# 16:332:599:02 – Smart Grid

## Project Report

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# 1 Case Study/Problem Formulation

For the single-line diagram in Figure 4 convert all positive-sequence impedance, load, and voltage data to per unit using the given system base quantities. Run the power flow program and obtain the bus, line, and transformer input/output voltages

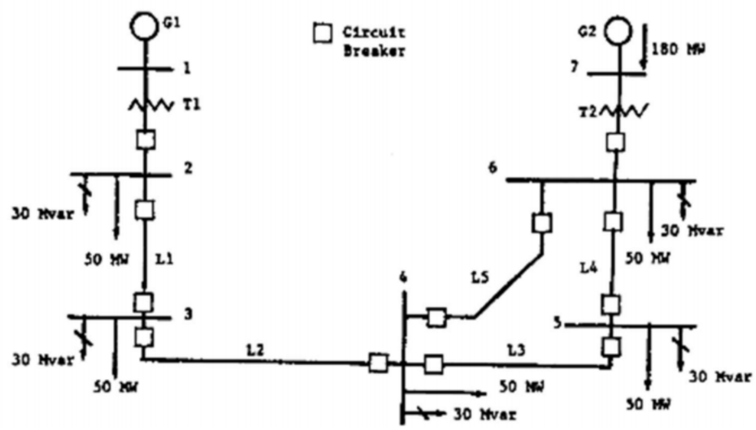



Figure 1: Original Circuit

| Generator Ratings | |
|---|---|
| **G1** | $100MVA$, $13.8kV$, $x'' = 0.12$ |
| **G2** | $200MVA$, $15.0kV$, $x'' = 0.12$ |
| *The generator neutrals are solidly grounded* | |

| Transformer Ratings | |
|---|---|
| **T1** | $100MVA$, $13.8kV\Delta/230kVY$, $x = 0.1$ per unit |
| **T2** | $200MVA$, $15kV\Delta/230kVY$, $x = 0.1$ per unit |
| *The transformer neutrals are solidly grounded* | |

| Transmission Line Ratings | |
|---|---|
| **All Lines** | $230kV$, $z_1 = 0.08 + j0.5\Omega/km$, $y_1 = j3.3E-6S/km$, $Max\ MVA = 400$ |
| **Line Lengths** | $L_1 = 15km$, $L_2 = 20km$, $L_3 = 40km$, $L_4 = 15km$, $L_5 = 50km$ |

| Power Flow Data | |
|---|---|
| **Bus 1** | Swing bus $V_1 = 13.8kV$, $\partial_1 = 0°$ |
| **Bus 2, 3, 4, 5, 6** | Load buses |
| **Bus 7** | Constant voltage magnitude bus, $V_7 = 15kV$, $P_{G7} = 180MW$, $-87MVAr < Q_{G7} < +87MVAr$ |

| System Base Quantities |
|---|
| $S_{base} = 100MVA$ (three-phase) |
| $V_{base} = 13.8kV$ (line-to-line) in the zone of $G_1$ |

Table 1: Circuit Values

# 2 Detailed Solution

## 2.1 Calculating Per Unit Values

$$per\ unit\ (pu)\ value = \frac{Actual\ value}{Base\ value}$$

In zone $G1$, base values are,

$$S_{base} = 100MVA$$

$$V_{base_{L-L}} = 13.8kV$$

@ $G1$

$$S_{G1_{(pu)}} = \frac{100MVA}{100MVA} = \boxed{1pu}$$

$$V_{G1_{(pu)}} = \frac{13.8kV}{13.8kV} = \boxed{1pu}$$

$$x''_{(new)} = \boxed{0.12pu}$$

@ $T1$

$$S_{T1_{(pu)}} = \frac{100MVA}{100MVA} = \boxed{1pu}$$

$$V_{T1_{(pu)}} = \frac{13.8kV}{13.8kV} = \boxed{1pu}$$

$$x_{(pu)} = \boxed{0.1pu}$$

@ Bus 2

$$Q_{Load} = 30MVAr$$

$$Q_{Load_{(pu)}} = \frac{30MVAr}{100MVA} = \boxed{0.3pu}$$

$$P_{Load} = 50MW$$

$$P_{Load_{(pu)}} = \frac{50MW}{100MVA} = \boxed{0.5pu}$$

@ $L_1$

$$L_1 = 15km$$

$$z = 0.08 + j0.5\Omega/km$$

$$Z_{total} = (15km)(0.08 + j0.5\Omega/km) = \boxed{1.2 + j7.5\Omega}$$

$$\theta = tan^{-1}\left(\frac{7.5}{1.2}\right) = \boxed{80.91^\circ}$$

$$|Z_{total}| = \sqrt{(1.2)^2 + (7.5)^2} = \boxed{7.59539\Omega}$$

$$Z_{total} = \boxed{7.59539\angle 80.91°\Omega}$$
$$Z_{total_{(pu)}} = 7.595 \cdot \left(\frac{100MVA}{(230kV)^2}\right) = \boxed{0.014358pu}$$

@ Bus 3

$$Q_{Load} = 30MVAr$$
$$Q_{Load_{(pu)}} = \frac{30MVAr}{100MVA} = \boxed{0.3pu}$$
$$P_{Load} = 50MW$$
$$P_{Load_{(pu)}} = \frac{50MW}{100MVA} = \boxed{0.5pu}$$

@ Bus 4

$$Q_{Load} = 30MVAr$$
$$Q_{Load_{(pu)}} = \frac{30MVAr}{100MVA} = \boxed{0.3pu}$$
$$P_{Load} = 50MW$$
$$P_{Load_{(pu)}} = \frac{50MW}{100MVA} = \boxed{0.5pu}$$

@ Bus 5

$$Q_{Load} = 30MVAr$$
$$Q_{Load_{(pu)}} = \frac{30MVAr}{100MVA} = \boxed{0.3pu}$$
$$P_{Load} = 50MW$$
$$P_{Load_{(pu)}} = \frac{50MW}{100MVA} = \boxed{0.5pu}$$

@ Bus 6

$$Q_{Load} = 30MVAr$$
$$Q_{Load_{(pu)}} = \frac{30MVAr}{100MVA} = \boxed{0.3pu}$$
$$P_{Load} = 50MW$$
$$P_{Load_{(pu)}} = \frac{50MW}{100MVA} = \boxed{0.5pu}$$

@ $L_2$

$$L_2 = 20km$$
$$z = 0.08 + j0.5\Omega/km$$

$$Z_{total} = (20km)(0.08 + j0.5\Omega/km) = \boxed{1.6 + j10\Omega}$$

$$\theta = tan^{-1}\left(\frac{10}{1.6}\right) = \boxed{80.91^\circ}$$

$$|Z_{total}| = \sqrt{(1.6)^2 + (10)^2} = \boxed{10.127191\Omega}$$

$$Z_{total} = \boxed{10.127191\angle 80.91^\circ\Omega}$$

$$Z_{total_{(pu)}} = 10.127191 \cdot \left(\frac{100MVA}{(230kV)^2}\right) = \boxed{0.019144pu}$$

@ $L_3$

$$L_3 = 40km$$

$$z = 0.08 + j0.5\Omega/km$$

$$Z_{total} = (40km)(0.08 + j0.5\Omega/km) = \boxed{3.2 + j20\Omega}$$

$$\theta = tan^{-1}\left(\frac{20}{3.2}\right) = \boxed{80.91^\circ}$$

$$|Z_{total}| = \sqrt{(3.2)^2 + (20)^2} = \boxed{20.254382\Omega}$$

$$Z_{total} = \boxed{20.254382\angle 80.91^\circ\Omega}$$

$$Z_{total_{(pu)}} = 20.254382 \cdot \left(\frac{100MVA}{(230kV)^2}\right) = \boxed{0.038288pu}$$

@ $L_4$

$$L_4 = 15km$$

$$z = 0.08 + j0.5\Omega/km$$

$$Z_{total} = (15km)(0.08 + j0.5\Omega/km) = \boxed{1.2 + j7.5\Omega}$$

$$\theta = tan^{-1}\left(\frac{7.5}{1.2}\right) = \boxed{80.91^\circ}$$

$$|Z_{total}| = \sqrt{(1.2)^2 + (7.5)^2} = \boxed{7.59539\Omega}$$

$$Z_{total} = \boxed{7.59539\angle 80.91^\circ\Omega}$$

$$Z_{total_{(pu)}} = 7.595 \cdot \left(\frac{100MVA}{(230kV)^2}\right) = \boxed{0.014358pu}$$

