# Simulation of the York University Keele Campus Microgrid in PSS/E

## An Analysis of the K1 Feeder

Ariel Laboriante, Linda Chigbo, Manraj Chauhan, Nudrat Chaudhry
Electrical Engineering Department
York University
Toronto, Canada
ariel.laboriante@gmail.com
mslindie@my.yorku.ca
manraj15@my.yorku.ca
nidia072@my.yorku.ca

***Abstract*—In an ideal power network, all energy supplied by the source is consumed by the load. However, a unity power factor is practically impossible to achieve. Reactive power is almost always present and the variation in power factor is caused by many factors such as loading conditions, harmonics, and capacitive or inductive components that generate or consume reactive power. Poor power quality results in higher currents drawn from the grid which leads to voltage instability, reduced loading capacity, and higher transmission costs. In this study, the K1 feeder from the York University Keele Campus is analyzed and simulated using PSS/E. The impact of loading conditions and power factor on the system is also explored using the software's power flow analysis. Lastly, the economic feasibility of a shunt capacitor is examined and a solution is implemented to improve the K1 feeder's power factor from 0.85 to 0.95.**

***Keywords—power factor, power flow analysis, PSS/E, switched shunt capacitor, transmission lines***

## I. INTRODUCTION

The objective of this project is to simulate the K1 feeder from the Keele Substation. The team was provided with the K1 system data, a campus single-line diagram, and a tunnel map for underground cables. The first task was to determine the missing data. The data calculations are explained in the next few sections. After obtaining all of the missing parameters, the feeder was simulated in PSS/E and power flow reports were generated. The power flow and subsystem summary reports were analyzed for voltage, voltage angle, current, power flow, injected power from generation and system losses. The simulations were performed for different loading conditions and for different power factor values. After reviewing the results, it was determined where in the system a shunt capacitor can be added to improve the power factor. The type of shunt capacitor determined the cost of installation. The last section analyzes the expenses, the long-term benefits, and the cost-effectiveness of installing a shunt capacitor.

## II. TOOLS

### *A. PSS/E*

PSS/E by Siemens (or Power System Simulator for Engineering) is a software tool used around the world by students, engineers, and research labs. It allows users to simulate circuits of buildings with a variety of components such as generators, loads, transformers, and buses. The software can generate different reports which can be used to do power flow analysis, short circuit analysis, power flow, transient stability, and other simulations. For power flow analyses, the animation of the power flow can be simulated as well. PSS/E performs the Newton-Raphson method on circuits. The reports can be generated to find voltage magnitudes, currents, angles, real and reactive powers, fault-detections, and powers losses.

### *B. Newton-Raphson Method*

The Newton-Raphson method is a powerful technique for solving equations numerically. It is based on the simple idea of linear approximation similar to differential calculus. For the Newton-Raphson method, a Taylor series expansion can be done for a function of two or more variables.

It starts with the initial estimation of all unknown variables. A Taylor series is written for each of the power balance equations ignoring higher-order terms. The steps are as follows:

1. For each guess of $\widehat{x}$, $x^{(v)}$, define:

$$\Delta x^{(v)} = \widehat{x} - x^{(v)} \tag{1}$$

2. Represent $f(\widehat{x})$ by a Taylor series about $f(x)$.

$$f(\widehat{x}) = f(x^{(v)}) + \frac{df(x^{(v)})}{dx}\Delta x^{(v)} + \frac{1}{2}\frac{d^2 f(x^{(v)})}{dx^2}(\Delta x^{(v)})^2 + \ldots \tag{2}$$

3. Approximate $f(\widehat{x})$ by neglecting all terms except the first two.

$$f(\widehat{x}) = 0 \approx f(x^{(v)}) + \frac{df(x^{(v)})}{dx}\Delta x^{(v)} \tag{3}$$

4. Use this linear approximation to solve for $\Delta x^{(v)}$:

$$\Delta x^{(v)} = -\left[\frac{df(x^{(v)})}{dx}\right]^{-1} f(x^{(v)}) \tag{4}$$

5. Solve for a new estimate of $\widehat{x}$:

$$x^{(v+1)} = x^{(v)} + \Delta x^{(v)} \tag{5}$$

The solution is in the following form:

$$\Delta x = -J(x)^{-1} f(x) \tag{6}$$

$$x^{(v+1)} = x^{(v)} + \Delta x^{(v)} \tag{7}$$

$$x^{(v+1)} = x^{(v)} - J(x^{(v)})^{-1} f(x^{(v)}) \tag{8}$$

The process must be iterated until $|f(x^{(v)})| < \varepsilon$ is reached. Here, J(x) is the Jacobian Matrix. It can be solved as follows:

$$\mathbf{J(x)} = \begin{bmatrix} \frac{\partial f_1(\mathbf{x})}{\partial x_1} & \frac{\partial f_1(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_1(\mathbf{x})}{\partial x_n} \\ \frac{\partial f_2(\mathbf{x})}{\partial x_1} & \frac{\partial f_2(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_2(\mathbf{x})}{\partial x_n} \\ \vdots & \ddots & \ddots & \vdots \\ \frac{\partial f_n(\mathbf{x})}{\partial x_1} & \frac{\partial f_n(\mathbf{x})}{\partial x_2} & \cdots & \frac{\partial f_n(\mathbf{x})}{\partial x_n} \end{bmatrix} \tag{9}$$

To summarize, the process continues until a stopping condition is met. A common stopping condition is determined to terminate if the norm of the mismatch equations is below specified tolerance.

## III. DATA FOR POWER FLOW SIMULATION

The students were provided with the following resources: a single line diagram for the York University Campus, a single line diagram for the K1 feeder, a campus tunnel map, and initial data for buses, line and transformers. It was necessary to perform the calculations described in this section to determine the missing data. The following information was given: bus to bus connections, bus types, load locations, rated voltage at each bus, and the rated power and per-unit impedance for each transformer. The team calculated values for the following parameters: active and reactive power (P & Q) for each load bus, length of the transmission lines (L), transmission line reactive and resistive values (R & X), and transformer reactive and resistive values (R & X).

### *A. Transmission Line Calculations*

TABLE I. K1 Feeder Transmission Line Impedances

| Name | From | To | R (ohm) | X (ohm) |
|---|---|---|---|---|
| K114 | B354A | B355A | 0.00992 | 0.00937 |
| K115 | B354A | B361A | 0.02126 | 0.02008 |
| K193 | B361A | B441A | 0.01417 | 0.01339 |
| K191 | B366A | B355A | 0.00425 | 0.00402 |
| K117 | B368A | B378A | 0.00850 | 0.00803 |
| K116 | B373A | B354A | 0.00567 | 0.00535 |
| K140 | B373A | B367A | 0.00496 | 0.00468 |
| K128 | B386A | K1-3 | 0.00354 | 0.00335 |
| K139 | B386A | B347A | 0.00709 | 0.00669 |
| K141 | B404B | B355A | 0.00496 | 0.00468 |
| K101 | K1-0 | K1-1 | 0.02339 | 0.02209 |
| K129 | K1-0 | Keele Bus2 | 0.00354 | 0.00335 |
| K181 | K1-0 | KOHLFDR1 | 0.00354 | 0.00335 |
| K102 | K1-1 | B355A | 0.01913 | 0.01807 |
| K104 | K1-1 | B352A | 0.00496 | 0.00468 |
| K103 | K1-2 | B352A | 0.00496 | 0.00468 |
| K118 | K1-2 | B368A | 0.00496 | 0.00468 |
| K119 | K1-2 | B353A | 0.00567 | 0.00535 |
| K127 | K1-3 | B361A | 0.01417 | 0.01339 |
| K182 | KOHLFDR1 | OHLB1 | 0.00354 | 0.00335 |
| K183 | OHLB1 | B487H | 0.01842 | 0.01740 |
| K184 | OHLB1 | B488H | 0.01488 | 0.01405 |

