16:332:599:02 – Smart Grid
Project Report

By David Lambropoulos, Demetrios Lambropoulos

Professor Hana Godrich
May 9th, 2018

Rutgers University
School of Engineering

Contents

1 Case Study/Problem Formulation **1**

2 Detailed Solution **2**

2.1 Calculating Per Unit Values 2

2.1.1 Per-Unit One-Line Model 5

2.2 Compute All Bus Voltages 6

2.2.1 Newton-Raphson Method 7

2.3 Compute All Power Values 14

2.3.1 Compute Line Losses 14

3 Conclusions **16**

List of Figures

1 Original Circuit . . . 1
2 Per-Unit One-line Diagram . . . 5
3 PowerWorld Diagram . . . 6
4 PowerWorld Diagram . . . 7
5 PowerWorld Diagram . . . 7
6 PowerWorld Diagram . . . 8
7 PowerWorld Diagram . . . 8
8 PowerWorld Diagram . . . 9
9 PowerWorld Diagram . . . 9
10 PowerWorld Diagram . . . 10
11 PowerWorld Diagram . . . 10
12 PowerWorld Diagram . . . 11
13 PowerWorld Diagram . . . 11
14 PowerWorld Diagram . . . 11
15 PowerWorld Diagram . . . 12
16 PowerWorld Diagram . . . 12
17 PowerWorld Diagram . . . 13
18 PowerWorld Diagram . . . 13
19 PowerWorld Diagram . . . 14
20 Per Unit Voltages on buses. . . . 16
21 Nominal Voltage vs Actual Voltage of Buses. . . . 17

