

Distributed Flexible AC Transmission System (D-FACTS)



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Outline

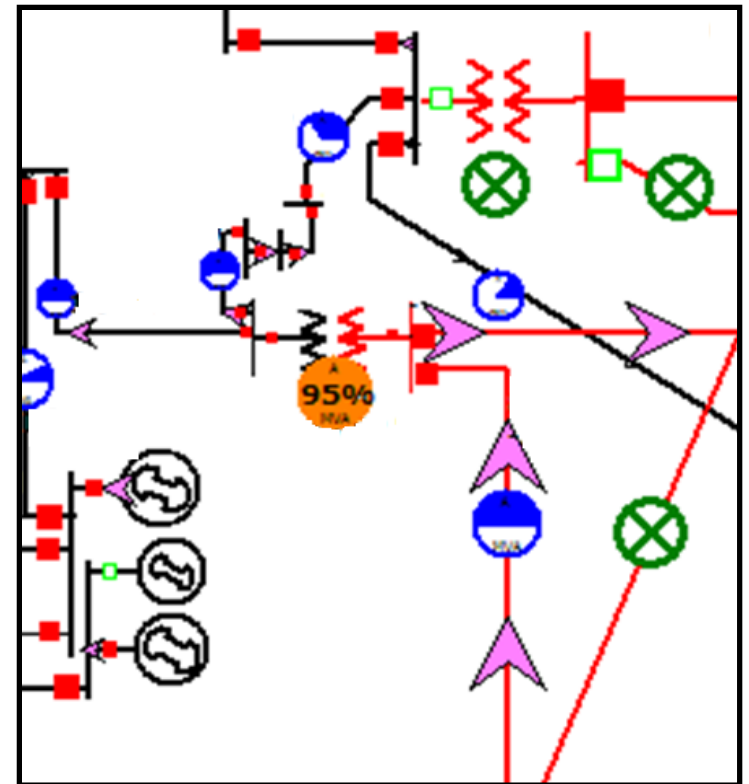


- Background
 - Power flow control
 - FACTS vs. D-FACTS
- PowerWorld D-FACTS Modeling
 - Stand alone operation
 - Line impedance sensitivities
 - Contingency analysis
- Continuing Work

Power Flow Control



- 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 voltages
 - Improve stability
 - Full utilization of existing system
- Limitations
 - Cost
 - Size and installation



