IGEE 402 Power System Analysis – Fall 2024

Experiment 2 Lab Report – Power Flow and Power System Operation

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Objective:

The objective of this lab is to analyze the formulation and solution methods for power flow problems in power systems. The lab focuses on developing strategies to address operational constraints in power flow, ensuring the system maintains safe voltage levels and power flows. Additionally, it explores operational and planning measures to enhance system stability and reliability.

I. Introduction

In this lab, we tackle the load flow problem in power system analysis, which involves solving simultaneous nonlinear equations to determine voltage levels and power flows across the network. Starting with an initial flat voltage profile, iterative methods such as Newton-Raphson are employed to find the mismatches to adjust voltage magnitudes and angles until convergence is achieved. The experiment also examines corrective operation and planning actions to solve problems such as constraint violation, load shedding, and voltage collapse under normal operation of the power system. Additionally, the laboratory focused on study the behaviour under the occurrence of a single line loss in the system. Solutions were proposed under the operation point of view.

II. Experiment and Analysis

Part 1 *Preliminary Calculations*

1.1 The per unit admittance matrix of this network is exported from the Power World to matlab. This matrix is a 5x5 matrix because there are 5 buses in the system.

	1	2	3	4	5
1	1.1900 -13.6700i	-0.5200 + 5.9100i	0.0000 + 0.0000i	-0.6800 + 7.8800i	0.0000 + 0.0000i
2	-0.5200 + 5.9100i	1.5500 -18.0600i	-0.4200 + 4.7300i	-0.6200 + 7.6400i	0.0000 + 0.0000i
3	0.0000 + 0.0000i	-0.4200 + 4.7300i	1.0200 -11.2700i	-0.2600 + 2.9500i	-0.3500 + 3.9400i
4	-0.6800 + 7.8800i	-0.6200 + 7.6400i	-0.2600 + 2.9500i	2.2300 -26.0500i	-0.6800 + 7.8800i
5	0.0000 + 0.0000i	0.0000 + 0.0000i	-0.3500 + 3.9400i	-0.6800 + 7.8800i	1.0200 -11.6600i

Table 1 Per unit Admittance Matrix

1.2 The active power injection at each bus is determined by subtracting the load from the generation, and the results are presented in per-unit values based on a 340 MVA system base.

$$P_{inject} = \begin{bmatrix} 1.8529 \\ -0.8853 \\ 0.3265 \\ -0.1588 \\ -1.1029 \end{bmatrix}$$

The team obtained a P_{inject} vector with 5 elements, representing the net active power injection at each of the 5 buses. The dimension of this vector is 5 by 1 since there are 5 buses in the network, and each element represents the power injection at a specific bus.

1.3 DC power flow method is used to approximate the voltage angles. When performing DC power flow analysis, the slack node is typically assumed to have a fixed voltage angle, eliminating the need to calculate its angle difference. Although the P_{inject} vector initially has 5 elements, only the 4 elements correspond to buses 2 to 5 are used in subsequent calculations. The imaginary part of the admittance matrix is extracted as shown below.

$$B = \begin{bmatrix} -13.67 & 5.91 & 0 & 7.88 & 0 \\ 5.91 & -18.06 & 4.73 & 7.64 & 0 \\ 0 & 4.73 & -11.27 & 2.95 & 3.94 \\ 7.88 & 7.64 & 2.95 & -26.05 & 7.88 \\ 0 & 0 & 3.94 & 7.88 & -11.66 \end{bmatrix}$$

B' matrix is derived by excluding the first row and first column of Matrix B as it corresponds to the slack bus.

$$B' = \begin{bmatrix} 18.06 & -4.73 & -7.64 & 0 \\ -4.73 & 11.27 & -2.95 & -3.94 \\ -7.64 & -2.95 & 26.05 & -7.88 \\ 0 & -3.94 & -7.88 & 11.66 \end{bmatrix}$$

To calculate the angle differences between buses, we take the inverse of the B' matrix and multiply it by the P_{inject} vector. Finally, we convert the angle differences from radians to degrees by multiplying by 180/π. The vector is shown below.

$$Angle\ Difference = \begin{bmatrix} -8.5407 \\ -8.8789 \\ -8.0529 \\ -13.8622 \end{bmatrix}$$

Part 2 ***Normal operation***

2.1 The system is shown below. The angle difference matches with theoretical prediction. There's no significant discrepancies.

