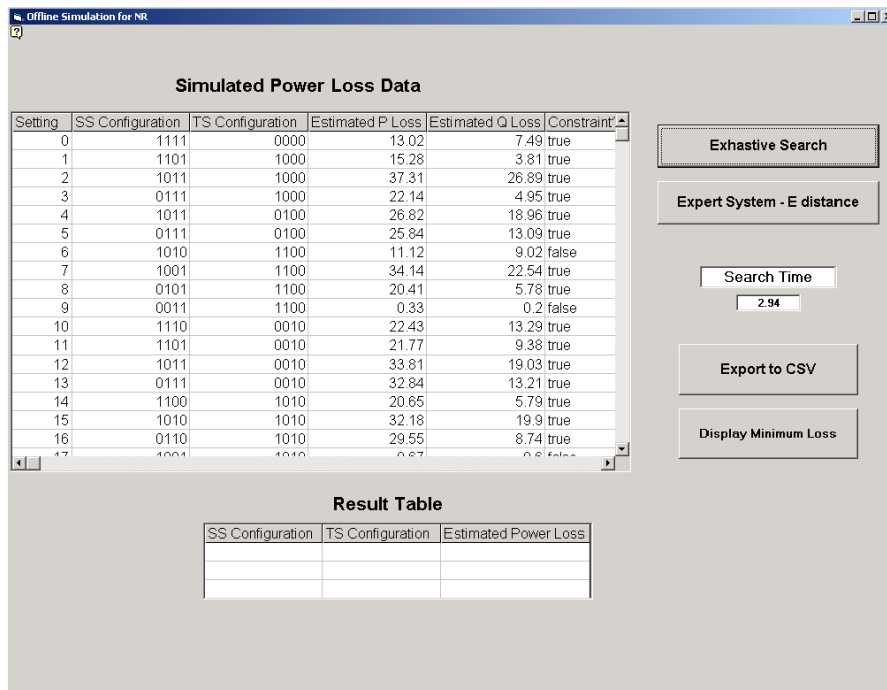


Figure 9. Offline Loss Estimation Screen

Step 2.c: Click on “Display Minimum Loss” button which pulls out the data of switch configuration with minimal real power loss and fills the “Result Table” (see Figure 10);

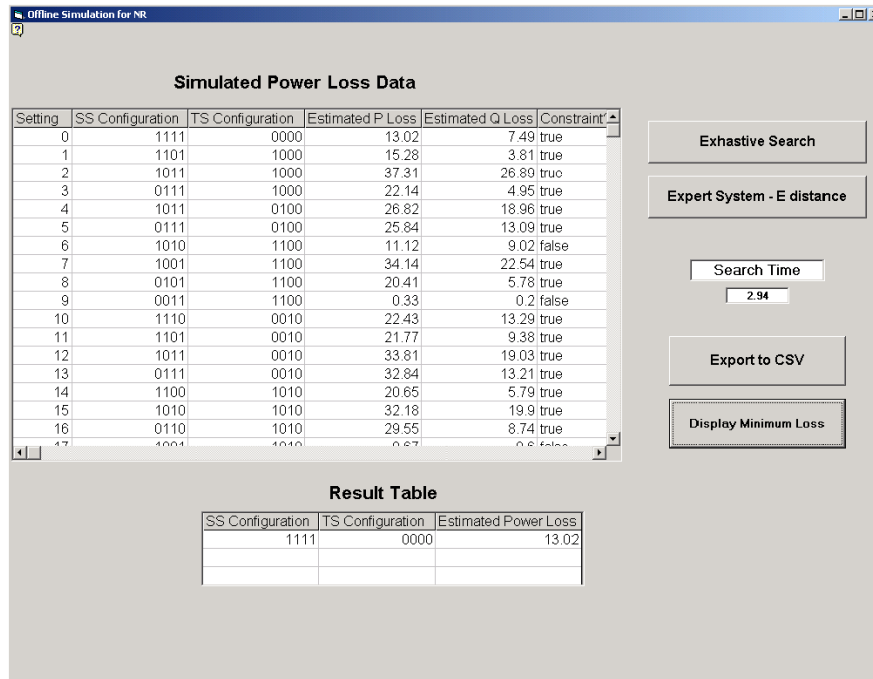


Figure 3. Optimal Switch Configuration shown at Minimal Power Loss

Step 2.d: Click on “Export to CSV” button to save data to desktop in .csv format;

Step 2.e: Click on “Expert System – E Distance” to perform expert system analysis (see Figure 11), record the switch configuration at minimum estimated metric;

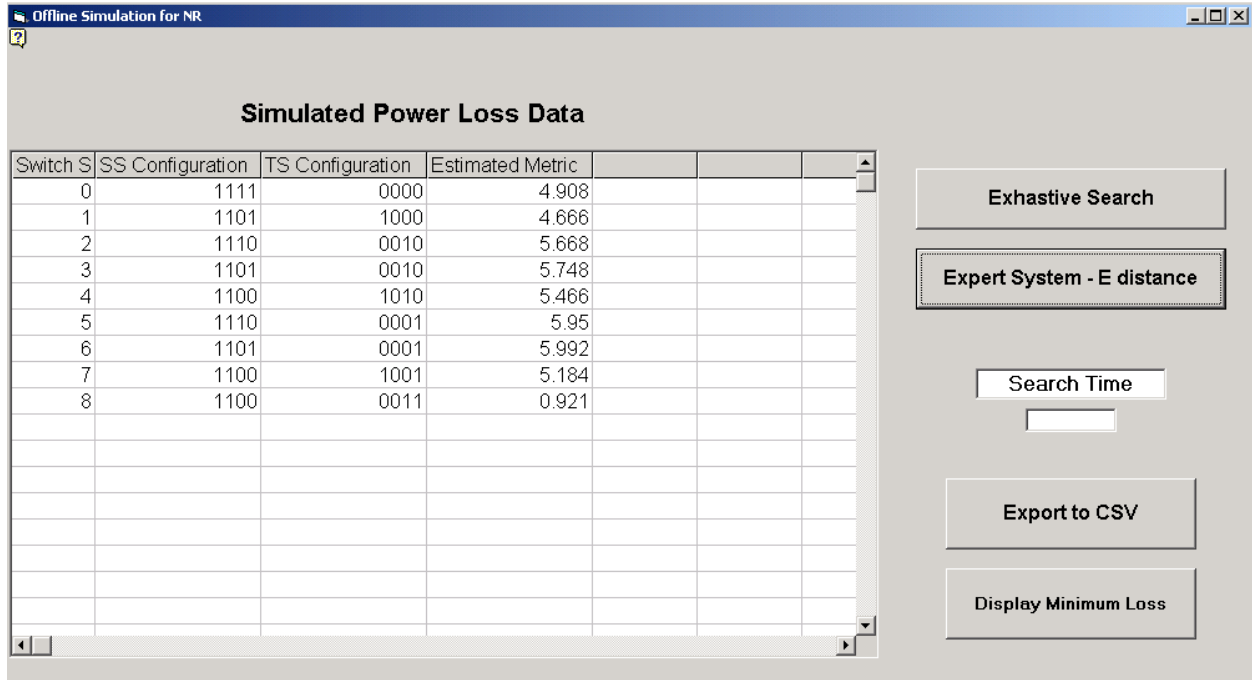


Figure 4. Expert System Analysis

Step 2.f: Click on “Change Load” and enter a new set of loading based on Table 1 below;