Flexible AC Transmission Systems (FACTS) – IEEE Definitions



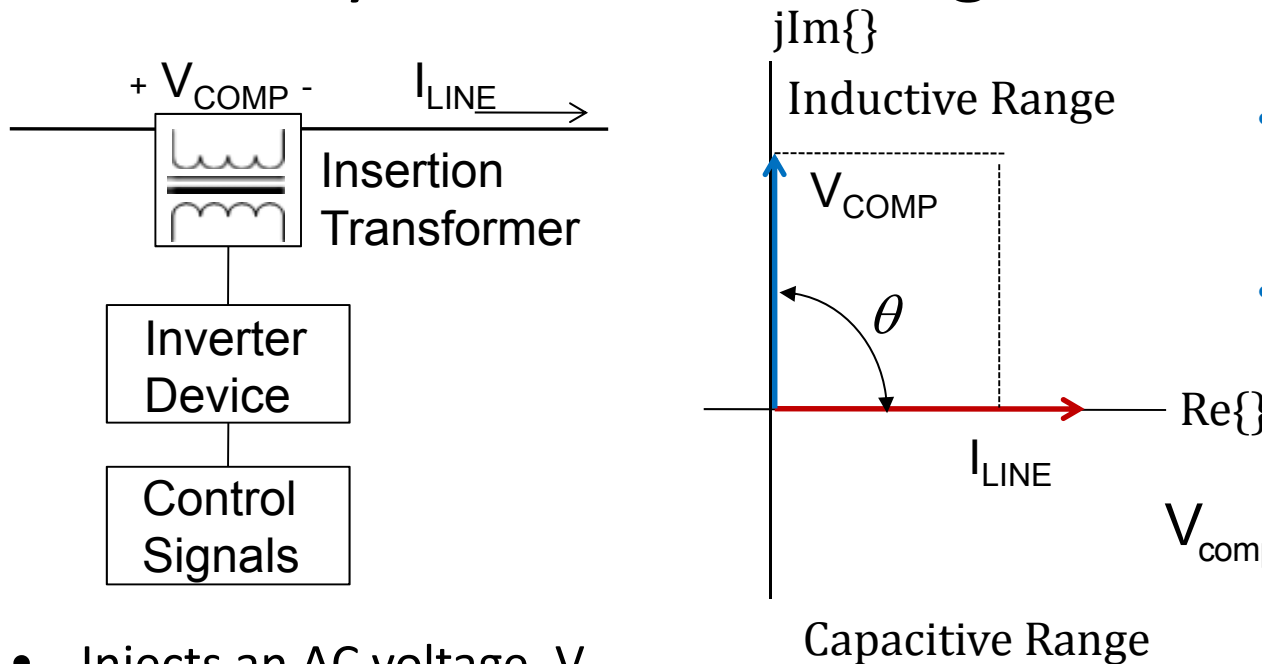
- Flexibility
 - ability to accommodate changes in the system or operating conditions without violating stability margins
- Flexible AC Transmission System
 - incorporates power electronics and other static controllers to enhance controllability and increase transfer capability
- FACTS Controller
 - 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 power source!

$$V_{comp} = I_{Line} Z$$

$$= -jI_{Line} X_c \text{ or } jI_{Line} X_L$$

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

FACTS Technologies



- Static Var Compensator (SVC)
 - Thyristor-controlled capacitors and reactors
 - Stability and voltage control
- Thyristor-Controlled Series Capacitors (TCSC) or Thyristor-Switched Series Capacitors (TSSC)
 - Thyristor-controlled capacitors and reactors
 - Capacitive or inductive compensation
- Static Synchronous Series Compensator (SSSC)
 - Uses a SVS
 - Capacitive or inductive compensation

