

Voltage Droop Control in Power Flow Solutions



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Presentation Outline

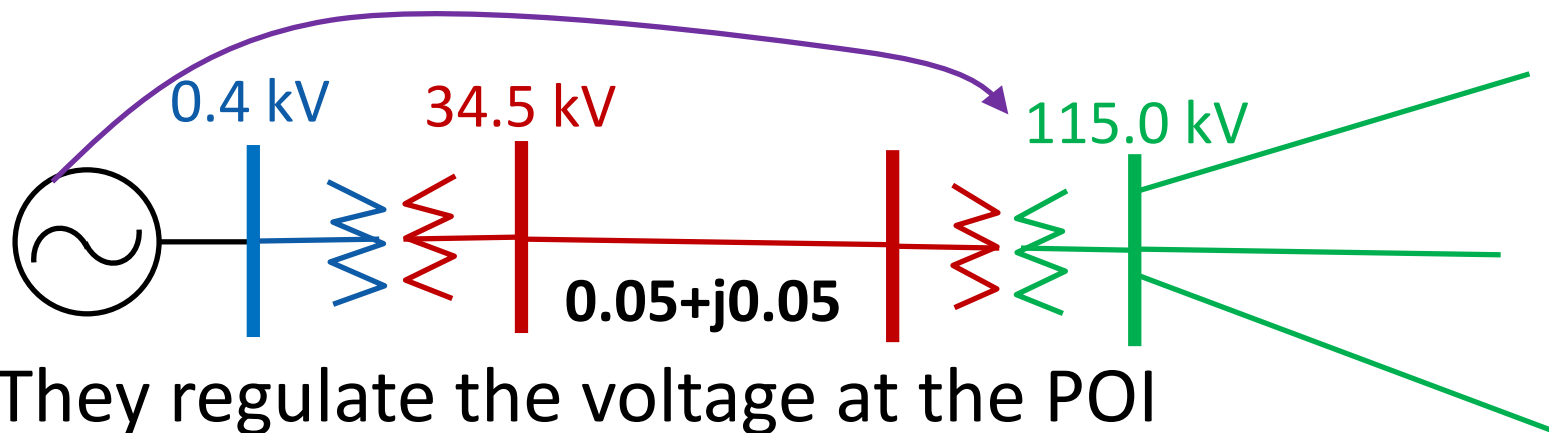


- Need: Renewable Plants Q-V characteristic at point of interconnection
- Solution: Introduction of Voltage Droop Control (with deadband)
- PowerWorld Help Documentation Link
 - https://www.powerworld.com/WebHelp/#MainDocumentation_HTML/PowerFlow%20Voltage%20Drop%20Control%20with%20Deadband.htm

Renewable Generator Questions started in 2013



- Renewable generators regulate a point closer to the point of interconnection

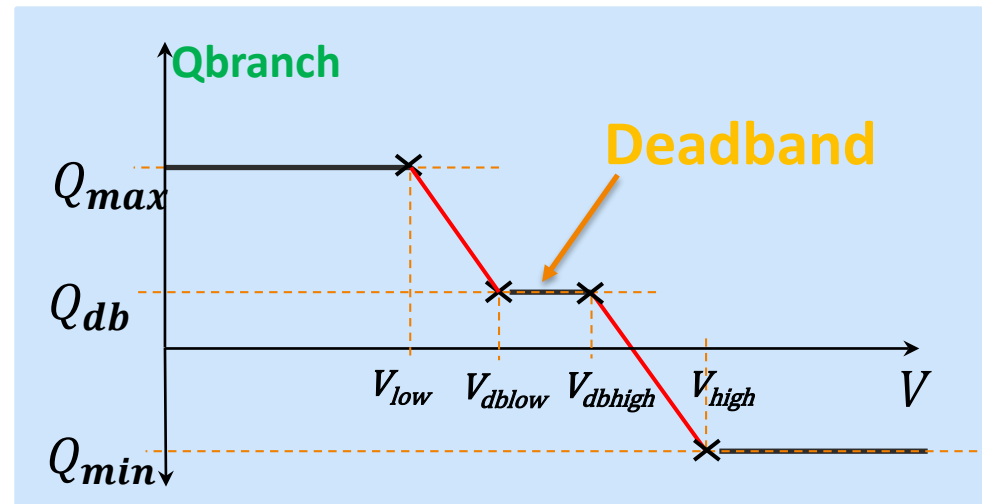
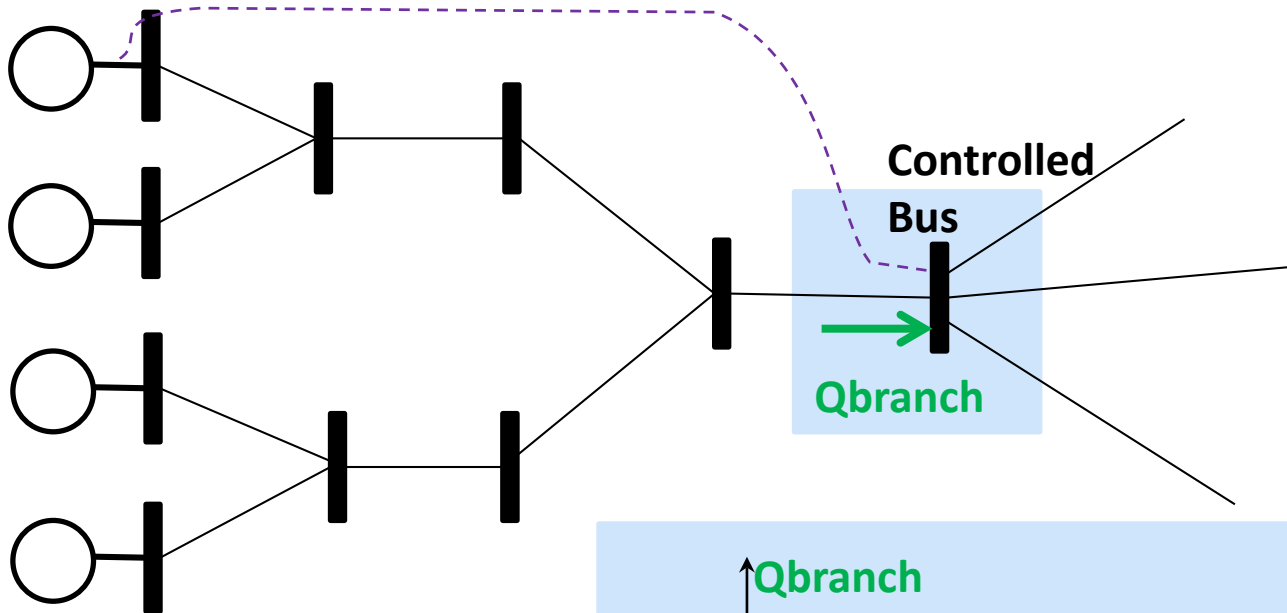


- They regulate the voltage at the POI (the 115 kV bus) against a QV characteristic curve
- Starting to get questions about Solar PV plant voltage control

Typical Configuration may have multiple Generators



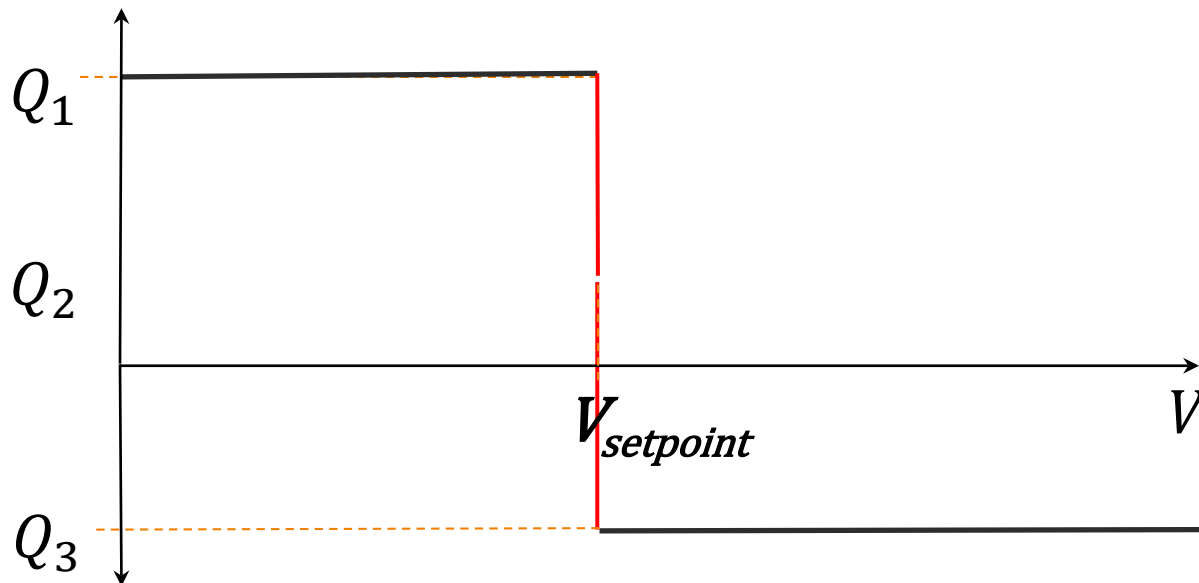
Generators are all configured to regulate the Controlled Bus



Traditional Generator Power Flow Model



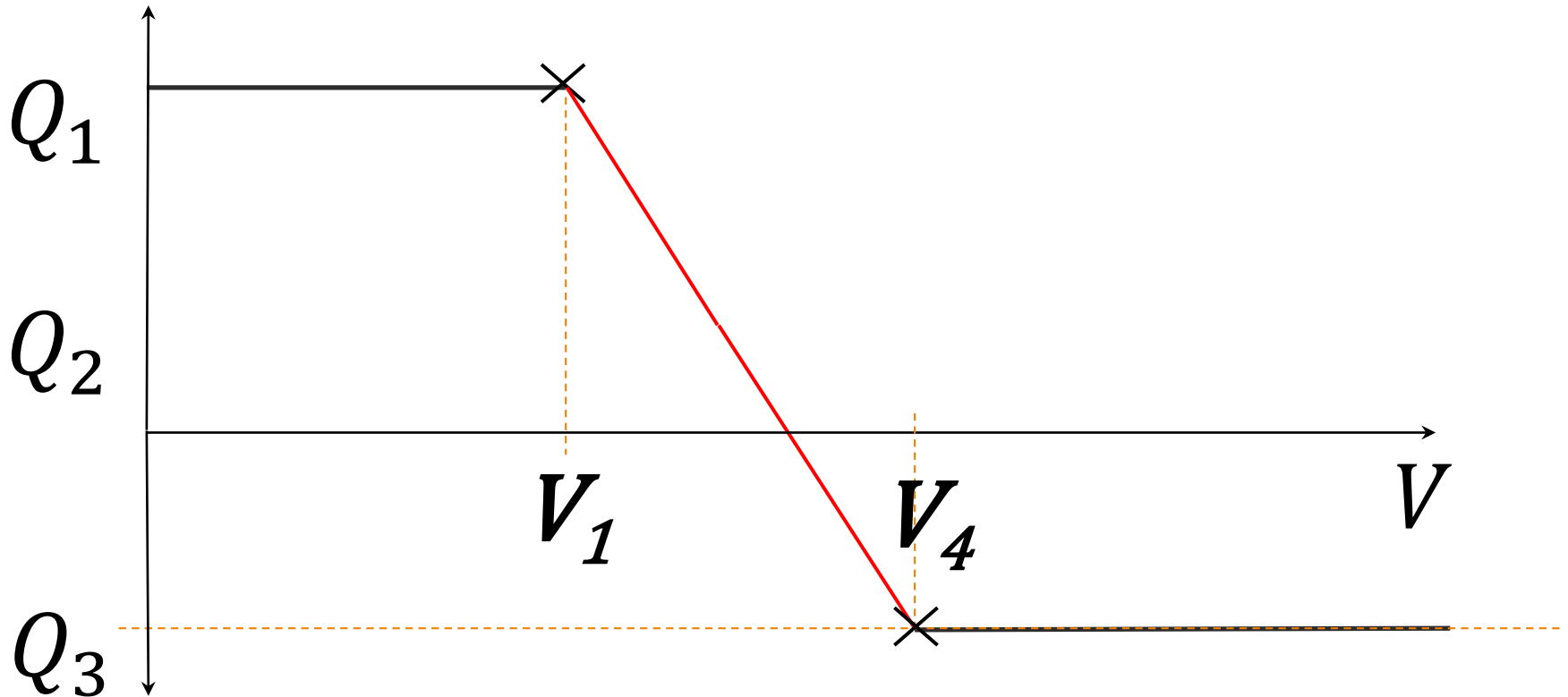
- PV and PQ bus
 - Either meeting the voltage setpoint (PV)
 - Or at a $Q_{\max}$ or $Q_{\min}$ limit (PQ)



Slope Control



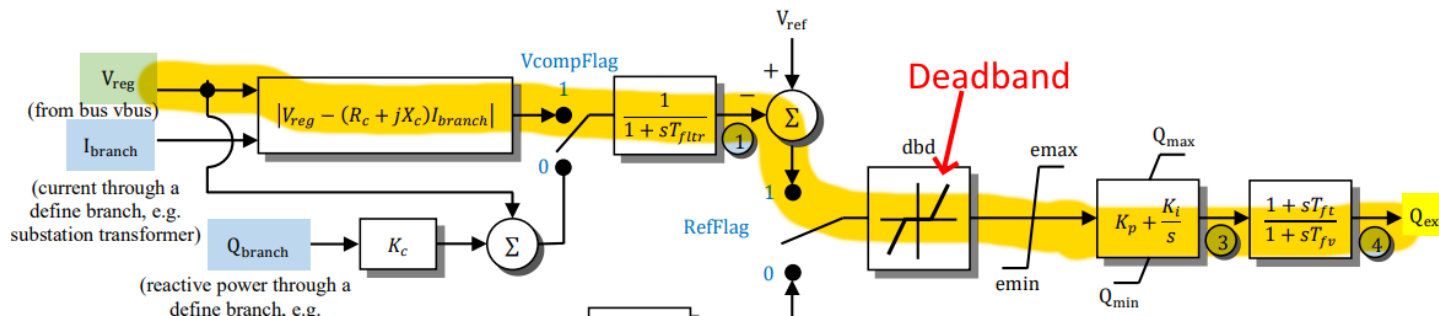
- Getting questions about solar farms that have voltage control that is not a setpoint



