

# Steady-State Power System Security Analysis with PowerWorld Simulator

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## S7: Voltage Stability Using QV Curves



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# QV Study



- Voltage stability studies how variations in reactive power (Q) affects the voltages (V) in the system
- QV relationship shows the sensitivity and variation of bus voltages with respect to reactive power injections or absorptions
  - A system is voltage stable if V-Q sensitivity is positive for every bus, and voltage unstable if V-Q sensitivity is negative for at least one bus
  - All control systems (transformer taps, generator Vars, etc...) assume that increasing Vars (Q) will increase Voltage (V). If this assumption is wrong, then the control systems will behave incorrectly and cause the system to collapse.

# How is a QV curve performed?

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- In order to create a QV curve, a fictitious generator is placed at the bus which is being analyzed
- The voltage set-point of this generator is then varied and its VAR output is allowed to be ANY value needed to meet this voltage set-point
  - The vertical axis depicts the output of the fictitious generator in Mvar
  - The horizontal axis depicts the respective voltage under this condition

# QV Curve determines the maximum MVAR load before voltage collapse

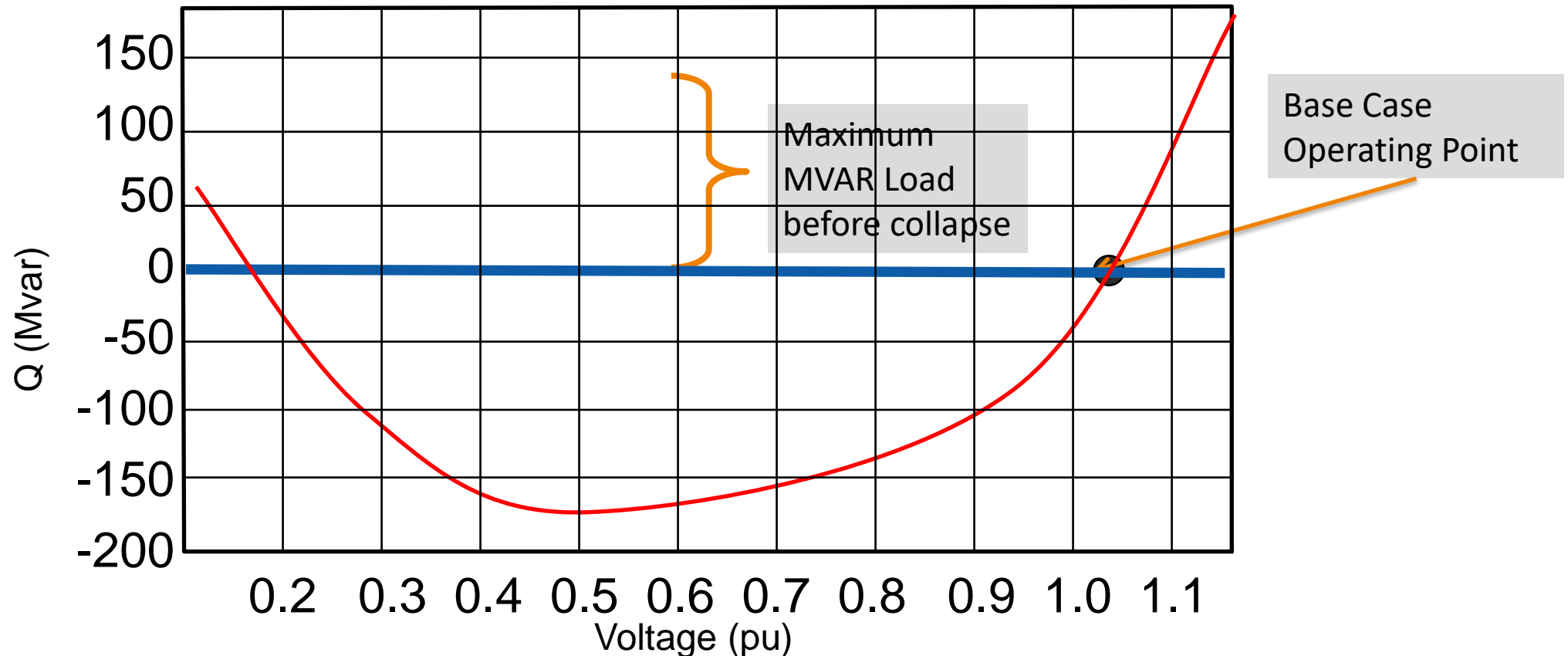


- The base case operating point of the system is represented by the X-intercept of the curve
  - This is the point where the fictitious generator is at 0 MVAR output, thus it represents the base case
- As you trace the curve down, this represents a decrease in the fictitious generator's MVAR output
  - This decrease represents an INCREASE in MVAR load
  - The curve is thus tracing what the voltage would be as you INCREASE the load MVAR
- At some point, the MVAR value of the generator will stop decreasing and reach the “bottom” of the curve
  - This point represents the maximum increase in the load MVAR at this bus. Any higher and voltage collapse would occur.

# Example QV Curve



- We actually plot the “VQ” Curve, but this is traditionally still called the QV Curve
- Most important value is the minimum Q (Mvar)

