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# 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

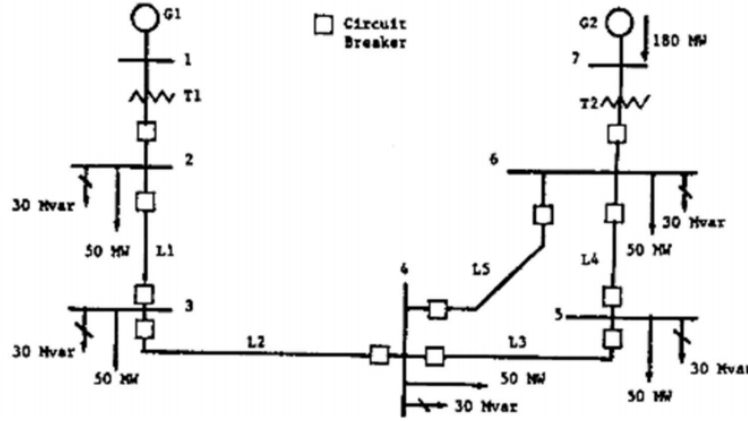


Figure 1: Original Circuit

Generator Ratings	
<b>G1</b>	100MVA, 13.8kV, $x'' = 0.12$
<b>G2</b>	200MVA, 15.0kV, $x'' = 0.12$
<i>The generator neutrals are solidly grounded</i>	

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

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

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

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

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

In zone G1, base values are,

$$S_{base} = 100 \text{ MVA}$$

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

@ G1

$$S_{G1(pu)} = \frac{100 \text{ MVA}}{100 \text{ MVA}} = \boxed{1pu}$$

$$V_{G1(pu)} = \frac{13.8 \text{ kV}}{13.8 \text{ kV}} = \boxed{1pu}$$

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

@ T1

$$S_{T1(pu)} = \frac{100 \text{ MVA}}{100 \text{ MVA}} = \boxed{1pu}$$

$$V_{T1(pu)} = \frac{13.8 \text{ kV}}{13.8 \text{ kV}} = \boxed{1pu}$$

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

@ Bus 2

$$Q_{Load} = 30 \text{ MVar}$$

$$Q_{Load(pu)} = \frac{30 \text{ MVar}}{100 \text{ MVA}} = \boxed{0.3pu}$$

$$P_{Load} = 50 \text{ MW}$$

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

@ L<sub>1</sub>

$$L_1 = 15 \text{ km}$$

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

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

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

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

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

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

@ Bus 3

$$Q_{Load} = 30MV Ar$$

$$Q_{Load(pu)} = \frac{30MV Ar}{100MV A} = \boxed{0.3 pu}$$

$$P_{Load} = 50MW$$

$$P_{Load(pu)} = \frac{50MW}{100MV A} = \boxed{0.5 pu}$$

@ Bus 4

$$Q_{Load} = 30MV Ar$$

$$Q_{Load(pu)} = \frac{30MV Ar}{100MV A} = \boxed{0.3 pu}$$

$$P_{Load} = 50MW$$

$$P_{Load(pu)} = \frac{50MW}{100MV A} = \boxed{0.5 pu}$$

@ Bus 5

$$Q_{Load} = 30MV Ar$$

$$Q_{Load(pu)} = \frac{30MV Ar}{100MV A} = \boxed{0.3 pu}$$

$$P_{Load} = 50MW$$

$$P_{Load(pu)} = \frac{50MW}{100MV A} = \boxed{0.5 pu}$$

@ Bus 6

$$Q_{Load} = 30MV Ar$$

$$Q_{Load(pu)} = \frac{30MV Ar}{100MV A} = \boxed{0.3 pu}$$

$$P_{Load} = 50MW$$

$$P_{Load(pu)} = \frac{50MW}{100MV A} = \boxed{0.5 pu}$$

@  $L_2$

$$L_2 = 20km$$

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

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

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

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

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

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

@  $L_3$

$$L_3 = 40km$$

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

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

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

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

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

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

@  $L_4$

$$L_4 = 15km$$

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

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

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

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

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

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

@  $L_5$

$$L_5 = 50km$$

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

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

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



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

@ Bus 7

$$\begin{aligned} P_{G7(pu)} &= \frac{180MW}{100MVA} = \boxed{1.8pu} \\ \frac{-87MVAr}{100} &< Q_{G7(pu)} < \frac{87MVAr}{100} \\ -0.87pu &< Q_{G7(pu)} < 0.87pu \\ V_{T2(pu)} &= \frac{15kV}{13.8kV} = \boxed{1.086956pu} \end{aligned}$$