Slope Control with Deadband

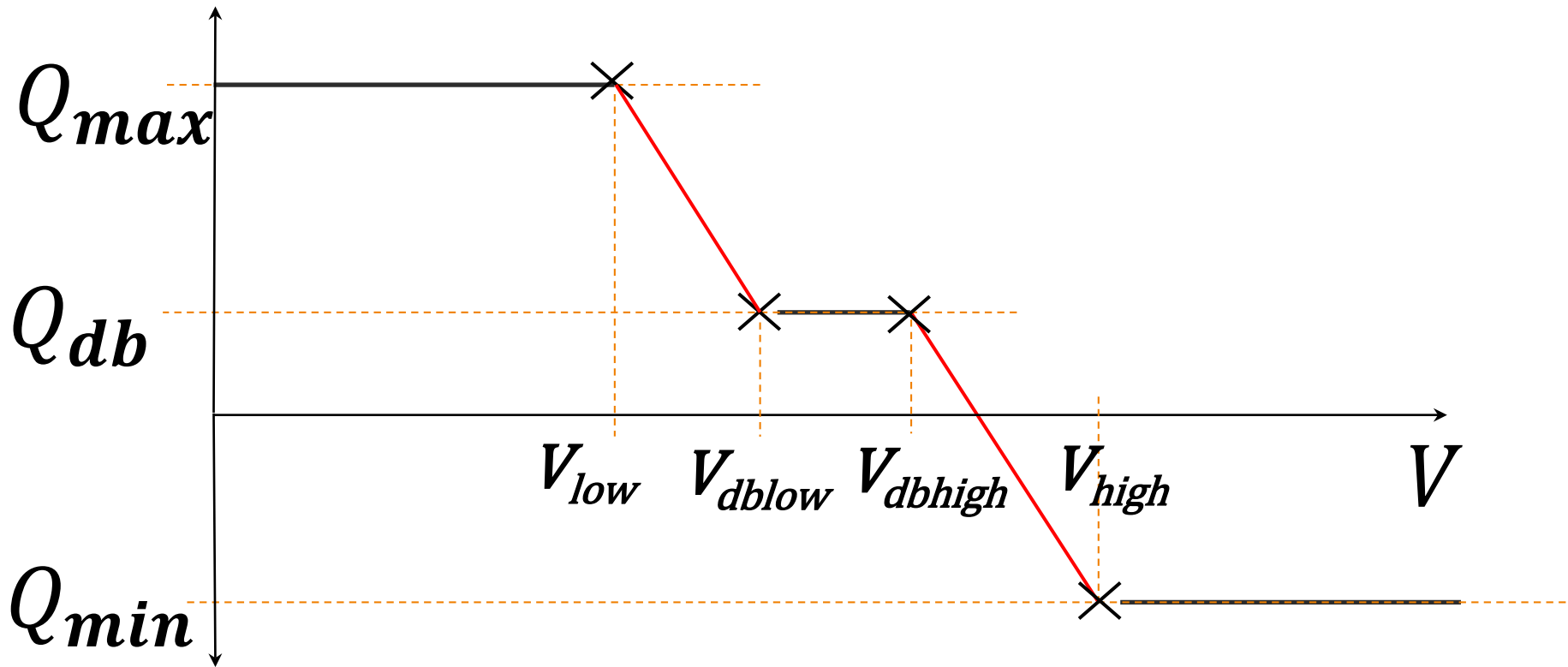


- Getting questions about solar farms that have voltage control that is not a setpoint
- A deadband is given**
 - 0.98 to 1.02 per unit voltage – provide zero Mvars (or a constant value)
- Once outside these deadband, a negative slope characteristic is followed
- Maximum and Minimum Mvar will be hit eventually
- The various transient stability models have features like this (REPC_A) → power flow however does not**



REPC_A

QV Characteristic with Deadband





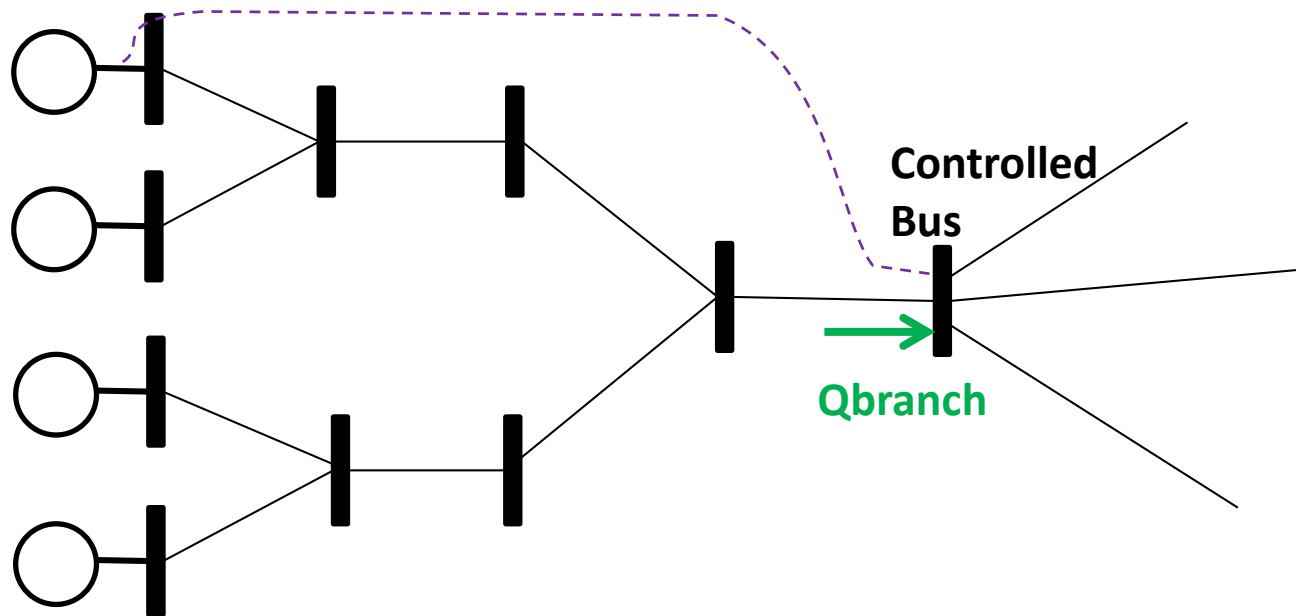
Conclusion: Voltage Droop Control (with deadband) is needed in the Power Flow Solution

Merge this with remote regulation: What extra data is needed?



- What voltage is being controlled?
 - Use the regulated bus specification with generators
- What reactive power is being used in compensation calculation?
 - User does **not** need to provide this. Software will look at the topology of the system to figure this out

Generators
are all
configured
to regulate
the
Controlled
Bus

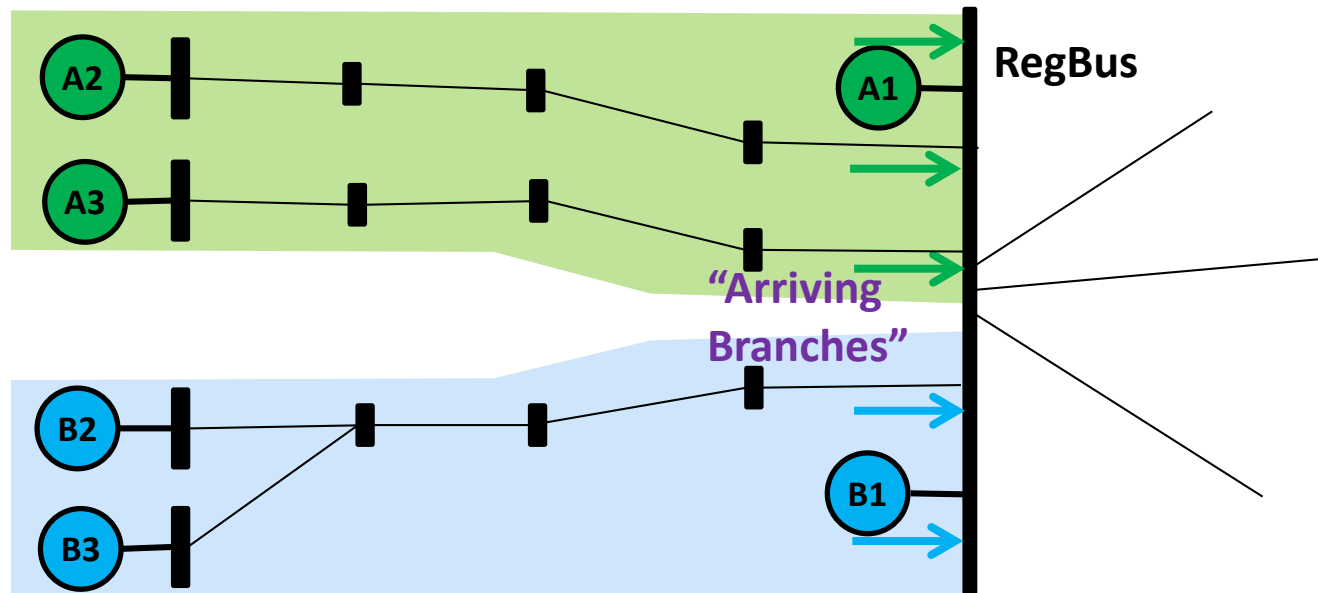


Extra Data for a Generator



- You might have two separate groups of generators that regulate the same bus, but operate on different Droop Curves
 - Green and Blue generators in separate groups
 - This is OK, because of the Droop! Not a voltage setpoint

Generators are
all configured to
regulate the
RegBus



New Object: VoltageDroopControl



Model Explorer: Voltage Droop Controls

Explore Fields

- Recent
- Network
 - Branches By Type
 - Branches Input
 - Buses
 - DC Transmission Lines
 - Generators
 - Impedance Correction Tables
 - Line D-FACTS Devices
 - Line Shunts
 - Loads
 - Mismatches
 - Multi-Terminal DC
 - Switched Shunts
 - Three-Winding Transformers
 - Transformer Controls
 - Voltage Control Groups
 - Voltage Droop Controls**
 - VSC DC Transmission Lines
 - Aggregations
 - Areas
 - Balancing Authorities

Open New Explorer

Voltage Droop Controls

Filter Advanced Voltage Droop Control Find... Remove Quick Filter

Voltage Droop Controls All Generators All Regulated Buses

	Name	Enabled	Qdb Qmax Qmin Auto	Volt Deviation	Qdb	Qmax	Qmin	Vlow	Vdblow	Vdbhigh	Vhigh	Validation	Equation Count	Droop Curve Mvar	Branch Mvar RegBus	Gen Mvar RegBus	Droop Curve Mismatch	Vpu Reg	Reg Bus Num	Reg Bus
1	Droop A	YES	NO	NO	10.000	50.000	-50.000	0.940000	0.970000	1.010000	1.040000	Good	1	-27.96	-17.96	-10.00	0.00	1.028979	1	Bus '1'
2	Droop B	YES	NO	NO	0.000	50.000	-50.000	0.950000	0.980000	1.020000	1.050000	Good	1	-14.96	-10.97	-4.00	0.00	1.028979	1	Bus '1'

Generators assigned to Selection Regulated Buses

	Number of Bus	Name of Bus	ID	Labels All	Status	Voltage Droop Control	RegBus Num (ZBR)	Remote Reg %	RegBus Num	Reg Bus	Gen MW	Gen Mvar	Set Volt	AVR	Min Mvar	Max Mvar
1	1	One	1		Closed	Droop B	1	4.000	1	Bus '1'	15.000	-3.999	1.04038	YES	-6.000	6.000
2	9	9	1		Closed	Droop B	1	8.000	1	Bus '1'	35.000	-7.999	1.04038	YES	-10.000	10.000

Control : Droop B
RegBus : One (1)

> Voltage Control Groups

Voltage Droop Controls

VSC DC Transmission Lines

Aggregations

PowerWorld Simulator: New Object:

VoltageDroopControl



Field	Type	Description
Name	String	Unique Identifier for the Object
Enabled	Boolean	Indicates if the control is turned on or off for the control
QAuto	Boolean	NO means to use the Qdb, Qmax, and Qmin values directly. If set to YES, then the values of Qdb, Qmax and Qmin are automatically calculated based on the summation of generator Qmax and Qmin
VDeviation	Boolean	NO means to use the values of Vlow, Vdblow, Vdbhigh, and Vhigh directly. If set to YES, then the input values of Vlow, Vdblow, Vdbhigh, and Vhigh are interpreted as deviations away from the voltage setpoints of the generators
Qdb	Float	The reactive power in Mvar between <i>Vdblow</i> and <i>Vdbhigh</i>
Qmax	Float	The maximum reactive power in Mvar for voltages below <i>Vlow</i>
Qmin	Float	The minimum reactive power in Mvar for voltages above <i>Vhigh</i>
Vlow	Float	Voltage in per unit below which the reactive power is <i>Qmax</i>
Vdblow	Float	Voltage in per unit above which the reactive power is <i>Qdb</i>
Vdbhigh	Float	Voltage in per unit below which the reactive power is <i>Qdb</i>
Vhigh	Float	Voltage in per unit above which the reactive power is <i>Qmin</i>

Voltage Droop Control Dialog



Voltage Droop Control

Name: ☒ Enabled

QV Characteristic:

Vlow	0.940000	Qmax	50.000
Vdblow	0.970000	Qdb	10.000
Vdbhigh	1.010000		
Vhigh	1.040000	Qmin	-50.000

☐ Treat Vlow, Vdblow, Vdbhigh, and Vhigh as the deviation from the voltage setpoint

☐ Automatically calculate Qmax and Qmin from generators in Voltage Droop Control

Control : Droop A

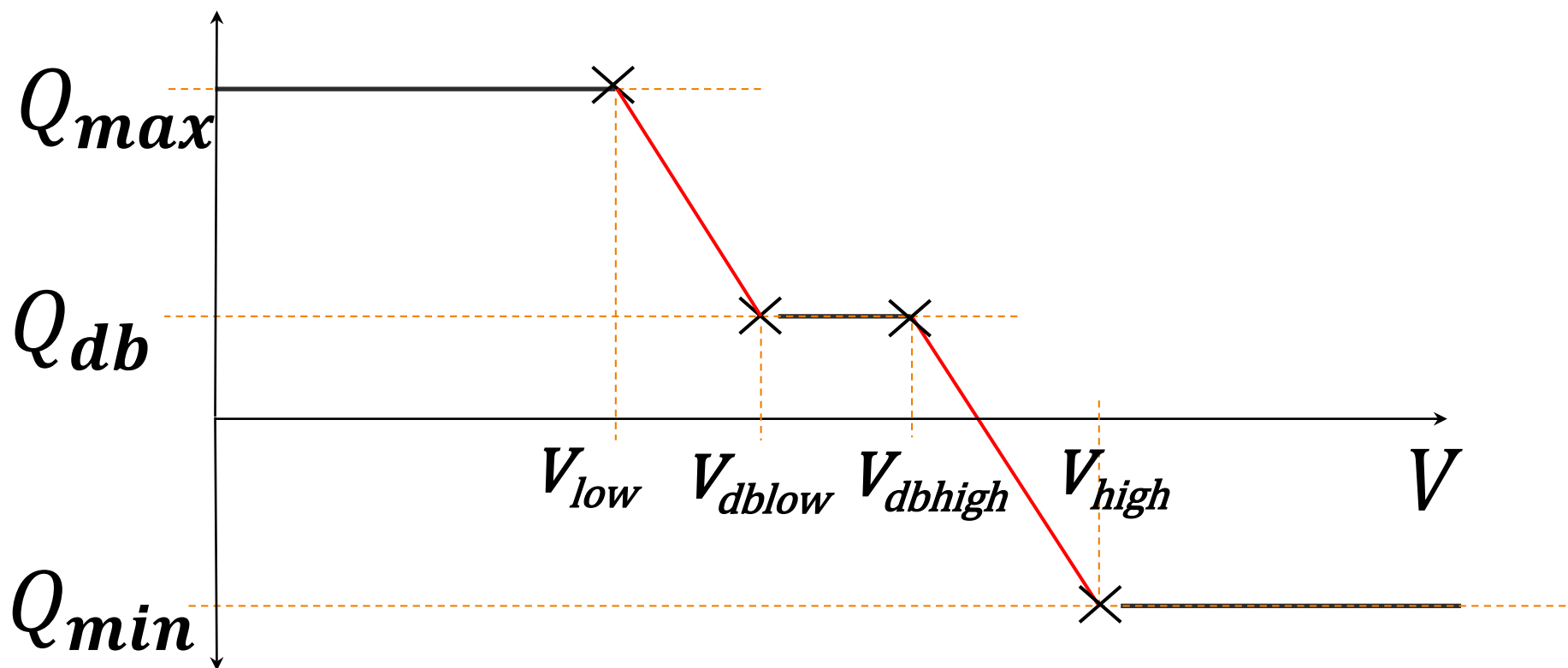
Graph showing Voltage Droop Control characteristic (Q vs V). The curve is a piecewise linear function with four segments:

- Segment 1: Vlow to Vdblow, Qmax to Qdb
- Segment 2: Vdblow to Vdbhigh, Qdb to Qdb
- Segment 3: Vdbhigh to Vhigh, Qdb to Qmin
- Segment 4: Vhigh to Vhigh, Qmin to Qmin

Buttons:

Droop Curve:

Reactive Power as Function of Voltage



Droop Curve:

Reactive Power as Function of Voltage



- When **Qauto=YES**, this means

QmaxUsed = Summation of Generator MvarMax

QminUsed = Summation of Generator MvarMin

QdbUsed = 0

- When **Vdeviation=YES**, this means

Vset = Voltage setpoint from generators

VlowUsed = **Vset** + Vlow

VdblowUsed = **Vset** + Vdblow

VdbhighUsed = **Vset** + Vdbhigh

VhighUsed = **Vset** + Vhigh

- White paper spells out special cases as well

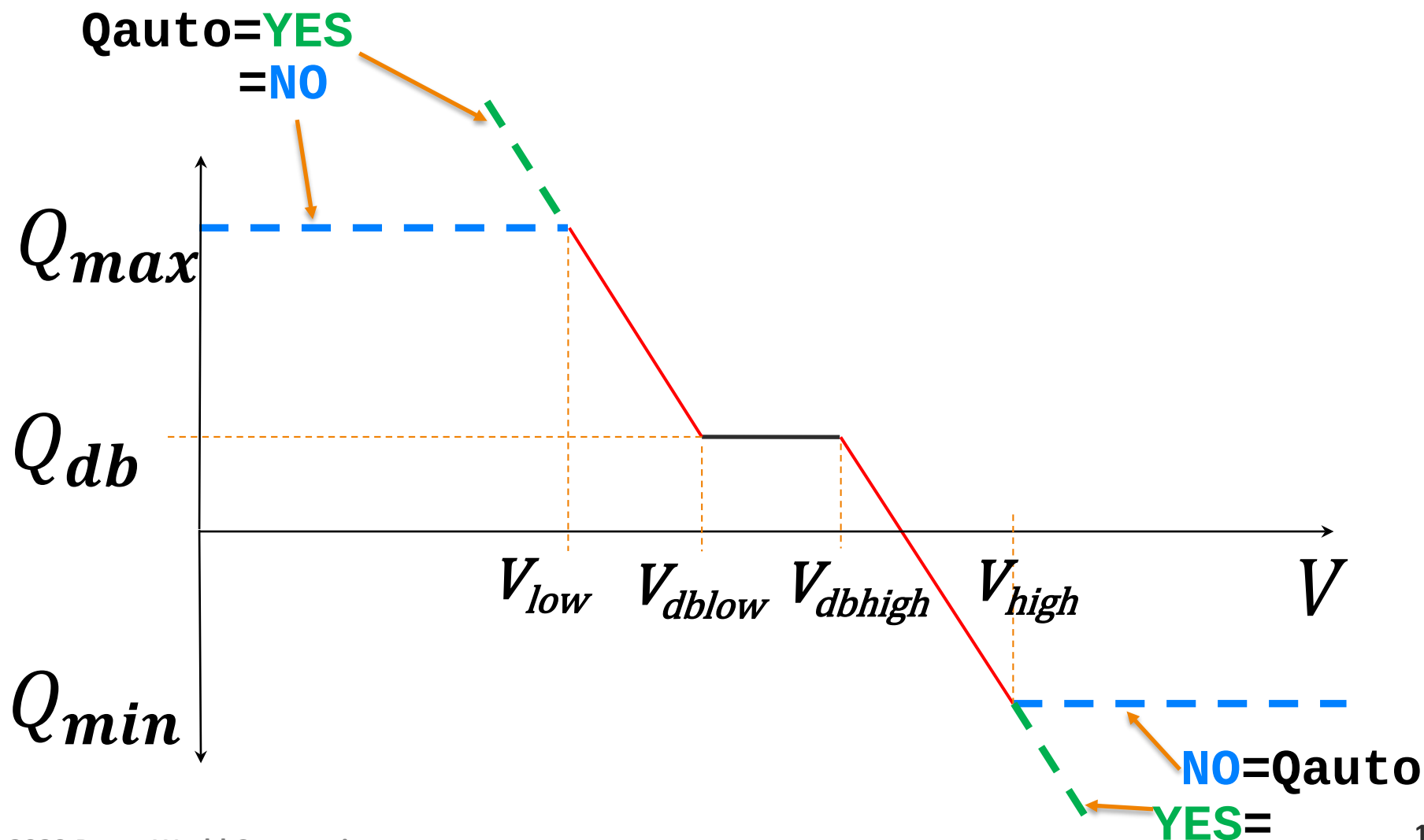
Comment about “Qmax” and “Qmin”



- For renewable energy plants, “Plant Qmax” and “Plant Qmin” is not always equal the summation of the individual generator MvarMax and MvarMin
 - Thus we enforce the curve as shown regardless
- When using the flag **Qauto=YES** however, we follow the slope base the Vhigh and Vlow points

Droop Curve:

Reactive Power as Function of Voltage



New Field for a Generator:

VoltageDroopControl



- **VoltageDroopControl** is a string field for a generator
 - This references the name of the **VoltageDroopControl** object to which the generator belongs
 - A blank string indicates it does not belong to such a control (default is blank)

Things that are NOT extra inputs



- The following are automatically determined by the software
 - The regulated bus (RegBus) of the **VoltageDroopControl** is determined by looking at the RegBus of the generators that are assigned to the **VoltageDroopControl** object
 - Also any buses connected by very low impedance branches are considered the same RegBus by the software
 - This uses the “ZBR Threshold” which defaults to 0.0002 in PowerWorld Simulator
 - A list of “Arriving Branches” will be automatically determined by looking at the network which connects the generators in the **VoltageDroopControl** to the RegBus

Example



- 2 **VoltageDroopControls** : “Droop A”, “Droop B”

X Voltage Droop Controls X Generators												
	Name	Enabled	Qdb	Qmax	Qmin	Vlow	Vdblow	Vdbhigh	Vhigh	Gen Mvar RegBus	Branch Mvar RegBus	Droop Curve Mvar
1	Droop A	YES	10.0	50.0	-50.0	0.940	0.970	1.010	1.040	-10.00	-17.9597	-27.9577
2	Droop B	YES	0.0	50.0	-50.0	0.950	0.980	1.020	1.050	-4.00	-10.9654	-14.9647

- Several generators assigned to these

X Generators X Voltage Droop Controls						
	Number of Bus	ID	Voltage Droop Control	Gen MW	Gen Mvar	Remote Reg %
1	1	1	Droop B	15.00	-4.00	4.000
2	1	2	Droop A	5.00	-10.00	2.000
3	1	3		0.00	10.00	100.000
4	9	1	Droop B	35.00	-8.00	8.000
5	10	1	Droop A	10.00	-15.00	3.000
6	10	2	Droop A	20.00	-5.00	1.000
7	10	3		0.00	-6.00	100.000
8	11	1	Droop A	15.00	-5.00	1.000
9	11	2		0.00	22.00	100.000

Voltage Droop Control Dialog



Model Explorer: Voltage Droop Controls

Explore Fields

- DC Transmission Lines
- Generators (13)
 - Impedance Correction Tables
 - Line D-FACTS Devices
 - Line Shunts
- Loads (6)
- Mismatches (11)
- Multi-Terminal DC
- Switched Shunts
- Three-Winding Transformers
- Transformer Controls
- Voltage Control Groups
 - Voltage Droop Controls (2)**
 - VSC DC Transmission Lines
- Aggregations
 - Areas (3)
 - Balancing Authorities (3)

Open New Explorer

Voltage Droop Controls X Buses

Filter Advanced Generator Find... Remove Quick Filter

Voltage Droop Controls All Generators

	Name	Enabled	Qdb	Qmax	Qmin	Vlow	Vdblow	Vdbhigh	Vhigh	Validation	Droop Curve Mvar	Branch Mvar RegBus	Gen Mvar RegBus	Droop Curve Mismatch
1	Droop A	YES	10.000	50.000	-50.000	0.940000	0.970000	1.010000	1.040000	Good	-27.96	-17.96	-10.00	0.00
2	Droop B	YES	0.000	50.000	-50.000	0.950000	0.980000	1.020000	1.050000	Good	-14.96	-10.97	-4.00	-0.00

Generators assigned to selected Voltage Droop Control

	Number of Bus	Name of Bus	ID	Labels All	Status	Voltage Droop Control	R
1	1	One	2		Closed	Droop A	
2	10	10	1		Closed	Droop A	
3	10	10	2		Closed	Droop A	
4	11	11	1		Closed	Droop A	

Search Search Now Options

Droop A

Coordination Between Generators



- The implementation in the power flow solution is similar to the implementation for coordination of remotely regulating generators that maintain a voltage setpoint (PV bus concept)
 - Same concept is used for sharing Mvar between multiple generators assigned to same VoltageDroopControl and Regulated Bus
- Then just replace the voltage equation with an equation representing the voltage droop curve
 - Multiple **VoltageDroopControls** sharing a regulated bus adds some complexity though

VoltageDroopControl Equation



- Define the following
 - **MvarArriving** = Summation of Mvar on AC branches arriving at Regulated Bus coming from the generators
 - **MvarGenRegBus** = Summation of Mvar for Generators assigned to the Voltage Droop Control that are at the regulated bus
 - Note: This includes generator with AVR=NO.
 - Any generator in the VoltageDroopControl contributes to the Mvars regardless
 - **MvarDroopCurve** = Evaluation of the Droop Characteristic Curve at the per unit voltage at the regulated Bus
- **VoltageDroopControl** will enforce an equation that

$$\text{MvarDroopCurve} = \text{MvarArriving} + \text{MvarGenRegBus}$$

- This replaces the voltage equality that is used in remotely regulated voltage equations that have always existed

