Steady-State Power System Security Analysis with PowerWorld Simulator

S6: Voltage Stability Using PV Curves

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Voltage Stability Concepts

- Voltage stability is the ability of a power system to maintain acceptable voltage at all buses under normal operating conditions and after being subjected to a contingency
- Voltage stability is a local phenomenon, but its consequences may have a widespread impact
  - A local voltage collapse can and does lead to a widespread collapse of the power system

Voltage Stability Studies

- Characteristics of interest are the relationships between transmitted power (P), receiving end voltage (V), and reactive power injection (Q)
- Traditional forms of displaying these relationships are PV and QV curves obtained through steady-state analysis
- V-Q sensitivities can also be used as indicators of voltage stability

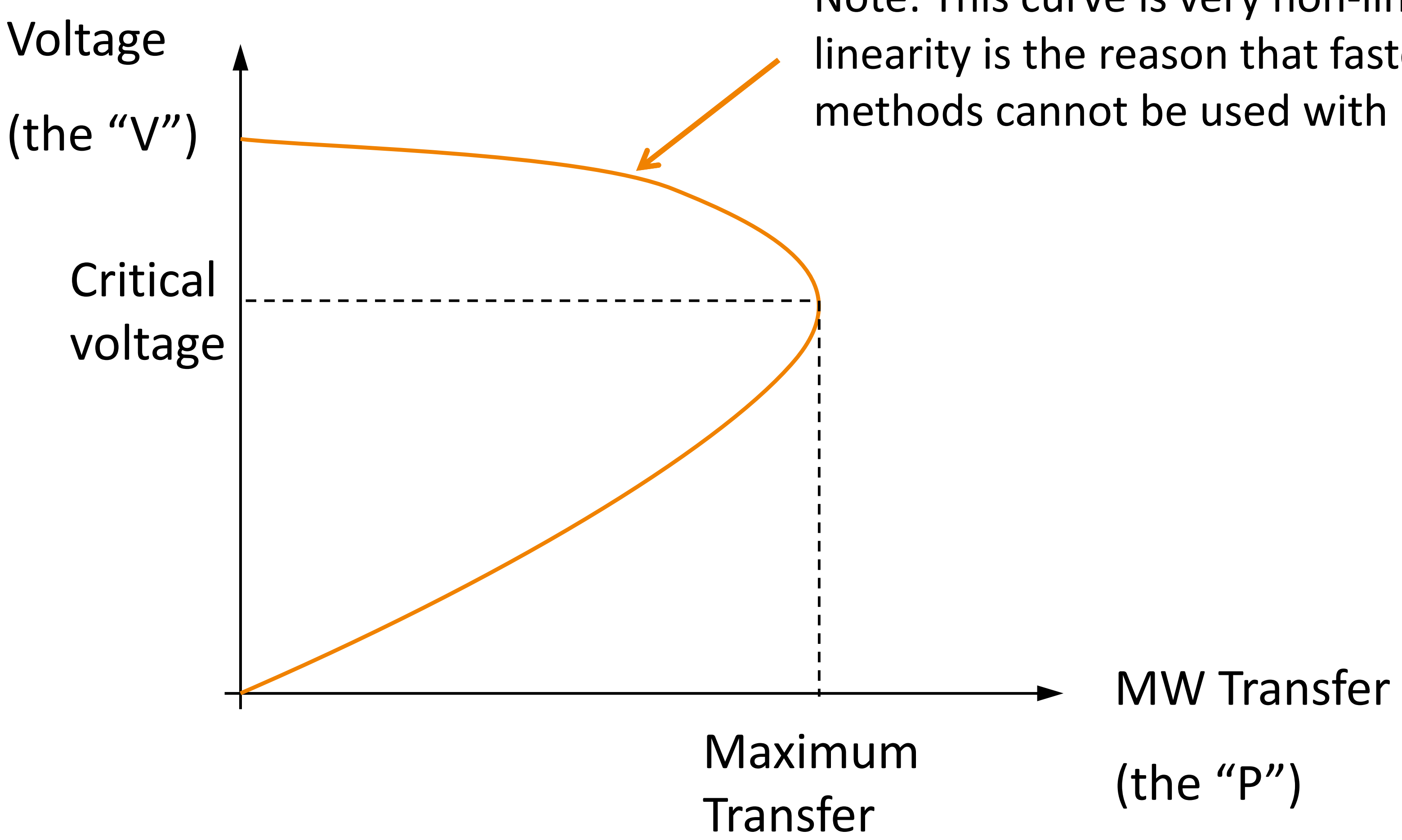
PV Study

- The "PV" (Power-Voltage) analysis process involves using a series of power flow solutions for increasing transfers of MW and monitoring what happens to system voltages as a result
- Relationship of voltage to MW transfer is non-linear, which requires the full power flow solutions

PV Study

- Traditionally, MW transfer is designed to model increasing load in a part of the system
- Specific buses must be selected for monitoring and PV curves are plotted for each bus

Typical PV Curve Plot



Note: This curve is very non-linear. This non-linearity is the reason that faster linear sensitivity methods cannot be used with PV curve analysis.

PV Curve Results

- At the “knee” of the PV curve, voltage drops rapidly with an increase in MW transfer
- The power flow solution fails to converge beyond this limit, which is indicative of instability
  - You may remember the term “Maximum Power Transfer” from electrical engineering courses. This is the same topic.
- Operation at or near the stability limit risks a large-scale blackout
  - A satisfactory operating condition is ensured by allowing sufficient “power margin”

PV Curve Example

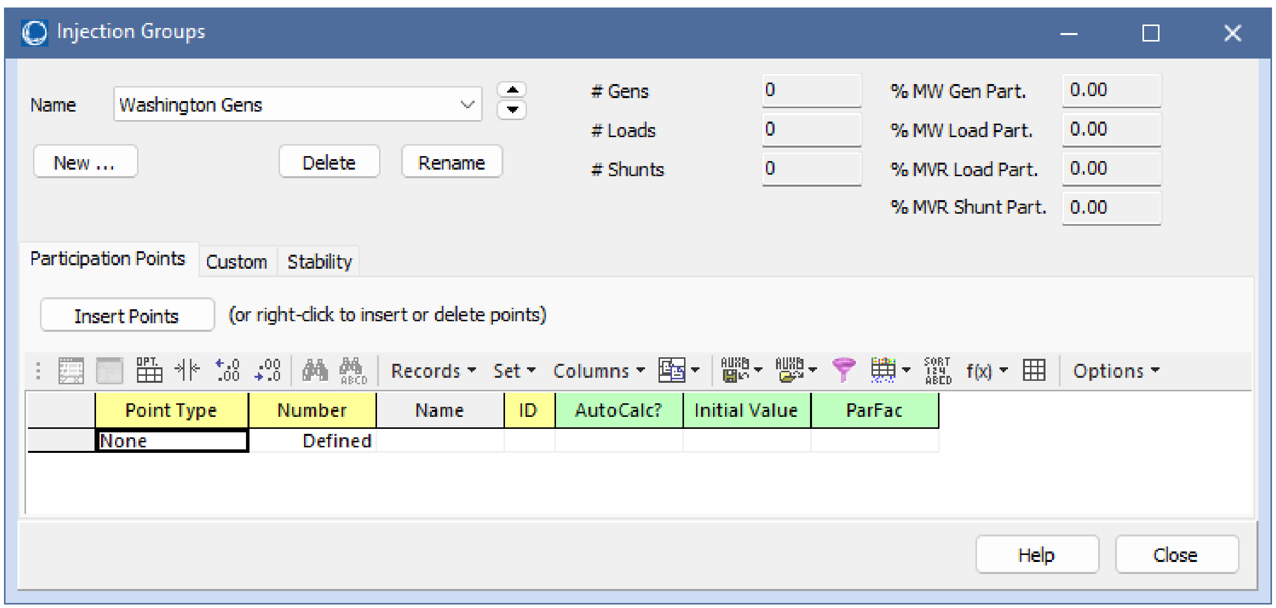
- Use the Synthetic 10,000 bus example
  - *ACTIVSg10k.pwb*
  - *ACTIVSg10k PV Injection Groups.aux*
  - *ACTIVSg10k PV Options.aux*
  - *KlamathFallsCTG.aux*
- We will study a transfer of power from generators in Washington State to an increasing Southern California load
- First step - define an injection group containing WA generators to serve as the source

Injection Groups

- *Injection Groups* in Simulator PVQV define which region or regions will import the transfer and which region or regions will supply it
- These are discussed in section I5: Data Aggregation
- The groups will act in unison to implement a power transfer
- One side is the source - the other is the sink

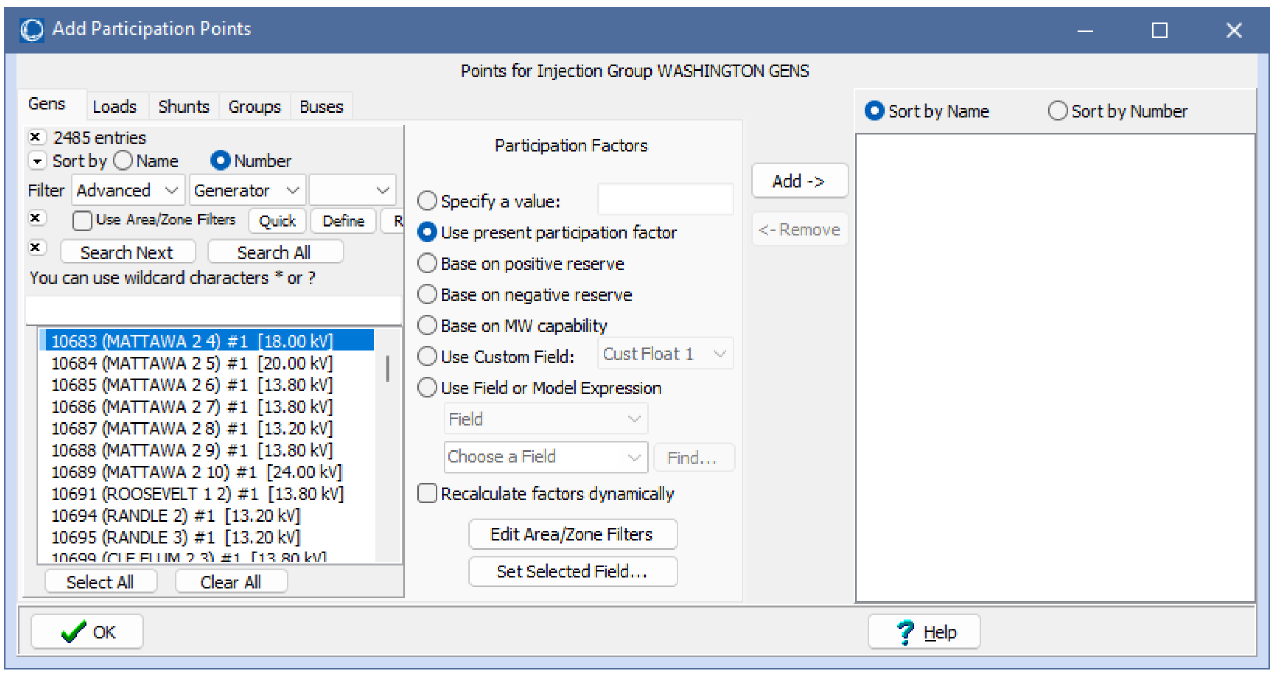
Defining Injection Groups

- Select **Aggregations → Injection Groups** from the Model Explorer
- Presently reads *None Defined*. Right click and select **Insert** from the local menu.
- Provide Group name *Washington Gens*
- This opens the following display