List of Tables

1 Circuit Values 1

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

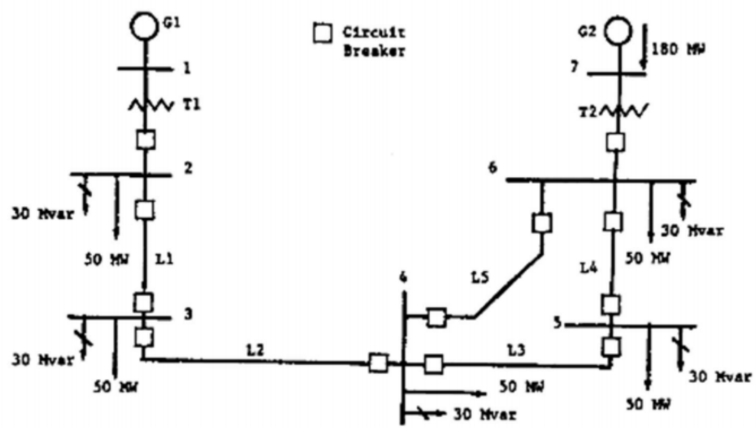


Figure 1: Original Circuit

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

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

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

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

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

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

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

@ L_3

$$L_3 = 40km$$

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

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

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

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

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

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

@ L_4

$$L_4 = 15km$$

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

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

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

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

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

