Steady-State Power System Security Analysis with PowerWorld Simulator

S2: Advanced Power Flow using PowerWorld Simulator

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Overview

• Detailed Overview of “Single Solution”
  – Pre-Processing
  – MW Control Loop
  – Voltage Control Loop
  – Inner Power Flow Loop

• Power Flow Solution Advanced Options
  – Minimum Per Unit Voltage for Constant Power and Current Loads
  – Parallel Tap Balancing
  – Regulation Range Correction
  – Minimum Tap Sensitivity
  – Generator Mvar Sharing
  – Switched Shunt and Transformer Solution Options

• Area Control with Multiple Islands
• Solution Diagnosis Aids
What Does It Mean to do a Single Solution in Simulator?

- Single solution should not be confused with a single Newton-Raphson (or other technique) power flow
- Simulator’s “Single Solution” encompasses three nested loops that iterate between a power flow routine, logic for control device switching, and generation control until the power flow is solved and no more device switching is detected
Overview of Single Solution Routine

• Pre-processing
  – Angle Smoothing
  – Generator remote regulation viability
  – Estimate MW change needed

• Three Nested Loops Solution Process
  – MW Control Loop
    • Voltage Controller Loop
      – Inner Power Flow loop

Note: The Inner Power Flow Loop was covered in S1

Traditionally called the Power Flow Solution

MW Control Loop covered in this section

MW Control Loop covered later
Pre-processing

• Angle Smoothing
  – Reduces large angle differences across transmission elements that have recently been closed to reduce initial power flow mismatches
  – If disabled, closing a line with a large angle difference often causes the power flow to diverge
  – Angle smoothing also works for a series of branches that are closed together

• Following a topology change, Simulator also adjusts zero-magnitude voltages in groups of buses connected by low impedance branches
Pre-processing

• When pre-processing the voltage profile of a solution before solving, Simulator will now look at groupings of buses connected by very low impedances lines. If a bus in a grouping of energized buses has a zero voltage while other buses in the group do not, the zero voltage will be changed to the first non-zero voltage found in the grouping.
Pre-processing

• Generator Remote Regulation Viability
  – Checks for a viable transmission path between a generator bus and its remotely regulated bus
  – If a generator has no transmission path, or if all possible transmission routes to the regulated bus are intercepted by other voltage controlled buses, the generator is internally turned off of voltage regulation

If a generator on left is set to control voltage at the bus on the right, this would cause convergence difficulty
Pre-processing

• Estimate MW Change
  – Stores the initial output of the generators for referencing during participation factor control
  – Modifies generator outputs in each area, super area, or island (depending on what control is being used) to meet approximate ACE requirements
  – Attempting to prevent slack bus from changing by drastic amounts during the first Newton-Raphson power flow calculation in the inner loop
MW Control Loop

• MW Control (Outer Loop)
  – Repeat
    • Voltage Controller Loop
      – Inner Power Flow Loop
    • Change generation/load to meet ACE requirements
      – Redispaches generation and/or load using the selected AGC control method for each area (Super area or island)
  – Until no more generation/load changes are required
Power Flow and Control Loop

- Voltage control switching and Inner Power Flow Loop
  - Repeat
    - 1: Inner Power Flow loop
      - 1a: Continuous SVC Switching
    - 2: Generator MVAR Limit Checking
    - 3: DC Line Solution
    - 4: Switched Shunt Switching
    - 5: Discrete SVC Switching
    - 6: Transformer Switching
    - 7: D-FACTS Switching
  - Until no more control switching is required or maximum control loop iterations reached
Step 1: Inner Power Flow Loop

Step 1a: Continuous SVC Control

• Step 1: Inner Power Flow loop, Repeat...
  – Evaluate Mismatch
  – Generator MVAR output automatically calculated for PV buses
  – SVC MVAR output automatically calculated for continuous SVCs
  – Optionally (enforce Generator MVAR limits at each step)
  – Perform power flow step
    » Newton’s Method (this is in rectangular form)
    » Decoupled Power Flow
    » Polar Form Newton’s Method
  …Until no mismatch

