D-FACTS Devices in PowerWorld Simulator

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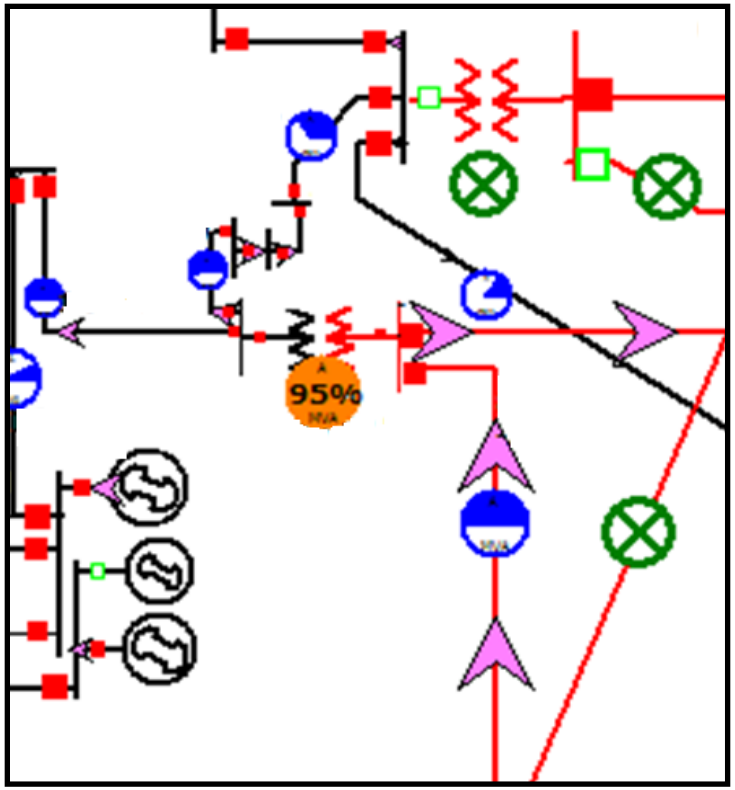
Power Flow Control Basics

- Power flow is not directly controllable - to change the way power flows in the system, we need to be able to change line impedance, voltage magnitude, or angle differences
- Benefits
  - Relieve overloaded lines
  - Reduce transmission losses
  - Maintain acceptable operating conditions
  - Improve stability
  - Improved utilization of existing system



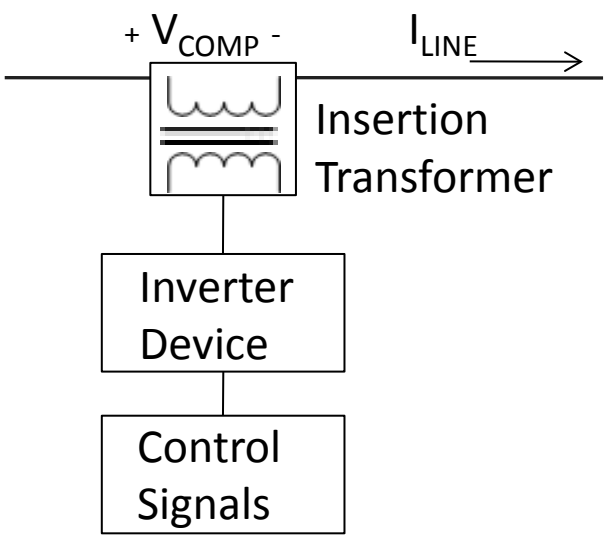
Flexible AC Transmission Systems (FACTS) – IEEE Definitions

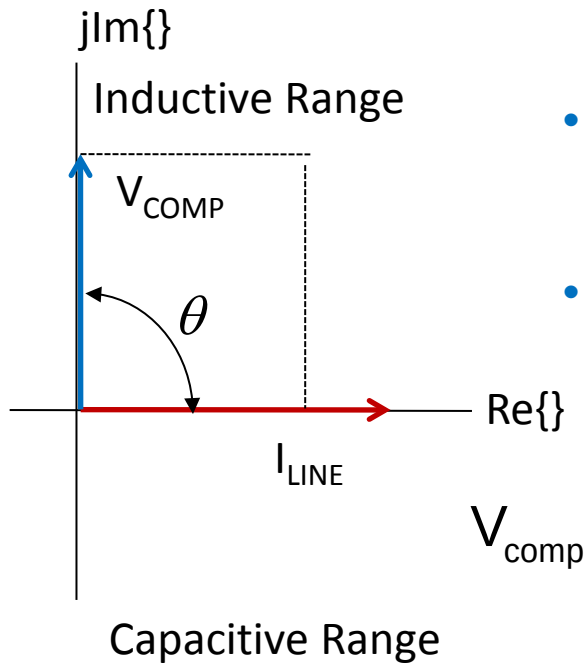
- Flexibility
  - ability to accommodate changes in the system or operating conditions without violating stability margins
- Flexible AC Transmission System
  - incorporates power electronics and other static controllers to enhance controllability and increase transfer capability
- FACTS Controller
  - provides control of one or more AC transmission system parameter

FACTS Working Group, "Proposed Terms and Definitions for Flexible AC Transmission System (FACTS)", *IEEE Transactions on Power Delivery*, Vol. 12, Issue 4, October 1997.

Active Impedance Injection

- The Synchronous Voltage Source (SVS)



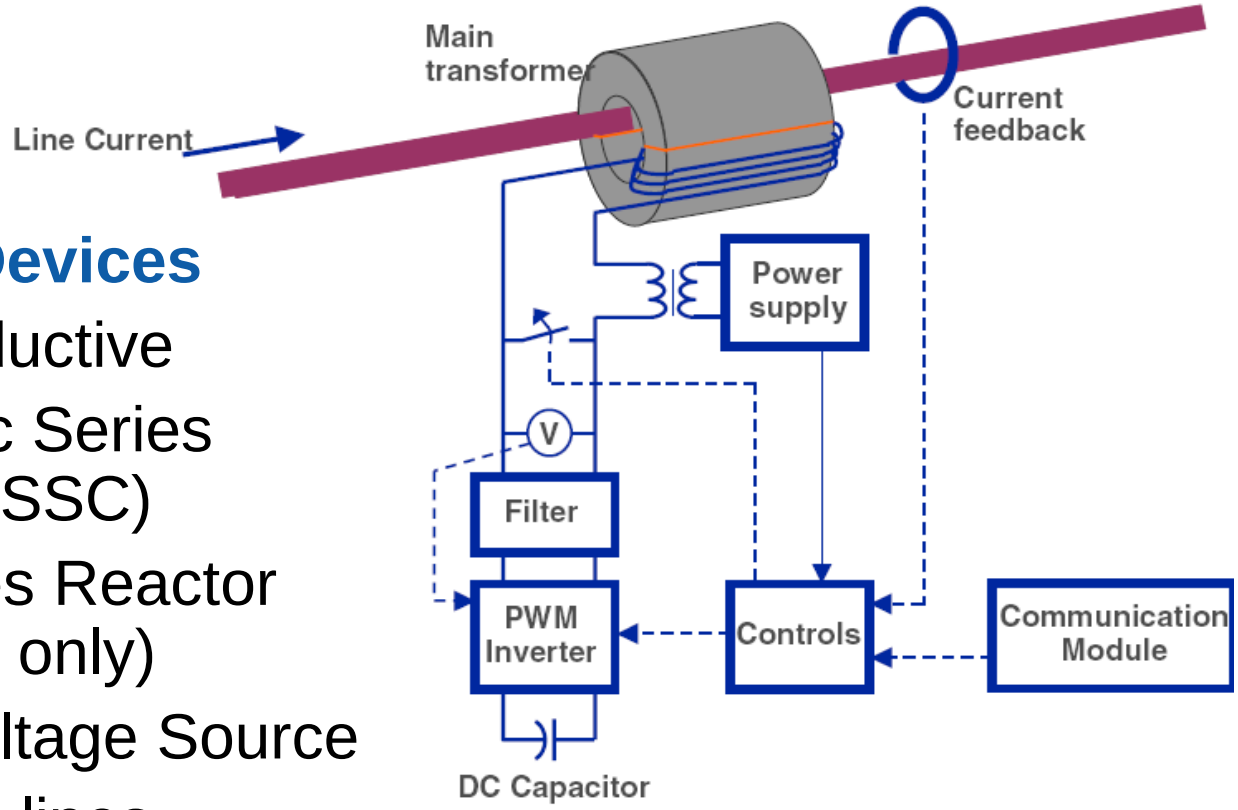


- In practice, V_{COMP} is 90 degrees out of phase with the line current)
- Otherwise you must have a real power source or sink!

$$V_{comp} = I_{Line} Z$$
$$= -jI_{Line} X_c \quad \text{or} \quad jI_{Line} X_L$$

- Injects an AC voltage, V_{COMP}
- Controls V_{COMP} with respect to I_{LINE}
- Changes effective line impedance
- Many FACTS devices use this concept

D-FACTS Devices



Distributed FACTS Devices

- Capacitive or inductive
- Distributed Static Series Compensator (DSSC)
- Distributed Series Reactor (DSR) (inductive only)
- Synchronous Voltage Source
- Attach directly to lines
- Small and modular

D. Divan, "Improving power line utilization and performance with D-FACTS devices," *IEEE PES General Meeting*, June 2005.

Potential D-FACTS Applications

- An inventory of applications to understand the full impact of DSRs may include
  - Contingency response capability
  - Control of loop flows
  - Increased transmission asset utilization
  - Phase balancing
  - Increase margin to voltage collapse
  - Enhance transient stability response
  - Increase flexibility for renewable energy transfers
  - De-localize Locational Marginal Prices (LMPs)
  - Reduction or delay of new transmission investment
  - Reduced risk in Financial Transmission Rights (FTR)

PowerWorld D-FACTS Support

- Overview of Program Support
  - Case information displays
  - Onelines
- Power Flow Control
  - In the power flow solution
  - Contingency analysis
  - Optimal Power Flow (OPF) tools
  - Sensitivity analysis
- Special features

Basic Program Support

- Power system object “DFACTSObject”
  - Settings dialog
  - PWB file support
  - AUX file support
- Oneline display object “DisplayDFACTS”
  - Fully customizable formatting
  - AXD file support
  - Auto-insertion
  - PWD file support (version 18 only)
- Full case information display support for both

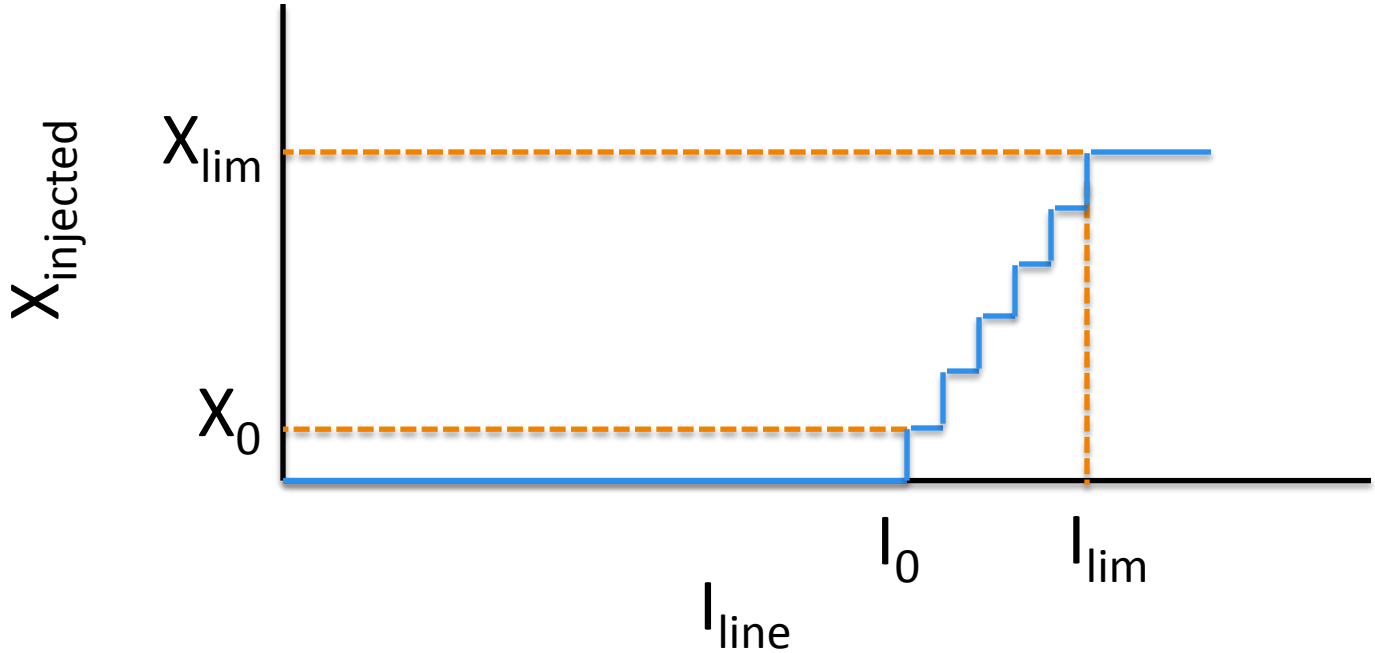
The D-FACTS Object

- A single object represents all the D-FACTS devices on a line
  - Attaches to a transmission line
  - All quantities are per-phase

- Operating characteristics
  - Typically 47 uH per module
  - Specify max compensation or total number of modules
  - Specify minimum and maximum line activation current

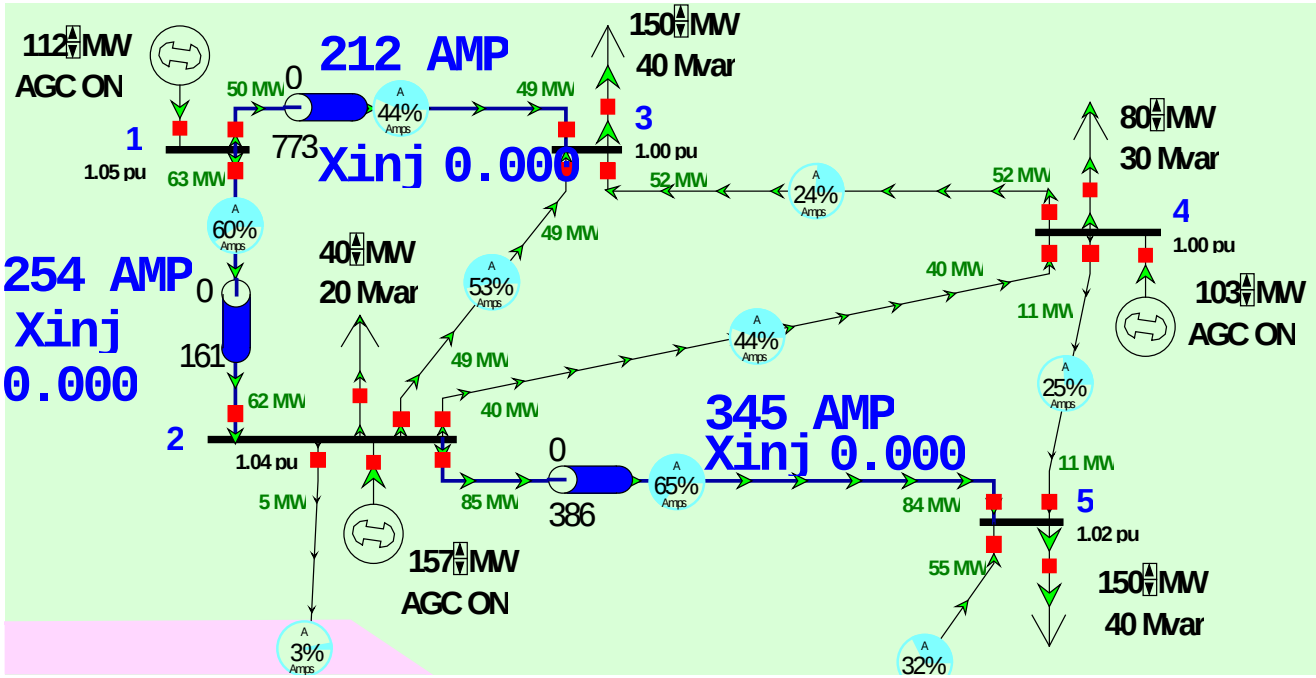
D-FACTS Operational Profile

- Below I_0, the D-FACTS devices are inactive
- Above I_{lim}, the cumulative injection of the D-FACTS devices is at its maximum value



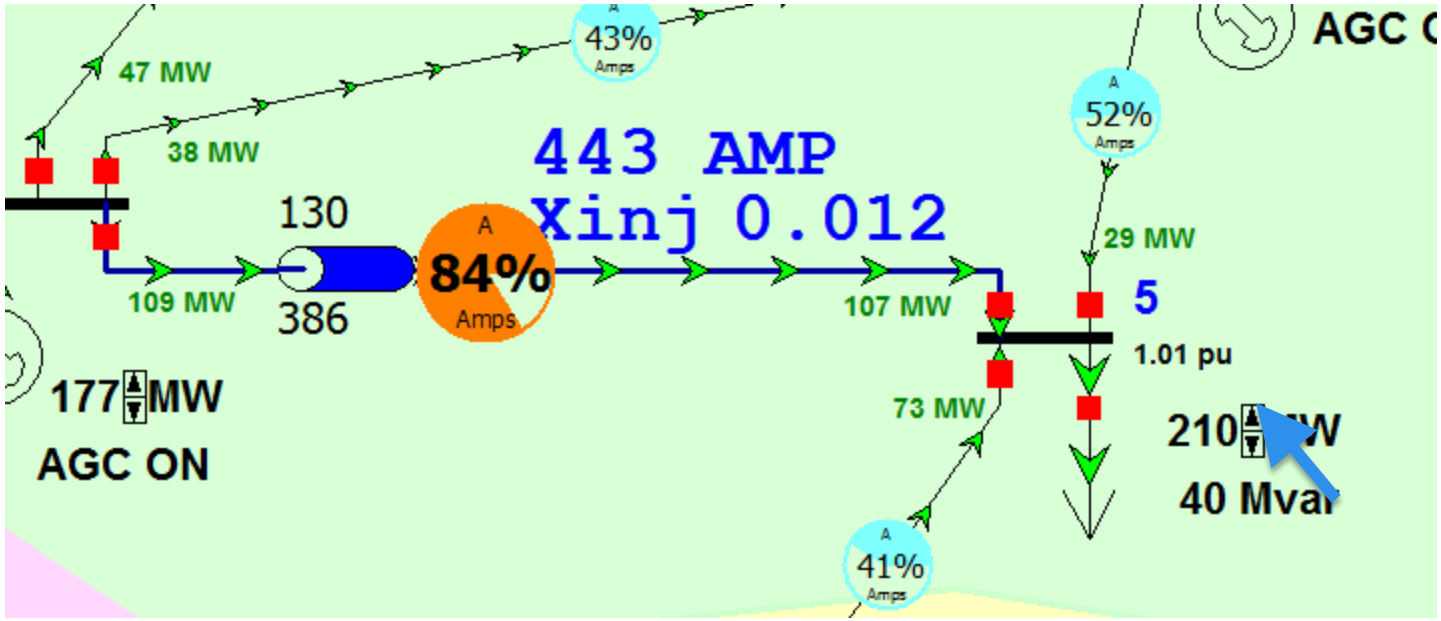
Basic D-FACTS Support

- Open "B7_DFACTS_Demo"
- This case has already been set up with D-FACTS devices on three lines, all in "Limit" mode



D-FACTS Devices in Limit Mode

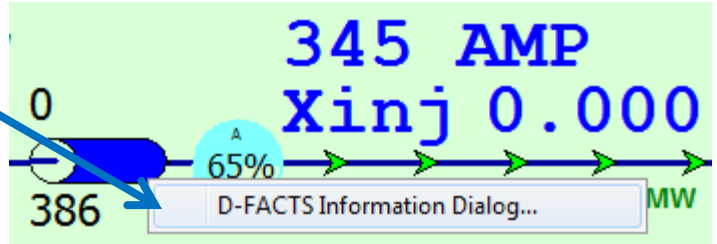
- Run the power flow simulation
- Increase the load at Bus 5 and watch D-FACTS devices become active

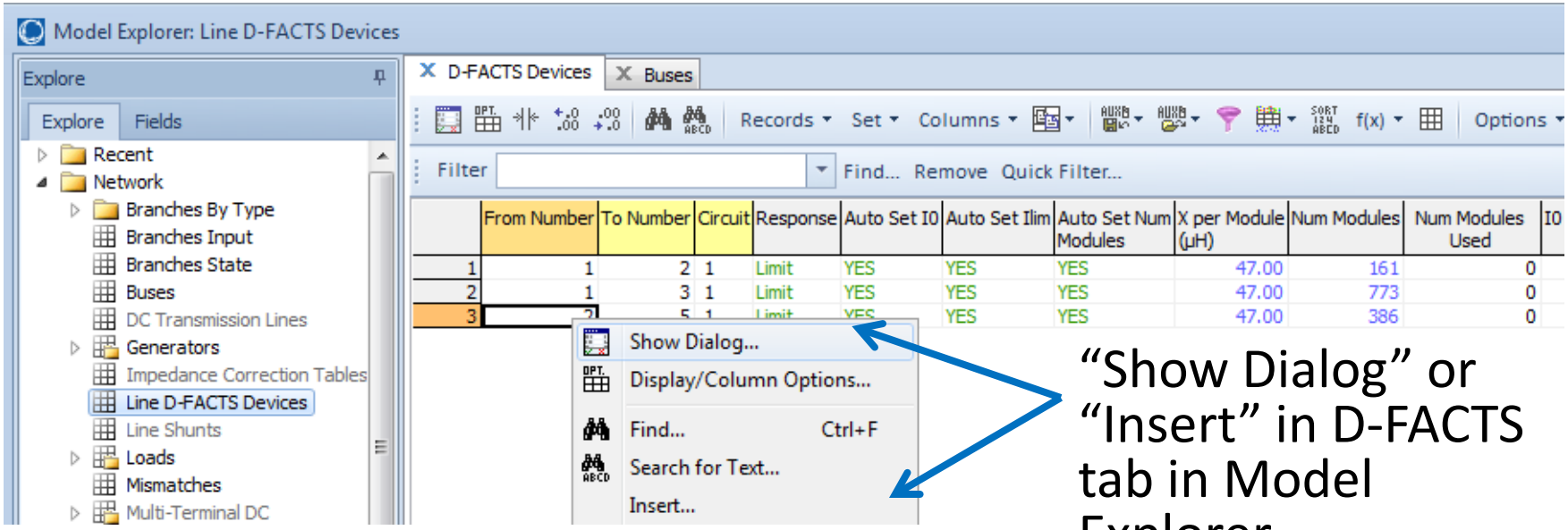


"B7_DFACTS_Demo"

Editing or Inserting D-FACTS

Open D-FACTS settings directly by right clicking on a D-FACTS object and choosing “show dialog”