- **Transmission line lengths (L):** Using the tunnel map provided, the team used google maps to estimate the distance between each building on campus and the Keele Substation.
- **Line Resistance and Reactance (R, X):** were calculated based on the conductor type - 250 MCM 15kV Teck cable with AC resistance of $6.58 * 10^{-6}\Omega/m$ and DC resistance of $6.22 * 10^{-6}\Omega/m$ [1].

$$R = L * R_{DC} \text{ and } X = L * R_{AC} \qquad (10)$$

To determine these values in the per-unit system, the team chose a base and calculated the base impedance. The chosen base is 10 MVA and 13.8 kV.

$$R_{P.U} = \frac{Actual}{Base} \qquad (11)$$

$$Z_{Base} = \frac{(Base\,kV)^2}{Base\,MVA} = \frac{(13.8)^2}{10} = 19.044 \qquad (12)$$

TABLE II. Transmission Line Impedances in Per Unit

| Name | Length (m) | R (p.u) | X (p.u) |
|---|---|---|---|
| K114 | 140 | 0.00052 | 0.00049 |
| K115 | 300 | 0.00112 | 0.00105 |
| K193 | 200 | 0.00074 | 0.00070 |
| K191 | 60 | 0.00022 | 0.00021 |
| K117 | 120 | 0.00045 | 0.00042 |
| K116 | 80 | 0.00030 | 0.00028 |
| K140 | 70 | 0.00026 | 0.00025 |
| K128 | 50 | 0.00019 | 0.00018 |
| K139 | 100 | 0.00037 | 0.00035 |
| K141 | 70 | 0.00026 | 0.00025 |
| K101 | 330 | 0.00123 | 0.00116 |
| K129 | 50 | 0.00019 | 0.00018 |
| K181 | 50 | 0.00019 | 0.00018 |
| K102 | 270 | 0.00100 | 0.00095 |
| K104 | 70 | 0.00026 | 0.00025 |
| K103 | 70 | 0.00026 | 0.00025 |
| K118 | 70 | 0.00026 | 0.00025 |
| K119 | 80 | 0.00030 | 0.00028 |
| K127 | 200 | 0.00074 | 0.00070 |
| K182 | 50 | 0.00019 | 0.00018 |
| K183 | 260 | 0.00097 | 0.00091 |
| K184 | 210 | 0.00078 | 0.00074 |

### B. *Transformer Calculations*

TABLE III. K1 Feeder Transformer Ratings

| Name | From | To | Rating (kVA) | Rating (kV) |
|---|---|---|---|---|
| XFMR#K2 | BTHRST85-M32 | Keele Bus2 | 10000 | 27.6 |
| XFMR#20 | B386A | B386 | 1000 | 13.8 |
| XFMR#32 | B347A | B347 | 1000 | 13.8 |
| XFMR#9 | B373A | B373 | 1000 | 13.8 |
| XFMR#7 | B361A | B361 | 1000 | 13.8 |
| XFMR#37 | B487H | B487L | 300 | 13.8 |
| XFMR#23 | B367A | B367 | 1500 | 13.8 |
| XFMR#40 | B441A | B441 | 1000 | 13.8 |
| XFMR#38 | B488H | B488L | 1000 | 13.8 |
| XFMR#3 | B354A | B354 | 1000 | 13.8 |
| XFMR#30 | B366A | B366 | 1000 | 13.8 |
| XFMR#39 | B404B | B404 | 600 | 13.8 |
| XFMR#2 | B355A | B355 | 750 | 13.8 |
| XFMR#5 | B353A | B353 | 600 | 13.8 |
| XFMR#1 | B352A | B352 | 1000 | 13.8 |
| XFMR#8 | B368A | B368 | 1000 | 13.8 |
| XFMR#15 | B378A | B378 | 600 | 13.8 |

TABLE IV. K1 Feeder Transformer Impedances

| Name | Z (p.u.) given | Z (p.u.) new | R (p.u.) | X (p.u.) |
|---|---|---|---|---|
| XFMR#K2 | 6.5 | 0.26 | 0 | 0.026 |
| XFMR#20 | 6.75 | 0.675 | 0 | 0.0675 |
| XFMR#32 | 6.3 | 0.63 | 0 | 0.063 |
| XFMR#9 | 6.73 | 0.673 | 0 | 0.0673 |
| XFMR#7 | 5.72 | 0.572 | 0 | 0.0572 |
| XFMR#37 | 2 | 0.667 | 0 | 0.0667 |
| XFMR#23 | 6.29 | 0.419 | 0 | 0.0419 |
| XFMR#40 | 5.98 | 0.598 | 0 | 0.0598 |
| XFMR#38 | 5.06 | 0.506 | 0 | 0.0506 |
| XFMR#3 | 5.91 | 0.591 | 0 | 0.0591 |
| XFMR#30 | 6.4 | 0.64 | 0 | 0.064 |
| XFMR#39 | 6.45 | 1.075 | 0 | 0.1075 |
| XFMR#2 | 5.9 | 0.787 | 0 | 0.0787 |
| XFMR#5 | 6.68 | 1.113 | 0 | 0.1113 |
| XFMR#1 | 6.57 | 0.657 | 0 | 0.0657 |
| XFMR#8 | 6.6 | 0.66 | 0 | 0.066 |
| XFMR#15 | 6.15 | 1.025 | 0 | 0.1025 |

The transformer data was obtained in a simple way. It was assumed that the resistances of the transformers were very small and negligible compared to the leakage reactance, and thus, the reactance of the transformer equals the total impedance.

$$Z = R + jX \tag{13}$$

$$R = 0 \Rightarrow Z = X \tag{14}$$

The team converted the given per-unit impedance to the new value using the chosen base.

$$Z_{P.U\,(new)} = \left(\frac{Base\ kV\ given}{Base\ kV\ new}\right)^2 * \left(\frac{Base\ KVA\ new}{Base\ KVA\ given}\right) \tag{15}$$

## V. BUILDING THE MODEL

In order to build the model in PSS/E, the team first created the case data file and maintained a base of 10 MVA with a frequency of 60Hz. To start modeling the Keele K1 Feeder system, the following information for each system component was entered in the network data spreadsheet interface:

**Bus Data:** The bus data was entered in the “buses and Equipments” tab. For each bus, a base kV of 13.8kV was used and the bus names provided on the single-line diagram was utilized for consistency. Appropriate bus numbers were used to organize the network. Finally, the team ensured that correct code for each bus type was entered. All 16 load buses have the code 1, and the swing bus (for the Keele Main Substation) has the code 3.