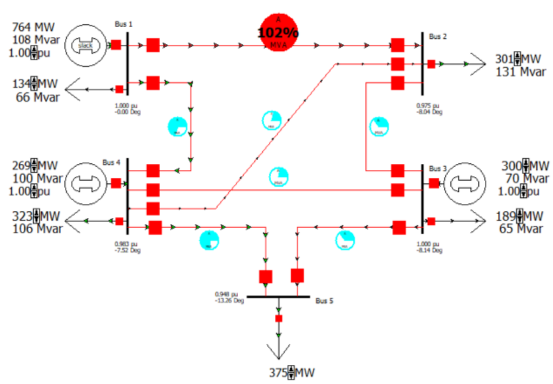

Figure 2.1.1 Experimental Power Flow Solution

2.2 There is a line MVA limit violation between Bus 1 and Bus 2. Voltage of Bus 5 is not within the limit. To address the operating constraint violations, we begin by adjusting bus voltages to bring all buses within the acceptable range of 1.00 p.u. ±5%.

Firstly, we need to Adjust Bus 1 Voltage to Improve Bus 5 Voltage. Initially, Bus 5 has a voltage of 0.948 p.u., which falls below the acceptable limit of 0.95 p.u. By increasing the voltage at the reference bus (Bus 1), we raise the downstream voltage levels, effectively bringing Bus 5's voltage up to approximately 0.95 p.u., within the acceptable range.

Then we adjust Bus 4 active power to address line limit violation from Bus 1 to Bus 2. Line flows must stay within their specified MVA limits to prevent thermal overloads and ensure safe operation. In this case, adjusting the active power output at Bus 4 can reduce the power flow on critical lines that might be experiencing overloads. By decreasing the active power output at Bus 4, we reduce the overall load on the line connected to Bus 4, bringing the power flow within its MVA limit and preventing any potential overloading issues.

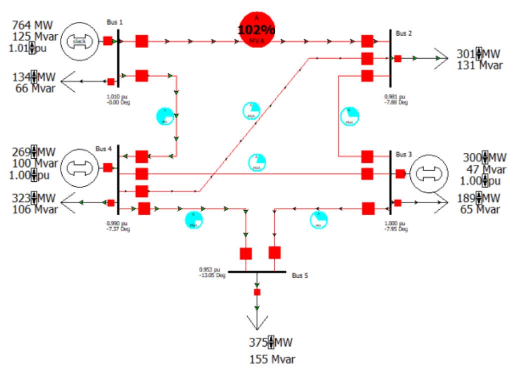

Figure 1.2.1 Solution for Voltage Limit Violation

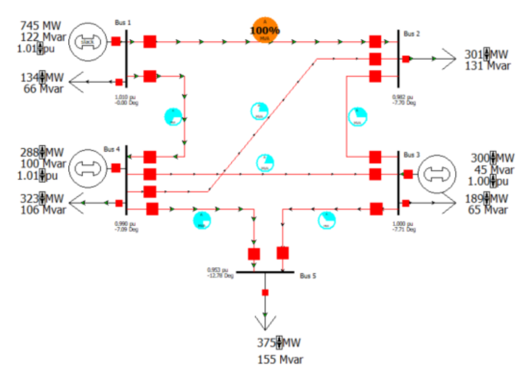

Figure 2.2.2 Solution for MVA Limit Violation

2.3 Bus 4 is at it's reactive power generation limit of 100 Mvar. It is not possible to continue to control the voltage at these buses. Once a generator hits this limit, it loses the ability to adjust its reactive output to control voltage. As voltage control at a bus typically relies on the generator's ability to modify its reactive power output. Consequently, with the generator Bus 4 constrained by their reactive power limits, they are unable to continue regulating voltage through reactive power adjustments.

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \theta} & \frac{\partial P}{\partial V} \\ \frac{\partial Q}{\partial \theta} & \frac{\partial Q}{\partial V} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix} = \begin{bmatrix} H & N \\ M & L \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

In the Jacobian matrix it has four submatrices: H, N, M, L where L represents the sensitivity of voltage magnitude to reactive power. When a generator reaches its reactive power limit, its contribution to L is effectively reduced, limiting its impact on voltage control. Adjusting active power affects N but has minimal influence on voltage magnitude due to the decoupled nature of Jacobian, making it ineffective for voltage regulation at these buses.