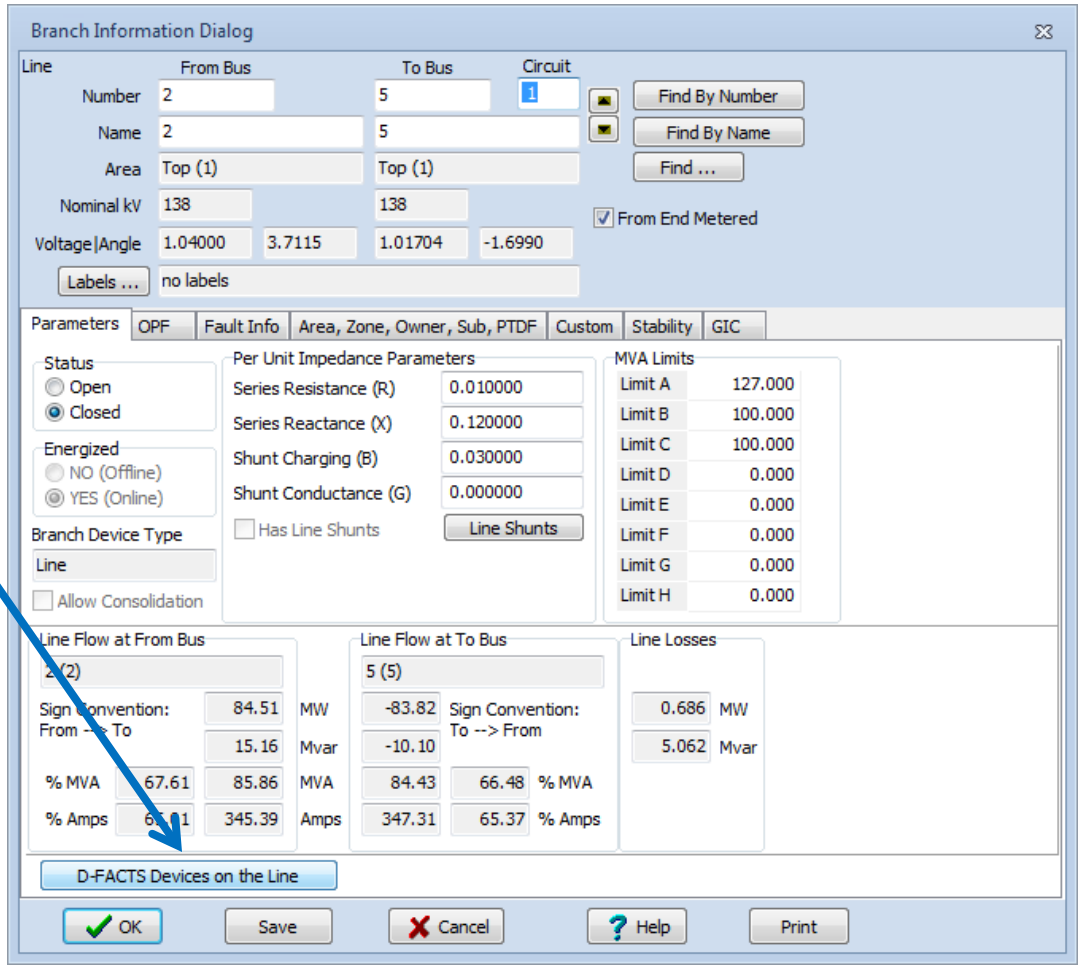


“Show Dialog” or “Insert” in D-FACTS tab in Model Explorer

“B7_DFACTS_Demo”

Editing or Inserting D-FACTS

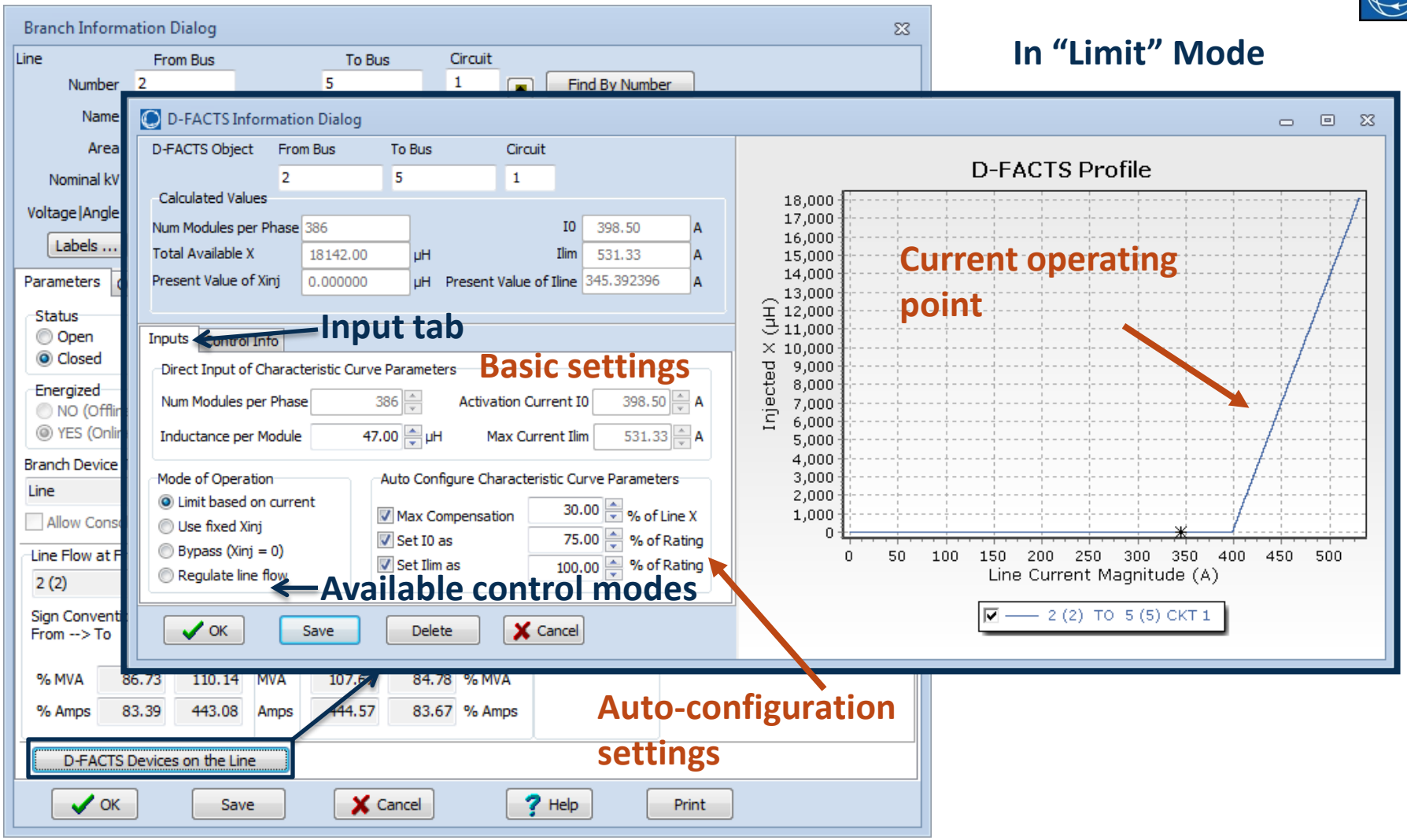
From the transmission line dialog, click “D-FACTS Devices on the Line” to see the D-FACTS settings



“B7_DFACTS_Demo”

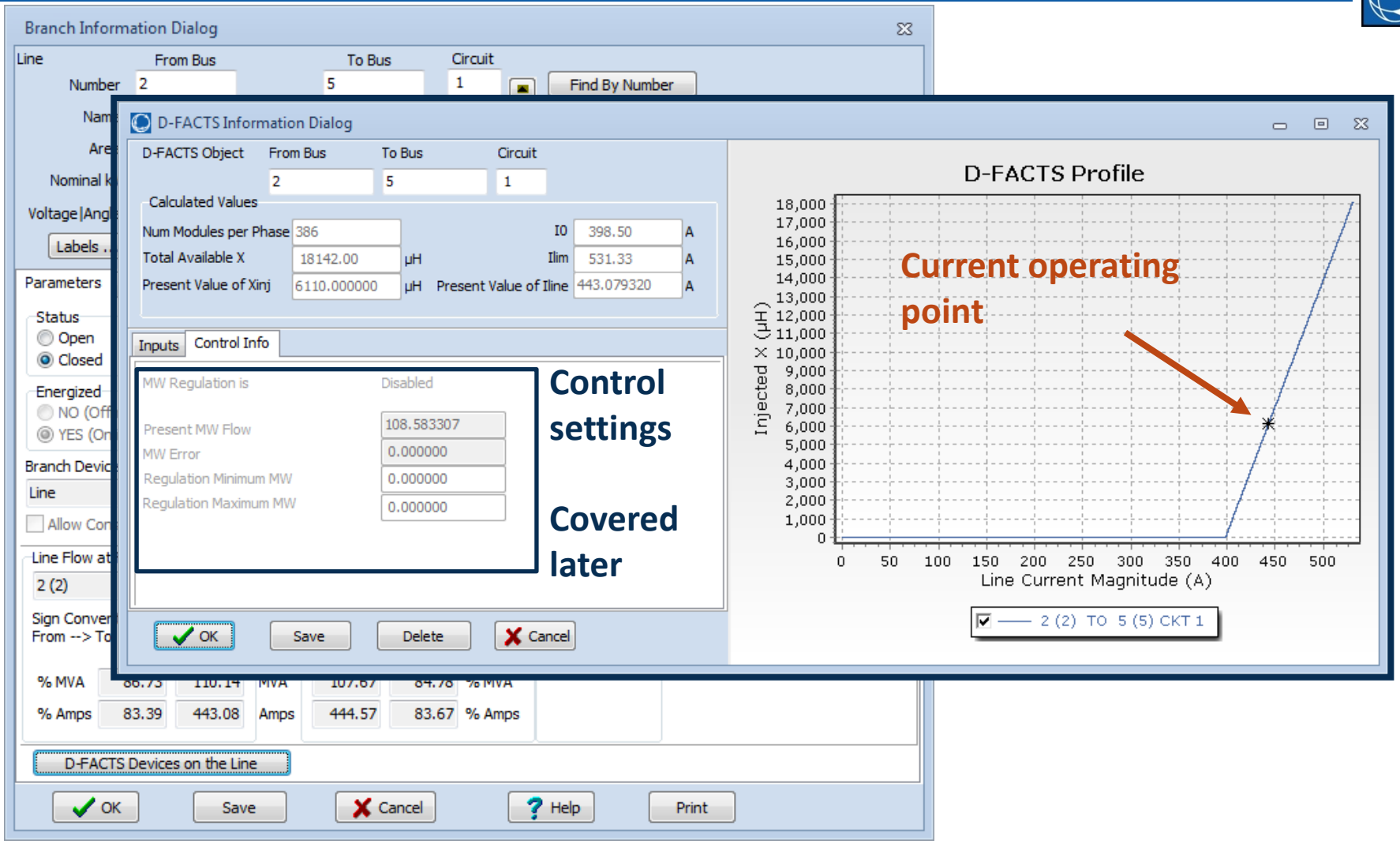
D-FACTS Dialog – Inputs

In "Limit" Mode



"B7_DFACTS_Demo"

D-FACTS Dialog – Control Info

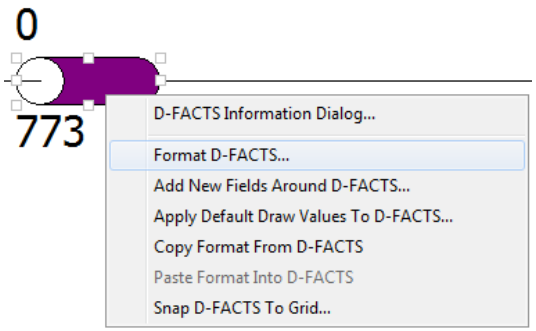


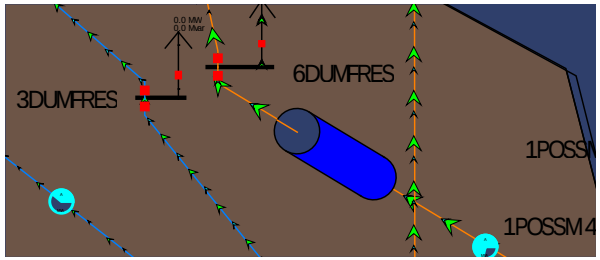
D-FACTS Case Information Displays

- On the “D-FACTS Devices” tab in the Model Explorer, click “Fields”
- These are all the supported D-FACTS fields
  - We’ll cover what these fields do
- Drag and drop to change which fields are displayed in the table
- Right click and choose to save as an AUX file
- Open to view sample D-FACTS aux file “B7_DFACTS_Demo_Aux.aux”
- Export data to Excel, edit values, and load in

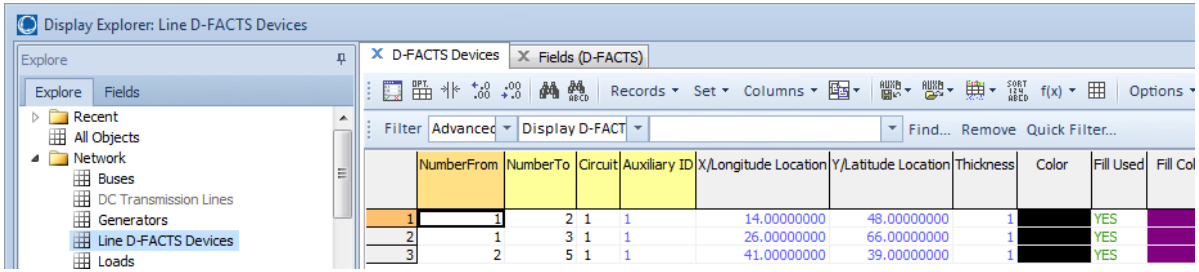
D-FACTS Oneline Displays

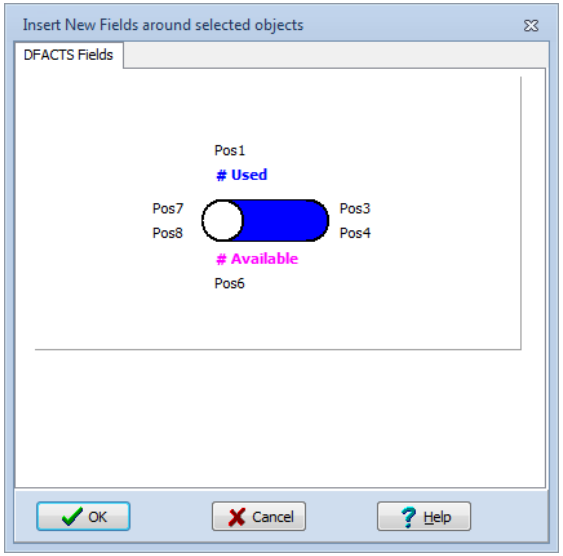
- Use formatting to fully customize the appearance





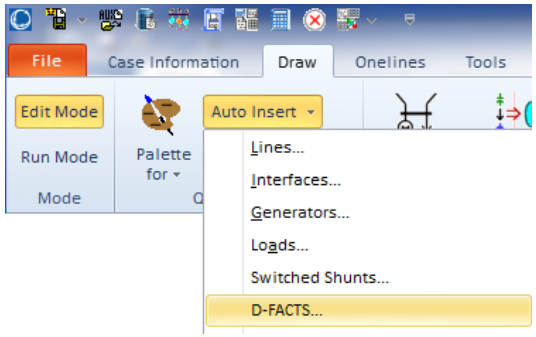
- Display any D-FACTS field
- Save with AXD or PWD (version 18) file
- Display Explorer support



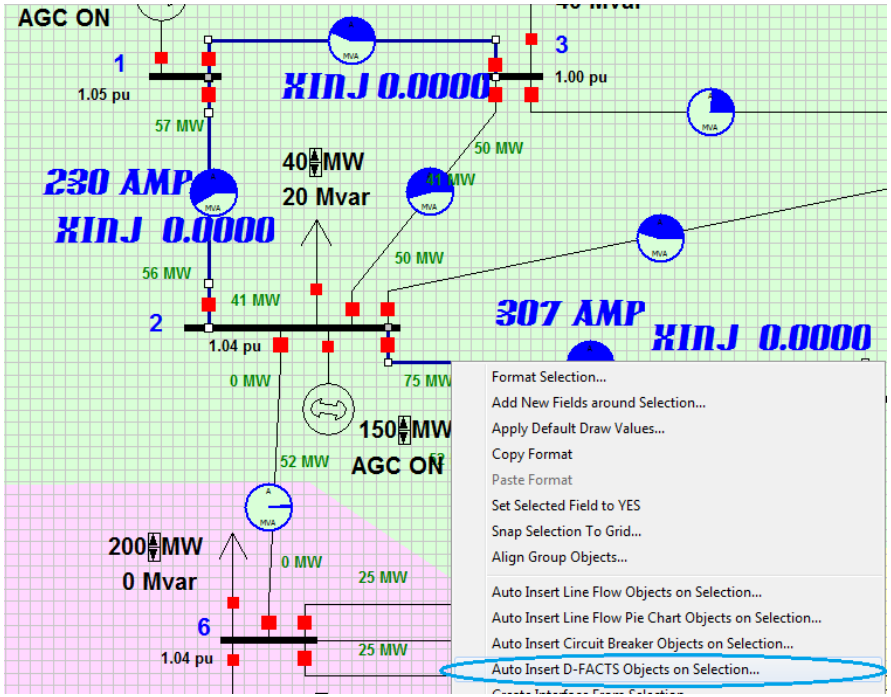


Oneline Auto Insertion of D-FACTS

- For the entire case

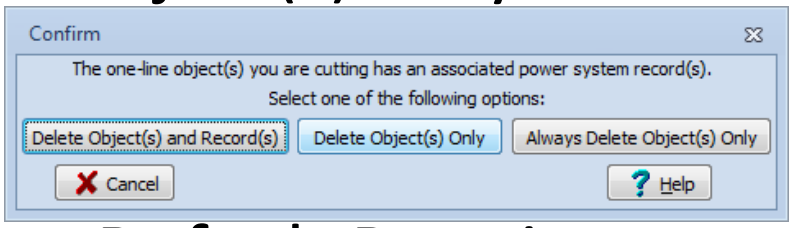


- For a single line or a group of selected lines



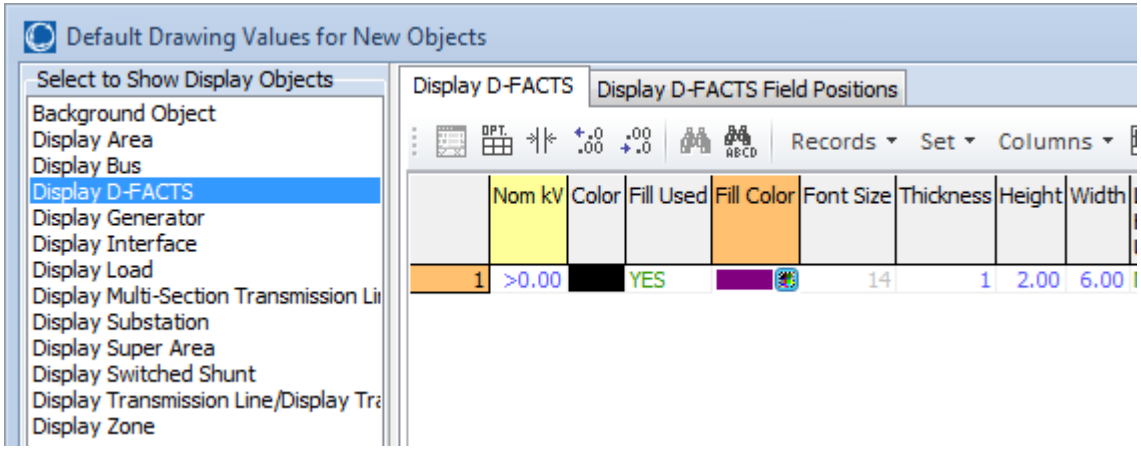
D-FACTS Oneline Example

- Reopen "B7_DFACTS_Demo"
- Select all D-FACTS oneline objects and delete them. Delete "Object(s) Only"!