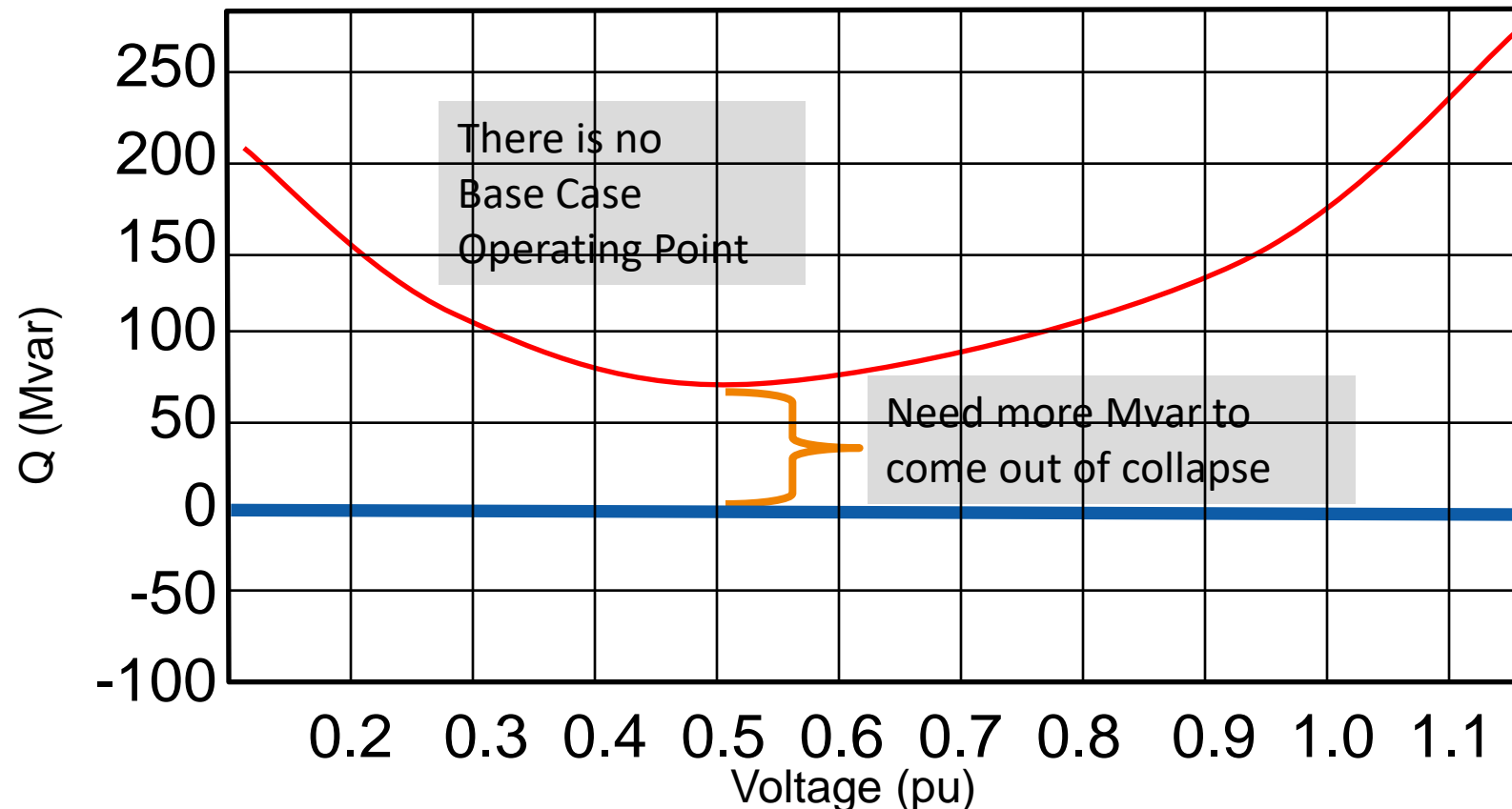


# Example QV Curve

## MVAR Deficiency



- If the QV curve does not cross the x-axis, this means the system can not solve this case



# V-Q Sensitivities

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- PV and QV curves require selection of specific buses for analysis
- Unless known problems exist, the selection of buses could exclude problem buses
- V-Q sensitivities can provide a more system-wide view of stability

# V-Q Sensitivities

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- V-Q sensitivities are calculated from a solved power flow solution at a particular operating point
- V-Q sensitivities can be calculated much more quickly than a full QV curve
- The V-Q sensitivity of a bus is the slope of its QV curve at the given operating point

