# OpenDSS Training Workshop - 2021

## PVSystem + InvControl

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EPRI Knoxville, TN

01 September 2021

# Instructor

- **Paulo Radatz**

**Paulo Radatz serves as Engineer/Scientist II at the Electric Power Research Institute (EPRI) in Knoxville, Tennessee, USA. He received both his Masters and Bachelors's degree in electrical engineering, emphasizing energy and automation, from the University of Sao Paulo, Sao Paulo, Brazil. He was awarded a prize for being the best bachelor's student of Polytechnic School of University of Sao Paulo (2015). He has six years of experience with OpenDSS, having taught several OpenDSS trainings in Brazil at conferences, universities, and industry. He is the founder of the largest YouTube channel about OpenDSS in the world.**

# Agenda

PVSystem Modeling

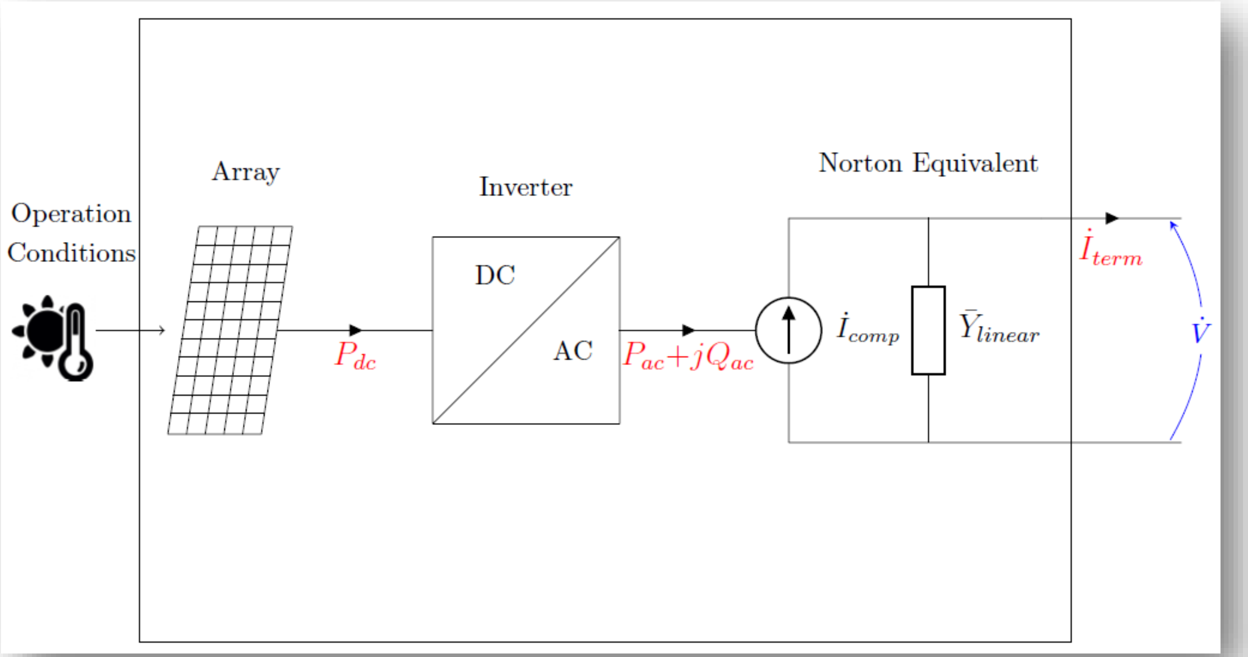
InvControl – Convergence Method

A Few Examples of Smart Inverter Functions According IEEE Std 1547-2018

# PVSystem Modeling

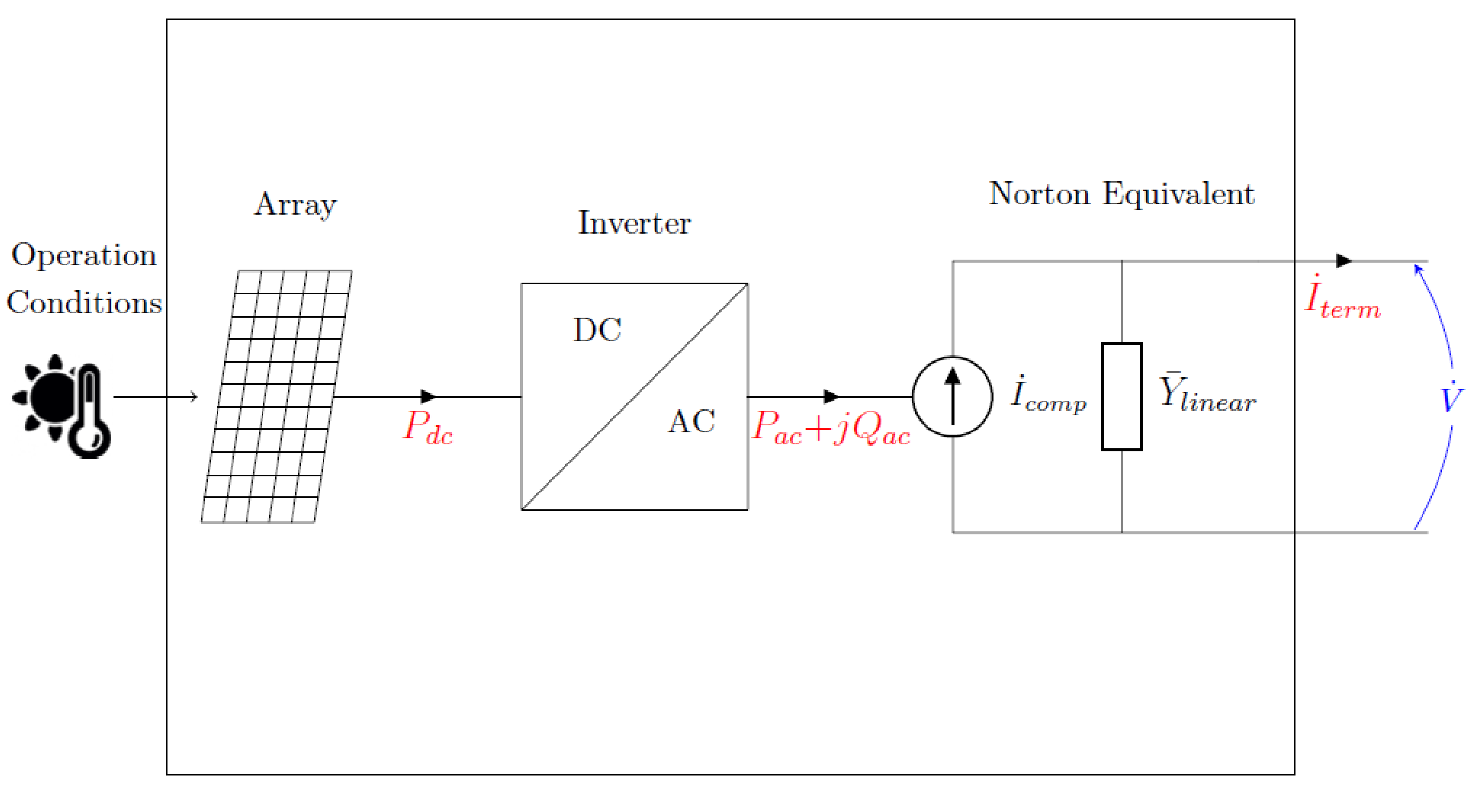
# PVSystem Element in OpenDSS

- The PVSystem model combines the photovoltaic (PV) array and the PV inverter into one convenient model to for distribution system impacts studies