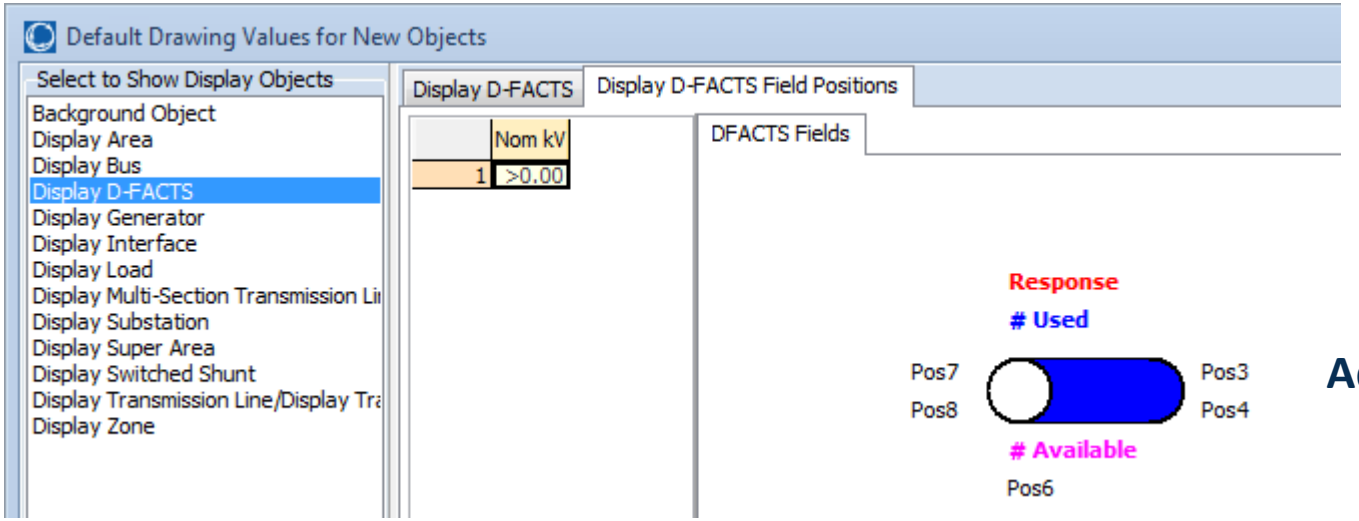


- Click Onelines > Default Drawing…
- Open the Display D-FACTS page
- Customize the settings for the appearance of new D-FACTS objects
  - Change fill color and the text fields to display
- Then click Draw> Auto Insert> D-FACTS…

D-FACTS Oneline Example

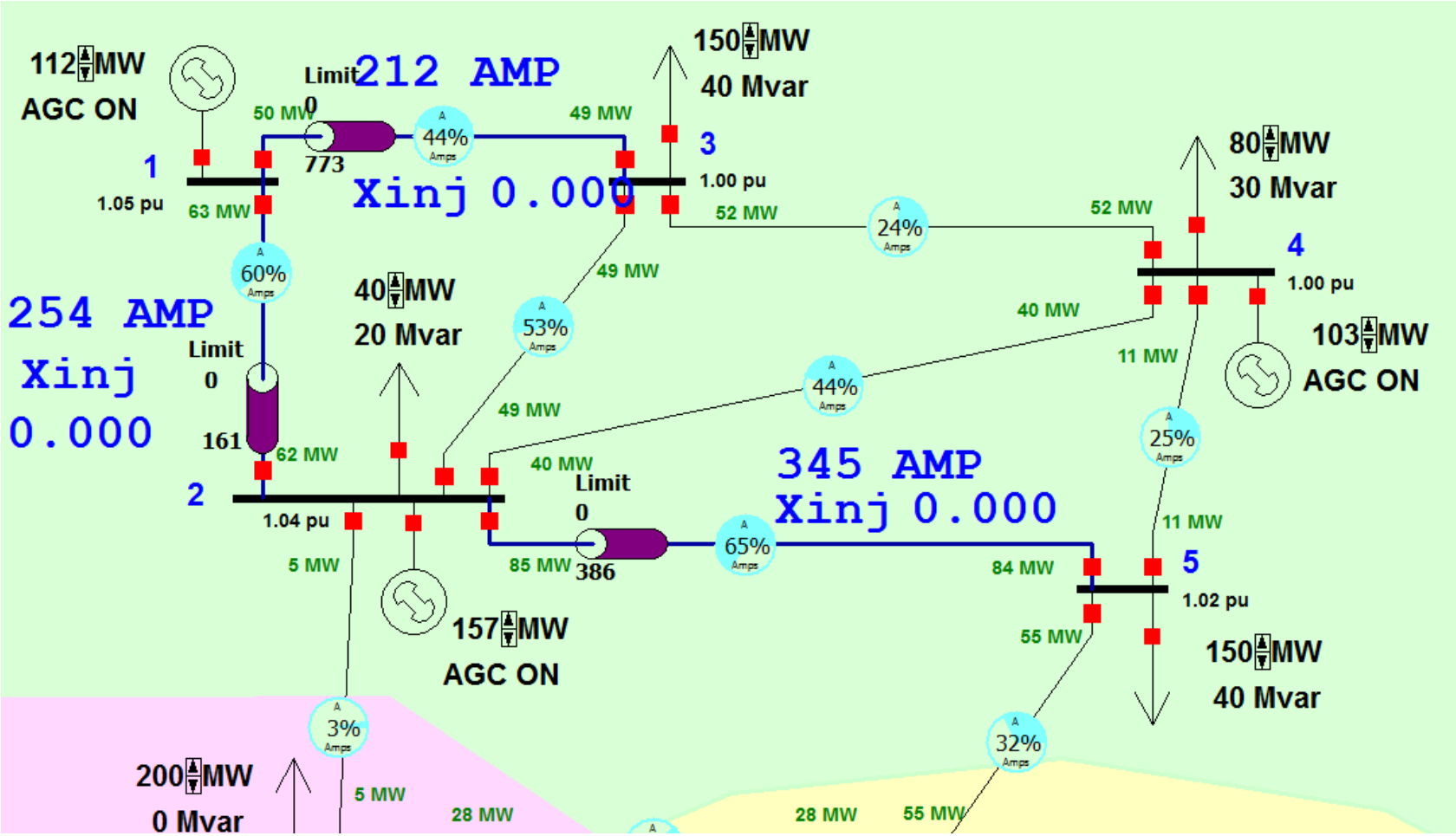


Changed fill color



Added text fields

D-FACTS Oneline Example



Power Flow Support

- Three modes of operation
  - Limit– Xinj responds based on line current (called Respond in version 17)
  - Fixed – Hold Xinj at a fixed value which may be set externally or manually
  - Bypass – Out of service (Xinj = 0)
  - Regulate – Control Xinj to achieve line flow in specified range (version 18 only)
- Oscillation detection logic
  - If switching on and off during the power flow solution, turn off of control (set to “Fixed”)

Power Flow Support

- Simulation Solution Process: Three Nested Loops
  - MW Control Loop
    - Voltage Controller Loop
      - Inner Power Flow loop

Traditionally called the *Power Flow*

Voltage Control Loop

MW Control Loop Generation Interchange Control

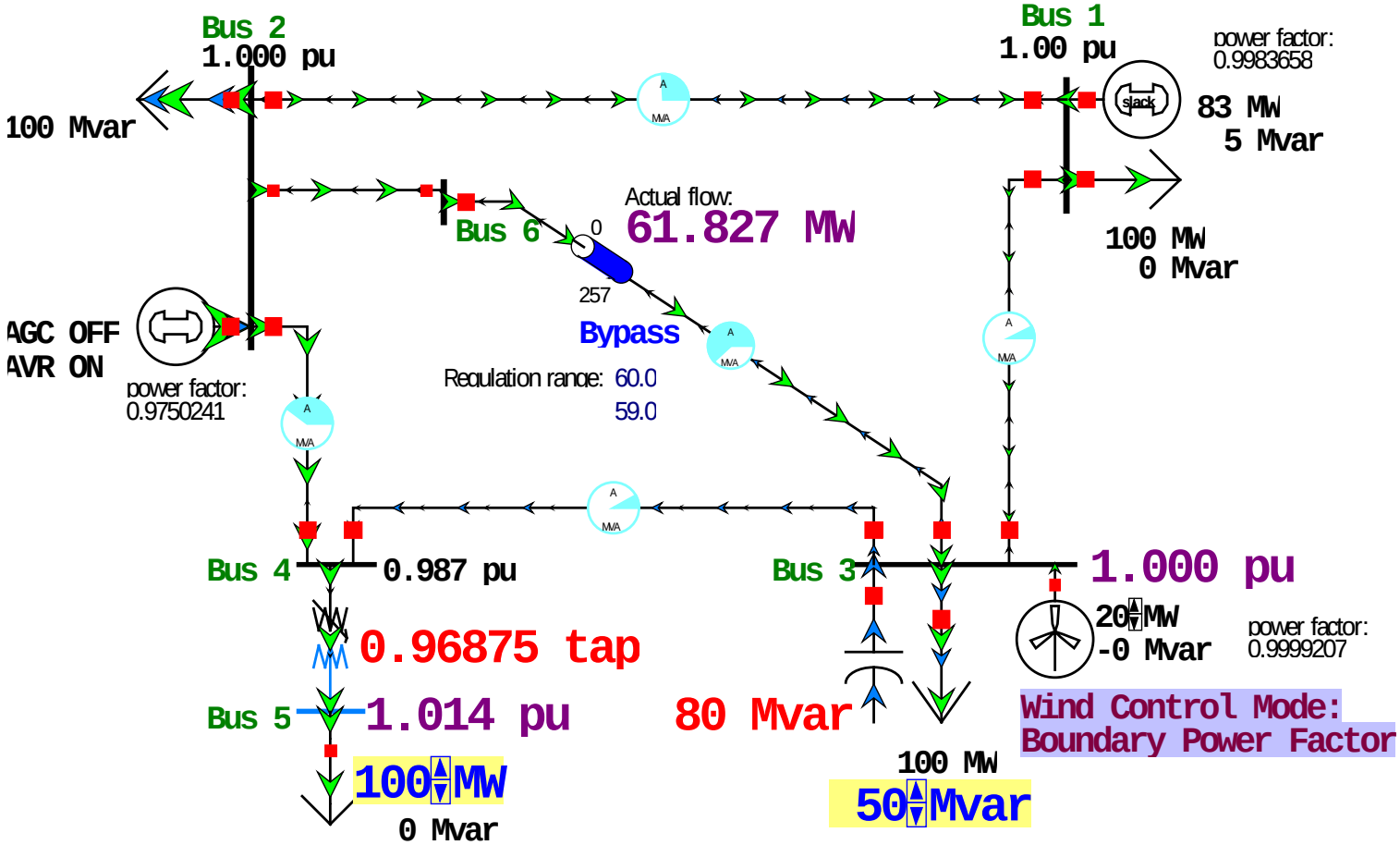
- PowerWorld Simulator implements the control of D-FACTS devices in the voltage control loop of the power flow solution
- Limit – Determine limited devices based on line current, adjust D-FACTS according to piecewise linear lookup function
- Regulate – Determine out of range flows, calculate sensitivities, adjust devices to bring back into range
- If the D-FACTS values are changed, an additional power flow inner loop is solved

New “Regulate” Mode

- Automatically determines D-FACTS settings within the power flow to achieve a certain line flow range
- Uses coordinated sensitivities
- Might require special handling when there are a large number of devices that cannot achieve their desired control range
- Open “B5RWind_DFACTSRegDemo.pwb”
- Initially, the D-FACTS object is in bypass mode

Power Flow Regulation Example

- Flow on line 6-3 is initially out of range

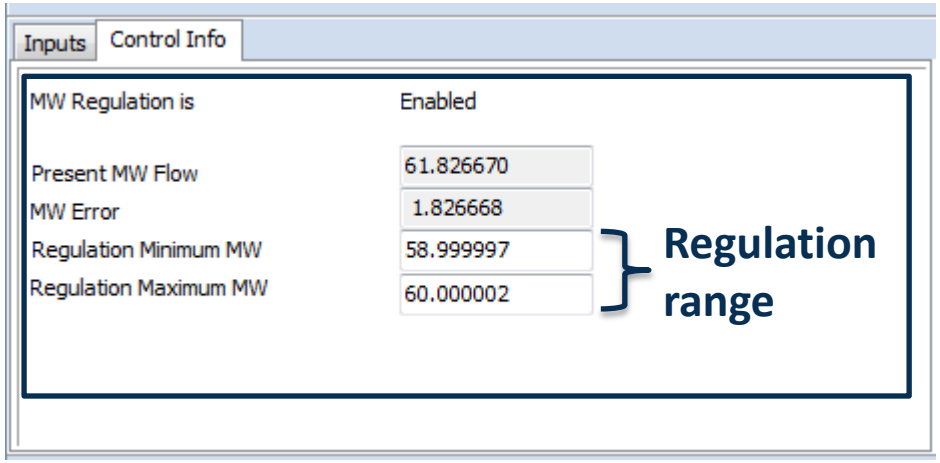


"B5RWind_DFACTSRegDemo"

Regulation Mode Example

- Open the D-FACTS Information Dialog
- Change the Mode of Operation to “Regulate line flow”
- Open the Control Info tab and set the regulation range

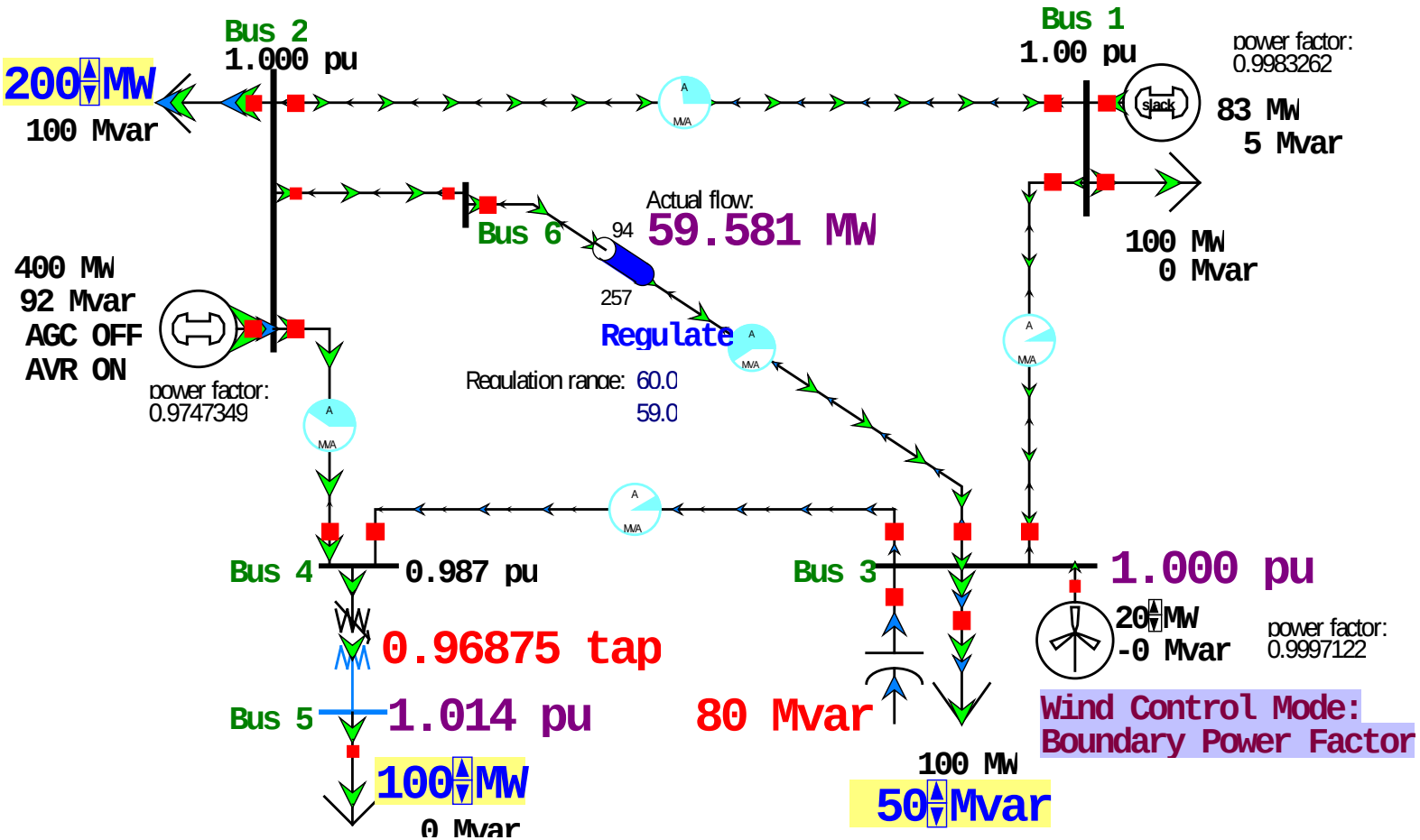
Control settings



“B5RWind_DFACTSRegDemo”

Regulation Mode Example

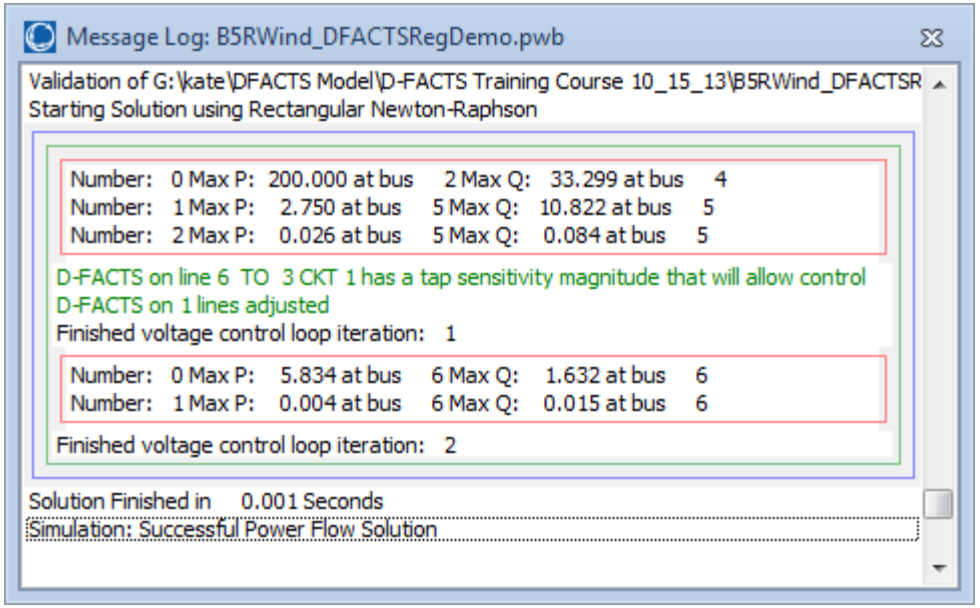
- Solve the power flow; flow is back in range



"B5RWind_DFACTSRegDemo"

Regulation Mode Example

- Open the system log to see what occurred



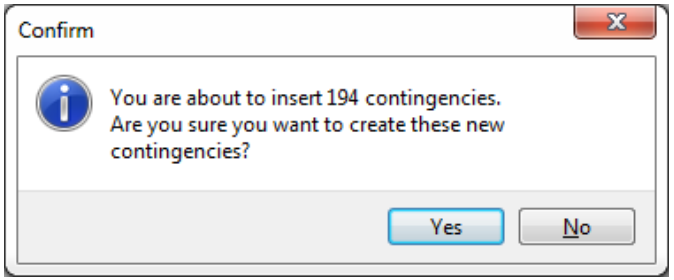
"B5RWind_DFACTSRegDemo"

Contingency Analysis

- Use Custom Monitors during contingency runs to see which D-FACTS lines respond for each contingency
- Placing D-FACTS devices on lines with the worst contingency overload can significantly improve the results
- It is also possible to designate more advanced responses to occur during a contingency
  - Remedial action schemes (RAS)
  - Special protection systems (SPS)

Contingency Analysis Example

- Open "IEEE118Bus_CTG_Demo.pwb"
- Open the Contingency Analysis dialog and set options
  - Under the Options Tab > Limit Monitoring > Advanced Limit Monitoring, select "Do not report base case violations"
  - Open "Limit Monitoring Settings"
    - Check "Do not monitor radial lines and buses"
- Auto-insert all single-line or transformer contingencies
- Click "Start Run"
- View the results



Aggregate MVA Overload Metric

- Aggregate MVA Overload (AMWCO) can be calculated per line, per contingency, or for the entire system

Element	Measure of	AMWCO
Line or Transformer, i-j	Weakness	$\sum_{c=1}^{Ncont} abs(P_{ij}^{c} - P_{jk}^{max})$
Contingency, c	Severity	$\sum_{ij=1}^{Nlines} abs(P_{ij}^{c} - P_{jk}^{max})$
System	Insecurity	$\sum_{ij=1}^{Nlines} \sum_{c=1}^{Ncont} abs(P_{ij}^{c} - P_{jk}^{max})$

Contingency Analysis Example

- Open the Results Tab > View Results by Element > Lines/Transformers
- Add Aggregate MVA Overload field
  - In the case information display, right click, choose Display/Column Options, select “Aggregate MVA Overload” from the Contingency Results folder, click “Add –> ”
  - Also add the Custom Integer field
- 56 violations, 1221.14 MVA aggregate overload for displayed lines
- Sort by Aggregate MVA Overload
- Number the most overloaded lines using the Custom Integer column

“IEEE118Bus_CTG_Demo”

Contingency Analysis Example

- Most severe contingencies sorted by AMWCO

Lines/Transformers

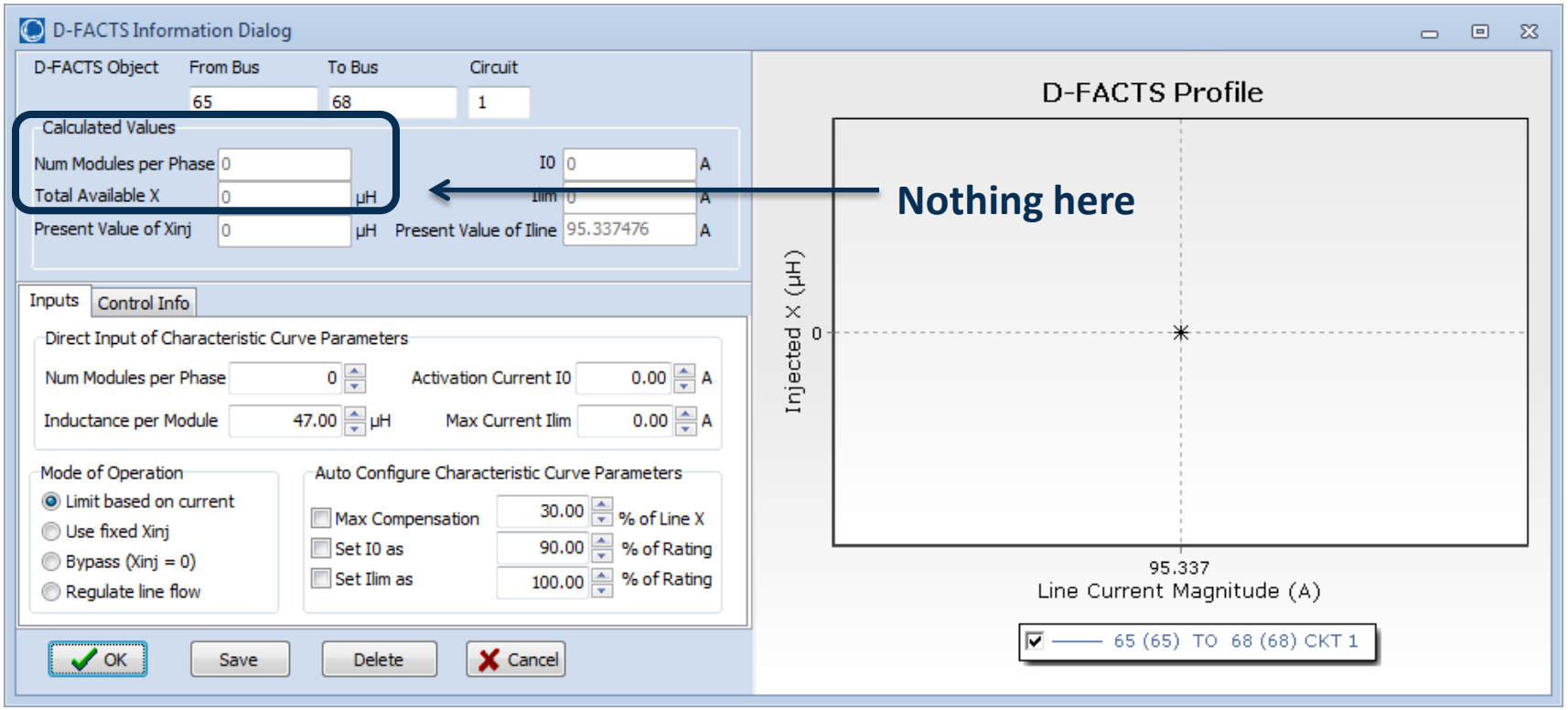
	From Number	From Name	To Number	To Name	Circuit	Xfrmr	Violations	Cust Int 1	Aggr MVA Overload	Max % Loading Cont.
1	65	65	68	68	1	NO	2	1	382.94	291.50
2	23	23	32	32	1	NO	10	2	237.94	163.27
3	68	68	81	81	1	NO	4	3	76.48	144.21
4	16	16	17	17	1	NO	1	4	66.25	166.25
5	5	5	6	6	1	NO	7	5	61.65	113.96
6	17	17	18	18	1	NO	4	6	56.92	130.26
7	5	5	11	11	1	NO	5	7	54.43	130.32
8	12	12	16	16	1	NO	1	8	42.04	142.04
9	100	100	104	104	1	NO	1	9	30.78	130.78
10	69	69	77	77	1	NO	3	10	25.66	111.04
11	85	85	89	89	1	NO	1		24.34	124.34

- Insert D-FACTS devices on these lines
  - Right click on each row, choose Show Dialog, then “D-FACTS Devices on the Line” to open the dialog
  - On D-FACTS dialog, check “Max Compensation,” “Set I0 as,” and “Set Ilim as” to auto-configure using defaults
  - Click “Save”

“IEEE118Bus_CTG_Demo”