# Interpreting V-Q Sensitivities

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- V-Q sensitivity indicative of stable/unstable operation
  - Positive sensitivity indicates a stable system. Smaller positive sensitivity indicates more stable system.
  - Negative sensitivity indicates an unstable system. To maintain stability expect voltage (V) to increase as vars (Q) are increased.

# Interpreting V-Q Sensitivities

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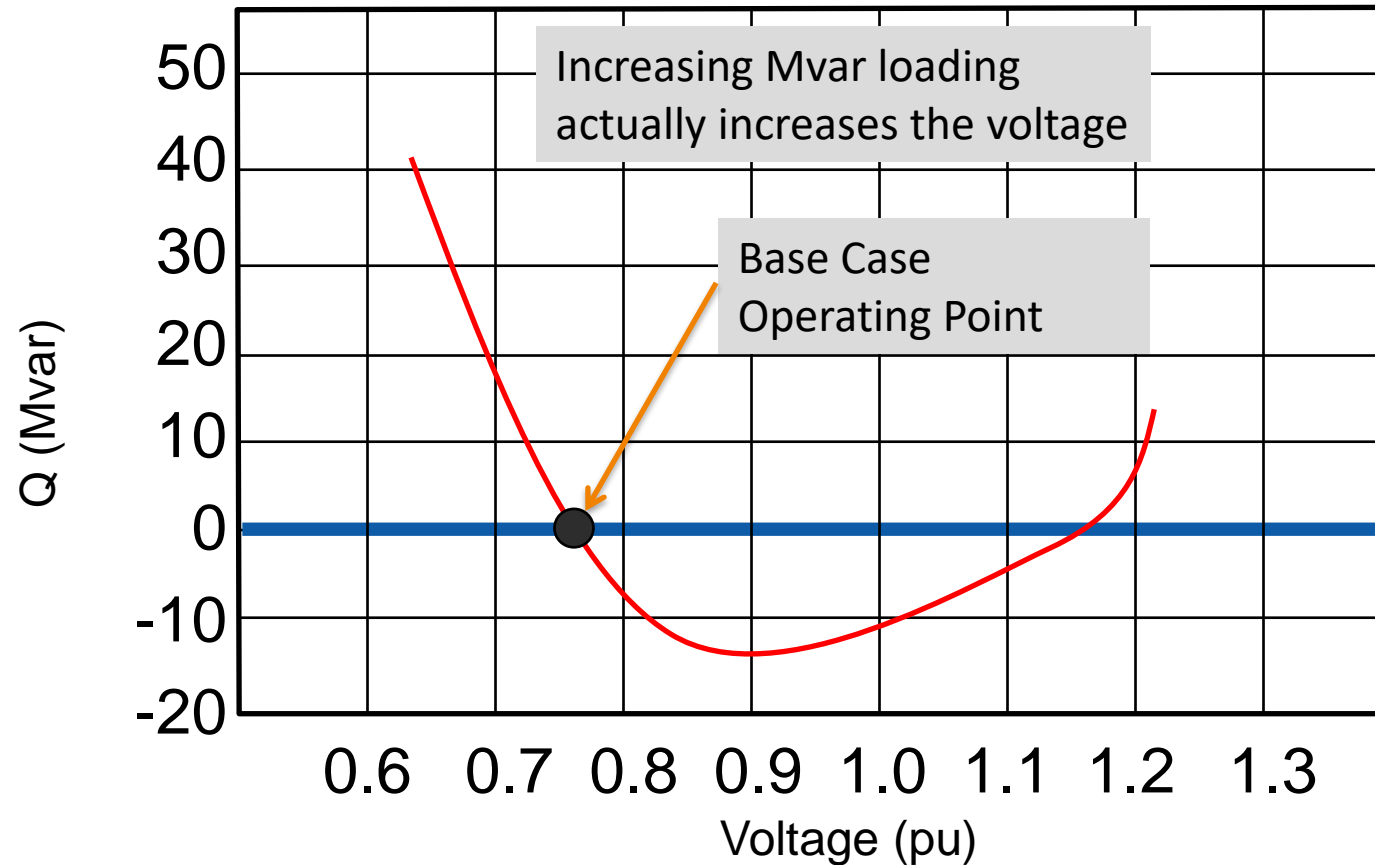
- Non-linearity of V-Q relationship makes comparing the magnitudes of sensitivities between different operating points difficult to determine a relative degree of sensitivity
- Negative V-Q sensitivities can occur at buses near branches that have a negative series reactance
  - Fictitious “star bus” of a three-winding transformer
  - Buses near series capacitors
  - Generally ignore these particular negative values