• Step 1a: Continuous SVC Limit Check and Discrete Component Switching
  – Check MVAR limits on continuous SVCs
    » SVSMO1 and SVSMO3
  – Switch any fixed shunts controlled by continuous SVCs
  – Goto Step 1 if any SVCs or controlled fixed shunts move
Step 2: Generator MVAR Limits

Step 3: Solve DC line equations

• Step 2: Generator MVAR Limit Check
  – Backs off or enforces MVAR limits
  – Checks for controller oscillation
    » Generators that appear to be oscillating between control settings are internally set off of control
  – Updates mismatch and voltage vectors
    » Incorporates voltage vector changes by processing each generator

• Step 3: Solve DC line equations
  – DC Lines will be discussed later, but to the power flow solution they look like a fixed MW injection with a Mvar injection that is a function of the AC line terminal voltages
Step 4: Switched Shunt Control

- Step 4: Switched shunt control
  - Checks regulated buses for voltage limit violations and adjusts switched shunt control appropriately
    - Also can control the total VAR output for generators controlling the voltage at a particular bus (good for modeling a shunt that maintains VAR reserves)
    - Shunts are adjusted one at a time with each shunt only considering its impact on the regulated bus’ voltage. The interaction between different shunts is not modeled here.
  - Checks for controller oscillations
    - Switched shunts that appear to be oscillating between control settings are internally set off of control
  - Updates mismatch and voltage vectors
Step 5: Discrete SVC Control

- Only SVCs that are discrete-type SVCs are switched in this step
  - SVSMO2
- Checks regulated buses for voltage limit violations and adjusts SVC control appropriately
  - Any fixed shunts controlled by the SVC are adjusted in this step
  - SVCs are adjusted one at a time with each SVC only considering its impact on the regulated bus’ voltage. The interaction between different SVCs is not modeled here.
- Checks for controller oscillations
  - SVCs that appear to be oscillating between control settings are internally set off of control
- Updates mismatch and voltage vectors
Step 6: Transformer Switching

• Step 6: Transformer switching
  – Checks regulated Voltages, MVAR flows, and MW flows for limit violations and adjusts transformer controls in a manner dependent on the Transformer Stepping Methodology
    » Coordinated Sensitivities: tap change calculation requires the construction and factorization of a full matrix dimensioned by the number of transformers which need to be switched. Normally a small number are changed.
    » Self-Sensitivity Only: each transformer does not consider how it affects other transformers. This calculation is much faster, but may be less accurate and lead to more iterations
    » Note: If more than 50 transformers are involved, Simulator always uses Self-Sensitivity Only
  – Checks for controller oscillations
    » Transformers that appear to be oscillating between control settings are internally set off of control
  – Updates mismatch and voltage vectors
Step 7: D-FACTS Control

• Step 7: D-FACTS Control
  – D-FACTS devices attempt to keep the current on a branch within a specified range
  – Impedance of the D-FACTS is modified to adjust the current
  – D-FACTS that appear to be oscillating between control settings are internally set off of control
  – Updates Ybus with new impedance values
Complete Process

- Pre-processing
  - Angle Smoothing, Remote Viability Check, Area Generator Estimation
- Repeat (MW Control Loop)
  - Repeat (Controller Loop)
    - 1: Repeat (Inner Power Flow loop)
      - Evaluate Mismatch
      - Generator MVAR output automatically calculated for PV buses
      - SVC MVAR output automatically calculated for continuous SVCs
      - Optionally (enforce Generator MVAR limits at each step)
      - Perform power flow step
        » Newton’s Method
        » Decoupled Power Flow
        » Polar Newton
    - Until no more mismatch (or max iteration)
      - 1a: Continuous SVC Limit Check and Discrete Component Switching
      - Goto Step 1 until no more SVC switching
    - 2: Generator MVAR Limit Checking
    - 3: DC Line Solution
    - 4: Switched Shunt Control Switching
    - 5: Discrete SVC Switching
    - 6: Transformer Switching
    - 7: D-FACTS Switching
    - Until no more control switching is required (or at max iteration)
    - Change generation/load to meet ACE requirements
      - Redispatches generation/load using the AGC control method for area (island)
  - Until no more generation changes are required
Example Message Log 1/2
(Image Only)

Colors of Messages determined by the Simulator, Message Log colors
Example Message Log 2/2
(Image Only)