Contingency Analysis Example

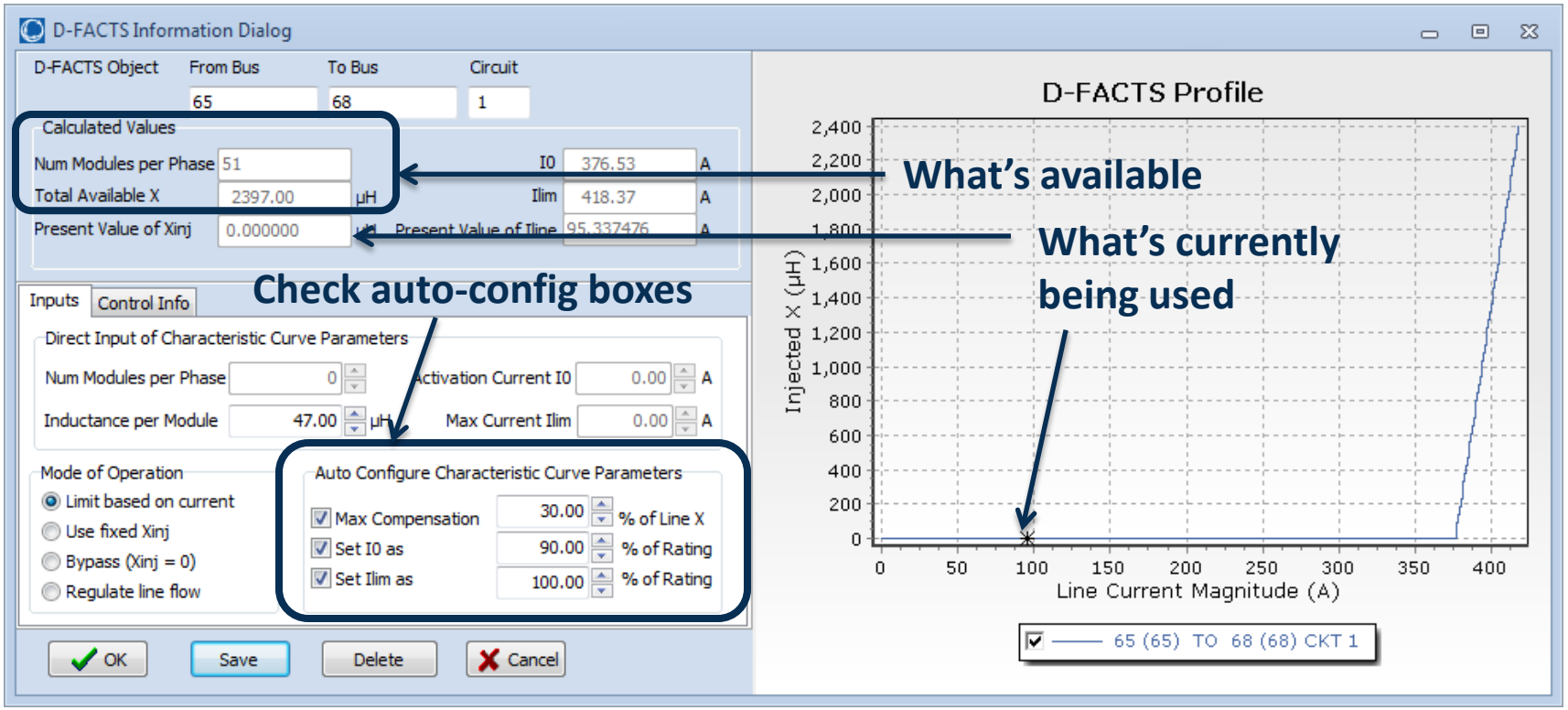
- Dialog without D-FACTS



"IEEE118Bus_CTG_Demo"

Contingency Analysis Example

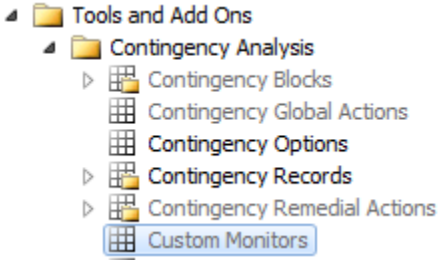
- Dialog with D-FACTS

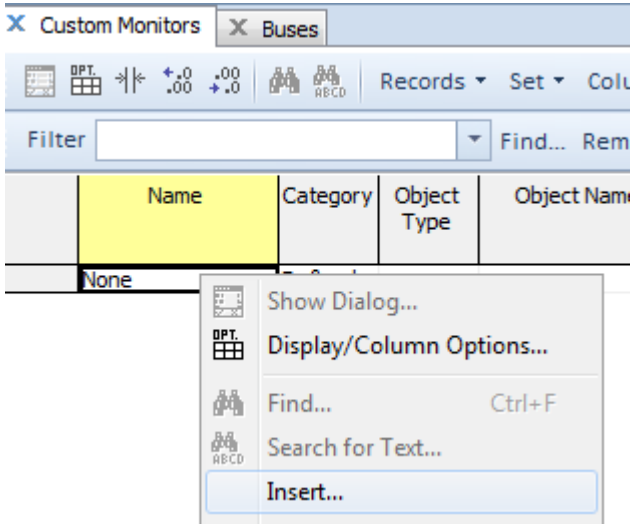


"IEEE118Bus_CTG_Demo"

Setting up Custom Monitors

- Custom Monitors report the value of monitored fields during contingency analysis
  - One custom monitor per field
  - Can be specified by an *AUX file.
- We'll monitor how many D-FACTS devices have responded and on which lines by tracking changes in the Xinj field
- Open the Custom Monitor dialog from the Model Explorer in the "Tools and Add Ons" > "Contingency Analysis" folder

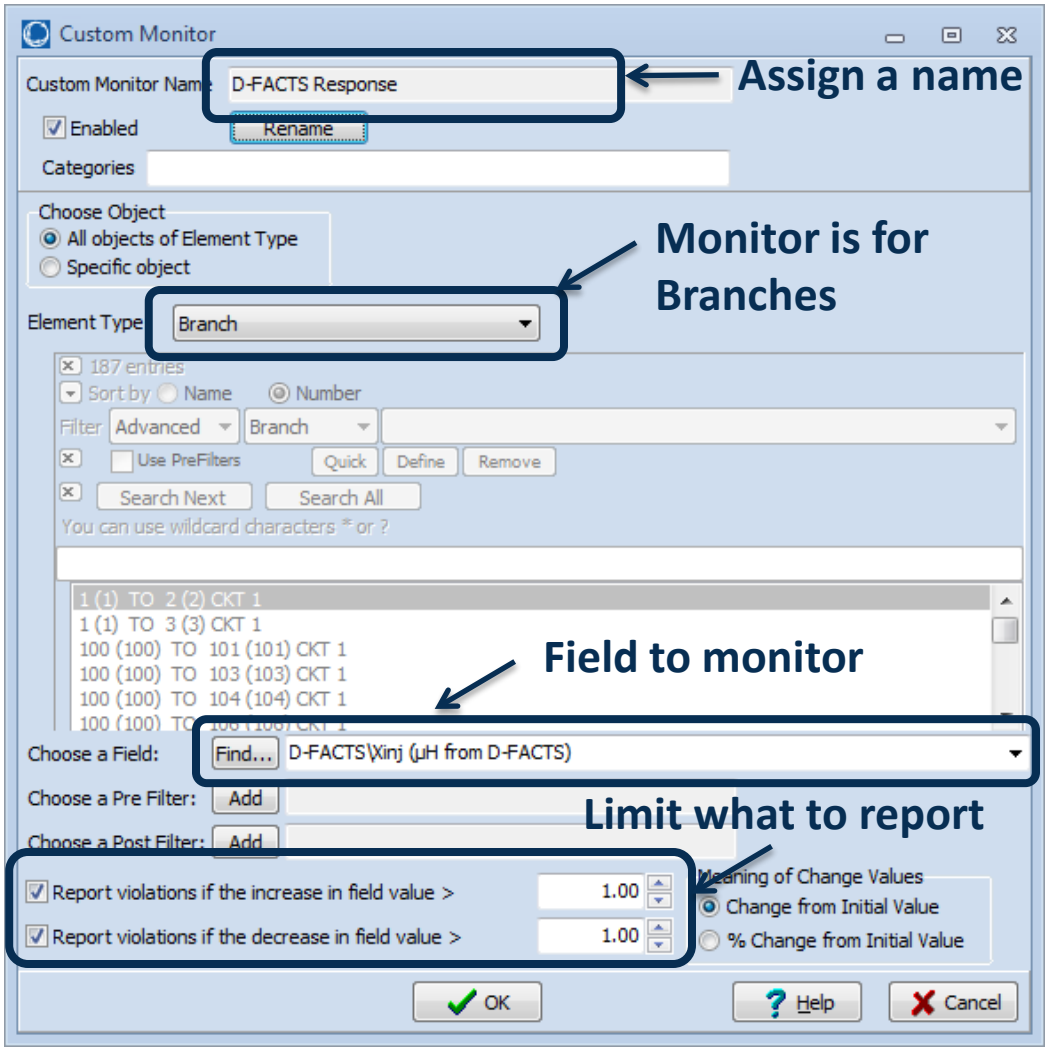




"IEEE118Bus_CTG_Demo"

Custom Monitor Dialog

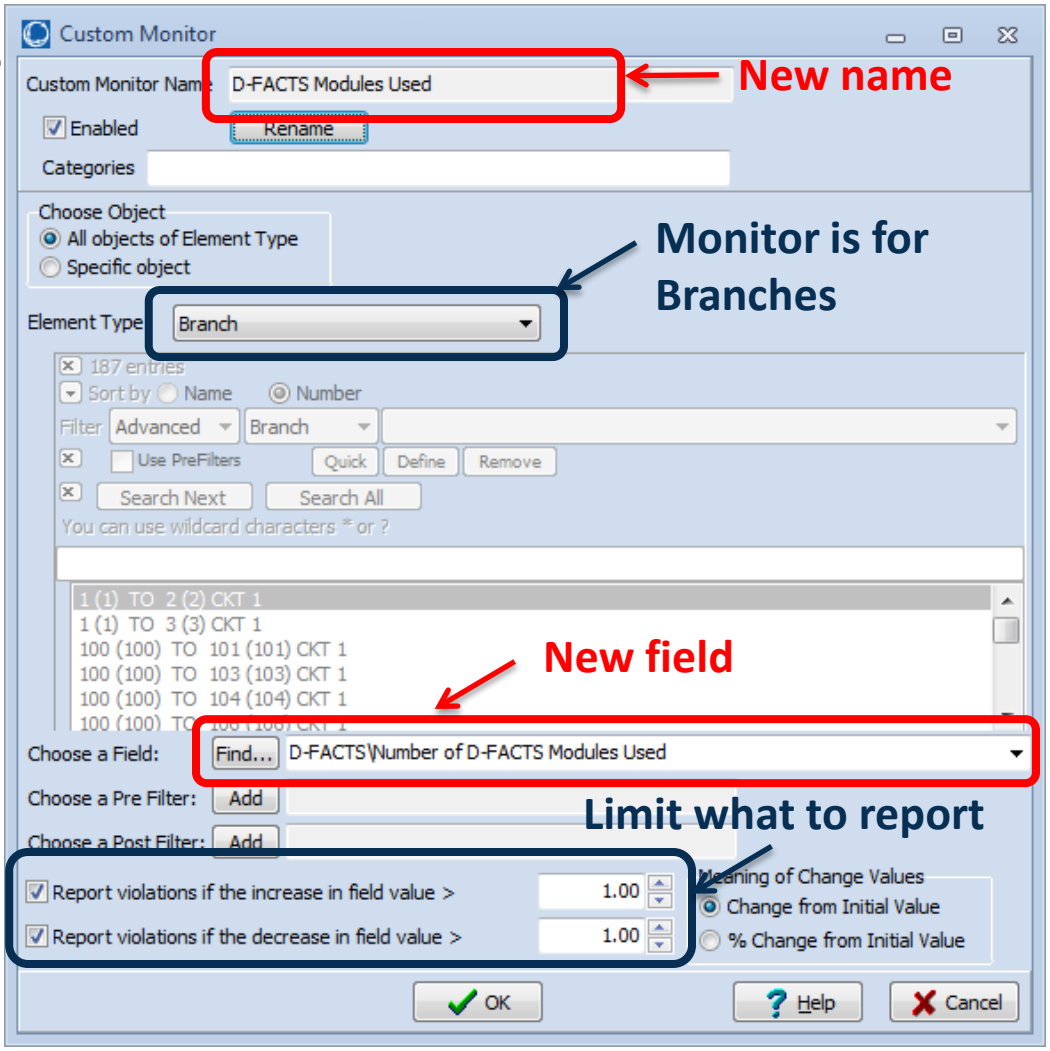
- Set up to monitor D-FACTS Xinj
- Only report Xinj if it changes from the base case



"IEEE118Bus_CTG_Demo"

Custom Monitor Dialog

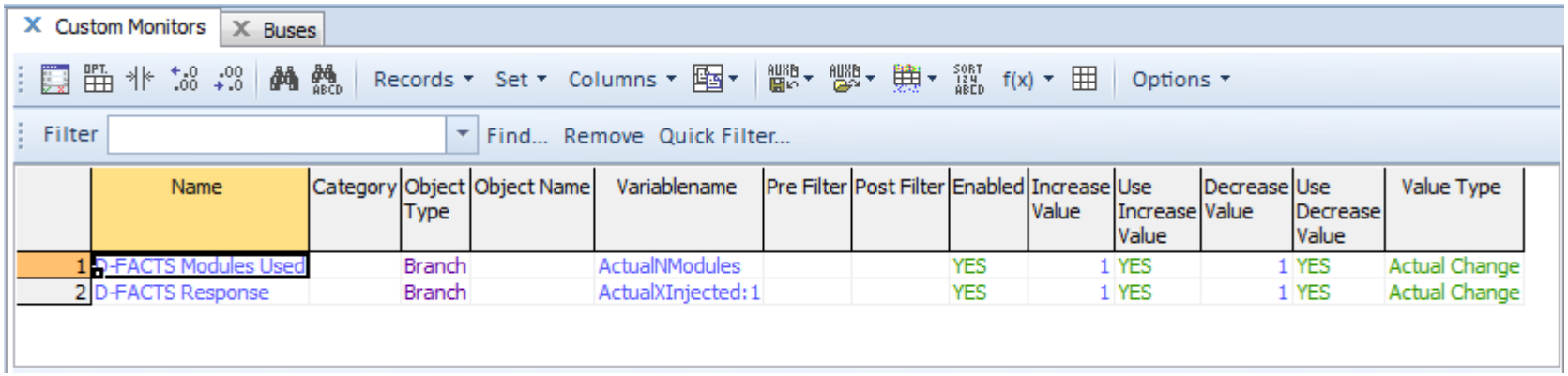
- Set up another Custom Monitor to report number of modules used
- Only report if DSRs have changed



"IEEE118Bus_CTG_Demo"

D-FACTS Custom Monitors

- Case Information Display with new Custom Monitors



	Name	Category	Object Type	Object Name	Variablename	Pre Filter	Post Filter	Enabled	Increase Value	Use Increase Value	Decrease Value	Use Decrease Value	Value Type
1	D-FACTS Modules Used		Branch		ActualNModules			YES	1	YES	1	YES	Actual Change
2	D-FACTS Response		Branch		ActualXInjected:1			YES	1	YES	1	YES	Actual Change

- Open the Contingency Analysis Dialog and run with the D-FACTS and Custom Monitors inserted

Results with D-FACTS

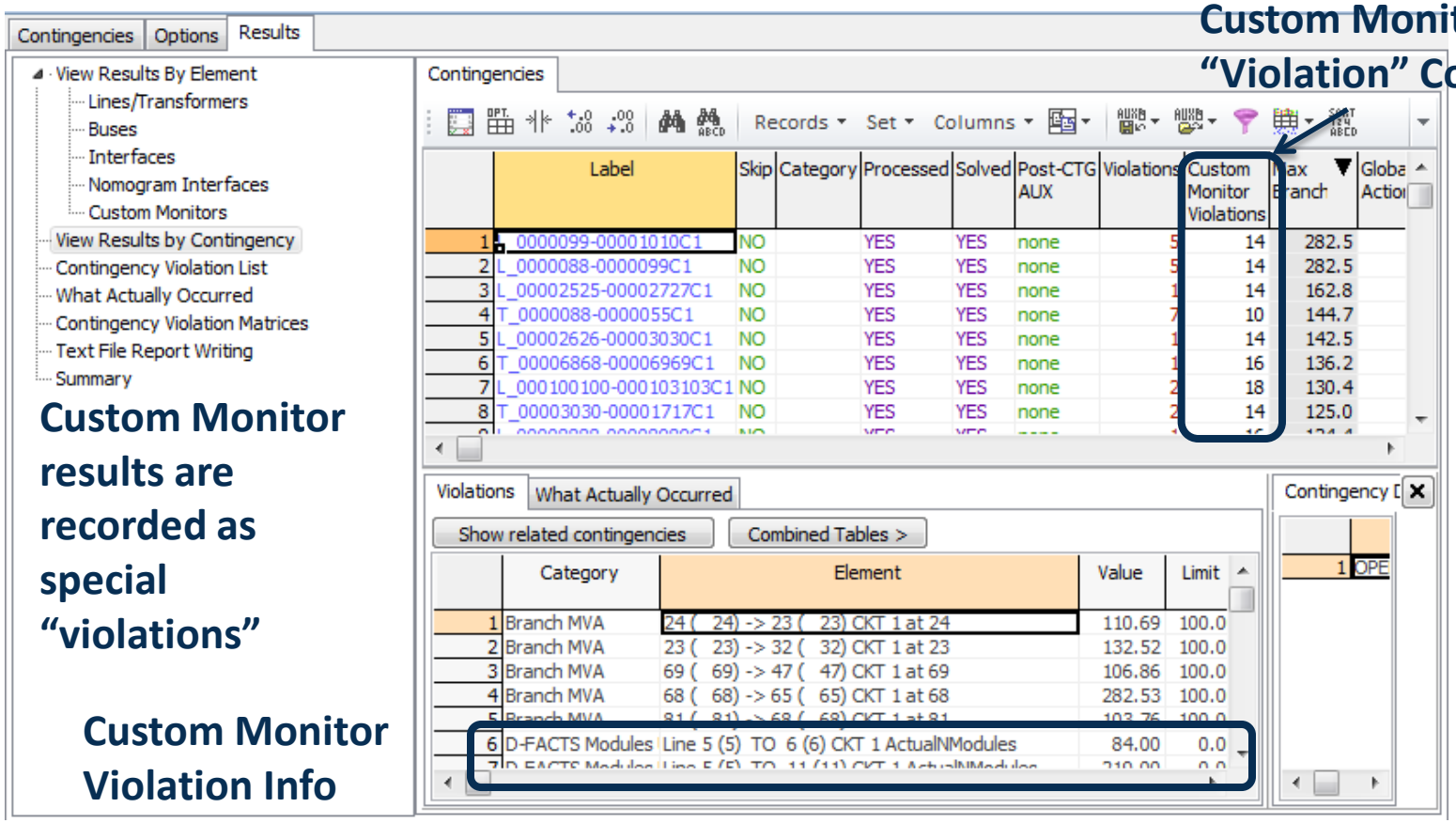
- System AMCO decreased from 1221.14 to 1081.1
- Violations decreased from 56 to 49

Lines/Transformers

	From Number	From Name	To Number	To Name	Circuit	Xfrmr	Violations	Cust Int 1	Aggr MVA Overload	Max % Loading Cont.
1	65	65	68	68	1	NO	2	1	365.0	282.53
2	23	23	32	32	1	NO	10	2	235.9	162.80
3	5	5	6	6	1	NO	7	5	55.5	115.97
4	16	16	17	17	1	NO	1	4	44.7	144.69
5	68	68	81	81	1	NO	4	3	43.9	136.18
6	17	17	18	18	1	NO	3	6	35.7	123.55
7	14	14	15	15	1	NO	1		32.1	132.13
8	100	100	106	106	1	NO	1		30.4	130.41
9	85	85	89	89	1	NO	1		24.4	124.42
10	79	79	80	80	1	NO	1		21.9	121.86
11	23	23	24	24	1	NO	2		21.4	110.69
12	12	12	16	16	1	NO	1	8	20.2	120.19

Viewing Custom Monitor Results

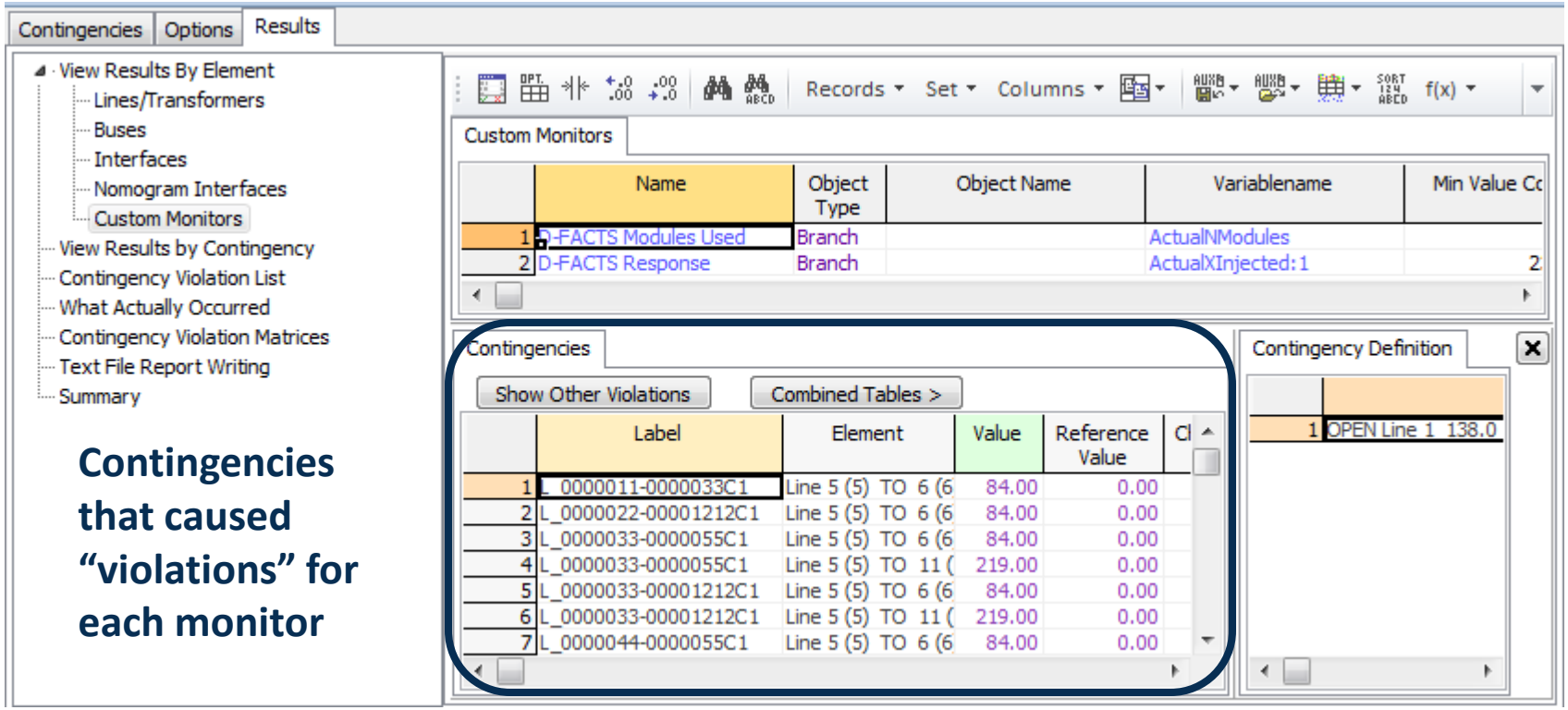
- Results by Contingency



"IEEE118Bus_CTG_Demo"