**Steady State model for QSTS Analysis**

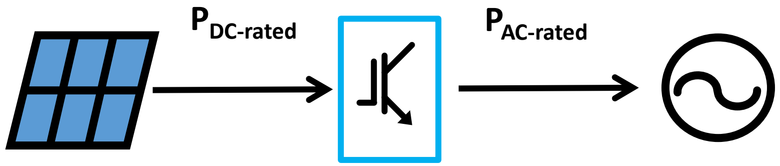
# PVSystem Element in OpenDSS




- PVSystem properties
  - PV Array
  - PV Inverter
  - Operating conditions

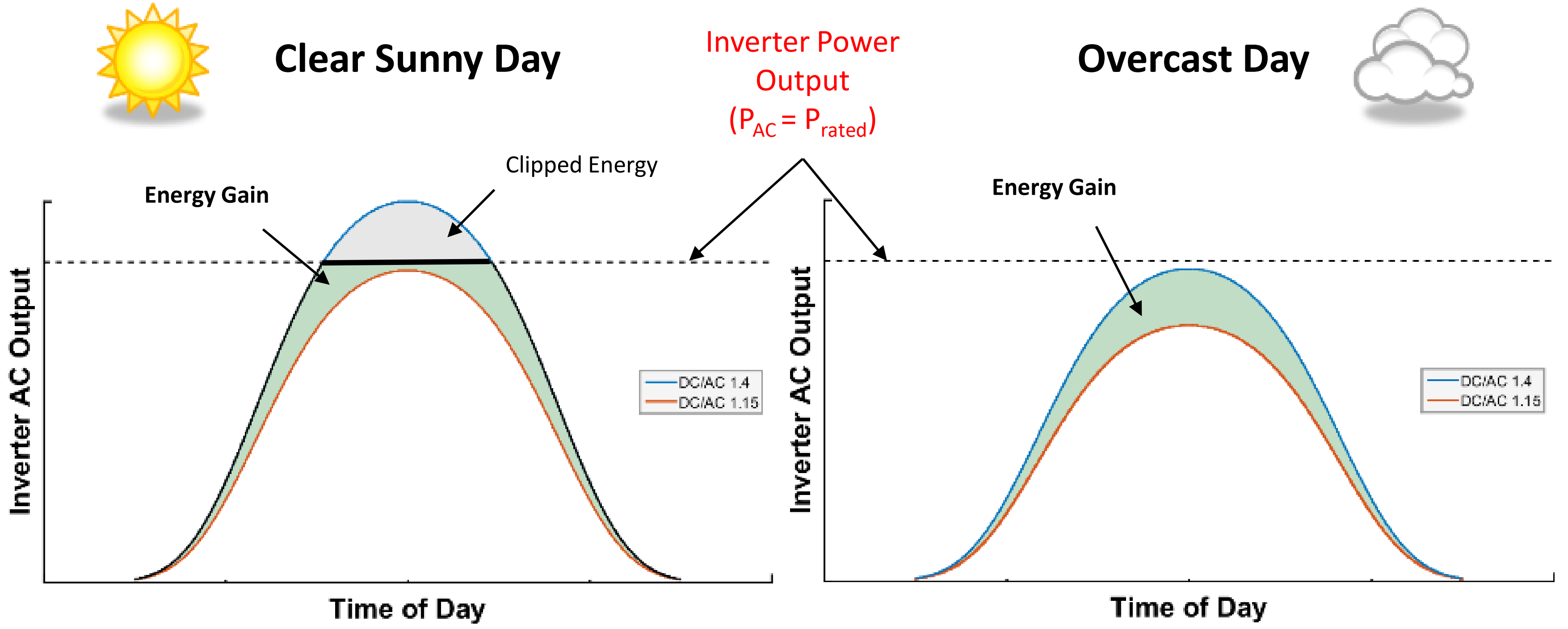
- Resources:
  - 2020 OpenDSS training record: https://www.epri.com/events/C97292AF-0790-4514-B9DF-CCEF80D685E1
  - OpenDSS example folder: C:\Program Files\OpenDSS\Examples\InverterModels\PVSystem
  - Pdf document: C:\Program Files\OpenDSS\Examples\InverterModels\PVSystem\PVSystem_InvControl.pdf
  - YouTube videos: https://www.youtube.com/playlist?list=PLhdRxvt3nJ8wTHIm0ohOOSxPr4O61YulY
  - Today's presentation and resource files: https://sourceforge.net/p/electricdss/code/HEAD/tree/trunk/Training/Virtual-2021/Session3/PVSystem_InvControl/

# PV system design: DC-to-AC Ratio




$$\frac{P_{DC\text{-}rated}}{P_{AC\text{-}rated}} = \text{DC-to-AC ratio}$$

- In a PV system with higher DC-to-AC ratio, inverter(s) will generate more active power/energy.
- PV system's AC power output should not exceed the aggregate AC power ratings of the inverters.