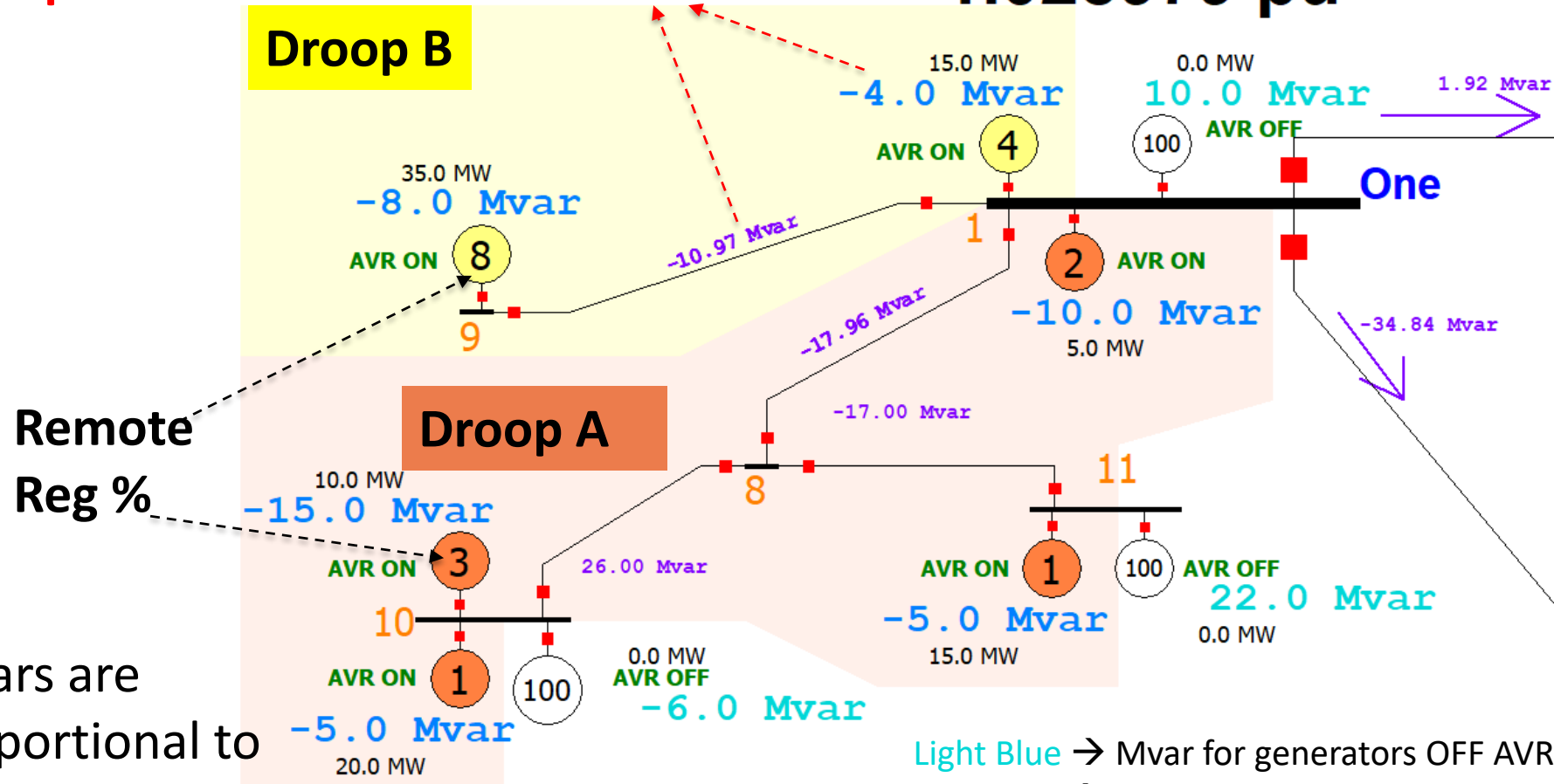
Example Operating Point



Droop A = -27.96 Mvar

Droop B = -14.97 Mvar = Summation

1.028979 pu



Mvars are
proportional to
Remote Reg %

Light Blue → Mvar for generators OFF AVR
Dark Blue → Mvar for generators ON AVR

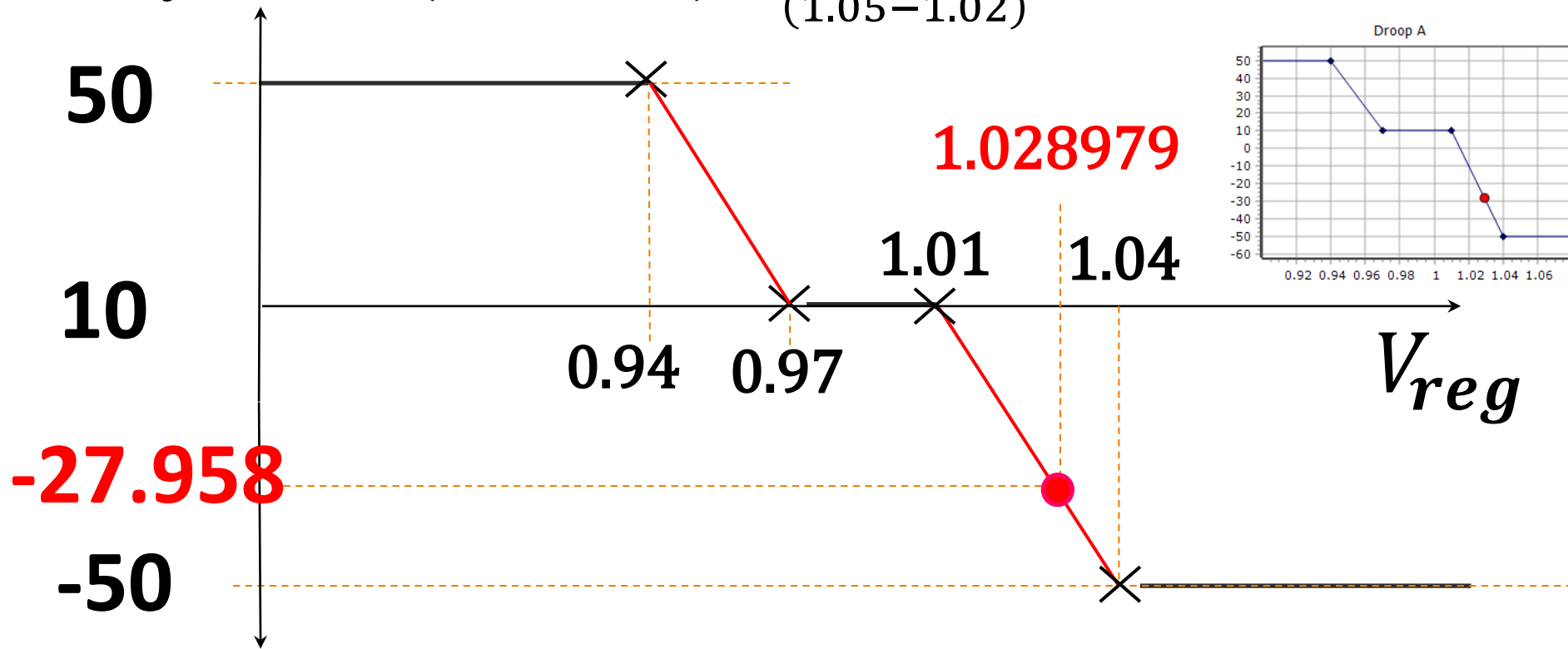
Droop A:

Example $V_{reg}=1.028979$



- Example Operating Point For “Droop A”

- $Q = 10 + (-50 - 10) \frac{(1.028979 - 1.02)}{(1.05 - 1.02)} = -27.958$



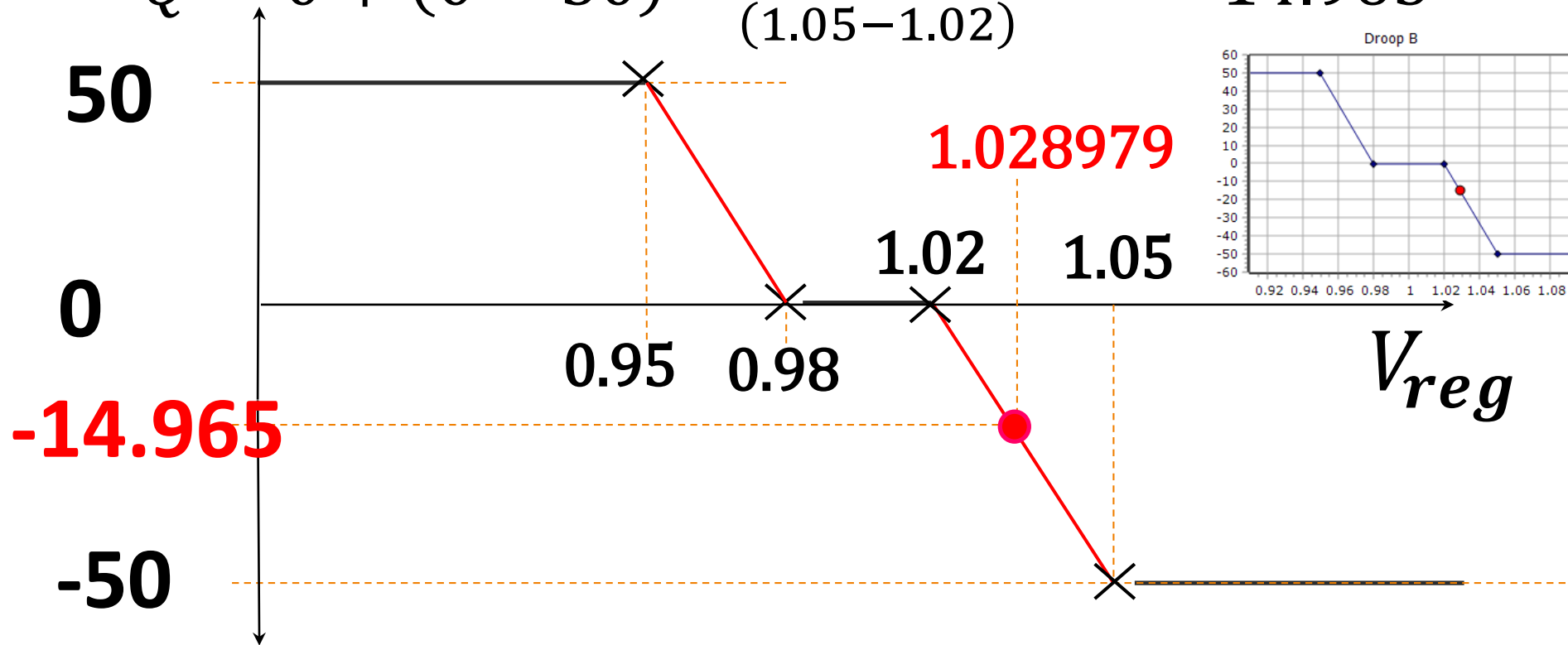
Droop B:

Example $V_{reg}=1.028979$

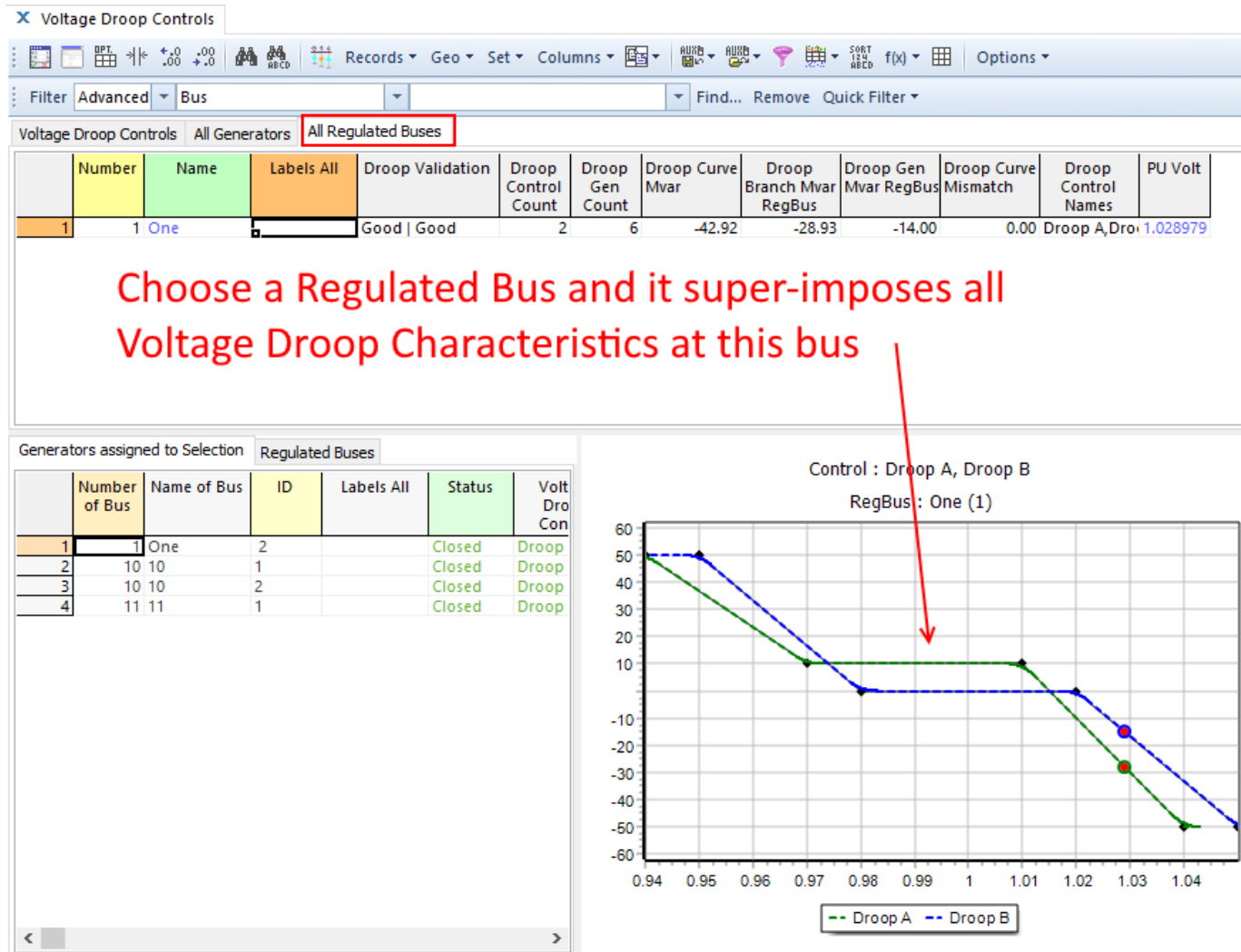


- Example Operating Point For “Droop B”

$$Q = 0 + (0 - 50) \frac{(1.028979 - 1.02)}{(1.05 - 1.02)} = -14.965$$



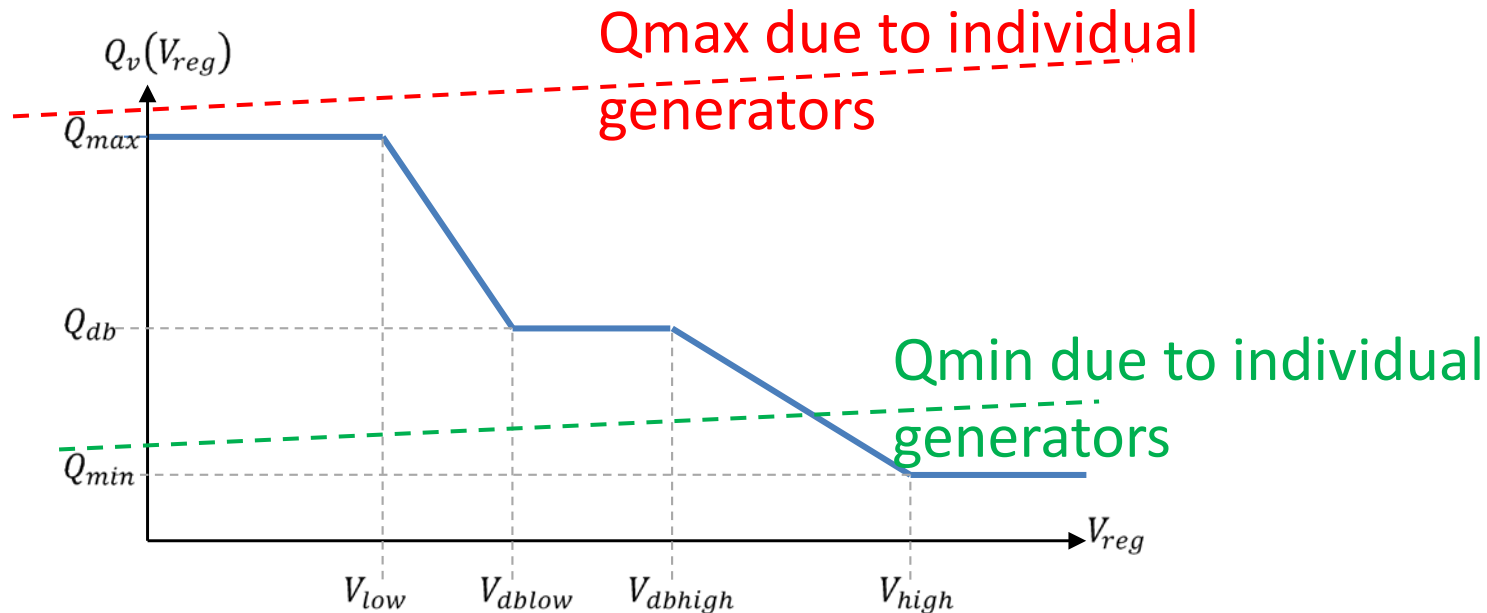
PowerWorld shows multiple characteristics at Regulated Bus



Generator Limits: Same as before



- Handling individual generator limits must still be handled
 - Same as existing remotely regulating voltage control
 - Also need to handle that there can be generators at the regulated bus that belong to the same VoltageDroopControl

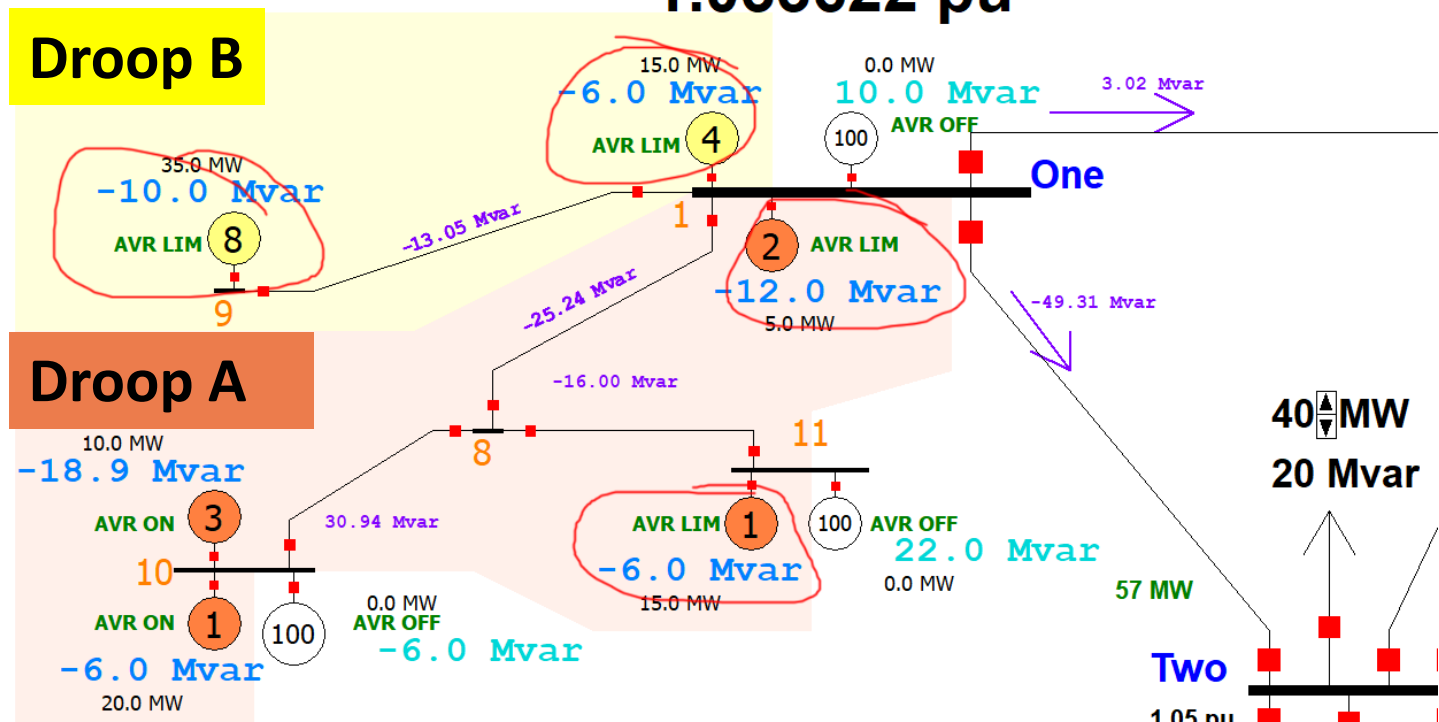


Generators Hitting Limits



- Change voltage setpoint at bus 2 to 1.05 per unit
- Generators at bus 1, 9, and 11 all hit Mvar Limits
- All generators in “Droop B” are at limits

