

Power System Economics and Market Modeling



M5: Security-Constrained Optimal Power Flow



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Additional OPF Topics

Additional OPF Topics



- 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

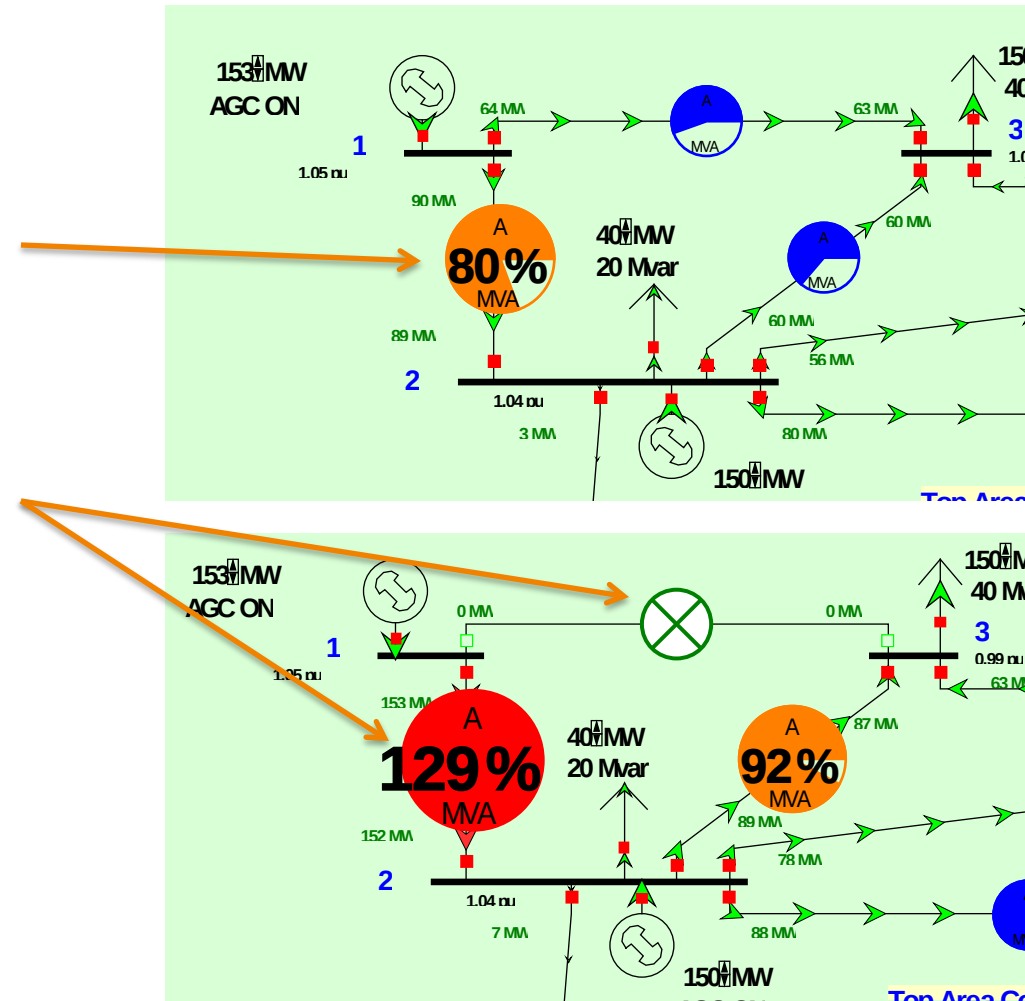


- Interfaces can have contingent elements
 - Line OPEN and Line CLOSE elements
- You must specify how you would like to treat these special interfaces
 - Choose the **Options** ribbon tab → **Simulator Options**
 - Go to **Power Flow Solution Page** (default)
 - Go to **General Tab**
 - Monitor/Enforce 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)

Interface Dialog

Interface Name: Line 1-2 flo 1-3 Find Interface...

Interface Number: 1 Add New Interface Delete Interface

Labels ...