2.4 When Bus 4 reaches its reactive power limit, it can no longer effectively adjust its reactive power (Q) output to support voltage regulation. This condition is often identified in the Jacobian matrix, which links changes in active (P) and reactive power (Q) to changes in voltage angles and magnitudes across the buses. For a generator bus (PV bus) like Bus 4, hitting the reactive power limit restricts its voltage control capability, effectively converting it to a load bus (PQ bus). This shift appears in the Jacobian as zeros or reduced values in rows or columns associated with reactive power control.

```
Jacobian
-1.0000        0        0        0        0        0        0        0        0        0
      0  -3.0444   1.0268   1.6062        0        0 -17.8811   4.5429   7.3549        0
      0   1.0466  -2.8546   0.6525   0.8707        0   4.6266 -11.0449   2.8922   3.8560
      0   1.5407   0.6150  -5.2712   1.6266        0   7.4336   2.8704 -25.3565   7.6586
      0        0   1.1510   2.2883  -2.3830        0        0   3.5870   7.1798 -11.3421
      0        0        0        0        0  -1.0000        0        0        0        0
      0 -16.8623   4.5429   7.3549        0        0   4.7264  -1.0268  -1.6062        0
      0        0  -1.9819        0        0        0        0   0.2684        0        0
      0   7.4336   2.8704 -25.2943   7.6586        0  -1.5407  -0.6150   5.4730  -1.6266
      0        0   3.5870   7.1798  -9.8971        0        0  -1.1510  -2.2883   4.4288
```

Figure 2.4.1The Jacobian Matrix of the Power System

Since Bus 4 is at its limit, increasing its voltage magnitude would not significantly change its reactive power output. However, because reactive power flow depends on voltage differences between buses, adding shunt capacitance at Bus 4 can provide a small boost in reactive power, helping to adjust the voltage differential between buses. This adjustment at Bus 4 offers the most effective relief for improving the voltage at Bus 5. Reflected by the Jacobian, it has the largest magnitude of change. While adding shunt capacitance at Bus 1 or Bus 5 could also enhance Bus 5’s voltage, it would require a larger reactive power injection to achieve the same effect as a smaller injection at Bus 4.

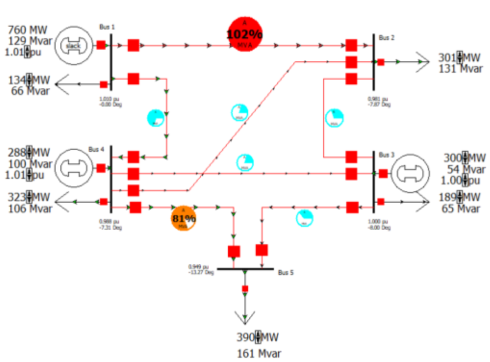

Figure 2.4.1 The Power System representation before shunt compensation

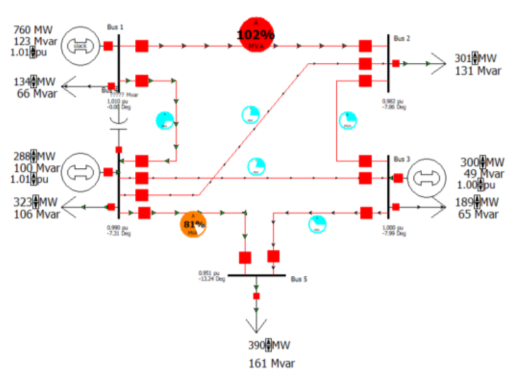

Figure 2.4.2 The Shunt Capacitance adding to the Bus 4

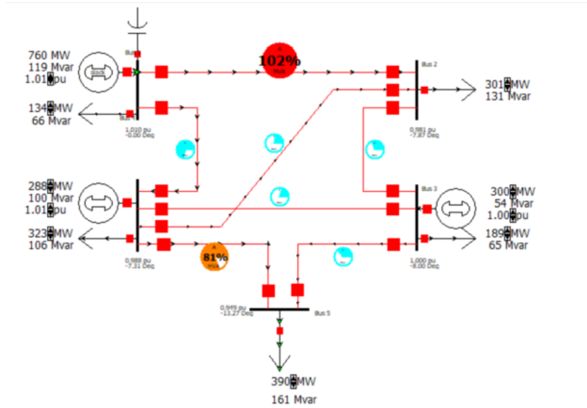

Figure 2.4.3 The Shunt Capacitance adding to the Bus 1.