Table 3: Load Setting 2

Number of Bulbs per Phase on Each Bus			
Bus	Phase A	Phase B	Phase C
A2	1	1	1
A4	3	3	3
B3	1	1	1
B4	1	1	1

Step 2.g: Repeat Step 2.a through 2.e;

Step 2.h: Click on “Change Load” and enter a new set of loading based on Table 2 below;

Table 4: Load Setting 3

Number of Bulbs per Phase on Each Bus			
Bus	Phase A	Phase B	Phase C
A3	1	1	1
A4	1	1	1

Step 2.i: Repeat Step 2.a through 2.e;

Hardware Experiment

NOTE: For each case record the data for the original system so you will be able to compare original vs. reconfigured system.

Case 1: Three-Phase Switching for Network Reconfiguration

This case involves three different sub-cases each based upon differing load levels.

CASE 1.A – Balanced Load with Even Distribution of Loads

CASE 1.B – Balanced Load with High Back End Load

CASE 1.C – Balanced Load with Back End Load on One Branch

CASE 1.A – Balanced Load with Even Distribution of Loads

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.A.1: Make and check connections for the following loads to the system (the connections will remain in the same place for the remainder of this case):

- One Three-Phase **Y**-connected resistive/light bulb load (**3-I**) on **Bus A4**
- One Single-Phase (**A**) resistive/light bulb load (**1-I**) on **Bus A2**
- One Two-Phase (**BC**) resistive/light bulb load (**2-I**) on **Bus A2**
- One Single-Phase (**B**) resistive/light bulb load (**1-II**) on **Bus B2**
- One Two-Phase (**CA**) resistive/light bulb load (**2-II**) on **Bus B2**
- One Three-Phase **Y**-connected resistive/light bulb load (**3-II**) on **Bus B4**

(Please note: in this case, these load connections actually form one three-phase Y connected load on each bus.)

Step 1.A.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.A.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.A.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.A.5: Initialize the DMS Software

Step 1.A.5.a. Double click the RDAC icon on the desktop

Step 1.A.5.b. Select “**Network Reconfiguration**” from the experiment list. Select the station number on which you are currently performing experiment (See Figure 12)

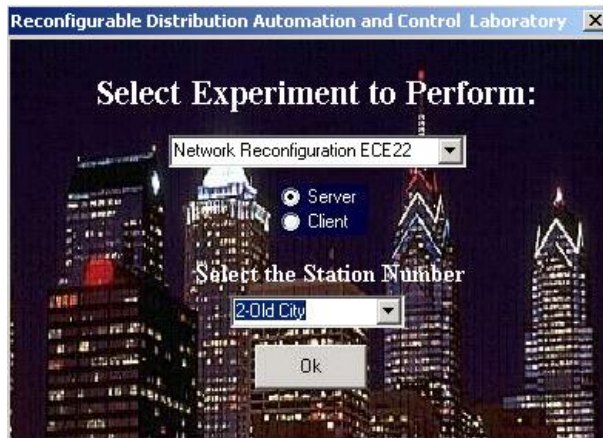


Figure 12. Station and Number Selection Screen

Step 1.A.5.c. On the load selection window, enter the number of loads connected to the on each bus. Refer to **Step 1.A.1** of the *Hardware Procedure* for the number and location of loads.

Step 1.A.5.d. On the measurement location window, input the measurement locations as given in the Hardware Set-up.

Step 1.A.5.e. The “Select Tie Switch Locations” window will now appear. At this point enter in the tie switch locations given in the Hardware Set-up. Then press DONE.

Step 1.A.5.f. The Network Reconfiguration Experiment program will be loaded in the DMS.

(Hardware/Software Interaction)

Step 1.A.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.A.7: Turn on the light bulbs on each phase according to the following table

Table 5. Load Settings for CASE 1.A for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	1	1	1
A2	1	1	1
B2	1	1	1
B4	1	1	1

Step 1.A.8: Turn on the SCXI-1001 chassis located below the station transfer panel.

Step 1.A.9: Switch the distribution feeder box input switch to setting “I” and then switch the power switch to the “ON” position

Step 1.A.10: *Slowly* turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.A.11: Click each phase of each distribution line and manually record the impedance.
Note: this date will remain the same for all cases.

Step 1.A.12: Using the measurements on main NR screen, obtain the voltage and current magnitude and phases at the Feeder bus. This will be used to calculate real power coming into the network

Step 1.A.13: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.A.14: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 6. Alternate Switch Configuration for CASE 1.A

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	0	1	1	0	0	0

(Hardware/Software Interaction)

Step 1.A.15: Repeat Steps 1.A.8 through 1.A.13 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.A.16: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

For the next portions of the laboratory, the tie switches will be in the same locations as in the initial hardware setup. The only things that will change in Cases 1.B and 1.C are the loads and

the alternate switch configuration. In each case, the base configuration (all sectionalizing switches closed and all tie switches open) will be tested first in order to have a baseline of comparison for the alternate switch configuration.

CASE 1.B – Balanced Load with High Back End Loads

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.B.1: Make and check connections for the following loads to the system (the connections will remain in the same place for the remainder of this case):

- One Three-Phase **Y**-connected resistive/light bulb load (**3-I**) on **Bus A4**
- One Single-Phase (**A**) resistive/light bulb load (**1-I**) on **Bus A2**
- One Two-Phase (**BC**) resistive/light bulb load (**2-I**) on **Bus A2**
- One Single-Phase (**B**) resistive/light bulb load (**1-II**) on **Bus B3**
- One Two-Phase (**CA**) resistive/light bulb load (**2-II**) on **Bus B3**
- One Three-Phase **Y**-connected resistive/light bulb load (**3-II**) on **Bus B4**

(Please note: in this case, these load connections actually form one three-phase Y connected load on each bus.)