### 2.1.1 Per-Unit One-Line Model

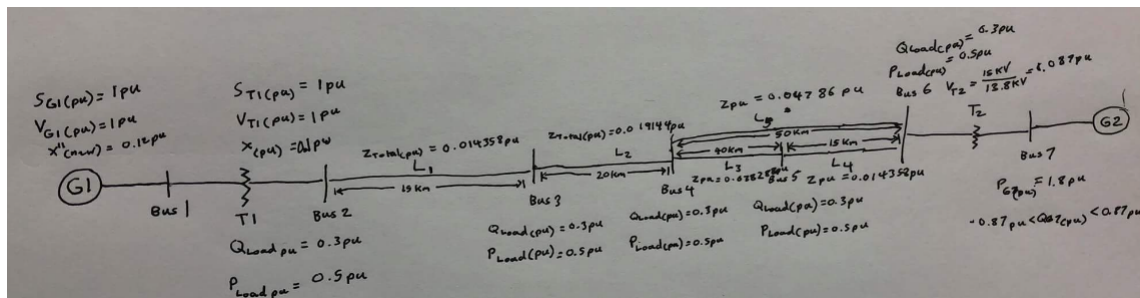


Figure 2: Per-Unit One-line Diagram

## 2.2 Compute All Bus Voltages

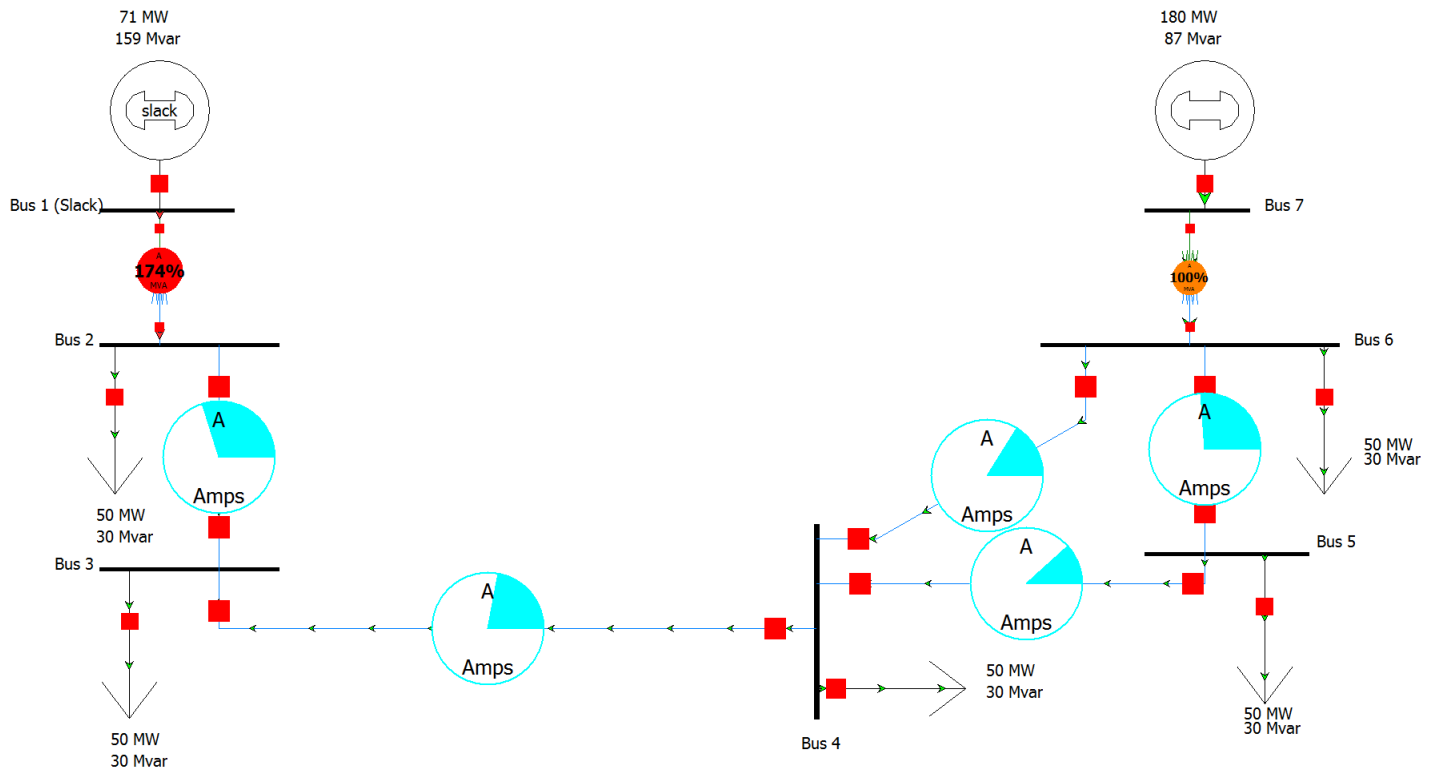


Figure 3: PowerWorld Diagram

## 2.2.1 Newton-Raphson Method

### Bus 1 (Slack)

Bus: Bus 1 (Slack) (1)  
 Nom KV: 13.80  
 Area: 1 (1)  
 Zone: 1 (1)  
 1.0000 pu  
 13.80 KV  
 0.00 Deg  
 Not Valid \$/MWh

System State

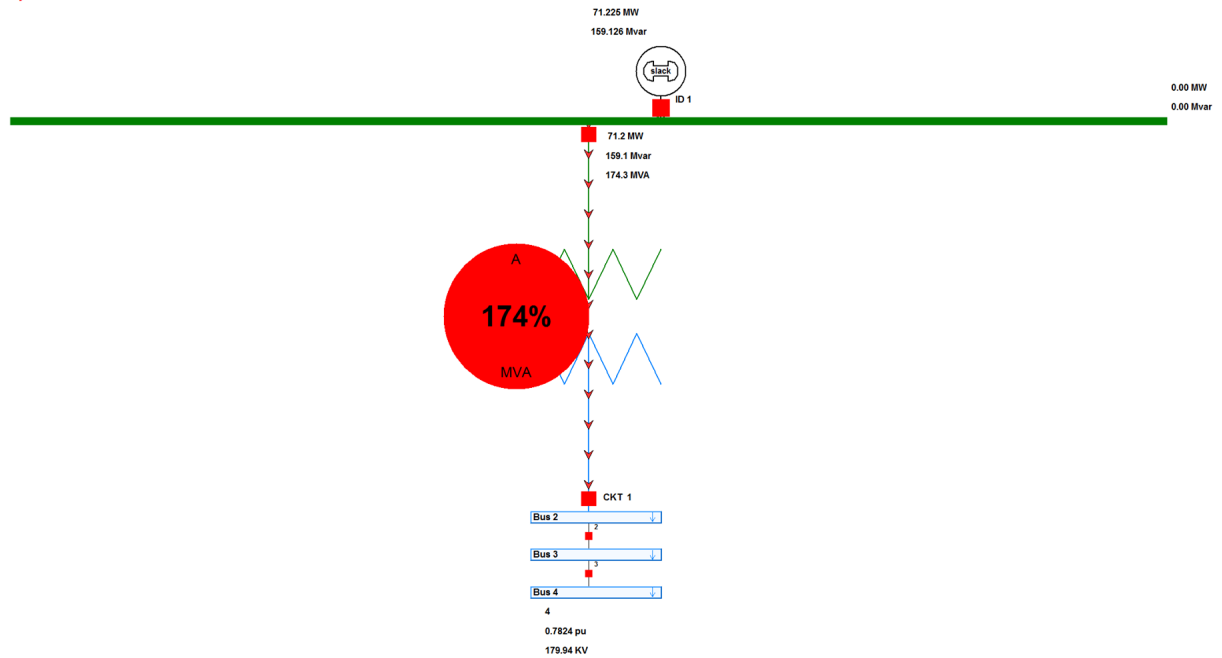


Figure 4: PowerWorld Diagram

### Bus 2

Bus: Bus 2 (2)  
 Nom KV: 230.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.8439 pu  
 194.09 KV  
 -4.94 Deg  
 Not Valid \$/MWh