Limits (MW)

Limit A	100
Limit B	0.000
Limit C	0.000
Limit D	0.000
Limit E	0.000

Monitoring Direction

☒ FROM --> TO ☐ TO --> FROM

☐ Monitor Both Directions

Noncontingent MW Flow Contribution: 89.5

Contingent MW Flow Contribution: 0.0

Total MW Flow: 89.5

OTDF Value (%): 0.00

Interface Elements: OPF Custom

Either Insert New Element

Clone Elements From Another Interface
or Right-Click to show the Element Dialog

Element Identifiers

☒ Name (Number) ☐ Name ☐ Number (Name) ☐ Number

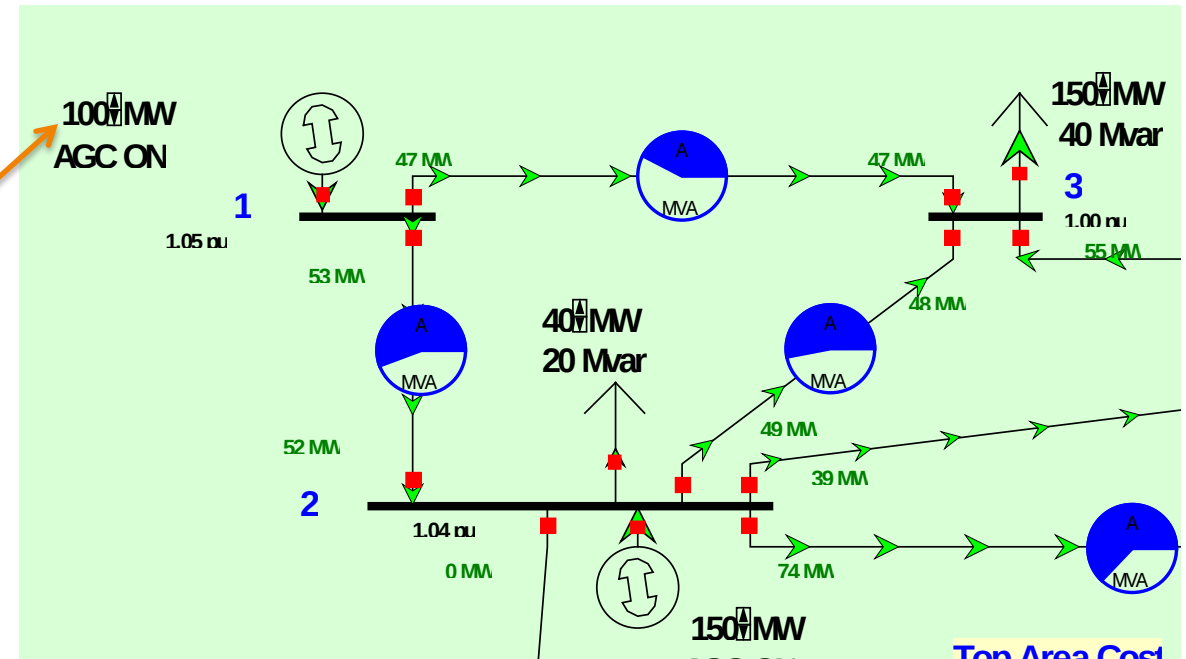
	Description	Flow	Weighting	Pre-Weight Flow
1	Line MW flow from bus '1 (1)' to bus '2 (2)' circuit 1	89.52	1.00	89.52
2	Contingency OPEN Line from bus '1 (1)' to bus '3 (3)' circuit 1	0.00		0.00

OK Save Cancel Help Print

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)

The screenshot shows the 'Transaction Dialog' window. Annotations with orange arrows point to specific fields:

- An arrow points from 'Specify a Min/Max Range for transfer' to the 'Transaction Minimum MW' and 'Transaction Maximum MW' fields.
- An arrow points from 'Specify an Export Cost Curve and Import Cost Curve (for areas that are NOT on OPF control)' to the 'Curve for Area 1 (Top)' and 'Curve for Area 2 (Left)' sections.
- An arrow points from 'Check to allow dispatch' to the 'Transaction Dispatchable in OPF' checkbox.
- An arrow points from 'Check to have OPF determine price (cost curves will not be used then)' to the 'Determine Price in OPF' checkbox.