Defining Participation Points

- Now add the points of injection to the group
- To do this, click **Insert Points** or choose **Records → Insert** on the Participation Points list
- This opens the dialog below



Use Filters to Choose Points

- Click the button **Edit Area/Zone Filters**
- Set all areas to *No* except Washington
- Close the Area/Zone Filters display
- Check the box **Use Area/Zone Filters**
- The list of generators will now only show those generators which are in Washington

Defining Participation Points

- Select all the generators in the list by clicking the button **Select All**
- For this example, assume all generators will participate proportional to their MW reserves
  - Therefore, select **Base on Positive Reserve**
- Use **Add ->** key to move the selected generators into the participation point list

Defining Participation Points

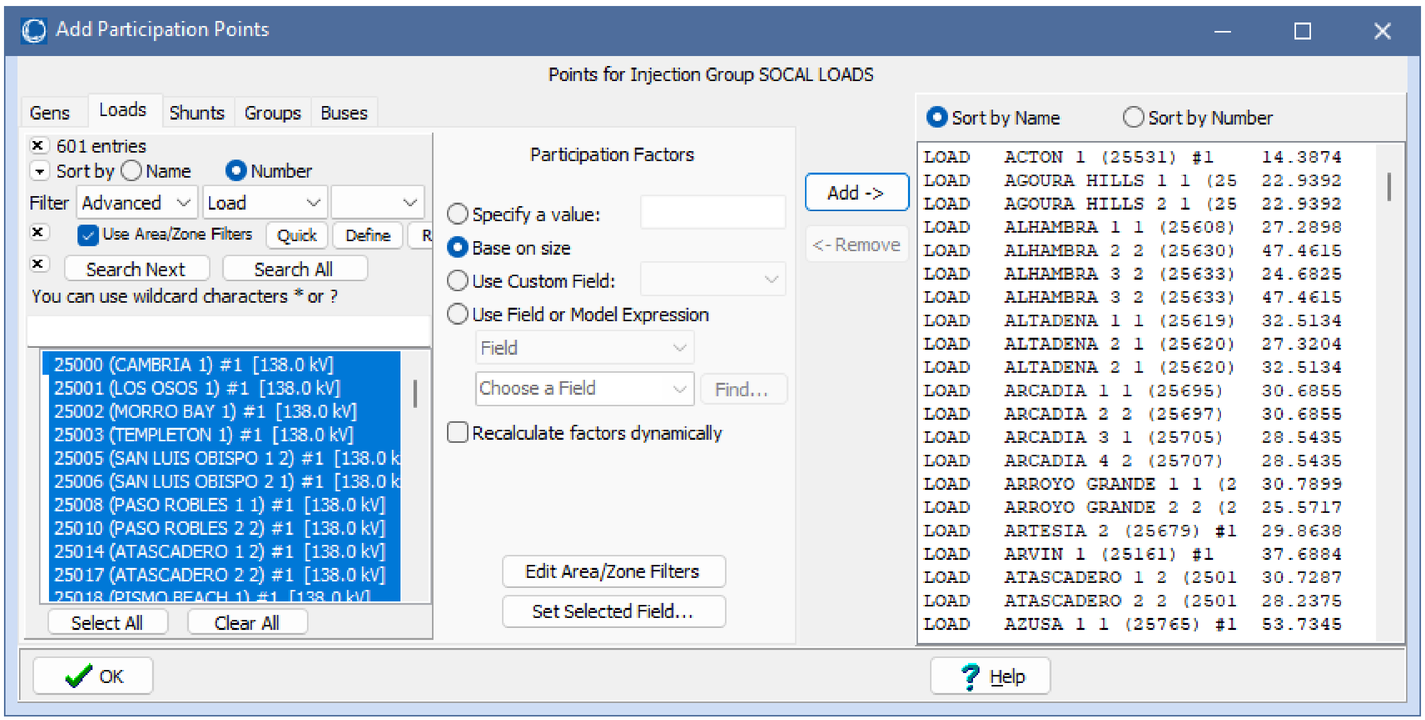
- Each generator will have a participation factor calculated for it based on the method of calculation selected, or will use the pre-defined values
- In this case, the participation factors will be proportional to the MW reserves
- Hit **OK** to add points to injection group

Define the Sink Group

- Process is very similar
- Change area/zone filters so that only area 6 (Southwest California) is set to YES
- Open Injection Groups display again. Select **Records → Insert**
- Call this group *SoCal Loads*
- Choose **Insert Points** or **Records → Insert**
- Switch to Load Tab, because we want the loads to serve as injection points

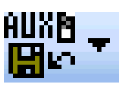
Define the Sink Group

- Select all the loads in the list
- Use **Base on Size** to calculate the participation factor, so that the larger loads will participate more heavily in the transfer
- Click the **Add ->** button to move loads into the list



Saving the groups

- We have now defined a set of source and sink points. The PV study will model an increasing transfer from source to sink.
- This procedure involved a lot of steps, so you don't want to have to redefine the groups for a slightly different case



To save the injection groups, select an injection group and use the Save Auxiliary Menu

- This will save the groups in a text file along with any other auxiliary data you may have
- The data can then be loaded into a different case as needed

Contingency Definition

- In addition to analyzing the system for its current topology, you may want to examine a specific set of contingencies
- Simulator's contingency analysis is fully integrated into the PVQV package to allow you to gauge the impact of contingencies
- To define a contingency list, go to **Tools → Contingency Analysis**

Contingency Definition

- For this example, we will use a pre-defined contingency called *OPEN Klamath Falls 765*
- The file *KlamathFallsCTG.aux* contains the contingency definition

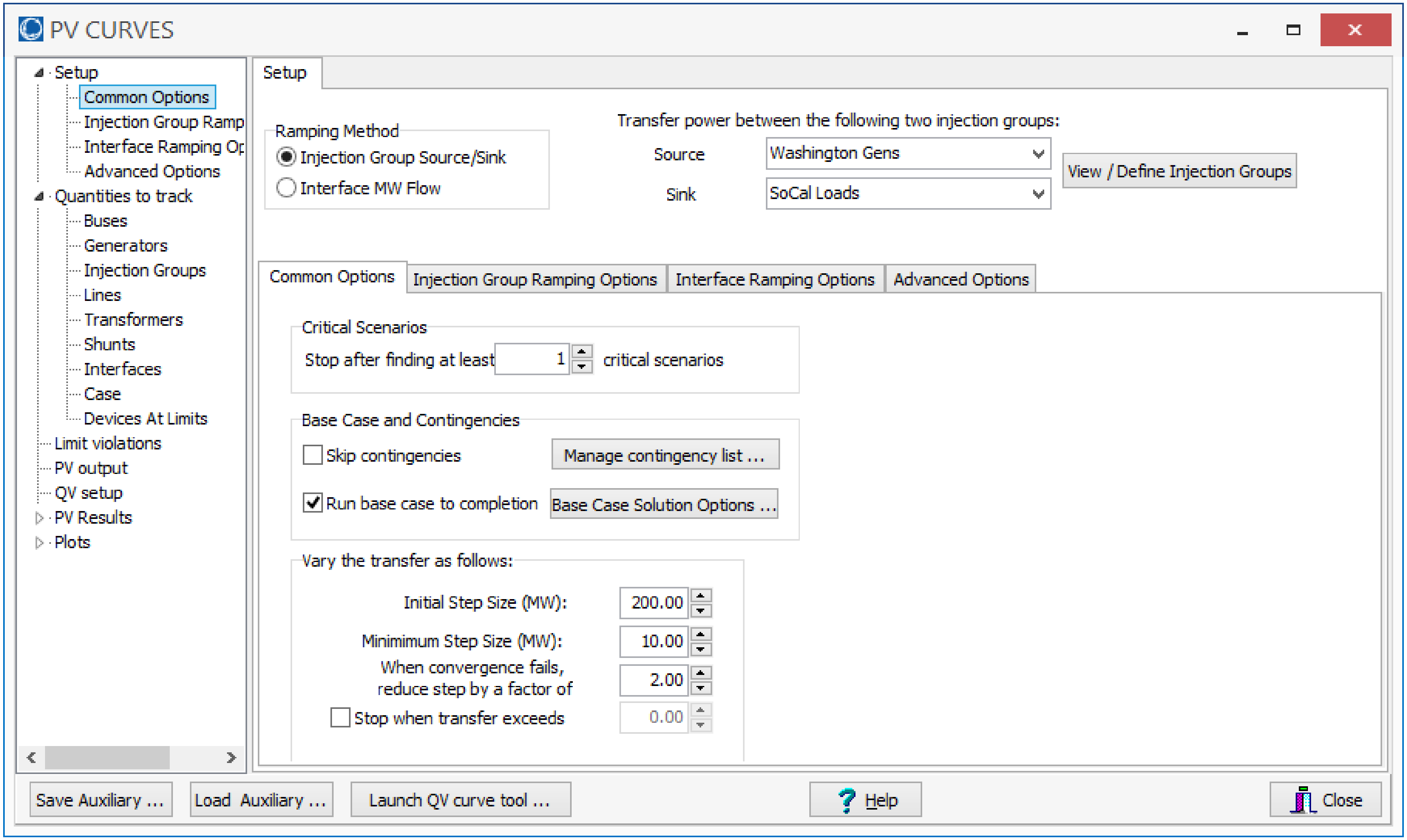
Performing a PV Curve Study: Open the PV Study

- We are finally ready to perform the PVQV study. Select **Add Ons** ribbon tab → **PV Curves**.
- This form is organized in a series of pages, that are arranged in the order they should be considered
- The options on the following slides are stored in *ACTIVSg10k PV Options.aux*

Setup: Common Options Transfer Definition

- Under Source, click on the drop-down box and select *Washington Gens*, our predefined injection group
- Under Sink, select *SoCal Loads*
- You can also define these groups from this dialog by selecting **View/Define Groups**