# Example QV Curve

## Negative V-Q Sensitivity



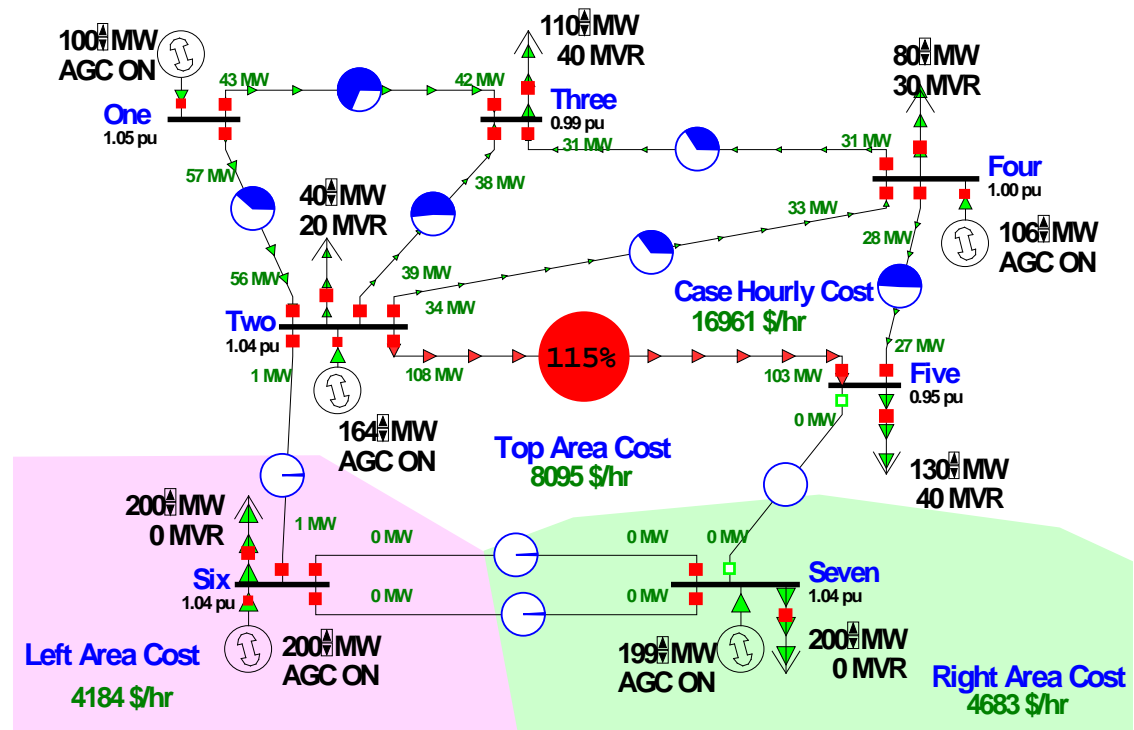
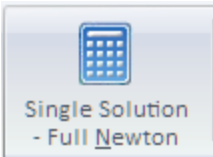
- Base case operating point is on the low voltage side of the curve