Transaction ID: 1 (Top) | Transaction ID: 1 | Switch Directions

Transacting Area: 1 (Top) | On OPF control

Transaction to Area: 2 (Left) | On OPF control | Rename Transaction ID

Information | Custom

(Exports are positive, imports negative)

Transaction MW Amount: -50.00

Transaction Minimum MW: -100.00

Transaction Maximum MW: 100.00

Exports Transmission Charge: 0.00

Imports Transmission Charge: 0.00

☒ Transaction Enabled

☒ Transaction Dispatchable in OPF

☒ Determine Price in OPF

Piecewise Linear Transaction Cost Curves for Area 1 (Top)

Note: Costs are only entered for areas that are not on OPF control. Use negative MW values for imports (purchases) and positive MW values for exports (sales). Costs must be monotonically increasing.

Curve for Area 1 (Top)

MW	\$/MWh
None	Defined

Curve for Area 2 (Left)

MW	\$/MWh
None	Defined

OK | Save | Cancel | Help

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

Transaction Dialog

Transaction ID: 1 (Top) Transaction ID: 1 Switch Directions

Transacting Area: 1 (Top) On OPF control

Transaction to Area: 2 (Left) On OPF control Rename Transaction Id

Information Custom

(Exports are positive, imports negative)

Transaction MW Amount: 50.27

Transaction Minimum MW: -100.00

Transaction Maximum MW: 100.00

Exports Transmission Charge: 0.00

Imports Transmission Charge: 0.00

☒ Transaction Enabled

☒ Transaction Dispatchable in OPF

☒ Determine Price in OPF

Piecewise Linear Transaction Cost Curves for Area 1 (Top)

Note: Costs are only entered for areas that are not on OPF control. Use negative MW values for imports (purchases) and positive MW values for exports (sales). Costs must be monotonically increasing.

Curve for Area 1 (Top)

MW	\$/MWh
None	Defined

Curve for Area 2 (Left)

MW	\$/MWh
None	Defined

OK Save Cancel Help

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

Bus Marginal Loss Sensitivities

Specify Loss Function

Loss Function Type

- ☐ Do Not Calculate Bus Loss Sensitivities
- ☒ Each Electrical Island
- ☐ Each Area
- ☐ Each Area or Superarea
- ☐ Areas Selected on Loss Sensitivity Form
- ☐ User-Specified (leave at present values)

Selected Areas

Number	Name	Include?
1	Top	No
2	Left	No
3	Right	No

Calculate Bus Marginal Loss Sensitivities

Close

Help

Buses Just Generators

Records Geo Set

☐ Only show the primary bus for each superbus

	Number	Name	Area Num	Area Name	Loss MW Sens	Penalty Factor	Loss Mvar Sens
1	1	1	1	Top	0.0177	1.0180	0.0000
2	2	2	1	Top	0.0117	1.0119	0.0000
3	3	3	1	Top	0.0057	1.0058	-0.0016
4	4	4	1	Top	0.0107	1.0108	0.0000
5	5	5	1	Top	-0.0024	0.9977	-0.0024
6	6	6	2	Left	0.0047	1.0048	0.0000
7	7	7	3	Right	0.0000	1.0000	0.0000