Viewing Custom Monitor Results

- Custom Monitors Results Tab

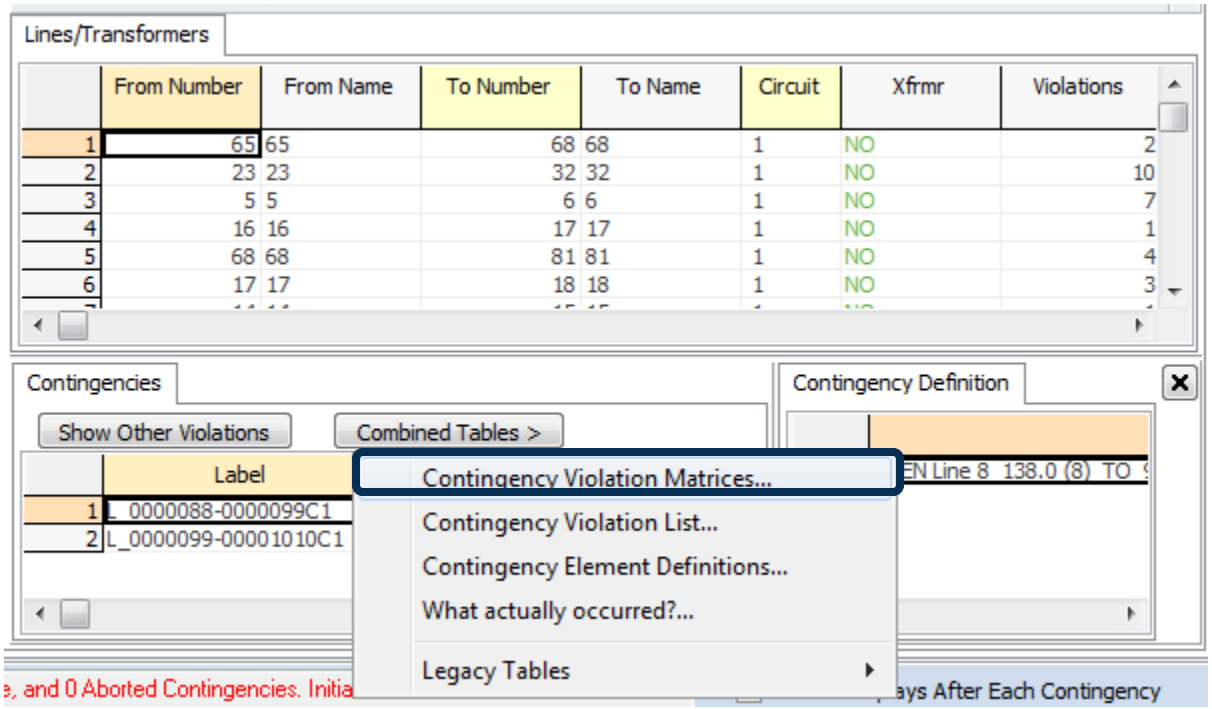


Contingencies that caused "violations" for each monitor

"IEEE118Bus_CTG_Demo"

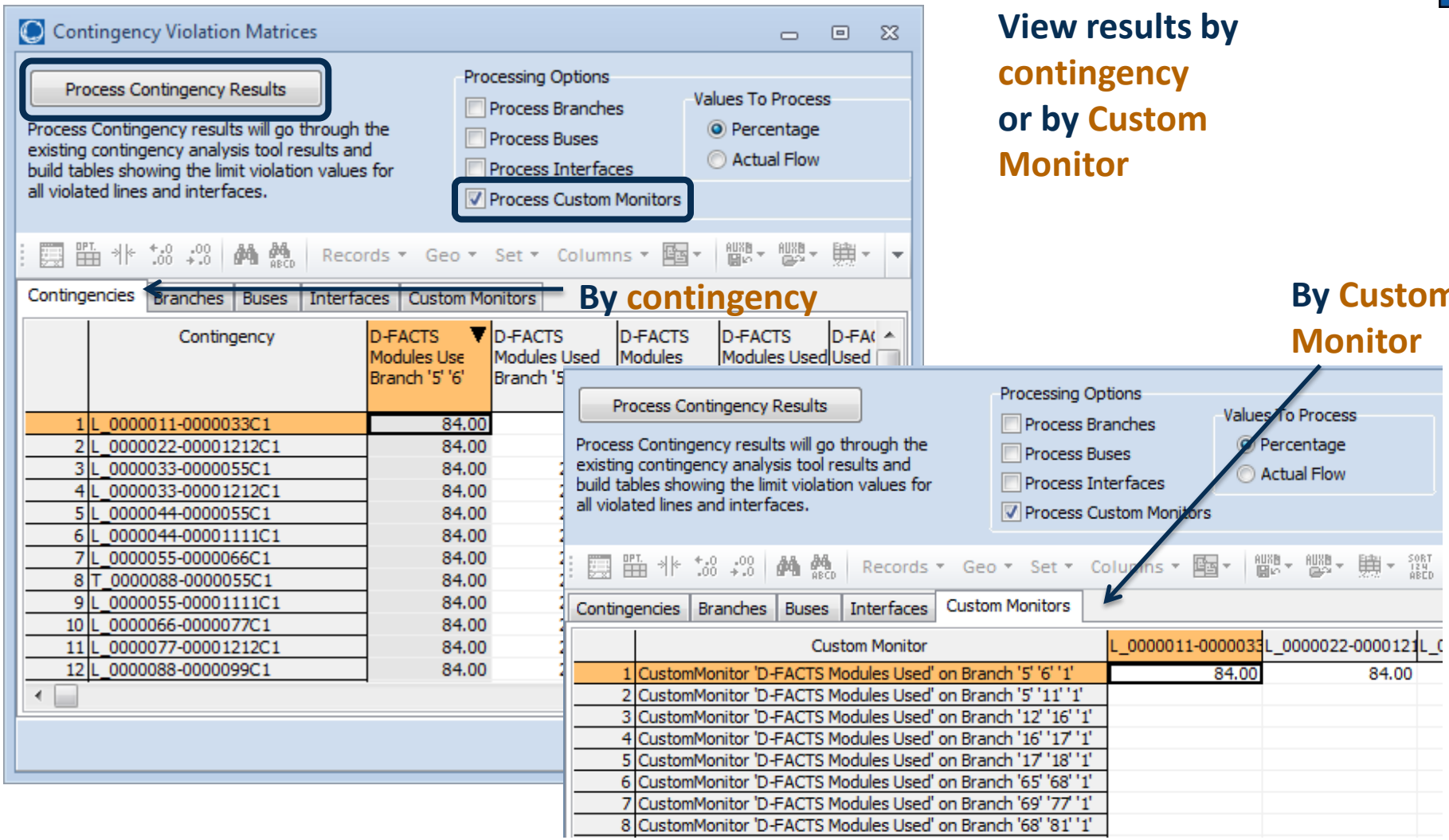
Contingency Violation Matrices

- "Combined Tables" shows other results tables



"IEEE118Bus_CTG_Demo"

Contingency Violation Matrices

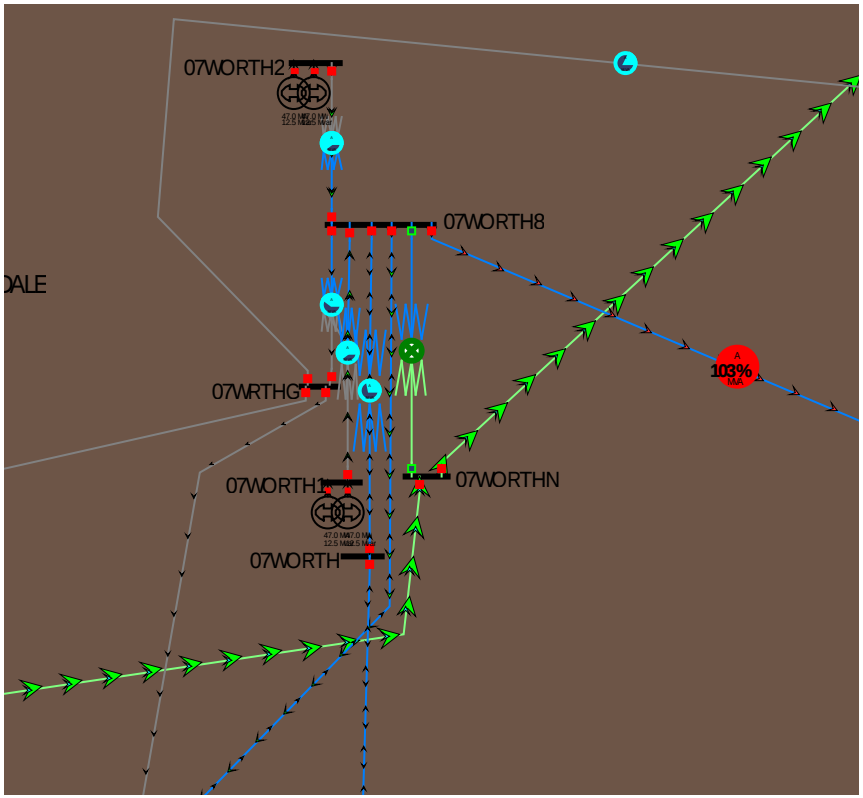


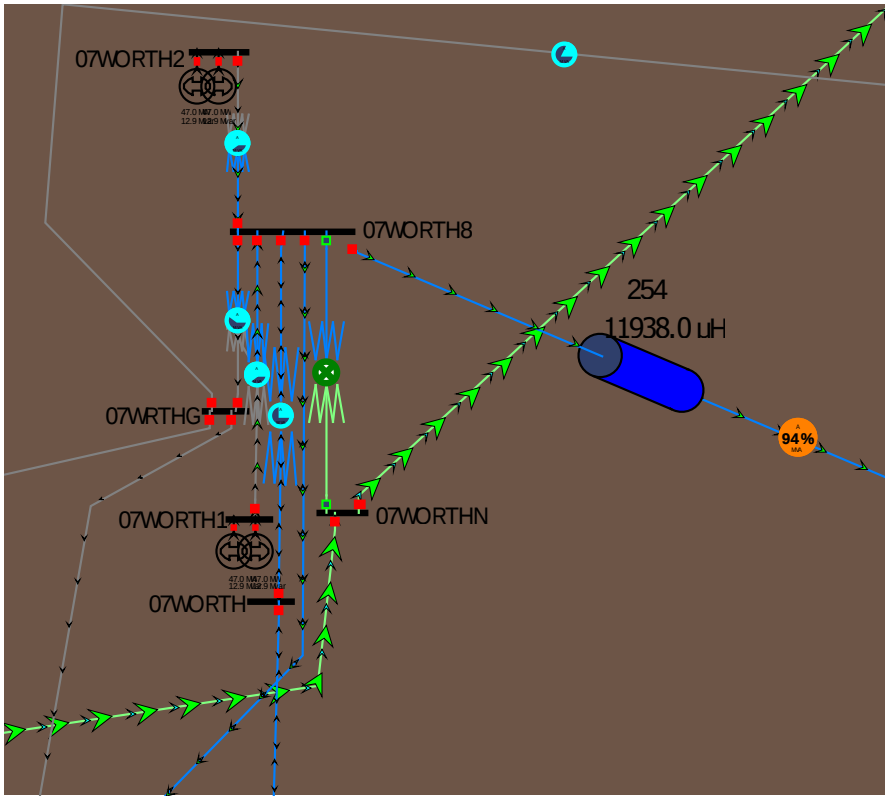
View results by contingency or by Custom Monitor

"IEEE118Bus_CTG_Demo"

Large Case Contingency

- Post-contingent response





Sensitivity Analysis

- How can D-FACTS devices help other lines?
  - Sensitivity analysis
  - Optimization
- Line impedance sensitivities
  - The first step towards a comprehensive power flow control solution
  - How does a change in line impedance affect the rest of the system?
  - What can be controlled by changing line impedances?
  - What D-FACTS settings will provide this control?

Line Impedance Sensitivities

$$\begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} = [\Phi] \begin{bmatrix} \Delta x_\ell \end{bmatrix}$$

$\Phi \triangleq$ State to Impedance sensitivity matrix

$$\frac{dP_{flow}}{dx_\ell} = \left[\frac{\partial P_{flow,\ell}}{\partial s_{(\theta,V)}} \frac{\partial s_{(\theta,V)}}{\partial x_\ell} + \frac{\partial P_{flow,\ell}}{\partial x_\ell} \right]$$

Φ

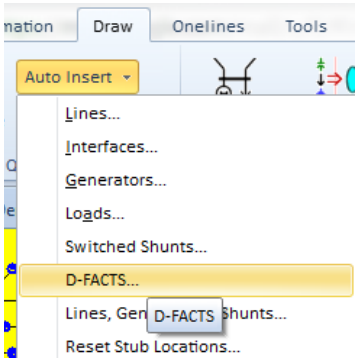
$\Sigma \triangleq$ Power Flow to State sensitivity matrix

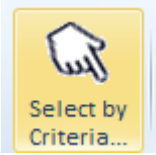
$\Gamma \triangleq$ Power Flow to Impedance sensitivity matrix

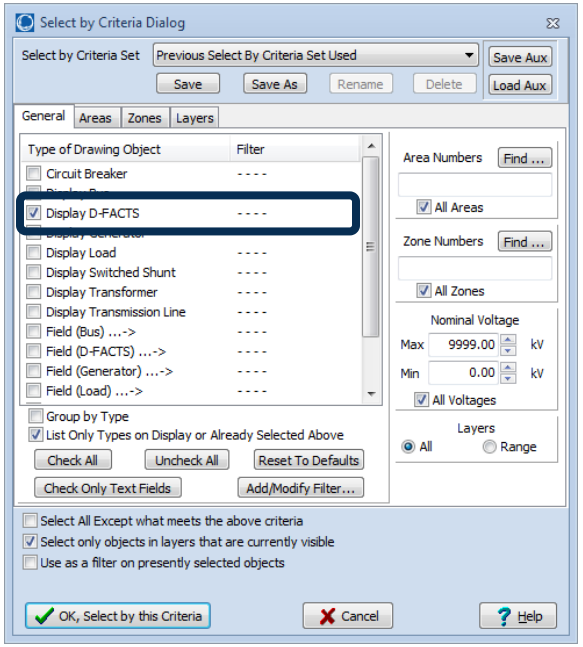
$$\begin{bmatrix} \Delta P_{flow,\ell} \end{bmatrix} = [\Sigma] \begin{bmatrix} \Delta\theta \\ \Delta V \end{bmatrix} + [\Gamma] \begin{bmatrix} \Delta x_\ell \end{bmatrix}$$

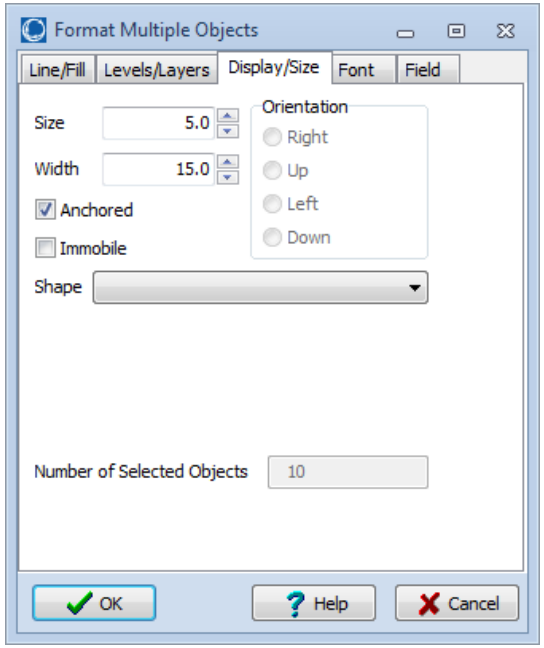
Sensitivity Analysis Example

- Auto insert D-FACTS objects
- Use Select by Criteria to resize



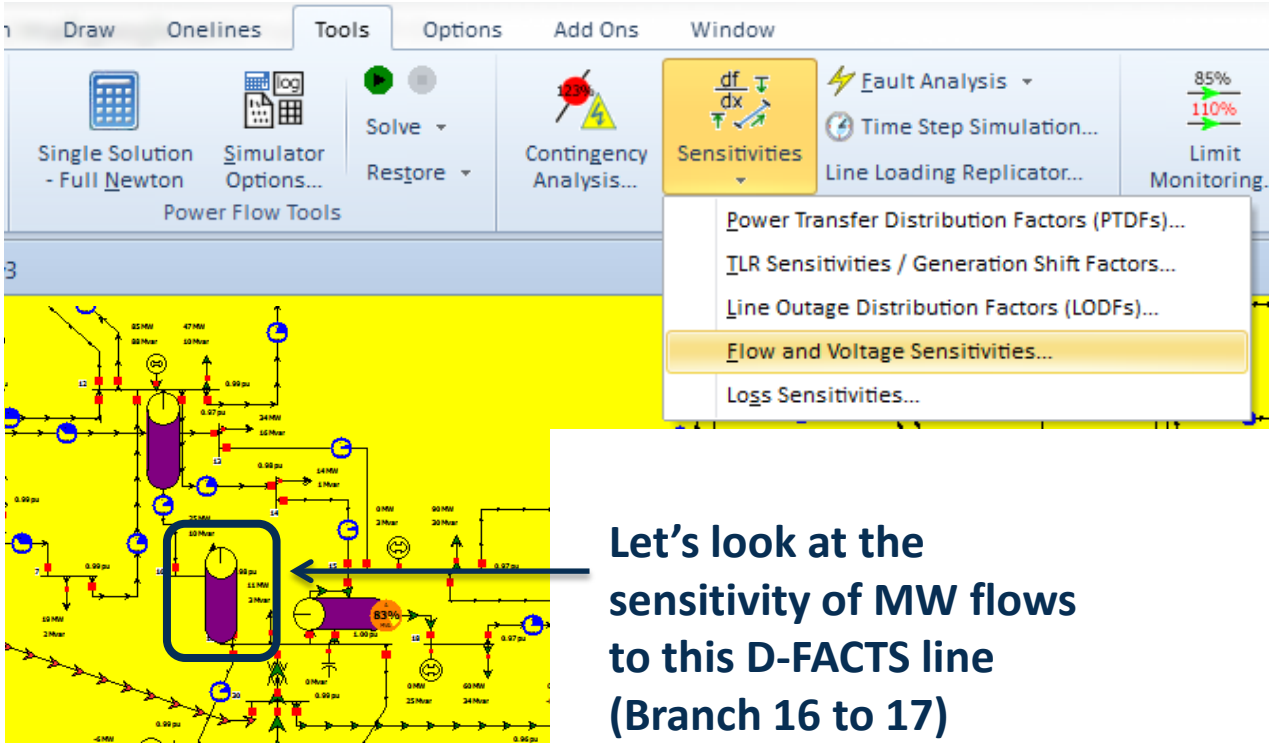






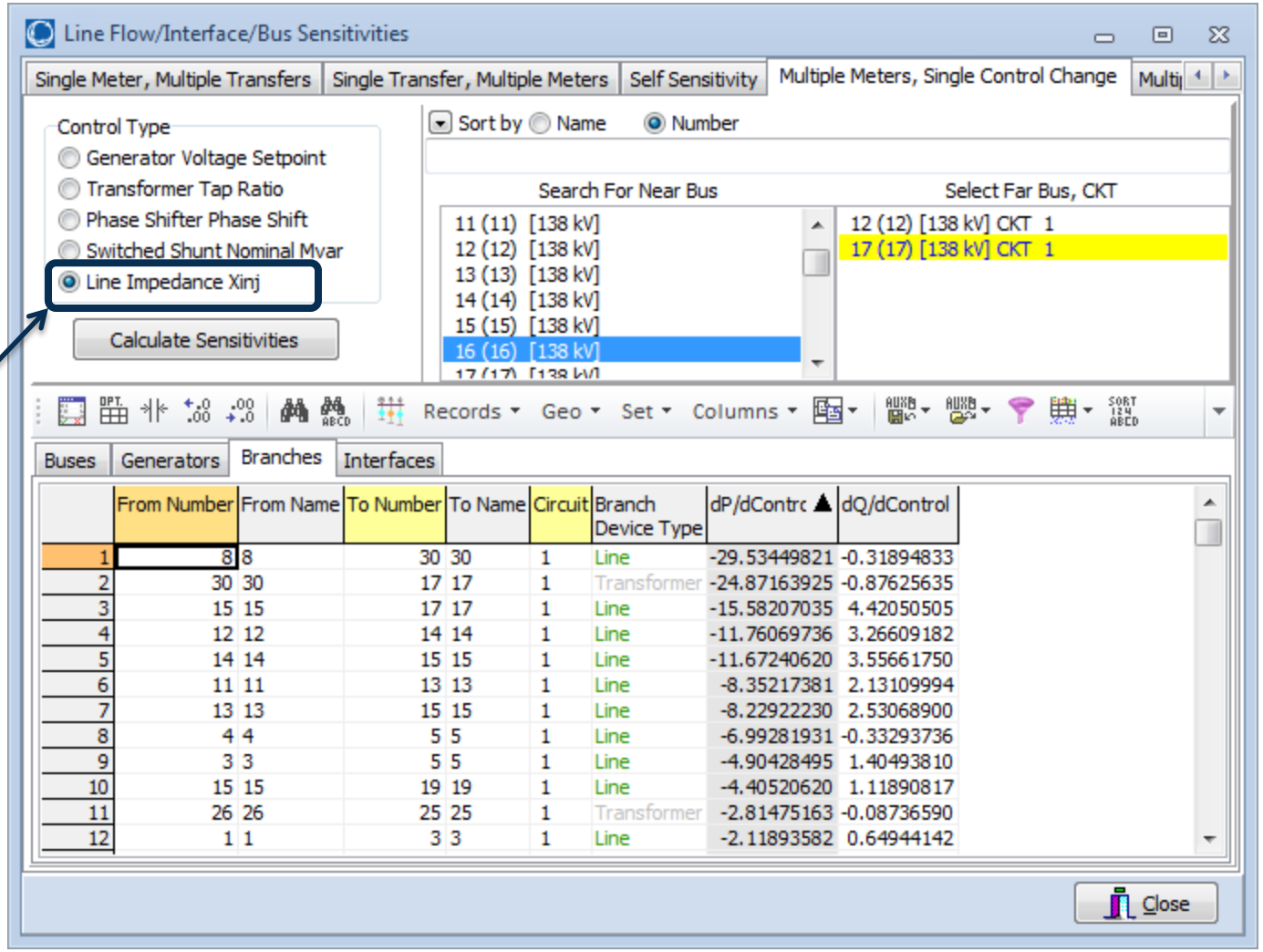
Sensitivity Analysis Example

- Open the Sensitivity Analysis Dialog from Sensitivities > Flow and Voltage Sensitivities