System State

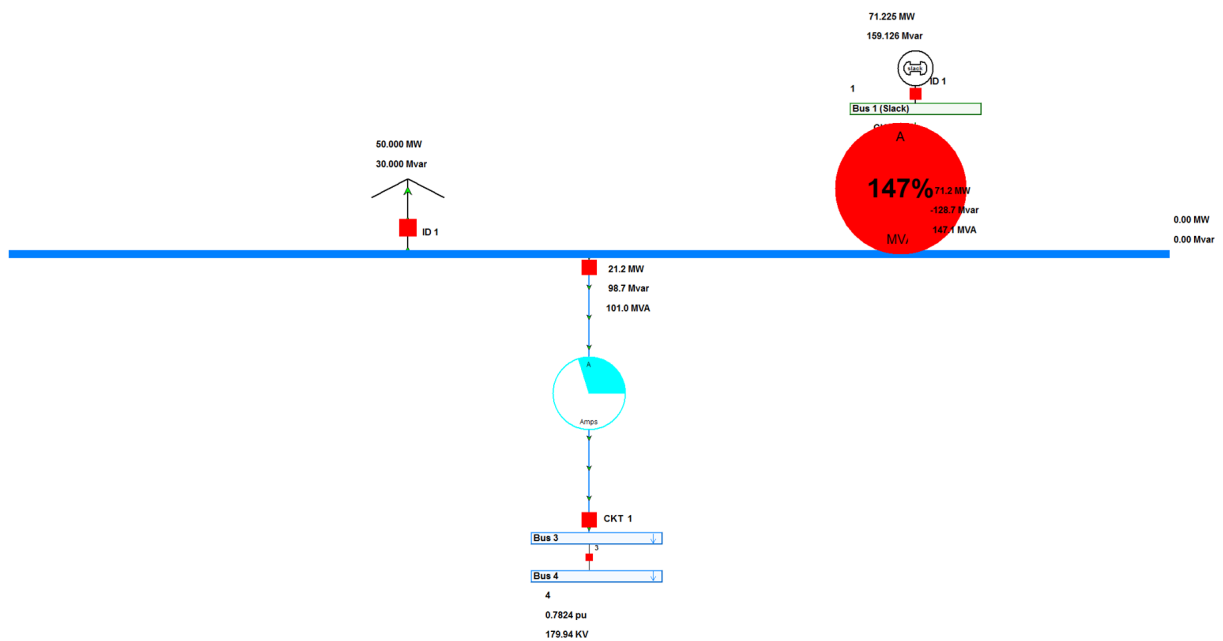


Figure 5: PowerWorld Diagram

**Bus 3**

Bus: Bus 3 (3)  
 Nom kV: 230.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.8267 pu  
 190.15 KV  
 -4.90 Deg  
 Not Valid \$/MWh

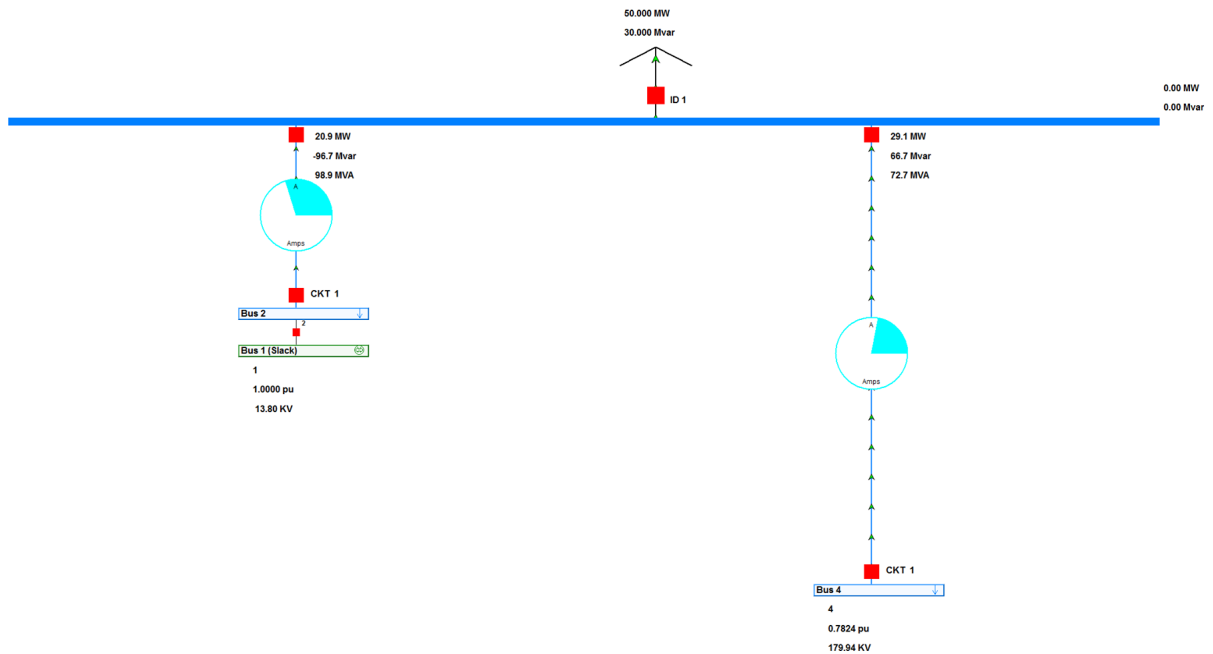


Figure 6: PowerWorld Diagram

**Bus 4**

Bus: Bus 4 (4)  
 Nom kV: 230.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.7824 pu  
 179.94 KV  
 -3.26 Deg  
 Not Valid \$/MWh

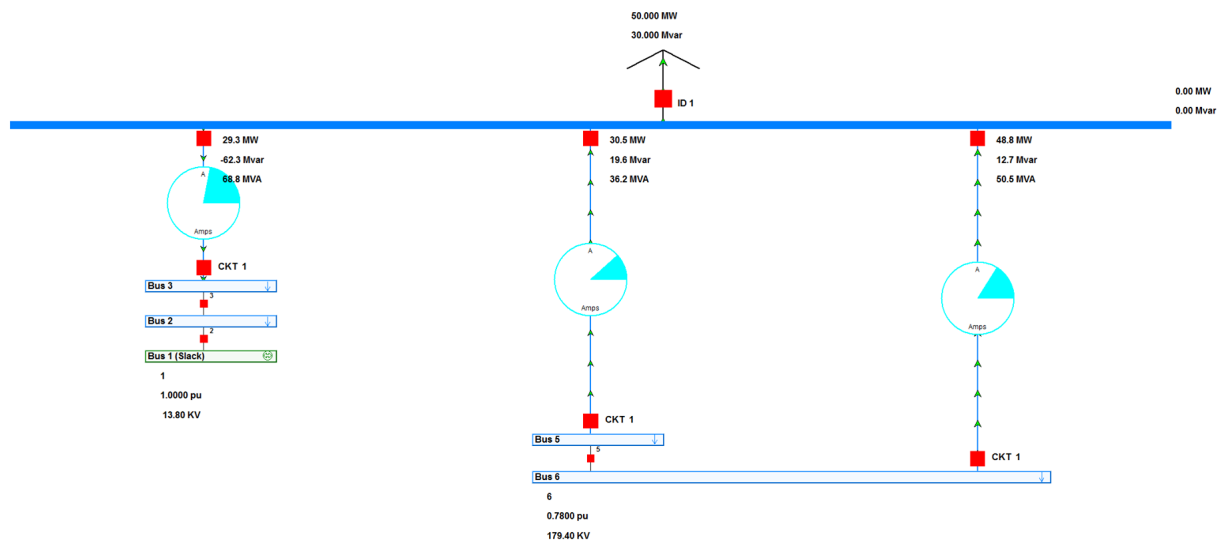


Figure 7: PowerWorld Diagram

**Bus 5**

Bus: Bus 5 (6)  
 Nom kV: 230.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.7754 pu  
 178.35 KV  
 -2.06 Deg  
 Not Valid \$/MWh