@ $L_5$

$$L_5 = 50km$$

$$z = 0.08 + j0.5\Omega/km$$

$$Z_{total} = (50km)(0.08 + j0.5\Omega/km) = \boxed{4 + j25\Omega}$$

$$\theta = tan^{-1}\left(\frac{25}{4}\right) = \boxed{80.91^\circ}$$

$$|Z_{total}| = \sqrt{(4)^2 + (25)^2} = \boxed{25.317978\Omega}$$

$$Z_{total} = \boxed{25.317978\angle 80.91°\Omega}$$

$$Z_{total_{(pu)}} = 25.317978 \cdot \left(\frac{100MVA}{(230kV)^2}\right) = \boxed{0.04786pu}$$

@ Bus 7

$$P_{G7_{(pu)}} = \frac{180MW}{100MVA} = \boxed{1.8pu}$$

$$\frac{-87MVAr}{100} < Q_{G7_{(pu)}} < \frac{87MVAr}{100}$$

$$-0.87pu < Q_{G7_{(pu)}} < 0.87pu$$

$$V_{T2_{(pu)}} = \frac{15kV}{13.8kV} = \boxed{1.086956pu}$$

### 2.1.1 Per-Unit One-Line Model

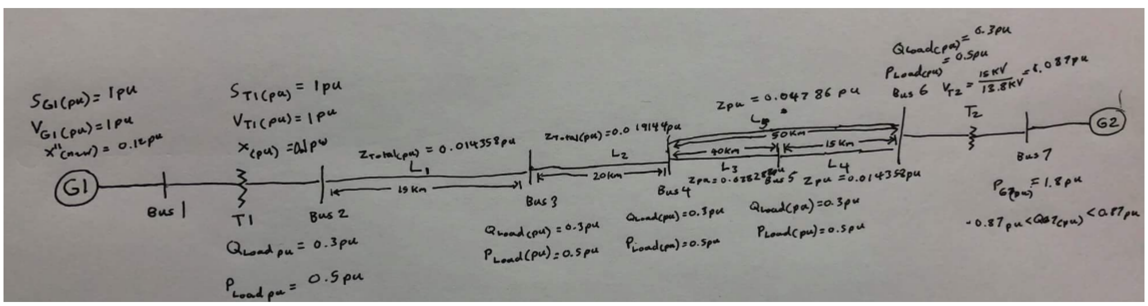



Figure 2: Per-Unit One-line Diagram

## 2.2 Compute All Bus Voltages

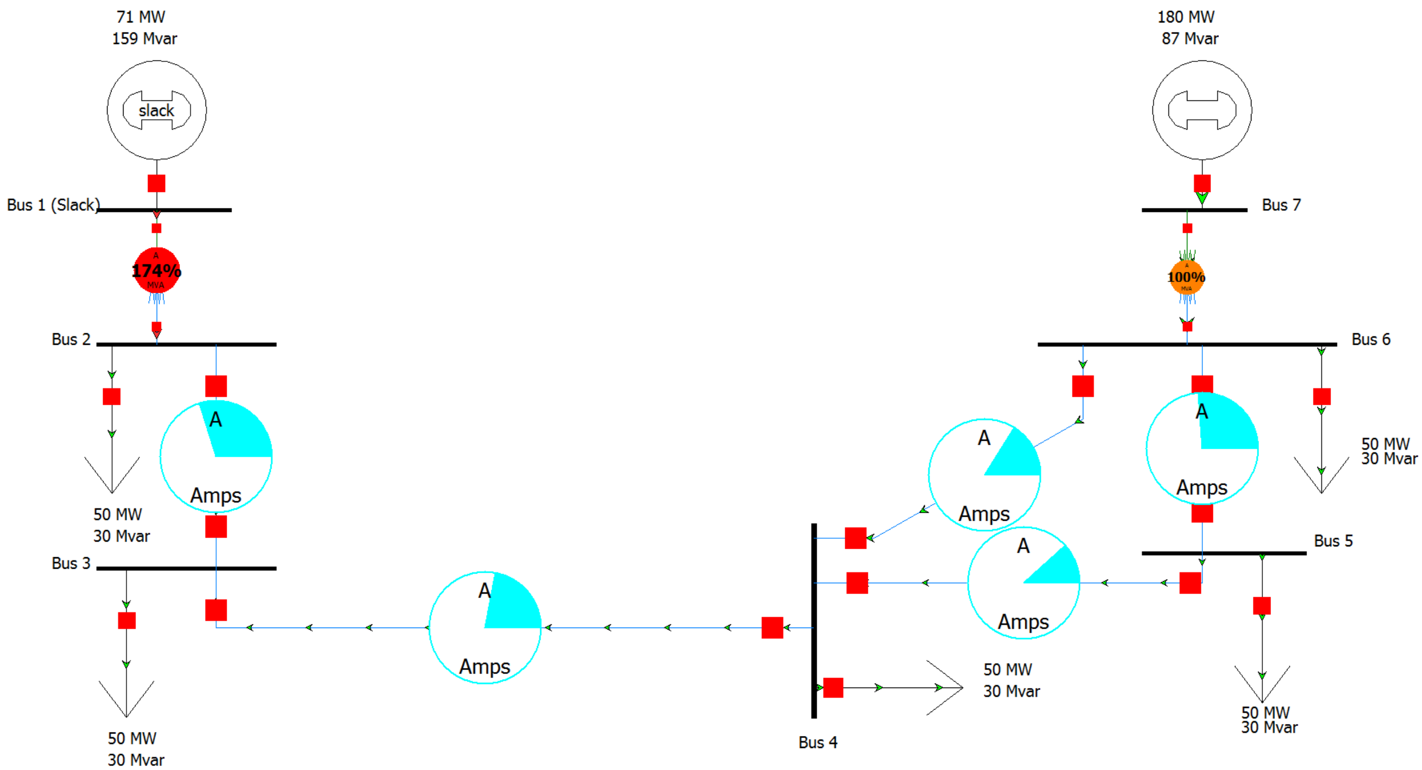



