# Power System Economics and Market Modeling

## M5: Security-Constrained Optimal Power Flow

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# Additional OPF Topics

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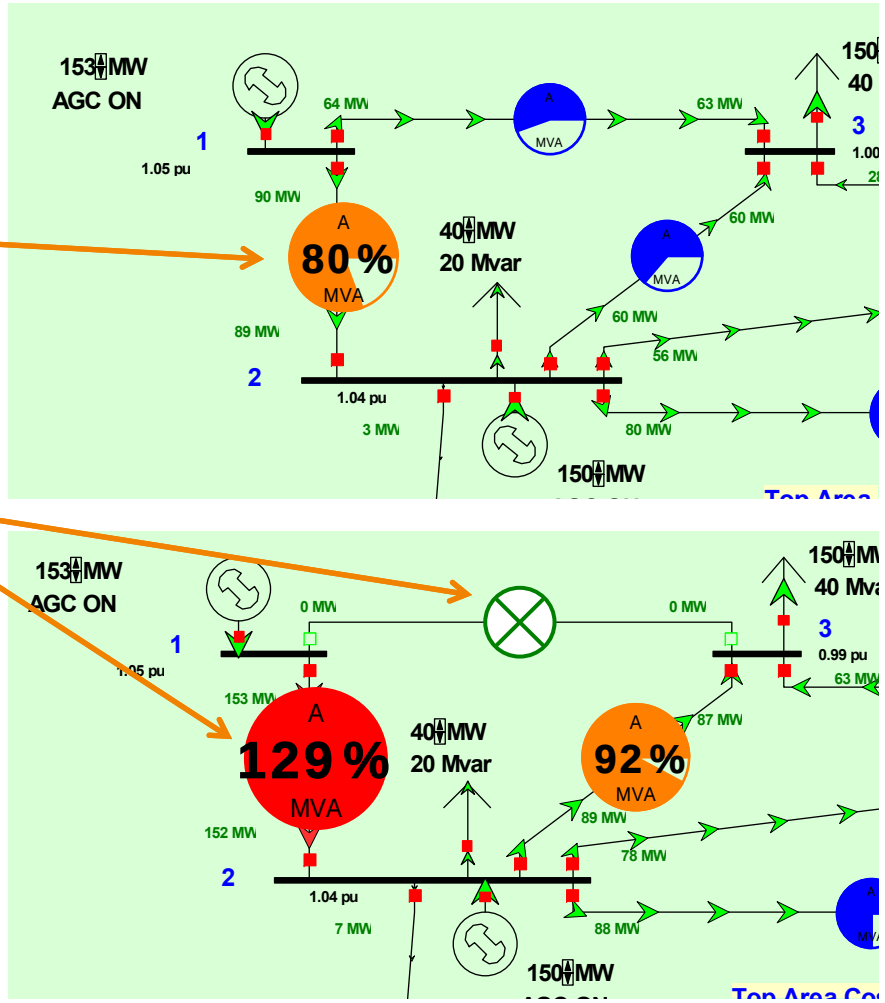
- Interfaces with Contingent elements (Flowgates)
- Area Transactions as OPF Controls
- DC Power Flow modeling for the OPF
  - Modeling of Losses in a DC power flow. Is this possible?
    - Both dispatch sensitivities
    - Reduction of generation requirement
  - Modeling of VAR flows. Is this possible?
    - Using the “power circle” and assuming unity voltages

# Interfaces with Contingent Elements

- Interfaces can have contingent elements
  - Line OPEN and Line CLOSE elements
- You must specify how you would like to treat these special interfaces
  - Choose the **Options** ribbon tab → **Simulator Options**
  - Go to **Power Flow Solution Page** (default)
  - Go to **General Tab**
  - Monitor/Enforce Contingent Interface Elements
    - Never
      - will never calculate the post-contingent flows on the interface
    - Power Flow/OPF, but not CA/SCOPF
      - in the powerflow and OPF we will show the “post-contingent” flow
    - All Applications including CA/SCOPF
      - In the SCOPF and CA we will also show the “post-contingent” flow

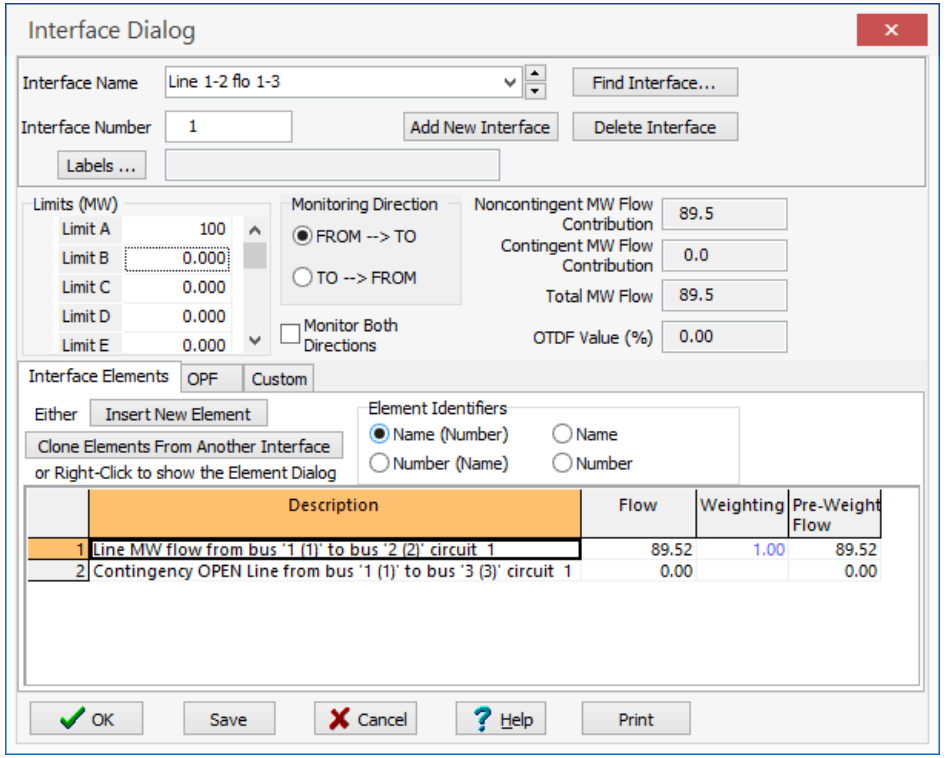
# Interfaces with Contingent Elements

- Open the B7SCOPF case
- Solve the OPF
- Line 1-2 is loaded at 80% of its rating
- If line 1-3 is lost, then line 1-2 becomes overloaded