Step 1.B.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.B.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.B.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.B.5: Initialize the DMS Software. (Use the same procedure as described in Case 1.A)

(Hardware/Software Interaction)

Step 1.B.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.B.7: Turn on the light bulbs on each phase according to the following table

Table 7. Load Settings for CASE 1.B for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	3	3	3
A2	1	1	1
B3	1	1	1
B4	1	1	1

Step 1.B.8: Slowly turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.B.9: Click each phase of each distribution line and manually record the impedance.
Note: this data will remain the same for all cases.

Step 1.B.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.B.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.B.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 8. Alternate Switch Configuration for CASE 1.B

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	0	1	1	0	0	0

(Hardware/Software Interaction)

Step 1.B.13: Repeat Steps 1.B.8 through 1.B.11 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.B.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

CASE 1.C – Balanced Load with Back End Load on One Branch

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.C.1: Make and check connections for the following loads to the system (the connections will remain in the same place for the remainder of this case):

- One Three-Phase **Y**-connected resistive/light bulb load (**3-I**) on **Bus A4**
- One Three-Phase **Y**-connected resistive/light bulb load (**3-II**) on **Bus A3**

(Please note: in this case, these load connections actually form one three-phase Y connected load on each bus.)

Step 1.C.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.C.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.C.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.C.5: Initialize the DMS Software. (Use the same procedure as described in Case 1.A)

(Hardware/Software Interaction)

Step 1.C.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.C.7: Turn on the light bulbs on each phase according to the following table

Table 9. Load Settings for CASE 1.C for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A3	1	1	1
A4	1	1	1

Step 1.C.8: *Slowly* turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.C.9: Click each phase of each distribution line and manually record the impedance.
Note: this date will remain the same for all cases.

Step 1.C.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.C.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.C.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 10. Alternate Switch Configuration for CASE 1.C

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	0	1	1	1	1	0	0	0

(Hardware/Software Interaction)

Step 1.C.13: Repeat Steps 1.C.8 through 1.C.11 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.C.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

Concluding Lab Activities for Hardware Experiment

Please check your data. If you feel there is a problem with your data file, consult with the TA and/or Professor.

- a) Calculate all voltages and line currents for the base case using the measured data and given line impedances. Also, estimate the total power loss.
- b) Calculate voltages, line currents, and power loss for the network reconfiguration case.
- c) Compare data from both cases with software data.
- d) Describe your observation in the experiment.

Appendix

Electric Hardware Setup

Step 1: Connect the power to the feeder box (See Figure 14)

Use three 100A cables to connect three phases on the power station to the transformer input port. Then, connect the transformer outputs to three single-phase connectors on side A (the front side close to the power station) of the distribution feeder box. Next, connect the neutral on the feeder box to the power station. The transformer's neutral **MUST** also be hooked up to the power station.

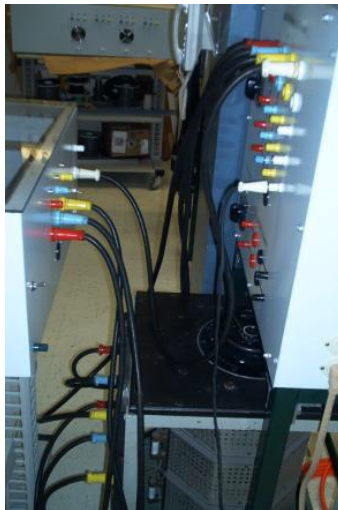


Figure 5. Power Station and Transformer Setup

On the front side of the feeder box, switch the “3-Phase Input Switch” toggle switch to “I” position (up). The power will be fed into the feeder through the three single-phase connectors.

Step 2: Connect the distribution feeder box and the transfer station (See Figure 15).

Jump “Bus X” on the feeder box to “Bus X” on the transfer station with a three-phase cable. X represents A1 to A4, and B1 to B4.



Figure 6. Wiring Connection on Bus B4 Between the Feeder Box and the Transfer Station

Step 3: Connect the loads to the distribution bus (See Figure 16)

On Transfer Station, there are four color binding posts under each bus. Color code-A: Red, B: Blue, C: Yellow: N: White.

- Single-phase resistive loads

Connect one phase (a, b, or c) & neutral on Bus X to the red, and white binding posts on resistive load 1-I/1-II. Connect neutral on Bus X to the white binding post on 1-I/1-II.

- Two-phase resistive loads

Connect two phases & neutral of Bus X to the red, blue, and white binding posts on resistive load 2-I/2-II

- Three--phase resistive loads

Connect three phase & neutral of Bus X to three-phase resistive load 3-I/3-II. Color code- A: Red, B: Blue, C: Yellow, N: White.



Figure 7. Wiring Connection for a 3-phase Resistive Load (3-I) on Bus B4

Wye connection (See Figure 17)

Connect the loads 3-I in Y connection on the light panel.



Figure 8. Resistive Loads and wye Wiring Connection

Measurement Hardware Setup

Step 1: On the front side of the distribution box, switch the “Power Switch” toggle switch to “On” position (up). It provides the power for the two fans and the dc power supply in the feeder box;

Step 2: With a measurement cable, hook up the connector with 22 pin on the cable to one of the nine measurement ports (from feeder bus to bus B4) on side D of the distribution box. The measurement cable has a SCXI-1327 voltage attenuator on it;

Step 3: Connect the SCXI-1327 to one of the four signal conditioning boards on the SCXI-1001 chassis that is under the transfer station;

Step 4: Turn on the power of SCXI-1001.

Appendix J

Drexel University

Electrical and Computer Engineering Dept.

A Hardware and Software Service Restoration Experiment for Maximum Power Delivered in Power Distribution Systems

Table of Contents

- Educational objectives
- Introduction
- Theory
- Procedure
- Concluding Activities
- Appendix

Educational objectives

The objective of this experiment is to gain experience with the different algorithms that may be used to determine the optimal switch configuration in a service restoration environment. Through this experiment, we will learn:

- Different types of search methods;
- Considerations into planning a distribution system;
- Evaluate advantages and disadvantages of various switch configurations;

Introduction

In power distribution systems, unexpected events cause customers to experience a power outage. The events include faults, maintenance, or other events. Ideally, network operators can reconfigure the network so that all loads are served, in minimal time. This is not always possible.