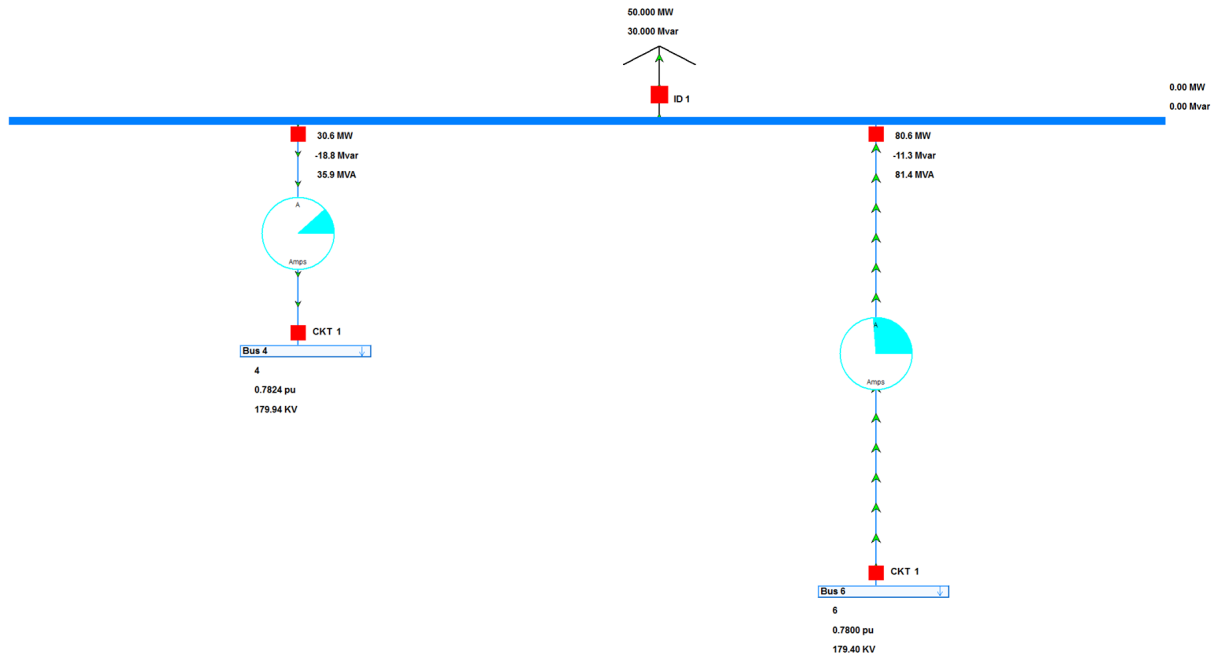


Figure 8: PowerWorld Diagram

**Bus 6**

Bus: Bus 6 (6)  
 Nom kV: 230.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.7800 pu  
 179.40 KV  
 -1.01 Deg  
 Not Valid \$/MWh

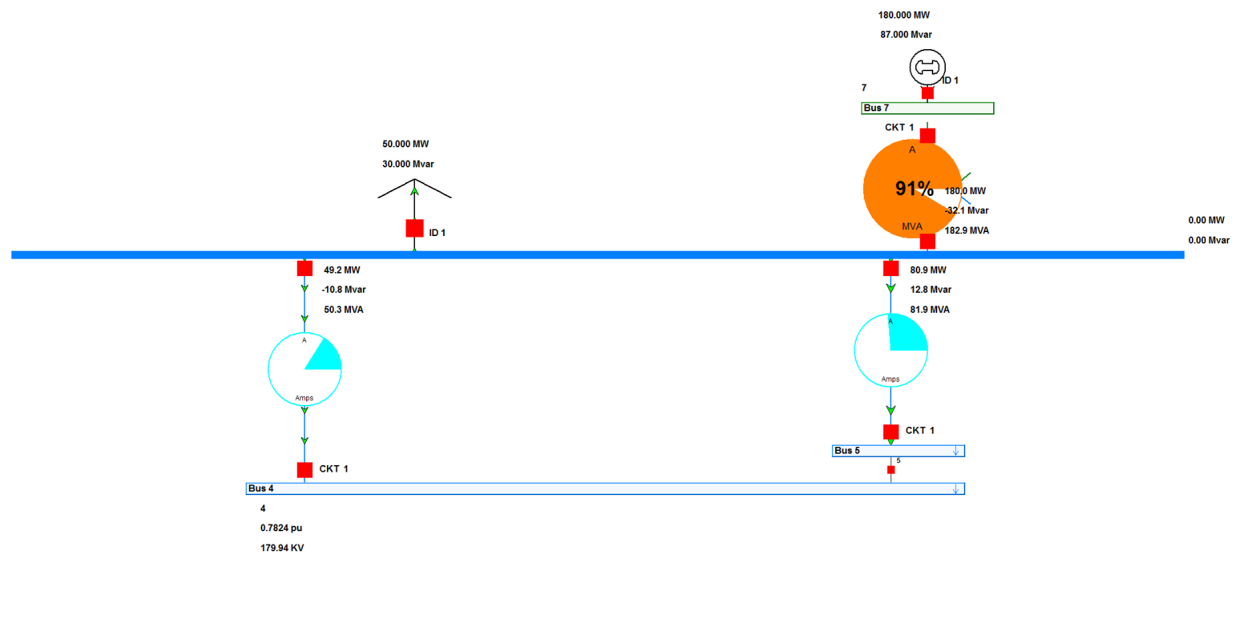


Figure 9: PowerWorld Diagram

**Bus 7**

Bus: Bus 7 (7)  
 Nom kV: 15.00  
 Area: 1 (1)  
 Zone: 1 (1)  
 0.8530 pu  
 12.79 KV  
 14.70 Deg  
 Not Valid \$/MWh