FACTS Technologies

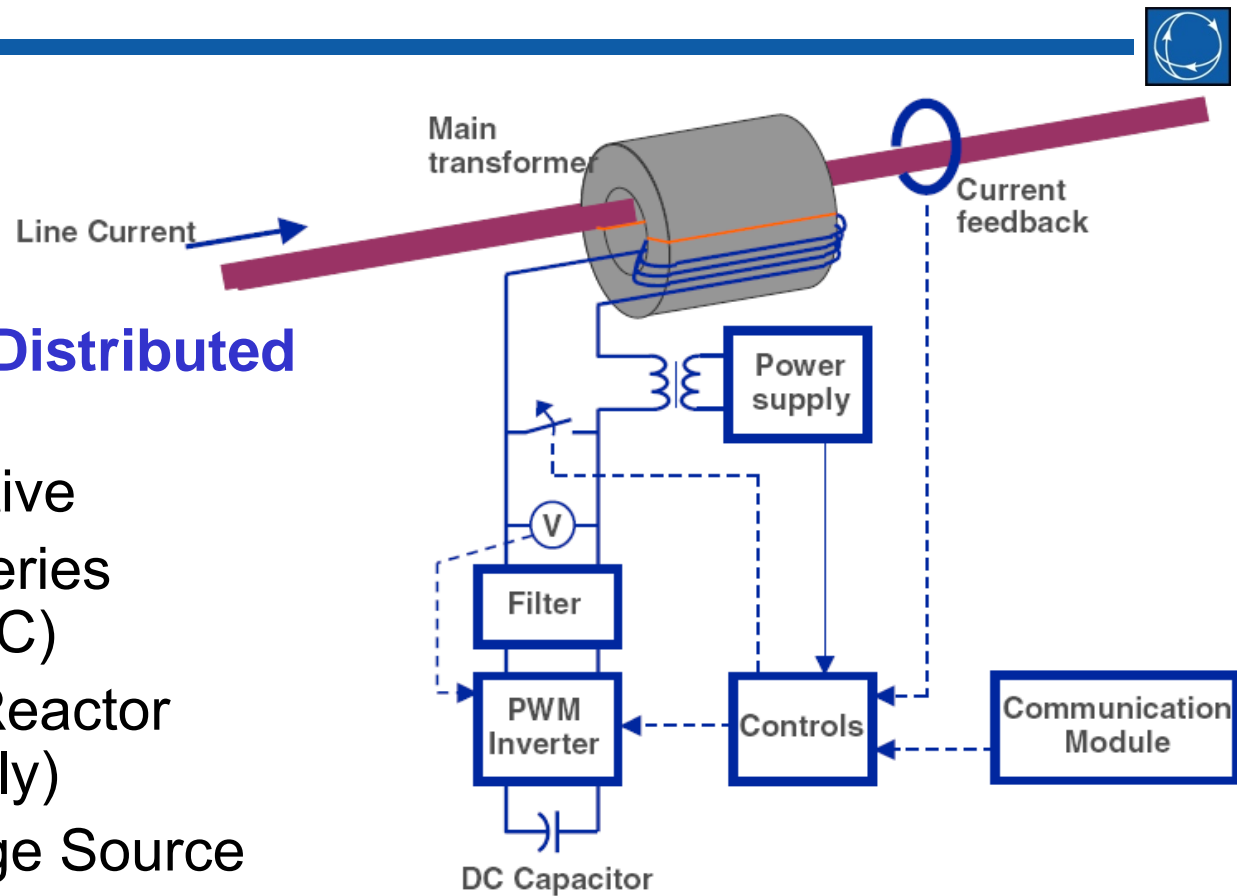


- Static Synchronous Compensator (STATCOM) or Static Synchronous Compensator (SSC)
 - Uses a SVS
 - Analogous to synchronous condensers
- Unified Power Flow Controller (UPFC)
 - Combination of STATCOM and SSSC
 - Control voltage and real and reactive power flows
- Variable Frequency Transformer (VFT)
 - Transfer power between asynchronous grids
 - First installation in Quebec, 2004
- And more...

D-FACTS Devices

Recently-Introduced 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.

How can D-FACTS Improve Operations



- Exploit the fact that not all locations have equal impact
- Determine the best locations for the applications of interest
- Then, determine D-FACTS settings to achieve the desired purpose
- Potential applications for D-FACTS include
 - reducing flow through overloaded lines
 - minimizing losses
 - minimizing cost

D-FACTS Technology



- Smart Wire Grid is currently building and deploying DSRs
- An ARPA-E project with Smart Wire Grid is in progress to implement D-FACTS devices in software and analyze their benefits to power systems

PowerWorld D-FACTS Support



- PowerWorld recently added implementation of the stand-alone functionality of D-FACTS devices, where the value of series reactive impedance X on the line is set as a function of the line current.
- This mode of operation for series-connected D-FACTS devices is described in [1] and [2].

[1] H. Johal and D. Divan, "Design considerations for series-connected distributed FACTS converters," *IEEE Transactions on Industry Applications*, vol. 43, no. 6, pp. 1609-1618, Nov./Dec. 2007.

[2] H. Johal and D. Divan, "Current limiting conductors: A distributed approach for increasing T&D system capacity and enhancing reliability," in *2005/2006 IEEE PES Transmission and Distribution Conference and Exhibition*, pp.1127-1133, May 2006.