**Branch Data:** Next, the team entered the network transmission line data in the “AC Line” tab. The bus numbers assigned to each bus came to be useful in this process. The bus-to-bus connections were created by entering the appropriate “from” and “to” buses. There were 22 AC lines in the system. The per-unit line R and X values that were calculated in the previous section were entered in this tab as well.

**Load Data:** From the “Load” tab under “Buses and Equipments”, each load in the network was connected to its appropriate bus number. Most of the buses in the K1 Feeder network had voltage of 0.6 kV. The calculated values of reactive power Q(Mvar) and active power P(MW) for each load bus was entered. From the project specifications, it was assumed that the system had a 0.89 power factor and was under 100% loading. Hence, the real power is P = S * PF and the reactive power is $Q^2 = S^2 - P^2$.

**Generator Data:** From the “Machine” tab under “Buses and Equipments”, the generator information was entered. In this case, our only machine is the Keele Substation generator. We entered the correct slack bus number along with the generator real power rating which was calculated in the previous section.

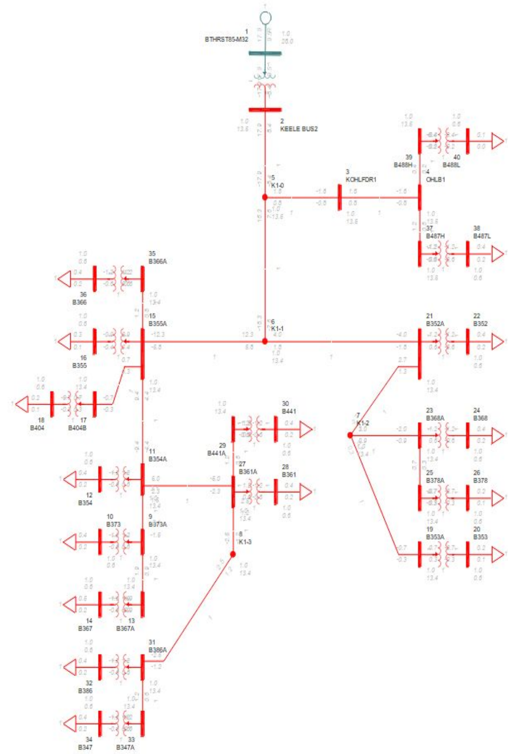

Fig. 1. Model of the K1 feeder in PSS/E

**Transformer Data:** From the “2 Winding” tab, the transformer system information was entered for each transformer using the results of the calculation performed in the previous section.

With all of the above information entered correctly into PSS/E, the team was able to develop the power system model shown in Fig. 1.

## VI. SIMULATION RESULTS

### *A. Impact of Different Loading Conditions*

The system was simulated under 0.89 lagging power factor while loading condition was varied from 20% to 140% in steps of 20%. The team graphed the voltage magnitude and voltage angles obtained for each bus and the results are shown in Fig. 2 and 3.

In PSS/E the system conditions were changed using the SCAL activity to uniformly increase or decrease system loads. This can be accessed by going to *Power Flow > Topology > Scale generation, load, shunt (SCAL)*. The *Scale Powerflow Data* window will open where the load [MW] can be adjusted. The power flow output and subsystem summary reports were generated to obtain the necessary data.

From Fig. 2, it can be seen that as loading conditions increased, the voltage magnitude decreases and the angle increases. For example, at 140% loading condition, the voltage magnitude at the buses are at the lowest values. The voltage magnitude is closest to 1 p.u. And 0 degrees at 20% loading. The voltage magnitude drops at higher loads because more current is drawn from the system and there are more losses in the transmission lines. It is also important to notice that a large voltage drop occurs from bus 1 to bus 2. This is the location of large step-down transformers between the Bathurst Keele substations which converts 28kV to 15kV. Moreover, oscillations in the voltage graphs occur in buses 10 to 40 due to large losses in the transformers. The buses were ordered and conveniently named so that the high-voltage side of the transformer would be consecutively next to the low-voltage side of the transformer (where the loads are connected). There are minimum voltage drops from bus 2 to bus 9 because there are no transformers or loads at these buses. The small voltage drops here exist because of line losses. Furthermore, from Fig. 3, the voltage angles increase proportionally to the load which indicate higher voltage instability as maximum loading capacity is reached.

Next, the real and reactive injected power from generation were plotted versus the loading condition (in Fig. 4 and 5). The values were positive for both real and reactive power, which means that power was flowing from the generator to the load and not backwards. The injected power from generation increases linearly as load condition increases because current flow is proportional to the amount of load in the system. Lastly, the real and reactive power losses were plotted versus the loading condition (in Fig. 6 and 7). The losses increases exponentially as load condition increases indicating instability at load conditions higher than 100%. The loading conditions must be maintained below maximum loading capacity to minimize system losses.

*B. 40% Loading & Varying Power Factor*

The effects of changing power factor on the system were investigated at 40% loading. The K1 feeder model was simulated for 0.7 lagging power factor to 0.7 leading power factor in steps of 0.1. The results can be seen in Fig. 8 to Fig. 13.

The voltage magnitude and angle graphs (in Fig. 8 and Fig. 9) are similar to the graphs in section VI, A. For lagging power factors, the voltage magnitudes are below 1 p.u., which is the voltage magnitude at the slack bus. A lagging power factor indicates that the load is inductive, which means that reactive power is drawn from the generator by the load. However, from Fig. 8. the voltage magnitudes for leading power factors are above 1 p.u. A leading power factor indicates that the load is capacitive which means that reactive power is flowing towards the source. This results in higher voltages at the buses and less real power losses in the power system. Moreover, it can be seen that the farther the power factor is from unity, the farther the voltages are from 1 p.u. This is because as power factor decreases, the amount of reactive power in the system increases.

Next, the real and reactive injected power from generation were plotted versus the leading and lagging power factors (in Fig. 10 and 11). For both leading and lagging power factors, the real power was positive as seen in Fig. 10 and increased proportionally to power factor. Systems are desired to function at unity power factor to maximize the real power, which is the usable power, that can be drawn by the load. In Fig. 11, the values of reactive power were positive for lagging power factors, as indicated by the red lines, which means that power was flowing from the generator to the load. For leading power factors, the reactive power was negative and was flowing backwards. Reactive power approached zero as the system approached unity power factor. Lastly, the real and reactive power losses were plotted versus the power factor (in Fig. 12 and 13). For both leading and lagging power factors, the real power losses was to small to observe at 40% loading. However the effects of the power factor on reactive power losses were visible. For leading power factors, there was no change in losses as power factor varied. However for lagging power factors, the reactive power losses peaked at around 0.9 power factor and approached zero as power factor reached unity.