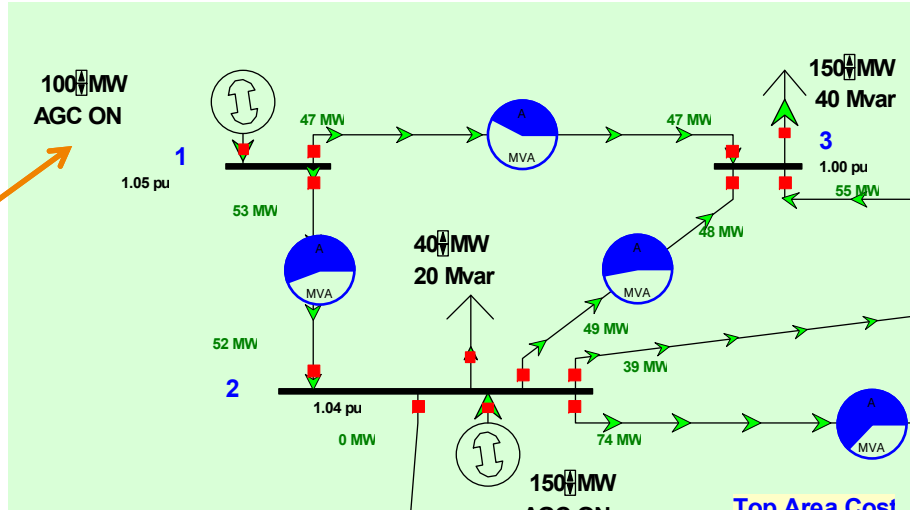
# Interfaces with Contingent Elements

- Add an interface to compute the flow on line 1-2 for loss of line 1-3
- Assign limit of 100 MW (Limit A)
- Solve power flow (to update contingent interface flows)



# Interfaces with Contingent Elements

- Interface flow is initially 153% of its limit
- Solve the OPF
- Generator at bus 1 is reduced to 100 MW to meet contingency limit
- Total hourly cost increases from $16,011 to $16,050



# Area Transactions as OPF Controls: Why would you do this?

- Situation #1: If the following situation is met
  - One Area/Superarea is on OPF control
  - A second Area/Superarea does not have cost information and is on Participation Factor Control
  - The second area interacts with the first area, and you have a general “cost curve” for how much the first area purchases/sells power from the second area
  - You can then create a MW transaction between the two areas and specify a “cost curve” which applies to the second area
  - The OPF can then be configured to essentially dispatch the second area as though it’s a giant generator available to buy or sell power from
    - The cost curve specified will be used to dispatch the transaction
    - The second area will spread power out using participation factors.

# Area Transactions as OPF Controls: Why would you do this?

- Situation #2: If the following situation is met
  - One Area/Superarea is on OPF control
  - A second Area/Superarea is also on OPF Control
  - You want the two areas to be able to freely transfer power between one another, however you want to limit the maximum amount of transfer between the two
    - You might also want to place a “premium” on the transfer so that the two areas will buy/sell only if the price difference is large than some threshold
  - If you wanted two areas to transfer power between one another without any limits, then you would just create a Super Area with both in it.

# Area Transactions as OPF Controls

- You may define area-to-area MW transactions that can be dispatched by the OPF
- Choose **Model Explorer → Aggregations → MW Transactions**
- Go to **List of Transactions** Tab
- Right-Click on Transaction between areas 1 and 2 and **Show Dialog…**
  - Check *Transaction Dispatchable in OPF* to allow OPF to determine the price (both areas are on OPF control, so it will optimize the transfer and price, within the min and max range specified)
  - Or enter a Cost Curve for the transaction (if one area is on OPF, and the other is on Part. Factor, then the area on OPF will "dispatch" the area on Part. Factor as though it's a big generator)

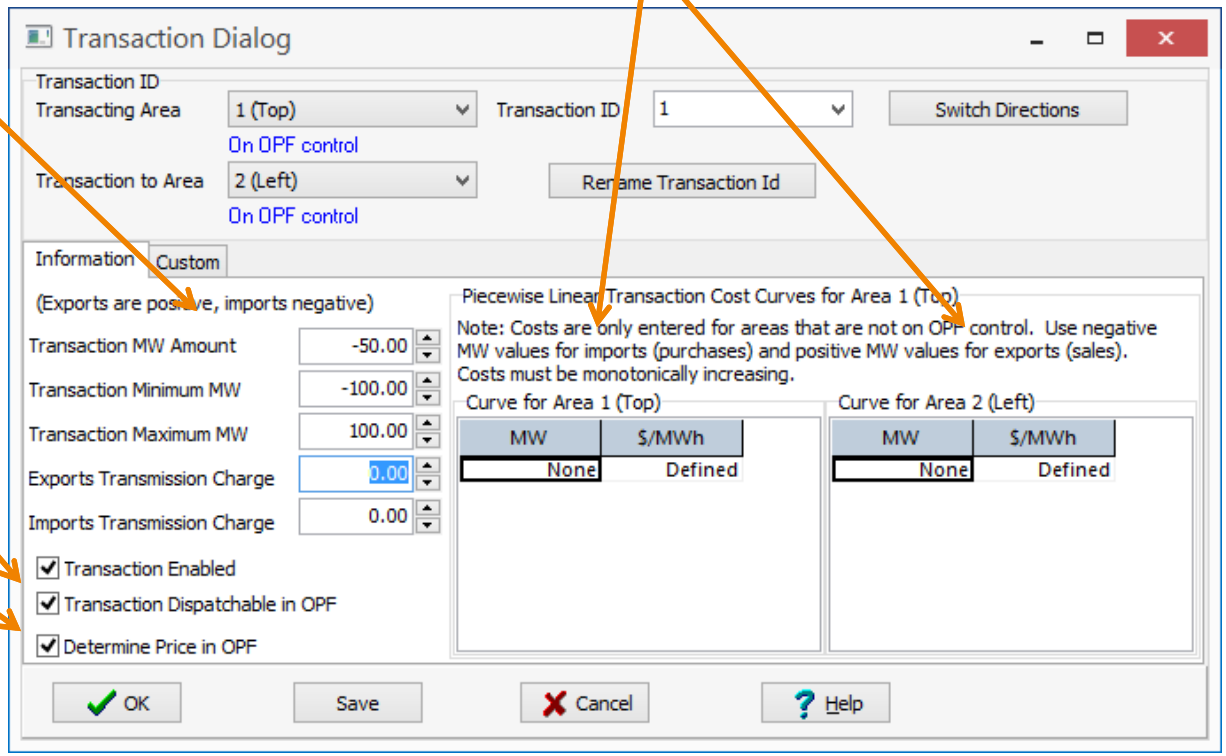
# Area Transactions as OPF Controls

Specify a Min/Max Range for transfer

Specify an Export Cost Curve and Import Cost Curve (for areas that are NOT on OPF control)