D-FACTS Model Inputs



- For each line with D-FACTS devices, the user enters the **number of modules** and the **reactive impedance per module**
- The user also specifies values of line current magnitude I_0 and I_{lim}
 - Below I_0 , the D-FACTS devices are inactive
 - Above I_{lim} , the cumulative impedance injection of the D-FACTS devices on the line is at its maximum value

Inserting D-FACTS



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

Branch Options

Line: From Bus: To Bus: Circuit: 1

Number: 63 Name: Tidd Area Name: IEEE11 (1) Nominal kV: 138.0

To Bus: 64 Kammer IEEE11 (1) 138.0

Find By Numbers Find By Names Find ... From End Metered Default Owner (Same as From Bus)

Labels ... no labels

Display Parameters Fault Info Owner, Area, Zone, Sub Custom Stability

Status: Open Closed

Branch Device Type: Line

Allow Consolidation:

Length: 0.00

Calculate Impedances >

Convert Line to Transformer

D-FACTS Devices on the Line

Per Unit Impedance Parameters

Series Resistance (R)	0.001720
Series Reactance (X)	0.020000
Shunt Charging (B)	0.216000
Shunt Conductance (G)	0.000000

Has Line Shunts: Line Shunts

MVA Limits

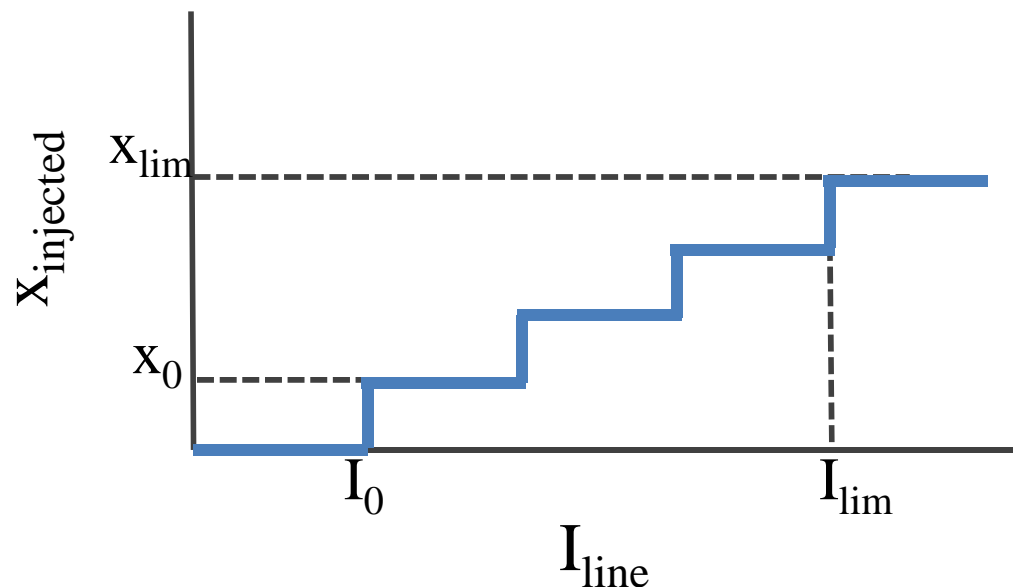
Limit A	350.000
Limit B	0.000
Limit C	0.000
Limit D	0.000
Limit E	0.000
Limit F	0.000
Limit G	0.000
Limit H	0.000

OK Save Cancel Help

D-FACTS Operational Profile



- A piecewise linear function of the form shown below is created and used internally based on the entered information



D-FACTS Dialog



Auto-configuration settings

Basic settings

Current operating point

The screenshot displays the D-FACTS dialog box with two main sections: 'Auto-configuration settings' and 'Basic settings'. The 'Auto-configuration settings' section includes a 'Calculated Values' table and an 'Auto Configure' tab with parameters for Max Compensation, Set I0, and Set Ilim. The 'Basic settings' section includes a 'Direct Input of Characteristic Curve Parameters' section with fields for Num D-FACTS Modules, Inductance per Module, Activation Current I0, and Max Current Imax, along with a 'Mode of Operation' section with radio buttons for 'Respond based on current', 'Use fixed Xinj', and 'Bypass (Xinj = 0)'. A 'D-FACTS Profile' graph shows 'Injected X' vs 'Line Current Magnitude' with a vertical line at approximately 725 A. A legend at the bottom identifies the profile as 'HARFRD5A (6105) TO PERRYMAN (6107) CKT 1'.