Figure 3: PowerWorld Diagram

### 2.2.1 Newton-Raphson Method

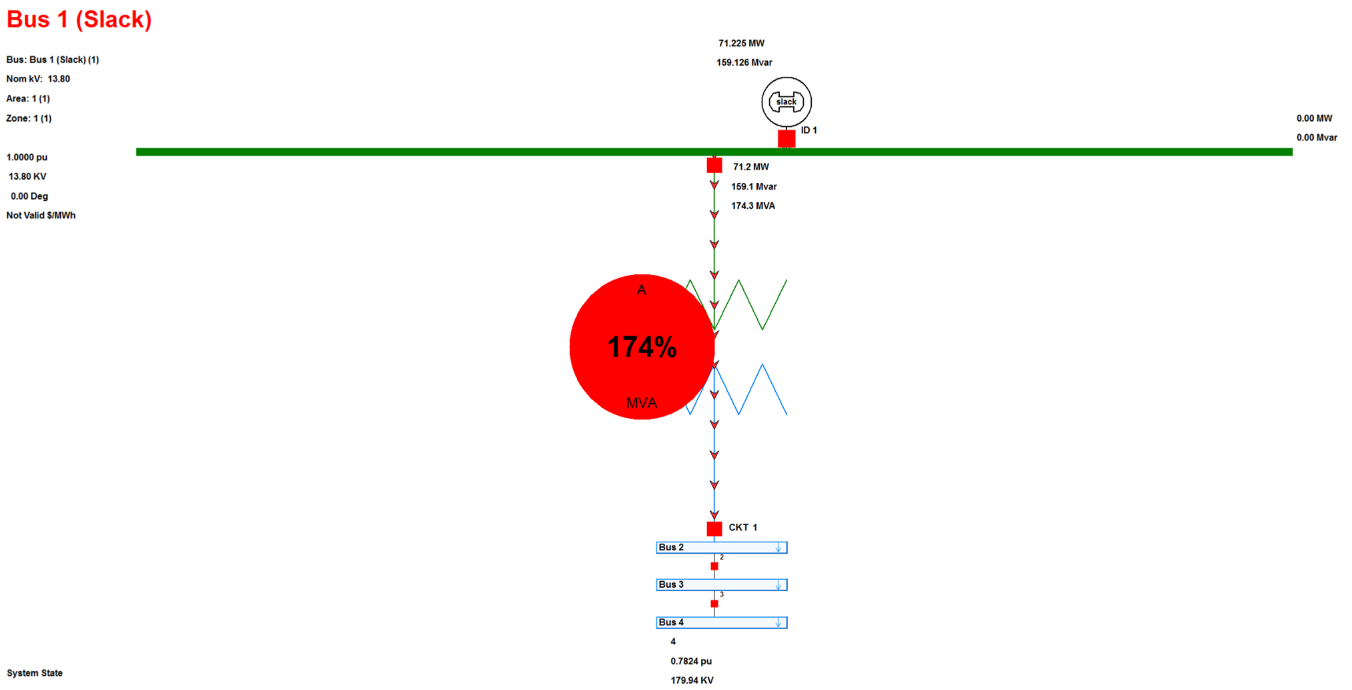



Figure 4: PowerWorld Diagram

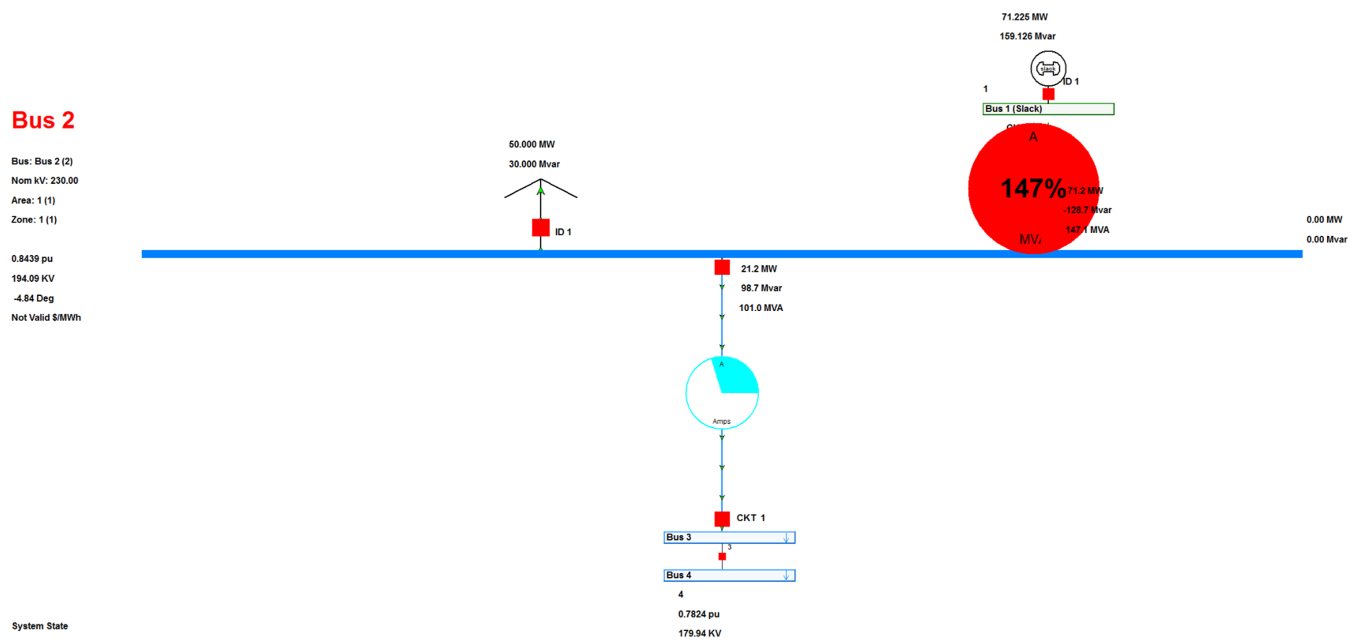



Figure 5: PowerWorld Diagram

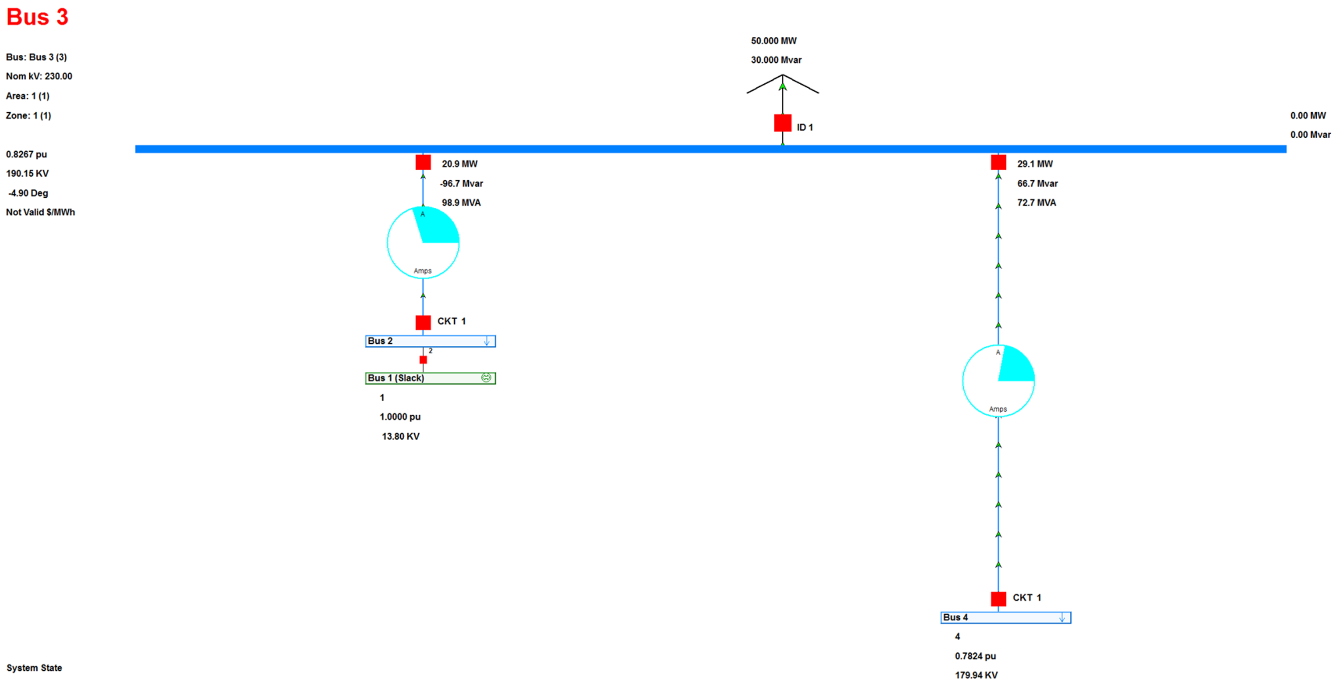



Figure 6: PowerWorld Diagram

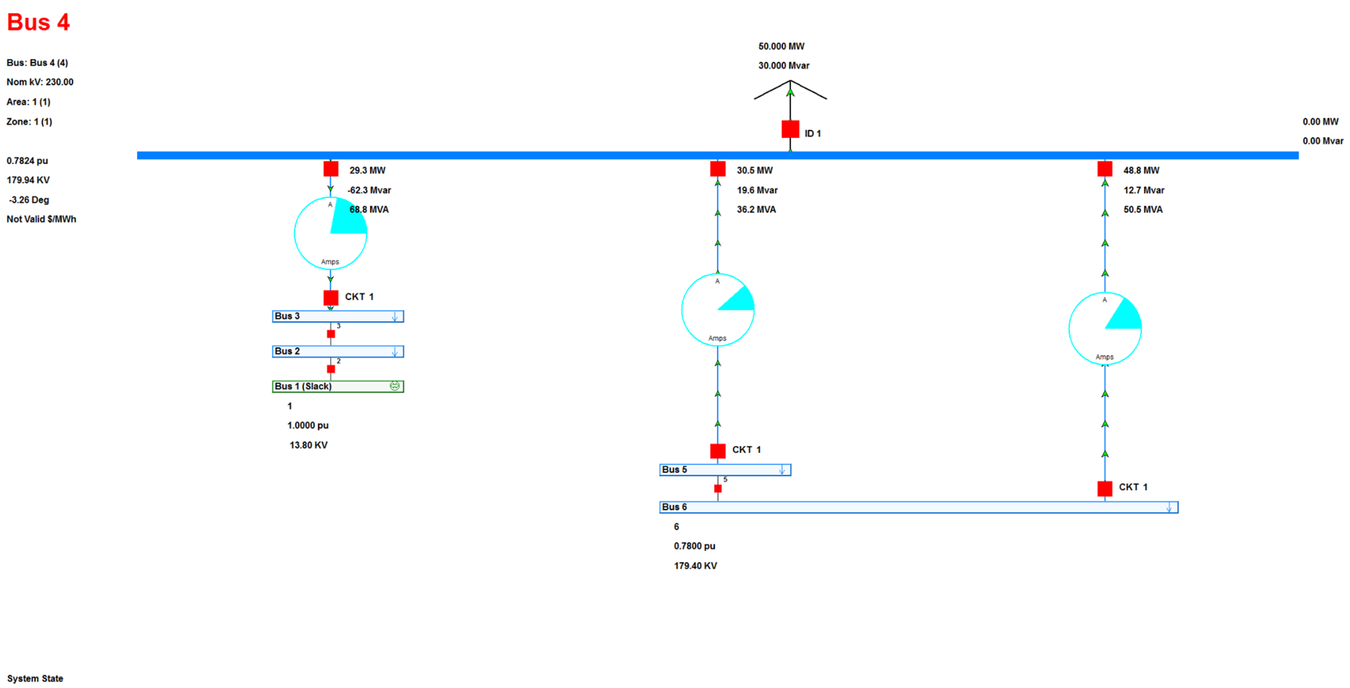



Figure 7: PowerWorld Diagram

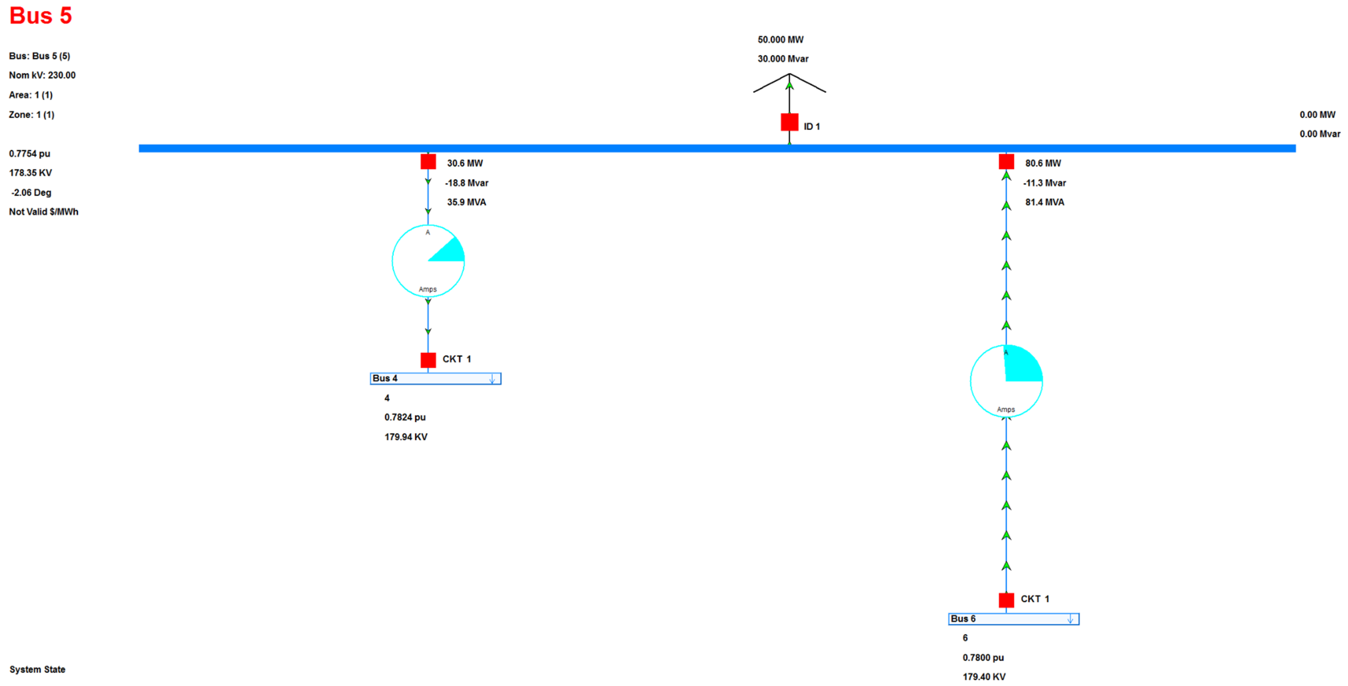



Figure 8: PowerWorld Diagram

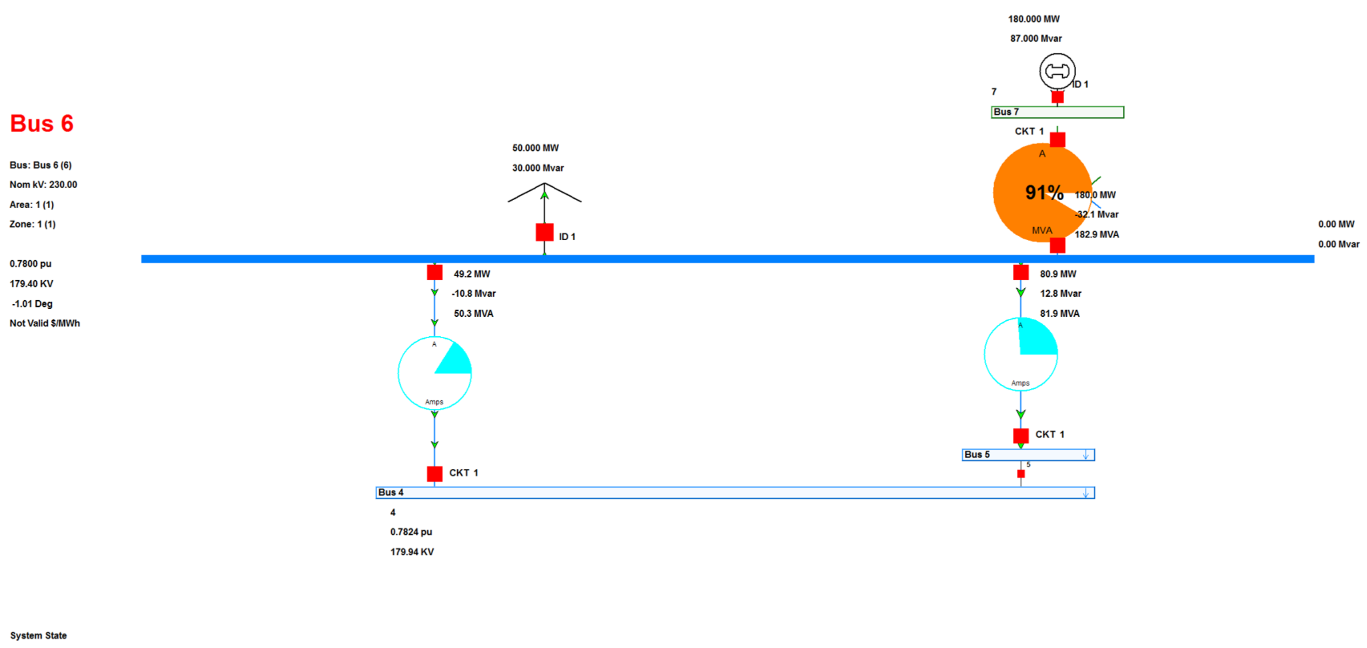



Figure 9: PowerWorld Diagram

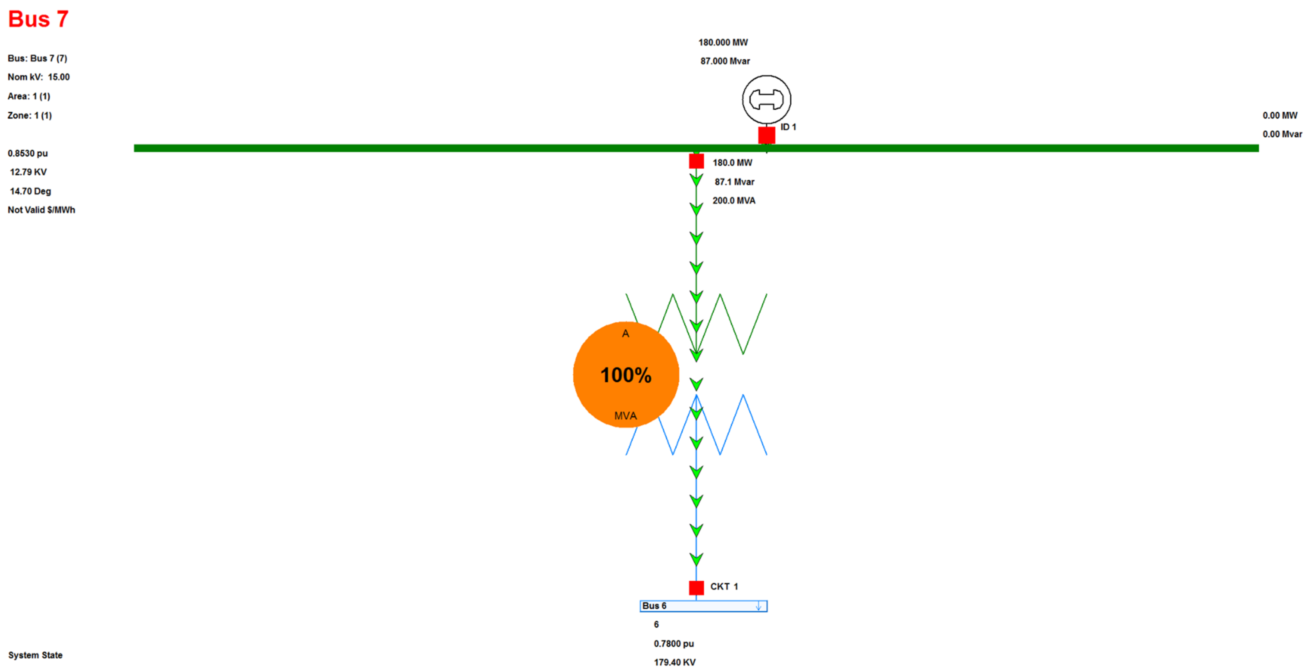
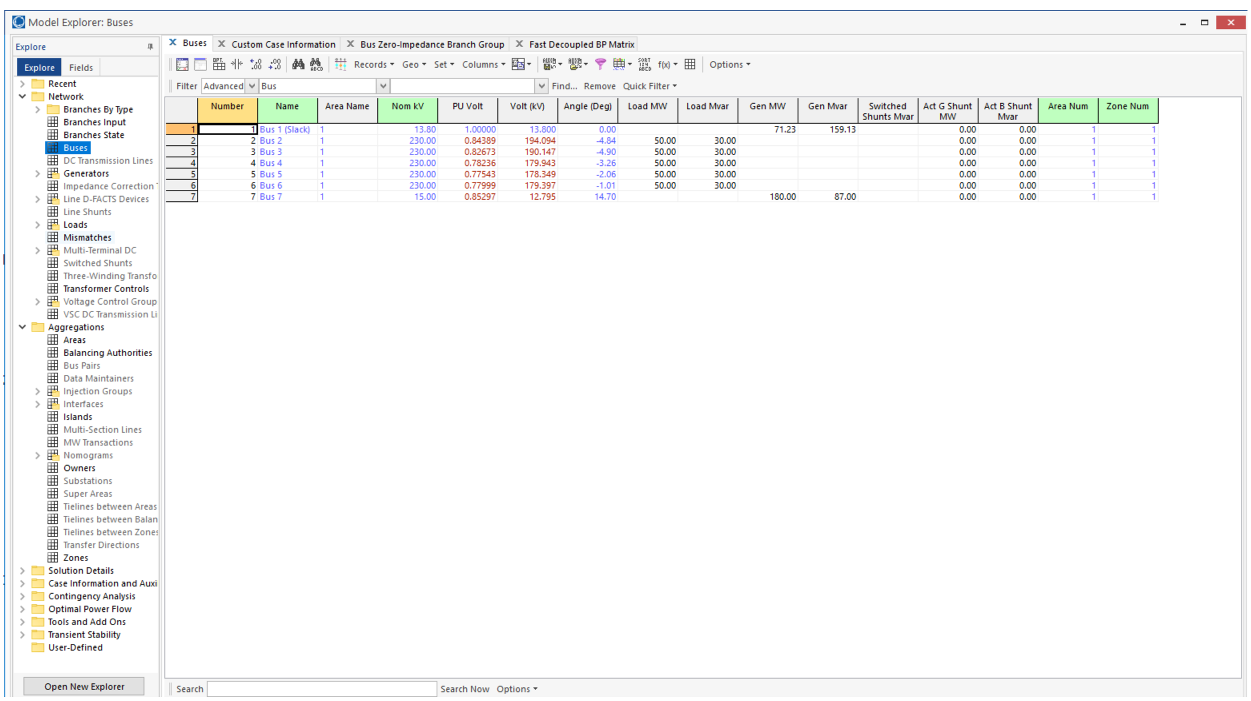



Figure 10: PowerWorld Diagram



| | Number | Name | Area Name | Nom kV | PU Volt | Volt (kV) | Angle (Deg) | Load MW | Load Mvar | Gen MW | Gen Mvar | Switched Shunts Mvar | Act G Shunt MW | Act