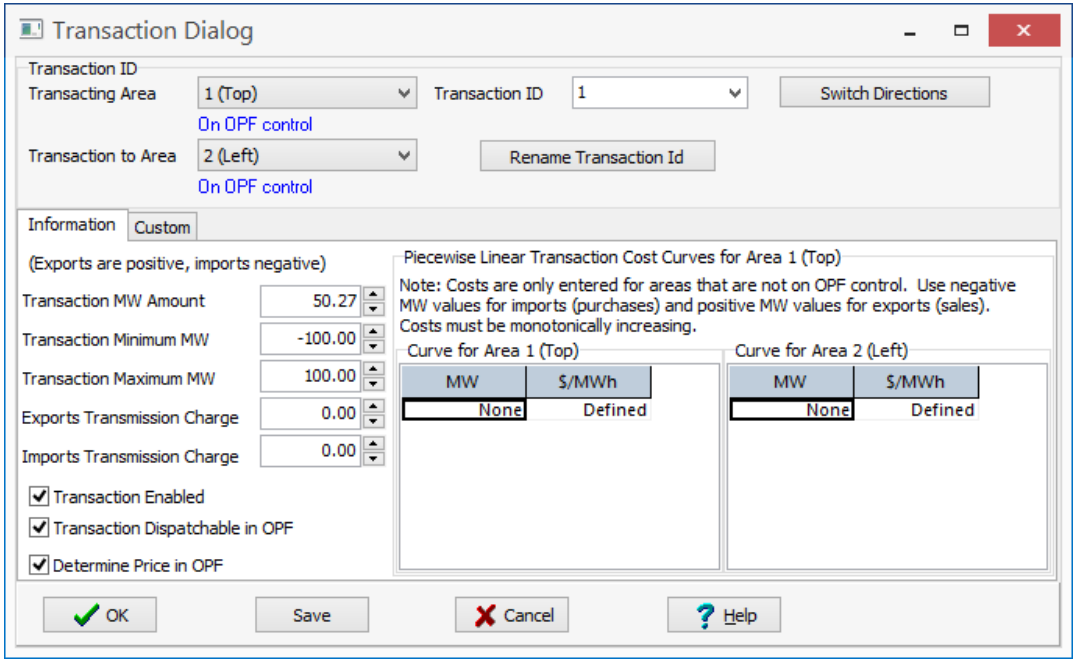
Check to allow dispatch

Check to have OPF determine price (cost curves will not be used then)



# Area Transactions as OPF Controls

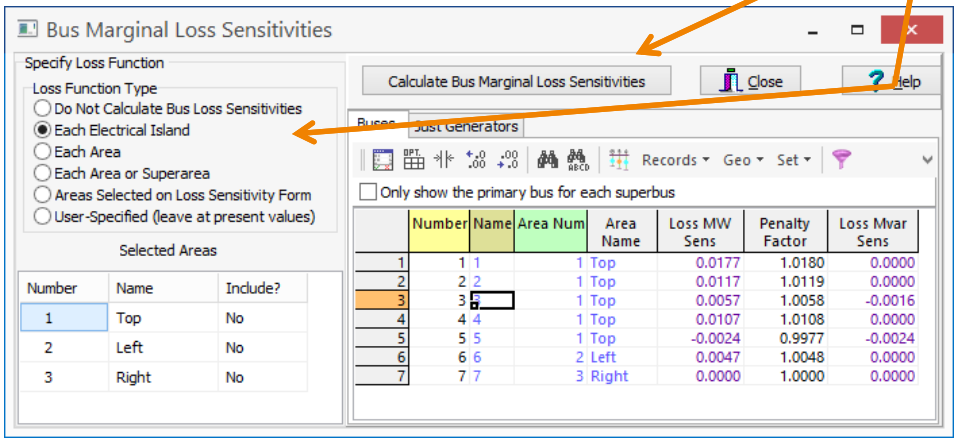
- Re-Solve OPF
- Transaction is dispatched to +50 MW (limited by min MW of generator at bus 6)




- Total hourly cost reduced by $337

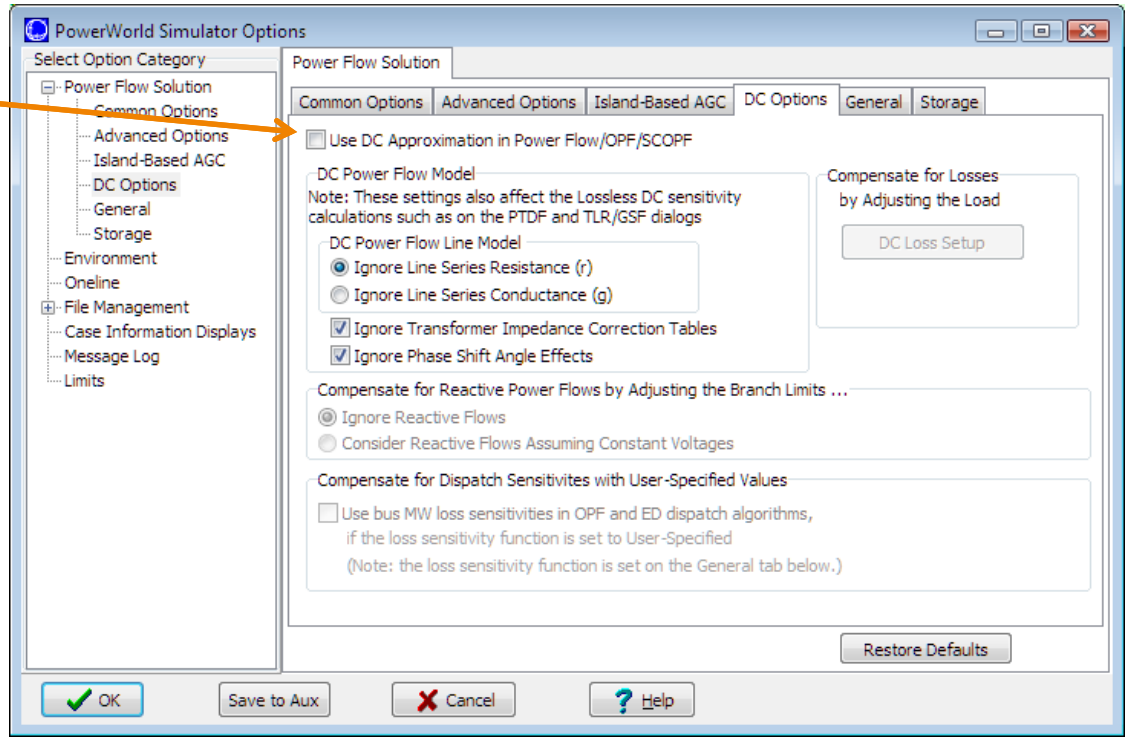
# DC Power Flow Modeling with Losses

- First open Loss Sensitivity dialog (**Tools** Ribbon → **Sensitivities → Loss Sensitivities…**)
- Select a *Loss Function Type*
- Click *Calculate Bus Marginal Loss Sensitivities*
- Change Loss Function Type to *User-Specified (leave at present values)*
- Penalty factors can now be applied to generators with DC power flow
  - This approximates how losses would affect the dispatch
  - Used in some markets



# Simulator Options: Power Flow Solution Page

- **DC Options** Tab → **Use DC Approximation in Power Flow/OPF/SCOPF**
  - Check this box to model the system using a DC power flow.




Note: Once you convert a large system to a DC power flow, it is very difficult to get the AC system to resolve.