Colors of Messages determined by the Simulator, Message Log colors
Advanced Options for Power Flow Solution

- To customize the power flow solution, go to the **Options** ribbon tab and select **Simulator Options → Power Flow Solution** page
  - Advanced Options Tab

Also on the Quick Access Toolbar

![Simulator Options ribbon](image)
Simulator Options: Power Flow Solution Page

• Advanced Options Tab
  – Dynamically add/remove slack buses as topology is changed (Allow Multiple Islands)
    • If a single island is split into two islands (by opening lines), then a new slack bus is chosen (usually generator with the largest MW limit that regulates its terminal bus)
  – Post Power Flow Solution Actions
    • Allow you to define a list of conditional actions (much like a contingency definition) which occur at the end of EVERY power flow solution
    • An example would be loads that are automatically taken out of service when the voltage drops too low
Simulator Options: Power Flow Solution Page

- **Advanced Options Tab**
  - **Disable Power Flow Optimal Multiplier**
    - The optimal multiplier is a mathematically calculated step size for Newton’s Method that prevents the mismatch equations from increasing between iterations
  - **Initialize From Flat Start Values**
    - Always starts power flow solution with voltages and angles set to specific values
    - Generator buses or buses regulated by a generator are set to the setpoint voltage of the generator
    - 1.0 per unit for all other buses
    - Angles equal to the slack bus angle (not recommended)
  - **Minimum Per Unit Voltage for Constant Power Loads and Constant Current Loads**
    - At voltages less than the defined values, the constant power and constant current loads will be reduced
    - To disable either of these features, set the values to 0
Minimum Per Unit Voltage for Constant Power and Current Loads

- When a bus voltage is below these thresholds the constant power or current load will gradually decrease to zero MW at zero voltage
  - Constant Power Loads
    - Uses a cosine function
  - Constant Current Loads
    - Uses a sine function multiplied by voltage
- Functions are chosen so that the derivative of the load with respect to voltage is continuous
Minimum Per Unit Voltage for Constant Power and Current Loads

- Minimum Per Unit Voltage for Constant Power

\[ MW(V_{pu}) = \frac{S_{MW}}{2} \left( 1 - \cos \left( \frac{\pi V_{pu}}{V_{S\min pu}} \right) \right) \]

(Default Values are 0.7 and 0.5)

- Minimum Per Unit Voltage for Constant Current

\[ MW(V_{pu}) = I_{MW} V_{pu} \sin \left( \frac{\pi}{2} \frac{V_{pu}}{V_{I\min pu}} \right) \]
Simulator Options: Power Flow Solution Page

• Advanced Options Tab
  – Disable Treating Continuous SSs as PV Buses
    • Continuous switched shunts are normally treated as buses with fixed real power and voltage inside the inner power flow loop
  – Disable Balancing of Parallel LTC taps
    • Parallel LTC taps normally have their tap values synchronized to prevent circulating var flow
  – Model Phase Shifters as Discrete Controls
    • Phase shifters will switch tap positions discretely based on the tap step size
    • Normally users do not model the discrete properties of the phase-shifters. Including this can slow power flow solution.
  – Min. Sensitivity for LTC Control
    • Transformers with a sensitivity lower than this will be disabled
Example: Parallel Tap Balancing and Minimum Tap Sensitivity

- Choose Open Case
  - ...\S02_AdvancedPowerFlow\AdvancedOptions.raw
- Do NOT solve yet
- Open the Bus View
  - Choose Views > Define Custom View
  - Click Load From File (in Bottom Right)
  - Open BusViewTaps.aux
  - Choose Transformer Taps From the Customizations
  - Click Switch to Custom Bus View
Parallel Tap Balancing

• On Bus View, go to Bus: RECTOR (24212)

Parallel Transformers should have the same tap ratios
Parallel Tap Balancing and Regulation Range Correction

- On Bus View, go to Bus: SHELL J9 (54199)

Two Transformers Regulate the same bus (54199), but have different regulation ranges.

<table>
<thead>
<tr>
<th>Left Range</th>
<th>Right Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.996</td>
<td>1.013</td>
</tr>
<tr>
<td>1.021</td>
<td>0.988</td>
</tr>
</tbody>
</table>

Simulator will use the intersection of the ranges. If no intersection, then control turned off.