Calculated Values	
Num D-FACTS Modules	43
Total Available X	2021 μH
Present Value of Xinj	2021 μH
I0	725.6037014728 A
Ilim	748.045053064 A
Present Value of Iline	751.770246702 A

Auto Configure Characteristic Curve Parameters	
<input checked="" type="checkbox"/> Max Compensation	30.00 % of Line X
<input checked="" type="checkbox"/> Set I0 as	97.00 % of Rating
<input checked="" type="checkbox"/> Set Ilim as	100.00 % of Rating

Direct Input of Characteristic Curve Parameters	
Num D-FACTS Modules	43
Inductance per Module	47.00000000 μH
Activation Current I0	725.60 A
Max Current Imax	748.05 A

Mode of Operation:

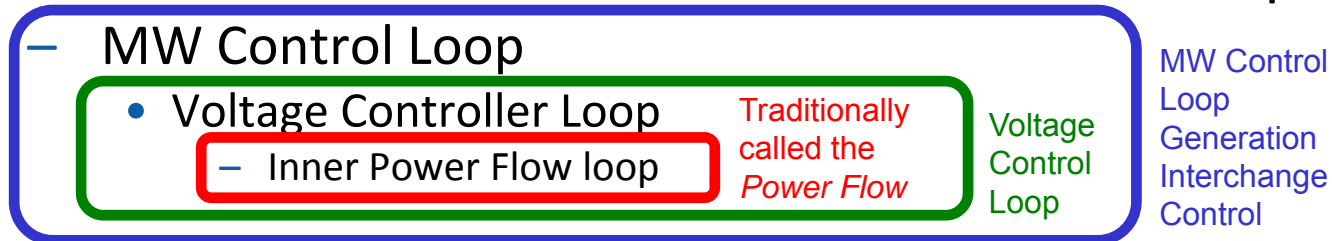
- Respond based on current
- Use fixed Xinj
- Bypass (Xinj = 0)