# DC Options: DC Power Flow Model

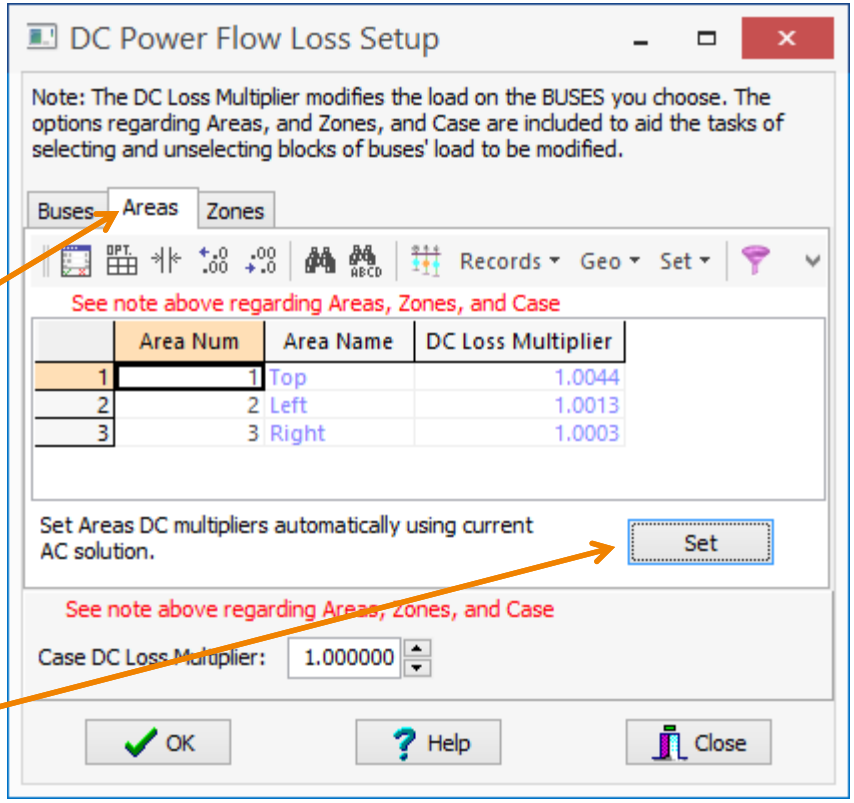
- Option to ignore real part of impedance (r) or real part of admittance (g)
  - Line series impedance Z = r + jx
  - Series admittance $Y = 1/Z = 1/(r + jx) = r/(r^2 + x^2) - j\, x/(r^2 + x^2) = g + jb$
  - *Ignore Line Series Resistance (r)*: then Y = -j/x and b = -1/x
  - *Ignore Line Series Conductance (g)*: then $b = -x/(r^2+x^2)$
- *Ignore Transformer Impedance Correction Tables* and *Ignore Phase Shift Angle Effects* (default is to ignore)
  - Impedance correction tends to increase impedance and phase shift effects tend to decrease impedance
  - By not ignoring, DC equations become a function of the system state and removes some of the advantages of the DC approximation

# DC Options

- Compensate for Losses by Adjusting Loads
  - Specify a load multiplier at each bus. When solving the DC power, Simulator will artificially increase loads by this multiplier (user load inputs do not change)
- Compensate for Reactive Power Flows by Adjusting the Branch Limits
- Compensate for Dispatch Sensitivities with User-Specified Values
  - Allows you to make use of loss sensitivities even in the DC power flow

# DC Options

- Compensate for Losses by Adjusting Loads
  - Click *DC Loss Setup*
  - Specify a load multiplier at each bus, OR
  - Set them by *Area/Zone* according to the losses in the Area/Zone at the present operating point (click *Set*)

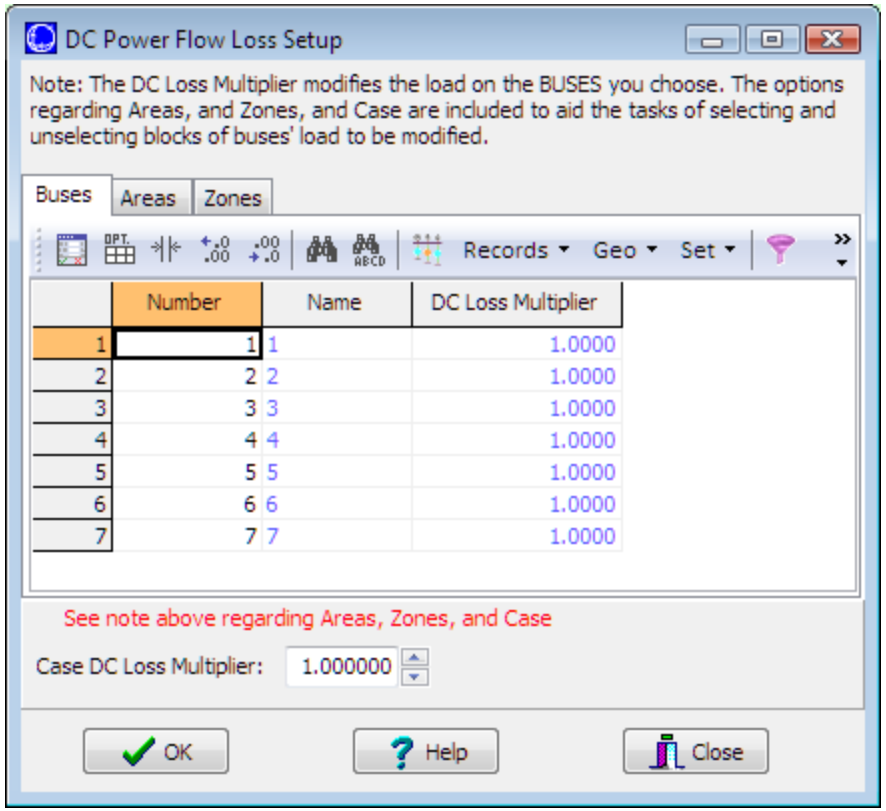


# Compensate for Mvar Flows by Adjusting the Branch Limits

- Option *Ignore Reactive Flows* means branch MVA limits become MW limits
- Choose *Consider Reactive Flows Assuming Constant Voltages*
  - This will modify Simulator so that it approximates Vars flows using a “power circle” (similar to impedance relay settings)
  - Simulator internally adjusts the branch limits (user inputs do not change)

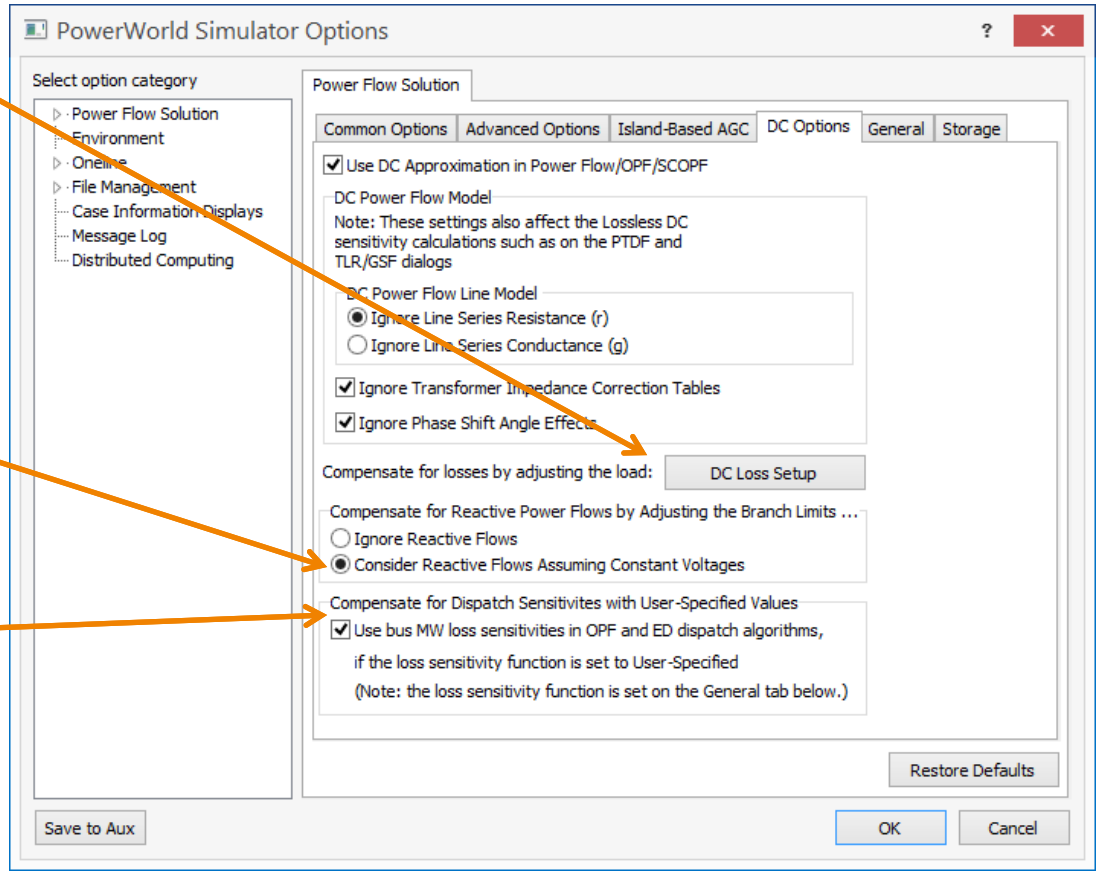
# DC Power Flow Loss Setup: Compensate for Losses with Loads