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

@ L_5

$$L_5 = 50km$$

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

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

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

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

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

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

@ 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

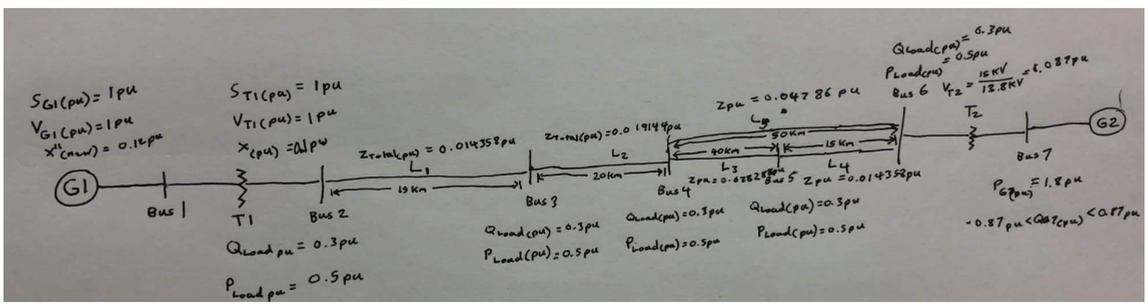


Figure 2: Per-Unit One-line Diagram

2.2 Compute All Bus Voltages

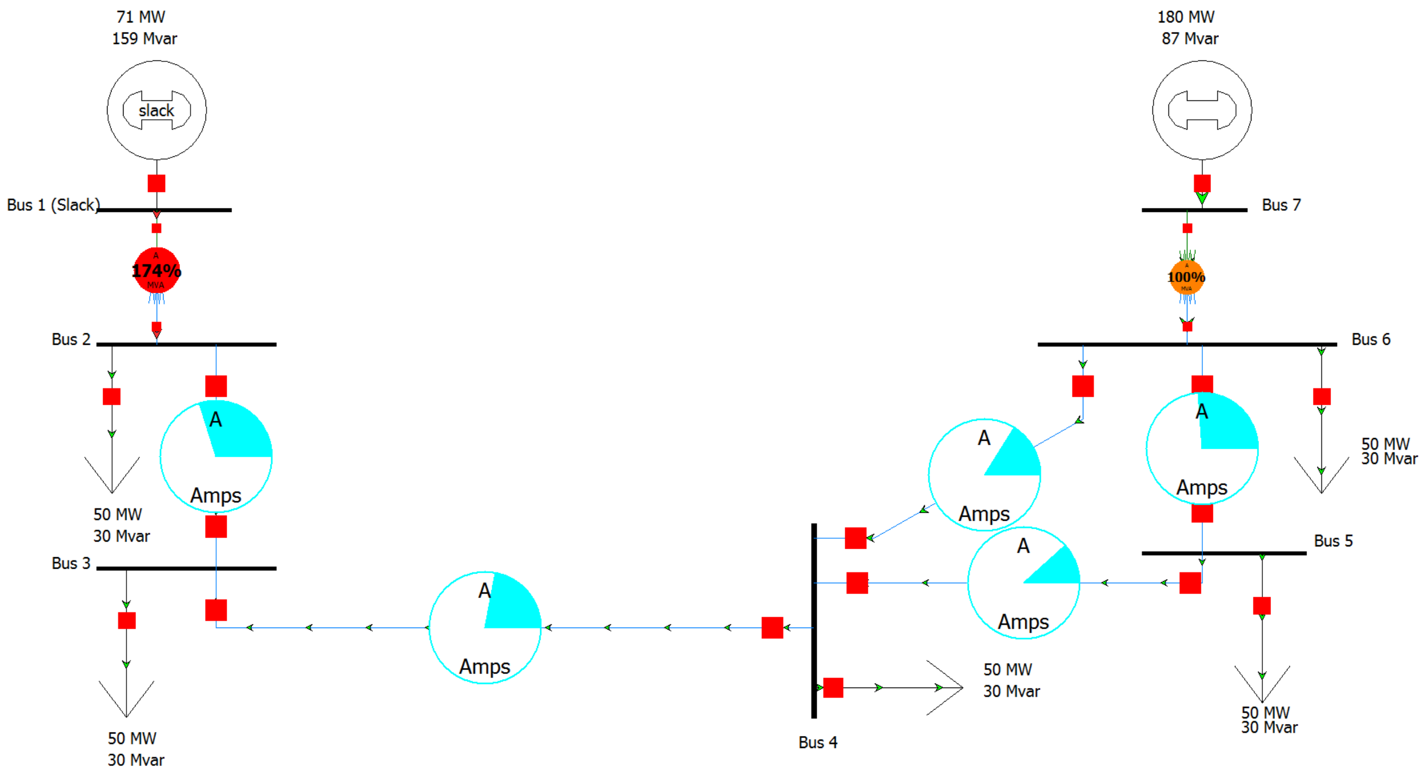


