ECEN 460
Power System Operation and Control
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Lecture 9: More Power Flow

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Sources of Technical Information

- There are many sources of technical information, with many students most familiar with textbooks and courses
- Journals, conferences, reports, presentations (e.g., webinars), patents, standards and software are extremely useful additional sources
- In rough order of the newest of the information (from oldest to newest)
  - Books including textbooks; often lectures (depending on the instructor); reports
  - Journals, Conferences; both can have peer review; software, patents
  - Webinars, and industry periodicals
- Many are publications are available open access. However, the challenge is ultimately someone needs to cover the publication expenses.
- TAMU IEEE Xplore access at ieeexplore.ieee.org/Xplore/home.jsp

My Research Publications

- My more recent publications are linked on my website at https://overbye.engr.tamu.edu/publications/
- The paper I presented at TPEC on Feb 11, 2025 provided results from a survey looking to identify the top papers of the last 50 years
- Google scholar provides information on how often particular papers are referenced by other papers
  - It is a useful, but certainly not perfect metric

Survey of High Impact Electric Power System Papers, 1975-2024

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Abstract—This paper discusses results of an informal survey intended to identify the most impactful electric power system papers from 1975 to 2024 written in English. The survey was shared primarily over email to a large number of electric power engineers asking them to identify up to three papers that they consider among the most impactful papers of the last 50 years. A total of 144 valid responses were received, identifying 101 unique publications. Of those publications, 18 received multiple votes. The paper receiving the most votes are in the areas of electricity markets, optimal power flow, synthetic electric grids, voltage phasor measurements, electric grid stability, and associated with the open-source power system analysis program. This paper is a follow-up to a 2000 paper identifying the top papers of the 20^{th} century.

Index Terms—***electric power systems, high impact papers, power engineering literature, 50 years***

I. Introduction

After more than 160 years of commercial use, electricity has transformed human society. As noted in [1], the majority of the top 20 engineering achievements of the 20th century would not have been possible without electricity. As a result, the top ranked achievement in [1] is the development of large-scale interconnected electric grids that made electricity ubiquitously available to many. This widespread electrification required the collective efforts of millions, and the ingenuity and hard work of thousands of engineers in many different disciplines. Certainly crucial to this is electric power systems engineering, which is focused on the design and operation of the large-scale electric grids that supply most of the world's electricity. While electric power systems engineering was important in the 20th century, it's importance has only accelerated in the 21st century, as the public. This public dissemination of knowledge helps to advance the field, and certainly one of the most impactful and lasting means of documenting and communicating progress is through technical journal and conference papers. To facilitate the further propagation of knowledge, we believe it is useful to identify the most impactful of these papers. This was done in 2000 using a survey approach [2] looking at determining the highest impact publications in power engineering from the 20th century (1900 to 1999). The purpose of this paper is to update and extend this prior work to include the first quarter of the 21st century.

In the original paper [2] a total of 39 publications were identified, including journal and conference articles, books and reports. Of the top eight all but one were journal or conference articles, and all were written before 1975. The top paper in [2] is "Method of Symmetrical Co-Ordinates Applied to the Solution of Polyphase Networks" from 1918 by Fortecue [3]. The second paper is "Two Reaction Theory of Synchronous Machines" from 1929 by Park [4] presenting what would become known as Park's Transformation, while the third is "Digital Computer Solutions of Power Flow Problems" by Ward and Hale from 1956 [5]. The latest publication in the top eight is "Fast Decoupled Load Flow" by Stott and Alsac from 1974 [6]. All of the publications in [2] were written in English. Note that the terms "power flow" and "load flow" have been used synonymously since at least the 1950's.

Since none of the top papers in [2] were written after 1974, we decided to ask the power system community to identify the most important papers from 1975 to 2024, or the last 50 years. We employed a survey process that largely mirrors the one used in [2]. That is, we issued a wide and open call to our colleagues in the electric power system community, asking them to identify the journal or conference publications that they view as the most

N-R Power Flow Solution

The power flow is solved using the same procedure discussed with the general Newton-Raphson:

Set $v = 0$; make an initial guess of $\mathbf{x}$, $\mathbf{x}^{(v)}$

While $\left\| \mathbf{f}(\mathbf{x}^{(v)}) \right\| > \varepsilon$ Do

$$\begin{aligned} \mathbf{x}^{(v+1)} &= \mathbf{x}^{(v)} - \mathbf{J}(\mathbf{x}^{(v)})^{-1}\mathbf{f}(\mathbf{x}^{(v)}) \\ v &= v+1 \end{aligned}$$

End While

PV Buses

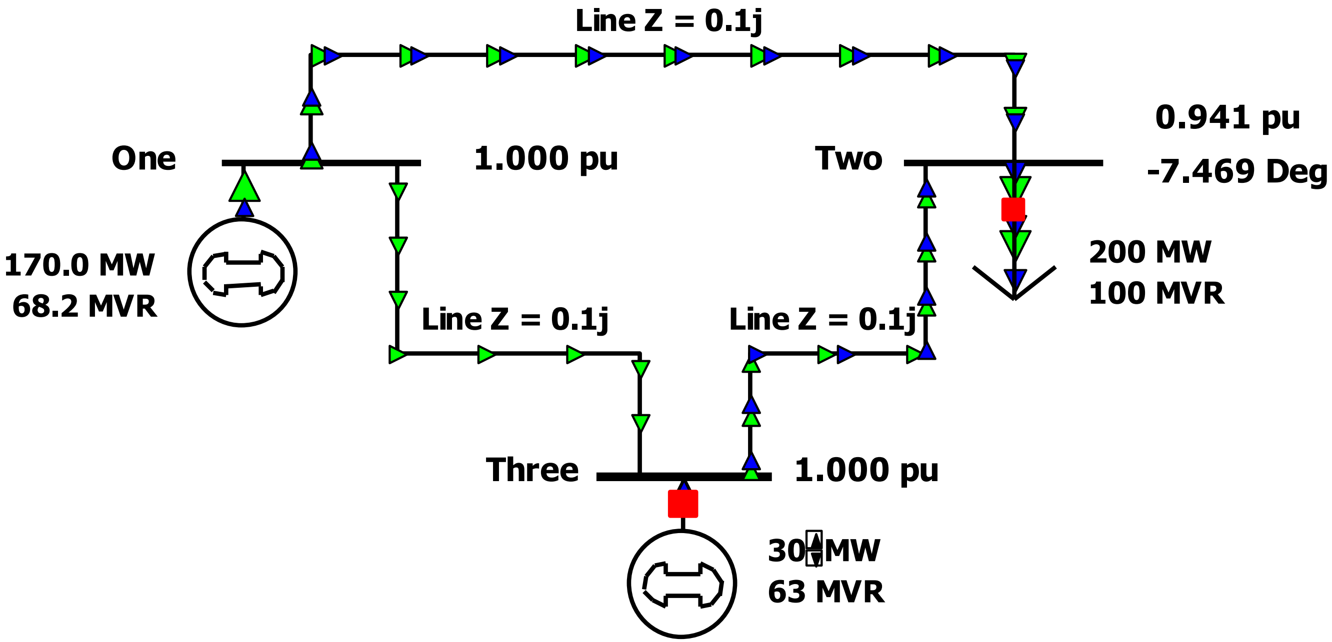
- Since the voltage magnitude at PV buses is fixed there is no need to explicitly include these voltages in **x** or write the reactive power balance equations
  - the reactive power output of the generator varies to maintain the fixed terminal voltage (within limits)
  - optionally these variations/equations can be included by just writing the explicit voltage constraint for the generator bus

$$|V_i| - V_{i\ \text{setpoint}} = 0$$

Three Bus PV Case Example

For this three bus case we have

$$\mathbf{x} = \begin{bmatrix} \theta_2 \\ \theta_3 \\ |V_2| \end{bmatrix} \qquad \mathbf{f}(\mathbf{x}) = \begin{bmatrix} P_2(\mathbf{x}) - P_{G2} + P_{D2} \\ P_3(\mathbf{x}) - P_{G3} + P_{D3} \\ Q_2(\mathbf{x}) + Q_{D2} \end{bmatrix} = 0$$