# Performing a QV Curve Study



- Open the B7flat.pwb case
- Modify your case by opening the line from Bus 5 to Bus 7
- Click **Single Solution**



# Contingency Definition

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- Go to **Tools** ribbon tab → **Contingency Analysis** to define the contingencies which will be used in the QV study
- Add only one contingency which has a single action:
  - Open Branch 2 (TWO) – 5 (FIVE) CKT 1

# QV Curves Dialog



- Open the QV Curves dialog by choosing **Add Ons** ribbon tab → **QV Curves**

To calculate QV curves at a set of buses, follow these steps: select the set of buses where you want QV curves to be calculated on the Buses tab, specify the settings for various options on the Options tab, and control and monitor the run from the Control/Results tab.

Run

Records Geo Set Columns Options

Buses

Number	Name	Nom kV	QV Selected	Min Volt	Max Volt	Step Size
1	One	138.00	NO			
2	Two	138.00	NO			
3	Three	138.00	YES			
4	Four	138.00	NO			
5	Five	138.00	YES			
6	Six	138.00	NO			
7	Seven	138.00	NO			

Modify Selected Buses to Select Only Single Bus Per Super Bus Note: The active defined contingencies affect the selection of super buses and resulting selected buses.

To add buses to the QV analysis, specify ...

A range of bus numbers  Add

or the name of a bus  Add

Additionally, automatically draw curves for

0 lowest-voltage buses and

0 highest dv/dq buses

from limit group Default

Save ... Load ... Help Close

# Buses Page

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- Choose the buses for which you would like to draw QV curves
  - Toggle the **QV Selected** Column to *YES* for the buses you would like to analyze
  - You may also enter the per unit voltage ranges for which you would like to draw the QV curve (or just leave them blank and a global setting on the Options tab will be used)
- There are also options to select buses for which to automatically draw curves
  - Lowest-voltage buses and
  - Highest  $dv/dq$  buses

# Quantities to Track



- Select system parameters to store as QV curve is traced for plotting after the run
- Select voltage and angle for buses 3 and 5

To calculate QV curves at a set of buses, follow these steps: select the set of buses where you want QV curves to be calculated on the Buses tab, specify the settings for various options on the Options tab, and control and monitor the run from the Control/Results tab.

Quantities to track

Number	Name	Nom kV	Voltage?	kV Voltage?	Angle?	MW Load?	Mvar
1	1 One	138.00	NO	NO	NO	NO	NO
2	2 Two	138.00	NO	NO	NO	NO	NO
3	3 Three	138.00	YES	NO	YES	NO	NO
4	4 Four	138.00	NO	NO	NO	NO	NO
5	5 Five	138.00	YES	NO	YES	NO	NO
6	6 Six	138.00	NO	NO	NO	NO	NO
7	7 Seven	138.00	NO	NO	NO	NO	NO

Modify Existing Bus Tracking to Track Only Single Bus Per Super Bus

Note: The active defined contingencies affect the selection of super buses and

# Options Page: Solution



- Voltage step size (pu), Minimum voltage (pu), and Maximum voltage (pu)
  - Specify default minimum and maximum voltage and step size for use in drawing the QV curves
- Use initial voltage as Vmax
  - Initial voltage at a bus can be selected to be the maximum voltage
  - This option overrides the default option for setting the maximum voltage as well as any bus-specific setting for the maximum voltage
- Global solution options
  - Opens the Simulator Options dialog for setting the default power flow solution options
- QV Power Flow Solution Options
  - Specify any QV-specific power flow solution options to override the default power flow solution options
  - Minimum per-unit voltage for constant power and constant current loads are set to 0 internally for both the base case and contingency scenarios