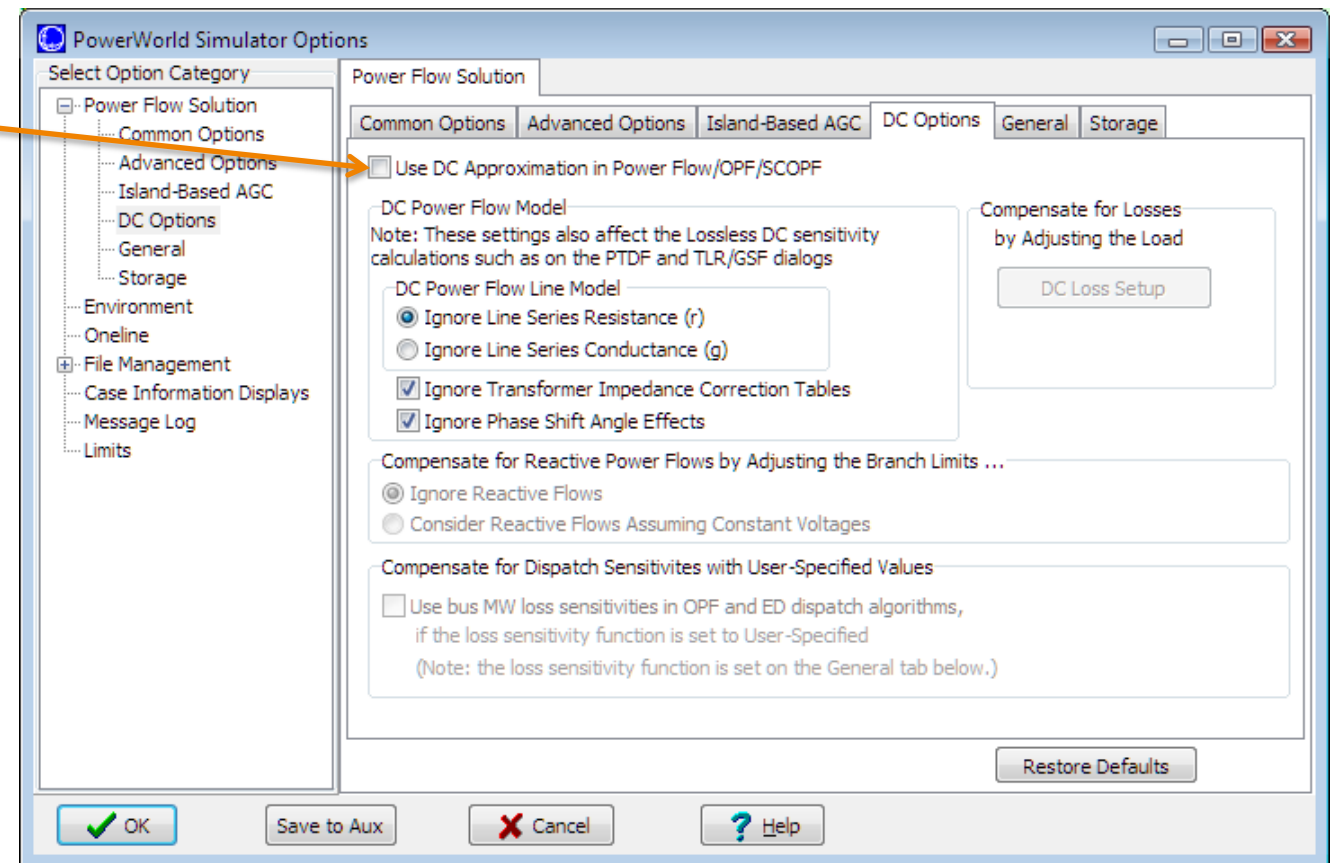
Simulator Options: Power Flow Solution Page