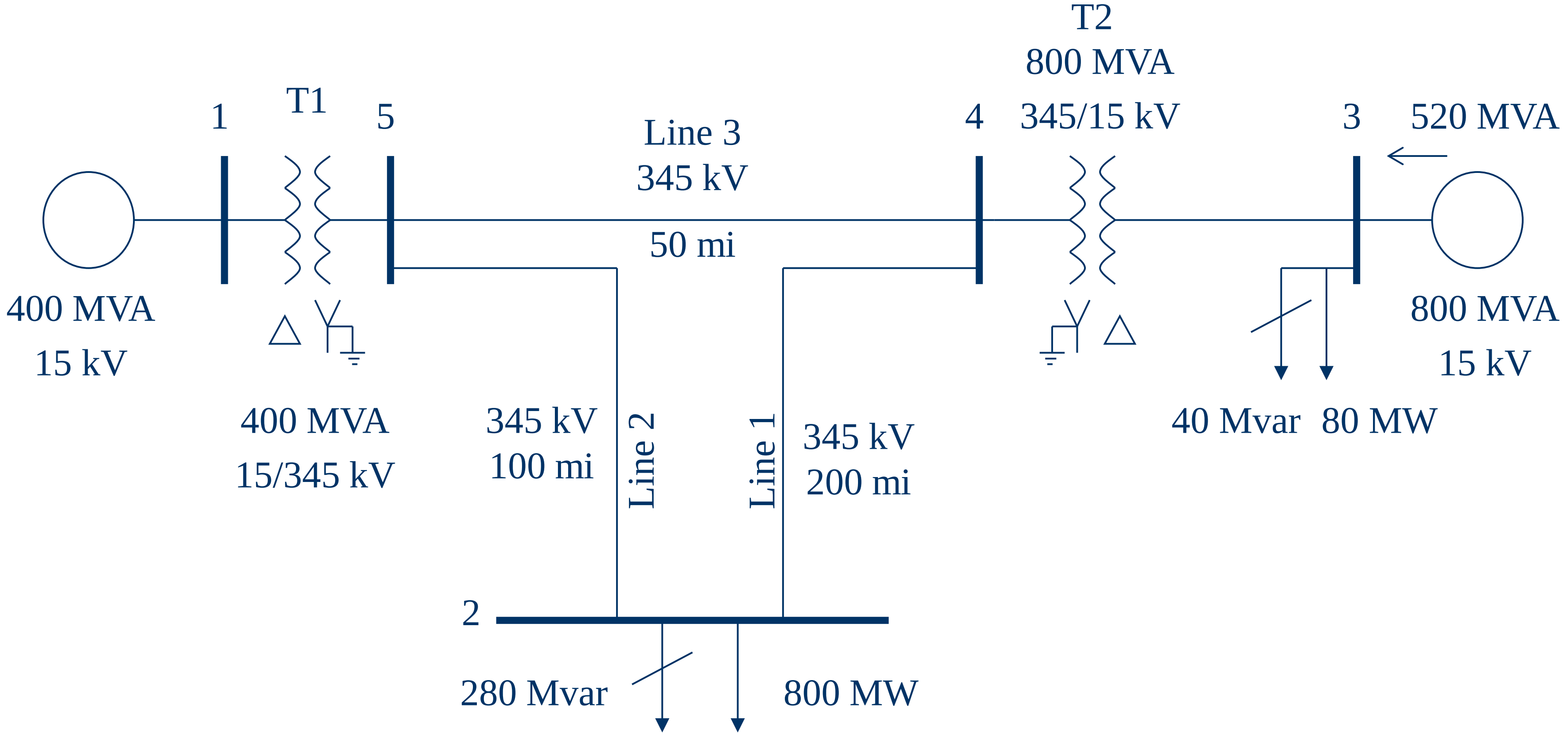
Generator Reactive Power Limits

- The reactive power output of generators varies to maintain the terminal voltage; on a real generator this is done by the exciter
- To maintain higher voltages requires more reactive power
- Generators have reactive power limits, which are dependent upon the generator's MW output
- These limits must be considered during the power flow solution.
- During the power flow once a solution is obtained there is a check to make sure the generator reactive power output is within its limits

Generator Reactive Limits, cont'd

- During the power flow once a solution is obtained there is a check to make sure the generator reactive power output is within its limits
- If the reactive power is outside of the limits, fix Q at the max or min value, and resolve treating the generator as a PQ bus
  - this is know as "type-switching"
  - also need to check if a PQ generator can again regulate
- Rule of thumb: to raise system voltage we need to supply more reactive power

The N-R Power Flow: 5-bus Example



This five-bus grid is Example 6.9 from the book

The N-R Power Flow: 5-bus Example

Table 1.
Bus input data

Bus	Type	V per unit	δ degrees	P_G per unit	Q_G per unit	P_L per unit	Q_L per unit	Q_{Gmax} per unit	Q_{Gmin} per unit
1	Swing	1.0	0	—	—	0	0	—	—
2	Load	—	—	0	0	8.0	2.8	—	—
3	Constant voltage	1.05	—	5.2	—	0.8	0.4	4.0	-2.8
4	Load	—	—	0	0	0	0	—	—
5	Load	—	—	0	0	0	0	—	—

Table 2.
Line input data

Bus-to-Bus	R' per unit	X' per unit	G' per unit	B' per unit	Maximum MVA per unit
2-4	0.0090	0.100	0	1.72	12.0
2-5	0.0045	0.050	0	0.88	12.0
4-5	0.00225	0.025	0	0.44	12.0

In this example δ, as opposed to θ, is used to indicate the bus angle

The N-R Power Flow: 5-bus Example

Table 3. Transformer input data

Bus-to-Bus	R per unit	X per unit	G_c per unit	B_m per unit	Maximum MVA per unit	Maximum TAP Setting per unit
1-5	0.00150	0.02	0	0	6.0	—
3-4	0.00075	0.01	0	0	10.0	—

Table 4. Input data and unknowns

Bus	Input Data	Unknowns
1	$V_1 = 1.0$, $\delta_1 = 0$	P_1, Q_1
2	$P_2 = P_{G2}-P_{L2} = -8$ $Q_2 = Q_{G2}-Q_{L2} = -2.8$	V_2, δ_2
3	$V_3 = 1.05$ $P_3 = P_{G3}-P_{L3} = 4.4$	Q_3, δ_3
4	$P_4 = 0$, $Q_4 = 0$	V_4, δ_4
5	$P_5 = 0$, $Q_5 = 0$	V_5, δ_5

In this example δ, as opposed to θ, is used to indicate the bus angle

Bus Admittance Matrix

- To see the Ybus, select **Case Information, Solution Details, Ybus**

YBus

	Number	Name	Bus 1	Bus 2	Bus 3	Bus 4	Bus 5
1	1	One	3.73 - j49.72				-3.73 + j49.72
2	2	Two		2.68 - j28.46		-0.89 + j9.92	-1.79 + j19.84
3	3	Three			7.46 - j99.44	-7.46 + j99.44	
4	4	Four		-0.89 + j9.92	-7.46 + j99.44	11.92 - j147.96	-3.57 + j39.68
5	5	Five	-3.73 + j49.72	-1.79 + j19.84		-3.57 + j39.68	9.09 - j108.58

PowerWorld Case Name:
GOS_FiveBus

Ybus Calculation Details

Elements of Y_{bus} connected to bus 2

$$Y_{21} = Y_{23} = 0$$

$$Y_{24} = \frac{-1}{R_{24}^{'} + jX_{24}^{'}} = \frac{-1}{0.009 + j0.1} = -0.89276 + j9.91964 \; per\ unit$$