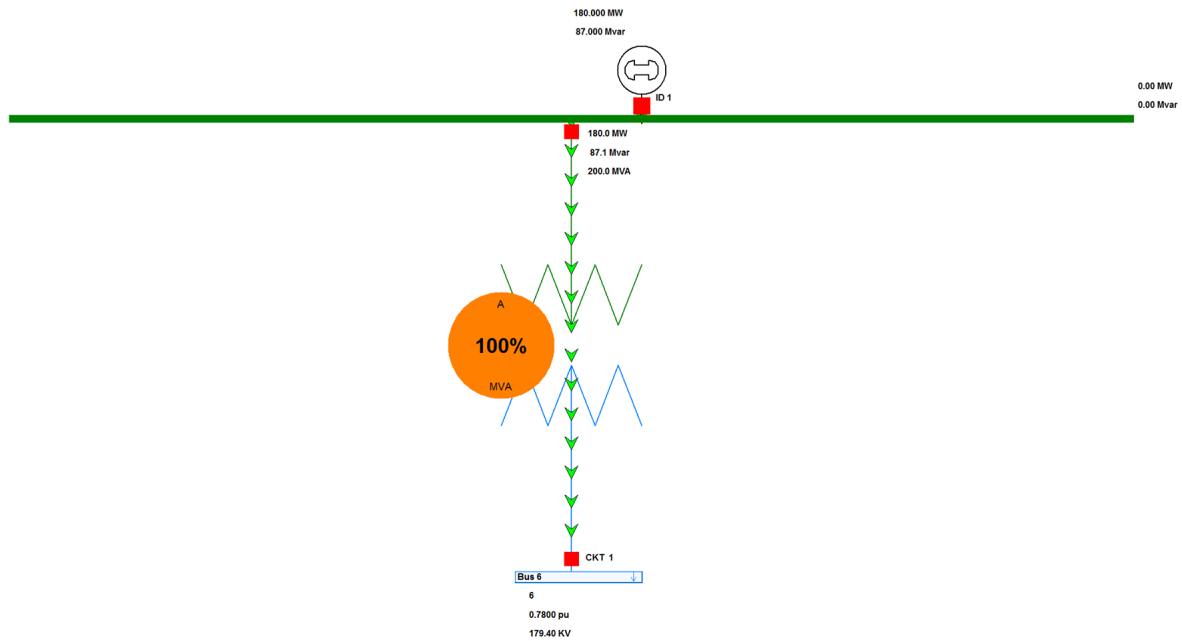


Figure 10: PowerWorld Diagram

Model Explorer: Buses

Explore Fields

Recent

Network

Branches By Type

Branches Input

Branches State

DC Transmission Lines

Generators

Impedance Correction

Line D-FACIS Devices

Line Shunts

Loads

Mismatches

Multi-Terminal DC

Switched Shunts

Three-Winding Transfo

Transformer Controls

Voltage Control Group

VSC DC Transmission Li

Aggregations

Areas

Balancing Authorities

Bus Pairs

Data Maintainers

Injection Groups

Interfaces

Islands

Multi-Section Lines

MW Transactions

Nomograms

Owners

Substations

Super Areas

TieLines between Areas

TieLines between Balan

TieLines between Zone

Transfer Directions

Zones

Solution Details

Case Information and Aux

Contingency Analysis

Optimal Power Flow

Tools and Add Ons

Transient Stability

Uses-Defined

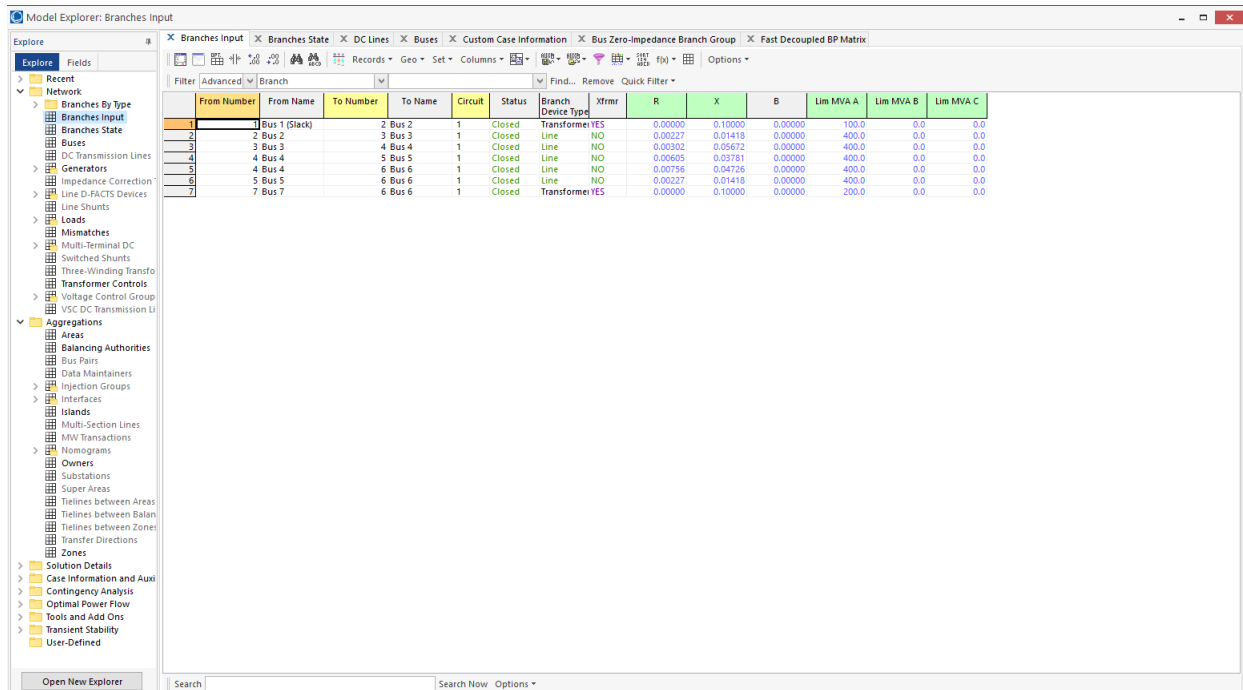
Open New Explorer

Search

Search Now Options

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	Bus 1 (Slack)	1	13.80	1.00000	13.800	0.00								1	1
2	Bus 2	1	230.00	0.84389	194.094	-4.84	50.00	30.00		71.23	159.13		0.00	0.00	1
3	Bus 3	1	230.00	0.82673	190.147	-4.90	50.00	30.00					0.00	0.00	1
4	Bus 4	1	230.00	0.78236	178.943	-3.26	50.00	30.00					0.00	0.00	1
5	Bus 5	1	230.00	0.77543	178.349	-2.06	50.00	30.00					0.00	0.00	1
6	Bus 6	1	230.00	0.77999	179.397	-1.01	50.00	30.00					0.00	0.00	1
7	Bus 7	1	15.00	0.85297	12.795	14.70			180.00	87.00			0.00	0.00	1

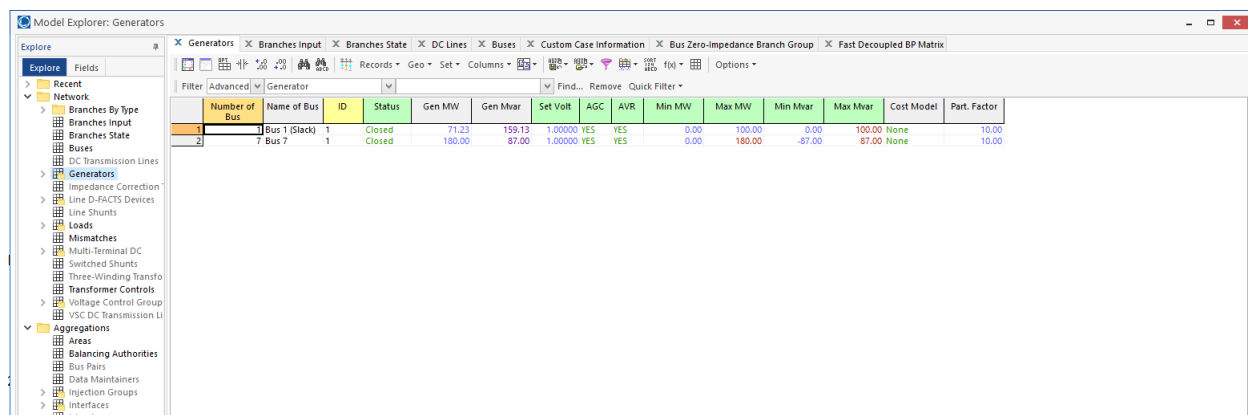
Figure 11: PowerWorld Diagram



The screenshot shows the 'Model Explorer: Branches Input' window. The left sidebar lists various components like Network, DC Transmission Lines, Generators, and Aggregations. The main table displays branch data with columns for From Number, From Name, To Number, To Name, Circuit, Status, Branch Device Type, Xfmr, R, X, B, and Lim MVA A, B, C.