- **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

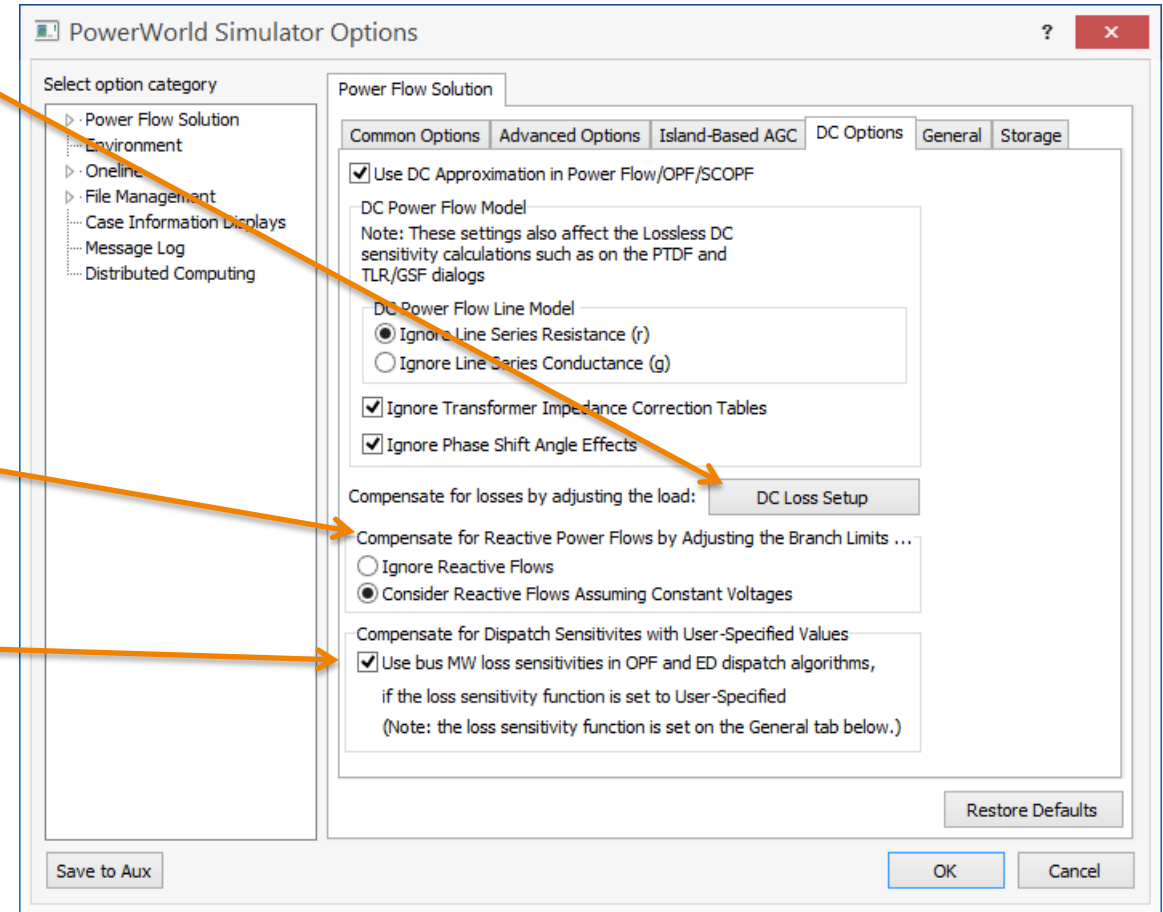


- Option to ignore real part of impedance (r) or real part of admittance (g)
 - Line series impedance $Z = r + jx$
 - Series admittance $Y = 1/Z = 1/(r + jx) = r/(r^2 + x^2) - j x/(r^2 + x^2) = g + jb$
 - *Ignore Line Series Resistance (r):* then $Y = -j/x$ and $b = -1/x$
 - *Ignore Line Series Conductance (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*)
 - In the DC Power Flow (and thus the OPF/SCOPF), Simulator will artificially adjust loads at these buses

DC Power Flow Loss Setup

Note: The DC Loss Multiplier modifies the load on the BUSES you choose. The options regarding Areas, and Zones, and Case are included to aid the tasks of selecting and unselecting blocks of buses' load to be modified.