1.033622 pu



Droop B at Mvar limits



- Droop B no longer operating on the Curve

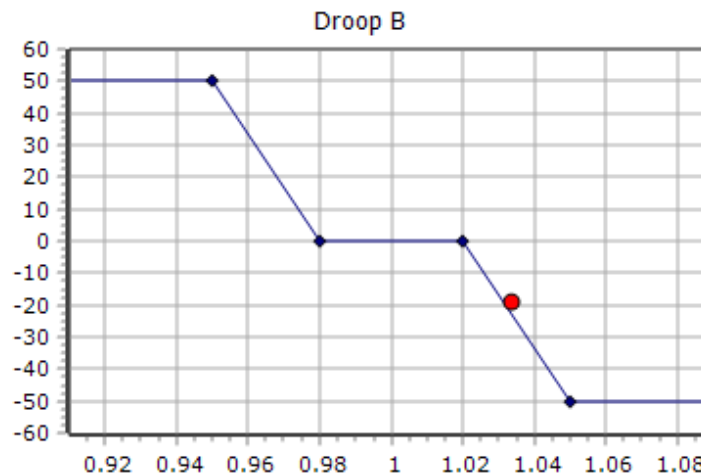
Voltage Droop Controls All Generators

	Name	Enabled	Qdb	Qmax	Qmin	Vlow	Vdblow	Vdbhigh	Vhigh	Validation	Droop Curve Mvar	Branch Mvar RegBus	Gen Mvar RegBus	Droop Curve Mismatch
1	Droop A	YES	10.000	50.000	-50.000	0.940	0.970	1.010	1.040	Good	-37.24	-25.24	-12.00	0.00
2	Droop B	YES	0.000	50.000	-50.000	0.950	0.980	1.020	1.050	Good	-22.70	-13.05	-6.00	-3.65

Mismatch
= -3.65

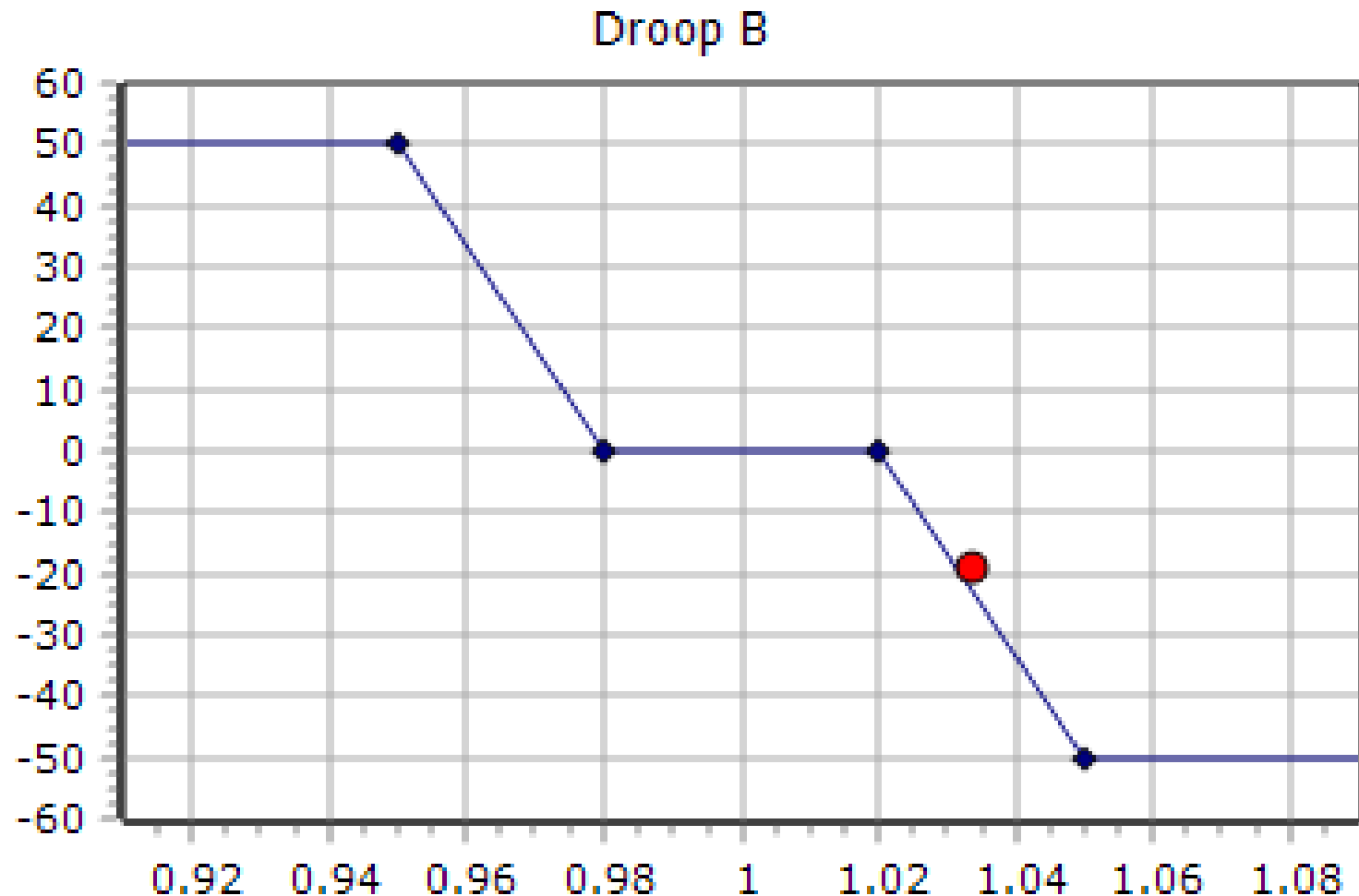
Generators assigned to selected Voltage Droop Control

	Number of Bus	Name of Bus	ID	Labels All	Status	Voltage Droop Control	Remote
1	1	One	1		Closed	Droop B	
2	9	9	1		Closed	Droop B	



Search Search Now Options ▾

Closeup of Red Dot not on Curve



Conclusion



- PowerWorld Simulator Version 21 has implemented these new features for Voltage Droop Control
 - New Object: VoltageDroopControl
 - Has a Name and a QV Characteristic curve
 - New Field for Generator
 - Name of VoltageDroopControl
- The remaining slides just have more detail on how this is implemented and what valid network topologies are



Implementation Details

Validation of the Network Topology Around the **VoltageDroopControl**



- Some network topologies are not allowed
 - Separate **VoltageDroopControl** objects can not have overlapping networks to connect to the regulated bus
 - All generators in the **VoltageDroopControl** must regulate the same bus (or buses connected by zero-impedance branches)
 - Having separate **VoltageDroopControl** objects that share the same regulated bus is fine and expected
 - For example, you can also have multiple generators at the same bus belong to different **VoltageDroopControl** objects

Generator Behavior when **VoltageDroopControl** is not valid



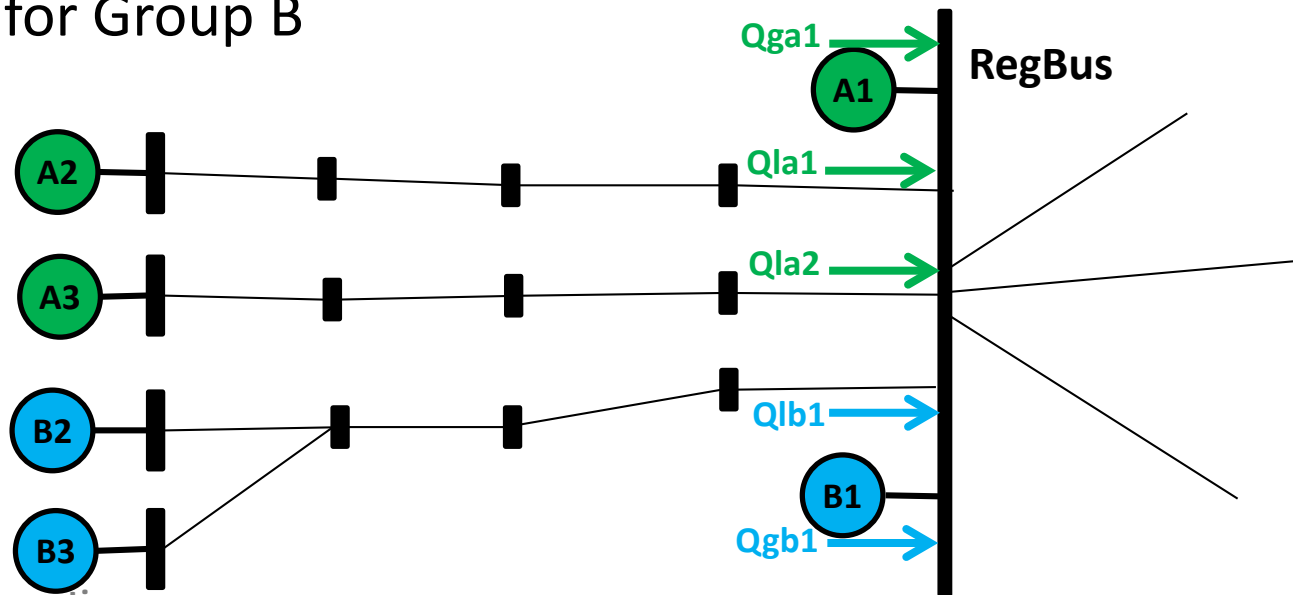
- If the **VoltageDroopControl** is blank, or if the **VoltageDroopControl.Enabled = NO**, then the generator will go back to its normal voltage setpoint behavior
- If the **VoltageDroopControl** and network topology around the generators is not a valid configuration for control, then the generators in the **VoltageDroopControl** will act as fixed Mvar outputs

Valid Example



- Two **VoltageDroopControl** objects (Green and Blue)
- Generators assigned to these
- All generators regulate RegBus
- Software automatically determines “Arriving Branches”
 - Qla1 and Qla2 for Group A
 - Qlb1 for Group B

Generators are
all configured to
regulate the
RegBus

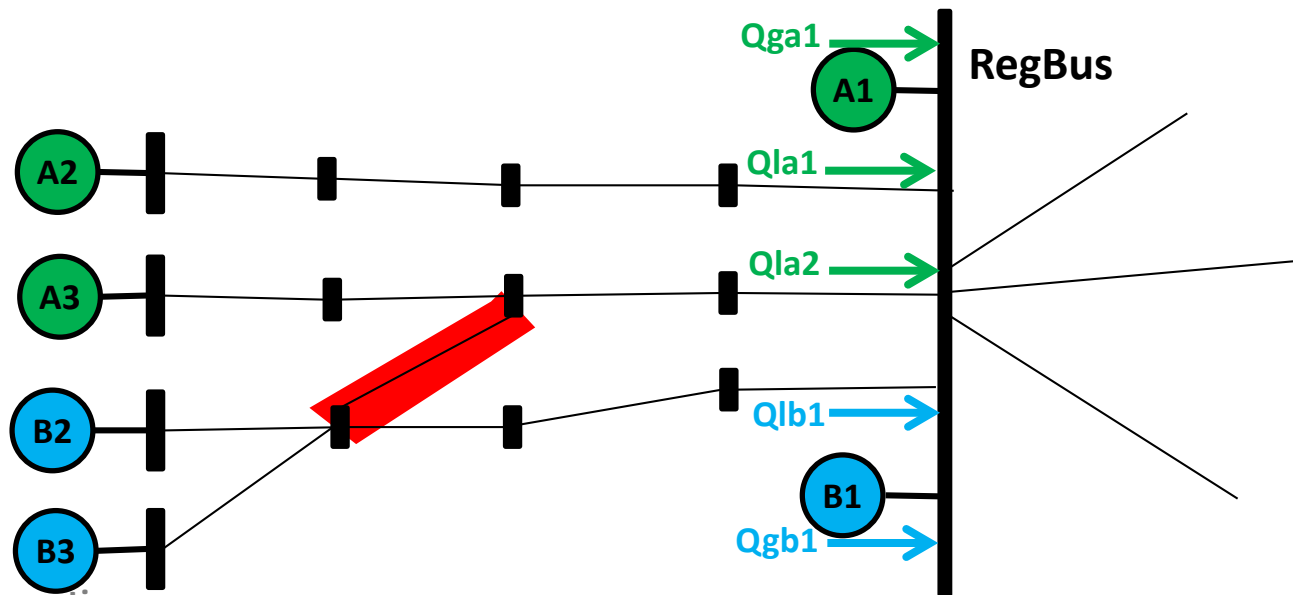


Invalid Topology: Conflicting Control



- The branch highlighted in red below makes this topology invalid (overlapping network)
 - All generators in BOTH of these **VoltageDroopControls** will be treated as fixed Mvar output because this is invalid