Service restoration is the process of changing the topological structure of a distribution system by opening and/or closing normally closed and normally open switches. Service restoration aims to minimize blackout time in a distribution system. Blackout time can have political, economic, and social effects on the population. Therefore, it is very important to gain practical experience as well as theoretical analysis skills on service restoration.

Theory

Problem Formulation

The problem in service restoration is finding the optimal switch configuration. The optimal switch configuration yields the greatest (or lowest) value of the objective function, while satisfying all constraints. Optimizing the objective function is expressed as follows

$$\text{Optimize } C(\mathbf{X}, u) \quad \text{Equation 1}$$

$u \in \mathbf{S}$

Where \mathbf{S} is the set of all possible switch configurations such that:

$$F(\mathbf{X}, u) = 0 \quad \text{Equation 2}$$

$$G(\mathbf{X}, u) \leq 0 \quad \text{Equation 3}$$

F is the set of non-linear power flow equations. G is the set of constraint equations. The variable u is a set of ones and zeros representing the statuses (open or closed) of all the tie and sectionalizing switches in the given network. Thus the topology of a network is uniquely determined by a given u vector.

$$u = [x_1, x_2, \dots, x_n] \quad x_i = \{0,1\}; \quad 1 < i \leq n, \text{ the number of switches} \quad \text{Equation 4}$$

There are 2^n unique u vectors for a system with n switches. The search space, \mathbf{S} 's rows are u vectors, and its columns are a list of the network's switches.

$$\mathbf{S} = \begin{bmatrix} u_1 \\ u_2 \\ \vdots \\ u_{2^{n-1}} \\ u_{2^n} \end{bmatrix} = \begin{bmatrix} 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & \dots & 0 & 1 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 1 & 1 & \dots & 1 & 0 \\ 1 & 1 & \dots & 1 & 1 \end{bmatrix} \quad \text{Equation 5}$$

To calculate the objective function, knowledge of the state of the system is needed. For a given load level, each u vector maps to a given state, denoted as \mathbf{X} . The state variable \mathbf{X} contains voltage magnitudes and phases at every bus in the system (except the slack bus). \mathbf{X} is a Φ by $2(i-1)$ matrix where Φ is the number of phases, and i is the number of buses.

$$\mathbf{X} = [|V_2|, \dots, |V_i|, \phi_2, \dots, \phi_i] \quad \text{Equation 6}$$

The voltage magnitudes for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$|V_i| = [|V_i^A|, |V_i^B|, |V_i^C|, |V_i^N|]^T \quad \text{Equation 7}$$

The voltage phase angles for each phase (A, B, C, and Neutral) at bus i are expressed by the vector

$$\phi_i = [\phi_i^A, \phi_i^B, \phi_i^C, \phi_i^N]^T \quad \text{Equation 8}$$

For service restoration, the objective function $C(\mathbf{X}, u)$ is defined as

$$C(\mathbf{X}, u) = \sum_{i=1}^{N_B} P_i^{bus}(\mathbf{X}, u) \quad \text{Equation 9}$$

This objective function is power delivered to the load. Another valid objective function would be number of loads restored (regardless of power consumption).

The first two equality constraints is that j unbalanced multi-phase power flow for each bus must be satisfied.

$$-P_i + \sum_{o=1}^N |V_i||V_o|(G_{io} \cos(\theta_{io}) + B_{io} \sin(\theta_{io})) = 0 \quad \text{Equation 100}$$

$$-Q_i + \sum_{o=1}^N |V_i||V_o|(G_{io} \sin(\theta_{io}) - B_{io} \cos(\theta_{io})) = 0 \quad \text{Equation 11}$$

The third equality constraint is that the structure of the network must be maintained. This restraint is in place to simplify over current protection schemes.

Inequality Constraints

- Current constraint

$$|I_k| \leq |I_k^{Max}|, \text{ for all branches } k \quad \text{Equation 1112}$$

- Voltage constraint

$$|V_i^{min}| \leq |V_i| \leq |V_i^{max}|, \text{ for all buses } i \quad \text{Equation 13}$$

Types of Searches

As seen in the problem formulation, the search space for service restoration is all of the possible switch configuration. Thus, the problem grows exponentially with the number of switches in the network. To find the optimal switch configuration, one must first develop a model. The model should include assumptions for line and switch impedances, a method of calculating the objective function, a way to quantify loading levels, etc. Once the model is created, it can be used to predict which switch configuration will likely be the optimal.

The most basic search is an exhaustive search. This type of search essentially considers every switch configuration, and uses the model to compute the objective function as well as checking constraints. This method will find the absolute maximum in the search space. However, the simulated maximum may not be the actual maximum—it depends on the accuracy of the model. The downside of an exhaustive search is the amount of time it takes.

Another type of search is an Expert System search. An expert system search seeks to mimic the actions of an expert in the field. An expert system may or may not use network information, such as the results of a power flow. An example of an expert system would be to only look at switch configurations that have all switches connected to feeders open.

The last type of search we will discuss is a heuristic. A heuristic search essentially uses a rule of thumb to reduce the search space. The rule is usually based on presently available information, such as the results

of a power flow. These results, such as branch current and bus voltages can be used to eliminate switch configurations that will not likely be the optimal configuration.

Current Capacity Heuristic

The software lab utilizes a heuristic that reduces the search time for a near optimal switch configuration. The heuristic makes the following assumptions:

- A power flow has been performed on the base case (All sectionalizing switches are closed, and all tie switches are open), and there have been no constraint violations.
- All switches, both sectionalizing and tie, have the same current rating.
- The location of the fault is known. (and therefore which sectionalizing switch must be opened)
- The tie switch configuration is known.
- Network characteristics:
 - a. Switch rating: 5 A_{rms}
 - b. Switch resistance/reactance: 0.4/0.1 ohms
 - c. Line resistance/reactance: 0.16/0.1 ohms
 - d. Light bulb resistance: 200 ohms. Multiple bulbs are connected in parallel.
 - e. Feeder voltage: 120 V_{RMS}

With the results of the base case power flow, the algorithm calculates the amount of current through each switch, and normalizes it to the switches rating. Thus, the switch usage is denoted by Γ , and its value is given by

$$\Gamma_n = \frac{I_{base,n}}{I_{rated,n}}$$

where n is the switch number, I_{rated} is the switch's current rating, and I_{base} is the current flowing through the switch for the base case. The next step of the algorithm is to use this information, along with the fault switch location, to determine which u vectors to ignore.

Procedure

Five different loading levels will be examined. Within the loading level, different sectionalizing switch will be assumed to be the fault.

Table 1. Load levels for service restoration experiment. Each load is a three phase balanced load. Each bulbs is a 200 ohm, constant impedance loads. Multiple bulbs at one bus are connected in parallel.