Buses Areas Zones

See note above regarding Areas, Zones, and Case

Area Num	Area Name	DC Loss Multiplier
1	Top	1.0044
2	Left	1.0013
3	Right	1.0003

Set Areas DC multipliers automatically using current AC solution. **Set**

See note above regarding Areas, Zones, and Case

Case DC Loss Multiplier: 1.000000

OK Help Close

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)



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

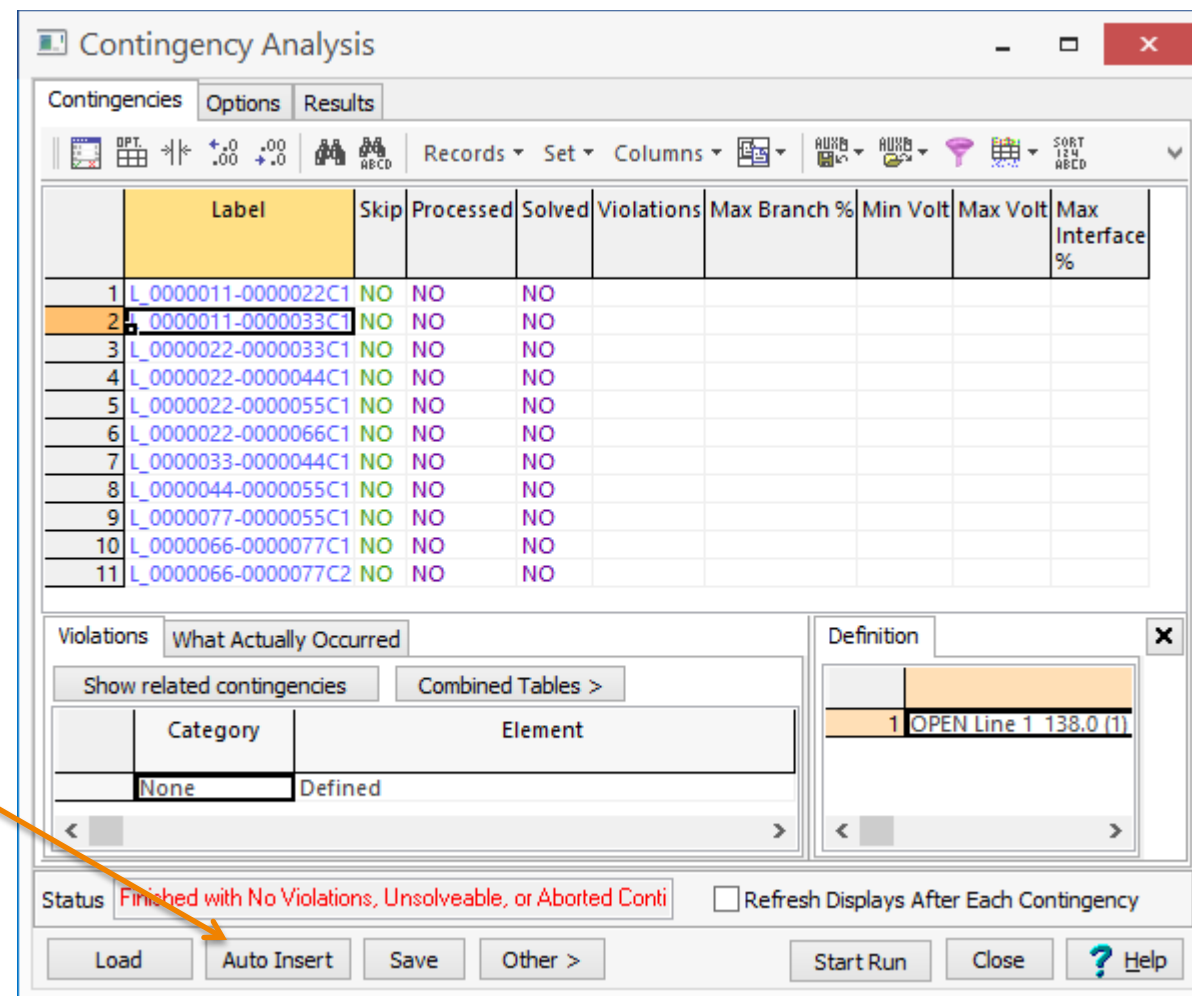
Contingency Analysis



- 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

Contingency Analysis

Contingencies Options Results

Records Set Columns

	Label	Skip	Processed	Solved	Violation	Max Branch %	Min Volt	Max Volt	Max Interface %
1	L_0000033-0000044C1	NO	YES	YES	1	111.2			
2	L_0000022-0000066C1	NO	YES	YES	1	107.0			
3	L_0000022-0000055C1	NO	YES	YES	1	106.3			
4	L_0000022-0000033C1	NO	YES	YES	0				
5	L_0000066-0000077C1	NO	YES	YES	0				
6	L_0000044-0000055C1	NO	YES	YES	0				
7	L_0000022-0000044C1	NO	YES	YES	0				
8	L_0000077-0000055C1	NO	YES	YES	0				
9	L_0000011-0000033C1	NO	YES	YES	0				
10	L_0000066-0000077C2	NO	YES	YES	0				
11	L_0000011-0000022C1	NO	YES	YES	0				

Violations What Actually Occurred

Show related contingencies Combined Tables >

Category	Element
1 Branch MVA	4 (4) -> 5 (5) CKT 1 at 4

Definition

Actions
1 OPEN Line 3 138.0 (3) TO 4 138.0 (4) CKT 1

Status Finished with 3 Violations, 0 Unsolveable, and 0 Aborted Contingencies. ☐ Refresh Displays After Each Contingency

Load Auto Insert Save Other > Start Run Close ? Help

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

Security Constrained Optimal Power Flow Form

Run Full Security Constrained OPF Close Help Save As Aux Load Aux

SCOPF Status SCOPF Solution not Initialized

Options

- Results
 - Contingency Violations
 - Bus Marginal Price Details
 - Bus Marginal Controls
- LP Solution Details
 - All LP Variables
 - LP Basic Variables
 - LP Basis Matrix

SCOPF Specific Options

Maximum Number of Outer Loop Iterations: 1