Setup: Common Options



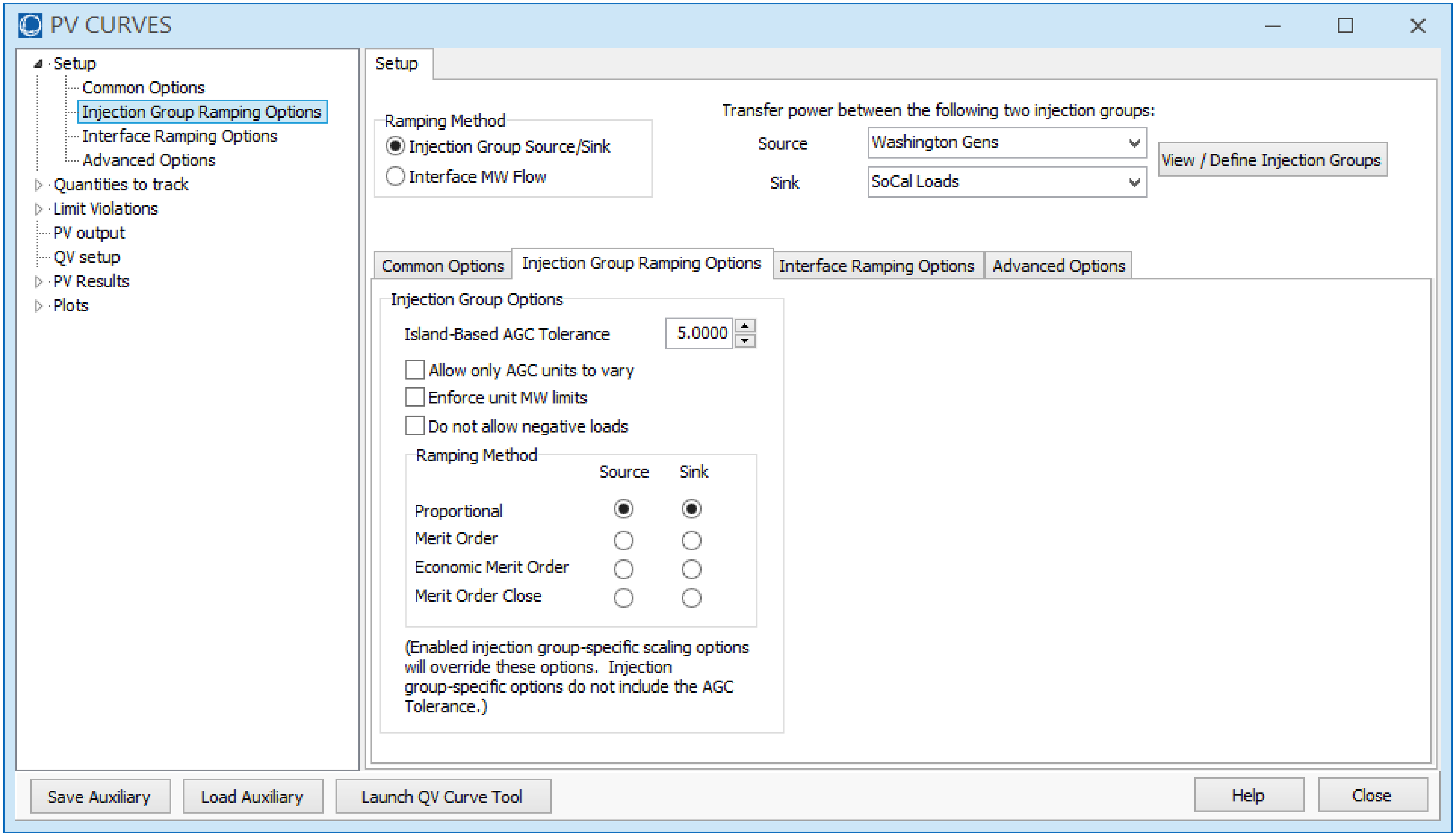
Setup: Common Options
Vary transfer options

- Initial Step Size
  - The rate at which transfer will increase initially
  - **200 MW for example**
- Minimum Step Size
  - Whenever Simulator fails to converge at a particular transfer level, it will return to the previous one and use a smaller increase. This is the minimum.
  - **10 MW for example**
- Reduce step by a factor of
  - Amount Simulator will reduce the transfer by in case of non-convergence (Not MWs)
  - **2 for example**
- Stop when transfer exceeds
  - When checked, the PV analysis will stop after a specified MW transfer level has been achieved
  - **Unchecked for example**

Setup: Common Options

- Stop after finding at least … critical scenarios
  - Minimum number of critical scenarios that will be found
  - **1 for example**
- Skip Contingencies
  - Check this box to run the analysis for the base case only
  - **Unchecked for example**
- Run Base Case to Completion
  - When checked, the critical transfer point is found for the base case in addition to the number of specified critical scenarios
  - **Checked for example**

Setup: Injection Group Ramping Options



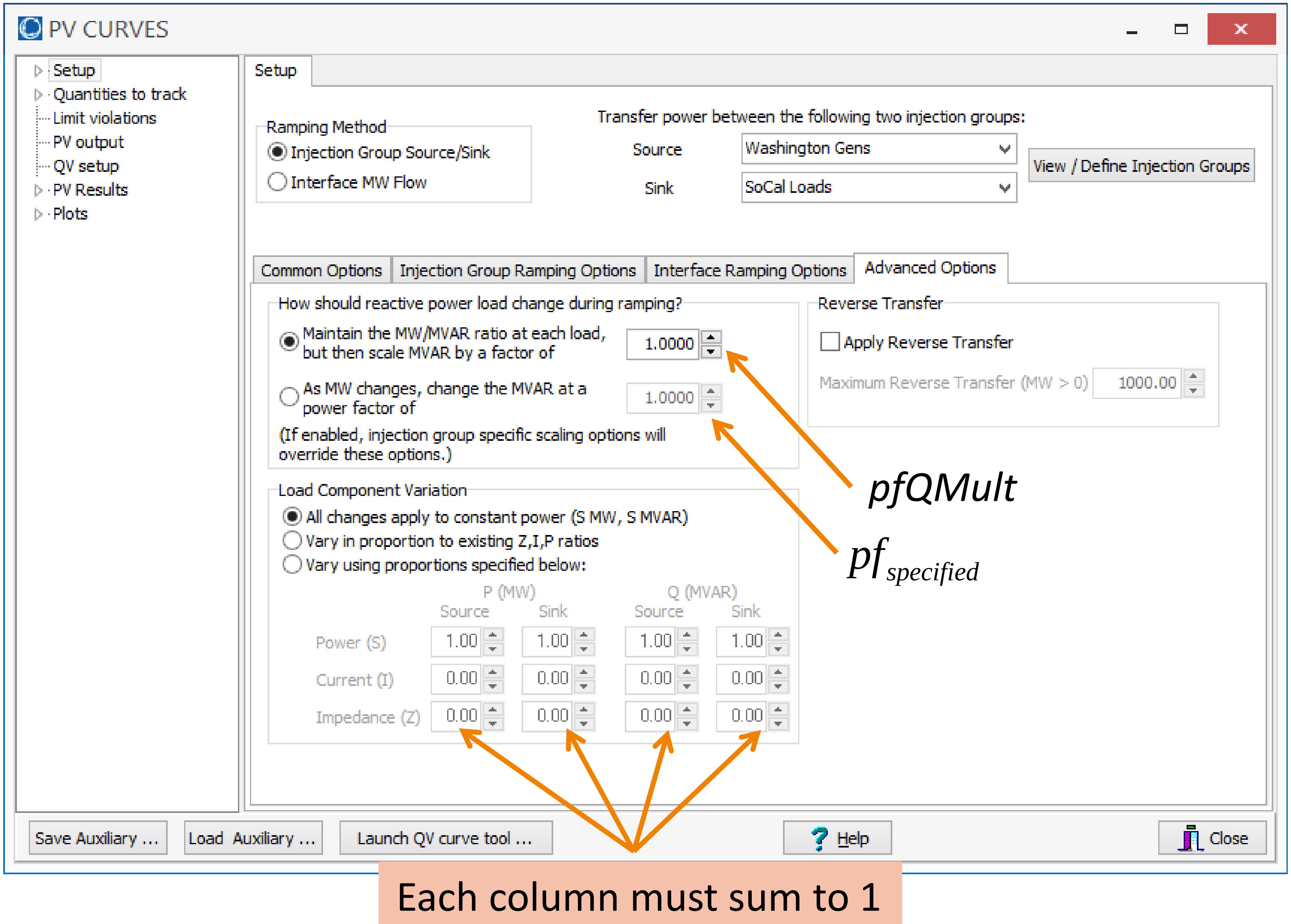
Setup: Injection Group Ramping Options

- Island-Based AGC Tolerance
  - Tolerance used in the MW control loop when solving the power flow during implementation of the transfer
  - General rule of thumb is that Minimum Step Size should be at least 1 to 2 times larger than this value
  - Simulator will modify this so that MVA convergence tolerance < AGC Tolerance < Minimum Step Size
  - **5 MW for example**
- Allow only AGC units to vary
  - In Simulator each unit may be on or off AGC. If this box is checked only those set on AGC can vary.
  - **Unchecked for example**

Setup: Injection Group Ramping Options

- Enforce unit MW limits
  - When checked generators will only participate in the transfer if they are within their min/max MW limits
  - **Unchecked for example**, so we may examine the transfer capacity regardless of reserve in Washington
- Do not allow negative load
  - When this box is checked, loads will be prevented from being set below zero
  - **Unchecked for example**
- Ramping Method
  - Merit Order method: individual generators and loads will be moved to their min/max in succession in order of descending participation factor (as set in its injection group participation point)
  - Economic Merit Order: maintains generators within an Economic Min/Max
  - Can select separately for the source and sink
  - **Source and Sink are Proportional for this example**

Setup: Advanced Options



Setup: Advanced Options

- How should reactive power load change during ramping?
  - Maintain the MW/MVAR ratio at each load, but then scale MVAR by a factor of

$$pf = \cos\left(\tan^{-1}\left(\frac{Q_{Existing}}{P_{Existing}}\right)\right)$$

$$\Delta Q = \tan\left(\cos^{-1}\left(pf\right)\right) * \Delta P * pfQMult$$

  - As MW changes, change the MVAR at a power factor of

$$\Delta Q = \tan\left(\cos^{-1}\left(pf_{specified}\right)\right) * \Delta P$$

Setup: Advanced Options

- Load Component Variation
  - Total load (P,Q) at a load can be specified as the sum of constant power (S), constant current (I), and constant impedance components (Z)
  - Constant current and constant impedance components are both functions of voltage at the bus
  - These options determine the proportion of the load change that each component receives

Setup: Advanced Options

- Load Component Variation
  - All changes apply to constant power (S MW, S MVAR)

$$\Delta P_S = \Delta P, \Delta P_I = 0, \Delta P_Z = 0, \Delta Q_S = \Delta Q, \Delta Q_I = 0, \Delta Q_Z = 0$$

  - Vary in proportion to existing Z,I,P ratios
    - Existing ratios determined based on the existing total nominal load (P_{nom},Q_{nom}) prior to any change due to the transfer

$$k_{PS} = \frac{P_{nomS}}{P_{nom}}, k_{PI} = \frac{P_{nomI}}{P_{nom}}, \ldots, k_{QS} = \frac{Q_{nomS}}{Q_{nom}}, \ldots, k_{QZ} = \frac{Q_{nomZ}}{Q_{nom}}$$

    - Ratios are multiplied by the total nominal load change to calculate the nominal load change for each component

$$\Delta P_{nomS} = k_{PS} * \Delta P_{nom}, \Delta P_{nomI} = k_{PI} * \Delta P_{nom}, \ldots, \Delta Q_{nomS} = k_{QS} * \Delta Q_{nom} \ldots$$