Legend: HARFRD5A (6105) TO PERRYMAN (6107) CKT 1

Power Flow Support



- Simulation Solution Process: Three Nested Loops



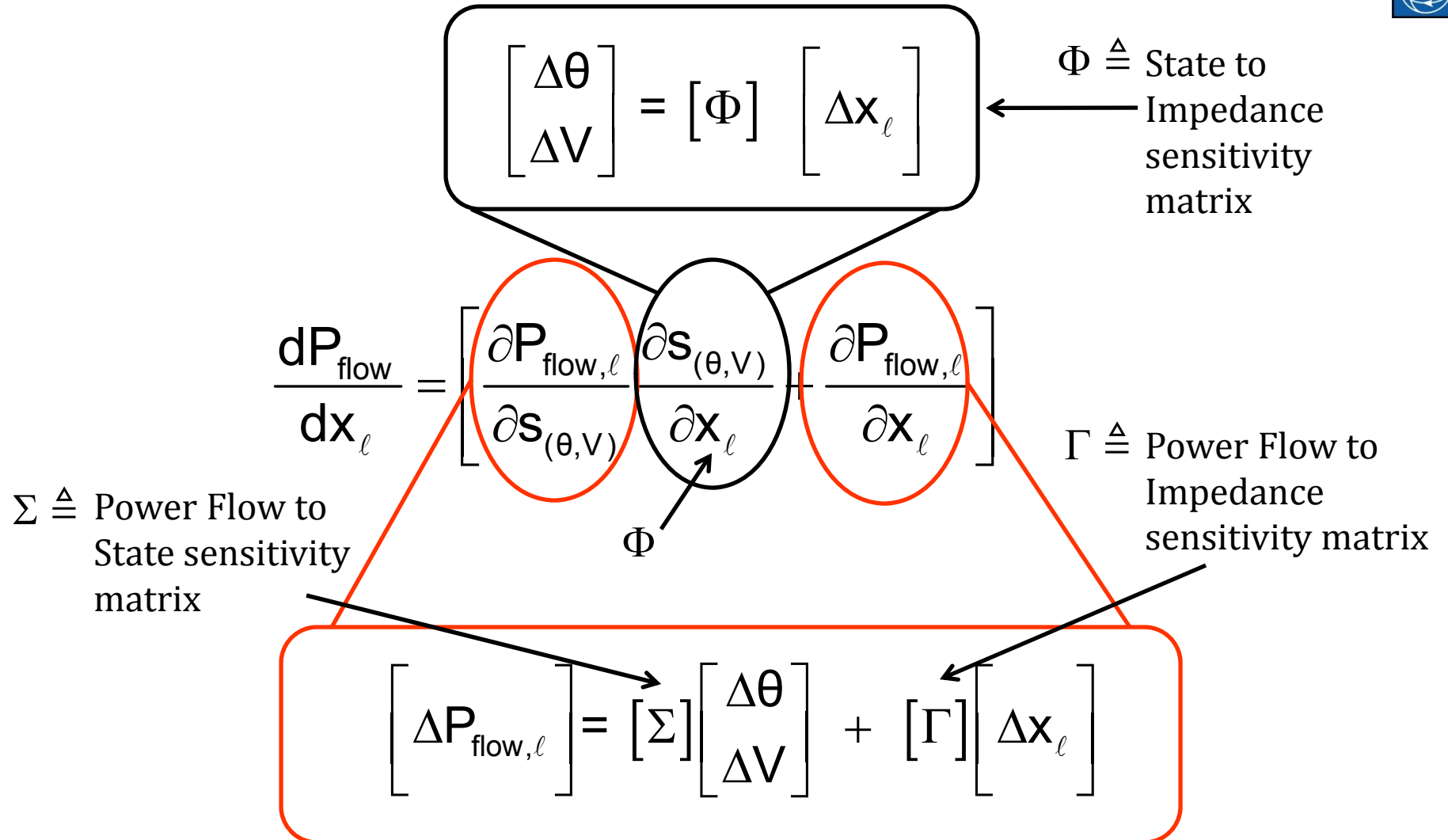
- PowerWorld Simulator implements the control of D-FACTS devices in the voltage control loop of the power flow solution.
- That is, after the inner power flow loop is solved to determine the state variables, the line current is calculated, and the D-FACTS values are adjusted according to their predefined piecewise linear lookup functions, if necessary.
- If the D-FACTS values are changed, an additional power flow inner loop is solved.

Line Impedance Sensitivities



- 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



Single Control Change



Line Flow/Interface/Bus Sensitivities

Single Meter, Multiple Transfers | Single Transfer, Multiple Meters | Self Sensitivity | Multiple Meters, Single Control Change | Multipl

Control Type

- Generator Voltage Setpoint
- Transformer Tap Ratio
- Phase Shifter Phase Shift
- Switched Shunt Nominal Mvar
- Line Impedance Xinj

Sort by Name Number

Search For Near Bus

1 (One) [138 kV]
2 (Two) [138 kV]
3 (Three) [138 kV]
4 (Four) [138 kV]
5 (Five) [138 kV]
6 (Six) [138 kV]
7 (Seven) [138 kV]