# Options Page: Solution

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- QV Make-Up Power
  - During the QV curve tracing, the system losses can change significantly requiring a MW adjustment
    - System Slack
      - All changes go to the system slack generator
    - Same as Contingency Analysis
      - Use the contingency analysis make-up power option
      - This is the default starting with Simulator version 19

# Options Page: Contingencies

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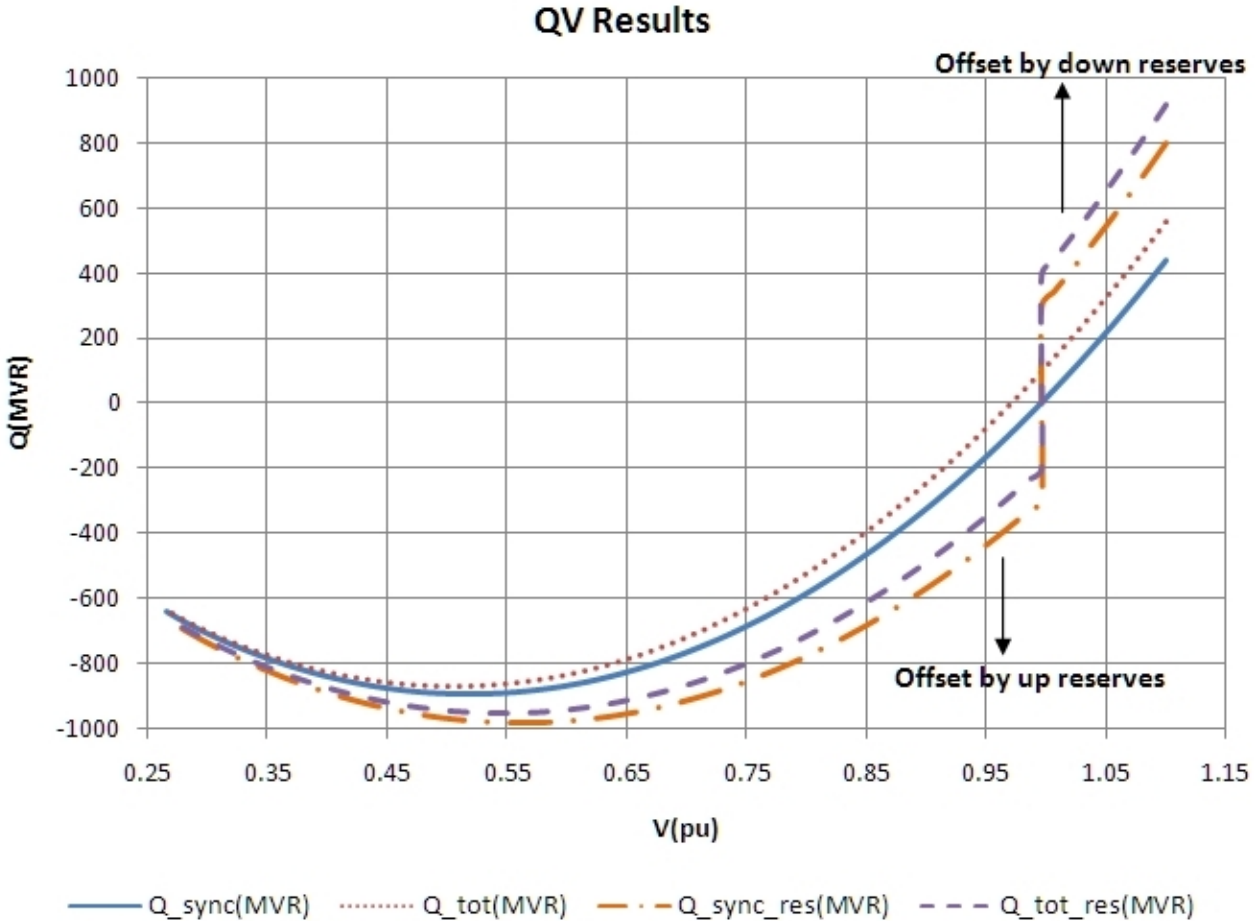
- Process each of the currently defined contingencies
  - **Skip** field must be set to *NO* with the contingency records
- Skip base case
- Attempt to make unsolvable contingencies solvable with synchronous condenser
  - Fictitious generator is allowed to have any output in an attempt at finding a solvable point for the contingency
  - If solvable point is found, QV curve is then determined starting from this point