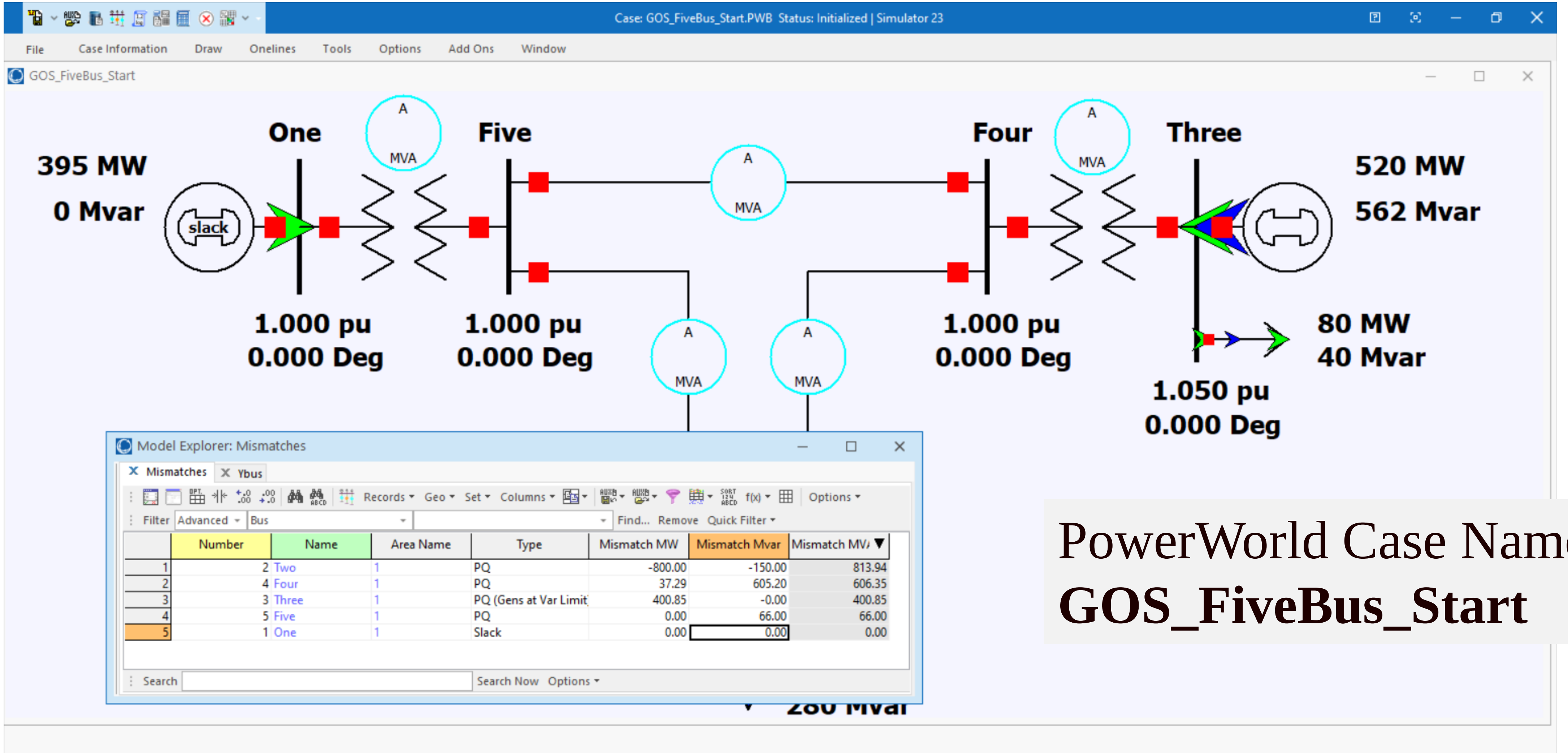
$$Y_{25} = \frac{-1}{R_{25}^{'} + jX_{25}^{'}} = \frac{-1}{0.0045 + j0.05} = -1.78552 + j19.83932 \; per\ unit$$

$$Y_{22} = \frac{1}{R_{24}^{'} + jX_{24}^{'}} + \frac{1}{R_{25}^{'} + jX_{25}^{'}} + j\frac{B_{24}^{'}}{2} + j\frac{B_{25}^{'}}{2}$$

$$= (0.89276 - j9.91964) + (1.78552 - j19.83932) + j\frac{1.72}{2} + j\frac{0.88}{2}$$

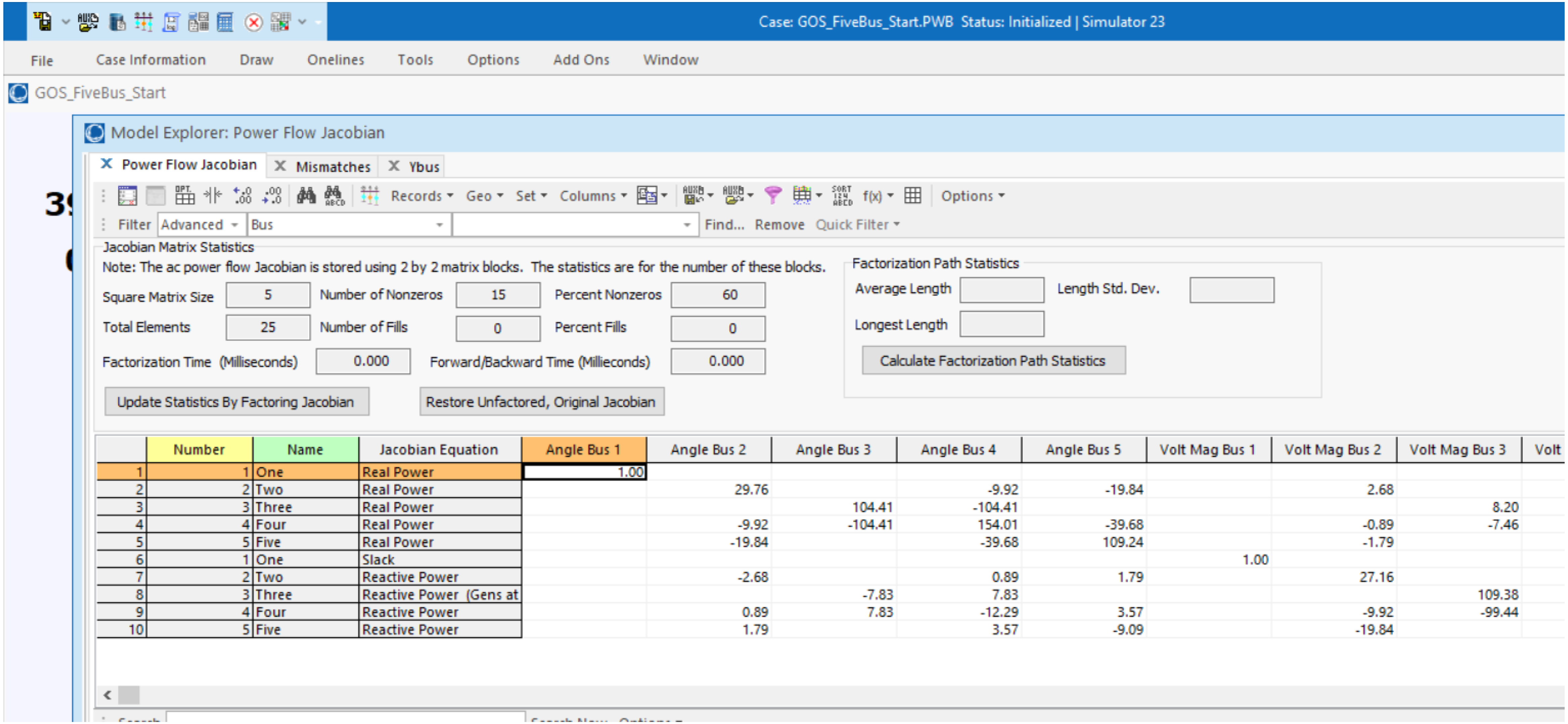
$$= 2.67828 - j28.4590 = 28.5847\angle -84.624^{\circ} \; per\ unit$$