- Click compensate for Losses by Adjusting Loads
- Specify a multiplier at each bus
  - In the DC Power Flow (and thus the OPF/SCOPF), Simulator will artificially increase loads at these buses



# DC Options

- Compensate for Losses by Adjusting Loads
- Compensate for Reactive Power Flows by Adjusting the Branch Limits
- Compensate for Dispatch Sensitivities with User-Specified Values



# Security Constrained OPF

# SCOPF Overview

- Secure power system operation requires that there be no unmanageable base case or contingent violations
- Complete optimization requires considering the base case and contingencies
- Solution of this problem is known as Security Constrained OPF (SCOPF)
- SCOPF seeks a single dispatch that has no violations in the base case or in any contingency
- Most of processing time is spent in contingency analysis

# Contingency Analysis Overview

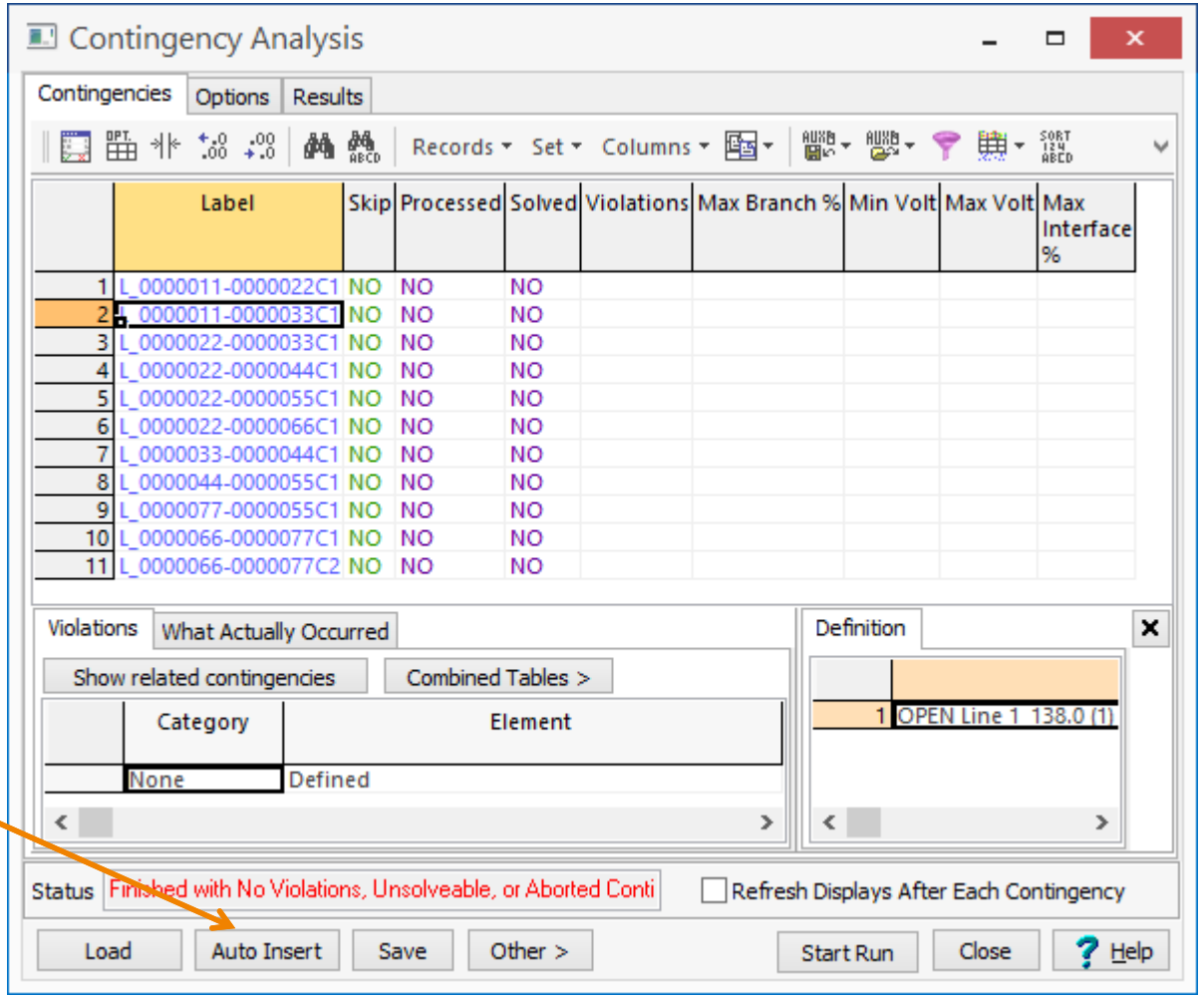
- Analysis of power system topology resulting from any statistically likely contingency
- Simulator is equipped with tools for analyzing contingencies in an automatic fashion
- Contingencies can be single or multiple element outage

# Contingency Analysis

- Contingencies Include:
  - Switching of Lines and Transformers
  - Loss or Recovery of Generating Units
  - Shifting of Load
  - Loss or Recovery of Switched Shunts
- Contingency Analysis tools can be accessed from the **Tools** ribbon tab → **Contingency Analysis**, or from the button on the SCOPF Form