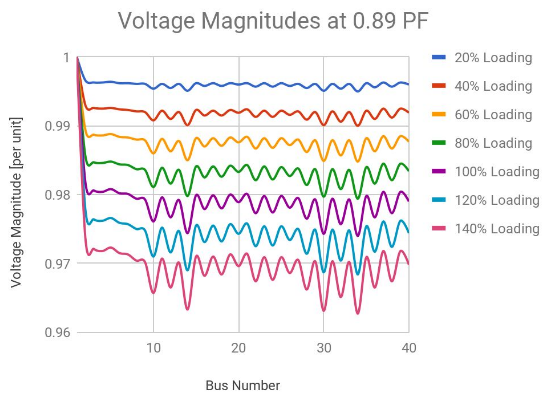


Fig. 2. Impact of different loading conditions on voltage magnitude for a system with 0.89 lagging power factor

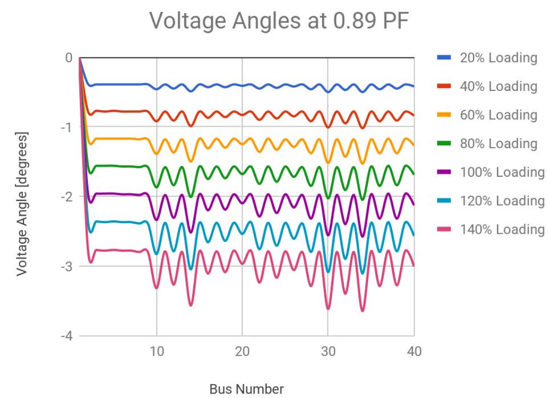


Fig. 3. Impact of different loading conditions on voltage angle for a system with 0.89 lagging power factor

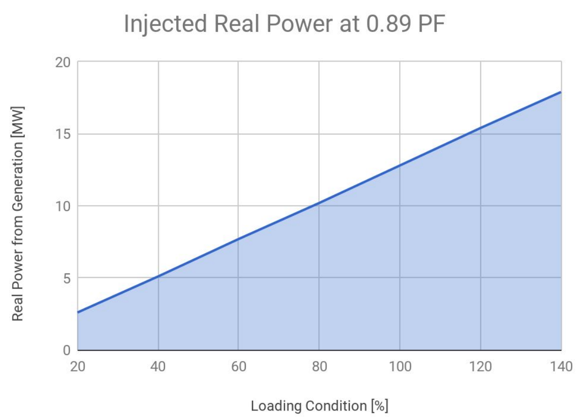


Fig. 4. Injected real power from generation vs loading condition for a system with 0.89 lagging power factor

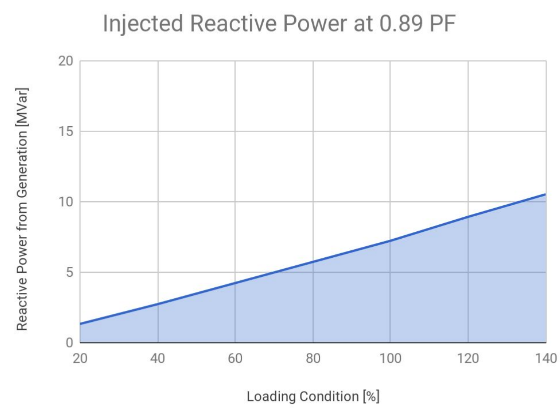


Fig. 5. Injected reactive power from generation vs loading condition for a system with 0.89 lagging power factor


Fig. 6. Real power losses vs loading condition for a system with 0.89 lagging power factor

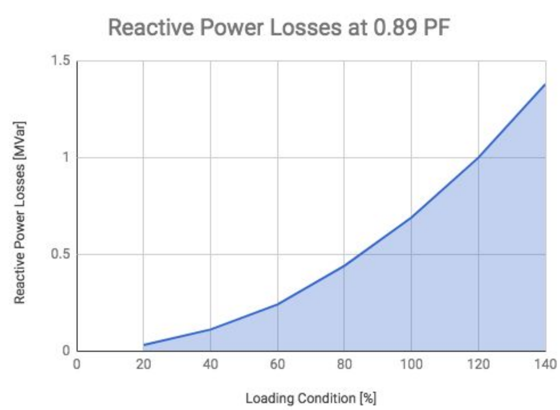


Fig. 7. Reactive power losses vs loading condition for a system with 0.89 lagging power factor

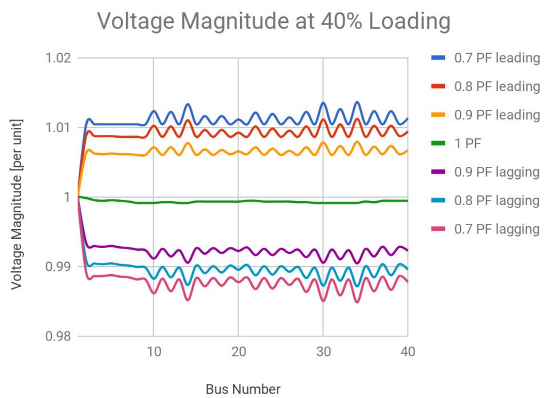


Fig. 8. Impact of different power factors on voltage magnitude for a system with 40% loading condition

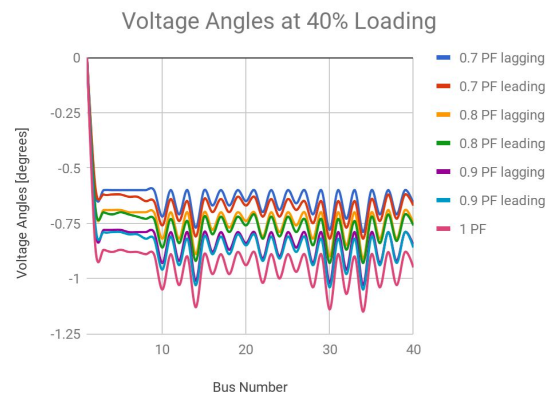


Fig. 9. Impact of different power factors on voltage angles for a system with 40% loading condition

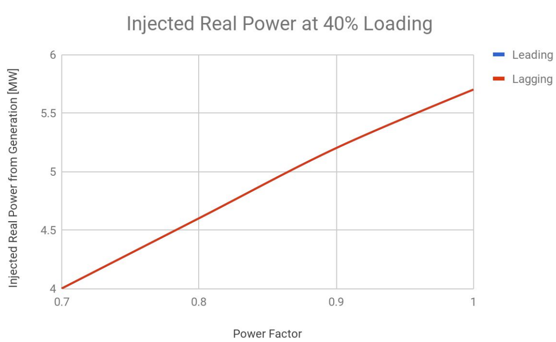


Fig. 10. Injected real power from generation vs power factor for a system at 40% loading

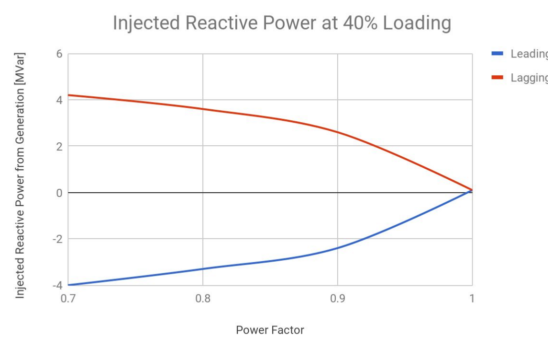


Fig. 11. Injected reactive power from generation vs power factor for a system at 40% loading