Figure 3: PowerWorld Diagram

2.2.1 Newton-Raphson Method

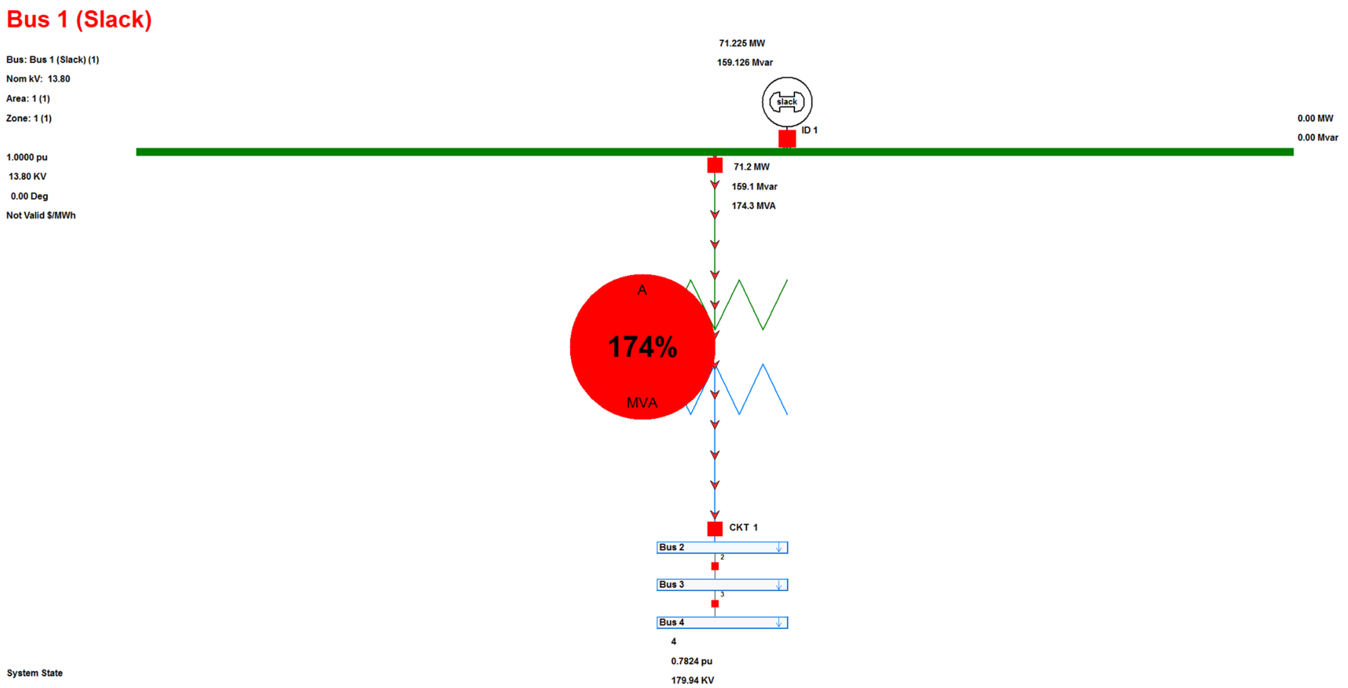


Figure 4: PowerWorld Diagram

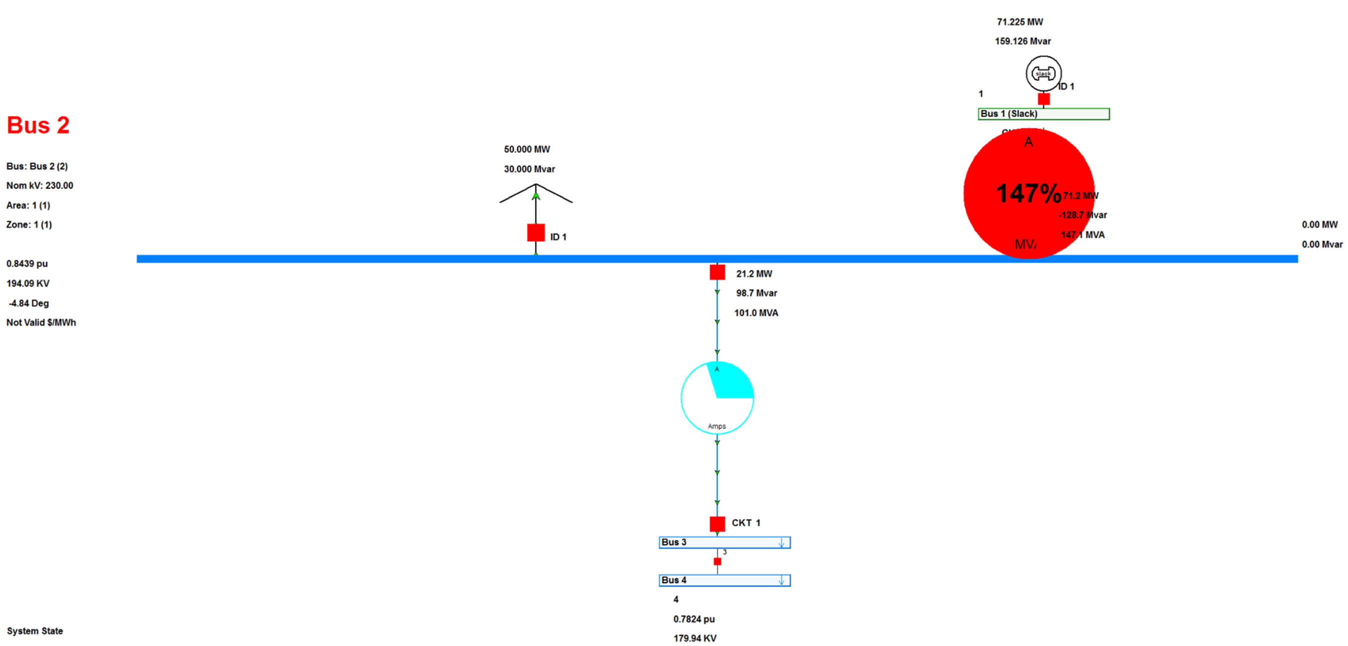


Figure 5: PowerWorld Diagram

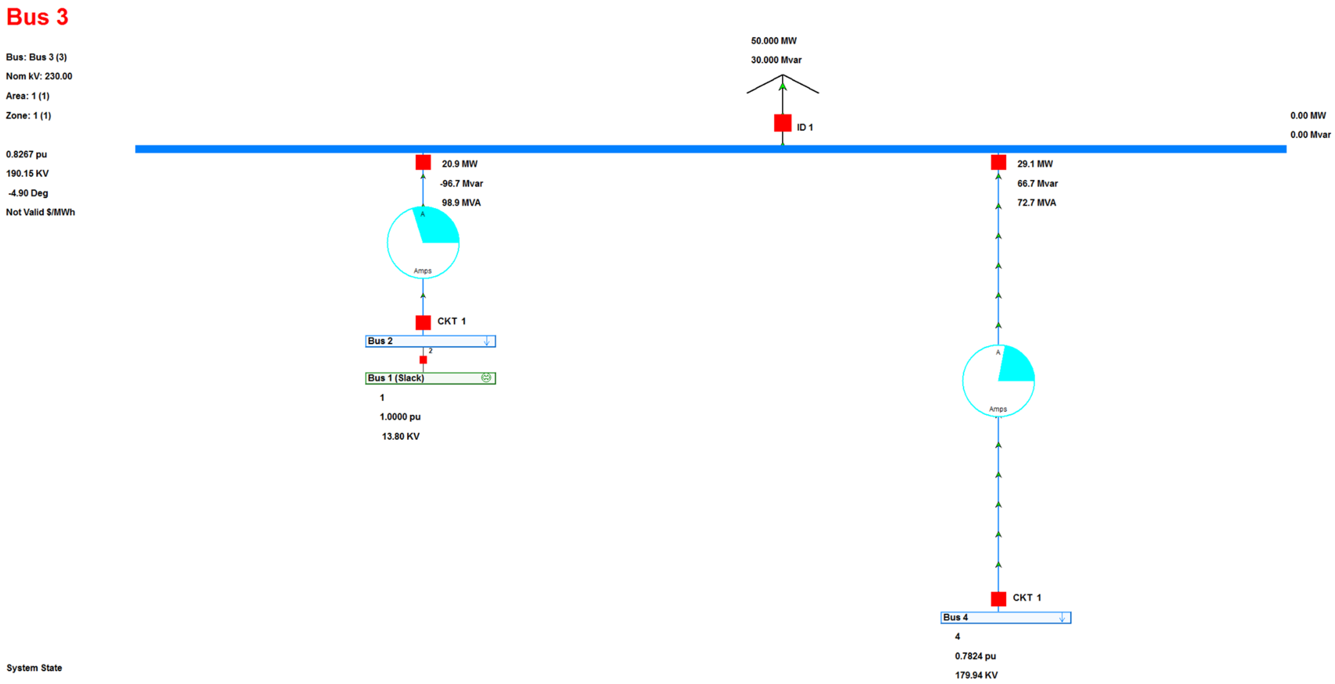


Figure 6: PowerWorld Diagram

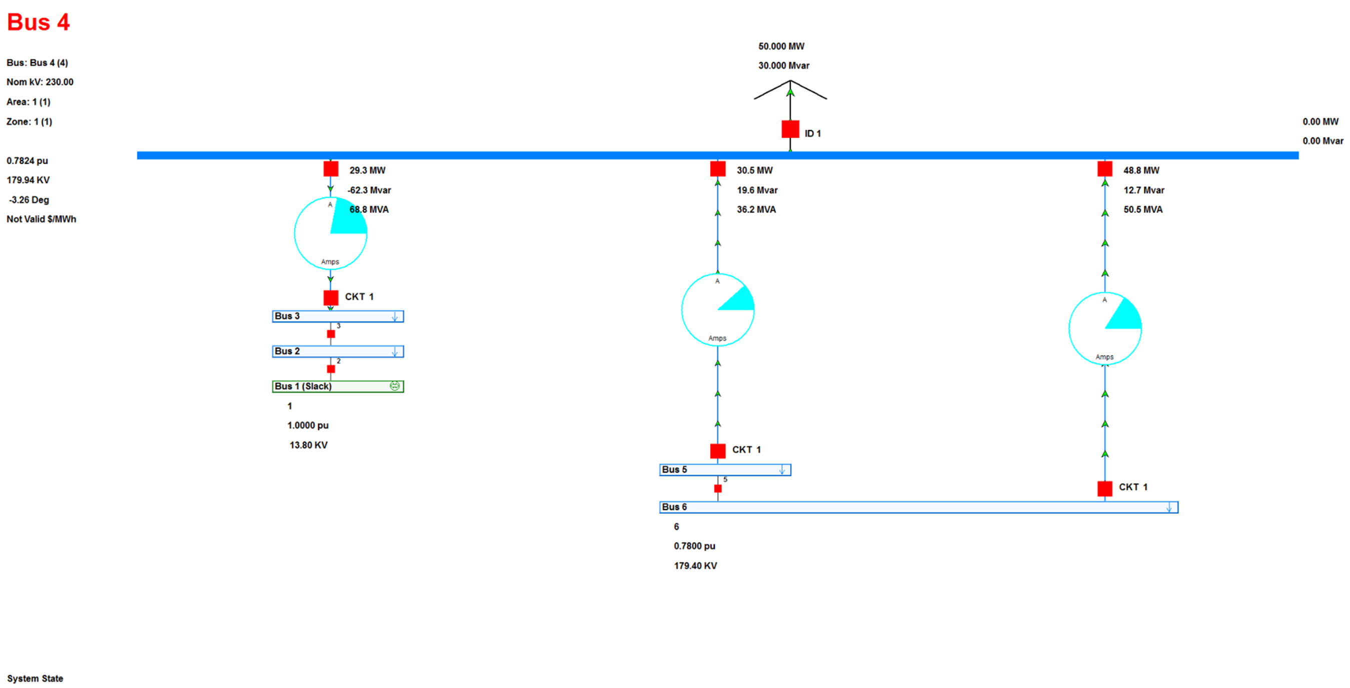


Figure 7: PowerWorld Diagram

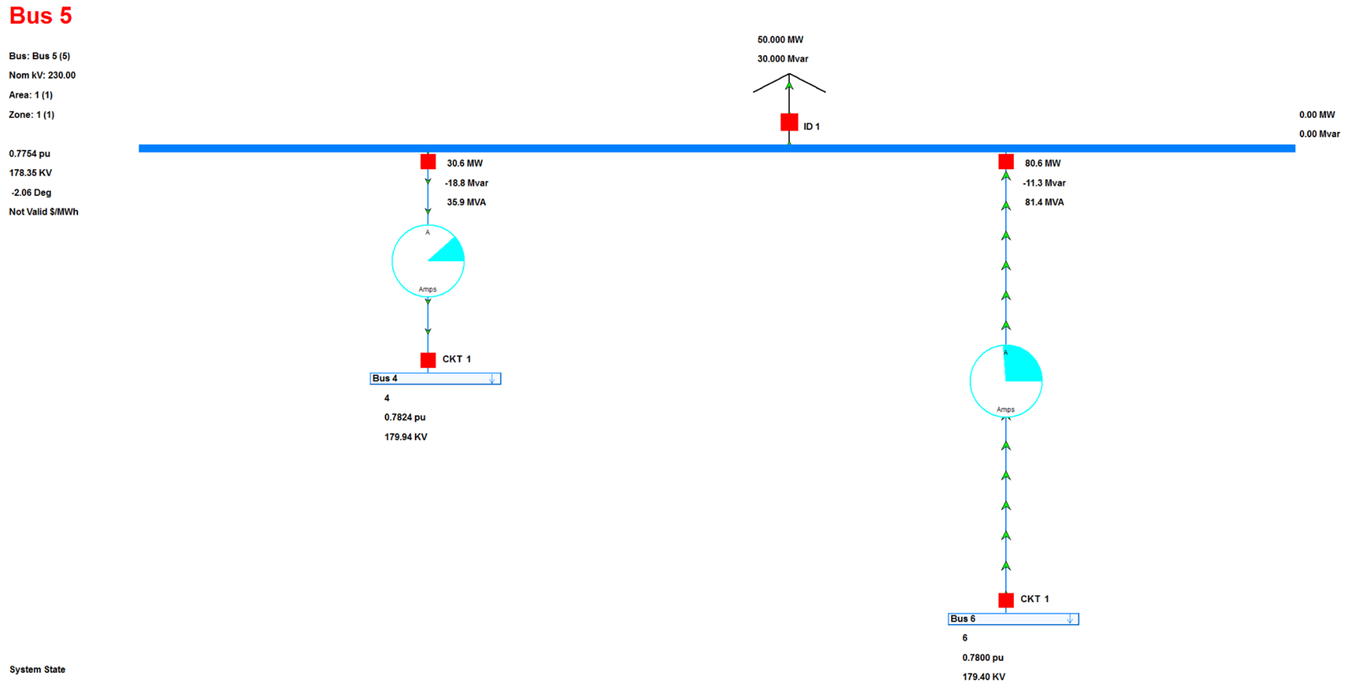


Figure 8: PowerWorld Diagram

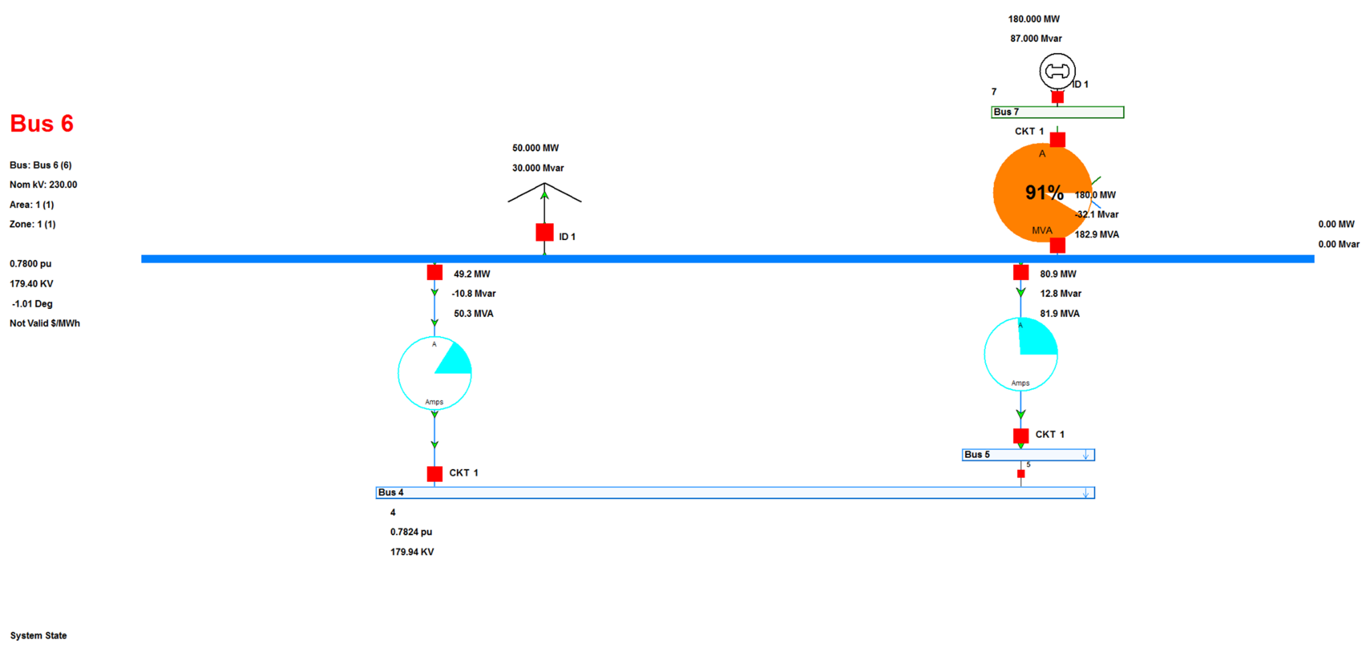


Figure 9: PowerWorld Diagram

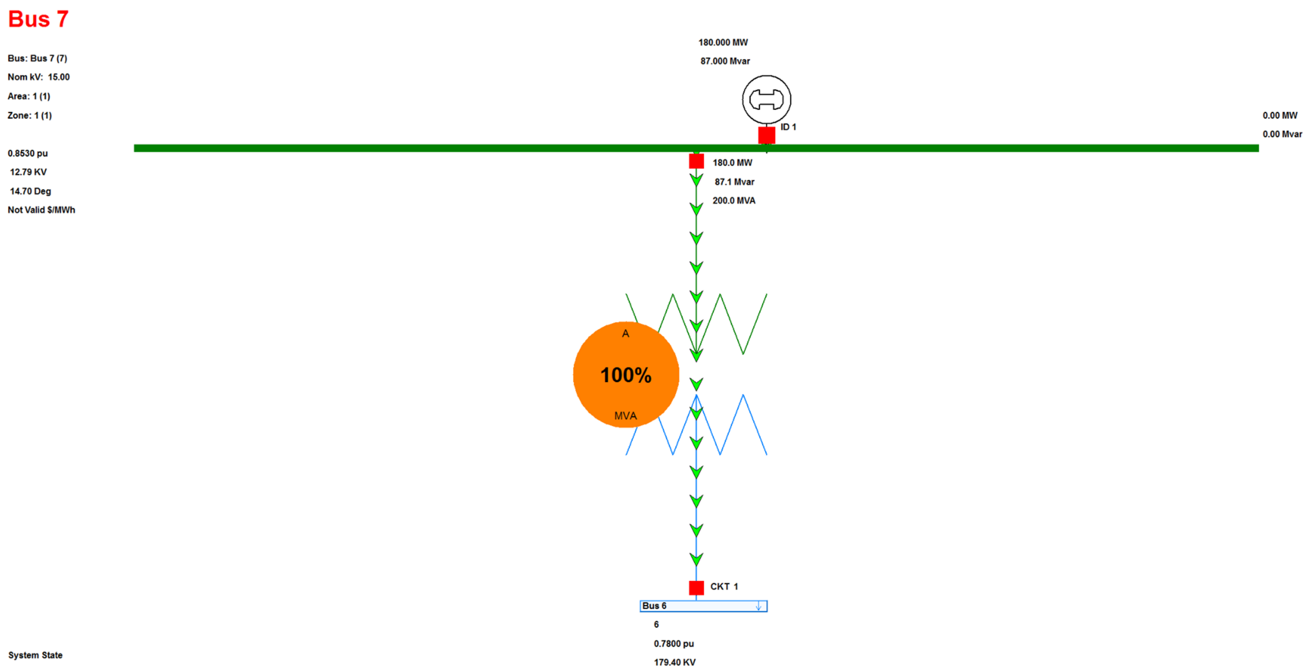
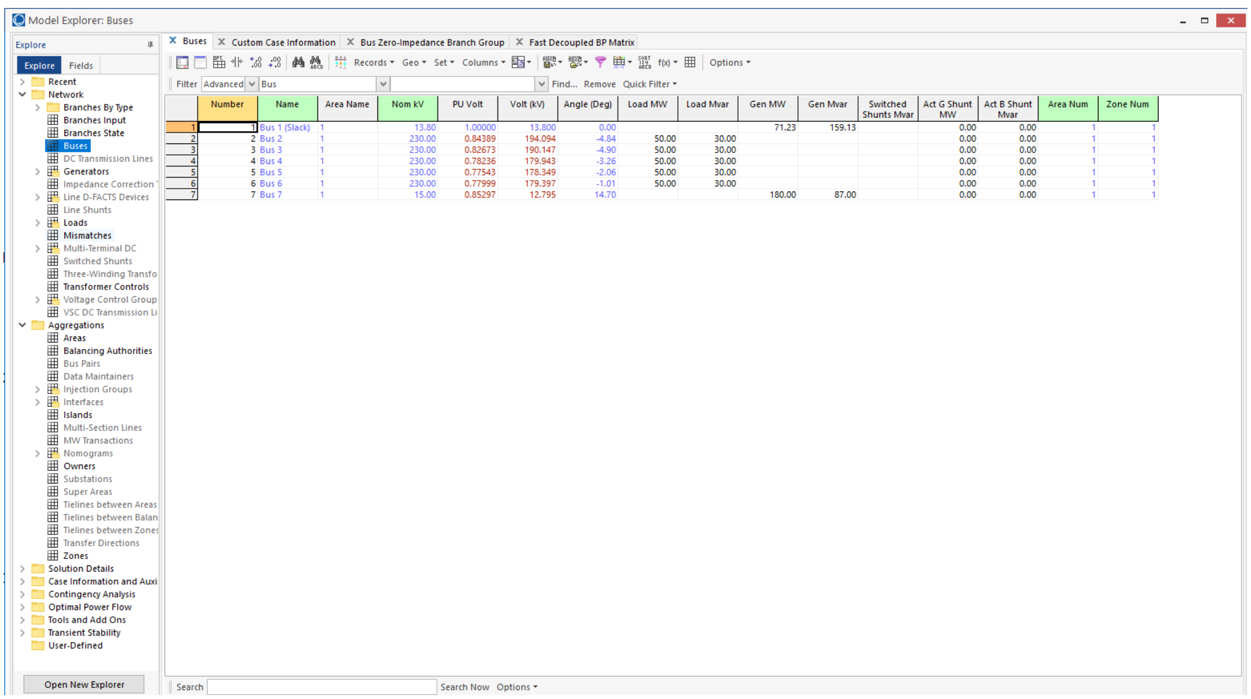