☒ Consider Binding Contingent Violations from Last SCOPF Solution

☐ Initialize SCOPF with Previously Binding Constraints

☒ Set Solution as Contingency Analysis Reference Case

Maximum Number of Contingency Violations Allow Per Element: 12

Basecase Solution Method

☒ Solve base case using the power flow

☐ Solve base case using optimal power flow

Handling of Contingent Violations Due to Radial Load

☒ Flag violations but do not include them in SCOPF

☐ Completely ignore these violations

☐ Include these violations in the SCOPF

DC SCOPF Options

Storage and Reuse of LODFs (when appropriate)

☒ None (used and discarded)

☐ Stored in memory only

☐ Stored in memory and case pwb file

Clear Stored Contingency Analysis LODFs

SCOPF Results Summary

Number of Outer Loop Iterations: 0

Number of Contingent Violations:

SCOPF Start Time: Not started

SCOPF End Time:

Total Solution Time (Seconds): 0.000

Total LP Iterations: 0

Contingency Analysis Input

Number of Active Contingencies: 11

View Contingency Analysis Form

Contingency Analysis Results

These fields are updated as contingency 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

The screenshot shows the 'Security Constrained Optimal Power Flow Form' window. The 'SCOPF Status' is 'SCOPF Solved Correctly'. The 'Results' tab is active, and the 'Contingency Violations' sub-tab is selected. The table below lists three violations with their details and error status.

	Contingency Name	Category	Element	Value	Scaled Limit	New Value	Error	Included	Marginal Cost	Unenforceable	Skip Violation?
1	L_0000022-0000066C1	Branch MVA	2 (2) -> 5 (5) CKT 1 at 2	128.42	118.55	118.55	0.00	YES	2.73	NO	NO
2	L_0000022-0000055C1	Branch MVA	4 (4) -> 5 (5) CKT 1 at 4	63.80	59.28	59.21	0.00	NO	0.00	NO	NO
3	L_0000033-0000044C1	Branch MVA	4 (4) -> 5 (5) CKT 1 at 4	66.71	59.28	59.28	0.00	YES	4.14	NO	NO

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

	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 f(x) 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)