Let's look at the sensitivity of MW flows to this D-FACTS line (Branch 16 to 17)

Single Control Change



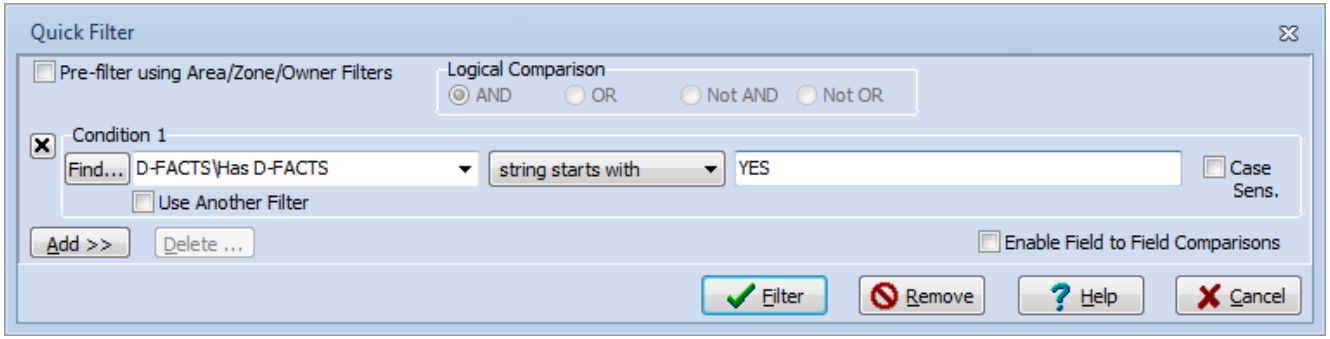
	From Number	From Name	To Number	To Name	Circuit	Branch Device Type	dP/dContrc	dQ/dControl
1	8	8	30	30	1	Line	-29.53449821	-0.31894833
2	30	30	17	17	1	Transformer	-24.87163925	-0.87625635
3	15	15	17	17	1	Line	-15.58207035	4.42050505
4	12	12	14	14	1	Line	-11.76069736	3.26609182
5	14	14	15	15	1	Line	-11.67240620	3.55661750
6	11	11	13	13	1	Line	-8.35217381	2.13109994
7	13	13	15	15	1	Line	-8.22922230	2.53068900
8	4	4	5	5	1	Line	-6.99281931	-0.33293736
9	3	3	5	5	1	Line	-4.90428495	1.40493810
10	15	15	19	19	1	Line	-4.40520620	1.11890817
11	26	26	25	25	1	Transformer	-2.81475163	-0.08736590
12	1	1	3	3	1	Line	-2.11893582	0.64944142

New control to calculate Xinj sensitivities for DSR placement

"IEEE118Bus_CTG_Demo"

Multiple Control Change

- Filter branches to select as control devices only lines that have D-FACTS

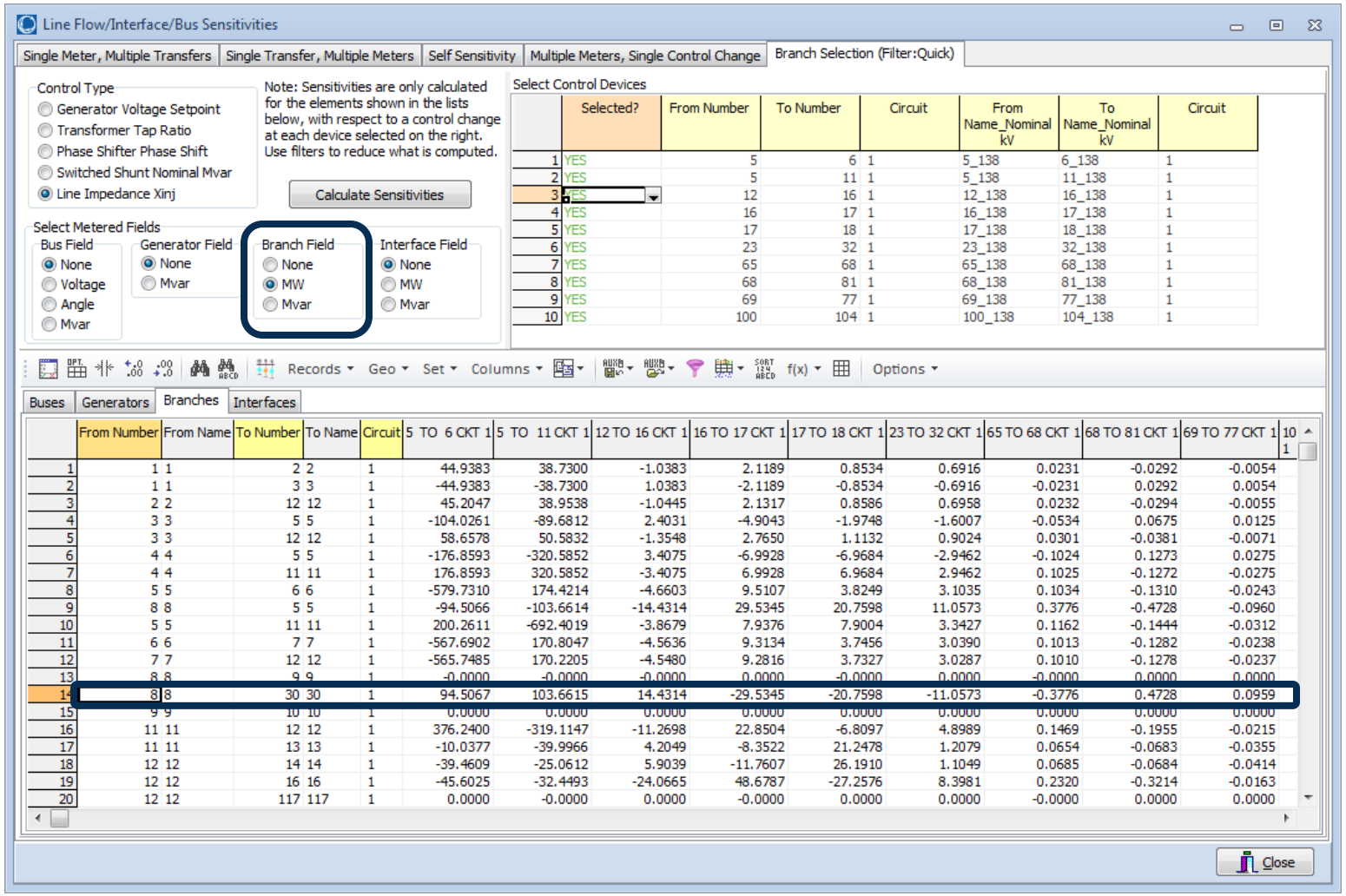


- Toggle Selected field for ALL branches to “NO” first

Select Control Devices

	Selected?	From Number	To Number	Circuit	From Name_Nominal kV	To Name_Nominal kV	Circuit
1	YES	5	6	1	5_138	6_138	1
2	YES	5	11	1	5_138	11_138	1
3	YES	12	16	1	12_138	16_138	1
4	YES	16	17	1	16_138	17_138	1
5	YES	17	18	1	17_138	18_138	1
6	YES	23	32	1	23_138	32_138	1
7	YES	65	68	1	65_138	68_138	1
8	YES	68	81	1	68_138	81_138	1
9	YES	69	77	1	69_138	77_138	1
10	YES	100	104	1	100_138	104_138	1

Multiple Control Change



	Selected?	From Number	To Number	Circuit	From Name_Nominal kV	To Name_Nominal kV	Circuit
1	YES	5	6	1	5_138	6_138	1
2	YES	5	11	1	5_138	11_138	1
3	YES	12	16	1	12_138	16_138	1
4	YES	16	17	1	16_138	17_138	1
5	YES	17	18	1	17_138	18_138	1
6	YES	23	32	1	23_138	32_138	1
7	YES	65	68	1	65_138	68_138	1
8	YES	68	81	1	68_138	81_138	1
9	YES	69	77	1	69_138	77_138	1
10	YES	100	104	1	100_138	104_138	1

	From Number	From Name	To Number	To Name	Circuit	5 TO 6 CKT 1	5 TO 11 CKT 1	12 TO 16 CKT 1	16 TO 17 CKT 1	17 TO 18 CKT 1	23 TO 32 CKT 1	65 TO 68 CKT 1	68 TO 81 CKT 1	69 TO 77 CKT 1	101
1	1	1	2	2	1	44.9383	38.7300	-1.0383	2.1189	0.8534	0.6916	0.0231	-0.0292	-0.0054	
2	1	1	3	3	1	-44.9383	-38.7300	1.0383	-2.1189	-0.8534	-0.6916	-0.0231	0.0292	0.0054	
3	2	2	12	12	1	45.2047	38.9538	-1.0445	2.1317	0.8586	0.6958	0.0232	-0.0294	-0.0055	
4	3	3	5	5	1	-104.0261	-89.6812	2.4031	-4.9043	-1.9748	-1.6007	-0.0534	0.0675	0.0125	
5	3	3	12	12	1	58.6578	50.5832	-1.3548	2.7650	1.1132	0.9024	0.0301	-0.0381	-0.0071	
6	4	4	5	5	1	-176.8593	-320.5852	3.4075	-6.9928	-6.9684	-2.9462	-0.1024	0.1273	0.0275	
7	4	4	11	11	1	176.8593	320.5852	-3.4075	6.9928	6.9684	2.9462	0.1025	-0.1272	-0.0275	
8	5	5	6	6	1	-579.7310	174.4214	-4.6603	9.5107	3.8249	3.1035	0.1034	-0.1310	-0.0243	
9	8	8	5	5	1	-94.5066	-103.6614	-14.4314	29.5345	20.7598	11.0573	0.3776	-0.4728	-0.0960	
10	5	5	11	11	1	200.2611	-692.4019	-3.8679	7.9376	7.9004	3.3427	0.1162	-0.1444	-0.0312	
11	6	6	7	7	1	-567.6902	170.8047	-4.5636	9.3134	3.7456	3.0390	0.1013	-0.1282	-0.0238	
12	7	7	12	12	1	-565.7485	170.2205	-4.5480	9.2816	3.7327	3.0287	0.1010	-0.1278	-0.0237	
13	8	8	9	9	1	-0.0000	-0.0000	-0.0000	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	
14	8	8	30	30	1	94.5067	103.6615	14.4314	-29.5345	-20.7598	-11.0573	-0.3776	0.4728	0.0959	
15	9	9	10	10	1	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	
16	11	11	12	12	1	376.2400	-319.1147	-11.2698	22.8504	-6.8097	4.8989	0.1469	-0.1955	-0.0215	
17	11	11	13	13	1	-10.0377	-39.9966	4.2049	-8.3522	21.2478	1.2079	0.0654	-0.0683	-0.0355	
18	12	12	14	14	1	-39.4609	-25.0612	5.9039	-11.7607	26.1910	1.1049	0.0685	-0.0684	-0.0414	
19	12	12	16	16	1	-45.6025	-32.4493	-24.0665	48.6787	-27.2576	8.3981	0.2320	-0.3214	-0.0163	
20	12	12	117	117	1	0.0000	-0.0000	0.0000	-0.0000	0.0000	0.0000	-0.0000	0.0000	0.0000	

OPF Support

- Recently, PowerWorld added the ability to include D-FACTS as control variables in the optimal power flow (OPF) tools
  - Injected reactance X (Xinj) onto the line is the control
  - Device limits from the power flow settings are used
- OPF control allows…
  - D-FACTS to respond to overloads on lines throughout the system and reduce or eliminate the need to re-dispatch more expensive generation
  - Global coordination and control
  - Comparison of OPF control vs. stand-alone control
- OPF updates
  - Fixed a bug in OPF sensitivity calculation for D-FACTS

Primal LP OPF Solution Algorithm

- Simulator's optimization tools are based on Linear Programming (LP)
- Solution iterates between
  - Solving a full AC power flow solution
    - Enforces real/reactive power balance at each bus
    - Enforces generator reactive limits
    - System controls are assumed fixed
    - Takes into account non-linearities
  - Solving a primal LP
    - Changes system controls to enforce linearized constraints while minimizing cost (or control change)

Optimal Power Flow (OPF)

- Inequality constraints
  - Transmission line/transformer/interface flow limits
  - Generator MW limits
  - Generator reactive power capability curves
  - Bus voltage magnitudes (not yet implemented in Simulator OPF)
- Available Controls
  - Generator MW outputs
  - Load MW demands
  - Phase shifters
  - Area Transactions
  - **D-FACTS Devices**

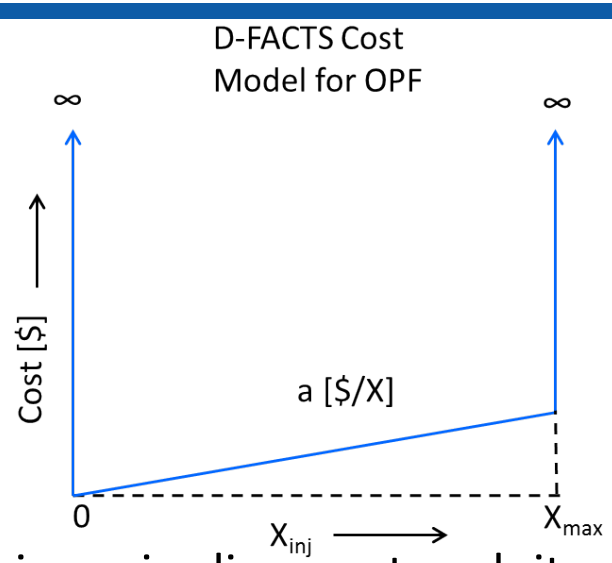
LP OPF Solution

- Cost model tells how to weight the control
  - For generators, this is a real cost and easy to understand
  - For all controls, a cost model is needed for the LP OPF
- Sensitivities tell how much effect each control has
- Combined cost and sensitivity in the LP tells how to get the most effect for the least cost

D-FACTS Sensitivities in LP

- LP basis matrix or tableau – sensitivity of each constraint to each basic variable
- Basic variables are not zero and not at a breakpoint in the cost function
- Tableau now includes the sensitivity of constraints (i.e., line MVA flows) to impedance x of DSR lines

D-FACTS Cost Model

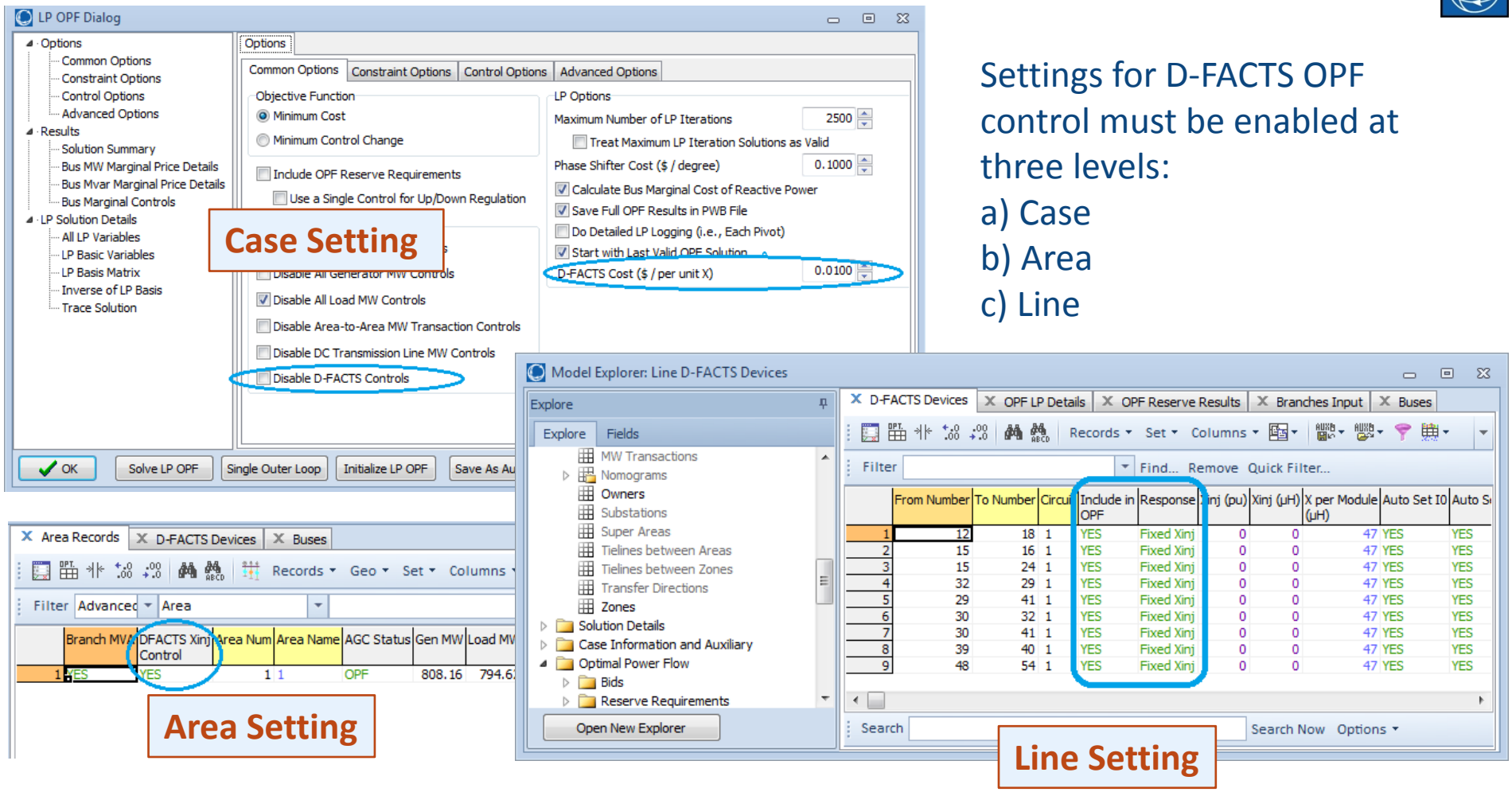


- Cost functions are piecewise linear; at each iteration we are only looking at one piece
- Limits are enforced using an extremely high penalty function outside physically viable range
- Inside viable range, we model a slight incremental cost as the devices turn on
- If Simulator's OPF determines that it would cost more to enforce these limits, it will just "pay" this cost and overload the constraint

OPF Solution Examples

- Open GSO_37Bus_DSRsOPF_basecase.pwb
- This case has an overloaded line and is set up to allow D-FACTS devices to be used as a control in the OPF
- Solve the OPF
- Alternatively, inserting D-FACTS on the overloaded line also relieves the overload

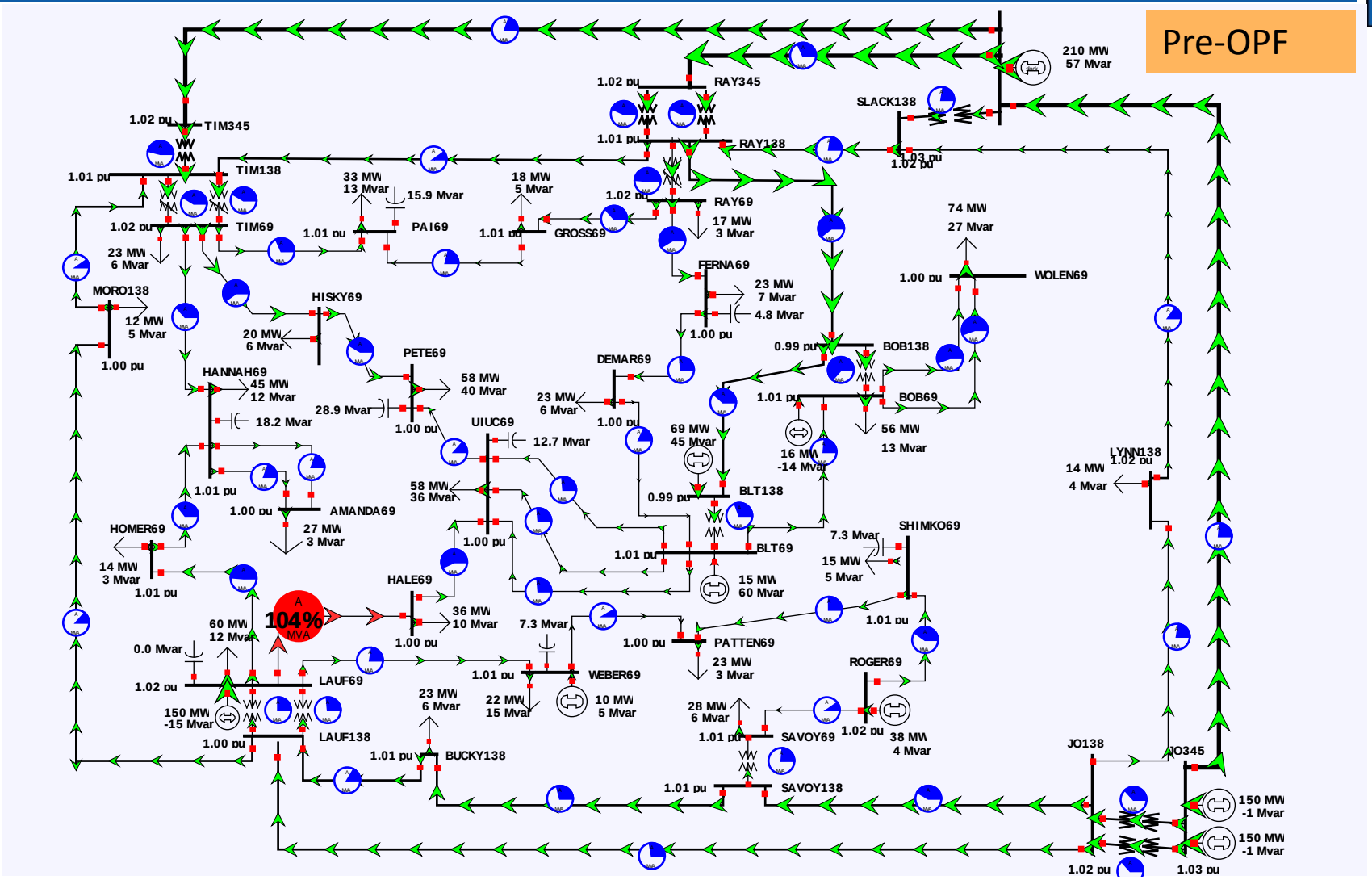
D-FACTS OPF Setup



Settings for D-FACTS OPF control must be enabled at three levels:

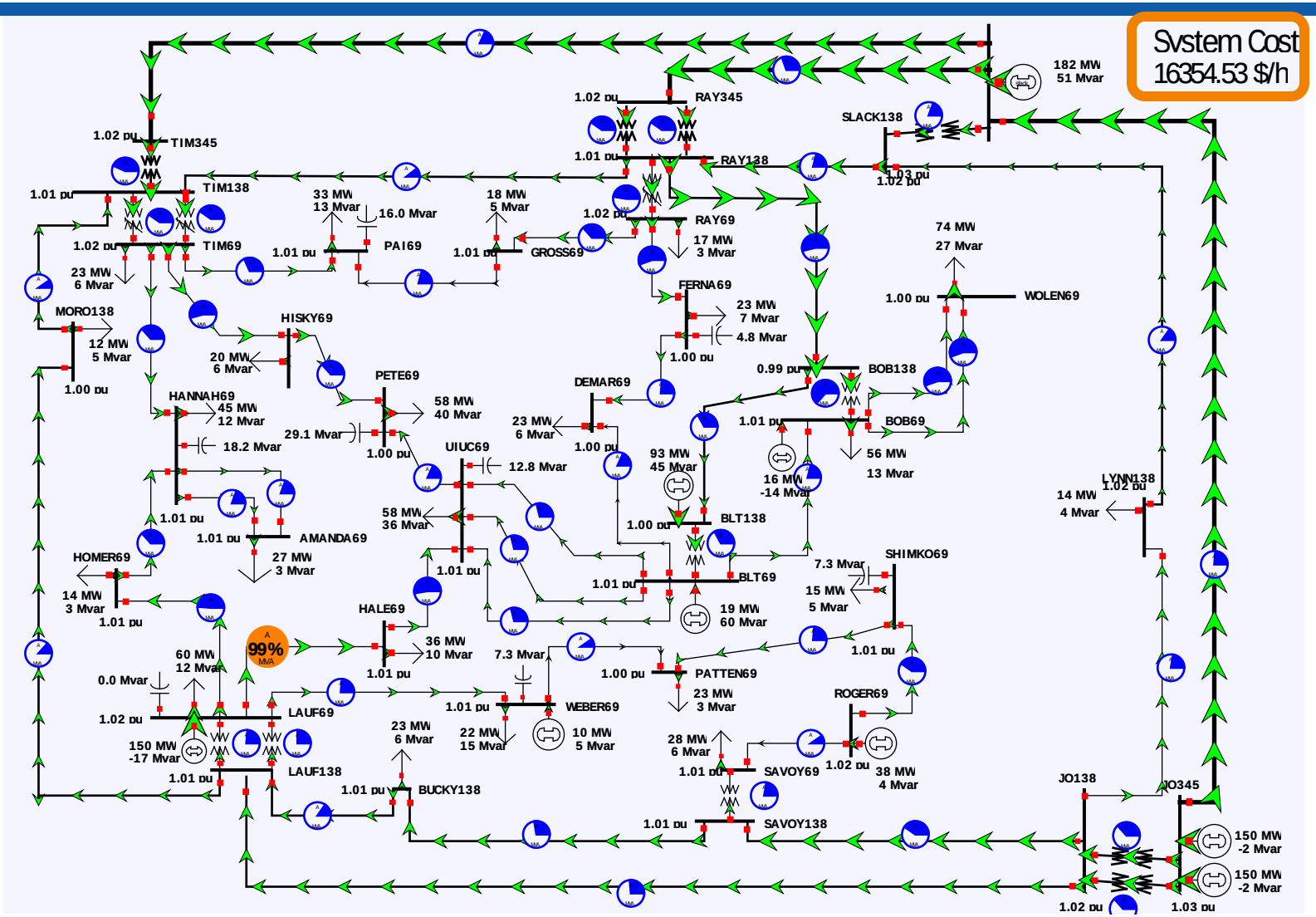
a) Case
b) Area
c) Line

Line LAUF69-HALE 69 is Overloaded



GSO_37Bus_DSRsOPF_basecase

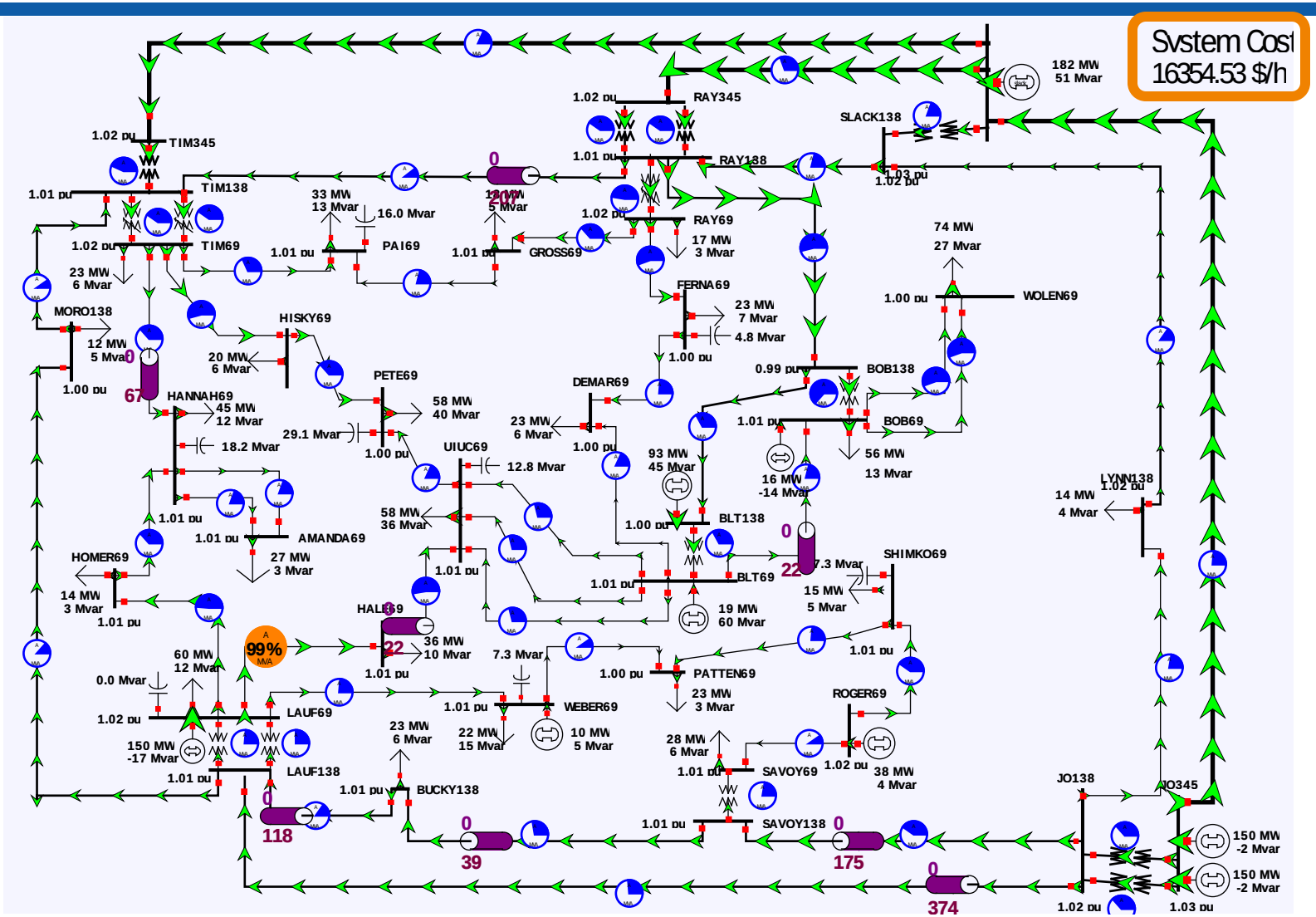
a) OPF without DSRs as Controls



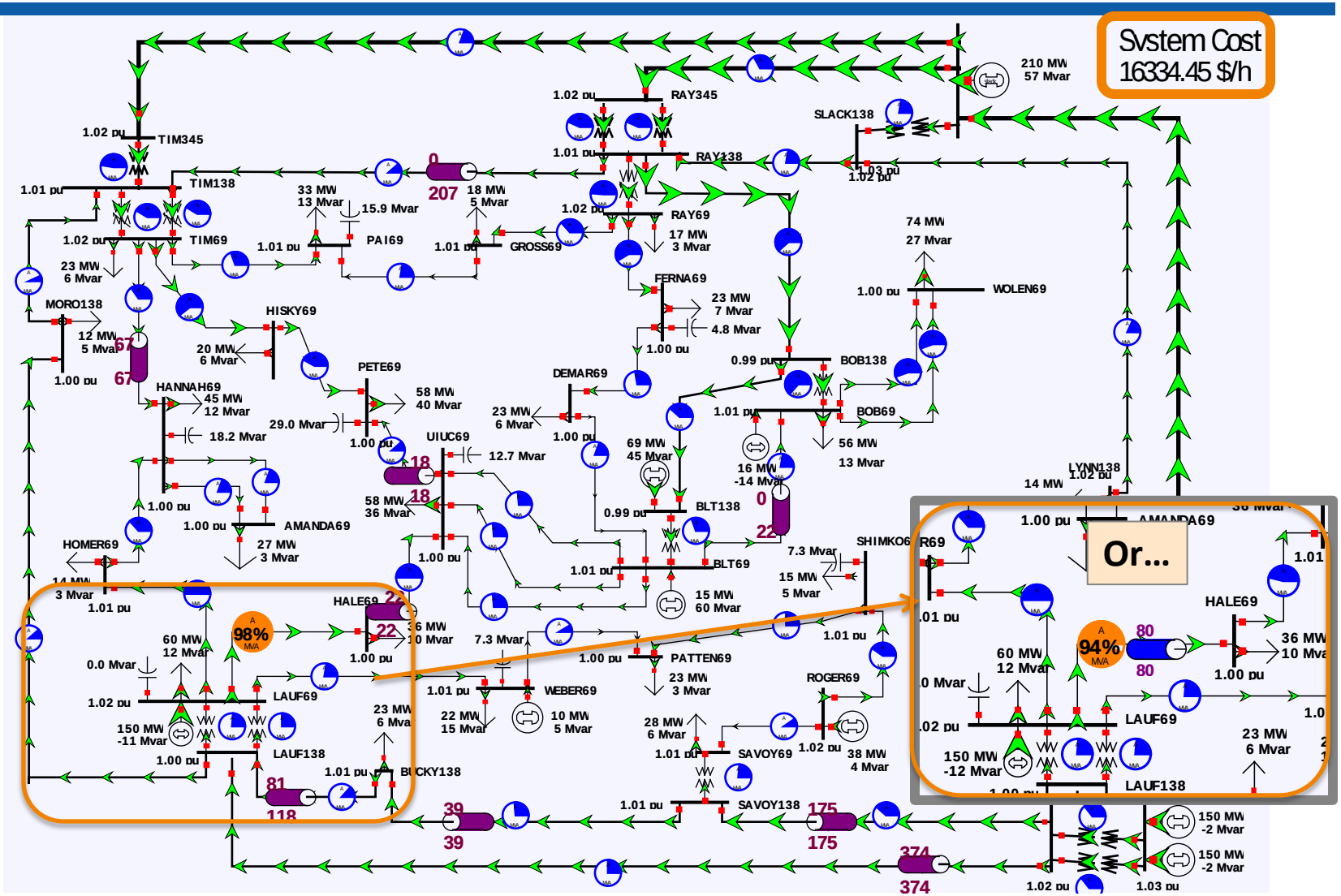
Example DSR Lines

DFACTSObject										
From Number	To Number	Circuit	X per Module (µH)	Auto Set I0	Auto Set Ilim	Auto Set Num Modules	I0 % of Rating	Ilim % of Rating	Max % of Line X	Num Modules
12	18	1	47	YES	YES	YES	90	100	30	67
15	16	1	47	YES	YES	YES	90	100	30	18
15	24	1	47	YES	YES	YES	90	100	30	22
32	29	1	47	YES	YES	YES	90	100	30	175
29	41	1	47	YES	YES	YES	90	100	30	374
30	32	1	47	YES	YES	YES	90	100	30	39
30	41	1	47	YES	YES	YES	90	100	30	118
39	40	1	47	YES	YES	YES	90	100	30	207
48	54	1	47	YES	YES	YES	90	100	30	22

b) OPF with DSR local control only



c) OPF with DSRs as Controls



GSO_37Bus_DSRsOPF_basecase

OPF Results – LP Solution Details

Model Explorer: LP Details

Explore | Fields

- Aggregations
  - Areas
  - Injection Groups
  - Interfaces
  - Islands
  - Multi-Section Lines
  - MW Transactions
  - Nomograms
  - Owners
  - Substations
  - Super Areas
  - Tielines between Areas
  - Tielines between Zones
  - Transfer Directions
  - Zones
- Solution Details
- Case Information and Auxiliary
- Optimal Power Flow
  - Bids
  - Reserve Requirements
  - Results
    - Bus Marginal Controls
    - Bus Mvar Price Details
    - Bus MW Price Details
    - LP Details
    - Reserve Results

OPF LP Solution Details | Areas | D-FACTS Devices | Transformer Controls | VSC DC Lines | Buse

Records Set Columns f(x)

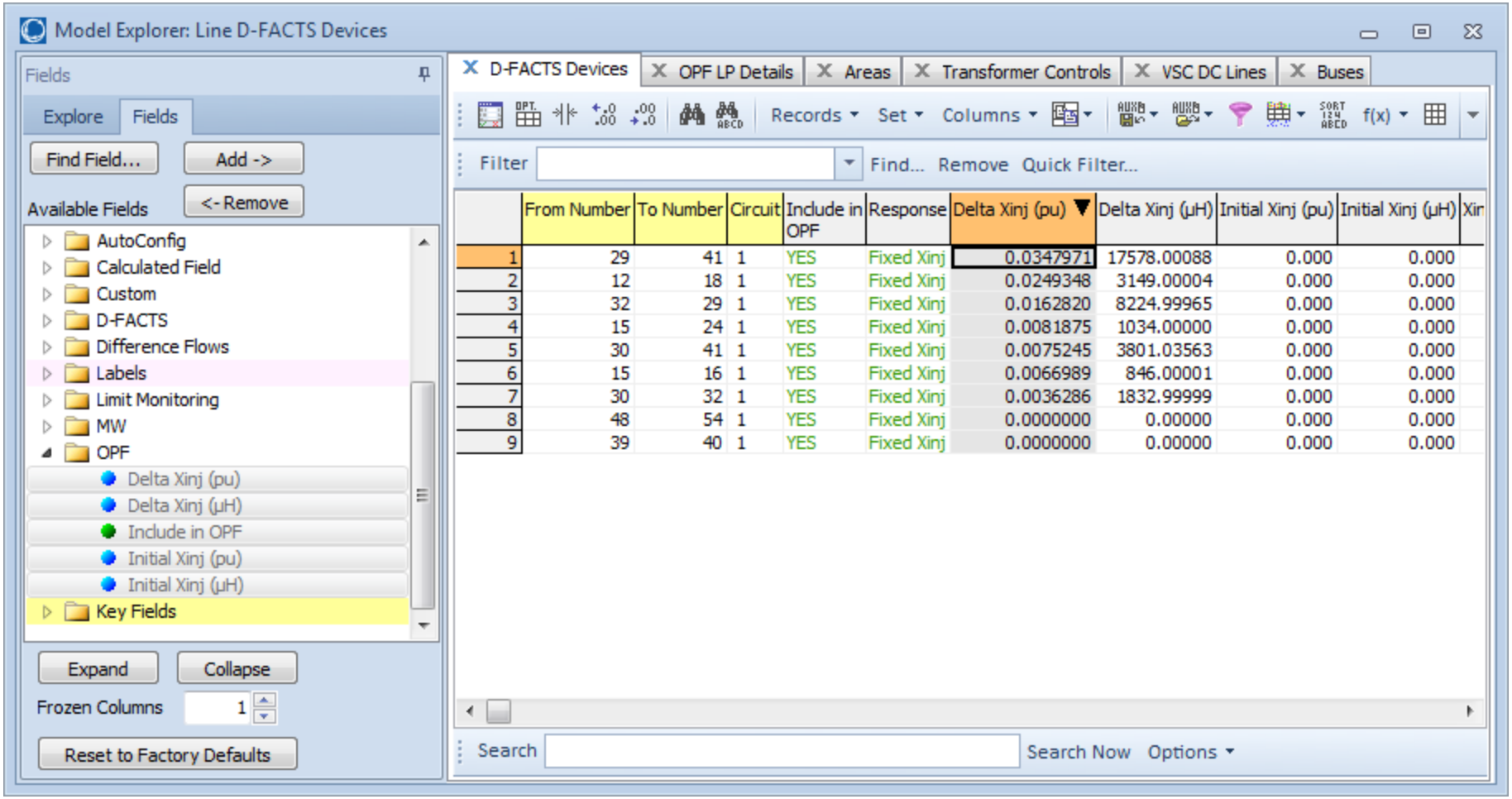
Filter Find... Remove Quick Filter...

All LP Variables | LP Basic Variables | LP Basis Matrix | Inverse of LP Basis | Trace Solution

	ID	Org. Value	Value	Delta Value	BasicVar	NonBasicVar
1	Gen 14 #1 MW Control	10.000	10.000	0.000	0	1
2	Gen 28 #1 MW Control	150.000	150.000	0.000	0	2
3	Gen 28 #2 MW Control	150.000	150.000	0.000	0	3
4	Gen 31 #1 MW Control	209.955	209.708	-0.247	1	0
5	Gen 48 #1 MW Control	16.000	16.000	0.000	0	5
6	Gen 50 #1 MW Control	38.000	38.000	0.000	0	6
7	Gen 53 #1 MW Control	69.200	69.200	0.000	0	7
8	Gen 54 #1 MW Control	15.000	15.000	0.000	0	15
9	DFACTS Control Line from 12	0.000	0.025	0.025	0	9
10	DFACTS Control Line from 15	0.000	0.007	0.007	0	10
11	DFACTS Control Line from 15	0.000	0.008	0.008	0	11
12	DFACTS Control Line from 32	0.000	0.016	0.016	0	12
13	DFACTS Control Line from 29	0.000	0.035	0.035	0	13
14	DFACTS Control Line from 30	0.000	0.004	0.004	0	14
15	DFACTS Control Line from 30	0.000	0.008	0.008	2	0
16	DFACTS Control Line from 39	0.000	0.000	0.000	0	16
17	DFACTS Control Line from 48	0.000	0.000	0.000	0	17
18	Slack-Area 1	0.000	0.000	0.000	0	4
19	Slack-Line 24 TO 44 CKT 1	-4.367	0.000	4.367	0	8

GSO_37Bus_DSRsOPF_basecase

OPF Case Information Displays



	From Number	To Number	Circuit	Include in OPF	Response	Delta Xinj (pu)	Delta Xinj (µH)	Initial Xinj (pu)	Initial Xinj (µH)
1	29	41	1	YES	Fixed Xinj	0.0347971	17578.00088	0.000	0.000
2	12	18	1	YES	Fixed Xinj	0.0249348	3149.00004	0.000	0.000
3	32	29	1	YES	Fixed Xinj	0.0162820	8224.99965	0.000	0.000
4	15	24	1	YES	Fixed Xinj	0.0081875	1034.00000	0.000	0.000
5	30	41	1	YES	Fixed Xinj	0.0075245	3801.03563	0.000	0.000
6	15	16	1	YES	Fixed Xinj	0.0066989	846.00001	0.000	0.000
7	30	32	1	YES	Fixed Xinj	0.0036286	1832.99999	0.000	0.000
8	48	54	1	YES	Fixed Xinj	0.0000000	0.00000	0.000	0.000
9	39	40	1	YES	Fixed Xinj	0.0000000	0.00000	0.000	0.000

GSO_37Bus_DSRsOPF_basecase

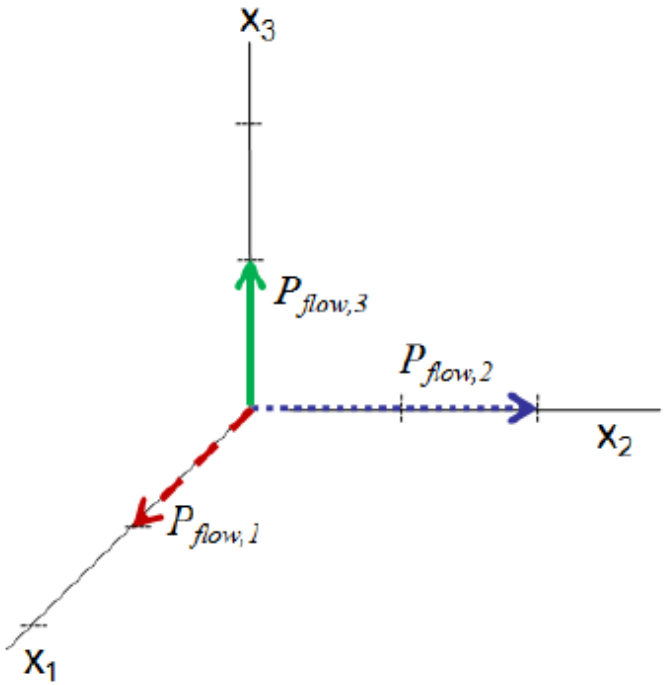
Special Features and Applications

General Power Flow Control

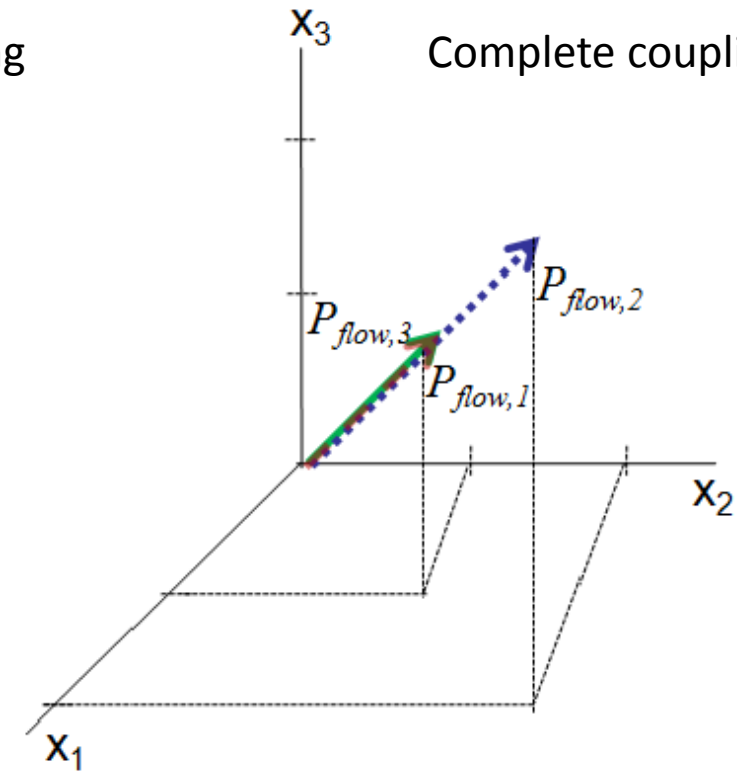
- Idea: D-FACTS devices in the system can respond to help each other obtain certain control objectives
- Find and exploit comprehensive power flow control capability – “power routing”
- Purpose is to enable
  - Automated D-FACTS placement and setup
  - Strategies for global D-FACTS control
- Exploit the fact that not all locations have equal impact

Device Placement and Independently Controllable Line Flows

Complete decoupling



Complete coupling



a.

$$\begin{array}{c} \\ P_{flow,1} \\ P_{flow,2} \\ P_{flow,3} \end{array} \begin{array}{c} \begin{array}{ccc} x_1 & x_2 & x_3 \end{array} \\ \begin{bmatrix} 1 & 0 & 0 \\ 0 & 2 & 0 \\ 0 & 0 & 1 \end{bmatrix} \end{array}$$

b.