Figure 10: PowerWorld Diagram



	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

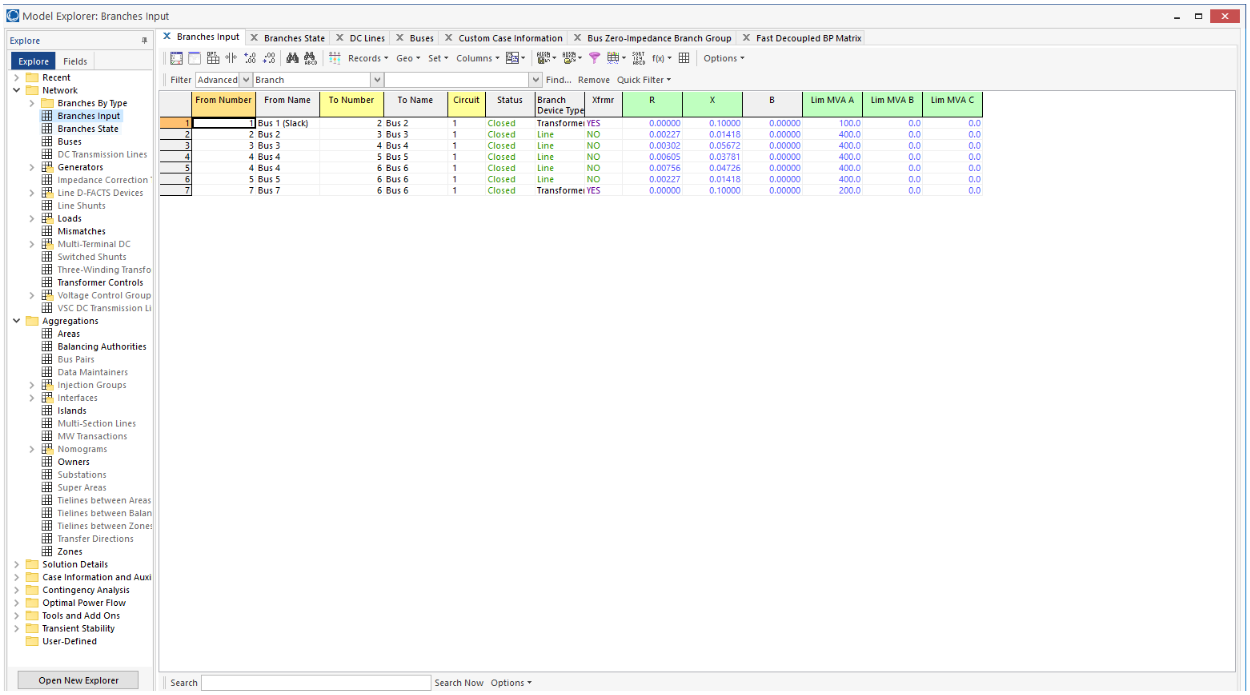


Figure 12: PowerWorld Diagram

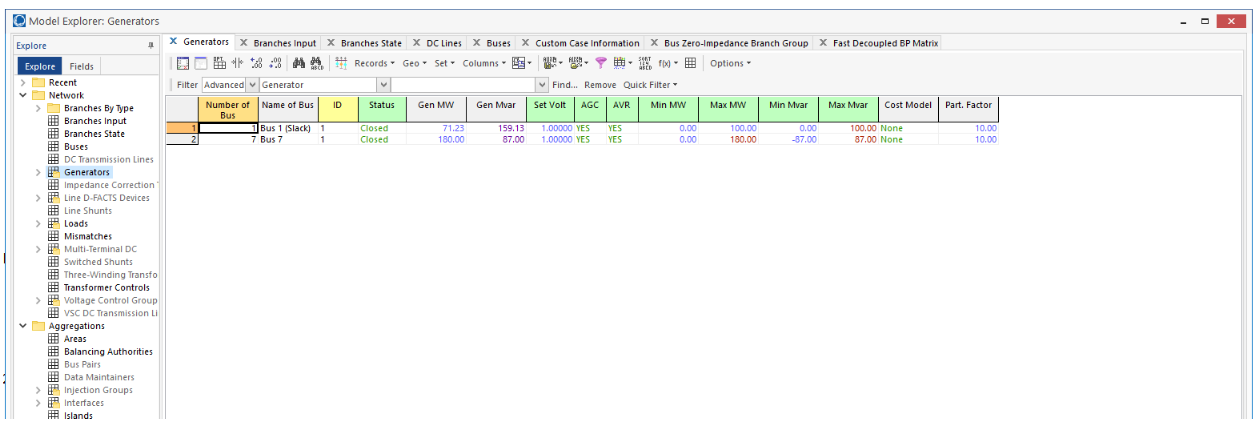


Figure 13: PowerWorld Diagram