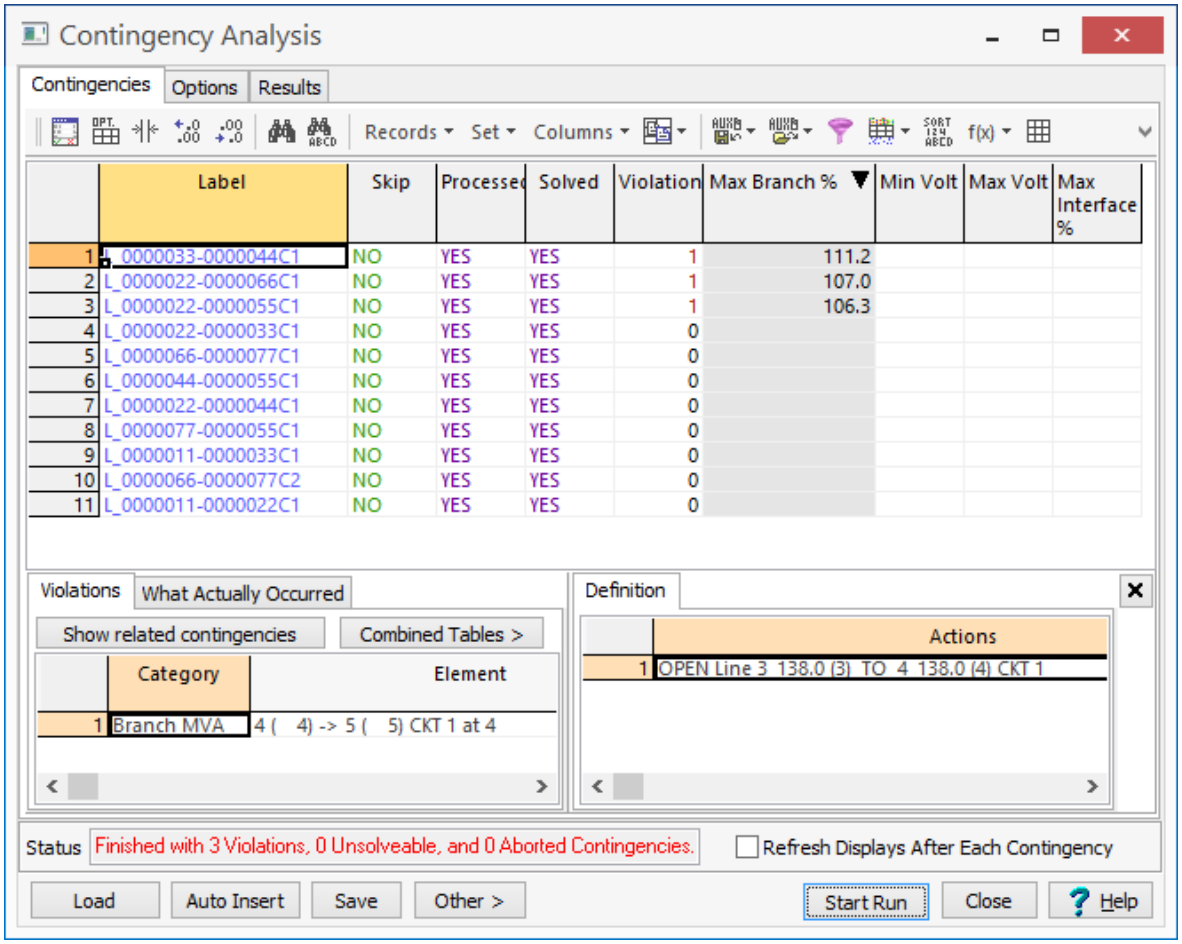
# Contingency Analysis Dialog

- The contingency analysis dialog is used to view the contingency analysis process and to edit the contingency set.
- Auto-insert the single element branch outages



# Contingency Analysis Dialog

- Click *Start Run*
- 3 initial violations
- Close **Contingency Analysis** dialog



# SCOPF Solution Process

- SCOPF has three major steps
  - initialization to setup the SCOPF LP tableau and control structures
  - contingency analysis, storing control sensitivities associated with each contingent violation
  - SCOPF iterations, with each iteration enforcing the newest most severe contingent violation
- Open SCOPF dialog from **Add Ons** ribbon tab → **SCOPF**
  - The three steps are solved automatically from the button **Run Full Security Constrained OPF**.

# SCOPF Solution Process, cont'd

- SCOPF terminates when all of the contingent violations have been processed
- After each violation is processed, all of the unprocessed violations are updated
  - this step is crucial since often resolving the most severe violation resolves numerous other violations
  - example: a single line might be violating in a number of contingencies; fixing the worst contingency fixes the others as well

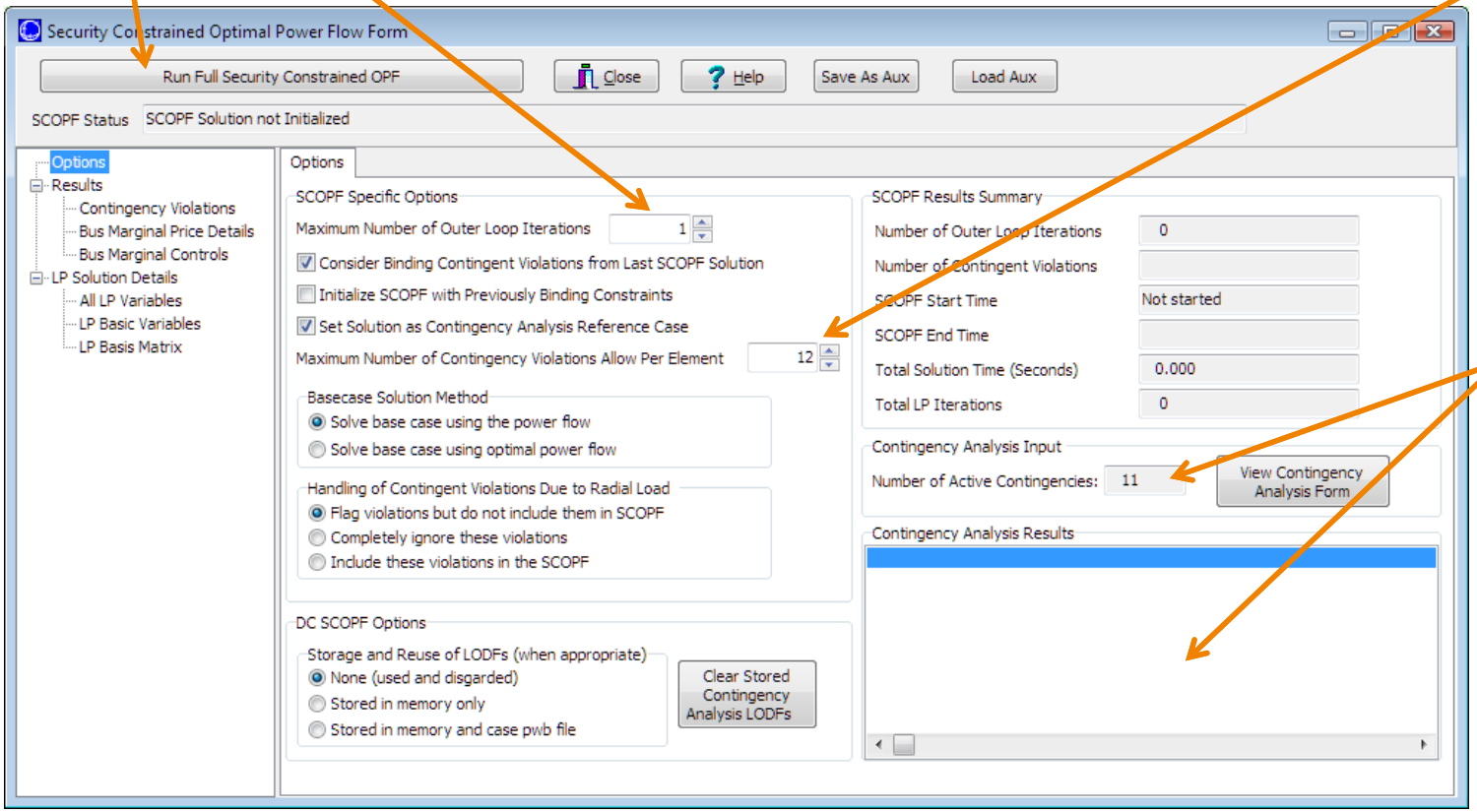
# SCOPF Solution Process, cont'd

- Adjusting controls to relieve some violations may result in new violations that did not previously occur.
- Checking for new violations requires a new contingency solution
  - SCOPF performs this function by iterating the entire process around an Outer Loop
  - Care must be taken since the corrected violations will not be binding in the next Outer Loop Iteration and hence will be excluded from the LP tableau