Load Level	A2	A4	B2	B4
	Number of Bulbs			
1	4	4	4	4
2	4	1	5	1
3	5	1	4	1
4	5	2	1	4
5	1	4	5	2

Software

Open the service restoration software experiment.



Figure 1. Experiment and Station Number Selection Screen

Tabulate the loads in the load level screen

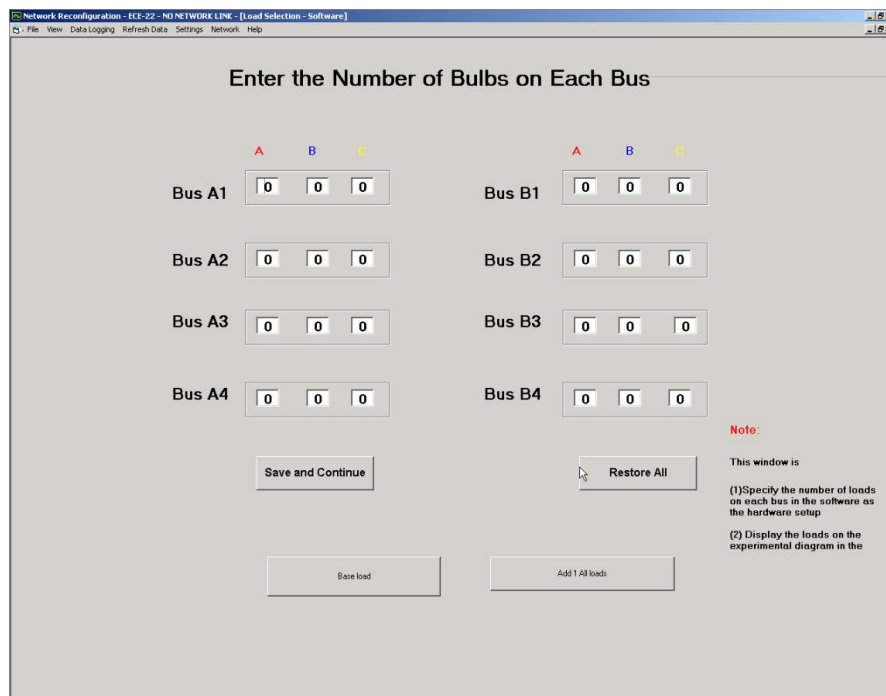


Figure 2. Load Level Screen

Run the base case simulation by clicking on the Run Current Case

Click on the search button to open the search GUI

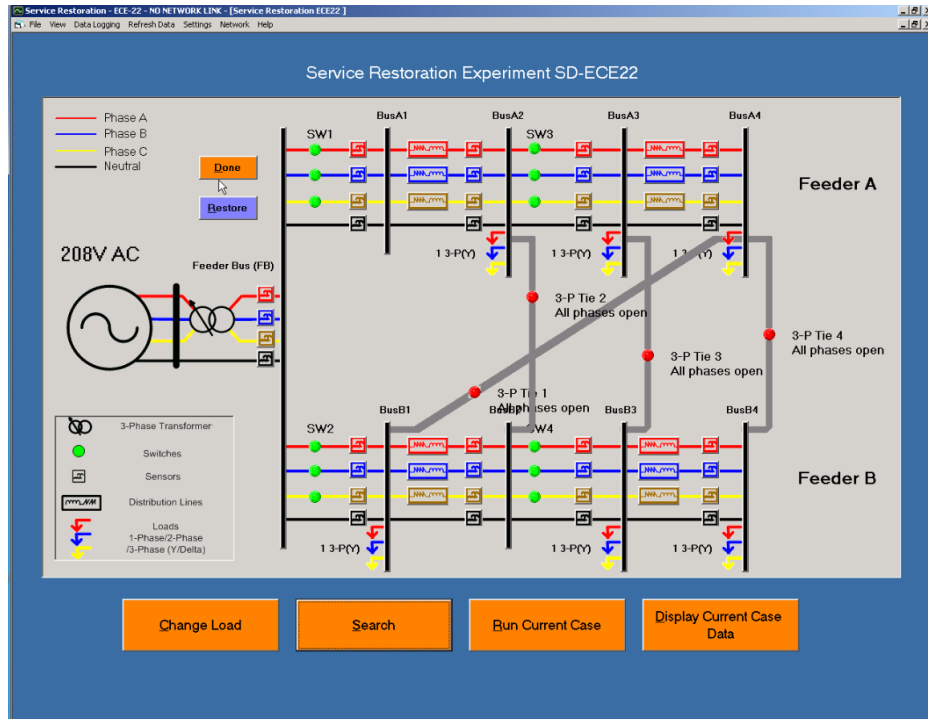


Figure 3. Main Screen for Service Restoration Experiment. Run Current Case and Display Current Case Data Buttons are on the bottom in orange.

Fill out the following table.

Load Level	Fault Switch	U vector	Max Power Delivered, W	Time Elapsed, s	Number of search elements	Type of Search
1	N/A	Base Case		N/A	N/A	N/A
	SS1					Exhaustive
	SS1					Heuristic
	SS2					Exhaustive
	SS2					Heuristic
	SS3					Exhaustive
	SS3					Heuristic
	SS4					Exhaustive
2	SS4					Heuristic
	N/A	Base Case		N/A	N/A	N/A
	SS1					Exhaustive
	SS1					Heuristic
	SS2					Exhaustive
3	SS2					Heuristic
	N/A	Base Case		N/A	N/A	N/A
	SS1					Exhaustive
	SS1					Heuristic
	SS2					Exhaustive
4	SS2					Heuristic
	N/A	Base Case		N/A	N/A	N/A
	SS3					Exhaustive
	SS3					Heuristic
	SS4					Exhaustive
5	SS4					Heuristic
	N/A	Base Case		N/A	N/A	N/A
	SS3					Exhaustive
	SS3					Heuristic
	SS4					Exhaustive
5	SS4					Heuristic

Hardware Procedure

In the hardware portion of the lab, the switch configurations predicted by the model, will be tested to check accuracy.

Warnings

The voltages and currents that are used during this lab may be much larger than you are used to working with in other Drexel laboratories. The voltage that will be used in this laboratory is 120 VAC Phase-to-Neutral (208 VAC Line-to-Line) voltage with currents as high as 10 amps (or higher if circuits are improperly connected!). Please take the proper precautions and use your head before touching any circuitry.

NEVER change any circuit connections while the power supply is turned on. Please, wear **goggles** at all times in the laboratory!