Again Parallel Taps should balance.
Parallel Taps Regulated Bus Error Checking

Note: Sample case does not have this problem. Slide is just example

- Parallel transformer taps which do not have the same regulated bus
  - Transformer will be turned off control if this occurs
  - Log message will be shown

Error: The following parallel transformers do not share the same regulated bus
Transformer 55649 TO 55649 CKT T2 has been turned off control.
Transformer 56649 TO 55649 CKT T1 has been turned off control.

- Also allow control if the regulated buses are within the a group of buses connected by very low impedance branches
Minimum Tap Sensitivity

- On Bus View, go to Bus: ICGLDC (51050)

Because the Generator at bus 51039 controls the voltage at bus 51040,
The two transformer taps will not be able to influence their voltages.

Taps will only be useful when generator hits its Mvar limits.
What Simulator does with these

- Click Single Solution
- Open the Message Log

...etc...

...etc...

The following parallel transformers have control ranges (Reg Min - Reg Max) that are not the same.
Reg range of 0.99600-1.01300 is being used for all (intersection of the control ranges).
- Transformer 54182 TO 54199 CCT T1 Reg Range specified: 0.99800-1.01300
- Transformer 54182 TO 54199 CCT T2 Reg Range specified: 0.99600-1.02100

...etc...

Calculating Transformer Tap Sensitivities for 24 Transformers

- Transformer 50139 TO 50130 CCT 1 can not effectively control voltage at bus 50130; control will be ignored until the tap sensitivity magnitude increases
- Transformer 50140 TO 50140 CCT 1 can not effectively control voltage at bus 50140; control will be ignored until the tap sensitivity magnitude increases
- Transformer 54617 TO 54617 CCT 1 can not effectively control voltage at bus 54617; control will be ignored until the tap sensitivity magnitude increases

...etc...
Simulator Options: Power Flow Solution Page

- Advanced Options Tab
  - Disable Angle Rotation Processing
    - Voltage angles are rotated so that the angle range in an island is equally spaced around zero degrees if any angles fall outside +/- 160 degrees
  - Sharing of generator vars across groups of buses
    - Allocate across buses using the user-specified remote regulation percentages
    - Allocate so all generators are at same relative point in their [min..max] var range
    - Allocate across buses using the SUM OF user-specified remote regulation percentages
  - Options for Areas on Economic Dispatch
    - Include Loss Penalty Factors in ED will consider losses in determining the dispatch
    - Enforce Convex Cost Curves in ED will turn units that are operating outside the convex portion of their cost curve off automatic control
Sharing of Generator Vars across a group of buses

- On Bus View, go to Bus: COLSTRP (62057)
  - Generators at 62047, 62048, 62049, 62050 all regulate the voltage at this bus
Var “Responsibility” Sharing

• Go to Model Explorer
  – Navigate to Network → Generators
  – Present setting is to “Allocate across buses using the user-specified remote regulation percentages”

Sum = 347.68
Var “Responsibility”
Sharing using Remote Reg %

• If you modify the values for Min Mvar and Max Mvar, the Gen Mvar values will not change
  – Change the Max Mvar value for generator at bus 62047 to 150 Mvar

  ![Table showing modified Mvar values](image)

  – Click Single Solution
  – No change in Gen Mvar outputs are seen
  – Change the Max Mvar value for generator at bus 62047 back to 270.7 Mvar
Var “Responsibility” Sharing using relative [min..max] var range

- Open the Simulator Options Dialog again
  - Go to Power Flow Options, Advanced Options
  - Change to “Allocate so all generators are at same relative point in their [min..max] var range”
  - Click Single Solution
  - Not much change now because the Var Range Ratio is the same as the Remote Reg % values
  \[
  \frac{270.70}{115.00} = \frac{0.35}{0.15}
  \]
  - To see the different behavior, change Min Mvar and Max Mvar values
Var “Responsibility” Sharing using relative [min..max] var range