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfmr	R	X	B	Lim MVA A	Lim MVA B	Lim MVA C
1	Bus 1 (Slack)	2	Bus 2	1	Closed	Transformer	YES	0.00000	0.10000	0.00000	100.0	0.0	0.0
2	2 Bus 2	3	Bus 3	1	Closed	Line	NO	0.00027	0.01419	0.00000	400.0	0.0	0.0
3	3 Bus 3	4	Bus 4	1	Closed	Line	NO	0.00030	0.05672	0.00000	400.0	0.0	0.0
4	4 Bus 4	5	Bus 5	1	Closed	Line	NO	0.00005	0.03781	0.00000	400.0	0.0	0.0
5	4 Bus 4	6	Bus 6	1	Closed	Line	NO	0.00756	0.04726	0.00000	400.0	0.0	0.0
6	5 Bus 5	6	Bus 6	1	Closed	Line	NO	0.00027	0.01419	0.00000	400.0	0.0	0.0
7	7 Bus 7	6	Bus 6	1	Closed	Transformer	YES	0.00000	0.10000	0.00000	200.0	0.0	0.0

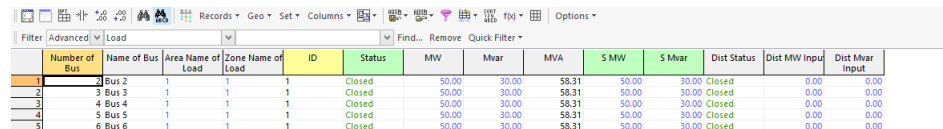
Figure 12: PowerWorld Diagram



The screenshot shows the 'Model Explorer: Generators' window. The main table displays generator data with columns for Number of Bus, Name of Bus, ID, Status, Gen MW, Gen Mvar, Set Volt, AGC, AVR, Min MW, Max MW, Min Mvar, Max Mvar, Cost Model, and Part. Factor.

Number of Bus	Name of Bus	ID	Status	Gen MW	Gen Mvar	Set Volt	AGC	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Cost Model	Part. Factor
1	Bus 1 (Slack)	1	Closed	71.23	159.13	1.00000	YES	YES	0.00	100.00	0.00	100.00	None	10.00
2	7 Bus 7	1	Closed	180.00	87.00	1.00000	YES	YES	0.00	180.00	-87.00	87.00	None	10.00

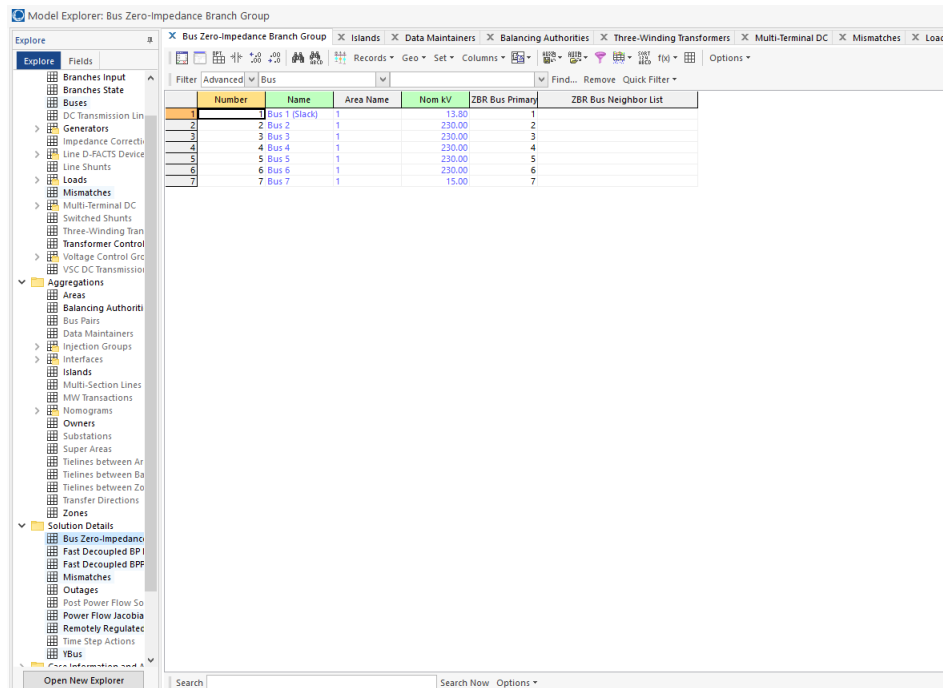
Figure 13: PowerWorld Diagram



The screenshot shows the 'Model Explorer: Loads' window. The main table displays load data with columns for Number of Bus, Name of Bus, Area Name of Load, Zone Name of Load, ID, Status, MW, Mvar, MVA, S MW, S Mvar, Dist Status, Dist MW Input, and Dist Mvar Input.

Number of Bus	Name of Bus	Area Name of Load	Zone Name of Load	ID	Status	MW	Mvar	MVA	S MW	S Mvar	Dist Status	Dist MW Input	Dist Mvar Input
2	Bus 2	1	1	1	Closed	50.00	30.00	58.31	50.00	30.00	Closed	0.00	0.00
3	3 Bus 3	1	1	1	Closed	50.00	30.00	58.31	50.00	30.00	Closed	0.00	0.00
4	4 Bus 4	1	1	1	Closed	50.00	30.00	58.31	50.00	30.00	Closed	0.00	0.00
5	5 Bus 5	1	1	1	Closed	50.00	30.00	58.31	50.00	30.00	Closed	0.00	0.00
6	6 Bus 6	1	1	1	Closed	50.00	30.00	58.31	50.00	30.00	Closed	0.00	0.00