In case of emergency, PUSH the Emergency Stop (Red button) on the power station.

It will shut down all the power on the four stations. DO NOT PULL the Emergency Stop.

During this experiment, we will study and test network reconfiguration and service restoration schemes in various networks and under different loading conditions with a combination of software (visual basic) and hardware activities.

Loads connected in the networks will be three-phase loads in the forms of light bulbs. During the experiment, we will vary:

- a) The numbers of light bulbs connected
- b) The condition (open/close) of some sectionalizing as well as tie switches.

The location of sectionalizing and tie switches are fixed and will be provided.

We will be studying the distribution network shown below in Figure 1. The network can be configured as a 9-bus radial distribution system. It is supplied by 208VLL three-phase ac power from PECO Energy. For safety reasons, the power is fed to the 9-bus radial distribution system through a 1:1 autotransformer. The radial system has one feeder and one lateral with four three-phase lines. There are four three-phase sectionalizing switches embedded along the feeders, and four possible tie switches that can be connected between any two buses (with the exception of the feeder bus) through the transfer station for network reconfiguration (one shown in Figure 4). The switches are mimicked using 12 normally closed digital relays (a, b, c) for the four sectionalizing switches, and 16 normally open digital relays (for phases a, b, c, and neutral) for the four tie switches. At each bus, multi-phase resistive loads and three-phase capacitors can be connected as well as inductive loads. The RTU in the experiment is built on a PC with data acquisition, signal conditioning and digital control circuits.

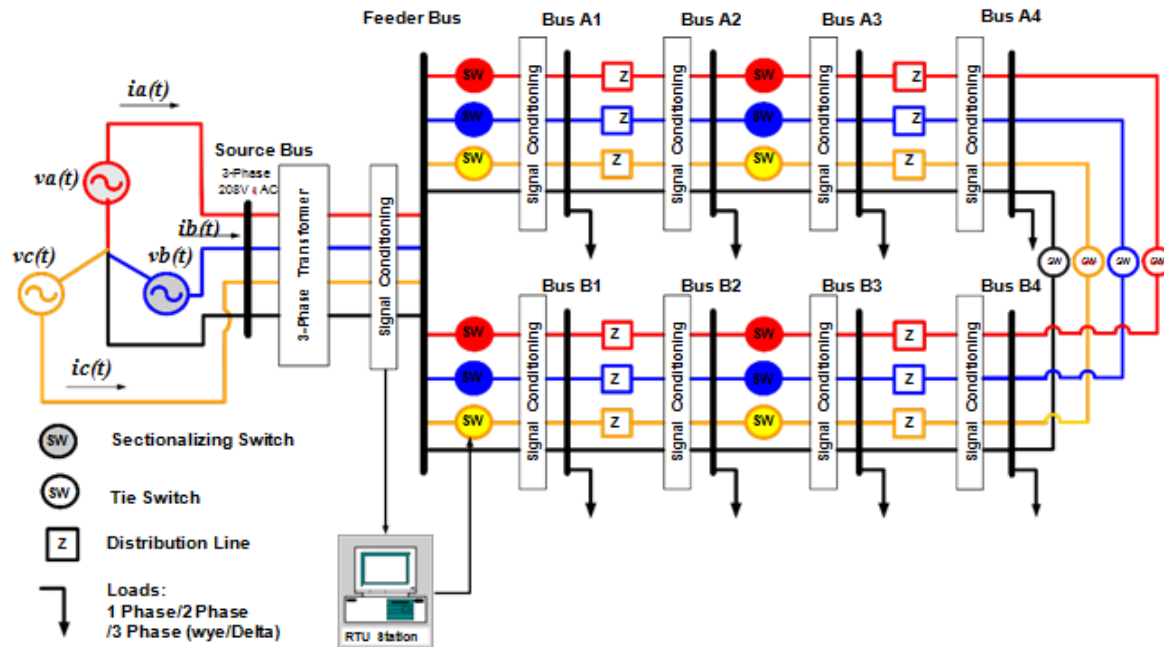


Figure 4. System Diagram for a Three-Phase Network Reconfiguration Experiment.

The actual hardware setup of this experiment is shown in Figure 2. Before starting the lab please check the three-phase circuit (shown in Figure 2) at your station and be able to identify the following equipment/accessories:

- Remote Terminal Unit (RTU) computer with the experiment program running
- Power Station (120 Volts Sinusoidal Source)
- Three-Phase Auto Transformer
- Multi-Phase Distribution Line Feeder Box
- Transfer Station with 4 Tie Switches
- 1 Light Panel
- 1 PC Floppy Disk/USB Key Drive to save your experiment data

If you cannot identify any of the above equipment please ask your TA for assistance.

Hardware Set-up

Step 0: Setup the circuit as shown in Figure 1. The details of the setup process can be seen in the Appendix. To save your time, the TAs might have already setup the hardware for the first part of the experiment, with the exception of the tie switches.

Step 1: Add the tie switches as indicated in Table 1 below.

Table 2. Tie Switch Locations for Each Case

Tie Switch	From Bus	To Bus
Tie 1	B1	A4
Tie 2	A2	B2
Tie 3	A3	B3
Tie 4	A4	B4

Step 2: The measurement connections are indicated in Table 2 below.

Table 3. Measurement Locations for Each Case

Measurement 1	Measurement 2	Measurement 3	Measurement 4
Feeder Bus	Bus A2	Bus B2	Bus B4

EXPERIMENTAL PROCEDURE

NOTE: For each case record the data for the original system so you will be able to compare original vs. reconfigured system.

Case 1: Three-Phase Switching for Service Restoration. This case involves three different sub-cases each based upon differing load levels.

CASE 1.A – Balanced Load with High Evenly Distributed Loading

CASE 1.B – Balanced Load with High Front End Loading (Version 1)

CASE 1.C – Balanced Load with High Front End Loading (Version 2)

CASE 1.D – Balanced Load with High Back End Loading on One Branch (Version 1)

CASE 1.E – Balanced Load with High Back End Loading on One Branch (Version 2)

CASE 1.A – Balanced Load with High Evenly Distributed Loading

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration for SR (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

Step 1.A.1: Make and check connections for the following loads to the system (these connections are the same as in Step 1.A.1 and the connections will remain in the same place for the remainder of this case):

Step 1.A.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.A.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.A.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.A.5: Initialize the DMS Software

Step 1.A.5.a. Double click the RDAC icon on the desktop

Step 1.A.5.b. Select “**Network Reconfiguration**” from the experiment list. Select the station number on which you are currently performing experiment (See Figure 3)



Figure 5. Station and Number Selection Screen

Step 1.A.5.c. On the load selection window, enter the number of loads connected to the on each bus. Refer to **Step 1.A.1** of the *Hardware Procedure* for the number and location of loads.