Initial Bus Mismatches



PowerWorld Case Name:
GOS_FiveBus_Start

Initial Power Flow Jacobian



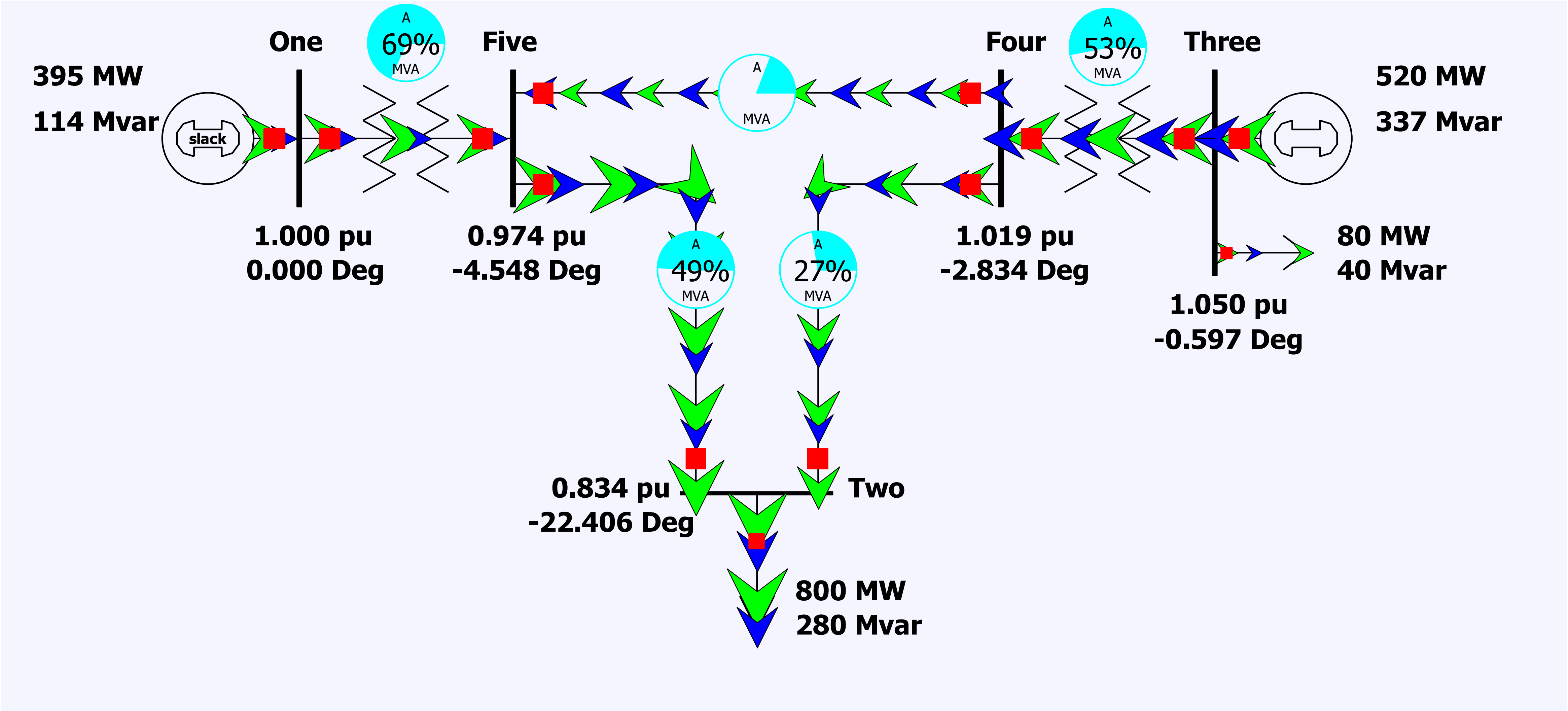
	Number	Name	Jacobian Equation	Angle Bus 1	Angle Bus 2	Angle Bus 3	Angle Bus 4	Angle Bus 5	Volt Mag Bus 1	Volt Mag Bus 2	Volt Mag Bus 3	Volt
1	1	One	Real Power	1.00								
2	2	Two	Real Power		29.76		-9.92	-19.84		2.68		
3	3	Three	Real Power			104.41	-104.41				8.20	
4	4	Four	Real Power		-9.92	-104.41	154.01	-39.68		-0.89	-7.46	
5	5	Five	Real Power		-19.84		-39.68	109.24		-1.79		
6	1	One	Slack						1.00			
7	2	Two	Reactive Power		-2.68		0.89	1.79		27.16		
8	3	Three	Reactive Power (Gens at			-7.83	7.83				109.38	
9	4	Four	Reactive Power		0.89	7.83	-12.29	3.57		-9.92	-99.44	
10	5	Five	Reactive Power		1.79		3.57	-9.09		-19.84		

Hand Calculation Details

$$\Delta P_2(0) = P_2 - P_2(x) = P_2 - V_2(0)\{Y_{21}V_1\cos[\delta_2(0)-\delta_1(0)-\theta_{21}]$$
$$+Y_{22}V_2\cos[-\theta_{22}] + Y_{23}V_3\cos[\delta_2(0)-\delta_3(0)-\theta_{23}]$$
$$+Y_{24}V_4\cos[\delta_2(0)-\delta_4(0)-\theta_{24}]$$
$$+Y_{25}V_5\cos[\delta_2(0)-\delta_5(0)-\theta_{25}]\}$$
$$= -8.0 - 1.0\{28.5847(1.0)\cos(84.624°)$$
$$+9.95972(1.0)\cos(-95.143°)$$
$$+19.9159(1.0)\cos(-95.143°)\}$$
$$= -8.0 - (-2.89\times 10^{-4}) = -7.99972 \textit{ per unit}$$

$$J1_{24}(0) = V_2(0)Y_{24}V_4(0)\sin[\delta_2(0)-\delta_4(0)-\theta_{24}]$$
$$= (1.0)(9.95972)(1.0)\sin[-95.143°]$$
$$= -9.91964 \textit{ per unit}$$

Five Bus Power System Solved



Additional Power Flow

- Next slides cover some more advanced power flow topics that need to be considered in many commercial power flow studies
- An important consideration in the power flow is the assumed time scale of the response, and the assumed model of operator actions
  - Planning power flow studies usually assume automatic modeling of operator actions and a longer time frame of response (controls have time to reach steady-state)
    - For example, who is actually doing the volt/var control
  - In real-time applications operator actions are usually not automated and controls may be more limited in time

Quasi-Newton Power Flow Methods

- First we consider some modified versions of the Newton power flow (NPF)
- Since most of the computation in the NPF is associated with building and factoring the Jacobian matrix, **J**, the focus is on trying to reduce this computation
- In a pure NPF **J** is build and factored each iteration
- Over the years pretty much every variation of the NPF has been tried; here we just touch on the most common
- Whether a method is effective can be application dependent
  - For example, in contingency analysis we are usually just resolving a solved case with an often small perturbation

Quasi-Newton Power Flow Methods

- The simplest modification of the NPF results when **J** is kept constant for a number of iterations, say k iterations
  - Sometimes known as the Dishonest Newton
- The approach balances increased speed per iteration, with potentially more iterations to perform
- There is also an increased possibility for divergence
- Since the mismatch equations are not modified, if it converges it should converge to the same solution as the NPF
- These methods are not commonly used, except in very short duration, sequential power flows with small mismatches

Dishonest N-R Example

$$x^{(v+1)} = x^{(v)} - \left[\frac{1}{2x^{(0)}}\right]((x^{(v)})^2 - 2)$$

Guess $x^{(0)} = 1$. Iteratively solving we get

v	$x^{(v)}$ (honest)	$x^{(v)}$ (dishonest)
0	1	1
1	1.5	1.5
2	1.41667	1.375
3	1.41422	1.429
4	1.41422	1.408

We pay a price in increased iterations, but with decreased computation per iteration; that price is too high in this example and in the power flow in general so it is not used.

Decoupled Power Flow

- Rather than not updating the Jacobian, the decoupled power flow takes advantage of characteristics of the power grid in order to decouple the real and reactive power balance equations
  - There is a strong coupling between real power and voltage angle, and reactive power and voltage magnitude
  - There is a much weaker coupling between real power and voltage magnitude, and reactive power and voltage angle

Decoupled Power Flow Formulation

General form of the power flow problem

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)} \\[2ex] \dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta \boldsymbol{\theta}^{(v)} \\ \Delta |\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta \mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta \mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

where

$$\Delta \mathbf{P}(\mathbf{x}^{(v)}) = \begin{bmatrix} P_2(\mathbf{x}^{(v)}) + P_{D2} - P_{G2} \\ \vdots \\ P_n(\mathbf{x}^{(v)}) + P_{Dn} - P_{Gn} \end{bmatrix}$$

Decoupling Approximation

Usually the off-diagonal matrices, $\dfrac{\partial \mathbf{P}}{\partial |\mathbf{V}|}^{(v)}$ and $\dfrac{\partial \mathbf{Q}}{\partial \boldsymbol{\theta}}^{(v)}$

are small. Therefore we approximate them as zero:

$$-\begin{bmatrix} \dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)} & \mathbf{0} \\ \mathbf{0} & \dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)} \end{bmatrix} \begin{bmatrix} \Delta\boldsymbol{\theta}^{(v)} \\ \Delta|\mathbf{V}|^{(v)} \end{bmatrix} = \begin{bmatrix} \Delta\mathbf{P}(\mathbf{x}^{(v)}) \\ \Delta\mathbf{Q}(\mathbf{x}^{(v)}) \end{bmatrix} = \mathbf{f}(\mathbf{x}^{(v)})$$