Setup: Advanced Options

- Load Component Variation
  - Vary in proportion to existing Z,I,P ratios
    - The total nominal power change is determined based on the total real power change required due to the transfer, the calculated ratios, and present voltage at a bus

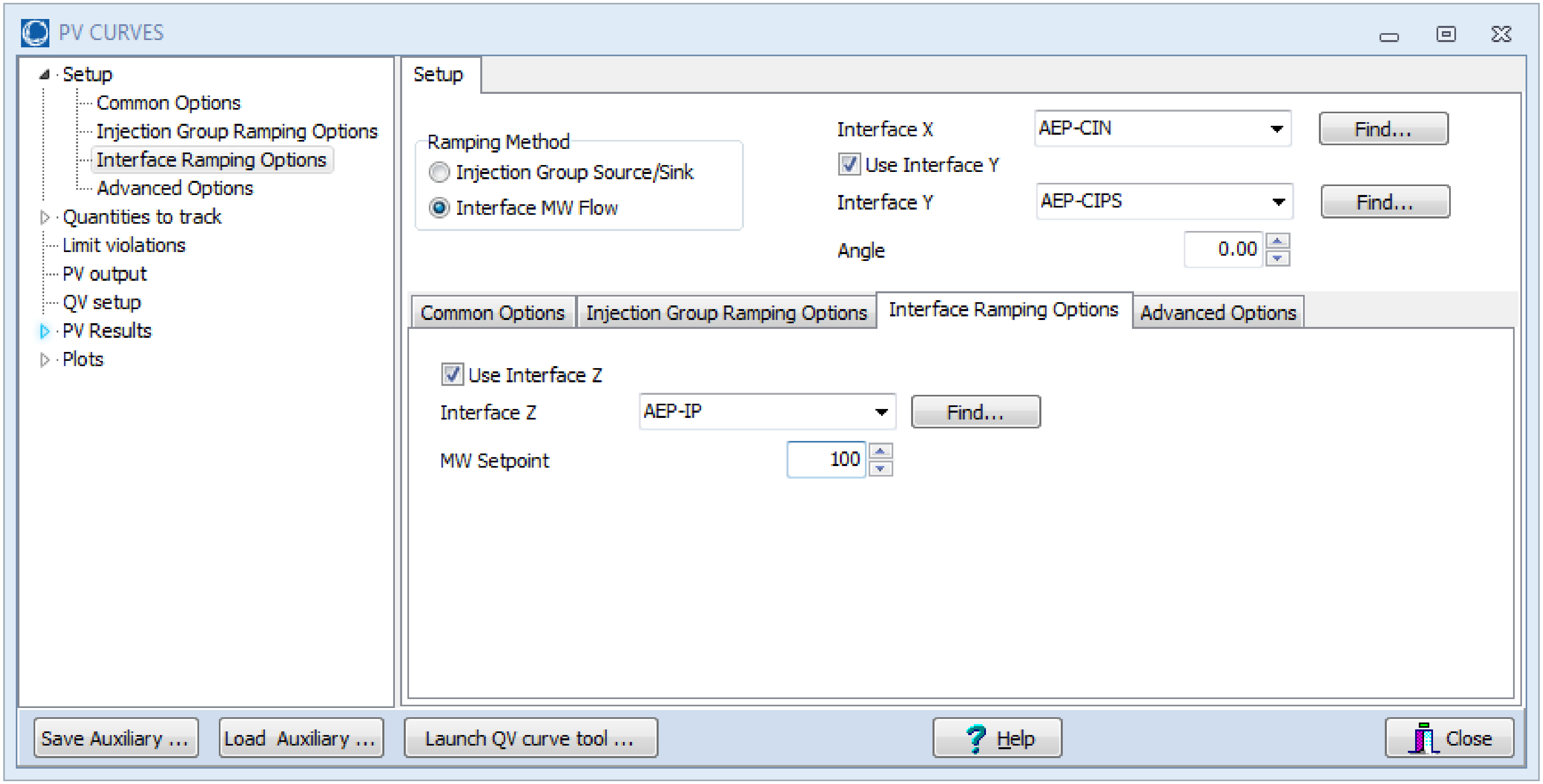
$$\Delta P_{nom} = \frac{\Delta P}{k_{PS} + k_{PI} * V + k_{PZ} * V^2}$$

    - Change in nominal reactive power is determined based on the option selected for how reactive power should change during the transfer

Setup: Advanced Options

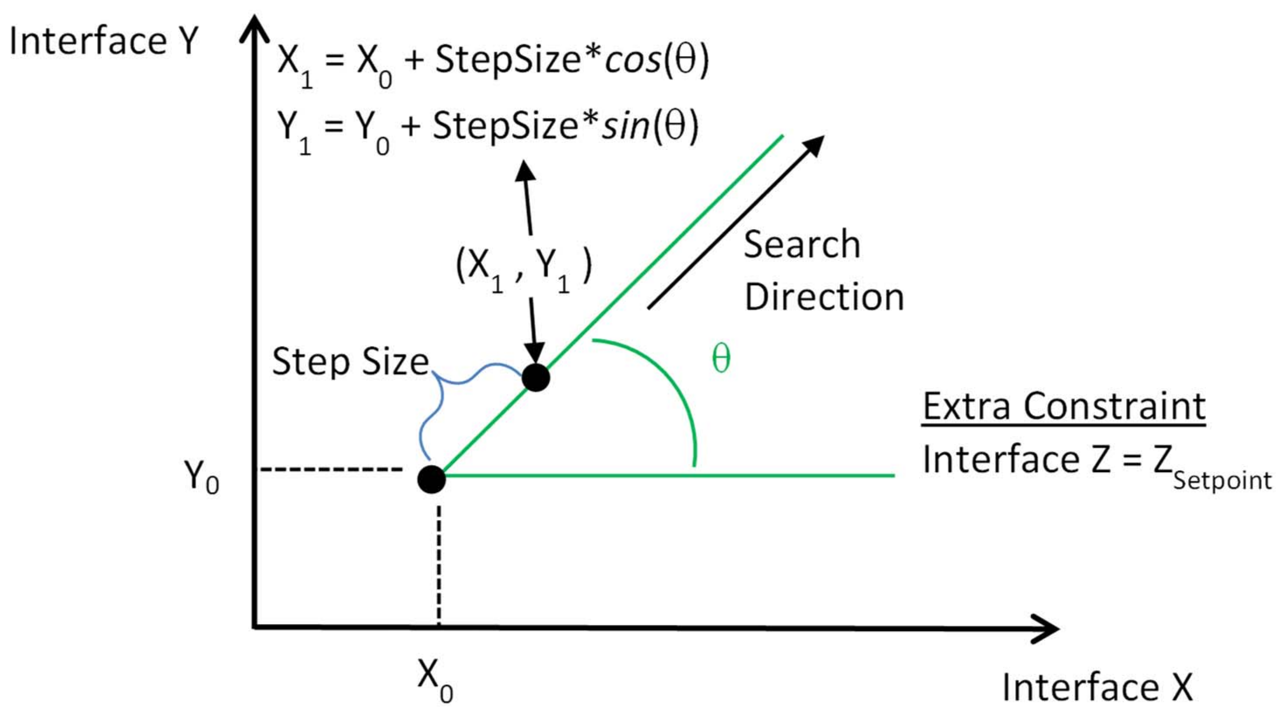
- Load Component Variation
  - Vary using proportions specified below
    - Proportions are grouped by real and reactive power and then source or sink
    - Proportions for each group must sum to 1 so that component changes sum to the total load change
    - Same calculations as option to use existing Z,I,P ratios except that the ratios are user-specified
- Apply Reverse Transfer
  - For any contingency that does not solve in the base case, apply a transfer from the Sink to the Source in an attempt to find a solution
  - Must specify the Maximum Reverse Transfer because it is possible that a solvable point will not be found

Interface MW Flow Ramping Method



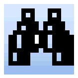
Interface MW Flow Ramping Method

- Requires the OPF add-on
- Ramps transfer by increasing flow on 1 or 2 interfaces
  - Search direction determined by **Step Size** and **Angle**
- Optional constraint to maintain flow on a third interface



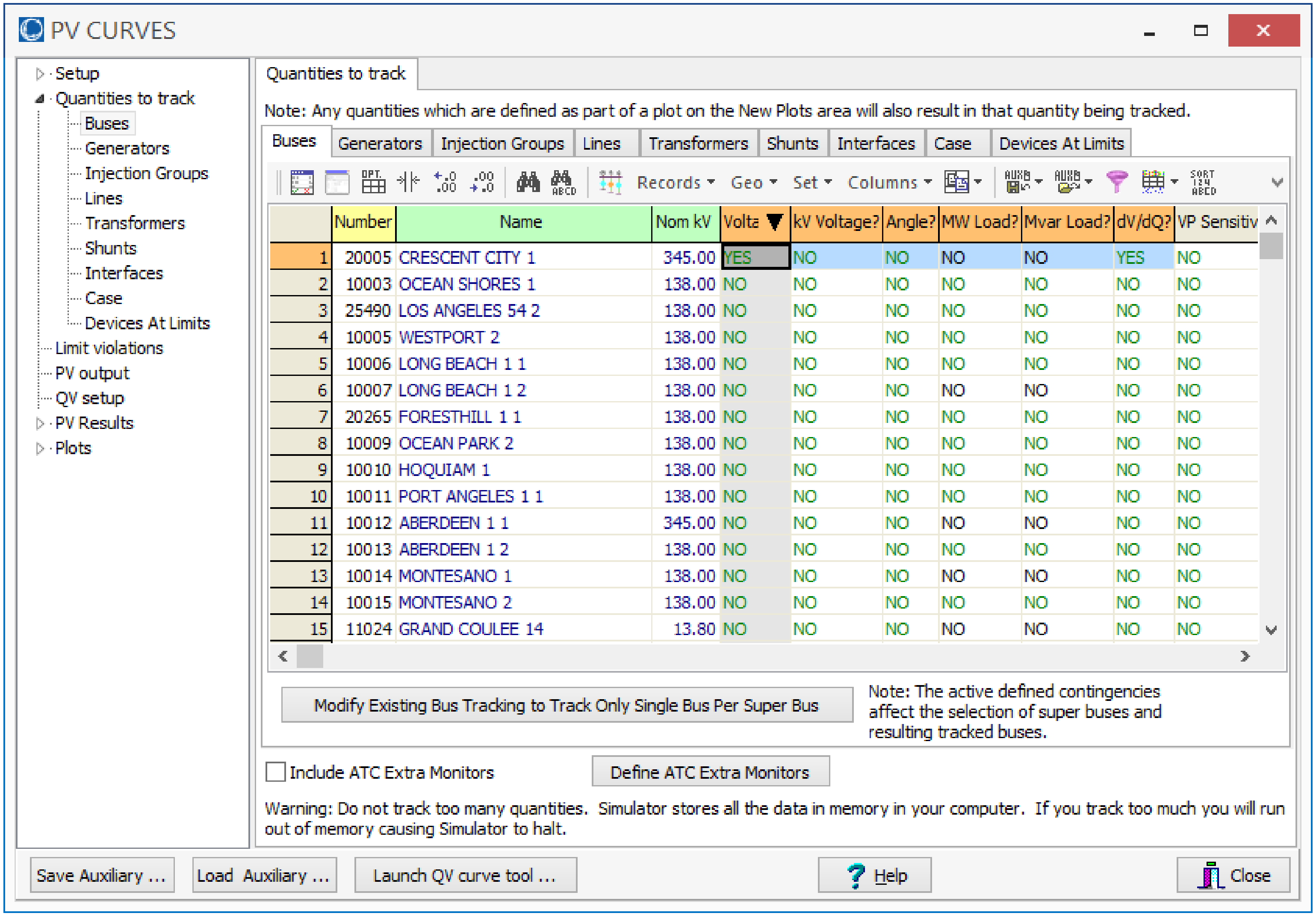
Quantities to Track

- On the **Quantities to track** page, there are several sub pages that allow you to track values for various devices