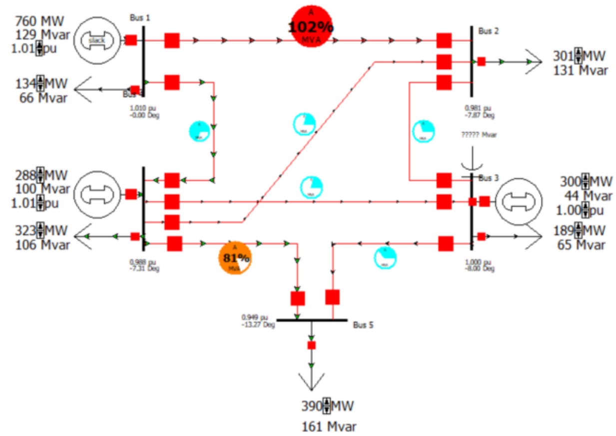

Figure 2.4.4 The Shunt Capacitance adding to the Bus 3

Part 3 *Operation under contingencies*

3.1 The system is simulated under the loss of each single transmission line. As shown in Figure 3.1.1, the line is disconnected from Bus 1 to Bus 2. Based on inspection, there are line limit violation from Bus 1 to Bus 4 and Bus 2 to Bus 4. Bus 2 and Bus 5 are under voltage. The disconnection from Bus 1 to Bus 4 is shown in Figure 3.1.2 . There is a blackout. The system can no longer supply load. The system collapsed.

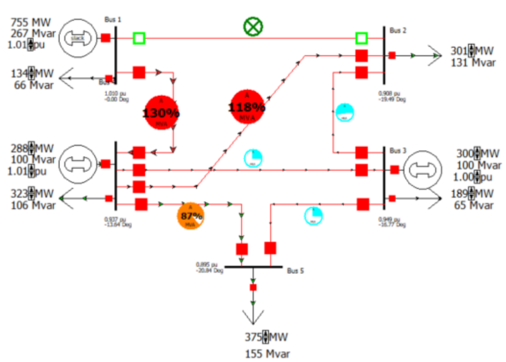

Figure 3.1.1 Disconnection from Bus 1 to 2

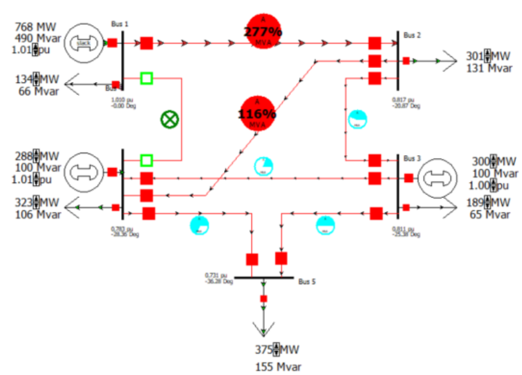

Figure 3.1.2 Disconnection from Bus 1 to 4

As shown in the Figure 3.1.3, line from Bus 2 to Bus 3 is disconnected. There is a line limit violation from Bus 1 to Bus 2. Bus 4 is undervoltage. The disconnection of Bus 3 and 4 is shown in the Figure 3.1.4. There is a line limit violation from Bus 1 to 2. Bus 2 and Bus 5 are undervoltage.