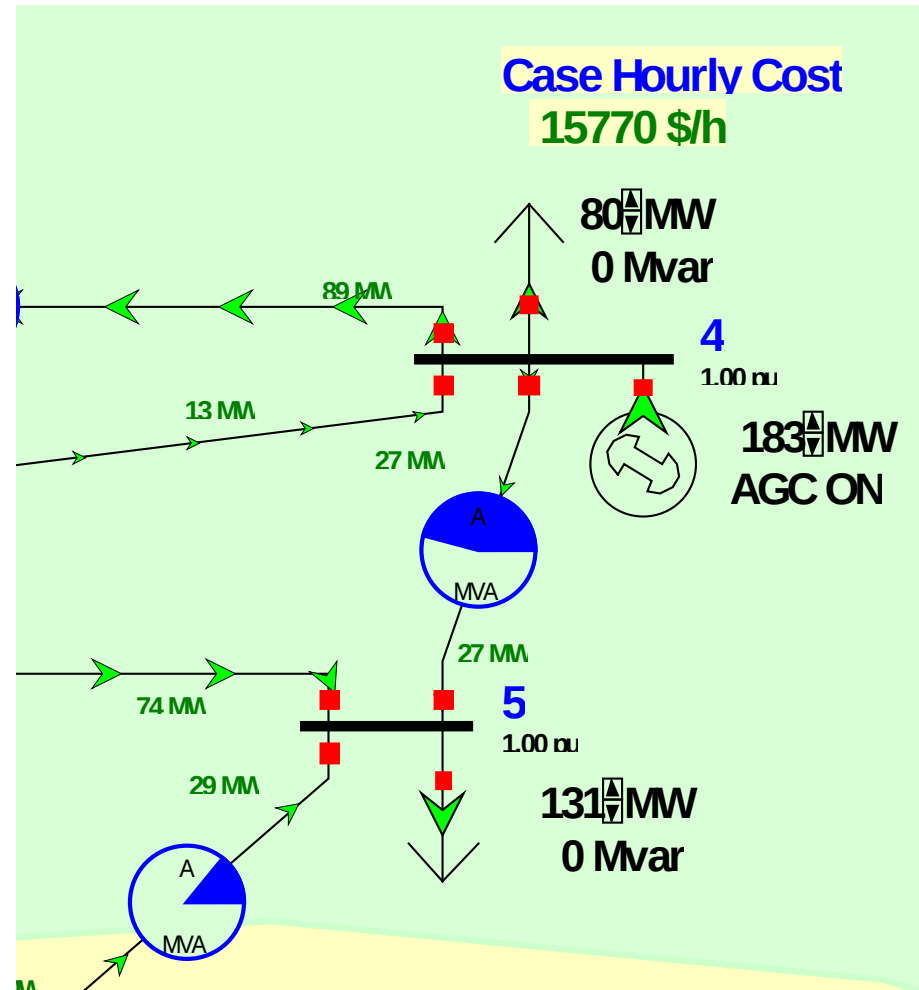
The screenshot shows the 'Model Explorer: Branches' window with the 'Interfaces' tab selected. The 'Interface Constraints' section is active, displaying settings for 'Interface Constraints' and 'Monitor/Enforce Contingent Interface Elements'. The 'Monitor/Enforce Contingent Interface Elements' section has three radio buttons: 'Never', 'Power Flow/OPF but not CA/SCOPF' (selected), and 'All Applications including CA/SCOPF'. Below this, a table lists interface constraints for 'Lines/Transformers', 'Interfaces', and 'Nomogram Interfaces'. The 'Interfaces' tab is selected, showing a table with columns: Name, Monitor, Interface MW Flow, MW Limit, Percent, Monitor Direction, Monitor Both Directions, MW Marg. C \$/MWh, and Constraint Status.

	Name	Monitor	Interface MW Flow	MW Limit	Percent	Monitor Direction	Monitor Both Directions	MW Marg. C \$/MWh	Constraint Status
1	Line 1-2 flo 1-3	YES	100.0	100.0	100.0	FROM -> TO NO		2.07	Binding
2	Right-Top	NO	29.1	0.0		FROM -> TO NO			
3	Left-Right	NO	29.1	0.0		FROM -> TO NO			
4	Left-Top	NO	-61.1	0.0		FROM -> TO NO			

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
 - 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

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