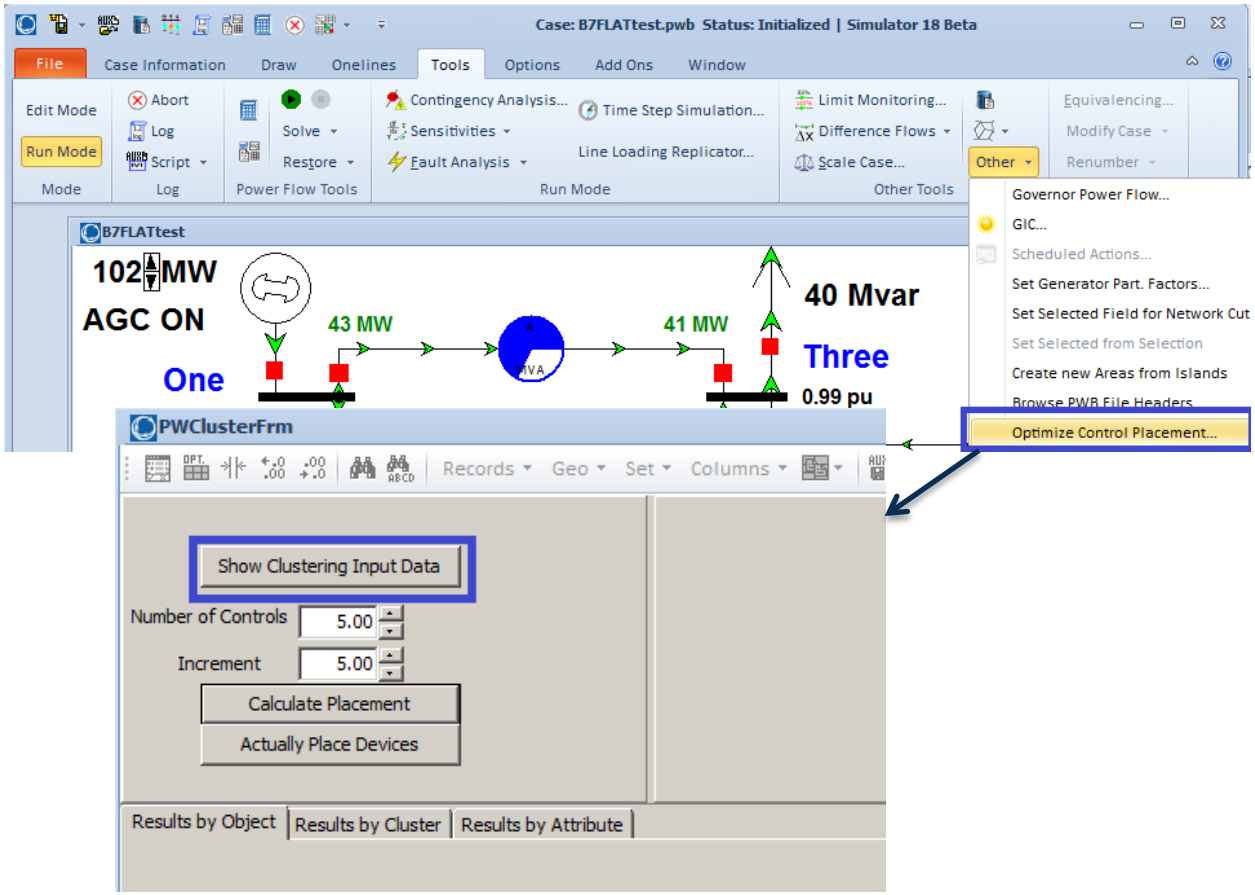
$$\begin{array}{c} \\ P_{flow,1} \\ P_{flow,2} \\ P_{flow,3} \end{array} \begin{array}{c} \begin{array}{ccc} x_1 & x_2 & x_3 \end{array} \\ \begin{bmatrix} 1 & 1 & 1 \\ 2 & 2 & 2 \\ 1 & 1 & 1 \end{bmatrix} \end{array}$$

Placement Tool Overview

- Developing a new generalized tool to make these power flow control concepts a reality
- Towards a longer-term outlook of what we want from D-FACTS devices (and other distributed control devices)
- Use clustering and device placement dialog to determine how to set the D-FACTS devices to achieve a generic, user-specified control objective
- This tool is still being developed
  - Working on completing the tool, user interface, testing
  - Preliminary tool in version 18 beta only
  - More details, analysis, and examples to come
  - Let us know your feedback! What would be useful?

Placement Dialog

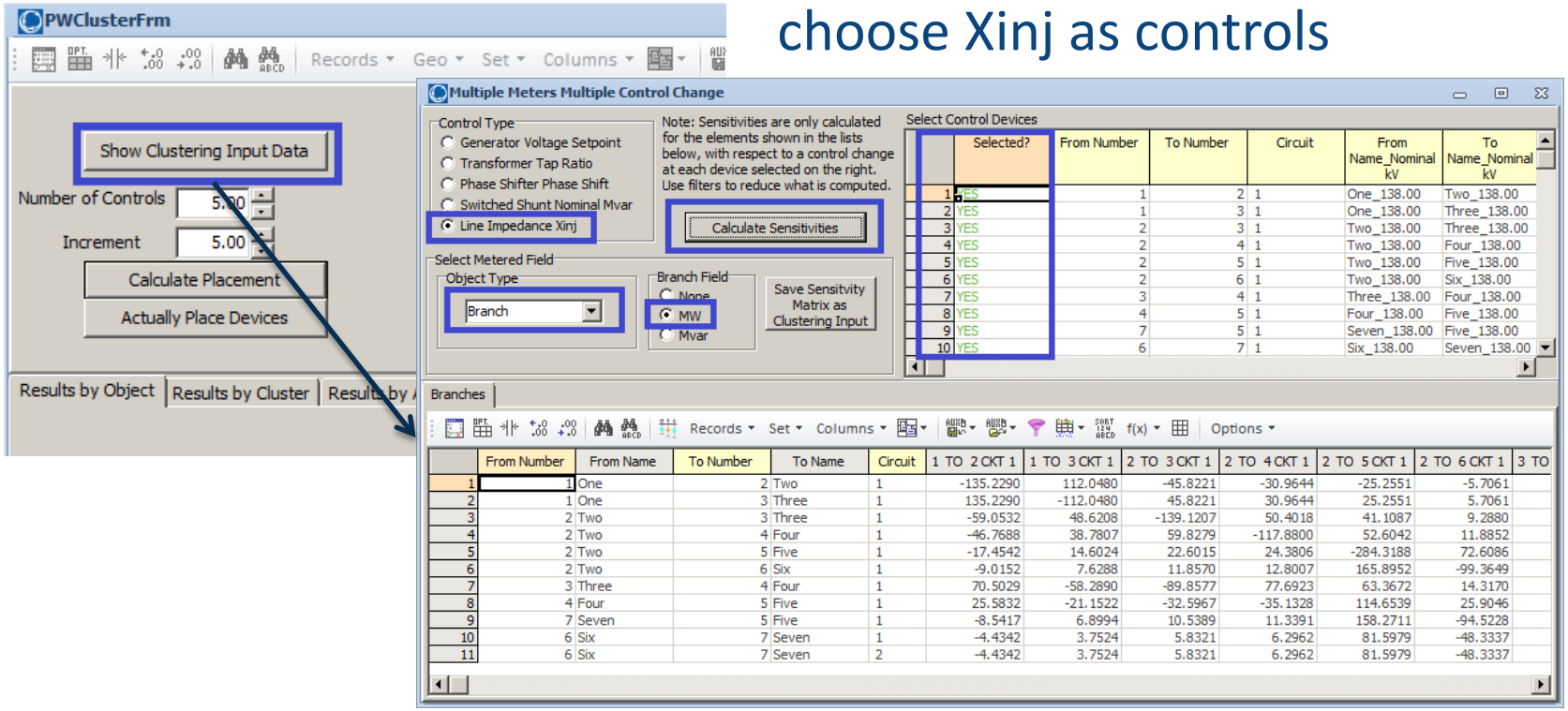
- Open new dialog



Select Input Data

- Select sensitivities

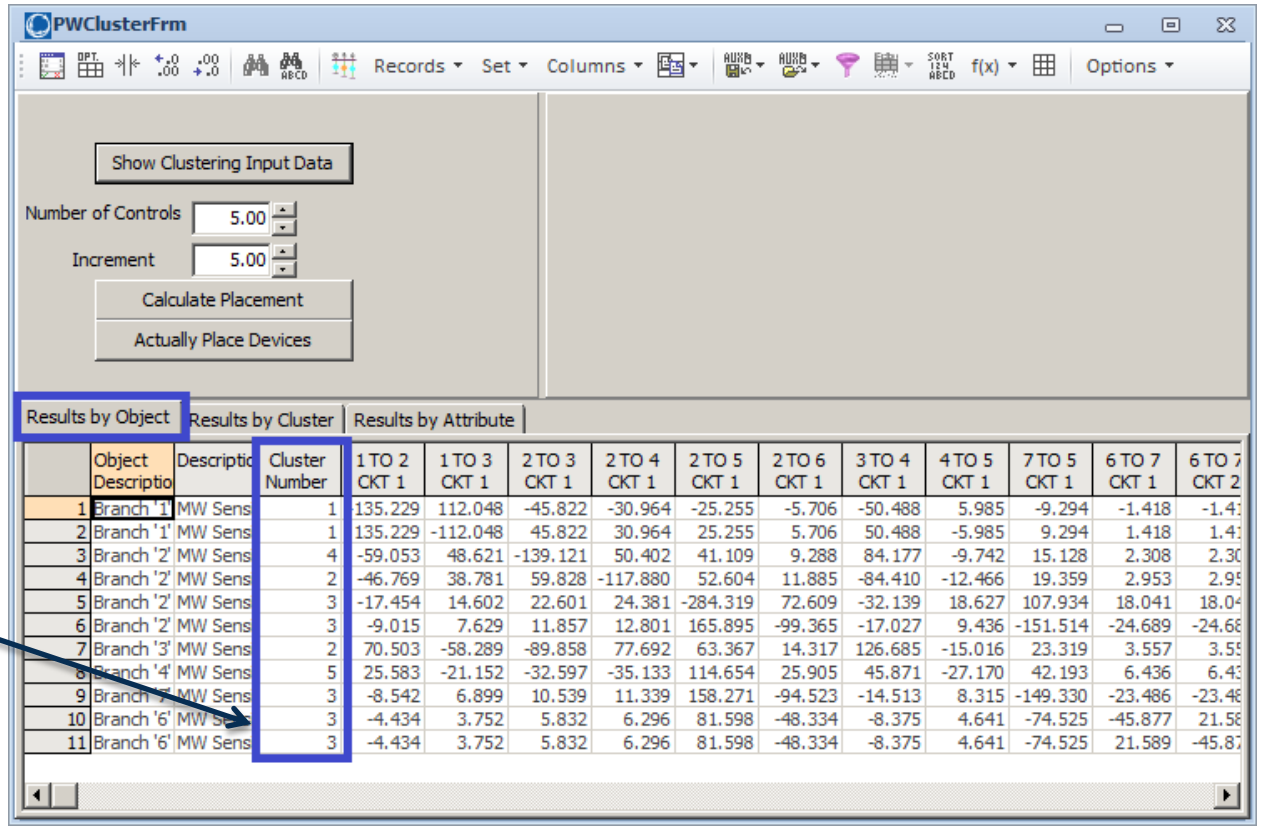
For DSRs, meter MW flows and choose Xinj as controls



- Save sensitivity matrix as clustering input

“Results by Object” Tab

- Shows input sensitivities and clustering results



	Object Descriptio	Descriptio	Cluster Number	1 TO 2 CKT 1	1 TO 3 CKT 1	2 TO 3 CKT 1	2 TO 4 CKT 1	2 TO 5 CKT 1	2 TO 6 CKT 1	3 TO 4 CKT 1	4 TO 5 CKT 1	7 TO 5 CKT 1	6 TO 7 CKT 1	6 TO 7 CKT 2
1	Branch '1'	MW Sens	1	135.229	112.048	-45.822	-30.964	-25.255	-5.706	-50.488	5.985	-9.294	-1.418	-1.4
2	Branch '1'	MW Sens	1	135.229	-112.048	45.822	30.964	25.255	5.706	50.488	-5.985	9.294	1.418	1.4
3	Branch '2'	MW Sens	4	-59.053	48.621	-139.121	50.402	41.109	9.288	84.177	-9.742	15.128	2.308	2.3
4	Branch '2'	MW Sens	2	-46.769	38.781	59.828	-117.880	52.604	11.885	-84.410	-12.466	19.359	2.953	2.9
5	Branch '2'	MW Sens	3	-17.454	14.602	22.601	24.381	-284.319	72.609	-32.139	18.627	107.934	18.041	18.0
6	Branch '2'	MW Sens	3	-9.015	7.629	11.857	12.801	165.895	-99.365	-17.027	9.436	-151.514	-24.689	-24.6
7	Branch '3'	MW Sens	2	70.503	-58.289	-89.858	77.692	63.367	14.317	126.685	-15.016	23.319	3.557	3.5
8	Branch '4'	MW Sens	5	25.583	-21.152	-32.597	-35.133	114.654	25.905	45.871	-27.170	42.193	6.436	6.4
9	Branch '6'	MW Sens	3	-8.542	6.899	10.539	11.339	158.271	-94.523	-14.513	8.315	-149.330	-23.486	-23.4
10	Branch '6'	MW Sens	3	-4.434	3.752	5.832	6.296	81.598	-48.334	-8.375	4.641	-74.525	-45.877	21.5
11	Branch '6'	MW Sens	3	-4.434	3.752	5.832	6.296	81.598	-48.334	-8.375	4.641	-74.525	21.589	-45.8

Line flow clusters

Device Grouping and Placement

- Clustering is used to determine groups
  - Line flows that can be independently controlled
  - Line flows that are highly coupled
  - D-FACTS lines with similar impact
  - D-FACTS lines with capabilities that span the space

[*]

$$cos\theta_{v_1 v_2} = \frac{\boldsymbol{v_1} \cdot \boldsymbol{v_2}}{\|\boldsymbol{v_1}\| \|\boldsymbol{v_2}\|}$$

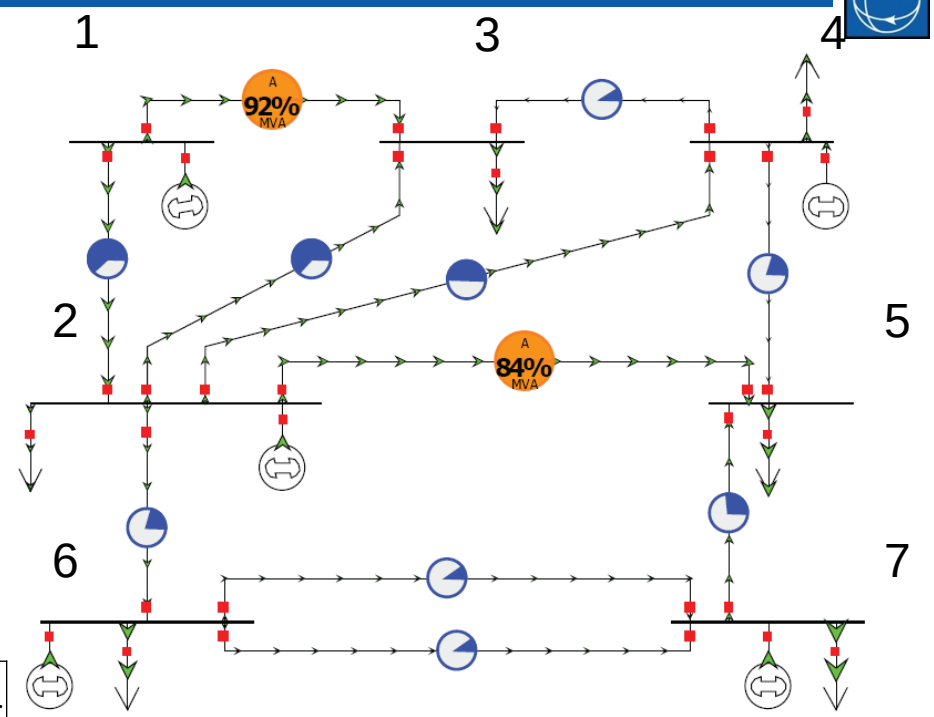
- User selects up to one prototype line per cluster to control since line flows within a group cannot be controlled independently

[*] Here, v_i denotes the row of the total sensitivity matrix of real power flows to reactive line impedance.

Flow Coupling Index

The line flows on the two overloaded lines are highly decoupled.

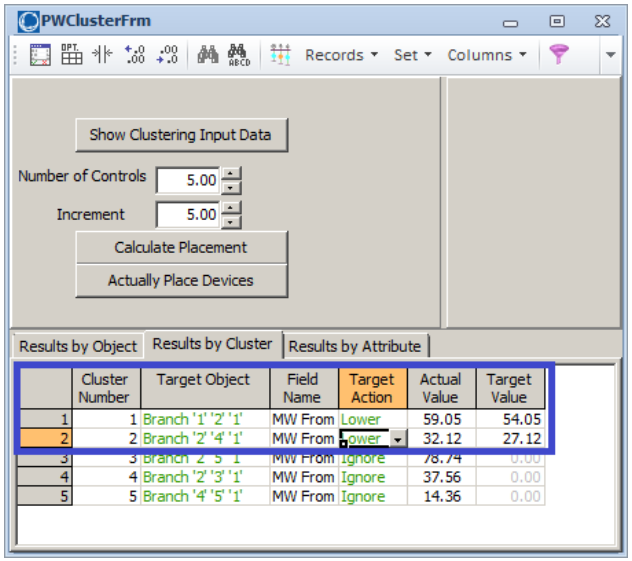
Thus, they can both be controlled independently with D-FACTS devices.



	(7,6)	(7,5)	(1,2)	(1,3)	(2,4)	(2,6)	(2,3)	(2,5)	(4,3)	(4,5)
(7,6)	1									
(7,5)	-1	1								
(1,2)	-0.014	0.014	1							
(1,3)	0.014	-0.014	-1	1						
(2,4)	-0.08	0.084	0.452	-0.45	1					
(2,6)	-1	1	0.0143	-0.014	0.083	1				
(2,3)	-0.077	0.076	0.59	-0.59	-0.19	0.076	1			
(2,5)	0.89	-0.886	0.14	-0.14	-0.19	-0.89	-0.12	1		
(4,3)	0.056	-0.056	0.63	-0.63	0.72	-0.056	-0.25	0.27	1	
(4,5)	-0.183	0.18	-0.313	0.31	0.26	0.18	0.12	-0.62	-0.49	1

“Results by Cluster” Tab

- Each row corresponds to one cluster



- Refine parameters for placement and optimization

Target Control Objective

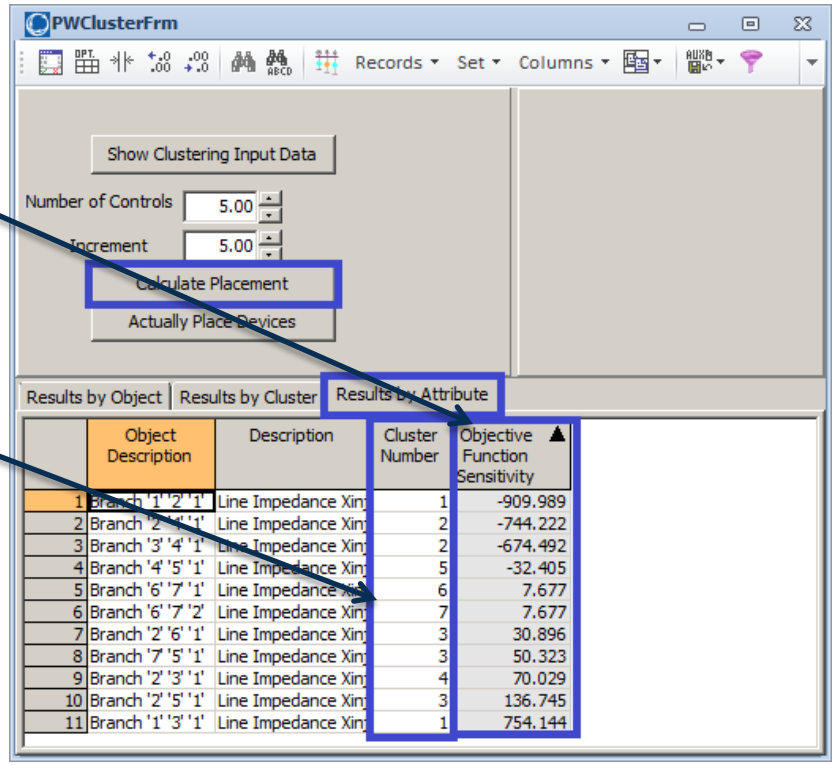
- Fields
  - Target Action – Raise, Lower, Don't Care, or Maximize Control
  - Actual Value – The present value of the line flow
  - Target Value – The desired value of the line flow
- Inputs
  - Number of Controls – max number of D-FACTS lines to consider
  - Increment – Amount by which to change all of the target values
- Tool determines D-FACTS groups and placement from control objective

“Results by Attribute” Tab

- For displaying information for “attributes” or columns (i.e., the D-FACTS lines)

Objective function sensitivity

Device clusters



“Actually Place Devices” inserts devices on the appropriate lines and sets Xinj values to achieve the control objective

Resulting Flows

- Newly inserted D-FACTS

D-FACTS Devices | Branches State | Buses

Records Set Columns f(x) Options

Filter Find... Remove Quick Filter...

	From Number	From Name	To Number	To Name	Circuit	Response	Auto Set I0	Auto Set Ilim	Auto Set Num Modules	X per Module (µH)	I0 % of Rating	Ilim % of Rating	Max % of Line X	Num Modules Used	Xinj (µH)	Num Modules
1	1	One	2	Two	1	Fixed Xinj	YES	YES	YES	47.00	97.00	100.00	30.00	193	9071.00	193
2	2	Two	4	Four	1	Fixed Xinj	YES	YES	YES	47.00	97.00	100.00	30.00	330	15501.41	580
3	3	Three	4	Four	1	Fixed Xinj	YES	YES	YES	47.00	97.00	100.00	30.00	96	4512.00	96
4	4	Four	5	Five	1	Fixed Xinj	YES	YES	YES	47.00	97.00	100.00	30.00	0	0.00	773

- New line flows on targeted lines

Line and Transformer Records | Buses

Records Geo Set Columns

Filter Advanced Branch Find... Remove

	From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar
1	1	One	2	Two	1	Closed	Line	NO	55.2492	
2	1	One	3	Three	1	Closed	Line	NO	46.1483	
3	2	Two	3	Three	1	Closed	Line	NO	38.4438	
4	2	Two	4	Four	1	Closed	Line	NO	27.3418	
5	2	Two	5	Five	1	Closed	Line	NO	78.7542	
6	2	Two	6	Six	1	Closed	Line	NO	40.0760	
7	3	Three	4	Four	1	Closed	Line	NO	-28.0255	

	Target	Before Control	After Control
1-2	54.06 MW	59.05 MW	55.25 MW
2-4	27.12 MW	32.12 MW	27.34 MW