Select Far Bus, CKT

1 (One) [138 kV] CKT 1
2 (Two) [138 kV] CKT 1
4 (Four) [138 kV] CKT 1

Calculate Sensitivities

Records Geo Set Columns

Buses Generators Branches Interfaces

	From Number	From Name	To Number	To Name	Circuit	Branch Device Type	dP/dControl	dQ/dControl
1	1	One	2	Two	1	Line	112.04796600	-33.32395172
2	1	One	3	Three	1	Line	-112.04797363	-4.23593855
3	2	Two	3	Three	1	Line	48.62076187	-7.30688715
4	2	Two	4	Four	1	Line	38.78074646	-10.88691521
5	2	Two	5	Five	1	Line	14.60239887	-3.30750036
6	2	Two	6	Six	1	Line	7.62883997	-2.33606482
7	3	Three	4	Four	1	Line	-58.28896713	-14.26168251
8	4	Four	5	Five	1	Line	-21.15219307	6.20461607
9	7	Seven	5	Five	1	Line	6.89942408	-1.84581923
10	6	Six	7	Seven	1	Line	3.75235510	-1.04953587
11	6	Six	7	Seven	2	Line	3.75235510	-1.04953587

Close

New control to calculate Xinj sensitivities for DSR placement

Multiple Control Change



Line Flow/Interface/Bus Sensitivities

Single Meter, Multiple Transfers | Single Transfer, Multiple Meters | Self Sensitivity | **Multiple Meters, Single Control Change** | Branch Selection

Control Type

- Generator Voltage Setpoint
- Transformer Tap Ratio
- Phase Shifter Phase Shift
- Switched Shunt Nominal Mvar
- Line Impedance Xinj

Note: Sensitivities are only calculated for the elements shown in the lists below, with respect to a control change at each device selected on the right. Use filters to reduce what is computed.

Calculate Sensitivities

Select Metered Fields

Bus Field: None, Voltage, Angle, Mvar

Generator Field: None, Mvar

Branch Field: None, MW, Mvar

Interface Field: None, MW, Mvar

Select Control Devices

	Selected?	From Number	To Number	Circuit	From Name_Nominal kV	To Name_Nominal kV	Circuit
1	YES	1	2	1	One_138.00	Two_138.00	1
2	YES	1	3	1	One_138.00	Three_138.00	1
3	YES	2	3	1	Two_138.00	Three_138.00	1
4	YES	2	4	1	Two_138.00	Four_138.00	1
5	YES	2	5	1	Two_138.00	Five_138.00	1
6	YES	2	6	1	Two_138.00	Six_138.00	1
7	YES	3	4	1	Three_138.00	Four_138.00	1
8	YES	4	5	1	Four_138.00	Five_138.00	1
9	YES	7	5	1	Seven_138.00	Five_138.00	1
10	YES	6	7	1	Six_138.00	Seven_138.00	1
11	YES	6	7	2	Six_138.00	Seven_138.00	2

Records | Geo | Set | Columns | Options

Buses | Generators | Branches | Interfaces

	From Number	From Name	To Number	To Name	Circuit	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
1	1	One	2	Two	1	-135.2290	112.0480	-45.8221	-30.9644	-25.2551	-5.7061	-50.4882	
2	1	One	3	Three	1	135.2290	-112.0480	45.8221	30.9644	25.2551	5.7061	50.4882	
3	2	Two	3	Three	1	-59.0532	48.6208	-139.1207	50.4018	41.1087	9.2880	84.1769	
4	2	Two	4	Four	1	-46.7688	38.7807	59.8279	-117.8800	52.6042	11.8852	-84.4101	
5	2	Two	5	Five	1	-17.4542	14.6024	22.6015	24.3806	-284.3188	72.6086	-32.1394	
6	2	Two	6	Six	1	-9.0152	7.6288	11.8570	12.8007	165.8952	-99.3649	-17.0273	
7	3	Three	4	Four	1	70.5029	-58.2890	-89.8577	77.6923	63.3672	14.3170	126.6852	
8	4	Four	5	Five	1	25.5832	-21.1522	-32.5967	-35.1328	114.6539	25.9046	45.8707	
9	7	Seven	5	Five	1	-8.5417	6.8994	10.5389	11.3391	158.2711	-94.5228	-14.5125	
10	6	Six	7	Seven	1	-4.4342	3.7524	5.8321	6.2962	81.5979	-48.3337	-8.3751	
11	6	Six	7	Seven	2	-4.4342	3.7524	5.8321	6.2962	81.5979	-48.3337	-8.3751	