- If you modify the values for Min Mvar and Max Mvar, the Gen Mvar values will change
  - Change the Max Mvar value for generator at bus 62047 to 150 Mvar
  - Click Single Solution
  - Gen Mvar outputs change
    - We enforce constant ratio of
      \[
      \frac{\text{GenMvar} - \text{MinMvar}}{\text{MaxMvar} - \text{MinMvar}} = \text{Constant}
      \]
      
      \[
      \begin{align*}
      \frac{61.26 - (-270.7)}{150.0 - (-270.7)} &= 0.789 \\
      \frac{156.5 - (-270.7)}{270.7 - (-270.7)} &= 0.789 \\
      \frac{66.48 - (-115.0)}{115.0 - (-115.0)} &= 0.789
      \end{align*}
      \]
Var “Responsibility” Sharing

- The Var Sharing option only applies to generators that have different terminal buses.
- For a group of generators that have the same terminal bus, PowerWorld will always allocate the Mvar values using the “relative [min..max] var range” method.
- See bus GHOST A9 (54171) for an example:
  - Go back to the Model Explorer, Network Generators
  - Remove the Advanced Filter “Coal Strip”
  - Navigate to find GHOST A9 (54171)
Var “Responsibility” Sharing

- Generator at same bus GHOST A9 (54171) are obeying the ratio

\[
\frac{\text{GenMvar} - \text{MinMvar}}{\text{MaxMvar} - \text{MinMvar}} = \text{Constant}
\]

- Examples:
  - \[
  \frac{2.85 - (-10.0)}{10.0 - (-10.0)} = 0.642
  \]
  - \[
  \frac{4.64 - (-10.0)}{12.8 - (-10.0)} = 0.642
  \]
  - \[
  \frac{5.84 - (-10.6)}{15.0 - (-10.6)} = 0.642
  \]
Power Flow Solution: Switched Shunt-Specific Features

- Each Switched Shunt has an option to allow it to switch during the inner power flow loop
  - This allows discrete switched shunts to be treated as PV buses initially and then revert back to discrete shunts after an initial solution
  - Reverting back to discrete shunts is done in Step 1a of the overall power flow solution process. This will cause additional inner power flow loop iterations.
Power Flow Solution:
Transformer-Specific Features

• With each transformer, a field called “Regulation Range Target Type” is available
  – Choices are
    • Middle of Reg Range
    • Max/Min of Reg Range
  – Determines what the “target” is for the transformer control when it is not meeting its regulation range
Area Control with Multiple Islands

• When an area spans multiple electric islands, the MW Interchange Control for that area may not be possible

• An error check is done to allow for more complex situations
  – An area that belongs to multiple islands can be placed on control only if at most one of these islands contains multiple areas
Areas Spanning Multiple Islands: Example for Area #1 Control

**Control Allowed**
Only Island C has multiple areas

**Control NOT Allowed**
Island A and Island C have multiple areas

This situation occurs for WAPA and ERCOT in Eastern Interconnect cases
Areas Spanning Multiple Islands: Why control is NOT Allowed

• Not allowed because Simulator doesn’t have enough information to know which generators should respond when transactions are specified
  – For example: Area 1 – Area 2 transfer
  – Should transfer occur in Island A or Island C?
    • Because Simulator doesn’t know, control is NOT allowed
Power Flow Solution: Solution Diagnosis Aids

- Displays for showing which devices remotely regulate a particular bus are available (generators, LTCs, and shunts)
  - Appears on Run Mode Bus dialog
  - On Model Explorer under Solution Details\Remotely Regulated Buses display
Power Flow Solution: Solution Diagnosis Aids

- There is a field for buses called **Solution\Type (PV, PQ, Slack, etc.)**
  - Descriptive strings to better help understand the power flow solution
  - Column is shown by default on **Network\Mismatches** table

Slack, PQ, and PV

- PV (Remote Reg Master)
- PQ (Remote Reg Slave)
- PQ (Continuous Shunts at Var Limit)
- PQ (Gens at Var Limit)
- PQ (Remotely Regulated at Var Limit)
- PQ (Remotely Regulated)
Power Flow Solution: Solution Diagnosis Aids

- Bus Zero Impedance branch groupings display
  - Model Explorer under Solution Details\Bus Zero-Impedance Branch Group
Island Information dialog lists the buses, generators, loads, and switched shunts that are part of an island.