B Shunt Mvar | Area Num | Zone Num |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | Bus 1 (Slack) | 1 | 13.80 | 1.00000 | 13.800 | 0.00 | | | 71.23 | 159.13 | | 0.00 | 0.00 | 1 | 1 |
| 2 | 2 | Bus 2 | 1 | 230.00 | 0.84389 | 194.094 | -4.84 | 50.00 | 30.00 | | | | 0.00 | 0.00 | 1 | 1 |
| 3 | 3 | Bus 3 | 1 | 230.00 | 0.82673 | 190.147 | -4.90 | 50.00 | 30.00 | | | | 0.00 | 0.00 | 1 | 1 |
| 4 | 4 | Bus 4 | 1 | 230.00 | 0.78236 | 179.943 | -3.26 | 50.00 | 30.00 | | | | 0.00 | 0.00 | 1 | 1 |
| 5 | 5 | Bus 5 | 1 | 230.00 | 0.77543 | 178.349 | -2.06 | 50.00 | 30.00 | | | | 0.00 | 0.00 | 1 | 1 |
| 6 | 6 | Bus 6 | 1 | 230.00 | 0.77999 | 179.397 | -1.01 | 50.00 | 30.00 | | | | 0.00 | 0.00 | 1 | 1 |
| 7 | 7 | Bus 7 | 1 | 15.00 | 0.85297 | 12.795 | 14.70 | | | 180.00 | 87.00 | | 0.00 | 0.00 | 1 | 1 |