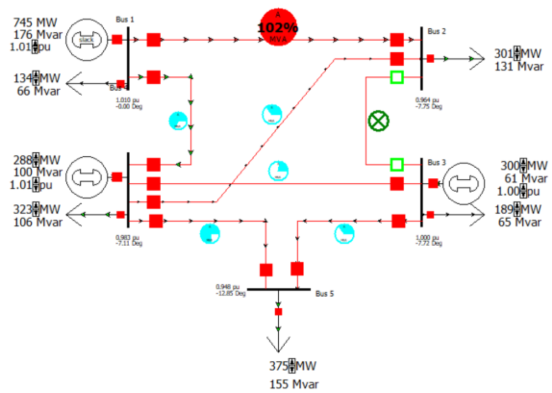

Figure 3.1.3 Disconnection from Bus 2 to 3

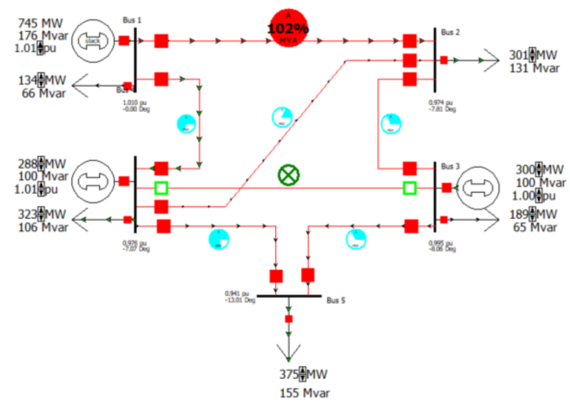

Figure 3.1.4 Disconnection from Bus 3 to 4

As shown in the Figure 3.1.5, line from Bus 3 to Bus 5 is disconnected. There is a line limit violation from Bus 4 to Bus 5. Bus 5 is undervoltage. The disconnection of Bus 4 to Bus 5 is shown in the Figure 3.1.6. Line limit violation occurs from Bus 1 to Bus 2 and Bus 3 to Bus 5. Bus 2, 3, 4, 5 all presents to be undervoltage.

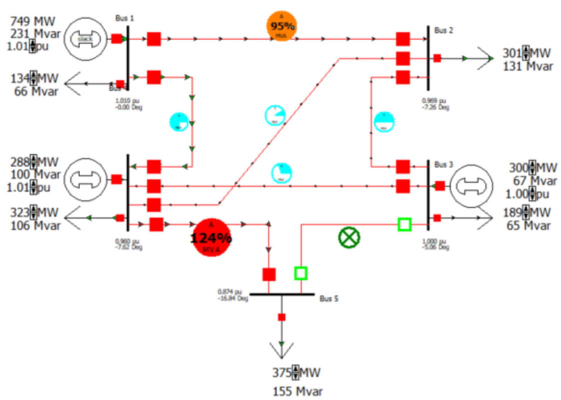

Figure 3.1.5 Disconnection of Bus 3 and Bus 5

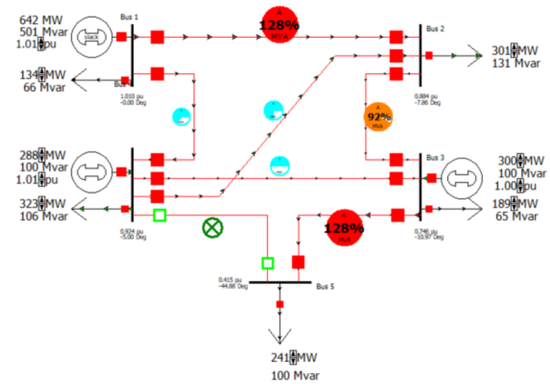

Figure 3.1.6 Disconnection of Bus 4 to Bus 5

The Figure below presents the disconnection from Bus 2 to Bus 4. There is a line limit violation from Bus 1 to Bus 2.

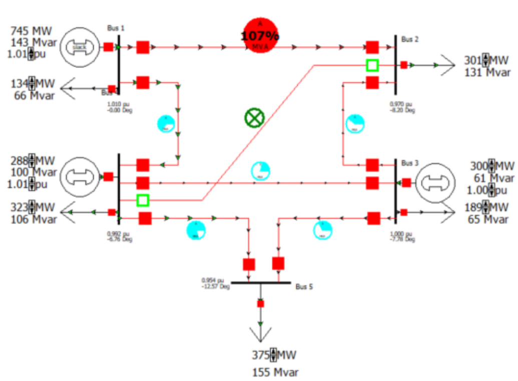

Figure3.1.7 Disconnection from Bus 2 to Bus 4

3.2 Starting from the disconnection of line from Bus 1 to Bus 2. To resolve the line limit violation from Bus 1 to Bus 4, the team increased the Bus 4 generating end active power to 420 MW. To resolve the limit violation on the line from Bus 2 to Bus 4, the active power generation at Bus 3 was raised to 430 MW, and to stabilize the voltage levels at Bus 2 and Bus 5, the impedance at Bus 3 was adjusted to 1.01 p.u.