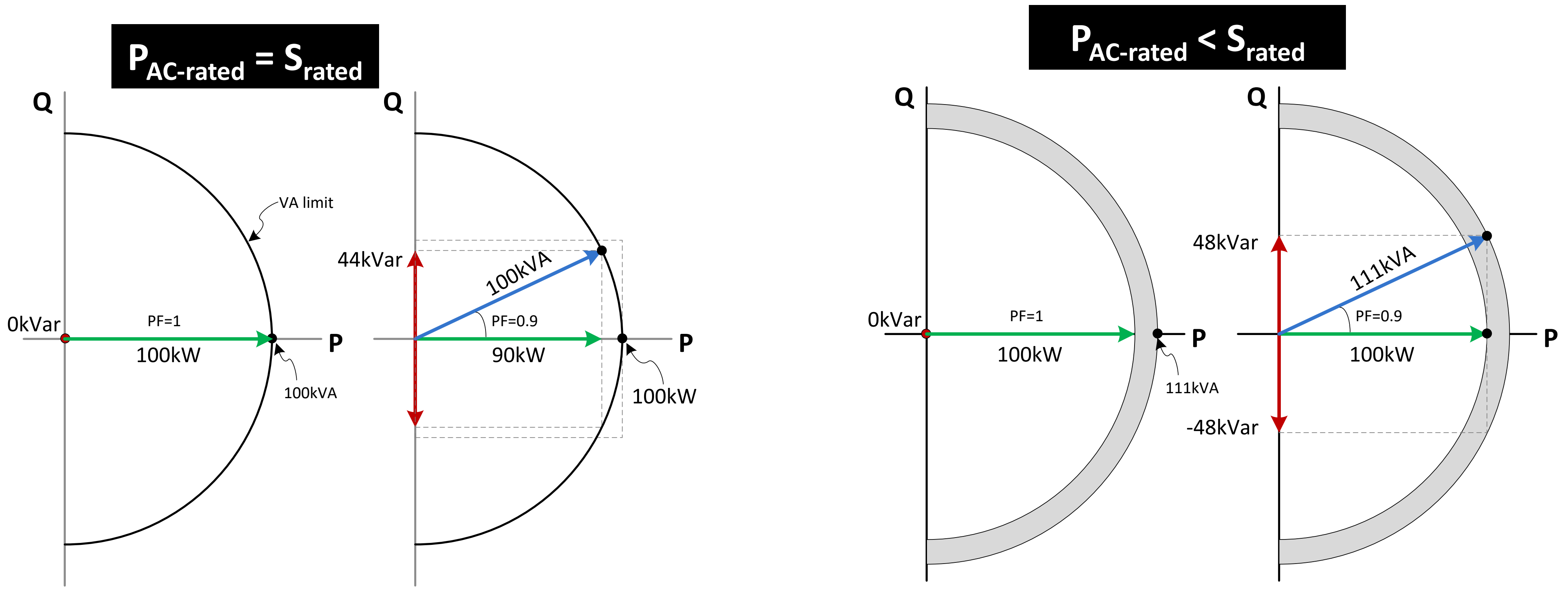



Reference:

**Tutorial on Inverter Fundamentals and Grid Support Functions (P174B, Contact: Aminul Huque, [mhuque@epri.com](mailto:mhuque@epri.com))**

# Inverter design - kVA vs kW Rating

- By design, inverters are volt-ampere (VA) limited device.
- Figures bellow show the transition of inverter operation from rated power at unity power factor to 0.9 power factor for two different inverter designs.

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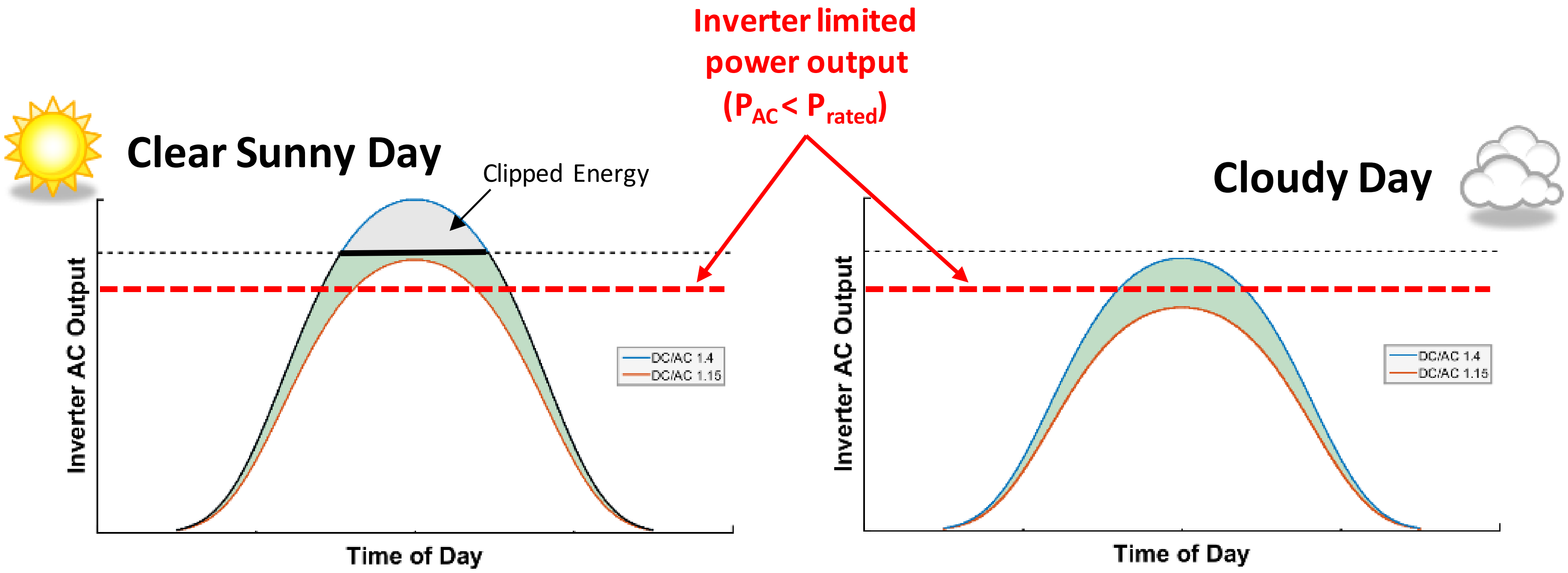
# DC-to-AC Ratio and kVA vs kW Rating

- If the inverter needs to limit it's active power output to generate reactive power (in case of kVA=kW ratings) required by the voltage control function, energy loss will be higher for systems with higher DC-to-AC ratio.

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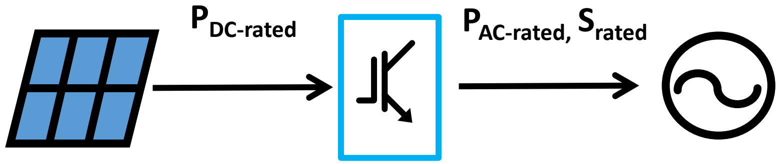
# Modeling PVSystem based on DC-to-AC and kVA vs kW




- **PDC-rated, PAC-rated, Srated** are the properties that should be modeled

- Current version of PVSystem Model (OpenDSS version 9.3.0.2)
  - There are only two properties: **Pmpp** and **kVA**.
    - When DC-to-AC ratio = 1, **Pmpp** represents both **PDC-rated** and **PAC-rated** (they are the same). And kVA is Srated