Figure 14: PowerWorld Diagram



Model Explorer: Bus Zero-Impedance Branch Group

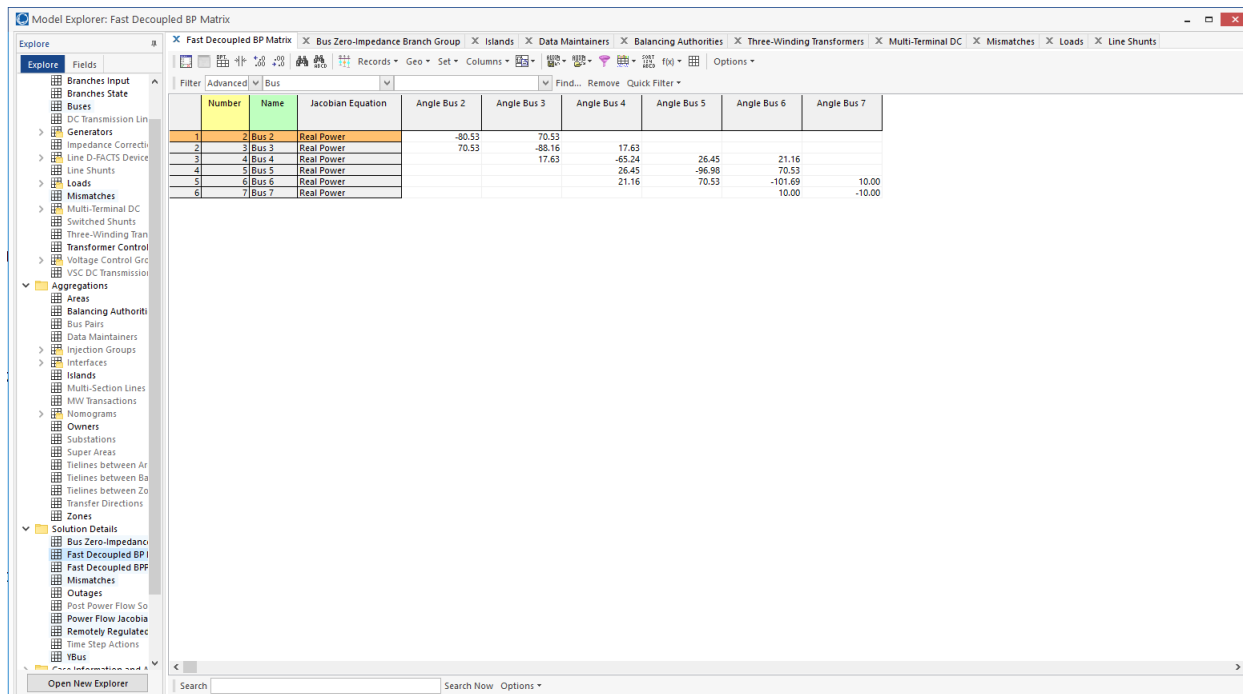
Explore Fields

Filter Advanced Bus

Number	Name	Area Name	Nom kV	ZBR Bus Primary	ZBR Bus Neighbor List
1	Bus 1 (Slack)	1	13.80	1	
2	2 Bus 2	1	230.00	2	
3	3 Bus 3	1	230.00	3	
4	4 Bus 4	1	230.00	4	
5	5 Bus 5	1	230.00	5	
6	6 Bus 6	1	230.00	6	
7	7 Bus 7	1	15.00	7	

Open New Explorer

Figure 15: PowerWorld Diagram



Model Explorer: Fast Decoupled BP Matrix

Explore Fields

Filter Advanced Bus

Number	Name	Jacobian Equation	Angle Bus 2	Angle Bus 3	Angle Bus 4	Angle Bus 5	Angle Bus 6	Angle Bus 7
1	2 Bus 2	Real Power	-80.53	70.53	17.63			
2	3 Bus 3	Real Power	70.53	-88.16	-65.04	26.45	21.16	
3	4 Bus 4	Real Power		17.63	26.45	-96.98	70.53	
4	5 Bus 5	Real Power			21.16	70.53	-101.69	10.00
5	6 Bus 6	Real Power					10.00	-10.00
6	7 Bus 7	Real Power						