# SCOPF Form: Options

Click to solve an integrated SCOPF

Set maximum number of Outer Loop Iterations




Limiting violations per element can speed up processing

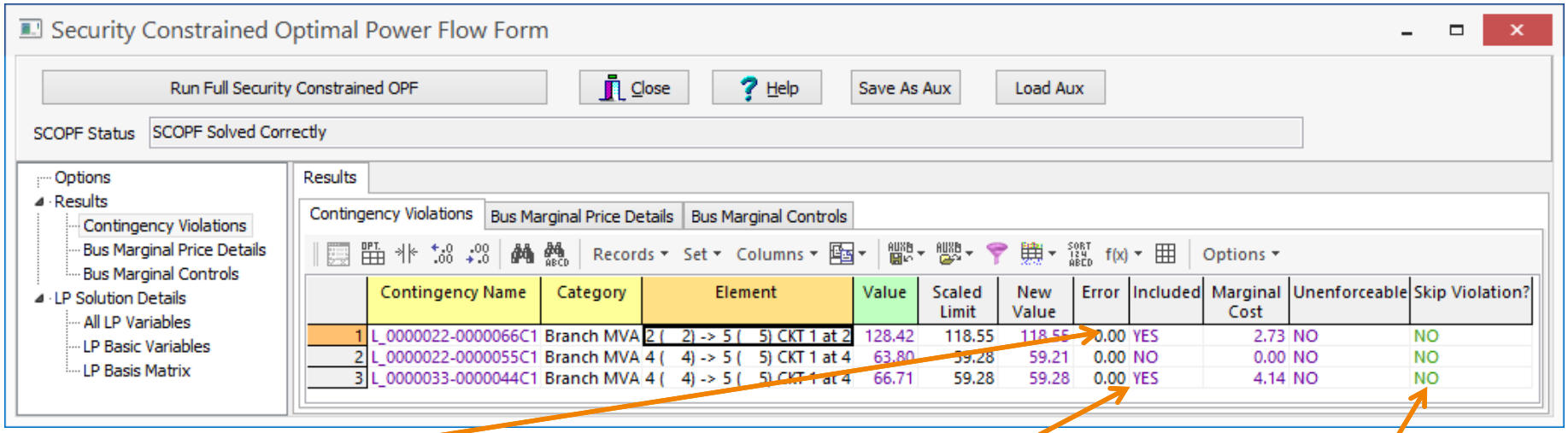
These fields are updated as contin-gency analysis solves

# SCOPF Form: Options

- Consider Binding Contingent Violations from Last SCOPF Solution
  - Can prevent the SCOPF from hunting between having a constraint binding in one solution, and resolving with it not binding in a later solution because it was previously remedied
  - Leave checked, unless major changes are made to the system since the previous solution
- Initialize SCOPF with Previously Binding Constraints
  - Forces the SCOPF to start with the same LP tableau from the previous solution
  - Helps solution speed when the changes to the system are small
  - Simulator automatically applies this option between multiple outer loops. This option allows the user to solve multiple outer loops by repeatedly solving the SCOPF manually, with outer loop counter = 1.
- Click *Run Full Security Constrained OPF* button

# SCOPF Violations

The CTG Violations page lists the results from contingency analysis, which violations were included in SCOPF solution, and the final error for each violation




Zero/negative errors indicate the violations have been corrected

Tells which violations were used to adjust controls

May be toggled when doing a manual SCOPF solution

# SCOPF Solution Details

- *LP Basic Variables* provide insight to control adjustments and unenforceable constraints

LP Solution Details

All LP Variables | LP Basic Variables | LP Basis Matrix

Records | Set | Columns | Options

| | ID | Org. Value | Value | Delta Value | BasicVar | Cost(Up) | Down Range | Up Range |
|---|---|---|---|---|---|---|---|---|
| 1 | Gen 1 #1 MW Control | 100.000 | 100.000 | -0.000 | 1 | 13.00 | 80.000 | 300.000 |
| 2 | Gen 2 #1 MW Control | 150.000 | 150.426 | 0.426 | 5 | 15.00 | 0.426 | 349.574 |
| 3 | Gen 4 #1 MW Control | 202.035 | 183.414 | -18.621 | 6 | 14.00 | 133.414 | 116.586 |
| 4 | Gen 6 #1 MW Control | 150.000 | 168.195 | 18.195 | 4 | 17.15 | 8.195 | 11.805 |
| 5 | Gen 7 #1 MW Control | 200.059 | 200.059 | 0.000 | 3 | 21.80 | 80.059 | 39.941 |
| 6 | Area Transaction Control from 1 to 2 | 50.264 | 32.070 | -18.195 | 2 | 0.00 | 32.070 | 67.930 |
| 7 | Slack-Line 1 TO 2 CKT 1 | -54.939 | 53.406 | 108.345 | 7 | 0.00 | 53.406 | 184.575 |

If a constraint is unenforceable, the Value field associated with its slack variable would be negative.