- Let’s monitor bus 20005 (Crescent City 1, 345 kV):
  - voltage
  - dV/dQ
- And Mvar Reserve (Max-MVR) for Injection Group Washington Gens
- Search for the fields and toggle to change values

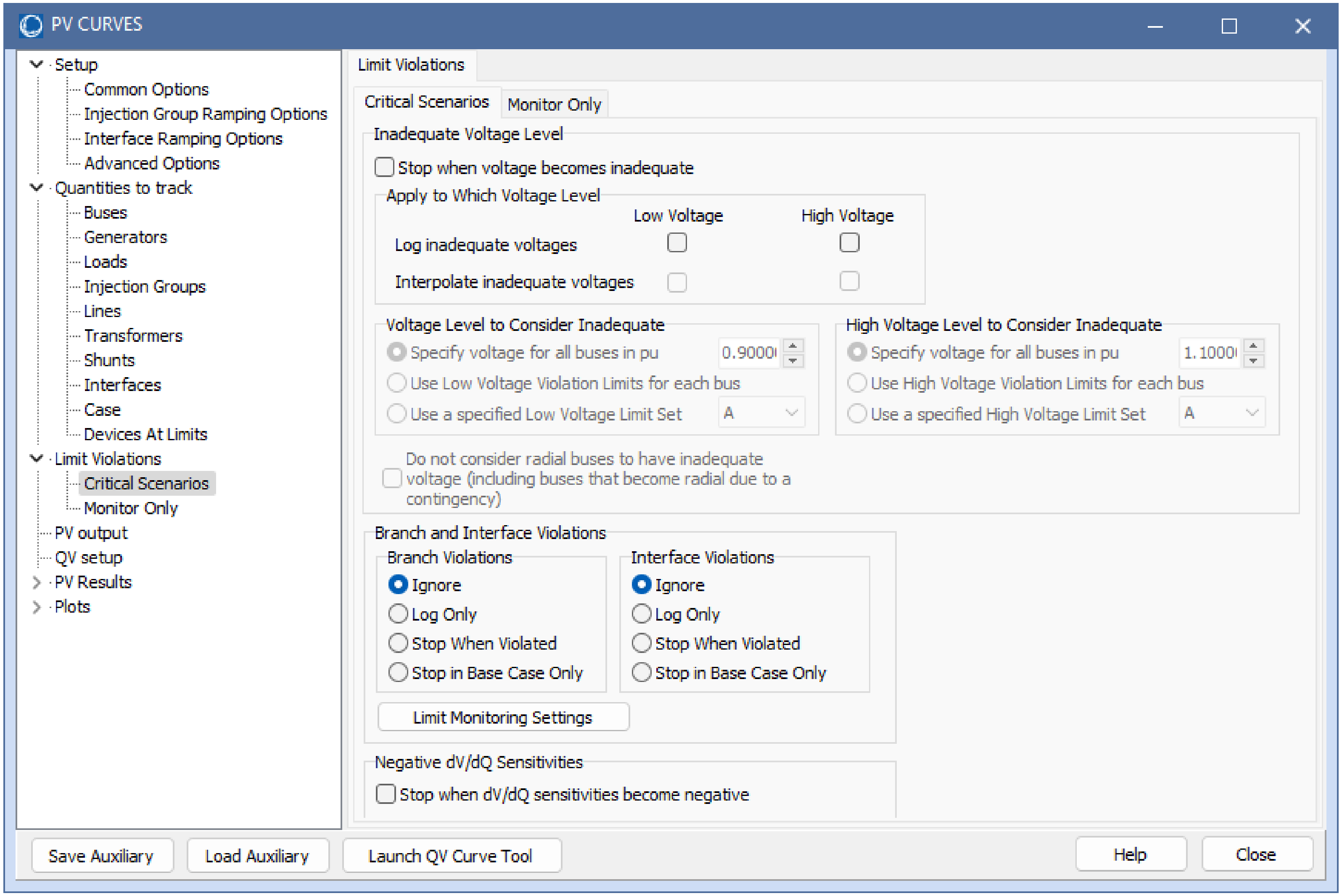
Quantities to Track



Quantities to Track: Devices At Limits

- Can track devices that hit or back off limits during the analysis
  - Limits are only tracked during the base case ramping and not during contingencies
  - Generator var, switched shunt var, LTC transformer tap, line thermal, and interface thermal limits can be tracked
- Limit the amount of elements that are tracked by defining filters for each type of element tracked
- Optionally track “Generators Var Limits” for the filter “COB In-service” (loaded with *ACTIVSg10k PV Options.aux*)

Limit Violations → Critical Scenarios



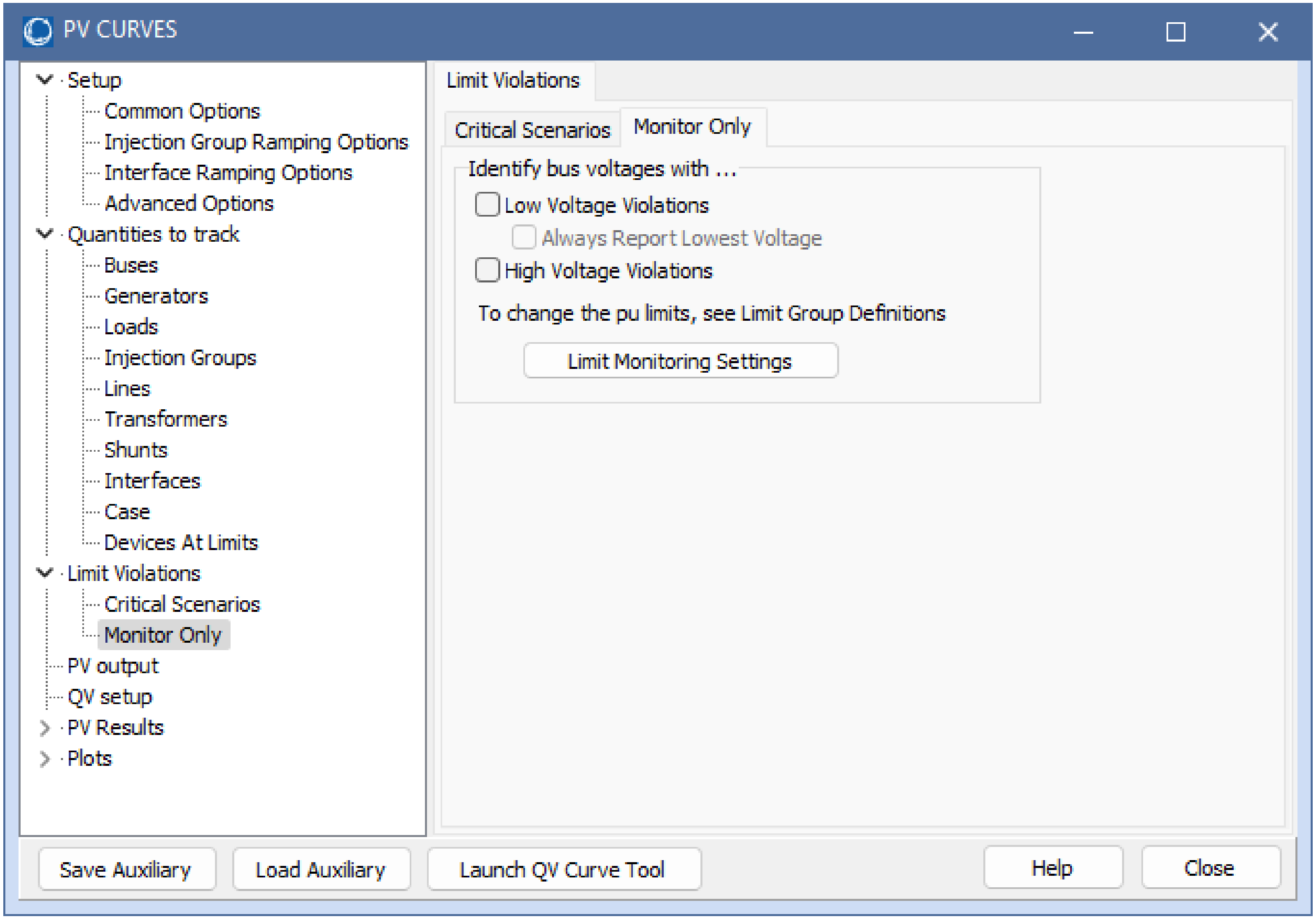
Limit Violations → Critical Scenarios

- Inadequate voltage level
  - Stop when voltage becomes inadequate
    - A scenario will be judged critical once any monitored voltage falls below the inadequate voltage level
  - Log inadequate voltages
    - Keeps track of inadequate voltages without considering a scenario to be critical
  - Interpolate inadequate voltages
    - Allows linear estimation of where a voltage becomes inadequate without having to reduce the step size in order to exactly determine when a voltage becomes inadequate
- **Limit Monitoring Settings** determine which buses are monitored and how high and low voltage violations are identified for each bus

Limit Violations → Critical Scenarios

- Inadequate Voltage Level
  - Specify voltage level to consider inadequate
    - Specify voltage for all buses
    - Use Low Voltage Violation Limits for each bus
    - Use a specified Low Voltage Limit Set
  - Do not consider radial buses to have inadequate voltage
    - Buses that are connected by only a single in-service branch are considered radial. If buses are connected by more than one branch, all but one of the branches is open.
    - Buses that are radial for a given scenario, even those that become radial due to a contingency, will not be monitored
    - Limit Monitoring Settings option to not monitor radial lines and buses will exclude from monitoring those buses that are connected by a single branch in the base case

Limit Violations → Monitor Only



Limit Violations → Monitor Only

- Use the **Identify Bus Voltages with…** section to tell the PV tool to keep track of buses that violate their voltage limits as of the last successful solution for each scenario
  - Low Voltage Violations
    - "Always Report Lowest Voltage" will report a voltage even if it does not violate a low voltage limit
  - High Voltage Violations
- Selecting either one of the two voltage violation boxes will make available a few tools and fields on the **Overview** table on the **PV Results** page