# Options Page: Output



- Save QV Curve Results to File: optionally specify a text file to save results
- Plot curves as they are computed
  - **QV Autoplot** field for contingencies must be set to YES for contingency scenarios to plot as they are computed
- When plotting V versus Q, treat Q as...
  - Output of fictitious generator ( $Q_{sync}$ )
  - Total reactive injection at the bus including the fictitious generator and any shunts but excluding load ( $Q_{tot}$ )
  - Optionally check “Include reserves” ( $Q_{sync\_res}$  or  $Q_{tot\_res}$ )

# Options: Output Plotting Options



# Handling Reserves



- All Mvar devices at a study bus are turned off control during the QV curve tracing
- Nominal Mvar reserves are recorded prior to starting the QV curve tracing
  - Generators on AVR control
  - Switched shunts not fixed
- Actual Mvar reserves are recorded at each voltage step
  - Actual switched shunts reserves equal to square of voltage multiplied by the nominal reserves
- QV curve can be offset by the available reserves when plotting

# Results Page



- Click the **Run** button to calculate QV curves
- Listing tab: Right-click on a scenario, then click **Plot QV curve**
  - Select multiple scenarios to show all on same plot
- Plots tab: Create custom plots based on tracked quantities

The screenshot shows the 'QV Curves' application window. The 'Results' tab is active, displaying a table with columns: Number, Name, Nom kV, Case Name, V at Q0, Q0, Qinj\_0, Vmax, Q at VMax, and Qinj at Vmax. The table contains four rows of data. The second row (Number 3) has a 'DIVERGED' status in the 'Q0' column. A context menu is open over this row, with the 'Plot QV Curve' option highlighted. The 'Run' button is visible at the top left of the window.

Number	Name	Nom kV	Case Name	V at Q0	Q0	Qinj_0	Vmax	Q at VMax	Qinj at Vmax
1	3 Three	138.00	BASECASE	0.99	0.00	0.00	1.1000	505.82	505.82
2	3 Three	138.00	BRANCH 2 T	DIVERGED	DIVERGED	DIVERGED	DIVERGED	DIVERGED	DIVERGED
3	5 Five	138.00	BASECASE	0.95	0.00	0.00	1.1000	191.52	191.52
4	5 Five	138.00	BRANCH 2 T	DIVERGED	DIVERGED	DIVERGED	1.1000	159.12	159.12

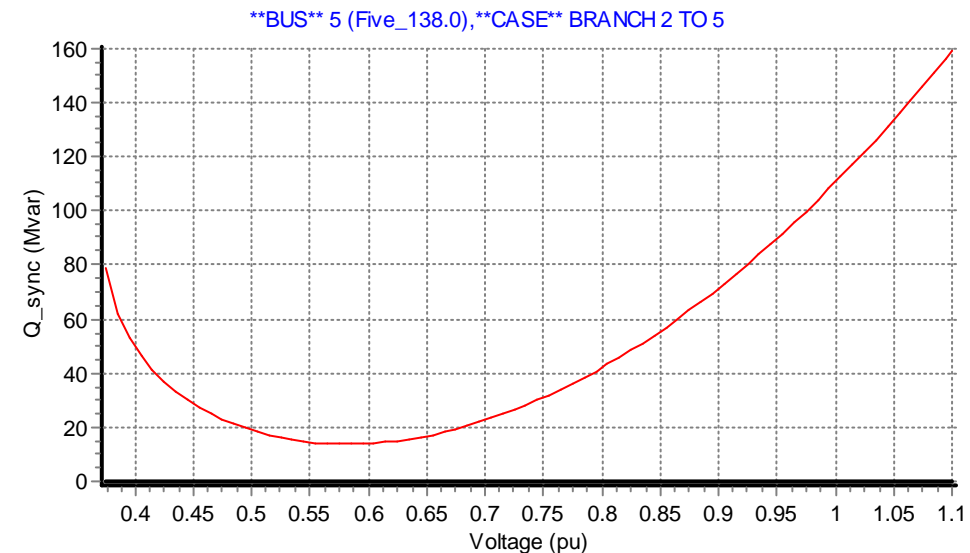
QV at Bus 3 diverged under contingency. Reactive support from the fictitious generator at Bus 3 cannot achieve a power flow solution.