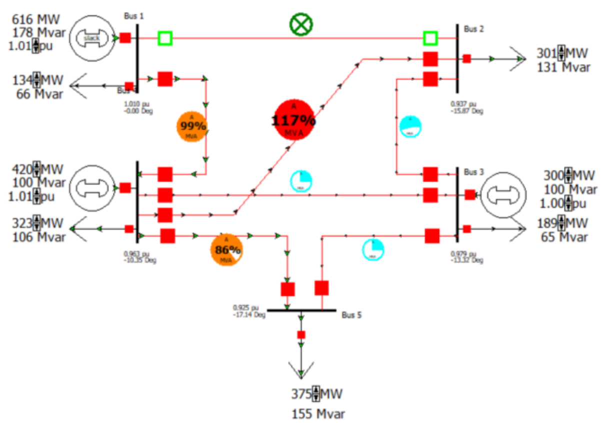

Figure 3.2.1 Bus 1 to Bus 4 Line Limit Violation Solution

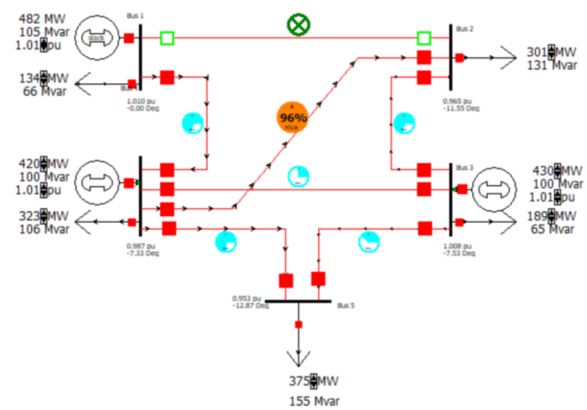

Figure 3.2.2 Bus 2 to Bus 4 Line Limit Violation and Undervoltage Solution

The line from Bus 4 to Bus 1 is then disconnected as shown in Figure 3.2.3. To address the overload on the line between Bus 1 and Bus 2, the team increased the active power generation at the sending end of Bus 4 from 420 MW to 495 MW. This adjustment helps to redistribute the load and mitigate the line limit violation effectively.

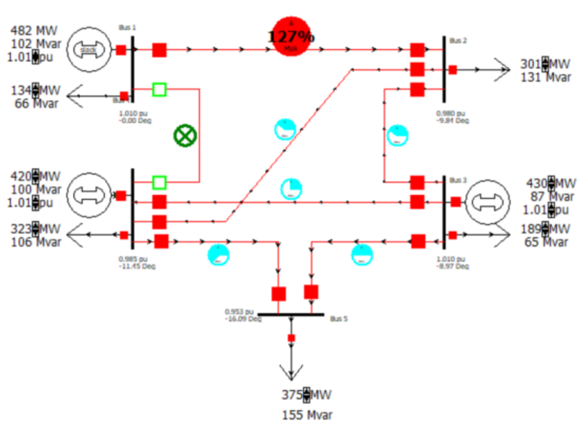

Figure 3.2.3 System After Bus 1 to Bus 4 Disconnection

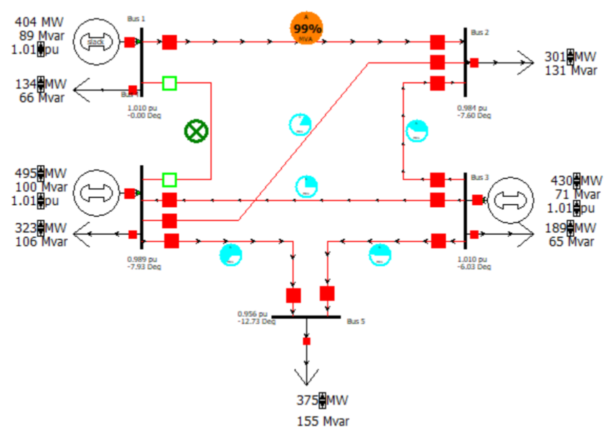

Figure 3.2.4 Bus 1 to Bus 2 Line Limit Violation Solution

The group then perform the disconnection from Bus 2 to Bus 4, Bus 2 to Bus 4, and Bus 3 to Bus 4 respectively. There appears to be no abnormal activities. All lines and voltages are within the limit.