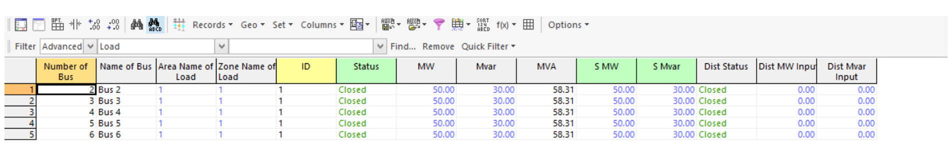


Figure 14: PowerWorld Diagram

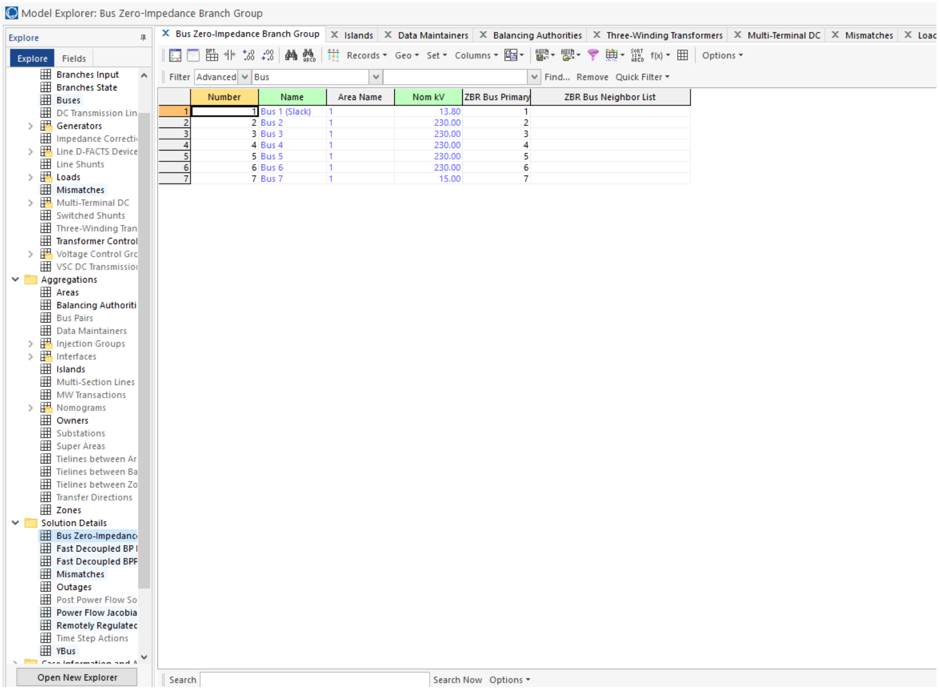


Figure 15: PowerWorld Diagram

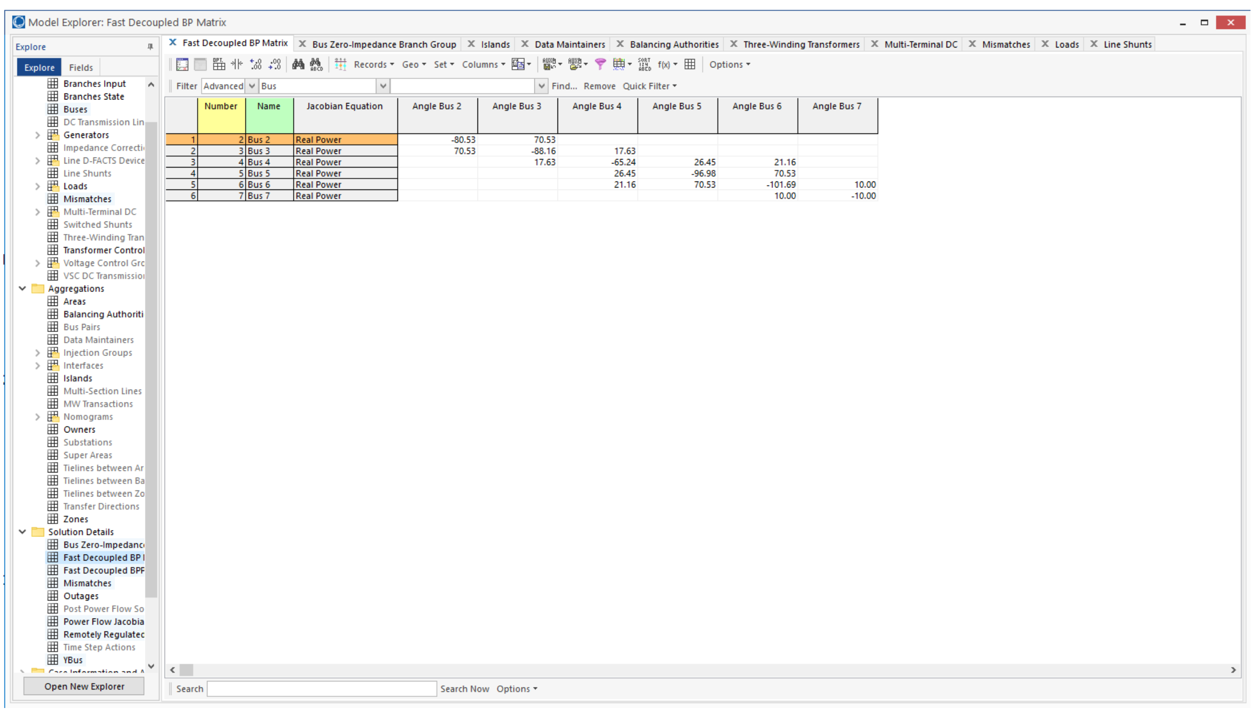
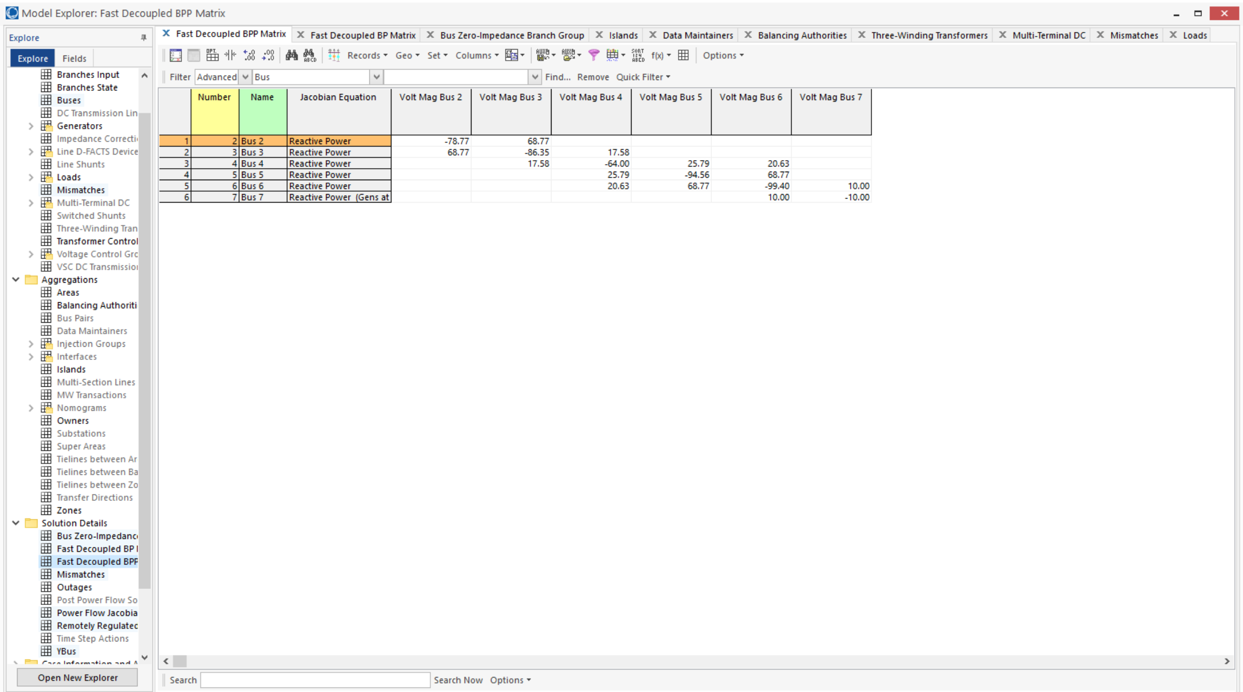
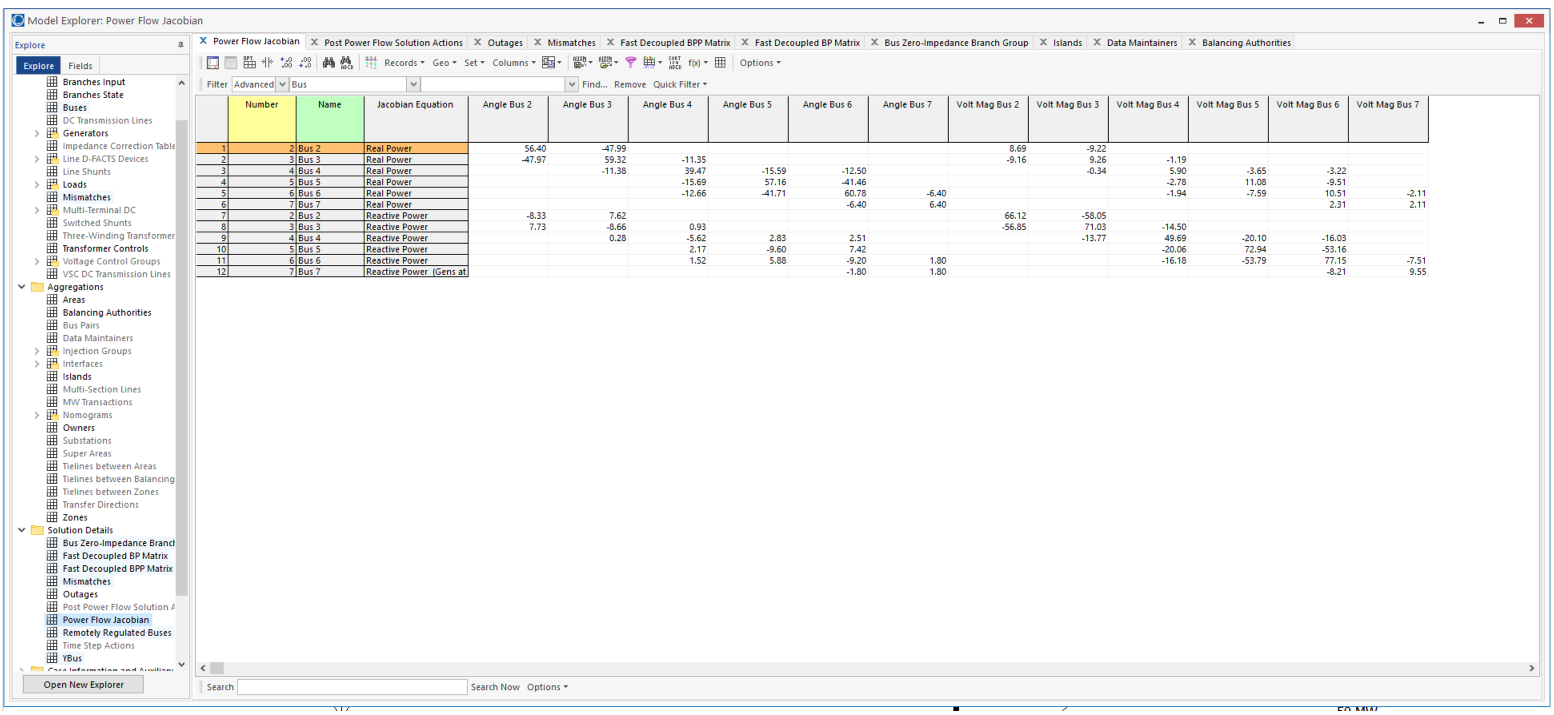