Generators are
all configured to
regulate the
RegBus

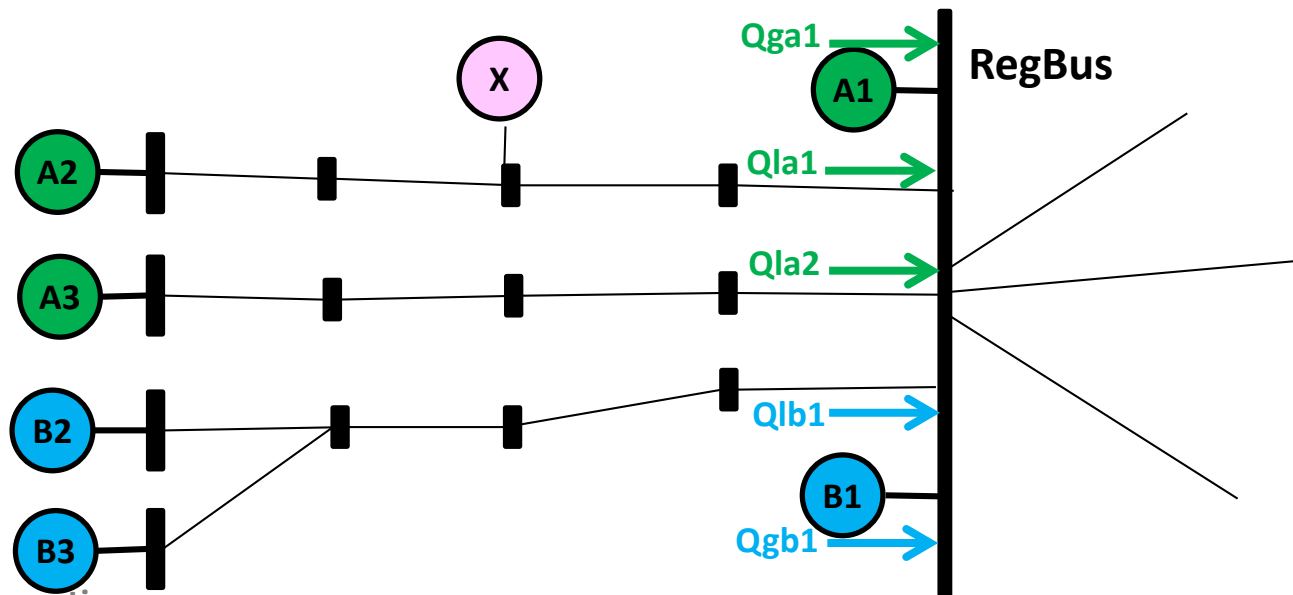


Invalid Topology: Conflicting Control



- Generator X below is set to regulate voltage in the normal manner
 - This conflicts with control for generators A1, A2, and A3, so **VoltageDroopControl** A is invalid
 - *Generators located at X are OK if they are not on any voltage control (AVR = NO)*

Generators are
all configured to
regulate the
RegBus

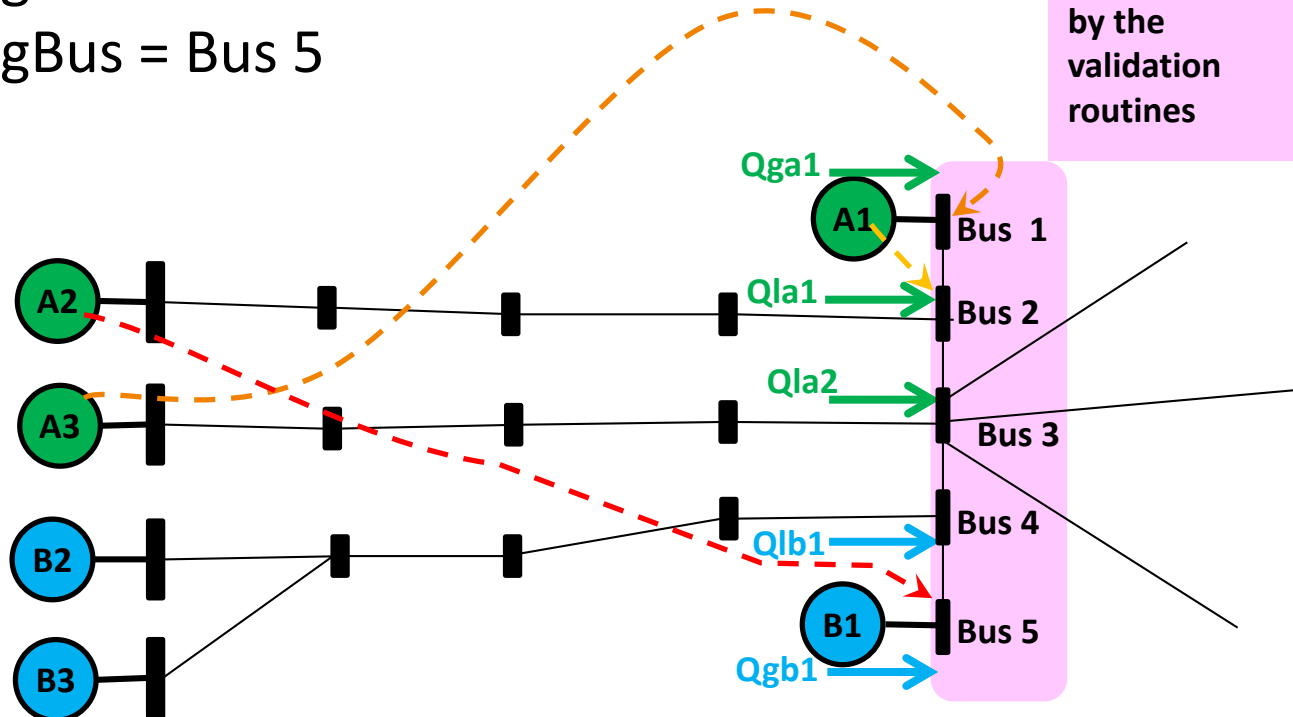


Valid Example



- Assume that Bus 1, 2, 3, 4, and 5 are all connected by branches below the ZBRTThreshold, then the following is acceptable input data
 - A2 RegBus = Bus 3
 - A1 RegBus = Bus 2
 - A3 RegBus = Bus 5

Generators are all configured to regulate the RegBus

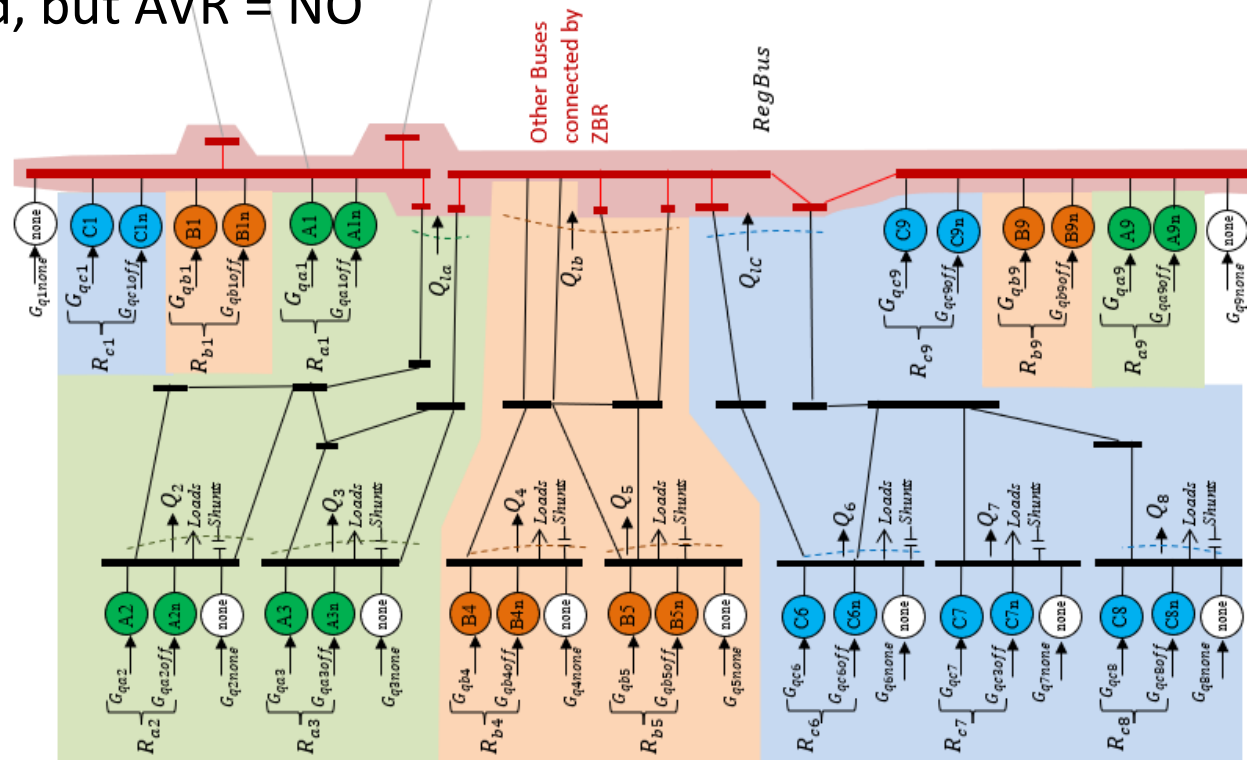
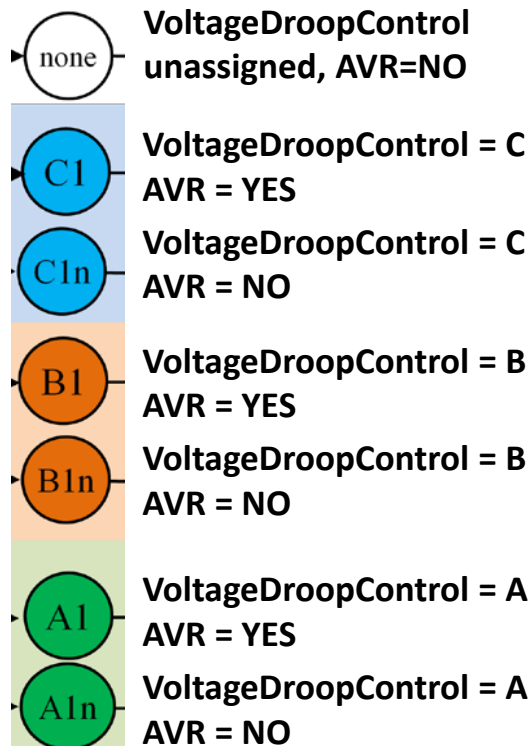


Extreme Example

But this is still Valid Network Topology



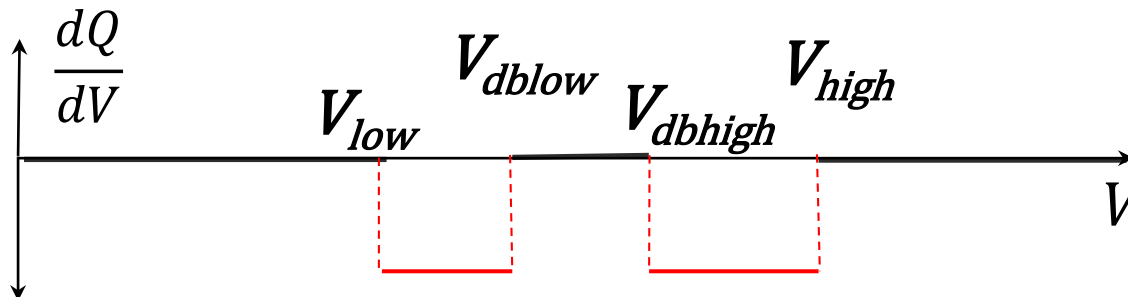
- *This is important for full-topology models including breakers*
- Blue, Orange, and Green represent different VoltageDroopControls
 - Each generator regulates any bus highlighted in Red within the “RegBus”
- White not assigned, but AVR = NO



New Numerical Implementation Issues due to Q versus V Characteristic



- Input Data Issue
 - The slopes between ($V_{low} \rightarrow V_{dblow}$) and ($V_{dbhigh} \rightarrow V_{high}$) may become too large
- QV Characteristic Issue
 - The “corner points” introduce discontinuous derivatives $\rightarrow$ This is very bad for solution algorithms



Input Data

Avoiding Numerical Problems



- Define tolerances
 - **Vtol** = 0.001 (this is hard-coded in PowerWorld Simulator)
 - Would not allow $V_{dblow} = 0.9500$ and $V_{low} = 0.9485$
 - **MaxSlope** = $1/(0.0002 * S_{Base}) = 500,000 \text{ Mvar/Vpu}$
 - This slope acts similarly to a line impedance in the equations, so it is similar to a minimum line impedance, jumper threshold, etc.
 - There is a “ZBR Threshold” in Simulator that defaults to 0.0002
 - user can change this. Other software tools have similar thresholds
 - Example assuming a $(V_{dblow} - V_{low}) = V_{tol} = 0.001$
 - $Q_{max} = 500.0 \text{ Mvar}$
 - $Q_{db} = 0.0 \text{ Mvar}$
 - $V_{dblow} = 0.950 \text{ per unit}$
 - $V_{low} = 0.949 \text{ per unit}$
 - $\text{Slope} = (Q_{max} - Q_{db}) / (V_{dblow} - V_{low}) = (500 - 0) / (0.950 - 0.949) = 500,000$
 - **MaxSlope** only enforced for extreme input data.
 - This means a range of 500 Mvar will force voltage difference of at least 0.001 per unit

Input Data :

Avoiding Numerical Problems



- Modify the input parameters using the following
 - If V_{dbhigh} and V_{dblow} are within V_{tol} of one another, set them equal to their average
 - Force V_{low} to be at least V_{tol} smaller than V_{dblow}
 - Force V_{high} to be at least V_{tol} larger than V_{dbhigh}
 - Force Q_{max} to not be smaller than Q_{db}
 - Force Q_{min} to not be larger than Q_{db}
 - If slope from V_{dblow} to V_{low} is larger than $MaxSlope$, modify V_{low} so that the slope is equal to $MaxSlope$
 - If slope from V_{dbhigh} to V_{high} is larger than $MaxSlope$, modify V_{high} so that the slope is equal to $MaxSlope$

Pseudo-Code for modifying input data



- Calculate the “used” values for the QV characteristic

```
// Enforce voltage thresholds that are not too close to one another
If (Vdbhigh - Vdblow) < VTol then
    VdbhighUsed = (Vdbhigh+Vdblow)/2
    VdblowUsed = (Vdbhigh+Vdblow)/2
Else
    VdbhighUsed = Vdbhigh
    VdblowUsed = Vdblow
EndIf
If (VdblowUsed - Vlow) < VTol then VlowUsed = VdblowUsed - VTol
Else VlowUsed = Vlow
If (Vhigh - VdbhighUsed) < VTol then VhighUsed = VdbhighUsed + VTol
Else VhighUsed = Vhigh
// Enforce decreasing relationship between reactive powers
If Qmax < Qdb then QmaxUsed = Qdb
Else QmaxUsed = Qmax
If Qmin > Qdb then QminUsed = Qdb
Else QminUsed = Qmin
// Enforce dQ/dV slopes not too big
MaxSlope = 1/(ZBRThreshold*SBase)
if (QmaxUsed - Qdb)/(VdbLowUsed - VlowUsed) > MaxSlope then
    VlowUsed = VdbLowUsed - 1/MaxSlope*(QmaxUsed - Qdb)
if (QminUsed - Qdb)/(VdbhighUsed - VhighUsed) > MaxSlope then
    VhighUsed = VdbhighUsed - 1/MaxSlope*(QminUsed - Qdb)
```