Then the problem can be decoupled

$$\Delta\boldsymbol{\theta}^{(v)} = -\left[\dfrac{\partial \mathbf{P}}{\partial \boldsymbol{\theta}}^{(v)}\right]^{-1} \Delta\mathbf{P}(\mathbf{x}^{(v)}) \quad \Delta|\mathbf{V}|^{(v)} = -\left[\dfrac{\partial \mathbf{Q}}{\partial |\mathbf{V}|}^{(v)}\right]^{-1} \Delta\mathbf{Q}(\mathbf{x}^{(v)})$$

Off-diagonal Jacobian Terms

Justification for Jacobian approximations:

1. Usually r << x, therefore $|G_{ij}| \ll |B_{ij}|$
2. Usually θ_{ij} is small so $\sin\theta_{ij} \approx 0$

Therefore

$$\frac{\partial \mathbf{P}_i}{\partial |\mathbf{V}_j|} = |V_i|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

$$\frac{\partial \mathbf{Q}_i}{\partial \boldsymbol{\theta}_j} = -|V_i||V_j|\left(G_{ij}\cos\theta_{ij} + B_{ij}\sin\theta_{ij}\right) \approx 0$$

By assuming half the elements are zero, we only have to do half the computations

Fast Decoupled Power Flow, cont.

- By continuing with Jacobian approximations we can obtain a reasonable approximation that is independent of the voltage magnitudes/angles.
  - This means the Jacobian need only be built/inverted once per power flow solution
- This approach is known as the fast decoupled power flow (FDPF)
- FDPF uses the same mismatch equations as standard power flow (just scaled) so it should have same solution
- The FDPF had been widely used, though usually only for an approximate solution; it is less commonly used now

FDPF Approximations

The FDPF makes the following approximations:

1. $\left|G_{ij}\right| = 0$
2. $\left|V_i\right| = 1$
3. $\sin\theta_{ij} = 0 \qquad \cos\theta_{ij} = 1$

To see the impact on the real power equations recall

$$P_i = \sum_{k=1}^{n} V_i V_k (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = P_{Gi} - P_{Di}$$

Which can also be written as

$$\frac{P_i}{V_i} = \sum_{k=1}^{n} V_k (G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) = \frac{P_{Gi} - P_{Di}}{V_i}$$

FDPF Approximations

- With the approximations for the diagonal term we get

$$\frac{\partial \mathrm{P_i}}{\partial \theta_i} \approx \sum_{\substack{k=1 \\ k \neq i}}^{n} B_{ik} = -B_{ii}$$

The for the off-diagonal terms (k ≠ i) with **G=0** and **V=1**

$$\frac{\partial P_i}{\partial \theta_k} = -B_{ik}\cos\theta_{ik} \approx -B_{ik}$$

- Hence the Jacobian for the real equations can be approximated as –**B**

FPDF Approximations

- For the reactive power equations we also scale by V_i

$$\mathrm{Q_i} = \sum_{k=1}^{n} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = Q_{Gi} - Q_{Di}$$

$$\frac{\mathrm{Q_i}}{V_i} = \sum_{k=1}^{n} V_k(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) = \frac{Q_{Gi} - Q_{Di}}{V_i}$$

- For the Jacobian off-diagonals we get

$$\frac{\partial Q_i}{\partial V_k} = -B_{ik}\cos\theta_{ik} \approx -B_{ik}$$

FDPF Approximations

- And for the reactive power Jacobian diagonal we get

$$\frac{\partial Q_{\mathrm{i}}}{\partial V_i} \approx -2B_{ii} - \sum_{\substack{k=1 \\ k\neq i}}^{n} B_{ik} = -B_{ii}$$

- As derived the real and reactive equations have a constant Jacobian equal to –**B**
  - Usually modifications are made to omit from the real power matrix elements that affect reactive flow (like shunts) and from the reactive power matrix elements that affect real power flow, like phase shifters
  - We'll call the real power matrix **B**' and the reactive **B**"

DC Power Flow

- The "DC" power flow makes the most severe approximations:
  - completely ignore reactive power, assume all the voltages are always 1.0 per unit, ignore line conductance
- This makes the power flow a linear set of equations, which can be solved directly

$$\boldsymbol{\theta} = -\mathbf{B}^{-1}\,\mathbf{P}$$

P sign convention is that generation is positive

- The term dc power flow actually dates from the time of the old network analyzers (going back into the 1930's)
  - Not to be confused with the inclusion of HVDC lines in the standard Newton power flow
- DC power flow is widely used in electric power market analysis

Book DC Power Flow Example

EXAMPLE 6.17

Determine the dc power flow solution for the five bus from Example 6.9.

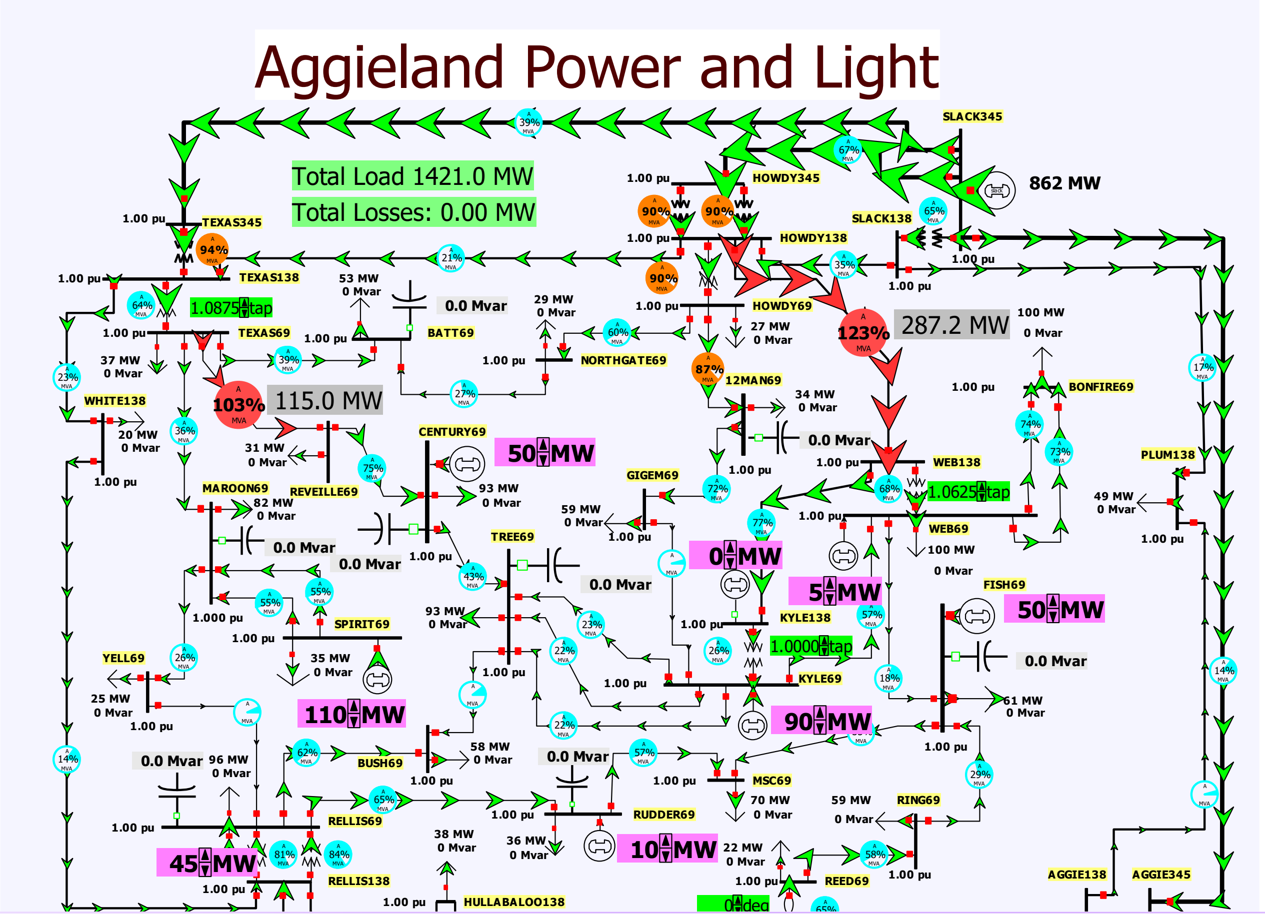
SOLUTION With bus 1 as the system slack, the **B** matrix and **P** vector for this system are