Close

Contingency Analysis Results Monitoring



Use custom monitors to monitor D-FACTS response

Automatically limit what gets reported



Contingency Violation Matrices



Contingency Violation Matrices

Process Contingency Results

Process Contingency results will go through the existing contingency analysis tool results and build tables showing the limit violation values for all violated lines and interfaces.

Processing Options

- Process Branches
- Process Buses
- Process Interfaces
- Process Custom Monitors

Values To Process

- Percentage
- Actual Flow

View DSR contingency results

Records Geo Set Columns f(x) Options

Contingencies	Branches	Buses	Interfaces	Custom Monitors			
	Contingency	D-FACTS Response Branch '2871' '2878' '1'	D-FACTS Response Branch '2876' '2878' '1'	D-FACTS Respor Branch '14284' '14344' '1'	D-FACTS Response Branch '14298' '14349' '1'	D-FACTS Response Branch '14344' '14349' '1'	D-FACTS Resp Branch '1407' '14074' '1'
1	205&2003			1457.00	470.00	1457.00	
2	2002&2003			1457.00			
3	PS15	1128.00	1457.00				
4	24JC	1128.00	1457.00				
5	37PS_A	1128.00	1457.00				
6	PS44B	1128.00	1457.00				
7	PS56B	564.00	752.00				
8	110615						
9	23JC	517.00	658.00				
10	PP37						
11	110517						
12	TR84 WAYNE_R-N						
13	TR83 DRESD_R-10F2-S						
14	73C	705.00	893.00				
15	110543						
16	AEP_TOWER65						
17	110518						
18	TR83_ELMHU_B-N						
19	TR83_SILVE_R-R						
20	COMED-GEN-57						
21	COMED-GEN-19						
22	CKT22074						
23	TR84_BLOOM_B-S						

View by contingency or by custom monitor

New tab showing DSR results

Process Contingency Results

Process Contingency results will go through the existing contingency analysis tool results and build tables showing the limit violation values for all violated lines and interfaces.

Processing Options

- Process Branches
- Process Buses
- Process Interfaces
- Process Custom Monitors

Values To Process

- Percentage
- Actual Flow

Records Geo Set Columns f(x) Options

Contingencies	Branches	Buses	Interfaces	Custom Monitors		
				Custom Monitor	1231_B3	5059_B3
1	CustomMonitor 'Num D-FACTS Change' on Branch '22998' '23018' '1'				50.00	
2	CustomMonitor 'D-FACTS Response' on Branch '22998' '23018' '1'				2.35	
3	CustomMonitor 'D-FACTS Response' on Branch '23243' '23295' '1'				0.00	0.00
4	CustomMonitor 'Num D-FACTS Change' on Branch '20459' '20481' '2'					
5	CustomMonitor 'D-FACTS Response' on Branch '23210' '23256' '1'					
6	CustomMonitor 'D-FACTS Response' on Branch '6020' '6199' '1'					
7	CustomMonitor 'D-FACTS Response' on Branch '1871' '1878' '1'					

Summary



- With the introduction of D-FACTS devices into operational systems, PowerWorld wants to make it possible to model their behavior in the system
- PowerWorld is taking the first steps to address this need by
 - Added D-FACTS device objects into the software
 - Implemented D-FACTS device in the power flow
 - Added feature to make custom monitoring in contingency analysis useful
 - Also working with Smart Wire Grid and DOE ARPA-E to implement D-FACTS in the OPF solution algorithm
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