Figure 11: PowerWorld Diagram - Buses

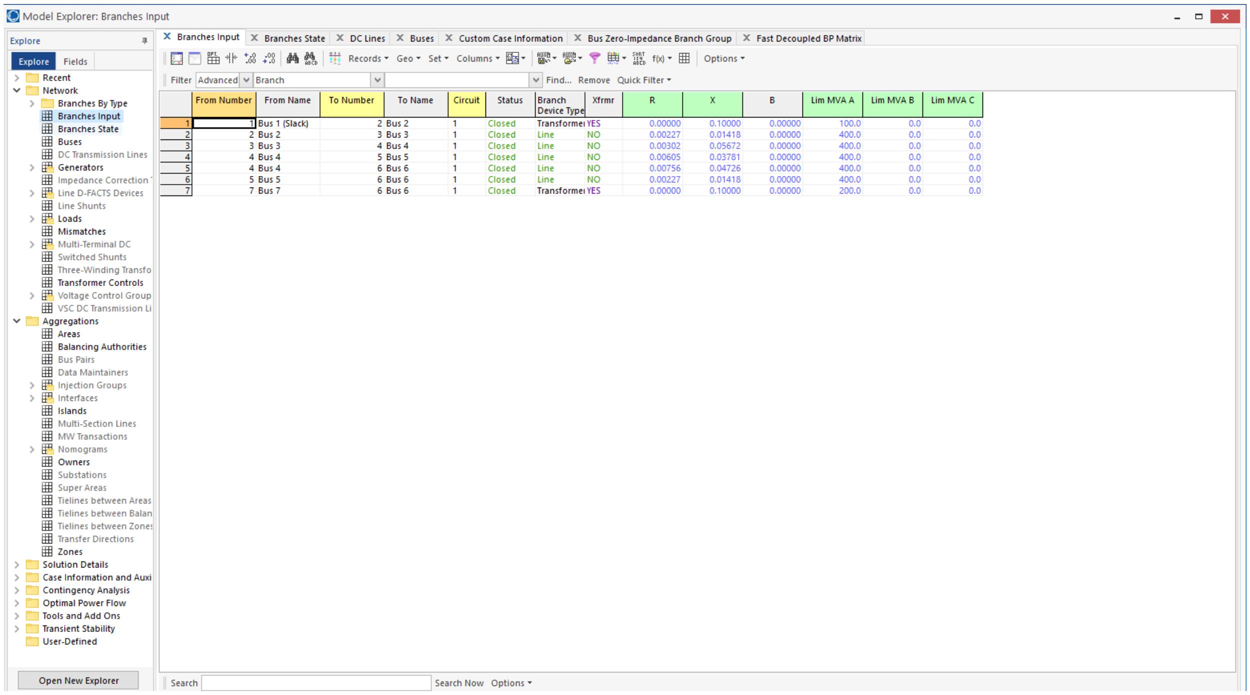



Figure 12: PowerWorld Diagram - Branch Inputs

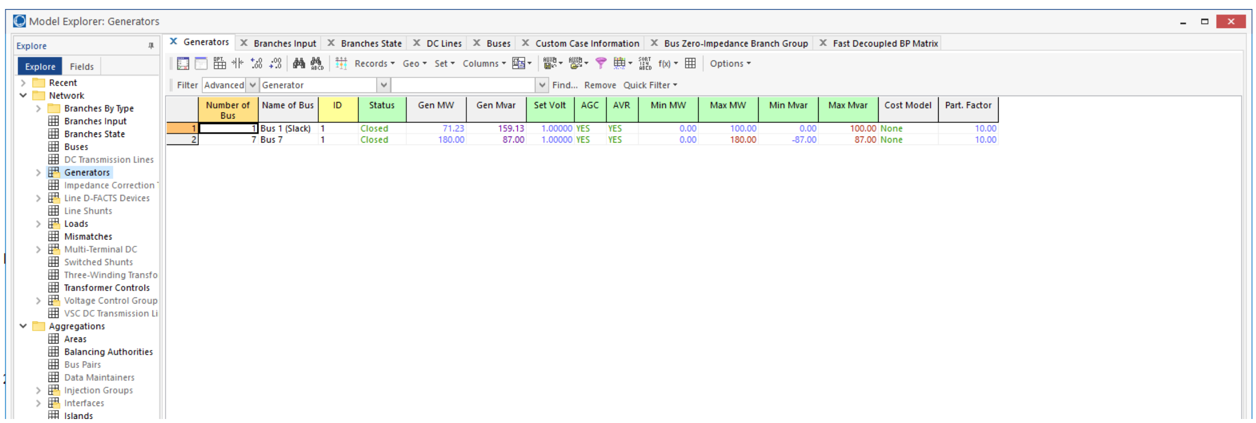



Figure 13: PowerWorld Diagram - Generators

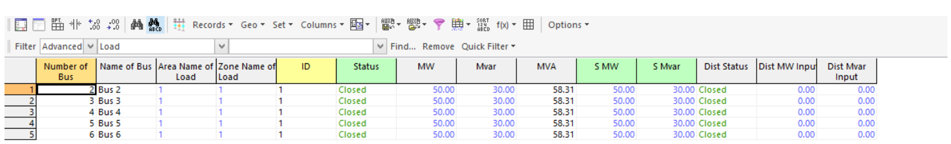