$$\mathbf{B} = \begin{bmatrix} -30 & 0 & 10 & 20 \\ 0 & -100 & 100 & 0 \\ 10 & 100 & -150 & 40 \\ 20 & 0 & 40 & -110 \end{bmatrix} \quad \mathbf{P} = \begin{bmatrix} -8.0 \\ 4.4 \\ 0 \\ 0 \end{bmatrix}$$

$$\boldsymbol{\delta} = -\mathbf{B}^{-1}\mathbf{P} = \begin{bmatrix} -0.3263 \\ 0.0091 \\ -0.0349 \\ -0.0720 \end{bmatrix} \text{radians} = \begin{bmatrix} -18.70 \\ 0.5214 \\ -2.000 \\ -4.125 \end{bmatrix} \text{degrees}$$

DC Power Flow in PowerWorld

- PowerWorld allows for easy switching between the dc and ac power flows (case **Aggieland37**)



To use the dc approach in PowerWorld select **Tools, Solve, DC Power Flow**

Notice there are no losses

Additional Power Flow Modeling Topics

- Over the years power flow algorithms have grown increasingly complicated, with this complication driven by a desire to better replicate the complexity of the actual power grid
- The next several slides cover some of these topics, with more details covered later in the semester (like modeling renewable generation)
- I cover more on solving large grids once we’ve covered the Chapter 7 material

Transformer Taps and Impedance Correction Tables

- With taps the impedance of the transformer changes; sometimes the changes are relatively minor and sometimes they are dramatic
  - A unity turns ratio phase shifter is a good example with essentially no impedance when the phase shift is zero
  - Often modeled with piecewise linear function with impedance correction varying with tap ratio or phase shift
  - Next lines give several examples, with format being (phase shift or tap ratio, impedance correction)
    - (-60,1), (0,0.01), (60,1)
    - (-25,2.43),(0,1),(25,2.43)
    - (0.941,0.5), (1.04,1), (1.15,2.45)
    - (0.937,1.64), (1,1), (1.1, 1.427)

Switched Shunt Control

- The status of switched shunts can be handled in an outer loop algorithm, similar to what is done for LTCs and phase shifters
  - Because they are discrete they need to regulate a value to a voltage range
- Switches shunts often have multiple levels that need to be simulated
- Switched shunt control also interacts with the LTC and PV control
- The power flow modeling needs to take into account the control time delays associated with the various devices

Switched Shunt System Design

- Because switched shunts tend to have a local impact, there needs to be a coordinated design in their implementation at the transmission level
  - Shunt capacitors used to raise the voltage, shunt reactors used to lower the voltage; used with LTCs and gens
- Often in the transmission system they are switched manually by a system operator
- The size and number of banks depends
  - Change in the system voltages caused by bank switching
  - The availability of different sizes
  - Cost for the associated switchgear and protection system

Switched Shunt Sizing

- A goal with switched shunt sizing is to avoid human irritation caused by excessive changes in lighting
- IEEE Std 1453-2015 gives guidance on the percentage of voltage changes as a function of time; Table 3 of the standard suggests keeping the voltage changes below about 3%
- We determine analytic methods to calculate this percentage later in the semester

There is a new version of this standard, 1453-2022

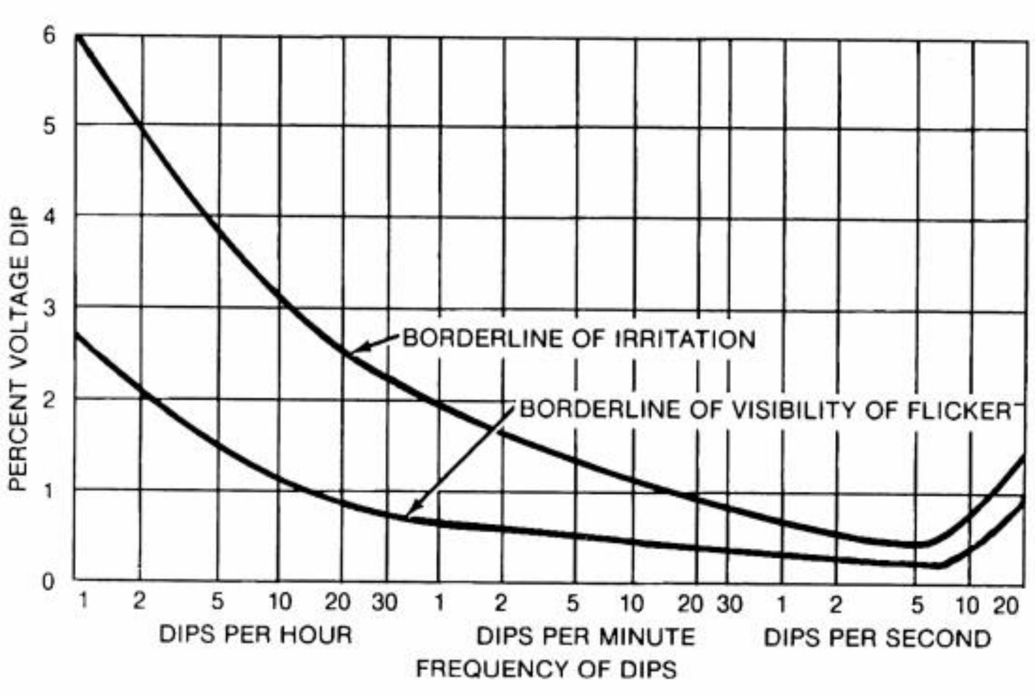


Image from IEEE Std. 1453-2015, "IEEE Recommended Practice for Measurement and Limits of Voltage Fluctuations and Associated Light Flicker on AC Power Systems"

Dynamic Reactive Capability

- Switched shunts are often used to maintain adequate dynamic reactive power from generators and SVCs
- FERC Order 827 (from June 2016, titled "Reactive Power Requirements for Non-Synchronous Generation") states that the power factor of generators should be between 0.95 leading to 0.95 lagging
  - Hence the absolute value of the Mvar output of the machines should be no more than 31% of the MW output
  - Often a value substantially better for reactive reserves
- Switched shunts are used to keep the generator power factor within this range