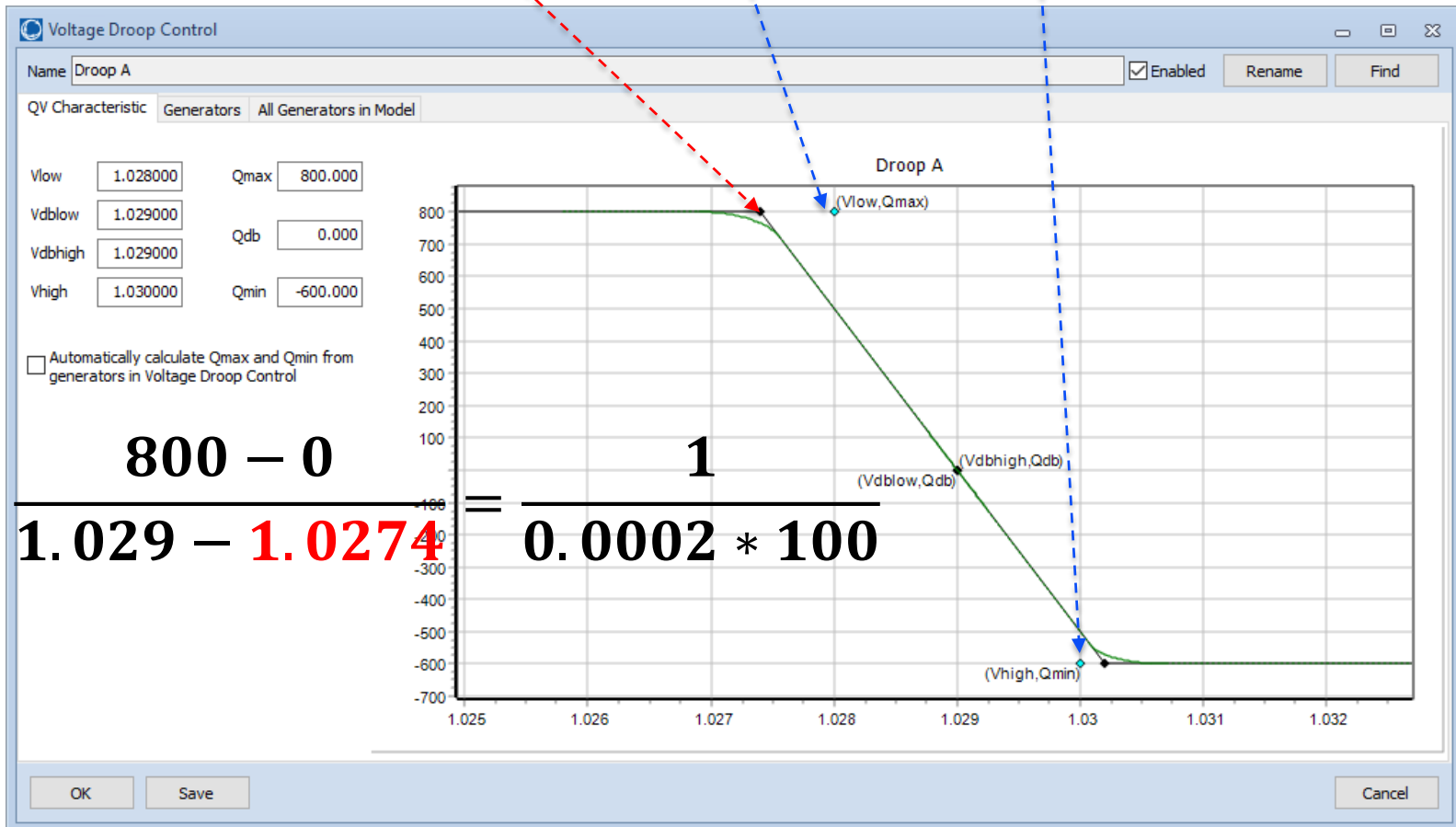
Might Modify Extreme Input Data Slightly



We have modified input data

Vlow changed to **1.0274** from **1.028**

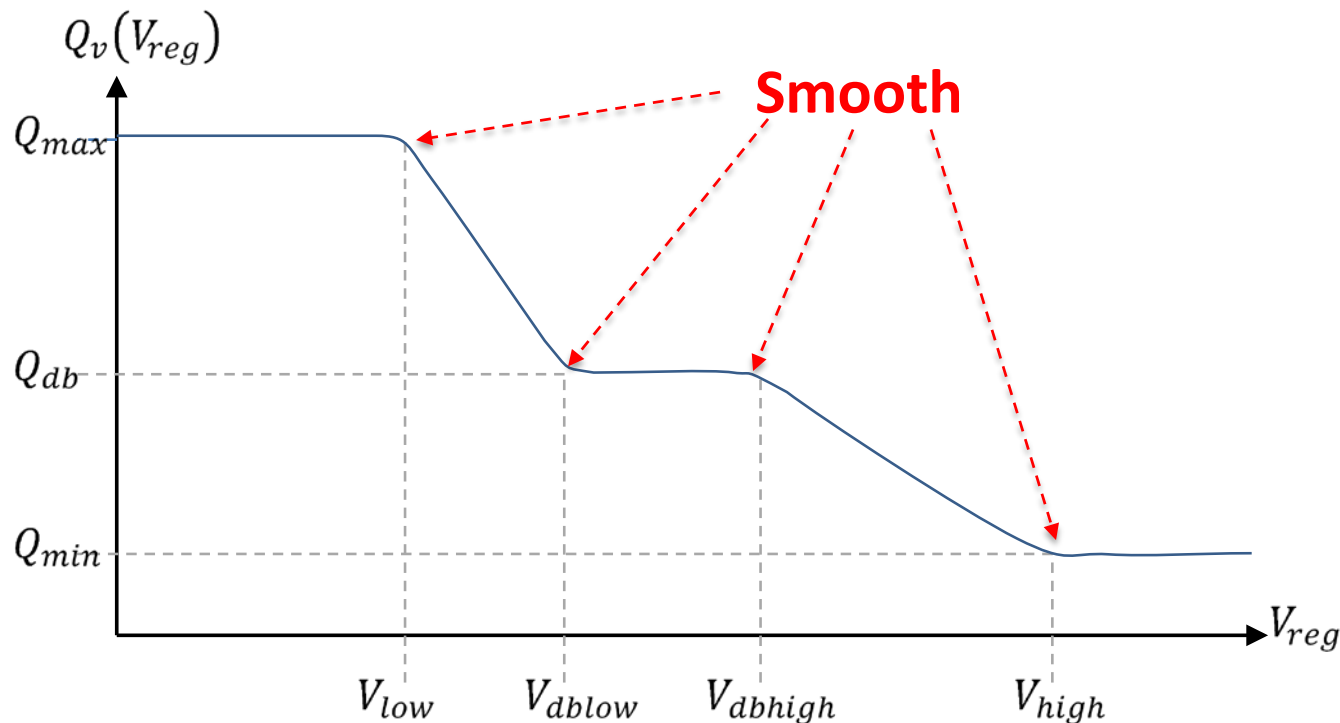
Input Data



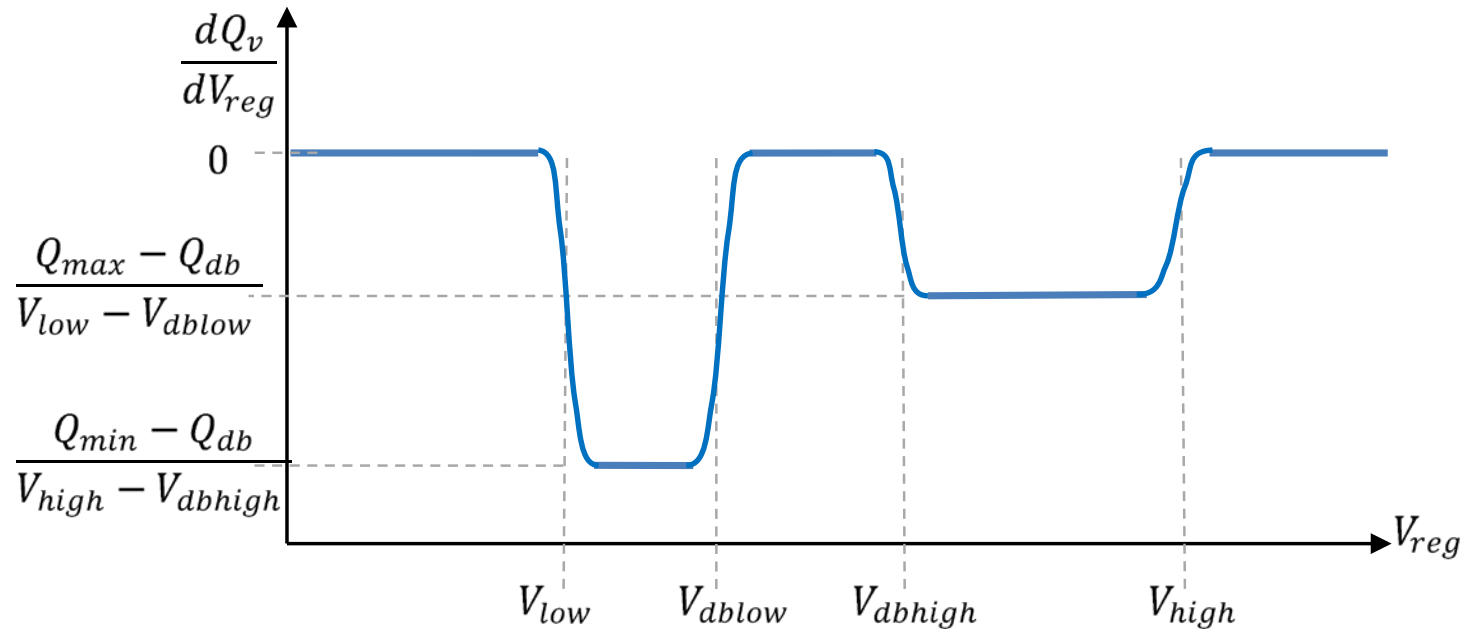
Avoiding Numerical Problems due to “corner points”



- Use splines to smooth the corners
- The curve will become the following



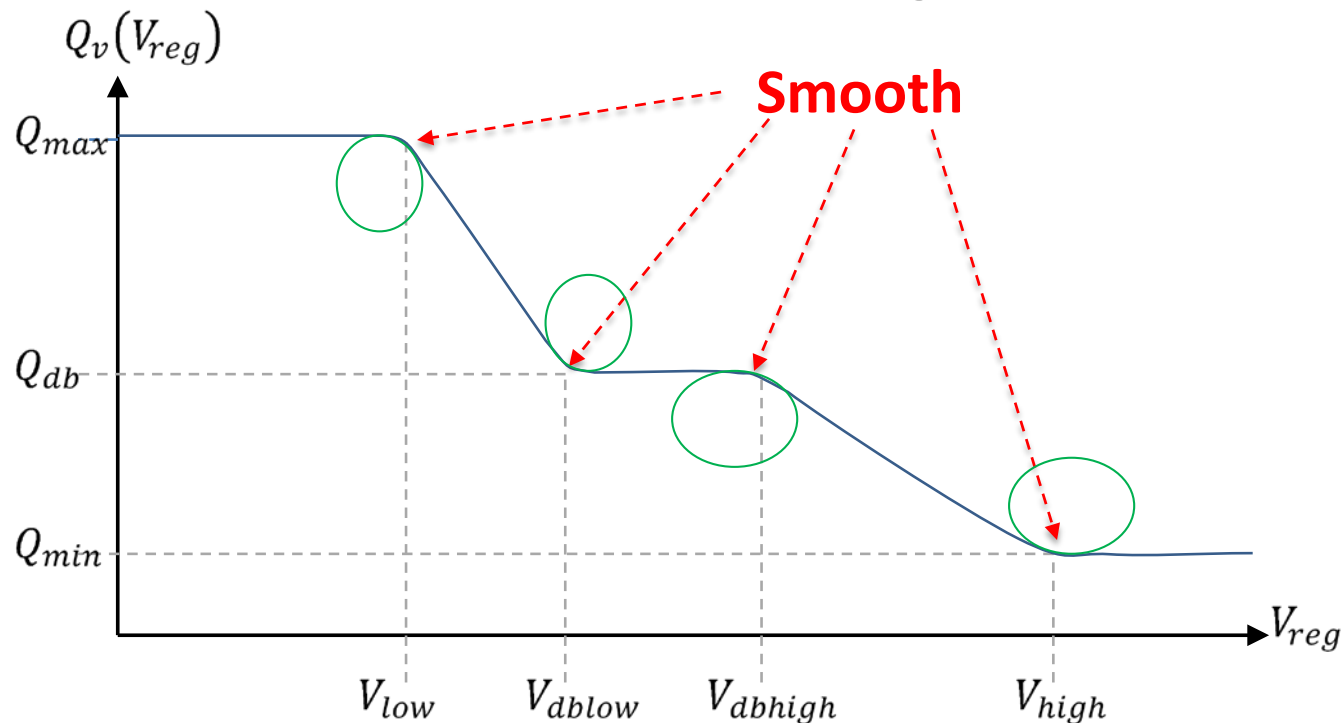
Derivatives after smoothing the corners



Avoiding Numerical Problems due to “corner points”



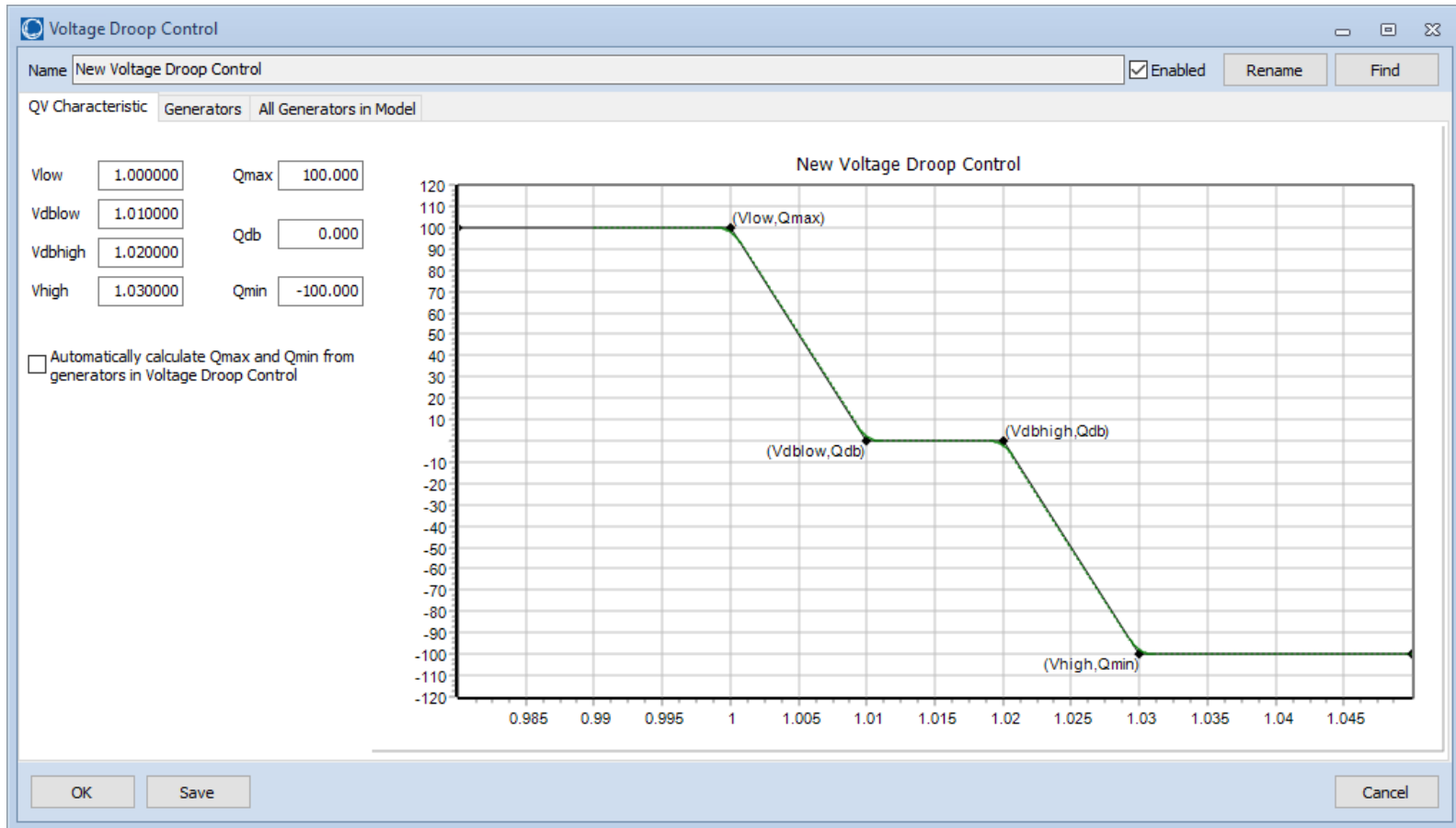
- Use elliptical splines to smooth the corners
 - Curves will follow an ellipse around corners instead
 - May also use cubic function as well
- The curve will become the following