**When DC-to-AC ratio > 1, how to model both PDC-rated and PAC-rated?**

# Modeling PVSystem based on DC-to-AC and kVA vs kW

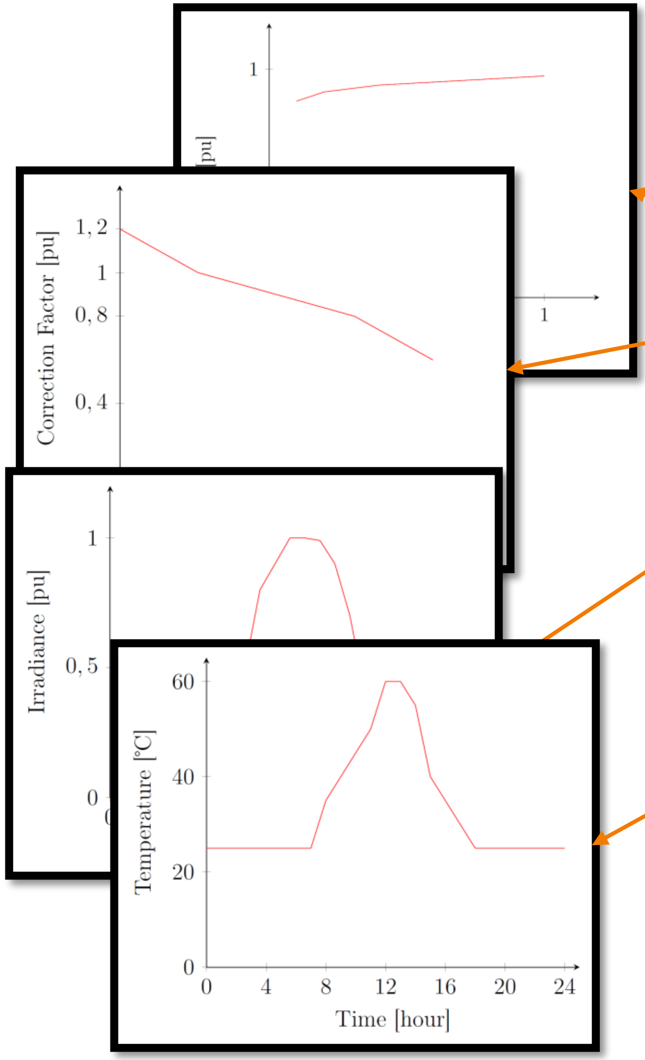
Nameplate information:

- Given
  - Srated, DC-to-AC ratio, and kVA-to-kW ratio
- Then,
  - PAC-rated = Srated / kVA-to-kW ratio
  - PDC-rated = PAC-rated * DC-to-AC ratio = Srated * DC-to-AC ratio / kVA-to-kW ratio

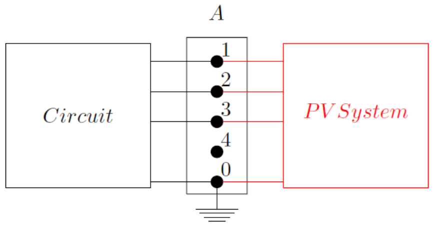
PVSystem modeling:

- kVA = Srated
- Pmpp = PDC-rated
- %Pmpp = 100 * PAC-rated / PDC-rated = 100 / DC-to-AC ratio

# Script Example



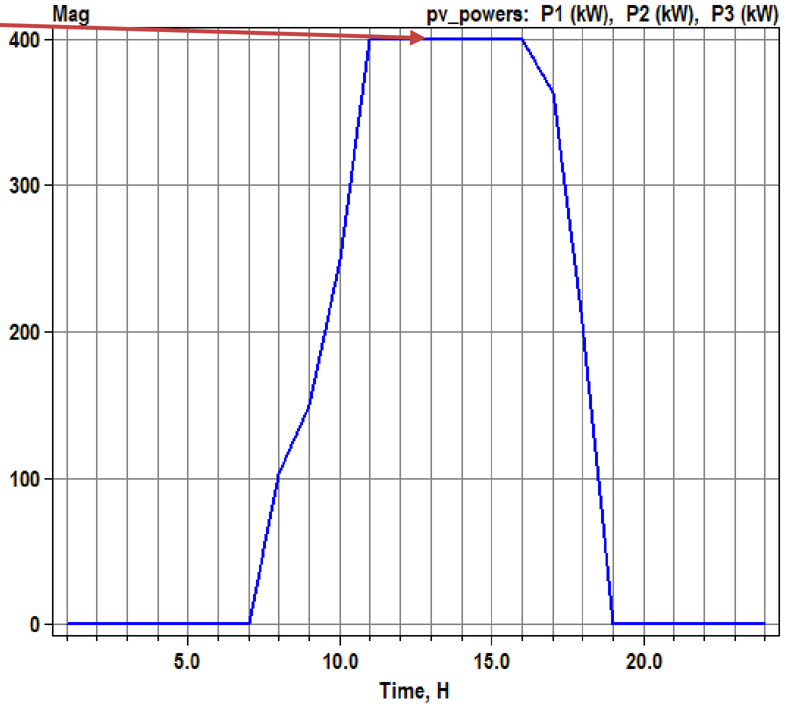

```
Clear

New Circuit.TheveninEquivalent bus1=A pu=1.0 basekv=13.8
~ Z0=[10, 10] Z1=[10, 10]

New XYCurve.Eff npts=4 xarray=[.1 .2 .4 1.0] yarray=[0.86 0.9 0.93 0.97]
New XYCurve.FatorPvsT npts=4 xarray=[0 25 75 100] yarray=[1.2 1.0 0.8 0.6]

New Loadshape.Irrad npts=24 interval=1
~ mult=[0 0 0 0 0 0 .1 .2 .3 .5 .8 .9 1.0 1.0 .99 .9 .7 .4 .1 0 0 0 0 0]

New Tshape.Temp npts=24 interval=1
~ temp=[25 25 25 25 25 25 25 25 35 40 45 50 60 60 55 40 35 30 25 25 25 25 25 25]

New line.switch bus1=A bus2=B switch=Yes

New PVSystem.PV phases=3 bus1=B kV=13.8 Pmpp=1680 %pmpp=71.428  kVA=1200 pf=0.95
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp wattpriority=Yes
```

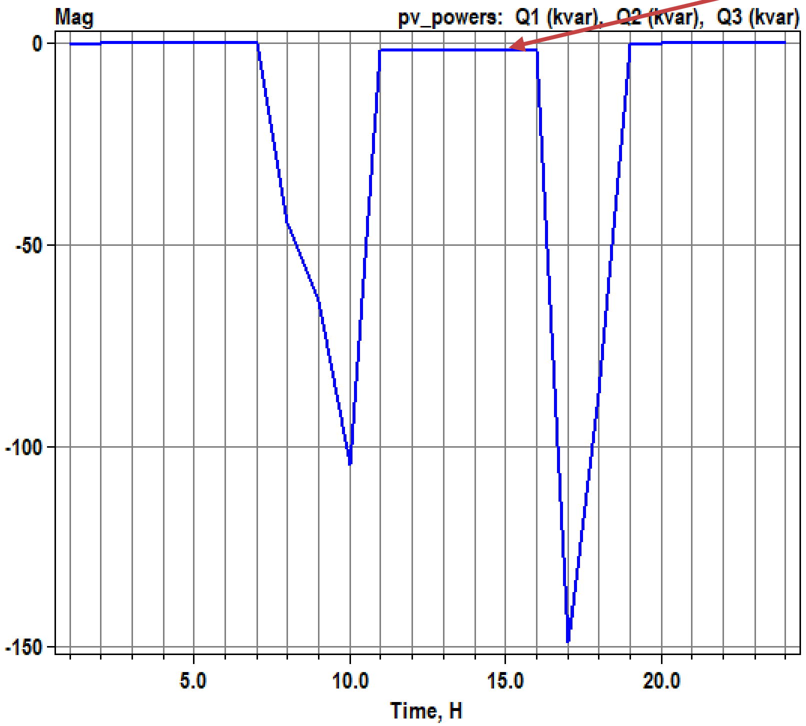


# Example 1: dc-ac-1_4--kw-kva-1-Ppriority.dss

```
New PVSystem.PV phases=3 bus1=B kV=13.8 Pmpp=1680 %Pmpp=71.428 kVA=1200
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp wattpriority=Yes
```