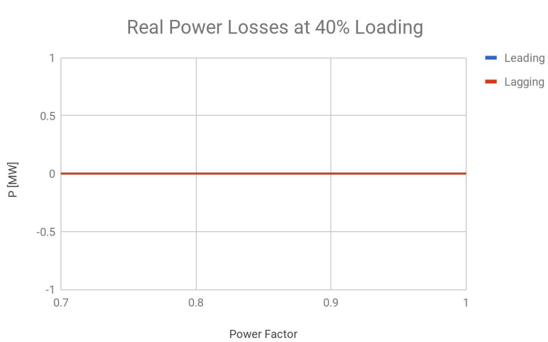


Fig. 12. Real power losses vs power factor for a system at 40% loading

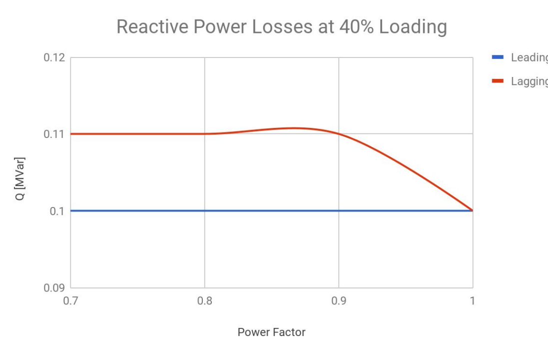


Fig. 13. Reactive power losses vs power factor for a system at 40% loading

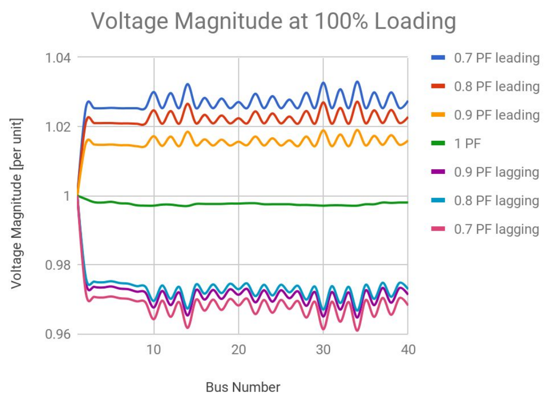


Fig. 14. Impact of different power factors on voltage magnitude for a system with 100% loading condition

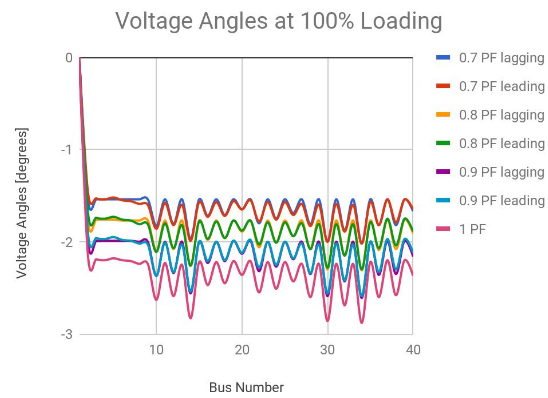


Fig. 15. Impact of different power factors on voltage angles for a system with 100% loading condition

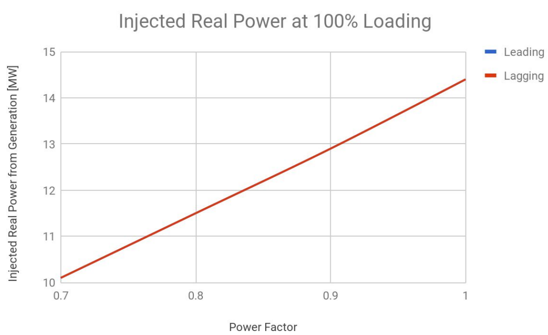


Fig. 16. Injected real power from generation vs power factor for a system at 100% loading

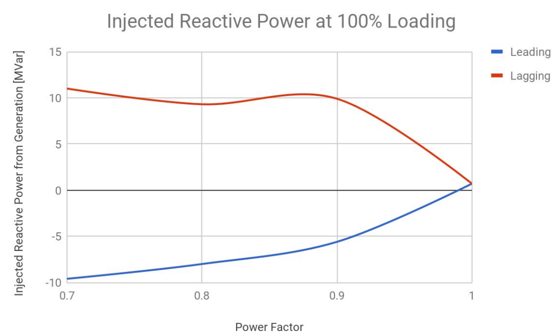


Fig. 17. Injected reactive power from generation vs power factor for a system at 100% loading

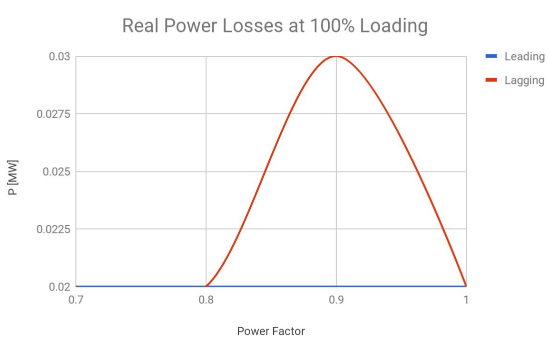


Fig. 18. Real power losses vs power factor for a system at 100% loading

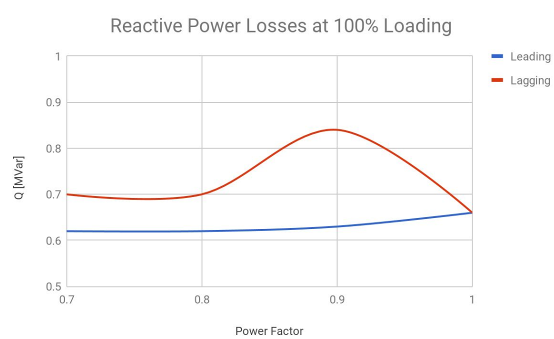


Fig. 19. Reactive power losses vs power factor for a system at 100% loading

### C. 100 % Loading & Varying Power Factor

The effects of changing power factor on the system were investigated at 100% loading. The K1 feeder model was simulated for 0.7 lagging power factor to 0.7 leading power factor in steps of 0.1. The results can be seen in Fig. 14 to Fig. 19.

The voltage magnitude and angle graphs (in Fig. 8 and Fig. 9) are similar to the graphs in section VI, B. For lagging power factors, the voltage magnitudes are below 1 p.u., which is the voltage magnitude at the slack bus. For leading power factors, the voltages at the buses are above 1 p.u. Indicating a capacitive load. As power factor approached unity, the voltages became closer to 1 p.u. The magnitude of the voltages were slightly higher at 100% loading than at 40% loading.

Next, the real and reactive injected power from generation were plotted versus the leading and lagging power factors (in Fig. 16 and 17). For both leading and lagging power factors, the real power was positive as seen in Fig. 16 and increased proportionally to power factor. In Fig. 11, the values of reactive power were positive for lagging power factors, as indicated by the red lines, which means that power was flowing from the generator to the load. For leading power factors, the reactive power was negative and was flowing backwards. Reactive power approached zero as the system approached unity power factor. Lastly, the real and reactive power losses were plotted versus the power factor (in Fig. 18 and 19). For leading power factors, the real power losses were very small. However, for lagging power factors it is clearly visible that the real power losses peak at around 0.9 lagging power factor. The effects of the power factor on reactive power losses were also visible. For leading power factors, the reactive power losses were minimal. For lagging power factors, the reactive power losses peaked at around 0.9 power factor and approached zero as power factor reached unity.