Area Interchange Control

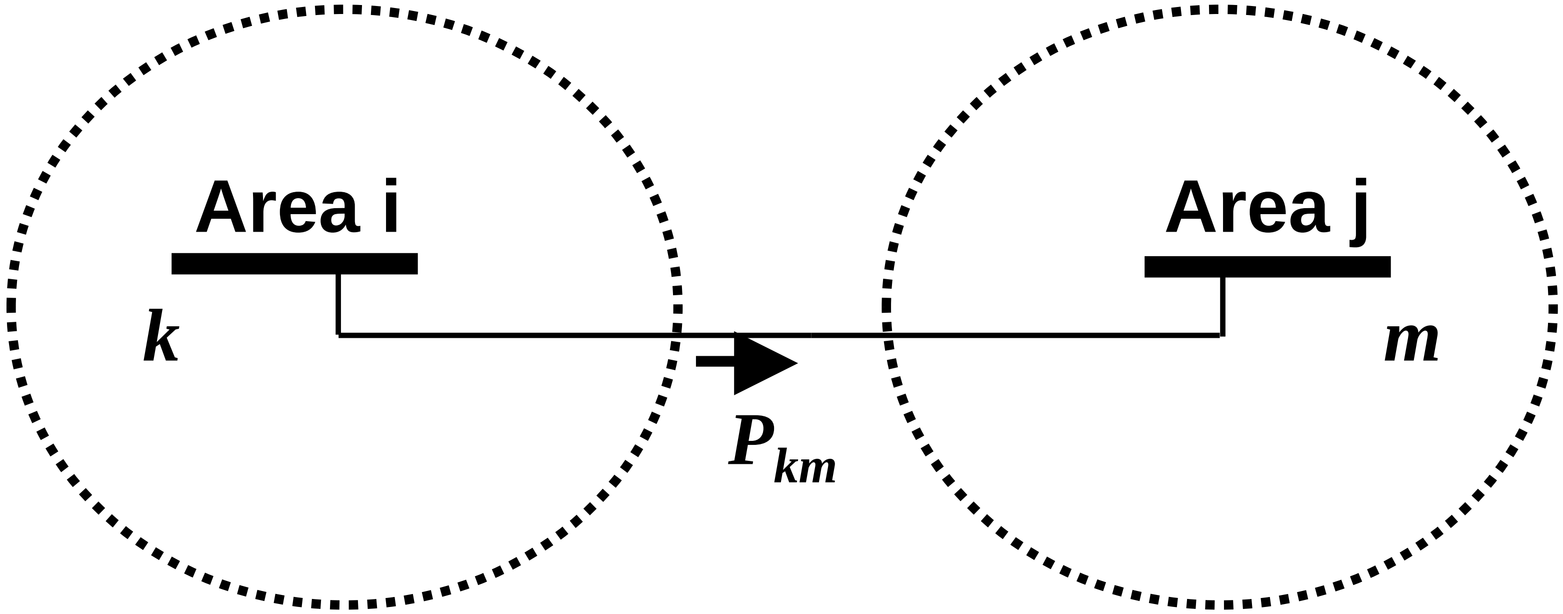
- The purpose of area interchange control is to regulate or control the interchange of real power between specified areas of the network
- Under area interchange control, the mutually exclusive subnetworks, the so-called areas, that make up a power system need to be explicitly represented
- These areas may be particular subnetworks of a power grid or may represent various interconnected systems
- The specified net power out of each area is controlled by the generators within the area
- A power flow may have many more areas than balancing authority areas

Area Interchange Control

- The net power interchange for an area is the algebraic sum of all its tie line real power flows
- We denote the real power flow across the tie line from bus k to bus m by P_{km}
- We use the convention that $P_{km} > 0$ if power leaves node k and $P_{km} \leq 0$ otherwise
- Thus the net area interchange S_i of area i is positive (negative) if area i exports (imports)
- Consider the two areas i and j that are directly connected by the single tie line (k, m) with the node k in area i and the node m in area j

Net Power Interchange

- Then, for the complex power interchange S_i, we have a sum in which P_{km} appears with a positive sign; for the area j power interchange it appears with a negative sign



Area i exports P_{km} and Area j imports P_{km}

Net Power Interchange

- Since each tie line flow appears twice in the net interchange equations, it follows that if the power system as *a* distinct areas, then

$$\sum_{i=1}^{a} S_i = 0$$

- Consequently, the specification of S_i for a collection of (a-1) areas determines the system interchange; we must leave the interchange for one area unspecified
  - This is usually (but not always) the area with the system slack bus

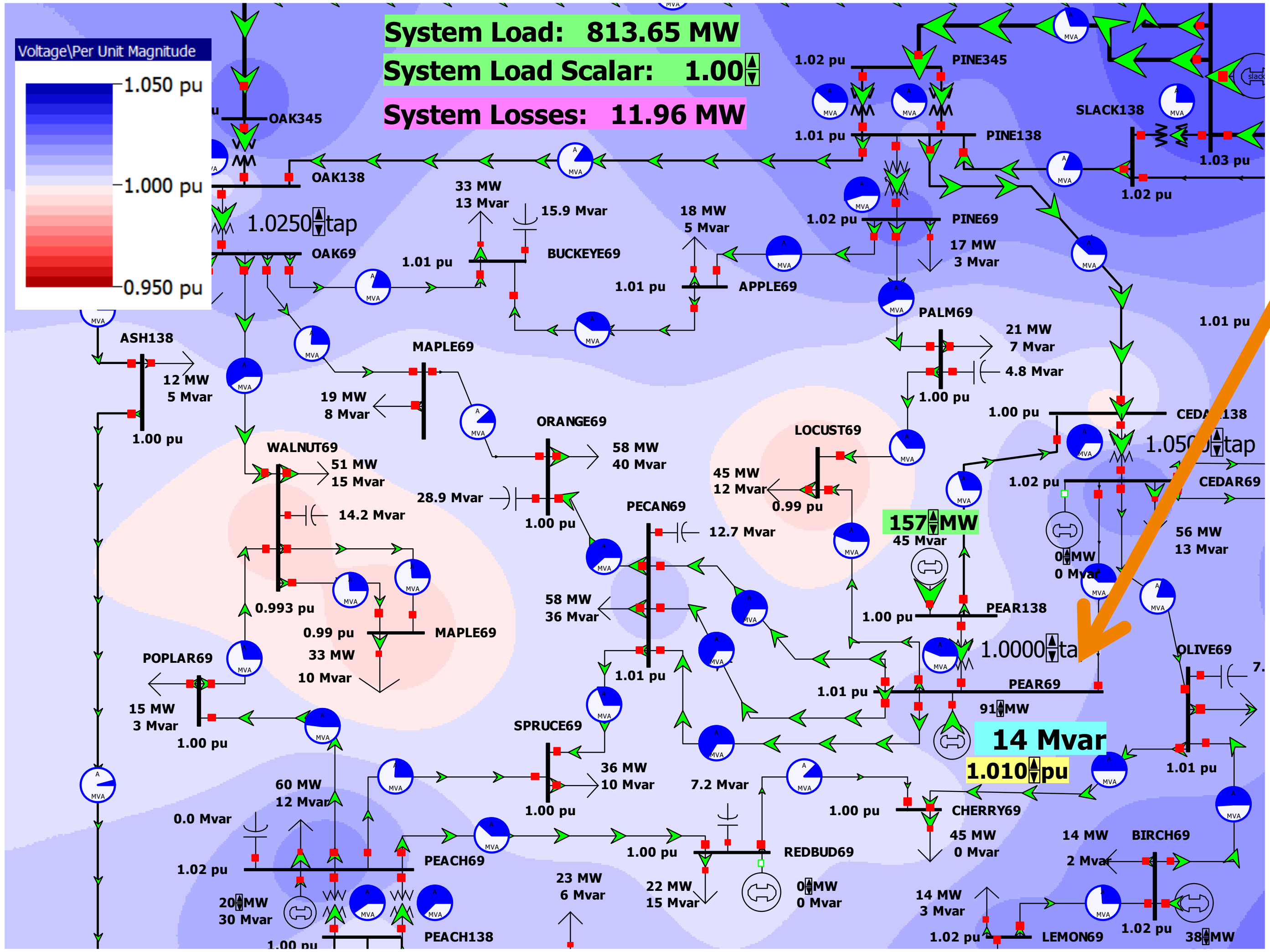
Modeling Area Interchange

- Area interchange is usually modeled using an outer loop control
- The net generation imbalance for an area can be handled using several different approach
  - Specify a single area slack bus, and the entire generation change is picked up by this bus; this may work if the interchange difference is small
  - Pick up the change at a set of generators in the area using constant participation factors; each generator gets a share
  - Use some sort of economic dispatch algorithm, so how generation is picked up depends on an assumed cost curve
  - Min/max limits need to be enforced

Generator Volt/Reactive Control

- Simplest situation is a single generator at a bus regulating its own terminal
  - Either PV, modeled as a voltage magnitude constraint, or as a PQ with reactive power fixed at a limit value. If PQ the reactive power limits can vary with the generator MW output
- Next simplest is multiple generators at a bus. Obviously they need to be regulating the bus to the same voltage magnitude
  - From a power flow solution perspective, it is similar to a single generator, with limits being the total of the individual units
  - Options for allocation of vars among generators; this can affect the transient stability results

Generator Voltage Control



This example uses the case **PSC_37Bus** with a voltage contour. Try varying the voltage setpoint for the generator at PEAR69