Figure 14: PowerWorld Diagram

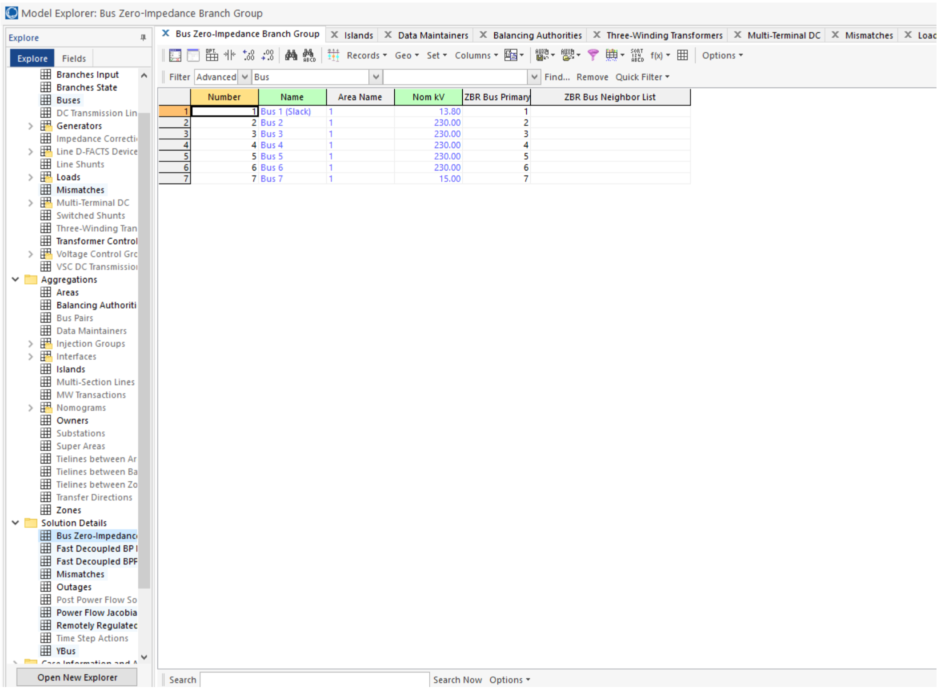



Figure 15: PowerWorld Diagram - Bus Zero Impedance Branch Groups

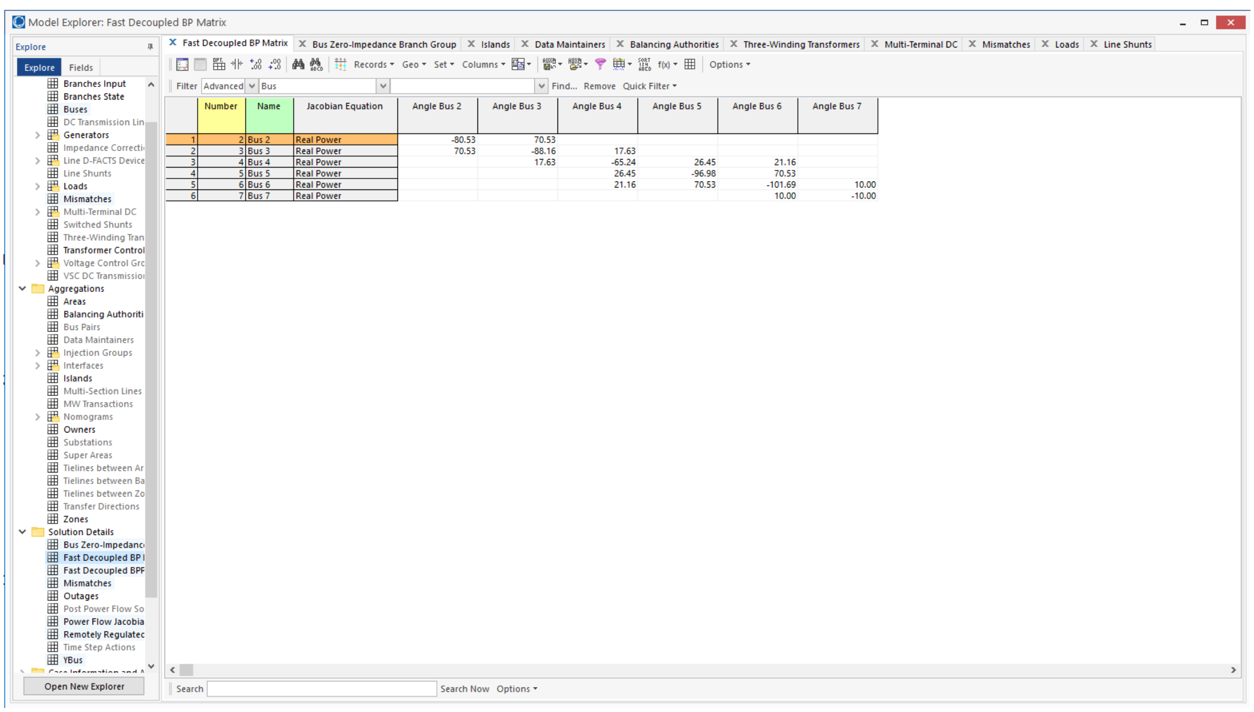
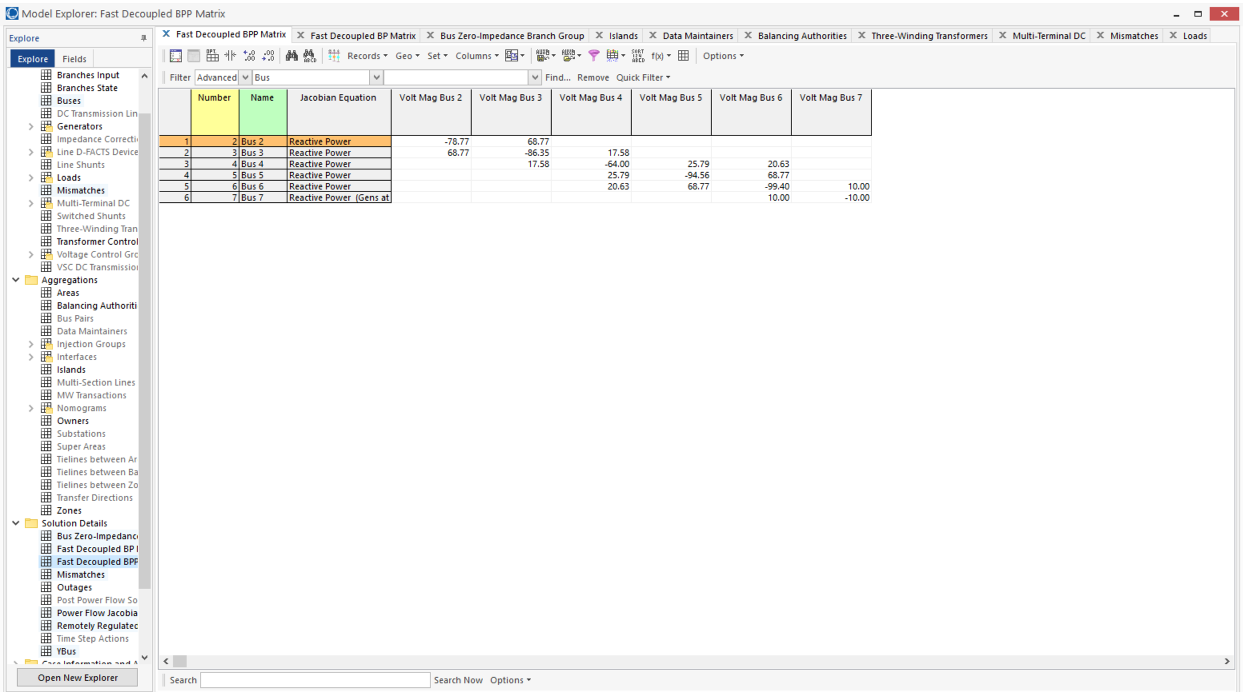
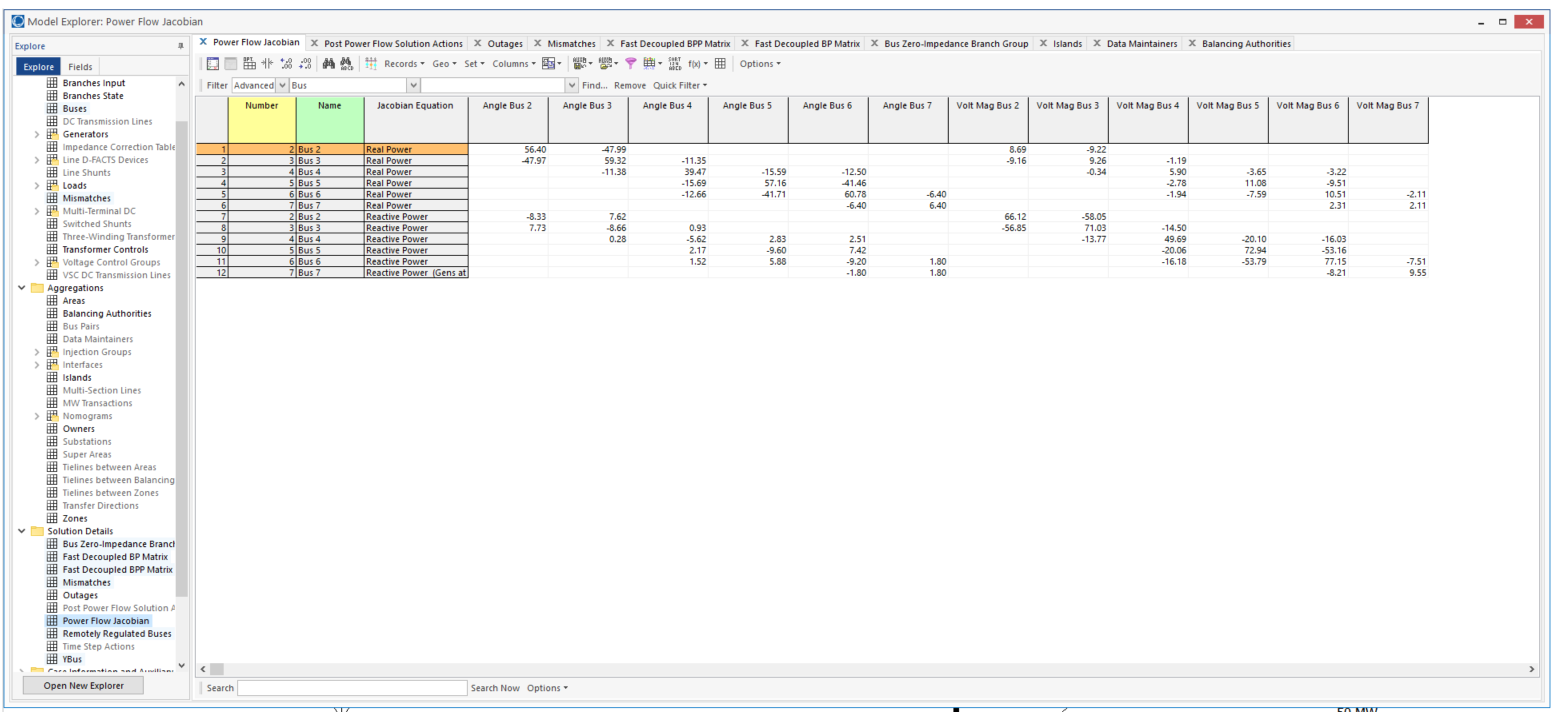