PV Output
Save results to file

- Simulator records the value of each monitored quantity at each transfer level for each contingency being studied
- Data only present in memory unless storage file and location specified
- Save results to file
  - Check and specify the file path and name
  - Results stored with transfer level in rows and tracked quantities in columns
  - Comma-separated file regardless of file extension chosen
  - For this example, choose file *PVResults.csv* in current directory
- Transpose results
  - Results stored with tracked quantities in rows and transfer levels in columns
- Single Header File
  - Only a single header is shown at the top of the file rather than repeating the header at the start of each scenario section

PV Output
State Archiving

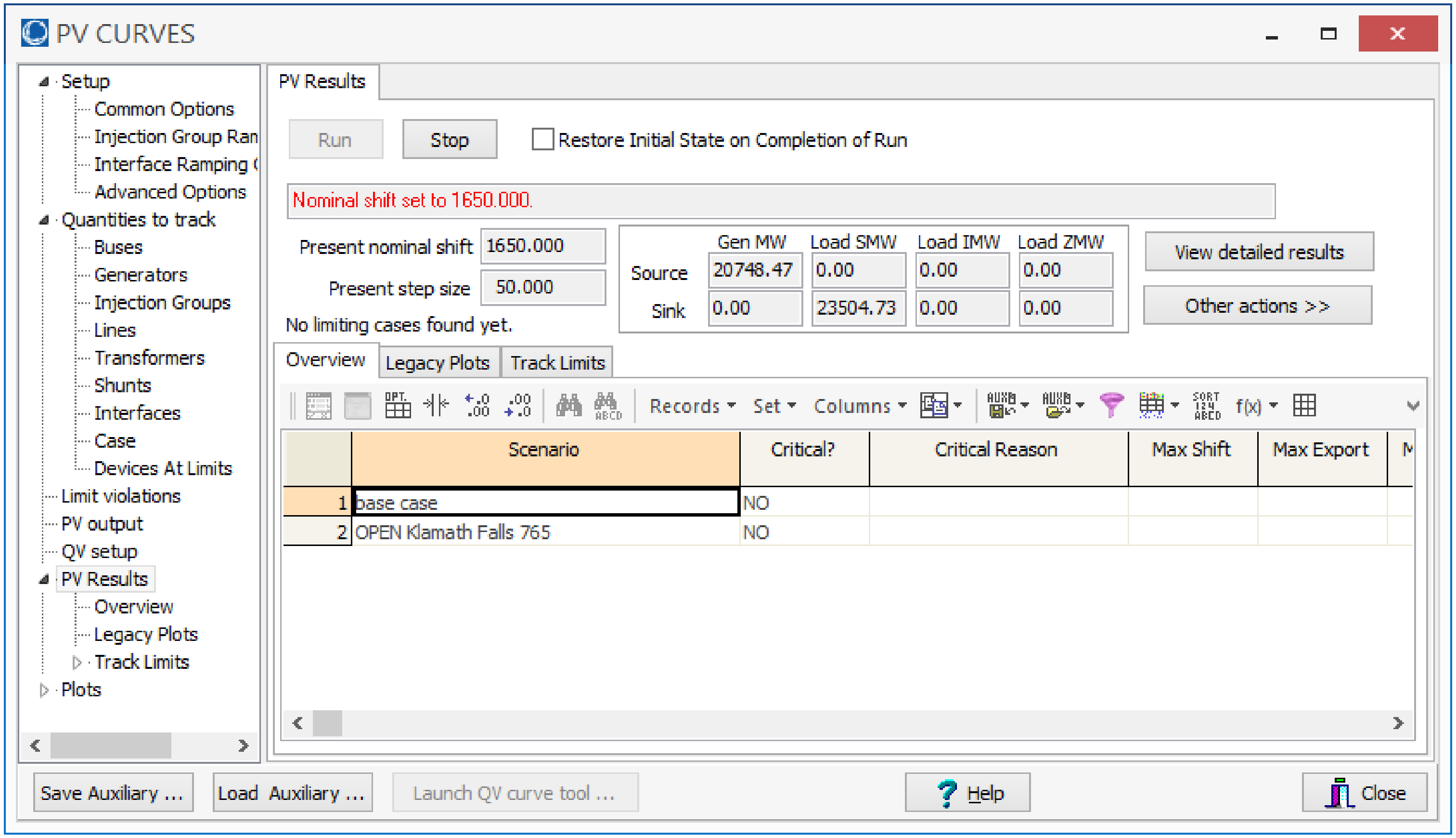
- Entire system can be saved during the analysis
- Directory and prefix must be specified to help in distinguishing between separate PV runs
- Can save as PWB, AUX, or both
- This can require significant disk space, but can be quite helpful to examine a particular transfer level
- Save only the base case for each critical contingency
  - Base case without contingency but with critical transfer level implemented will be saved for each critical scenario
- Save all states
  - All states at each valid transfer will be saved
  - Non-critical states will be saved with contingency implemented. Only base case saved at the critical transfer level.
  - Base case state without contingency implemented will be saved for all scenarios at all transfer levels at which that scenario will solve

Save/Load Auxiliary Options

- This form has a large number of options
- These do not have to be set every time - just use the **Save Auxiliary** button at the bottom of the form to transfer options between cases
- Options are saved in Simulator’s Auxiliary File format
- You may also load options back in by choose the **Load Auxiliary** button
- The options on these slides are stored in *ACTIVSg10k PV Options.aux*

PV Results
Performing the Analysis

- Go to the PV Results page to initiate the PV Curve analysis. Click **Run** to begin.

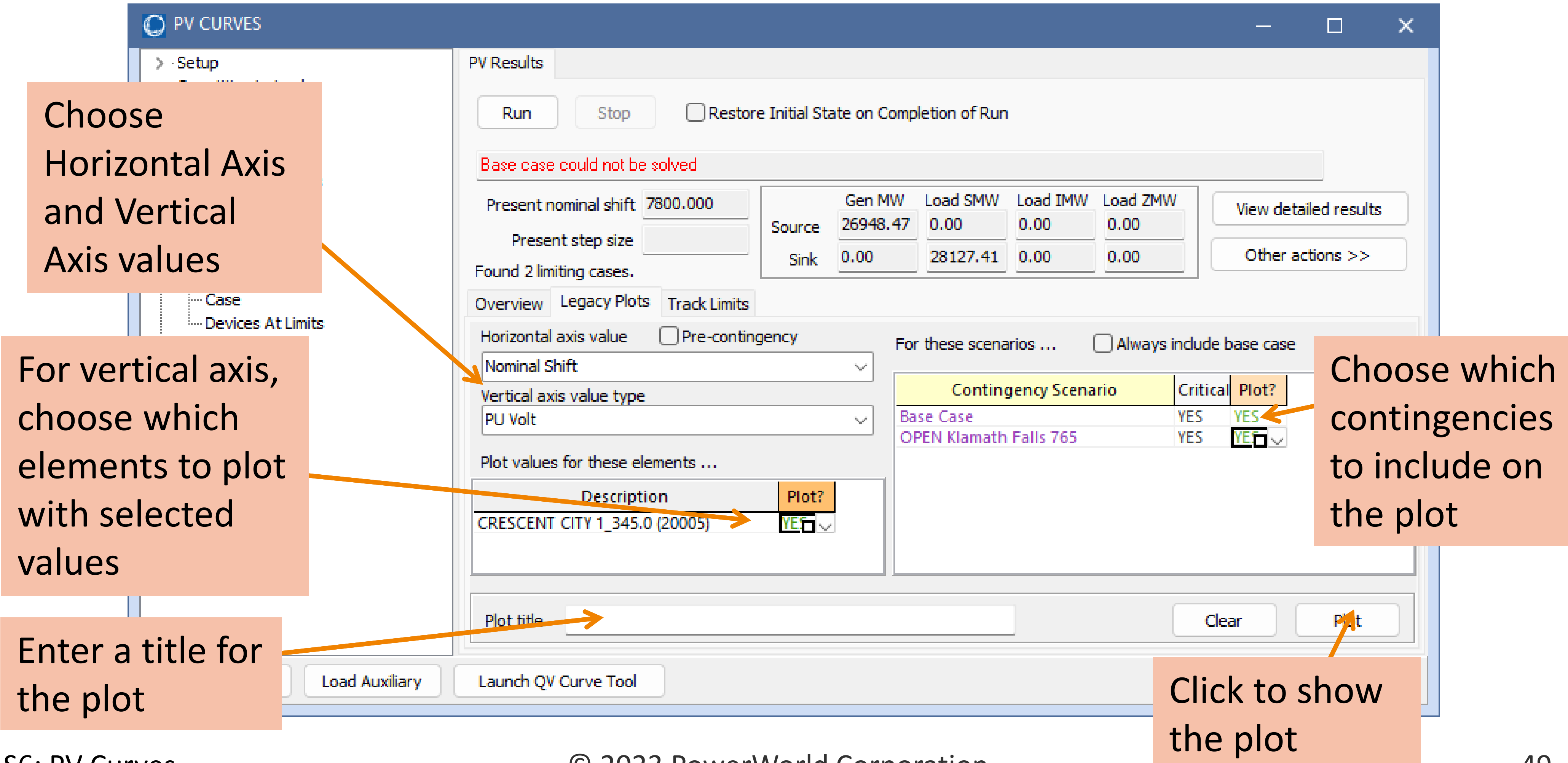


PV Results
Overview, Plot

- When the PV run is completed, the **Overview** list display will show a summary of the results
- Critical scenarios (contingencies) are identified along with information about the critical buses and maximum achieved transfer levels
- Plots of tracked quantities can be made from the **Legacy Plots** tab or **Plots** page
- System state is left at the transfer level of the last studied critical scenario with any contingency restored

PV Results
Legacy Plots Tab

- Once the PV tool has completed running, you may plot the results using the **Legacy Plots** tab of the **PV Results** page