Example QV Characteristic



- Faint Green Line shows the spline

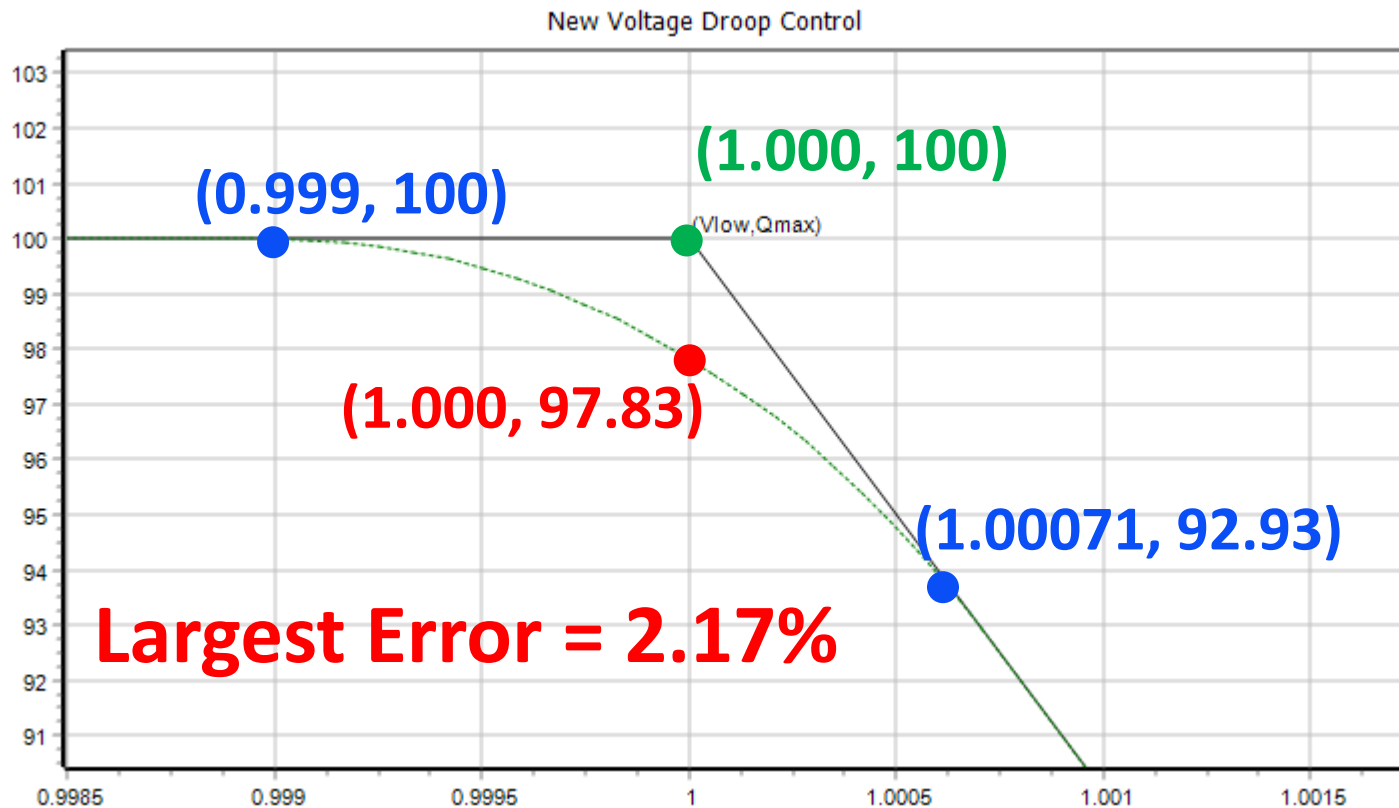


Close-up of Corner Point



Vscale = 0.001

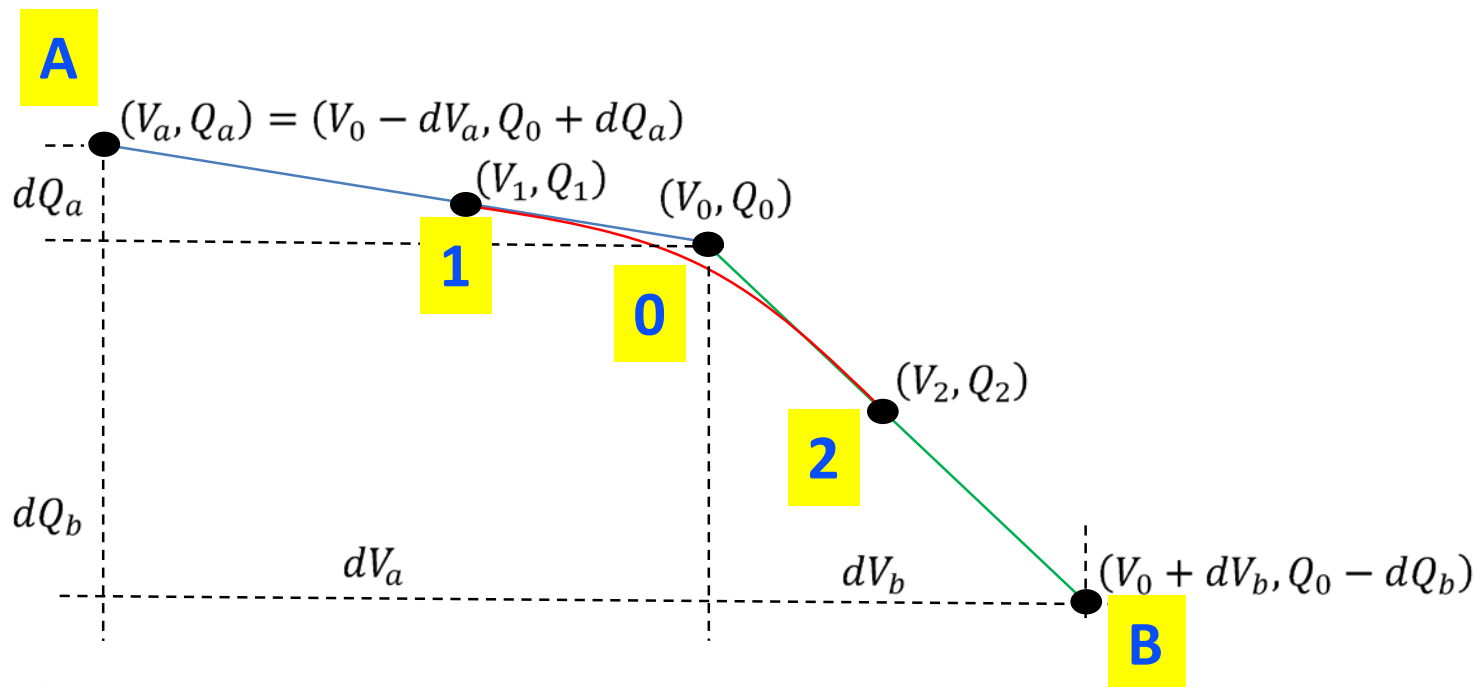
Qscale = 10 Mvar



Implementation of smoothing



- We start with two line segments from our QV characteristic defined by point **A**, **0** and **B** below
- Smooth between point **1** and **2**
- Scaling is chosen in a specific way to smooth enough that the solution can be achieved, but not more than necessary



White Paper



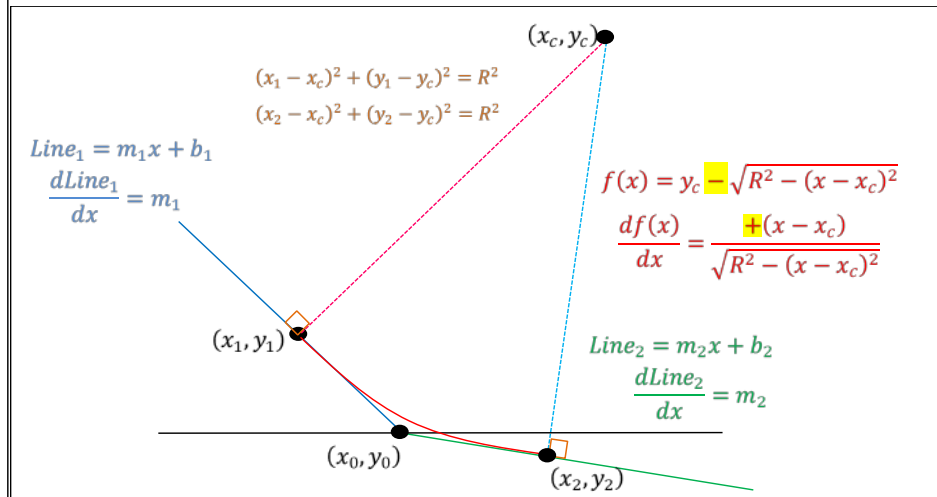
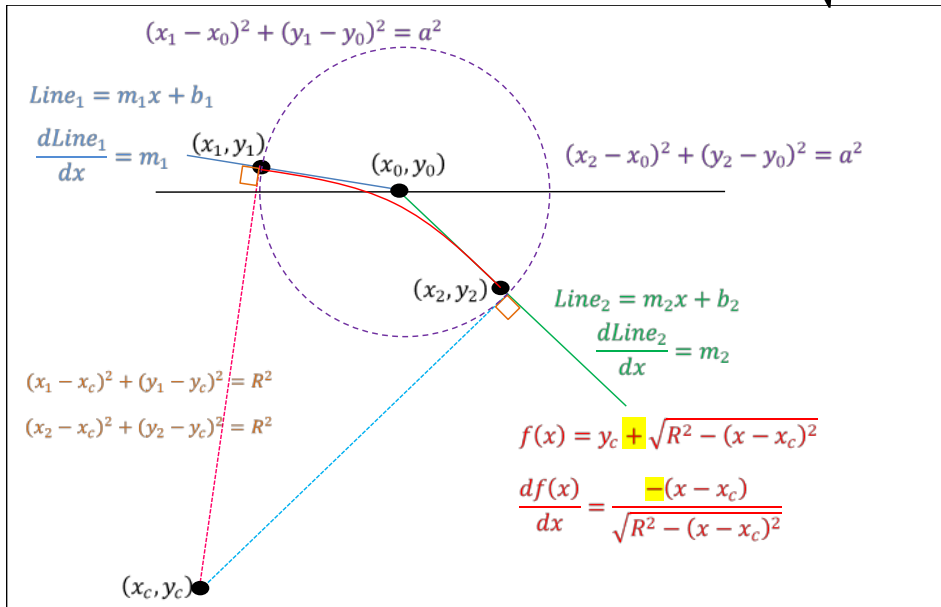
- Details of Spline Function Choice and Implementation in Power Flow solution are included in PowerWorld Corporation's public website
 - <https://www.powerworld.com/knowledge-base/renewable-generators-voltage-droop-control-with-deadband-in-power-flow-solution>
- Any other software vendor can implement this into their power flow algorithm using this information

Circular Spline Function



$$Q_{pu} = Q_{scale} \left[y_c + \text{Sign} \sqrt{R^2 - \left(\frac{V_{pu}}{V_{scale}} - x_c \right)^2} \right]$$

$$\frac{dQ_{pu}}{dV_{pu}} = \frac{Q_{scale}}{V_{scale}} \left[\frac{\text{Sign} \left(\frac{V_{pu}}{V_{scale}} - x_c \right)}{\sqrt{R^2 - \left(\frac{V_{pu}}{V_{scale}} - x_c \right)^2}} \right]$$

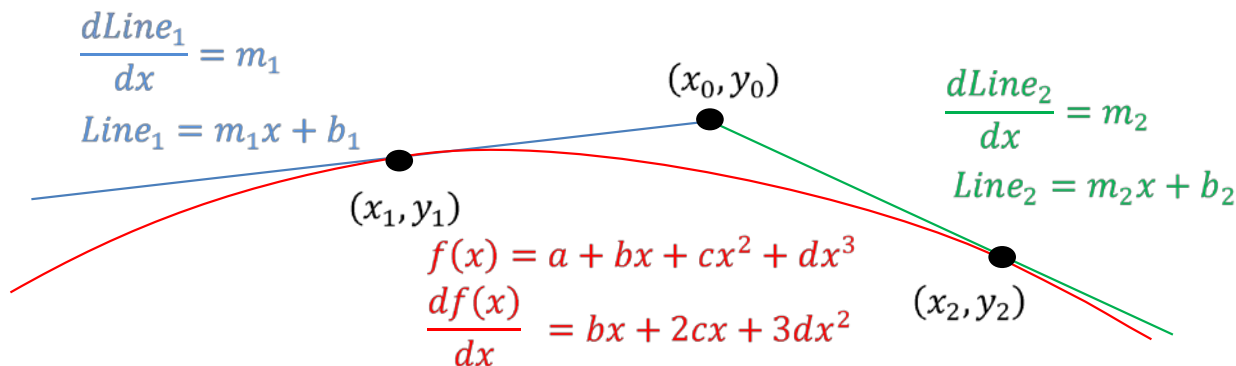


Cubic Spline Function



$$Q_{pu} = Q_{scale} \left[a + b \left(\frac{V_{pu}}{V_{scale}} - x_{shift} \right) + c \left(\frac{V_{pu}}{V_{scale}} - x_{shift} \right)^2 + d \left(\frac{V_{pu}}{V_{scale}} - x_{shift} \right)^3 \right]$$

$$\frac{dQ_{pu}}{dV_{pu}} = \frac{Q_{scale}}{V_{scale}} \left[b + 2c \left(\frac{V_{pu}}{V_{scale}} - x_{shift} \right) + 3d \left(\frac{V_{pu}}{V_{scale}} - x_{shift} \right)^2 \right]$$



Advantage of Spline



- Hardest part of existing power flow algorithms
 - Figuring out which generators are at Mvar limits
 - Introduces “equation switching” (similar to PV/PQ bus)
- Without the spline function, the power flow would get a lot more complicated (and slower)
 - We would keep track of jumping between each segment of the QV characteristic
 - This is also “equation switching”