kW maximum 1200kW




P priority
kVA-to-kW = 1.0

- DC-to-AC = 1.4
- kVA-to-kW = 1.0
- Inverter: P priority
- Inverter: Volt-Var

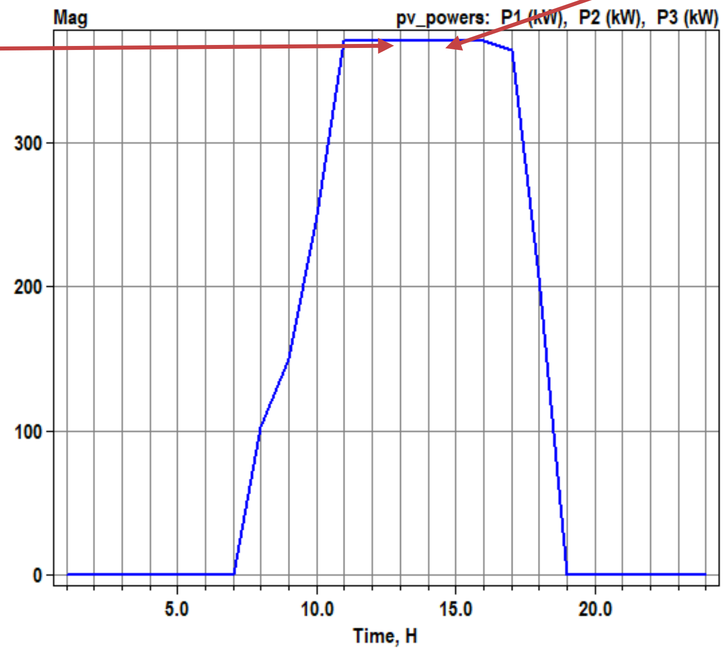
- kVA=1200
- Pmpp = kVA / kVA-to-kW * DC-to-AC = 1680
- %Pmpp = kVA / kVA-to-kW / Pmpp * 100 = 71.428

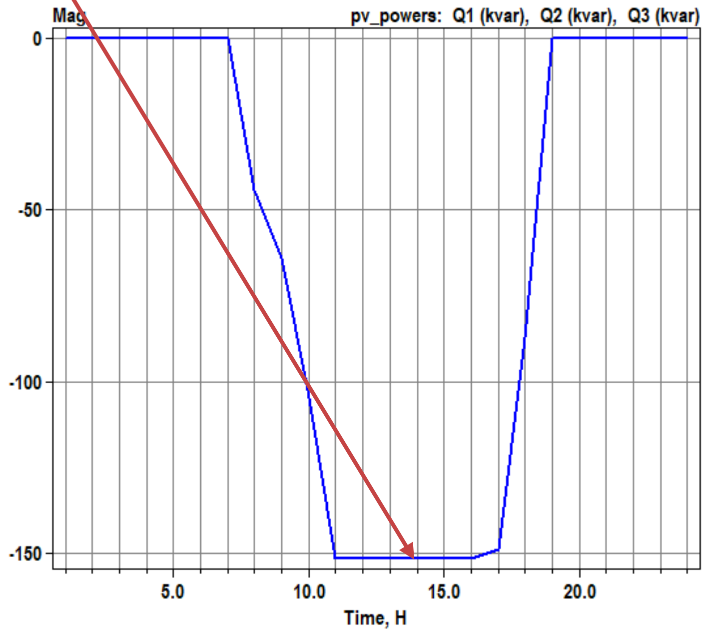
# Example 2: dc-ac-1_4--kw-kva-1-Qpriority.dss

```
New PVSystem.PV phases=3 bus1=B kV=13.8 Pmpp=1680 %Pmpp=71.428 kVA=1200
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp wattpriority=no
```

kVA maximum 1200kVA
kW not max

Q priority



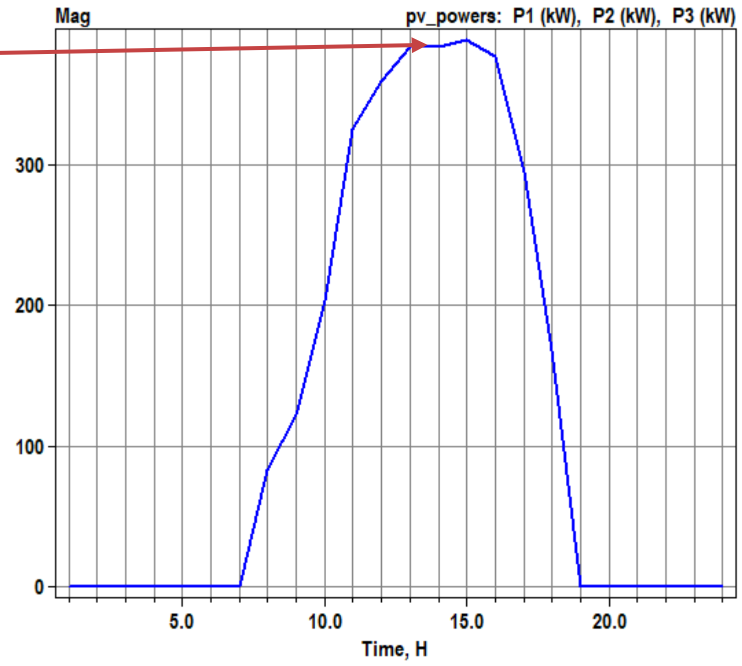

- DC-to-AC = 1.4
- kVA-to-kW = 1.0
- Inverter: Q priority
- Inverter: Volt-Var

- kVA=1200
- Pmpp = kVA / kVA-to-kW * DC-to-AC = 1680
- %Pmpp = kVA / kVA-to-kW / Pmpp * 100 = 71.428