Step 1.A.5.d. On the measurement location window, input the measurement locations as given in the Hardware Set-up.

Step 1.A.5.e. The “Select Tie Switch Locations” window will now appear. At this point enter in the tie switch locations given in the Hardware Set-up. Then press DONE.

Step 1.A.5.f. The Network Reconfiguration Experiment program will be loaded in the DMS.

(Hardware/Software Interaction)

Step 1.A.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.A.7: Turn on the light bulbs on each phase according to the following table

Table 7. Load Settings for CASE 1.C for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	4	4	4
A2	4	4	4
B2	4	4	4
B4	4	4	4

Step 1.A.8: Slowly turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.A.9: Click each phase of each distribution line and manually record the impedance. *Note: this date will remain the same for all cases.*

Step 1.A.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.A.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.A.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 8. First Alternate Switch Configuration for CASE 1.C

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	1	0	0	0	0	0

(Hardware/Software Interaction)

Step 1.A.13: Repeat Steps 1.A.8 through 1.A.11 to test the first alternate switch configuration and record the data.

Step 1.A.14: Repeat Steps 1.A.8 through 1.A.12 to test the second alternate switch configuration and record the data. The loading will remain the same and but the new switch configuration can be seen in the table below.

Table 9. Second Alternate Switch Configuration for CASE 1.C

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	0	1	0	0	0	0

After recording data, hit “**Restore**” button to open all tie switches and close all sectionalizing switches.

Step 1.A.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

CASE 1.B – Balanced Load with High Front End Loading (Version 1)

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration for SR (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.B.1: Make and check connections for the following loads to the system (the connections will remain in the same place for the remainder of this case):

- One Three-Phase **Y**-connected resistive/light bulb load (**3-I**) on **Bus A4**
- One Single-Phase (**A**) resistive/light bulb load (**1-I**) on **Bus A2**
- One Two-Phase (**BC**) resistive/light bulb load (**2-I**) on **Bus A2**
- One Single-Phase (**B**) resistive/light bulb load (**1-II**) on **Bus B2**
- One Two-Phase (**CA**) resistive/light bulb load (**2-II**) on **Bus B2**
- One Three-Phase **Y**-connected resistive/light bulb load (**3-II**) on **Bus B4**

(Please note: in this case, these load connections actually form one three-phase Y connected load on each bus.)

Step 1.B.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.B.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.B.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.B.5: Initialize the DMS software. (See step 1.A.5)

Step 1.B.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.B.7: Turn on the light bulbs on each phase according to the following table

Table 4. Load Settings for CASE 1.A for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	1	1	1
A2	4	4	4
B2	5	5	5
B4	1	1	1

Step 1.B.8: Turn on the SCXI-1001 chassis located below the station transfer panel.

Step 1.B.9: Switch the distribution feeder box input switch to setting “I” and then switch the power switch to the “ON” position

Step 1.B.10: *Slowly* turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.B.11: Click each phase of each distribution line and manually record the impedance. *Note: this date will remain the same for all cases.*

Step 1.B.12: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.B.13: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.B.14: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 5. Alternate Switch Configuration for CASE 1.B

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	0	1	0	1	1	0	0	0

(Hardware/Software Interaction)

Step 1.B.15: Repeat Steps 1.B.8 through 1.B.13 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.B.16: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

For the next portions of the laboratory, the tie switches will be in the same locations as in the initial hardware setup. The only things that will change in Cases 1.B, 1.C, 1.D, and 1.E are the loads and the alternate switch configuration. In each case, the base configuration (all sectionalizing switches closed and all tie switches open) will be tested first in order to have a baseline of comparison for the alternate switch configuration.

CASE 1.C – Balanced Load with High Front End Loading (Version 2)

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration for SR (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.C.1: Make and check connections for the following loads to the system (these connections are the same as in Step 1.A.1 and the connections will remain in the same place for the remainder of this case):

Step 1.C.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.C.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.C.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.C.5: Initialize the DMS Software. (Use the same procedure as described in Case 1.A)

(Hardware/Software Interaction)

Step 1.C.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.C.7: Turn on the light bulbs on each phase according to the following table

Table 6. Load Settings for CASE 1.C for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	1	1	1
A2	5	5	5
B2	4	4	4
B4	1	1	1

Step 1.C.8: Slowly turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.C.9: Click each phase of each distribution line and manually record the impedance. *Note: this data will remain the same for all cases.*

Step 1.C.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.C.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.C.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 7. Alternate Switch Configuration for CASE 1.C

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	0	0	1	0	0	0	1

(Hardware/Software Interaction)

Step 1.C.13: Repeat Steps 1.C.8 through 1.C.11 to test the alternate switch configuration and record the data.

After recording data, hit "Restore" button to open all tie switches and close all sectionalizing switches.

Step 1.C.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

CASE 1.D – Balanced Load with Back End Load on One Branch (Version 1)

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration for SR (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.D.1: Make and check connections for the following loads to the system (these connections are the same as in Step 1.A.1 and the connections will remain in the same place for the remainder of this case):

Step 1.D.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.D.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.D.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.D.5: Initialize the DMS Software. (Use the same procedure as described in Case 1.A)

(Hardware/Software Interaction)

Step 1.D.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.D.7: Turn on the light bulbs on each phase according to the following table

Table 10. Load Settings for CASE 1.D for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	2	2	2
A2	5	5	5
B2	1	1	1
B4	4	4	4

Step 1.D.8: *Slowly* turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.D.9: Click each phase of each distribution line and manually record the impedance. *Note: this data will remain the same for all cases.*

Step 1.D.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.D.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.D.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 11. Alternate Switch Configuration for CASE 1.D

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	0	0	1	0	0	1

(Hardware/Software Interaction)

Step 1.D.13: Repeat Steps 1.C.8 through 1.C.11 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.D.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

CASE 1.E – Balanced Load with Back End Load on One Branch (Version 2)

In this part of the laboratory, we will first run the *original* network configurations (all sectionalizing switches closed and all ties switches open) and record the required data. Then, we will test the predicted best case network configuration for SR (from the exhaustive or expert/heuristic simulation) by closing/opening the determined switches.