Figure 16: PowerWorld Diagram - Fast Decoupled BP Matrix




| | Number | Name | Jacobian Equation | Volt Mag Bus 2 | Volt Mag Bus 3 | Volt Mag Bus 4 | Volt Mag Bus 5 | Volt Mag Bus 6 | Volt Mag Bus 7 |
|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | Bus 2 | Reactive Power | -78.77 | 68.77 | | | | |
| 2 | 3 | Bus 3 | Reactive Power | 68.77 | -86.35 | 17.58 | | | |
| 3 | 4 | Bus 4 | Reactive Power | | 17.58 | -64.00 | 25.79 | 20.63 | |
| 4 | 5 | Bus 5 | Reactive Power | | | 25.79 | -94.56 | 68.77 | |
| 5 | 6 | Bus 6 | Reactive Power | | | 20.63 | 68.77 | -99.40 | 10.00 |
| 6 | 7 | Bus 7 | Reactive Power (Gens at | | | | | 10.00 | -10.00 |

Figure 17: PowerWorld Diagram - Fast Decoupled BPP Matrix




| | Number | Name | Jacobian Equation | Angle Bus 2 | Angle Bus 3 | Angle Bus 4 | Angle Bus 5 | Angle Bus 6 | Angle Bus 7 | Volt Mag Bus 2 | Volt Mag Bus 3 | Volt Mag Bus 4 | Volt Mag Bus 5 | Volt Mag Bus 6 | Volt Mag Bus 7 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | Bus 2 | Real Power | 56.40 | -47.99 | | | | | 8.69 | -9.22 | | | | |
| 2 | 3 | Bus 3 | Real Power | -47.97 | 59.32 | -11.35 | | | | -9.16 | 9.26 | -1.19 | | | |
| 3 | 4 | Bus 4 | Real Power | | -11.38 | 39.47 | -15.59 | -12.50 | | | -0.34 | 5.90 | -3.65 | -3.22 | |
| 4 | 5 | Bus 5 | Real Power | | | -15.69 | 57.16 | -41.46 | | | | -2.78 | 11.08 | -9.51 | |
| 5 | 6 | Bus 6 | Real Power | | | -12.66 | -41.71 | 60.78 | -6.40 | | | -1.94 | -7.59 | 10.51 | -2.11 |
| 6 | 7 | Bus 7 | Real Power | | | | | -6.40 | 6.40 | | | | | 2.31 | 2.11 |
| 7 | 2 | Bus 2 | Reactive Power | -8.33 | 7.62 | | | | | 66.12 | -58.05 | | | | |
| 8 | 3 | Bus 3 | Reactive Power | 7.73 | -8.66 | 0.93 | | | | -56.85 | 71.03 | -14.50 | | | |
| 9 | 4 | Bus 4 | Reactive Power | | 0.28 | -5.62 | 2.83 | 2.51 | | | -13.77 | 49.69 | -20.10 | -16.03 | |
| 10 | 5 | Bus 5 | Reactive Power | | | 2.17 | -9.60 | 7.42 | | | | -20.06 | 72.94 | -53.16 | |
| 11 | 6 | Bus 6 | Reactive Power | | | 1.52 | 5.88 | -9.20 | 1.80 | | | -16.18 | -53.79 | 77.15 | -7.51 |
| 12 | 7 | Bus 7 | Reactive Power (Gens at | | | | | -1.80 | 1.80 | | | | | -8.21 | 9.55 |