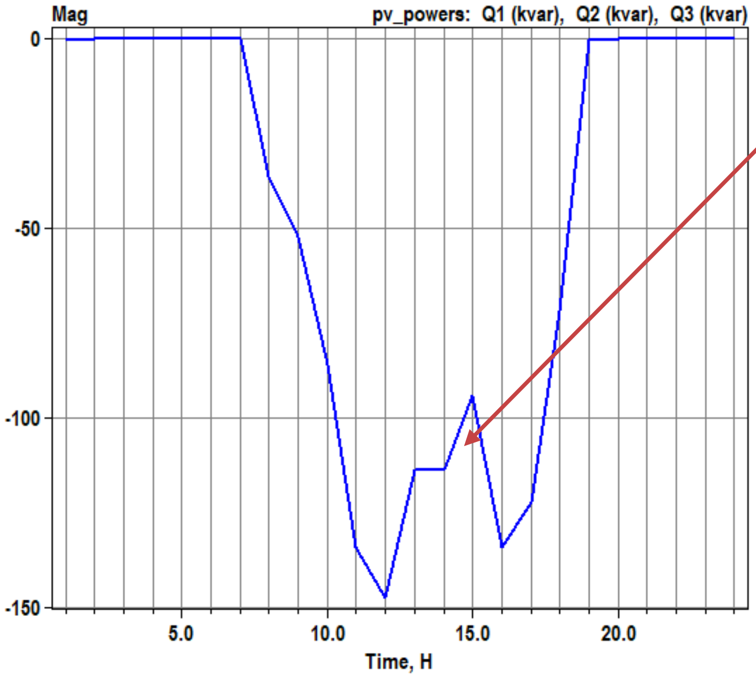
# Example 3 - dc-ac-1_15--kw-kva-1-Ppriority.dss

```
New PVSystem.PV phases=3 bus1=B kV=13.8 Pmpp=1380 %Pmpp=86.956 kVA=1200
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp wattpriority=Yes
```

Not limited
kW < 1200




P priority



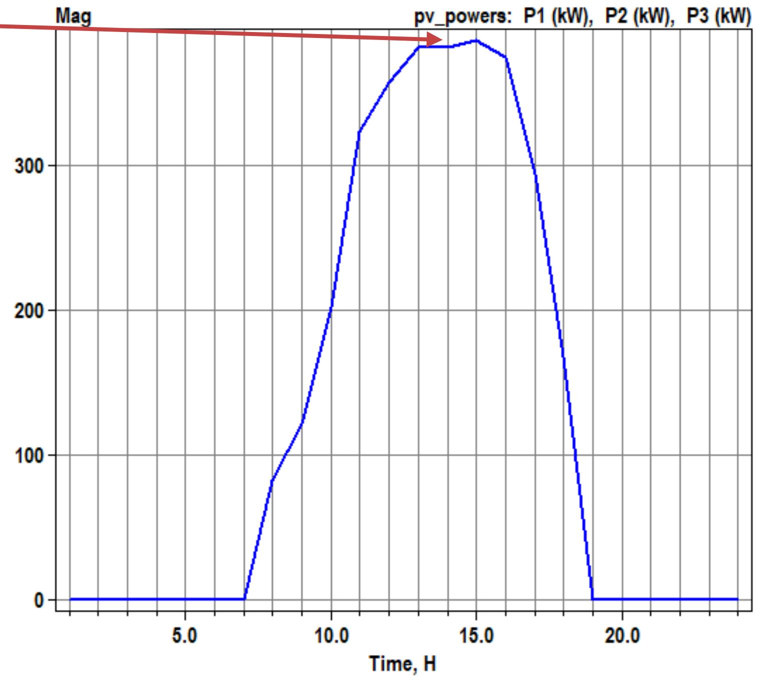

- DC-to-AC = 1.15
- kVA-to-kW = 1.0
- Inverter: P priority
- Inverter: Volt-Var

- kVA=1200
- Pmpp = kVA / kVA-to-kW * DC-to-AC = 1380
- %Pmpp = kVA / kVA-to-kW / Pmpp * 100 = 86.956

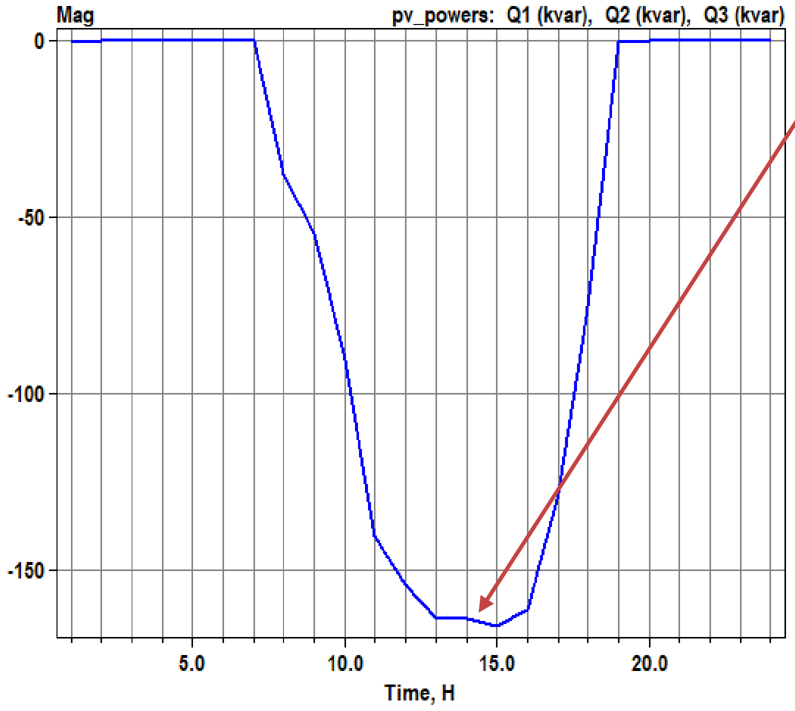
# Example 4 - dc-ac-1_15--kw-kva-1_1.dss

```
New PVSystem.PV phases=3 bus1=B kV=13.8 Pmpp=1380 %Pmpp=86.956 kVA=1320
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp
```

Not limited




Not limited




- DC-to-AC = 1.15
- kVA-to-kW = 1.1
- Inverter: Volt-Var

- kVA=1320
- Pmpp = kVA / kVA-to-kW * DC-to-AC = 1380
- %Pmpp = kVA / kVA-to-kW / Pmpp * 100 = 86.956

# Using PVSystem when having kW measurements (System operating with unity power factor)

PVSystem modeling:

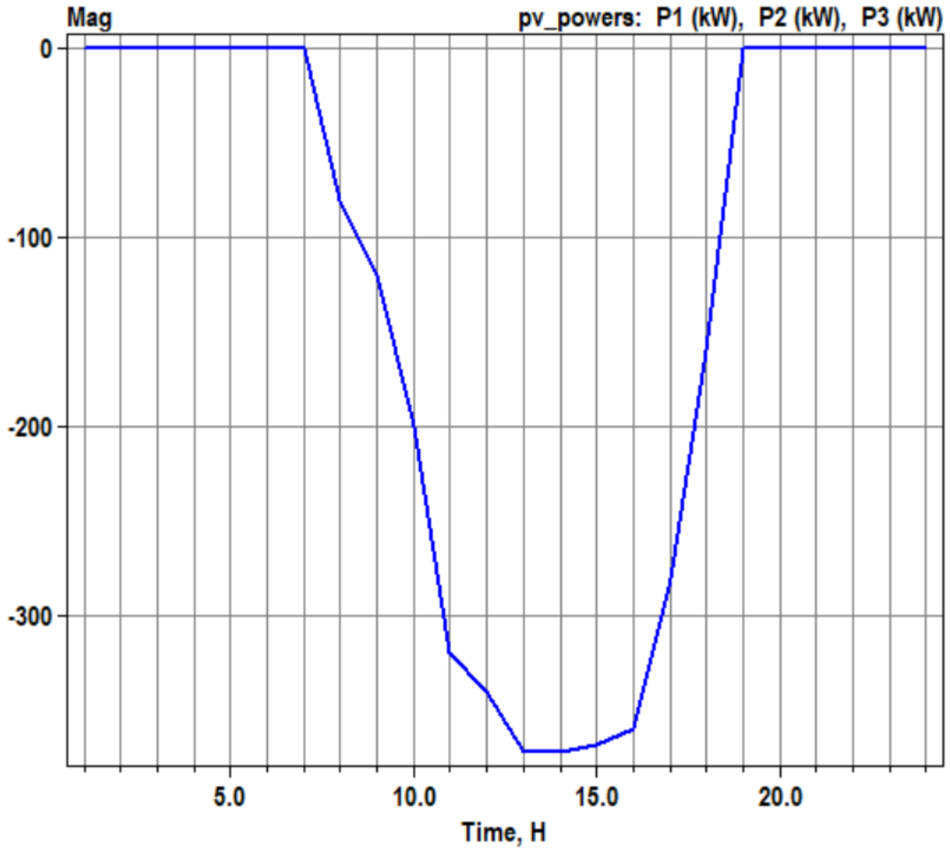
- Pmpp = PAC-rated
- %Pmpp = 100
- Irradiance=1
- Unitary PV system Curves
- kVA should be greater or equal to Pmpp
- Irradiance[t] = kW_measurements[t] / Pmpp

https://www.epri.com/research/products/000000003002020102

# Example (kwMeasurements.dss)

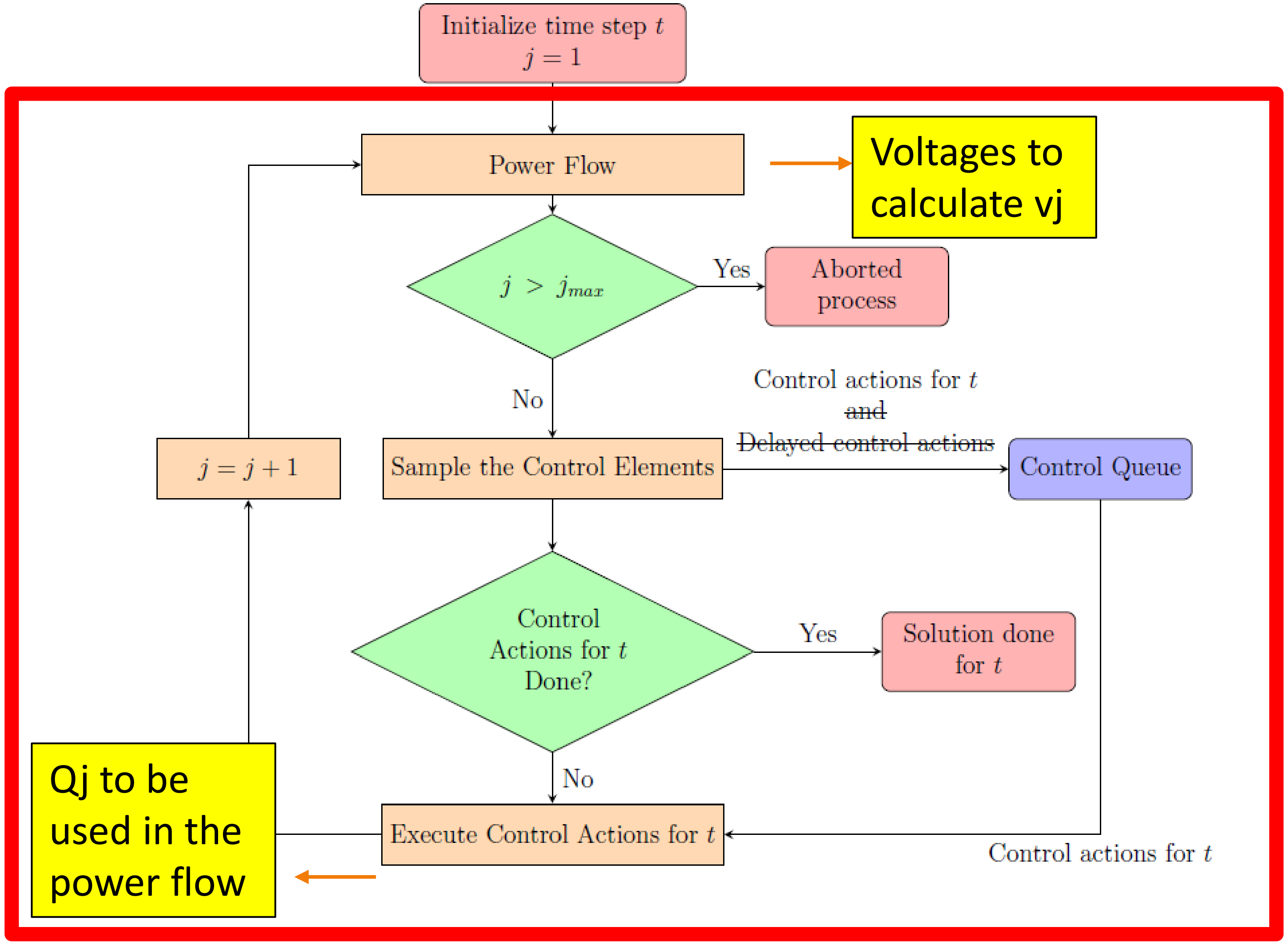
```
Clear

New Circuit.TheveninEquivalent bus1=A pu=1.0 basekv=13.8
~ Z0=[10, 10] Z1=[10, 10]

New XYCurve.Eff npts=4 xarray=[.1 .2 .4 1.0] yarray=[1 1 1 1]

New XYCurve.FatorPvsT npts=4 xarray=[0 25 75 100] yarray=[1 1 1 1]

New Loadshape.Irrad npts=24 interval=1
~ mult=[0 0 0 0 0 0 .1 .2 .3 .5 .8 .85 0.93 0.93 .92 .9 .7 .4 .1 0 0 0 0 0]

New Tshape.Temp npts=24 interval=1
~ temp=[25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25 25]

New PVSystem.PV phases=3 bus1=A kV=13.8 Pmpp=1200 %pmpp=100 kVA=1200
~ conn=wye effcurve=Eff P-TCurve=FatorPvsT irradiance=1 daily=Irrad Tdaily=Temp
```