Open New Explorer

Figure 16: PowerWorld Diagram



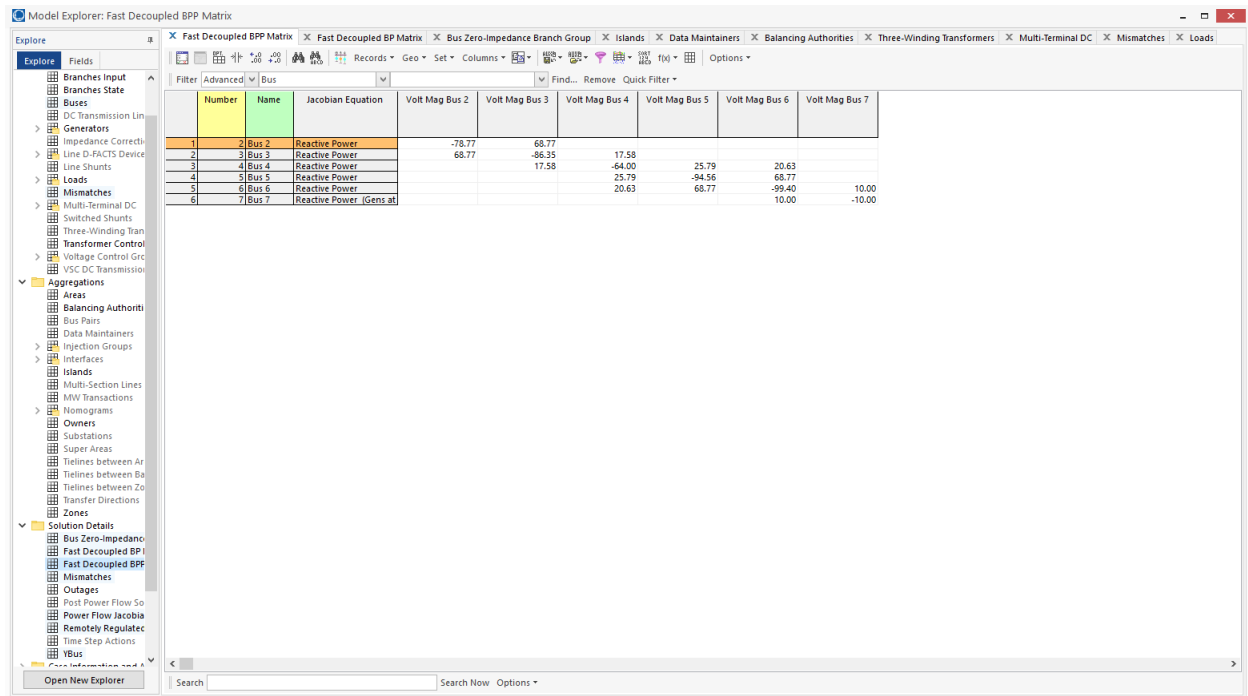


Figure 17: PowerWorld Diagram

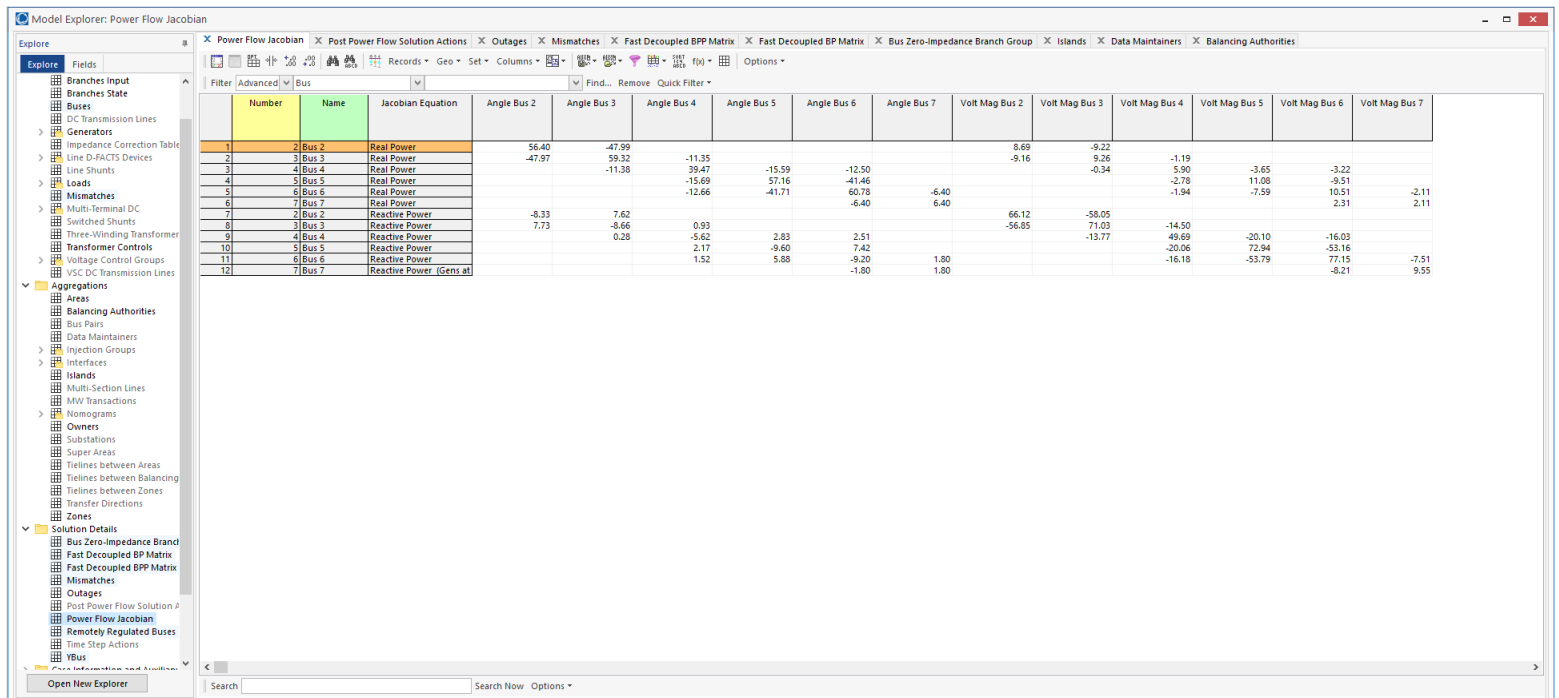


Figure 18: PowerWorld Diagram

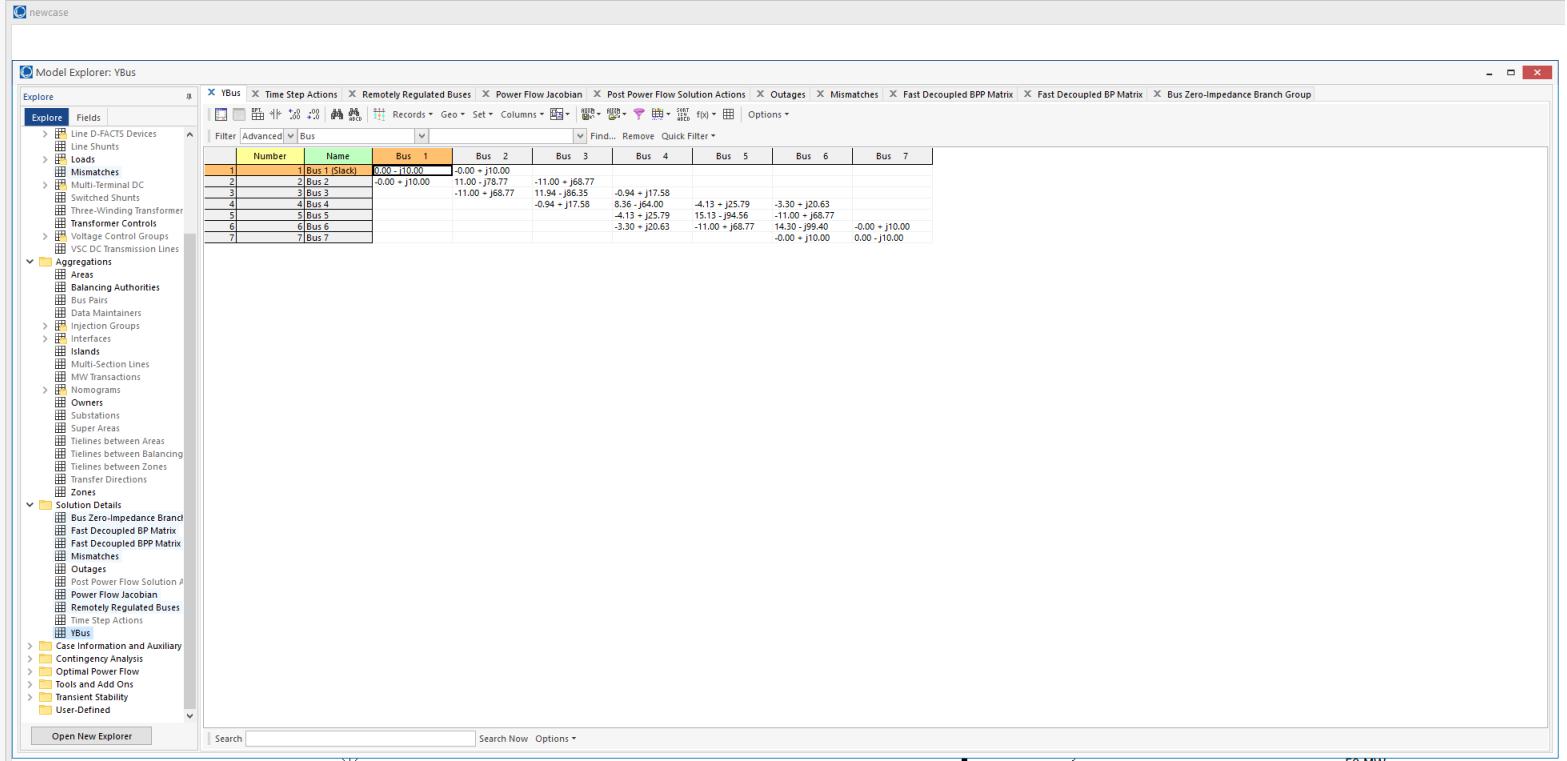


Figure 19: PowerWorld Diagram

## 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

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

### 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:

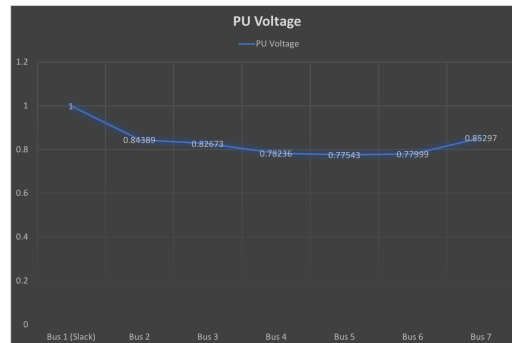


Figure 20: Per Unit Voltages on buses.