Figure 18: PowerWorld Diagram - Powerflow Jacobian Matrix

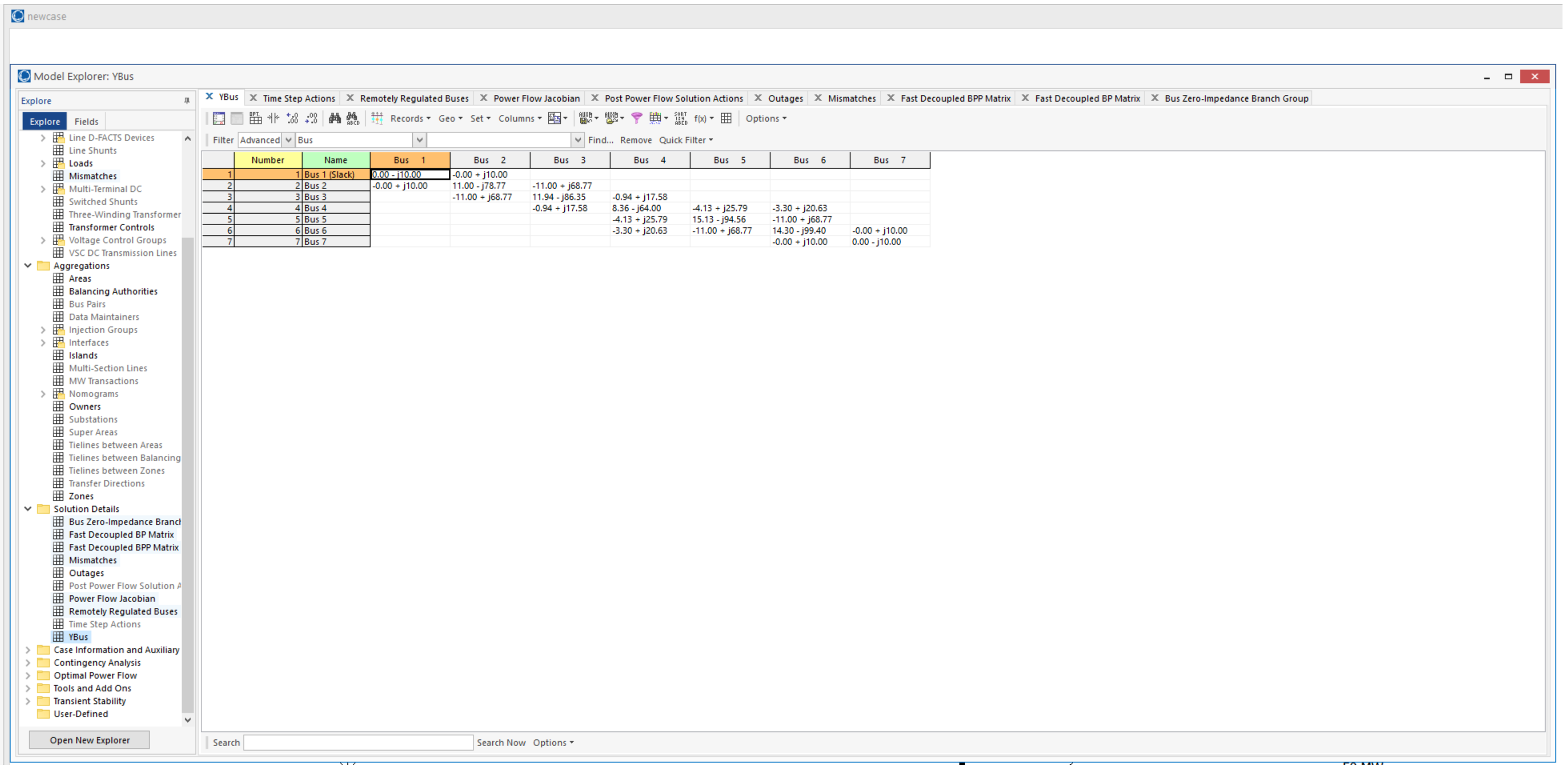



Figure 19: PowerWorld Diagram - Ybus values

## 2.3 Compute All Power Values

Line losses added in

### 2.3.1 Compute Line Losses

$$P_{loss} = \frac{P^2 R}{V^2}$$

@L1

$$Z = 1.2 + j7.5\Omega$$

$$P_{loss} = \frac{100^2 \cdot (1.2 + j7.5)}{13.8^2} = \frac{12000 + j75000}{190.44} = 63.01 + j393.82$$

@L2

$$Z = 1.6 + j10\Omega$$

$$P_{loss} = \frac{100^2 \cdot (1.6 + j10)}{13.8^2} = \frac{16000 + j100000}{190.44} = 84.02 + j525.1$$

@L3

$$3.2 + j20\Omega$$

$$P_{loss} = \frac{100^2 \cdot (3.2 + j20)}{13.8^2} = \frac{32000 + j200000}{190.44} = 168.03 + j1050.2$$

@L4

$$1.2 + j7.5\Omega$$

$$P_{loss} = \frac{100^2 \cdot (1.2 + j7.5)}{13.8^2} = \frac{12000 + j75000}{190.44} = 63.01 + j393.82$$

@L5

$$4 + j25\Omega$$

$$P_{loss} = \frac{100^2 \cdot (4 + j25)}{13.8^2} = \frac{40000 + j250000}{190.44} = 210.04 + j1312.75$$

# 3 Conclusions

What we learned from the PowerWorld simulation is that power flow is slower as we reach the center of the power grid. From the amp meters on the transmission lines we can see that less than 25% of the maximum handled Amps are being transferred through the line. This is unlike at the generators, where the two transformers T1 and T2 are extremely overpowered. We can also see the per unit voltage present at each bus in the following graph:

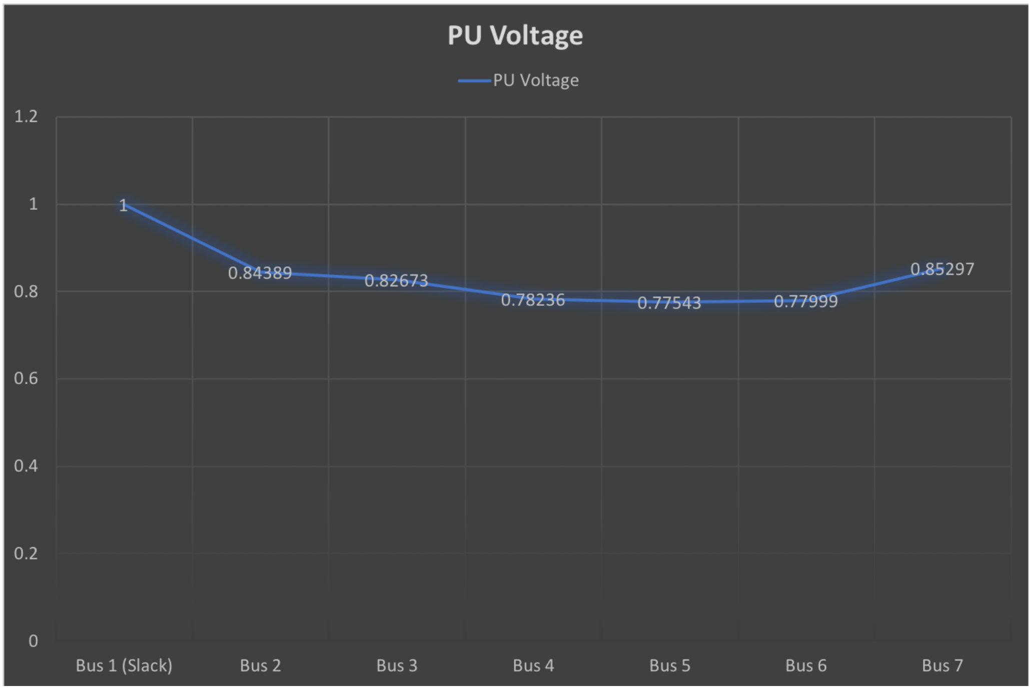



Figure 20: Per Unit Voltages on buses.

We can also see from the nominal voltage expected to what voltage was simulated at the bus points in the following:

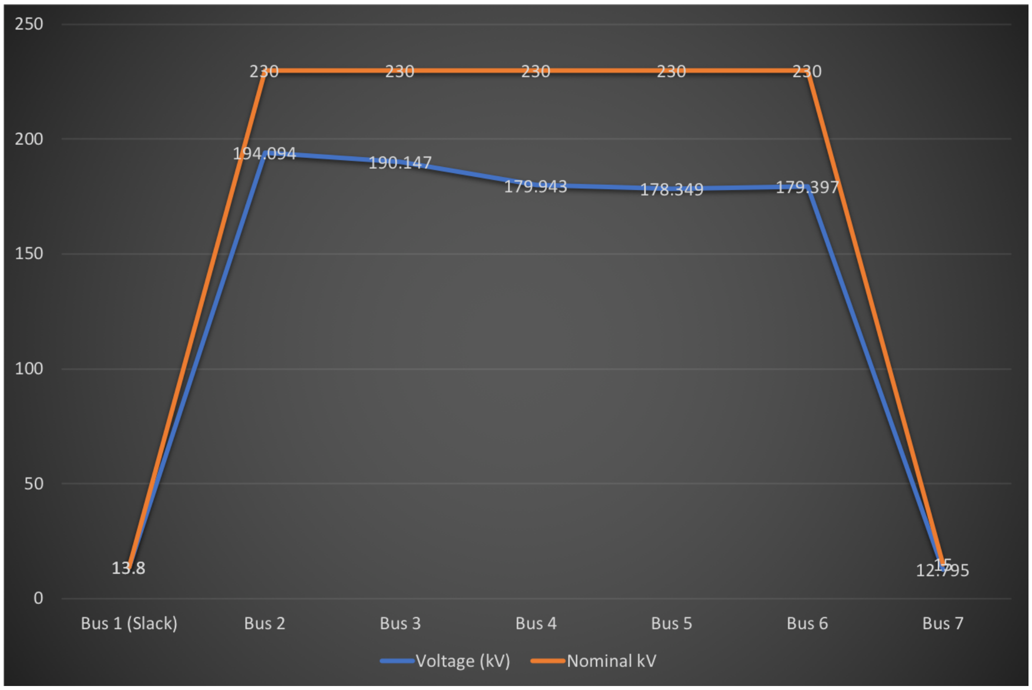



Figure 21: Nominal Voltage vs Actual Voltage of Buses.