## VII. INSTALLATION OF A SHUNT CAPACITOR

The team designed a shunt capacitor to improve the power factor from 0.85 lagging power factor to 0.95 lagging power factor at 100% loading. There are two types of capacitors that can be added to improve the system: switched shunt and fixed shunt. A switched shunt capacitor "is switched in and out of service, depending upon system operating conditions" [2]. Switched capacitors are expensive to install, but have many benefits. Due to their flexible ability to be switched on during heavy load periods and off during low periods, they are extremely efficient. The alternative capacitor that can be installed is called the fixed shunt capacitor. Fixed shunt capacitor are "continuously on the line" and are "applied to give a voltage boost to the system during heavy load periods"[2]. Fixed shunt capacitors are in place even during off-peak periods which consequently results in reactive power being injected into the system, which is costly to the utility company. Although the installation of a fixed shunt capacitor is cheaper, the team chose to add a switched shunt capacitor to the system because of its long-term benefits and cost efficiency. Adding this shunt capacitor would improve the power factor and reduce the losses within the system.

The team added the shunt capacitor at the Keele substation bus as opposed to a bus closer to the individual loads for a number of reasons. First, it is more accessible for the utility company to switch the capacitor on or off. Installation and maintenance of the switch shunt capacitor will not disrupt daily campus functions. Moreover, the added benefits of installing capacitors closer to the load do not outweigh the convenience of placing it closer to the substation. In the PSS/E model, a capacitor was placed at KEELEBUS2, as shown in Fig. 20, which will improve the power factor of the entire system.

The following calculations were performed to find the rating of the capacitor, $Q_c$:

$$Q_c = Q_2 - Q_1 = P(tan\Theta_2 - tan\Theta_1) \tag{16}$$

The simulation of PSS/E at 0.85 lagging power factor returned an injected power from generation (P) of 12.2 MW. The capacitor rating can be obtain using this value:

$$Q_c = (12.2\ MW)(tan\Theta_2 - tan\Theta_1) \tag{17}$$

$$tan\Theta_2 = tan(arccos(0.85)) = 0.619 \tag{18}$$

$$tan\Theta_1 = tan(arccos(0.95)) = 0.328 \tag{19}$$

$$Q_c = (12.2\ MW)(0.619 - 0.328) = 3.55\ MVar \tag{20}$$

From the PSS/E simulations, the apparent power for both power factor is 14.35 MVA. After adding the shunt capacitor and running the simulation, the system power factor was improved from 0.8432 to

0.9477. The total cost of the shunt capacitor can be found by the following equation:

$$Total\ cost = \$1000 + 100\ \$/Kvar\ x\ Qc \quad (21)$$

$$= \$1000 + 100\ (\$1000)(3550000)$$
$$= \$356{,}000\ MVar$$

Using the rate found on the IESO website [3] of 21.1 $(CAD)/MW, we found the cost per month at each power factor.

- Cost per month at 0.85 PF:
  = ( MVA) (PF)(Rate/MW)(24)(30) (22)
  = ( 14.35MVA)(0.85)(21.1$/MW)(24)(30)
  = $185,304.42

- Cost per month at 0.95 PF:
  = ( MVA) (PF)(Rate/MW)(24)(30) (23)
  = ( 12.5MVA)(0.95)(21.1$/MW)(24)(30)
  = $180,405

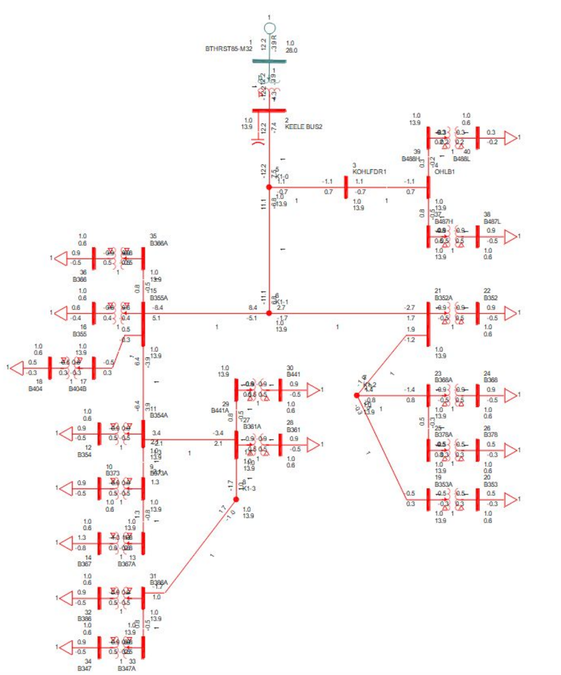

Fig. 20. PSS/E Simulation of K1 Feeder with shunt capacitor

The utility company will save around $4,899.42 per month. At this rate, it will take about 6 years to recover the cost that was invested for the installation and maintenance of the capacitor. Both the university (which is the customer) and the utility company will benefit from the increased efficiency of the system.

## VIII. BONUS SIMULATION

The bonus tasks for this project was to simulate the entire Keele feeder system which include the K1, K3 and K5 feeders. The missing information was obtained from the other groups in the class. The accuracy of the simulation depends on the correctness of the data from the K3 and K5 groups.

TABLE V. Keele Feeder Transmission Lines Data

| From | To | Name | Length (m) | R (p.u.) | X (p.u.) |
|---|---|---|---|---|---|
| B354A | B355A | K114 | 140 | 0.0005 | 0.0005 |
| B354A | B361A | K115 | 300 | 0.0011 | 0.0011 |
| B361A | B441A | K193 | 200 | 0.0007 | 0.0007 |
| B366A | B355A | K191 | 60 | 0.0002 | 0.0002 |
| B368A | B378A | K117 | 120 | 0.0005 | 0.0004 |
| B373A | B354A | K116 | 80 | 0.0003 | 0.0003 |
| B373A | B367A | K140 | 70 | 0.0003 | 0.0003 |
| B386A | K1-3 | K128 | 50 | 0.0002 | 0.0002 |
| B386A | B347A | K139 | 100 | 0.0004 | 0.0004 |
| B404B | B355A | K141 | 70 | 0.0003 | 0.0003 |
| K1-0 | K1-1 | K101 | 330 | 0.0012 | 0.0012 |
| K1-0 | KEELE BUS2 | K129 | 50 | 0.0002 | 0.0002 |
| K1-0 | KOHLF RD1 | K181 | 50 | 0.0002 | 0.0002 |
| K1-1 | B355A | K102 | 270 | 0.0010 | 0.0010 |
| K1-1 | B352A | K104 | 70 | 0.0003 | 0.0003 |
| K1-2 | B352A | K103 | 70 | 0.0003 | 0.0003 |
| K1-2 | B368A | K118 | 70 | 0.0003 | 0.0003 |
| K1-2 | B353A | K119 | 80 | 0.0003 | 0.0003 |
| K1-3 | B361A | K127 | 200 | 0.0007 | 0.0007 |
| KOHLF RD1 | OHLB1 | K182 | 50 | 0.0002 | 0.0002 |
| OHLB1 | B487H | K183 | 260 | 0.0010 | 0.0009 |
| OHLB1 | B488H | K184 | 210 | 0.0008 | 0.0007 |
| Keele Bus1 | K3-1 | K301 | 63 | 0.0006 | 0.0004 |
| K3-1 | K3-2 | K302 | 256 | 0.0025 | 0.0015 |
| K3-2 | K3-3 | K303 | 180 | 0.0018 | 0.0011 |
| K3-3 | K3-4 | K304 | 118 | 0.0012 | 0.0007 |
| K3-4 | B358A | K305 | 194 | 0.0019 | 0.0011 |
| B358A | K3-5 | K306 | 109 | 0.0011 | 0.0006 |
| K3-5 | B372-1A | K307 | 37 | 0.0004 | 0.0002 |
| B372-1A | B372-2A | K308 | 0 | 0.0000 | 0.0000 |