# Example QV Curve

## MVAR Deficiency



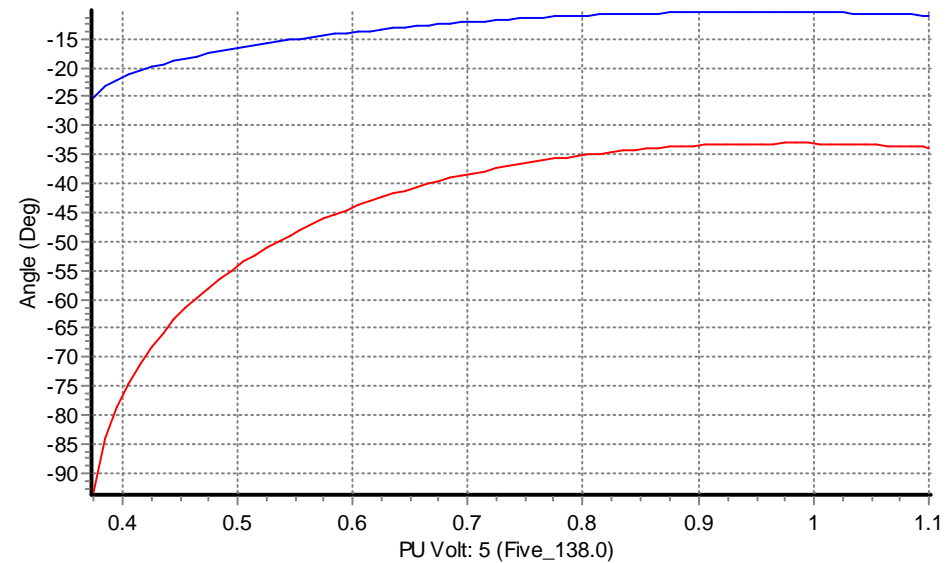
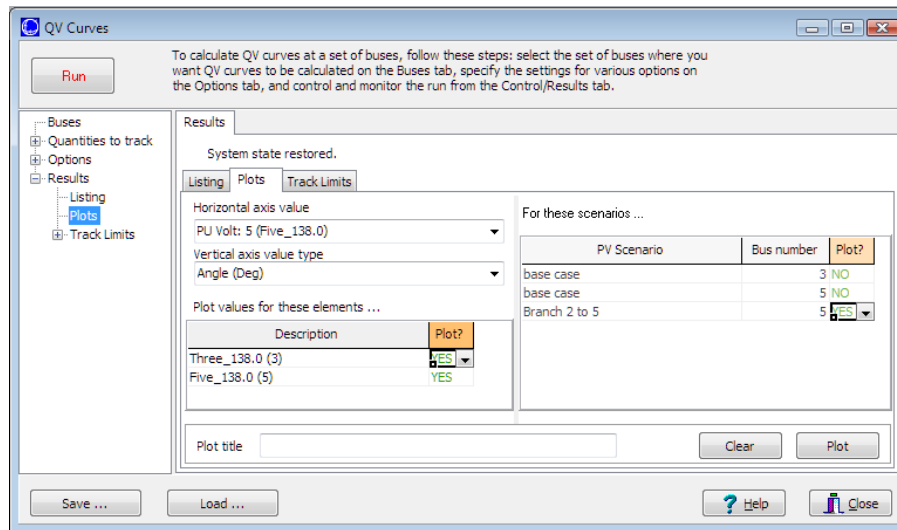
- QV curve at Bus 5 under contingency
- There is no X-intercept
  - This means there is no power flow solution without additional MVAR support
  - The curve shows that about 15 MVAR of support at the bus is needed in order to have a power flow solution.



# Results: Plots



- For the Branch 2-5 Contingency Scenario, plot bus 3 and 5 angles (vertical axis) as bus 5 voltage (horizontal axis) varies



— Branch 2 to 5: Three\_138.0 (3) — Branch 2 to 5: Five\_138.0 (5)

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