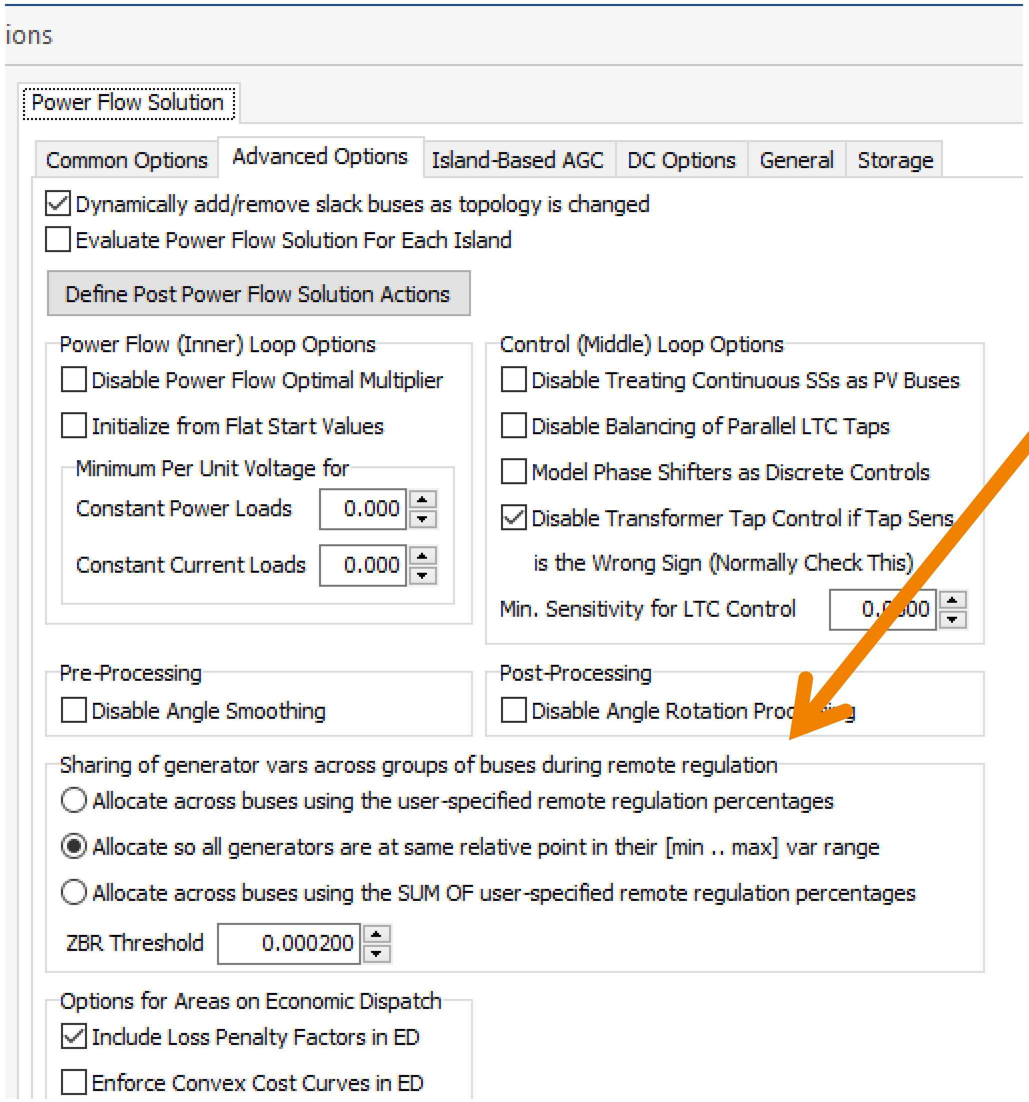
Generator Remote Bus Voltage Control

- Next complication is generators at a single bus regulating a remote bus; usually this is the high side of their generator step-up (GSU) transformer
  - When multiple generators regulate a single point their exciters need to have a dual input
  - This can be implemented in the power flow for the generators at bus j regulating the voltage at bus k by changing the bus j voltage constraint equation to be

$$\left|V_k\right| - V_{k,set} = 0$$

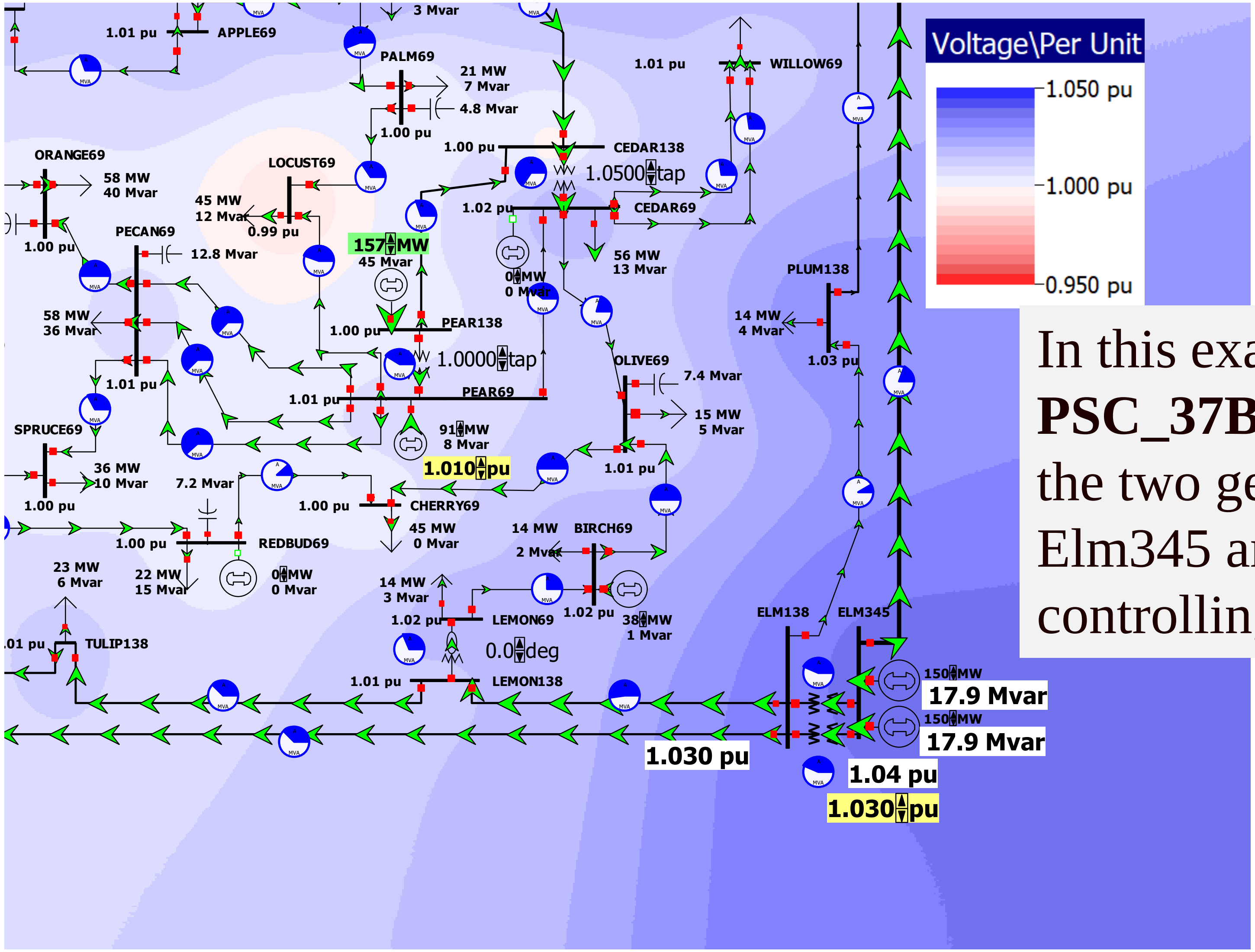
    (however, this does create a zero on the diagonal of the Jacobian)
  - Helps with power system voltage stability

Reactive Power Sharing Options



Different software packages use different approaches for allocating the reactive power; PowerWorld has several options.

Reactive Power Sharing



In this example, case **PSC_37Bus_Varsharing**, the two generators at Elm345 are jointly controlling Elms138

Generator Remote Bus Voltage Control

- The next complication is to have the generators at multiple buses doing coordinated voltage control
  - Controlled bus may or may not be one of the terminal buses
- There must be an a priori decision about how much reactive power is supplied by each bus; example allocations are a fixed percentage or placing all generators at the same place in their regulation range
- Implemented by designating one bus as the master; this bus models the voltage constraint
- All other buses are treated as PQ, with the equation including a percent of the total reactive power output of all the controlling bus generators