| | | | | | |
|---|---|---|---|---|---|
| B372-2A | B372-3A | K309 | 0 | 0.0000 | 0.0000 |
| B372-3A | B372-4A | K310 | 0 | 0.0000 | 0.0000 |
| K3-5 | K3-6 | K320 | 147 | 0.0014 | 0.0009 |
| K3-6 | B369A | K321 | 45 | 0.0004 | 0.0003 |
| B369A | B380A | K322 | 0 | 0.0000 | 0.0000 |
| K3-6 | B398A | K323 | 45 | 0.0004 | 0.0003 |
| K3-4 | B383A | K332 | 118 | 0.0012 | 0.0007 |
| B358A | B388B | K334 | 180 | 0.0018 | 0.0011 |
| B380A | B430B | K392 | 210 | 0.0021 | 0.0012 |
| K3-2 | B452A | K333 | 60 | 0.0006 | 0.0004 |
| KEELE BUS3 | K5-1 | K501 | 0.052 | 0.0033 | 0.0051 |
| K5-1 | K5-2 | K502 | 0.702 | 0.0443 | 0.0683 |
| K5-2 | K5-3 | K503 | 0.251 | 0.0158 | 0.0244 |
| K5-3 | K5-4 | K504 | 0.195 | 0.0123 | 0.0190 |
| K5-4 | K5-5 | K505 | 0.104 | 0.0065 | 0.0101 |
| K5-5 | K5-6 | K506 | 0.188 | 0.0118 | 0.0183 |
| K5-6 | K5-7 | K507 | 0.297 | 0.0187 | 0.0289 |
| K5-7 | K5-11 | K515 | 0.073 | 0.0046 | 0.0071 |
| K5-6 | B381A | K523 | 0.046 | 0.0029 | 0.0045 |
| K5-7 | K5-8 | K508 | 0.227 | 0.0143 | 0.0221 |
| K5-7 | B387A | K519 | 0.06 | 0.0038 | 0.0058 |
| K5-8 | B384A | K509 | 0.028 | 0.0018 | 0.0027 |
| K5-9 | K5-10 | K511 | 0.1 | 0.0063 | 0.0097 |
| K5-9 | B384A | K510 | 0.189 | 0.0119 | 0.0184 |
| K5-9 | B403A | K520 | 0.053 | 0.0033 | 0.0051 |
| K5-10 | B400A | K512 | 0.129 | 0.0081 | 0.0125 |
| K5-10 | B401A | K513 | 0.163 | 0.0102 | 0.0158 |
| K5-10 | B409A | K522 | 0.085 | 0.0053 | 0.0082 |
| K5-11 | B413A | K524 | 0.04 | 0.0025 | 0.0039 |
| K5-11 | B364A | K516 | 0.1 | 0.0063 | 0.0097 |
| B401A | B402A | K514 | 0.08 | 0.0050 | 0.0078 |
| B364A | K5-12 | K517 | 0.216 | 0.0136 | 0.0210 |
| B365A | K5-12 | K521 | 0.208 | 0.0131 | 0.0202 |
| B391A | K5-12 | K518 | 0.129 | 0.0081 | 0.0125 |

TABLE VI. Keele Feeder Transformer Ratings

| From | To | Name | Rating (kVA) |
|---|---|---|---|
| BTHRST85-M32 | KEELE BUS2 | XFMR#Keele2 | 10000 |
| B386A | B386 | XFMR#20 | 1000 |
| B347A | B347 | XFMR#32 | 1000 |
| B373A | B373 | XFMR#9 | 1000 |
| B361A | B361 | XFMR#7 | 1000 |
| B487H | B487L | XFMR#37 | 300 |
| B367A | B367 | XFMR#23 | 1500 |
| B441A | B441 | XFMR#40 | 1000 |
| B488H | B488L | XFMR#38 | 1000 |
| B354A | B354 | XFMR#3 | 1000 |
| B366A | B366 | XFMR#30 | 1000 |
| B404B | B404 | XFMR#39 | 600 |
| B355A | B355 | XFMR#2 | 750 |
| B353A | B353 | XFMR#5 | 600 |
| B352A | B352 | XFMR#1 | 1000 |
| B368A | B368 | XFMR#8 | 1000 |
| B378A | B378 | XFMR#15 | 600 |
| BTHRST85-M30 | KEELE BUS1 | XFMR#Keele1 | 10000 |
| B452A | B452 | XFMR#36 | 1500 |
| B383A | B383 | XFMR#34 | 2000 |
| B388B | B388 | XFMR#33 | 1000 |
| B358A | B358 | XFMR#6 | 1000 |
| B372-1A | B372-1 | XFMR#12 | 1000 |
| B372-2A | B372-2 | XFMR#13 | 1000 |
| B398A | B398 | XFMR#41 | 1000 |
| B372-3A | B372-3 | XFMR#11 | 1000 |
| B380A | B380 | XFMR#18 | 1500 |
| B372-4A | B372-4 | XFMR#10 | 1000 |
| B369A | B369 | XFMR#19 | 1500 |
| B430A | B430 | XFMR#50 | 2000 |
| BTHRST85-M30 | KEELE BUS1 | XFMR#Keele1 | 10000 |
| B381A | B381 | Xfmr#35 | 1500 |
| B387A | B387 | Xfmr#25 | 1500 |
| B384A | B384 | Xfmr#14 | 1000 |
| B403A | B403 | Xfmr#26 | 450 |
| B401A | B401 | Xfmr#16 | 450 |
| B402A | B402 | Xfmr#17 | 450 |
| B400A | B400 | Xfmr#22 | 450 |
| B409A | B409 | Xfmr#31 | 1000 |
| B413A | B413 | Xfmr#42 | 500 |
| B364A | B364 | Xfmr#24 | 750 |
| B391A | B391 | Xfmr#28 | 1500 |
| B365A | B365 | Xfmr#27 | 450 |