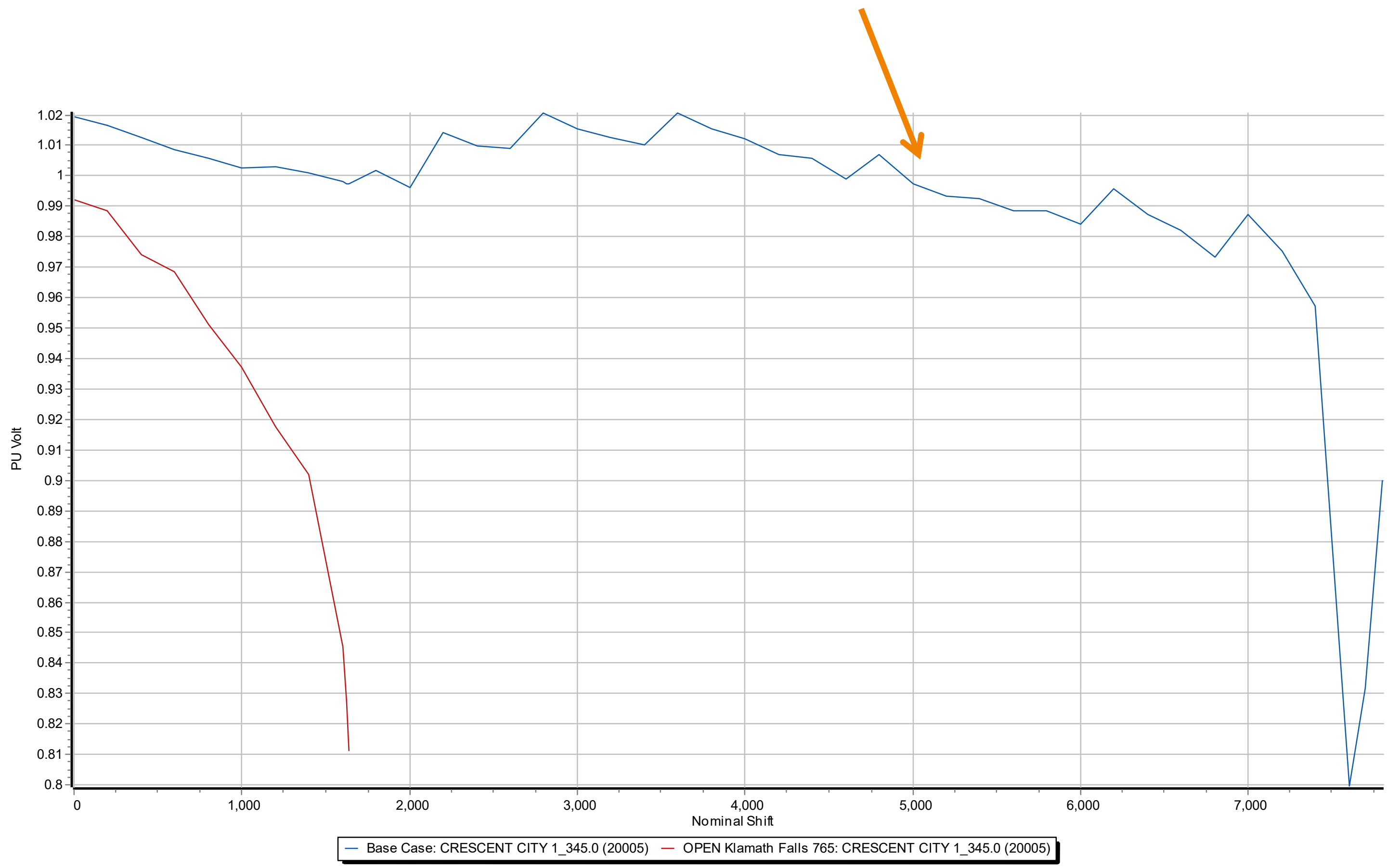


PV Results
Legacy Plots Tab

- The plot tab allows the user to plot all of the values that were designated to be monitored during the analysis
- For example, we can plot the bus voltages vs. the size of the transfer
- For Horizontal-Axis, select *Nominal Shift*
- For Vertical-Axis, select *PU Volt*
- Select all the Crescent City bus as elements
- Select all PV Scenarios
- Add title (optional)

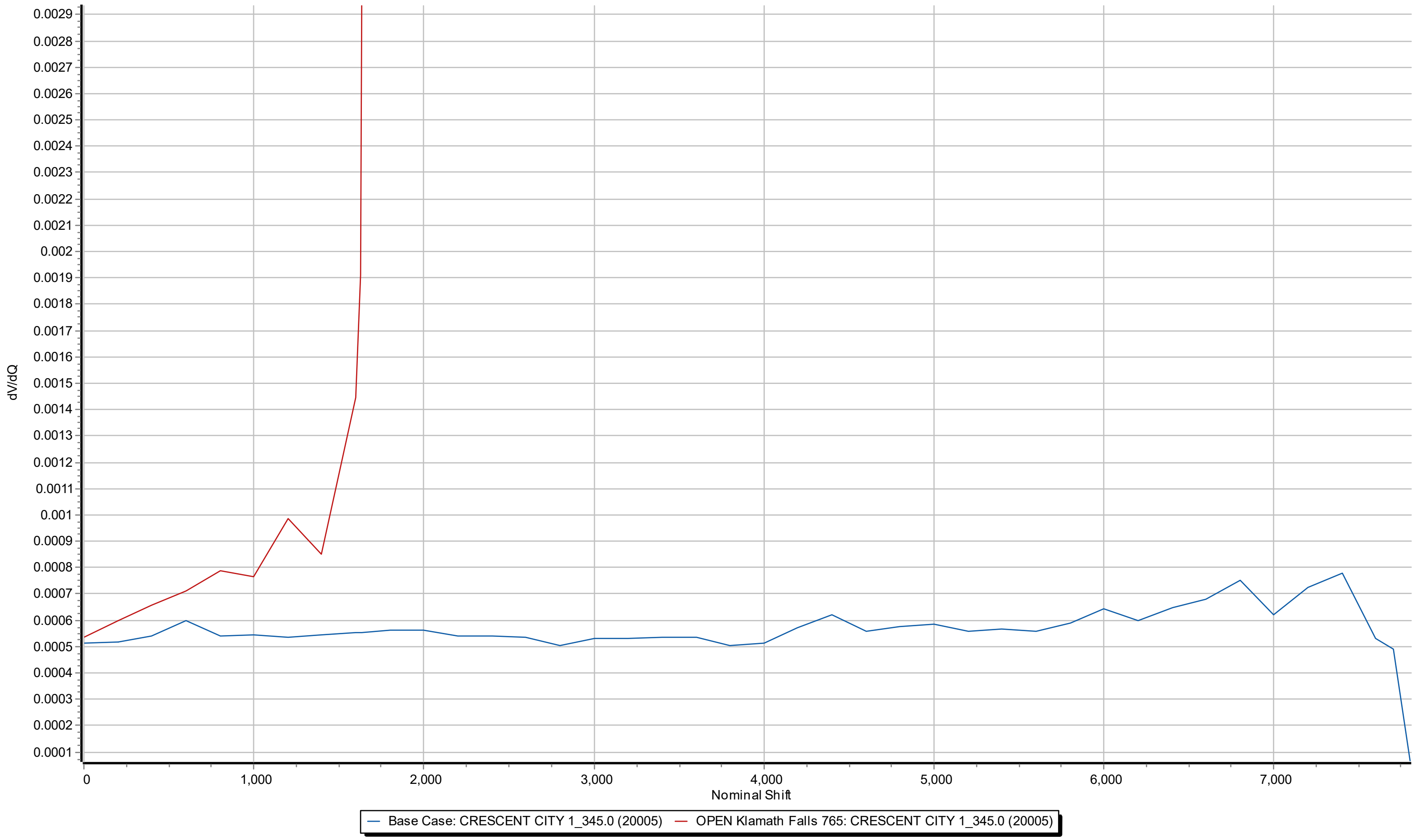
PV Results:
Example PV Curve

Note the “jaggedness”, especially for the Base Case plot. This is caused by the switched shunt and LTC transformer control actions trying to pull voltages up. Disable control switching to reduce this effect.



Right-click on the plot to Save it as a bitmap, metafile, or JPEG, or to copy or print the plot

PV Results: dV/dQ plot



Build Date: June 7, 2023

PV Results:
csv file

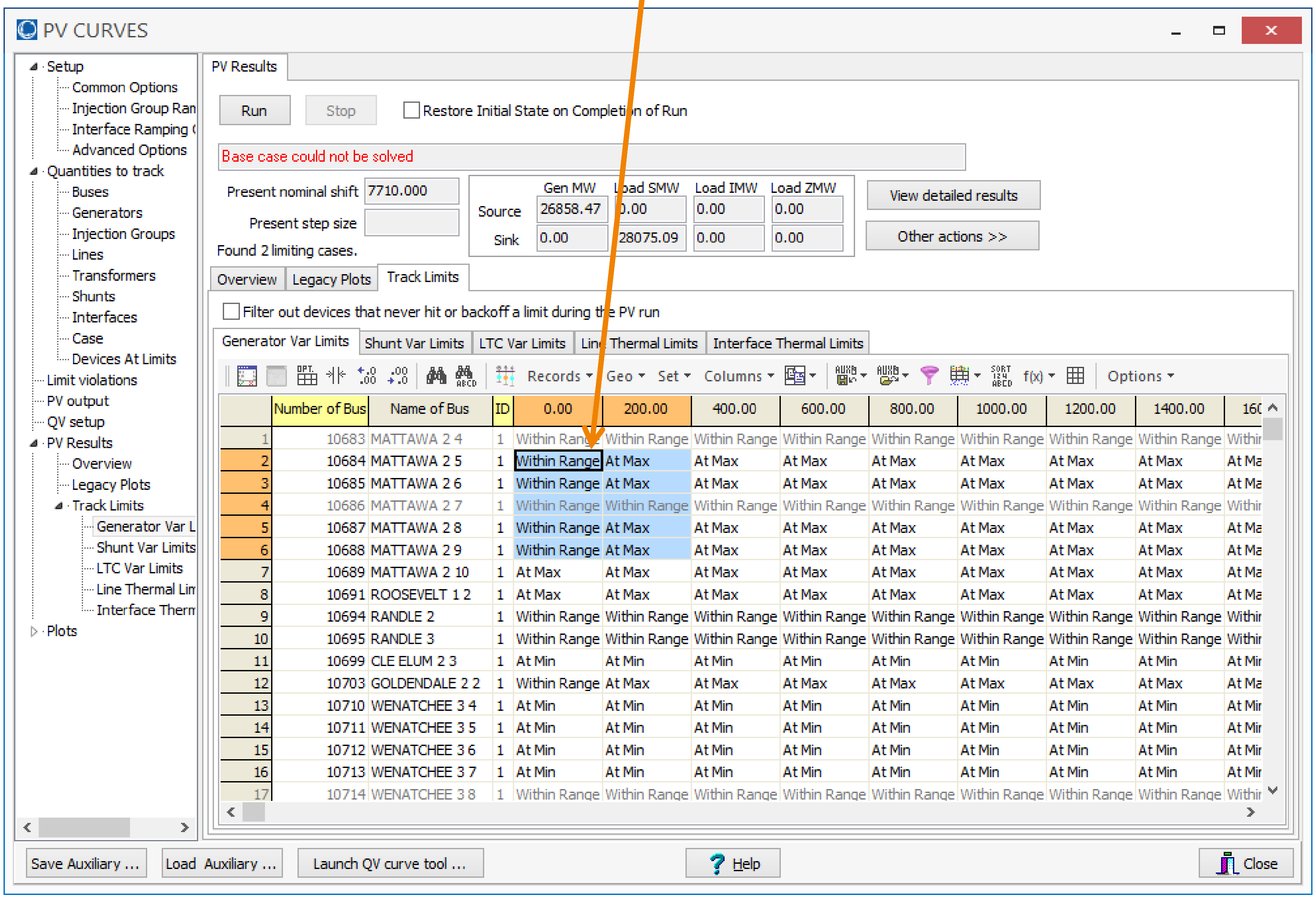
Tracked Quantities stored at each solution step

	A	B	C	D	E	F	G
1	RESULTS FOR PV STUDY ""						
2	**Scenario** "Base Case"						
3	Nominal	Export	"Import"	Bus 20005	Bus 20005	InjectionG	Newly Critical
4	0	0	0	1.01954	5.13E-04	6171.389	
5	200	199.997	-175.116	1.01668	5.16E-04	6094.321	
6	400	399.997	-349.735	1.01279	5.42E-04	6006.029	
7	600	599.9985	-522.89	1.00862	5.98E-04	5920.751	
8	800	800.0046	-697.267	1.00567	5.40E-04	5843.27	
9	1000	1000.005	-869.357	1.00275	5.42E-04	5766.665	
10	1200	1200.005	-1042.55	1.00308	5.35E-04	5733.854	
11	1400	1400	-1213.04	1.00102	5.45E-04	5700.343	
12	1600	1600	-1382.11	0.99798	5.52E-04	5650.678	
13	1625	1624.999	-1403.71	0.99744	5.53E-04	5643.462	
14	1637.5	1637.508	-1413.17	0.99717	5.53E-04	5639.922	OPEN Klamath Falls 765 (Reached Nose)
15	1800	1800	-1552.75	1.0017	5.62E-04	5630.666	
16	2000	2000	-1721.63	0.99614	5.63E-04	5563.683	
17	2200	2200.001	-1892.75	1.01429	5.38E-04	6035.164	
18	2400	2400.003	-2054.01	1.00986	5.42E-04	5925.212	

PVResults

PV Results
Track Limits

Tracked Generators reveal some devices that hit Max Mvar during the transfer



PV Results
Other actions

- View activity log
  - Outlines step-by-step the activities the PV tool performed during the run
- View detailed results
  - Opens a text file that contains the detailed results including the values of the tracked quantities at each step for each scenario
- Clear results
  - Purges the currently stored results from memory
- Restore Initial State
  - Brings back the case that was in memory prior to the PV run
- Restore Last Solved State
  - Brings back the solved power flow model that depicts the system at the largest transfer level that was studied. This is a base case state with no contingency implemented.