# SCOPF Solution Details

- *LP Basis Matrix* constraints are element/contingency pairs

LP Solution Details

All LP Variables | LP Basic Variables | LP Basis Matrix

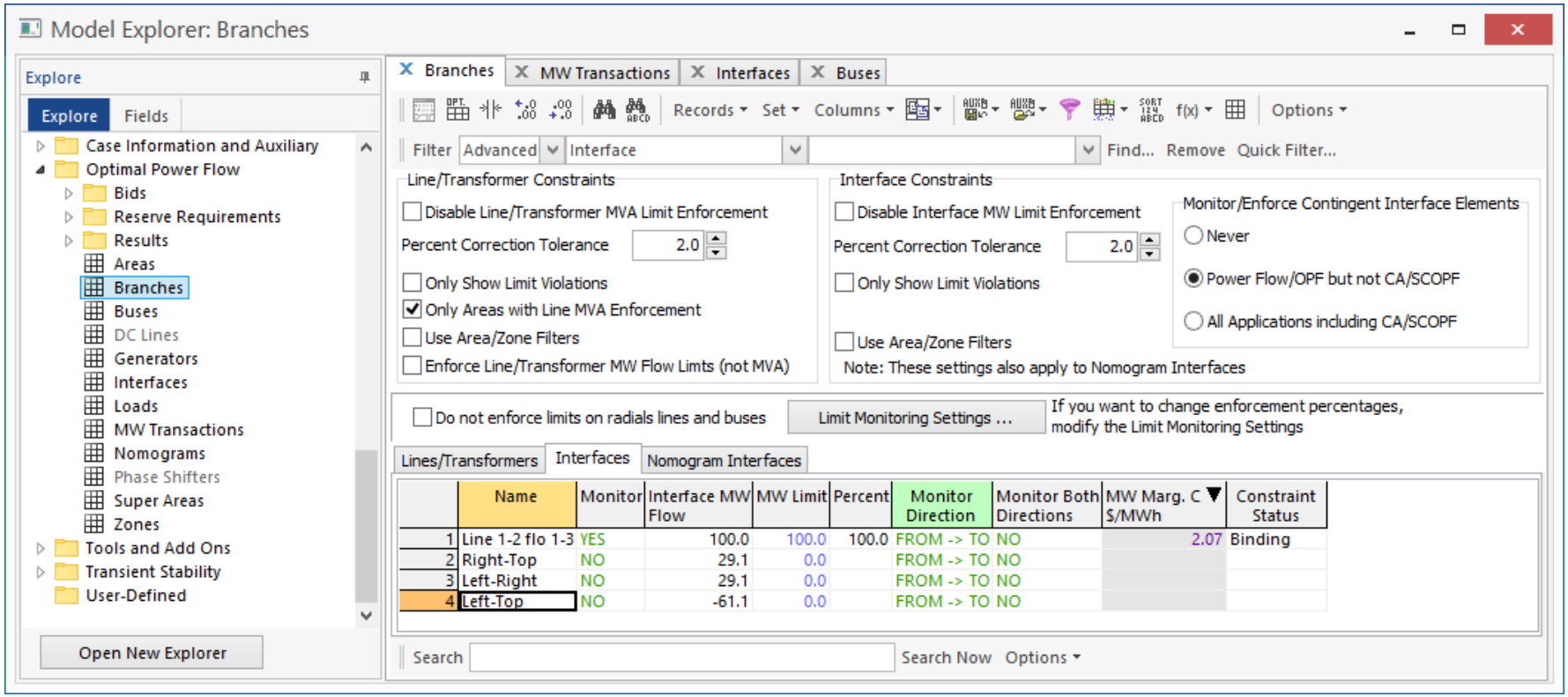
Records ▾ Set ▾ Columns ▾ Options ▾

| None | Constraint ID | Contingency ID | RHS b value | Lambda | Slack Pos | Gen 1 #1 MW Control | Area Transaction Control from 1 to 2 | Gen 7 #1 MW Control | Gen 6 #1 MW Control | Gen 2 #1 MW Control | Gen 4 #1 MW Control | Slack-Line TO 2 CKT 1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | Area 1 MW Constraint | Base Case | 0.000 | 17.482 | 7 | 1.000 | -1.000 | | | 1.000 | 1.000 | |
| 2 | Area 2 MW Constraint | Base Case | 0.000 | 17.482 | 8 | | 1.000 | | 1.000 | | | |
| 3 | Area 3 MW Constraint | Base Case | 0.000 | 21.804 | 9 | | | 1.000 | | | | |
| 4 | L_0000033-0000044C1 \| Line from 4 to 5 ckt. 1 | L_0000033-0000044C1 | 0.000 | 4.144 | 10 | 0.120 | | | 0.080 | 0.120 | 0.480 | |
| 5 | Line from 1 to 2 ckt. 1 | Base Case | 0.534 | 0.000 | 11 | 0.833 | | | -0.022 | -0.032 | 0.140 | 1.00 |
| 6 | Interface Line 1-2 flo 1-3 | Base Case | 0.000 | 2.067 | 12 | 1.000 | | | | | | |
| 7 | L_0000022-0000066C1 \| Line from 2 to 5 ckt. 1 | L_0000022-0000066C1 | 0.000 | 2.730 | 13 | 0.702 | | | | 0.727 | 0.547 | |

Lambdas/shadow prices of element/contingency constraint

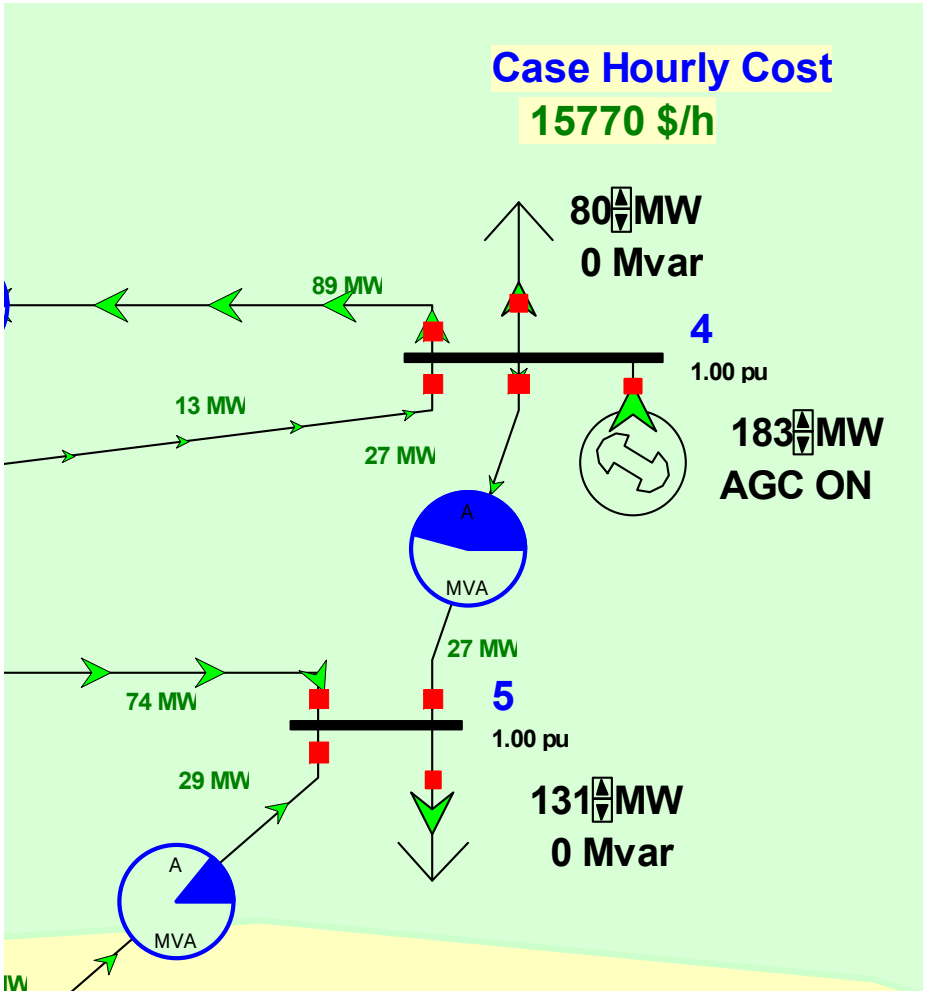
# OPF Interfaces

- Binding and unenforceable constraints are also indicated here, but shadow prices are only shown for base case constraints (use LP Basis Matrix for contingency constraints)



# SCOPF Results

- Note case hourly cost has increased by $57 ($15,713 to $ 15,770)
- Relieving the additional contingency violations required increased dispatch of more costly generation and adjustment to the Area Top-Left transaction



# How to handle interfaces with contingent elements in the SCOPF

- Interfaces can have contingent elements
  - Line OPEN and Line CLOSE elements
- Because the SCOPF is already modeling contingencies, you must specify now you would like to treat these special interfaces
  - Choose the **Options** ribbon tab → **Simulator Options**
  - Go to **Power Flow Solution** Page
  - Go to **General** Tab
  - Monitor/Enforce Contingent Interface Elements
    - Never- will never calculate the post-contingent flows on the interface
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