Figure 16: PowerWorld Diagram



	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



	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

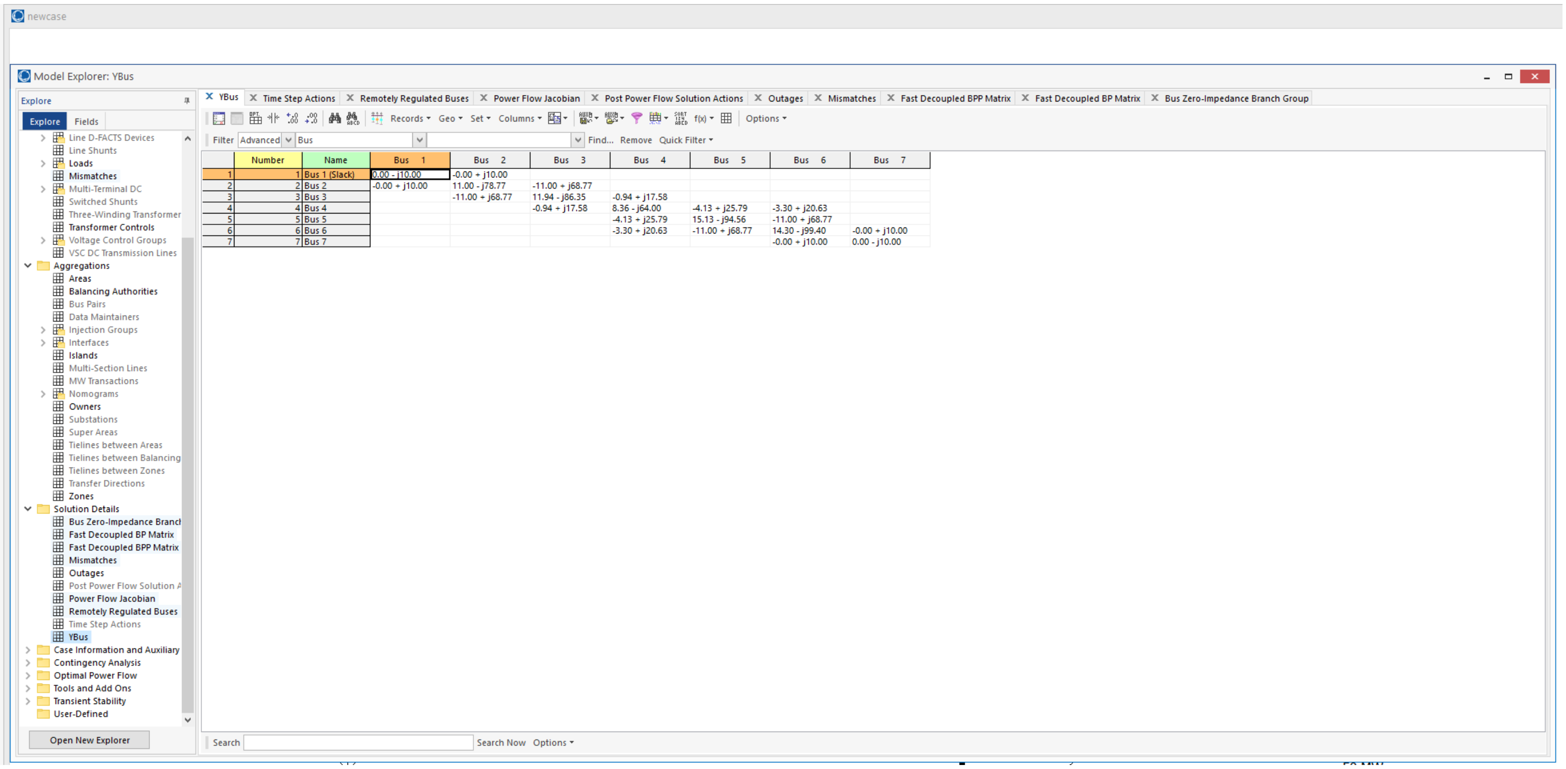


Figure 19: PowerWorld Diagram

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:

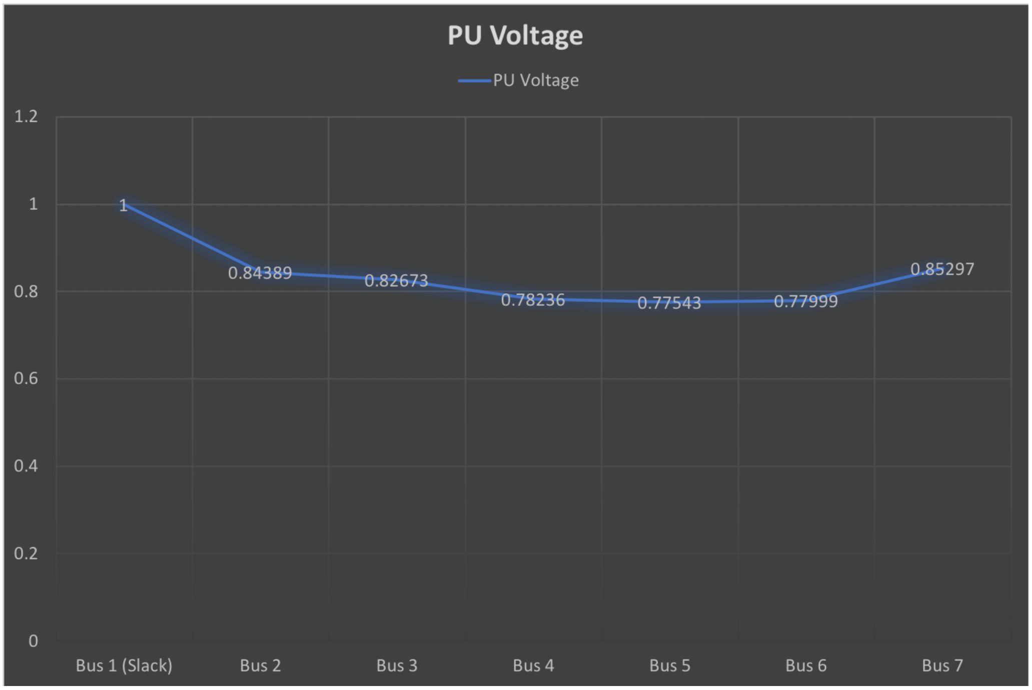


Figure 20: Per Unit Voltages on buses.

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

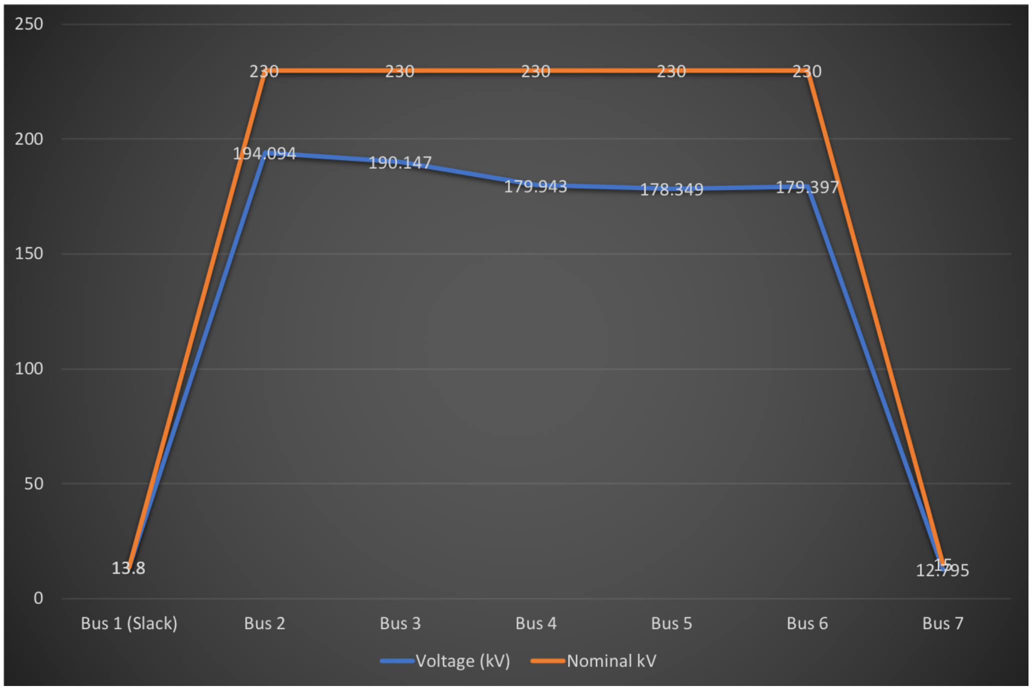


Figure 21: Nominal Voltage vs Actual Voltage of Buses.