TABLE VII. Keele Feeder Transformer Impedances

| Name | R (p.u.) | X (p.u.) |
|---|---|---|
| XFMR#Keele2 | 0.00 | 0.03 |
| XFMR#20 | 0.00 | 0.07 |
| XFMR#32 | 0.00 | 0.06 |
| XFMR#9 | 0.00 | 0.07 |
| XFMR#7 | 0.00 | 0.06 |
| XFMR#37 | 0.00 | 0.07 |
| XFMR#23 | 0.00 | 0.04 |
| XFMR#40 | 0.00 | 0.06 |
| XFMR#38 | 0.00 | 0.05 |
| XFMR#3 | 0.00 | 0.06 |
| XFMR#30 | 0.00 | 0.06 |
| XFMR#39 | 0.00 | 0.11 |
| XFMR#2 | 0.00 | 0.08 |
| XFMR#5 | 0.00 | 0.11 |
| XFMR#1 | 0.00 | 0.07 |
| XFMR#8 | 0.00 | 0.07 |
| XFMR#15 | 0.00 | 0.10 |
| XFMR#Keele1 | 0.38 | 2.66 |
| XFMR#36 | 0.01 | 0.09 |
| XFMR#34 | 0.02 | 0.11 |
| XFMR#33 | 0.01 | 0.05 |
| XFMR#6 | 0.01 | 0.06 |
| XFMR#12 | 0.01 | 0.07 |
| XFMR#13 | 0.01 | 0.07 |
| XFMR#41 | 0.01 | 0.06 |
| XFMR#11 | 0.01 | 0.07 |
| XFMR#18 | 0.01 | 0.10 |
| XFMR#10 | 0.01 | 0.07 |
| XFMR#19 | 0.01 | 0.10 |
| XFMR#50 | 0.02 | 0.11 |
| XFMR#Keele1 | 0.00 | 0.01 |
| Xfmr#35 | 0.00 | 0.01 |
| Xfmr#25 | 0.00 | 0.01 |
| Xfmr#14 | 0.00 | 0.01 |
| Xfmr#26 | 0.00 | 0.00 |
| Xfmr#16 | 0.00 | 0.01 |
| Xfmr#17 | 0.00 | 0.01 |
| Xfmr#22 | 0.00 | 0.01 |
| Xfmr#31 | 0.00 | 0.01 |
| Xfmr#42 | 0.00 | 0.01 |
| Xfmr#24 | 0.00 | 0.01 |
| Xfmr#28 | 0.00 | 0.01 |
| Xfmr#27 | 0.00 | 0.01 |

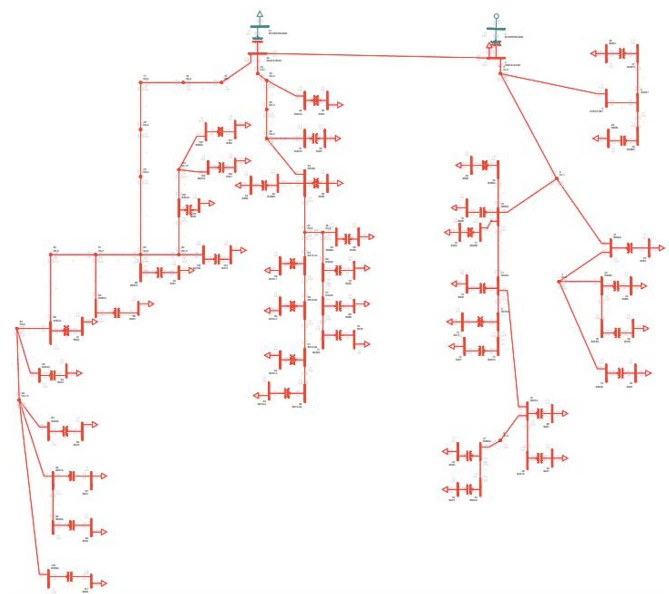

Fig. 21. PSS/E Simulation of K1, K3, and K5 feeders

## A. *Power Flow at 100% Load & 0.89 Power Factor*

```
                          SYSTEM SWING BUS SUMMARY
X-------- SWING BUS --------X X---- AREA -----X X---- ZONE -----X
 BUS#-SCT X-- NAME --X BASKV   # X-- NAME --X   # X-- NAME --X      MW      MVAR   MVABASE
    1     BTHRST85-M3228.000   1                1                  37.2     20.5     10.0
   41     BTHRST85-M3028.000   1                1                NO GENERATOR SLOT ASSIGNED

  108 BUSES        1 PLANTS          1 MACHINES      0 INDUCTION GENS      0 INDUCTION MOTORS
   42 LOADS        0 FIXED SHUNTS    0 SWITCHED SHUNTS
  108 BRANCHES    42 TRANSFORMERS    0 DC LINES      0 FACTS DEVICES       0 GNE DEVICES

                        X------ ACTUAL ------X X----- NOMINAL ------X
                              MW      MVAR          MW      MVAR
FROM GENERATION              37.2     20.5         37.2     20.5
FROM INDUCTION GENERATORS     0.0      0.0          0.0      0.0
TO CONSTANT POWER LOAD       36.4     13.9         36.9     14.6

 VOLTAGE        X----- LOSSES -----X   X-- LINE SHUNTS --X   CHARGING
 LEVEL BRANCHES     MW        MVAR        MW        MVAR       MVAR
  13.8    68       1.25       6.47       0.0        0.0        0.0
   0.6    35       0.03       0.28       0.0        0.0        0.0
   0.2     5       0.00       0.00       0.0        0.0        0.0
 TOTAL   108       1.27       6.75       0.0        0.0        0.0
```

Fig. 22. PSS/E subsystem summary report for three Keele feeders

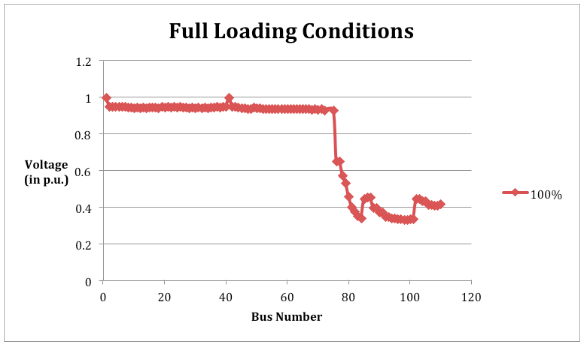


Fig. 23. Voltage magnitudes plotted at each bus in the entire Keele feeder system for 100% loading condition

## IX. CONCLUSION

In summary, all of the results in the K1 feeder met the expectations of the project. The team was able to find the parameters that were missing in the data file that was provided. The knowledge obtained in EECS 4622 for transmission line lengths were implemented for the derivation of the missing line parameters. The proximity of the buildings indicated that the equations for a short line must be applied. In deriving the missing elements for the transformer, the team applied the knowledge of per-unit calculations and base conversion. Using the completed data, the K1 feeder was simulated in PSS/E to observe the impact of load conditions and power factor on the system.

It was observed that the voltage magnitude decreased as load conditions increases or power factor decreases. Furthermore, the injected real power coming from generation increases with load and power factor. On the other hand, the injected reactive power varies depending on whether the system has a lagging or leading power factor. This is because leading power factors indicated that the system load was capacitive and reactive power was flowing backwards (towards the source). Finally, the system losses increased exponentially with increasing loading conditions. Large system losses were present for lagging power factors which indicated the need for a shunt capacitor.

The team observed that by adding a 3.55 MVar rated switched shunt capacitor at the Keele substation feeder, the power factor was corrected from 0.85 to 0.95. The total cost of adding this capacitor was found to be $356,000, which was calculated to be paid approximately in 6 years. Using the payback calculations, we concluded that this investment is worthwhile.

In conclusion, the students polished the necessary skills for the power industry. We also learned how to create single-line diagrams, model power networks and analyze power flow reports generated in PSS/E. More importantly, we learned how to work efficiently as a team. This project enabled us to perform power flow analysis, and correct the power factor to decrease the system losses. Finally, we learned to predict the economic feasibility of a shunt capacitor and appreciate the complexity of an electrical power network.

## X. REFERENCES

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