(Hardware Procedure)

Step 1.E.1: Make and check connections for the following loads to the system (these connections are the same as in Step 1.A.1 and the connections will remain in the same place for the remainder of this case):

Step 1.E.2: Ensure the connections for the **four** measurement ports to signal conditioning boards 1 to 4 respectively using measurement cables. These measurement locations were given in the Hardware Set-up.

Step 1.E.3: Ensure the connections for the **four** ties switches are properly connected as indicated in the Hardware Set-up.

Step 1.E.4: Have the TA double check your circuit before proceeding further.

(Software Procedure)

Step 1.E.5: Initialize the DMS Software. (Use the same procedure as described in Case 1.A)

(Hardware/Software Interaction)

Step 1.E.6: Turn on the power by turning the AC switch located on the Power Station to the ON position (the green light should now be illuminated).

Step 1.E.7: Turn on the light bulbs on each phase according to the following table

Table 12. Load Settings for CASE 1.E for Network Reconfiguration Experiment

# of light bulbs per phase on loaded buses			
Bus	Phase A	Phase B	Phase C
A4	4	4	4
A2	1	1	1
B2	5	5	5
B4	2	2	2

Step 1.E.8: *Slowly* turn up the auto-transformer until the voltage magnitude at the Feeder Bus is approximately 120V.

Step 1.C.9: Click each phase of each distribution line and manually record the impedance. *Note: this date will remain the same for all cases.*

Step 1.E.10: Using a fluke obtain the real power into the distribution network by taking a measurement at the Feeder Bus.

Step 1.E.11: Using a voltage probe, obtain the voltage magnitude at each of the loaded buses from along the side of the distribution line feeder box.

Now you will test an alternate network configuration.

(Software Procedure)

Step 1.E.12: In the main screen of the DMS, open and close switches as desired by double clicking on the LEDs. The desired switch configuration can be seen in the table below (a 1 indicates the switch is closed and a 0 indicates the switch is open).

Note: a green LED represents a closed switch, a red LED an open switch. Also, for tie switches, a pop-up window will appear which will allow you to click and operate the LEDs. (For 3-P switching, please make sure to click on each phase abc).

This will not only show the new network configuration on the screen, but it will remotely open/close the relays changing the actual hardware setup.

Table 13. Alternate Switch Configuration for CASE 1.E

Switch	SS1	SS2	SS3	SS4	TS1	TS2	TS3	TS4
State	1	1	0	1	0	0	0	0

(Hardware/Software Interaction)

Step 1.E.13: Repeat Steps 1.C.8 through 1.C.11 to test the alternate switch configuration and record the data.

After recording data, hit “Restore” button to open all tie switches and close all sectionalizing switches.

Step 1.E.14: Turn down the auto-transformer to zero. Then turn off the power (you do not need to exit the software).

Concluding Activities and Lab Report Requirements

Software

1. Consider the first loading level. For each of the different fault switch settings was the load restored? Why not? What constraint prevented the load from being restored? Is there another tie switch configuration that could have been employed to restore the load?
2. Consider loading levels two and three. What constraint failed? Should different switches have different current ratings? What does this depend upon?
3. Consider the last two loading levels. How could a different objective function affect the results of the search? Of the two objective functions discussed in the theory, is one superior?
4. Did the heuristic always achieve the same result as the exhaustive search?
5. The heuristic used line current information. Formulate a heuristic that uses bus voltage magnitude to make a decision.

Hardware

1. Compute all bus voltages and line currents.
2. For each case, compute the objective function and compare to software? Do they match? What are the sources of error? How could the software model be improved?

Appendix

Electric Hardware Setup

Step 1: Connect the power to the feeder box (See Figure 14)

Use three 100A cables to connect three phases on the power station to the transformer input port. Then, connect the transformer outputs to three single-phase connectors on side A (the front side close to the power station) of the distribution feeder box. Next, connect the neutral on the feeder box to the power station. The transformer’s neutral **MUST** also be hooked up to the power station.

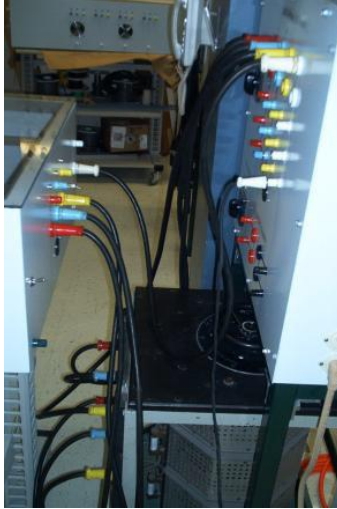


Figure 6. Power Station and Transformer Setup

On the front side of the feeder box, switch the “3-Phase Input Switch” toggle switch to “I” position (up). The power will be fed into the feeder through the three single-phase connectors.

Step 2: Connect the distribution feeder box and the transfer station (See Figure 15).

Jump “Bus X” on the feeder box to “Bus X” on the transfer station with a three- phase cable. X represents A1 to A4, and B1 to B4.



Figure 7. Wiring Connection on Bus B4 Between the Feeder Box and the Transfer Station

Step 3: Connect the loads to the distribution bus (See Figure 16)

On Transfer Station, there are four color binding posts under each bus. Color code-A: Red, B: Blue, C: Yellow: N: White.

- Single-phase resistive loads

Connect one phase (a, b, or c) & neutral on Bus X to the red, and white binding posts on resistive load 1-I/1-II. Connect neutral on Bus X to the white binding post on 1-I/1-II.

- Two-phase resistive loads

Connect two phases & neutral of Bus X to the red, blue, and white binding posts on resistive load 2-I/2-II

- Three--phase resistive loads

Connect three phase & neutral of Bus X to three-phase resistive load 3-I/3-II. Color code- A: Red, B: Blue, C: Yellow, N: White.



Figure 8. Wiring Connection for a 3-phase Resistive Load (3-I) on Bus B4

Wye connection (See Figure 17)

Connect the loads 3-I in Y connection on the light panel.



Figure 9. Resistive Loads and wye Wiring Connection

Measurement Hardware Setup

- Step 1:** On the front side of the distribution box, switch the “Power Switch” toggle switch to “On” position (up). It provides the power for the two fans and the dc power supply in the feeder box;
- Step 2:** With a measurement cable, hook up the connector with 22 pin on the cable to one of the nine measurement ports (from feeder bus to bus B4) on side D of the distribution box. The measurement cable has a SCXI-1327 voltage attenuator on it;
- Step 3:** Connect the SCXI-1327 to one of the four signal conditioning boards on the SCXI-1001 chassis that is under the transfer station;
- Step 4:** Turn on the power of SCXI-1001.