PV Results
Other actions

- Save critical contingencies
  - Saves contingency settings and records in an auxiliary file for each scenario where a critical state was reached
- Set current state as initial
  - Removes the case that was in memory at the beginning of the PV run and replaces it with what is currently in memory
- Start Over
  - Removes all results from memory, restores the initial case, and removes all entries from the activity log
- Run QV tool
  - Launches the QV tool using the case that is currently in memory as its basis

Time Saving Measures

- Only define a few contingencies - each contingency monitored can add significant time to the PV study
- Try to limit the number of Quantities to Track. There is no hard limit on this, but the amount of computer memory can become substantial if you try to monitor too much.

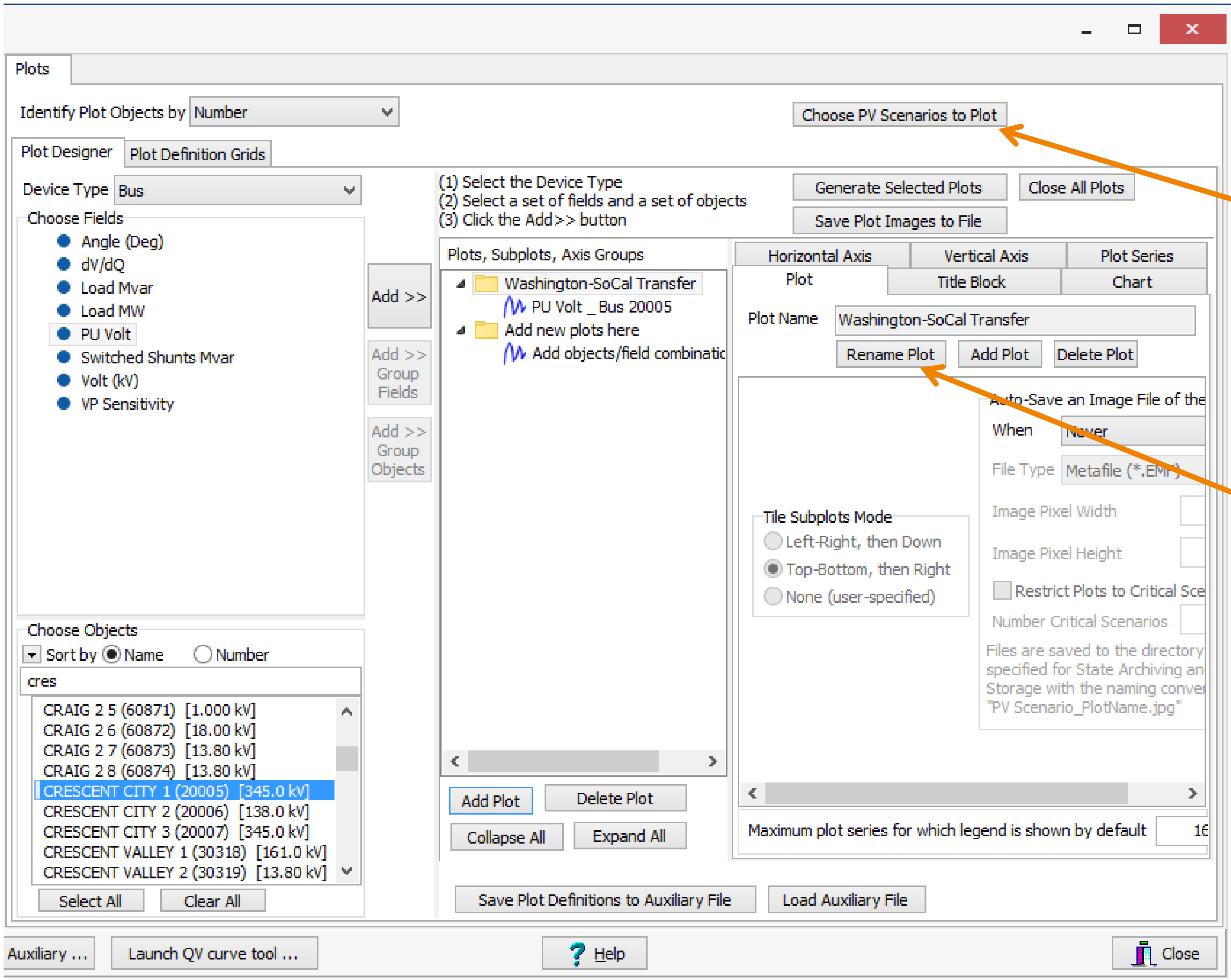
Plot Designer

- A general-purpose tool with more flexibility and options than **Legacy Plots**
  - Presents a complete list of PV track-able objects and variables, but only those selected on **Quantities to track** will have actual data to plot
  - **Legacy Plots** presents a reduced set of options, specific to PV curve plotting and the quantities tracked
- Saving plot options
  - **Save Auxiliary…** always visible on the PV Curves dialog
  - **Save Plot Definitions to Auxiliary File** on the Plot Designer

Plot Designer

- Replicate PV plot drawn with the Legacy Plot tool
  - Device Type: Bus
  - Choose Fields: PU Volt
  - Choose Object: 20005
  - Click the Add >> button (or drag them to the Plots, Subplots, Axis Groups) window
- These settings and those on following slides are in *ACTIVSg10k PV Plot Definition.aux*
- More details on the Plot Designer tool are in training topic **T7: Plot Definitions**

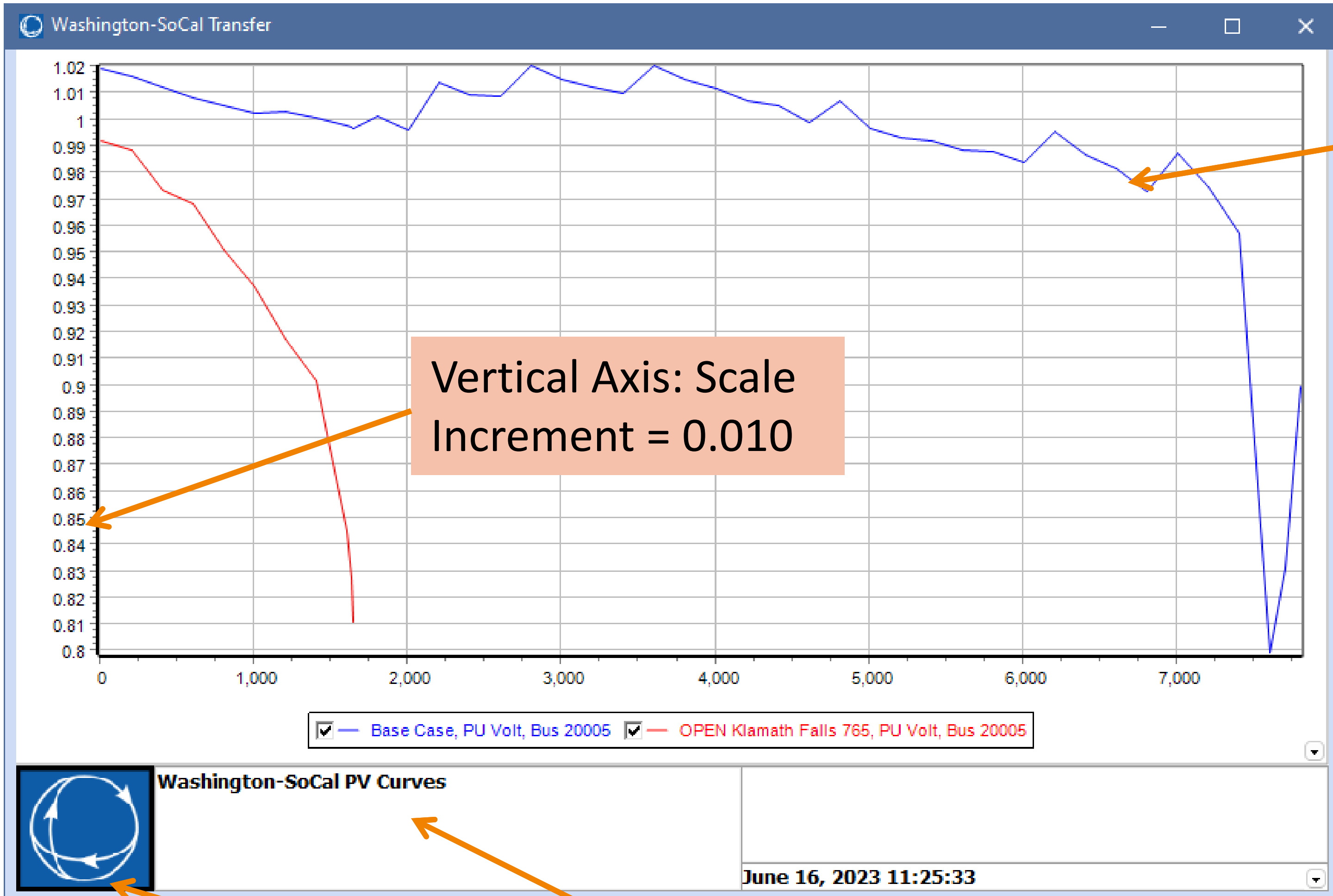
Plot Designer



To show only certain PV Scenarios (base case, contingencies), click **Choose PV Scenarios to Plot**

Optionally rename the plot

Plot Designer



Vertical Axis: Scale Increment = 0.010

Plot Series List: set color, thickness, style, etc.

To vary them for each scenario, open "Choose PV Scenarios to Plot"

Title Block: Logo Image, Left Memo, Right Memo

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