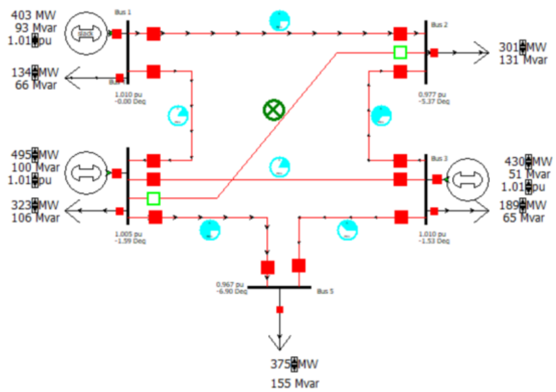

Figure 3.2.5 Line Disconnection from Bus 2 to Bus 4

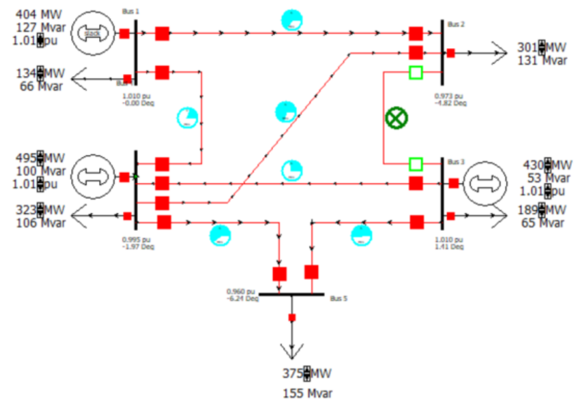

Figure 3.2.6Line Disconnection from Bus 2 to Bus 3

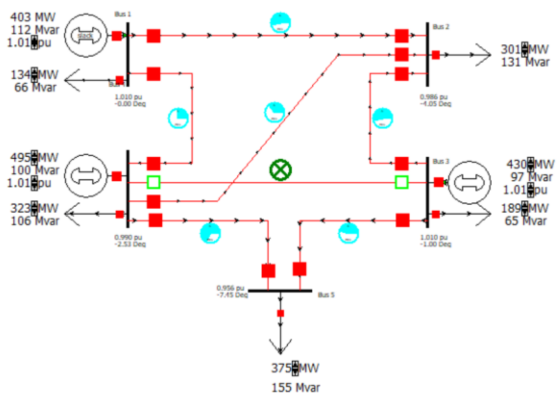

Figure 3.2.7Line Disconnection from Bus 3 to Bus 4

The team then continues to disconnect line from Bus 4 to Bus 5 and Bus 3 to Bus 5 respectively. From the operational point of view, there’s no solution to resolve the issues shown in Figure 3.2.8 and Figure 3.2.9. However, planning actions such as addition of reactive compensations or new lines can be applied to resolve such issue.

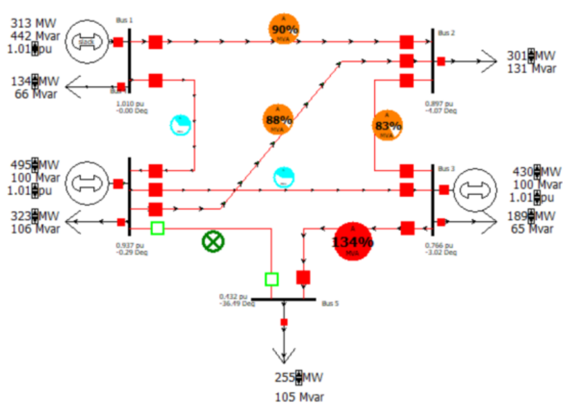

Figure 3.2.8 Disconnection from Bus 4 to Bus 5

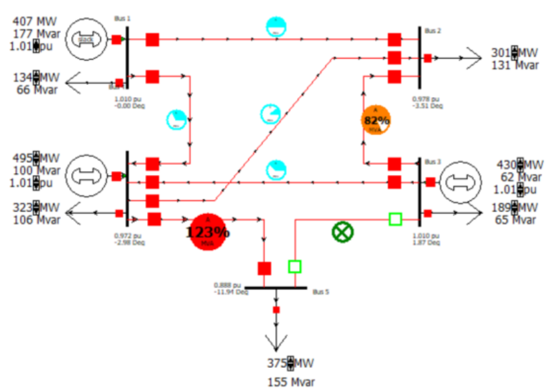

Figure 3.2.9 Disconnection from Bus 3 to Bus 5

III. Conclusion

This lab demonstrated the application of power flow analysis and implementation of corrective actions within the power system. The team analyzed voltage, line limits, and identified necessary actions needed to bring the system within limits. Contingency analysis of single line disconnections revealed vulnerabilities, leading to corrective planning and operational actions, emphasizing the need for both immediate and long-term planning to ensure system reliability.