Pac[t] = kW measurements = irrad x Pmpp



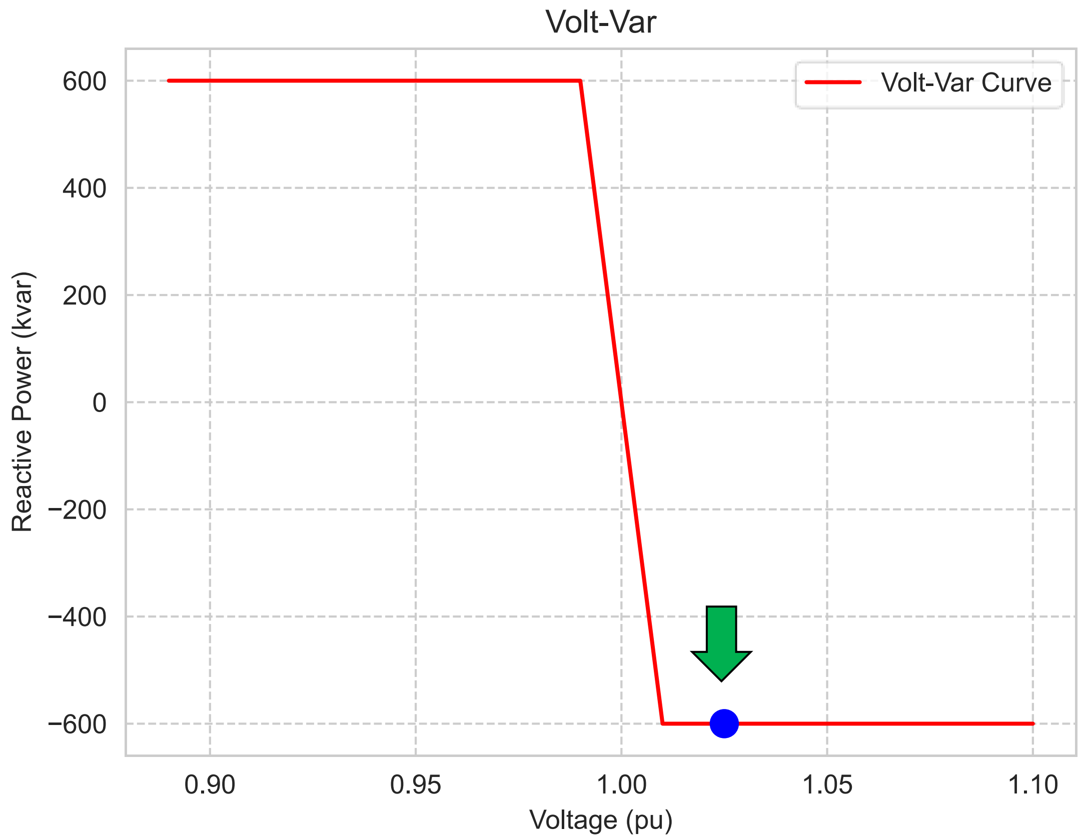
# InvControl – Convergence Method

# OpenDSS QSTS Simulation Process



# The reason to have the convergence method

| Control Iteration (i) | Voltage vi | Desired Reactive power Qi |
|---|---|---|
| 1 | 1.025 | -600 |
| 2 | 0.967 | 600 |
| 3 | 1.030 | -600 |
| 4 | 0.967 | 600 |
| 5 | 1.030 | -600 |




**NoConvergence.dss**

# The reason to have the convergence method

| Control Iteration (i) | Voltage vi | Desired Reactive power Qi |
|---|---|---|
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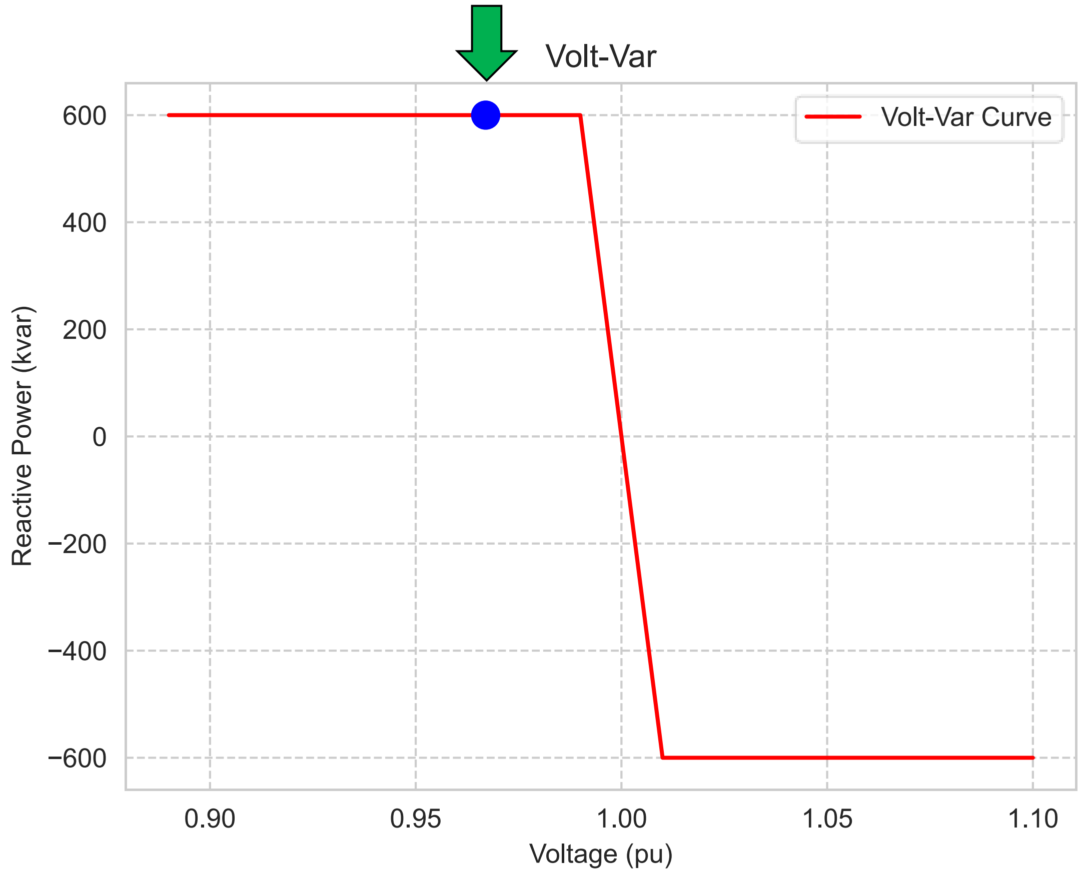

# The reason to have the convergence method

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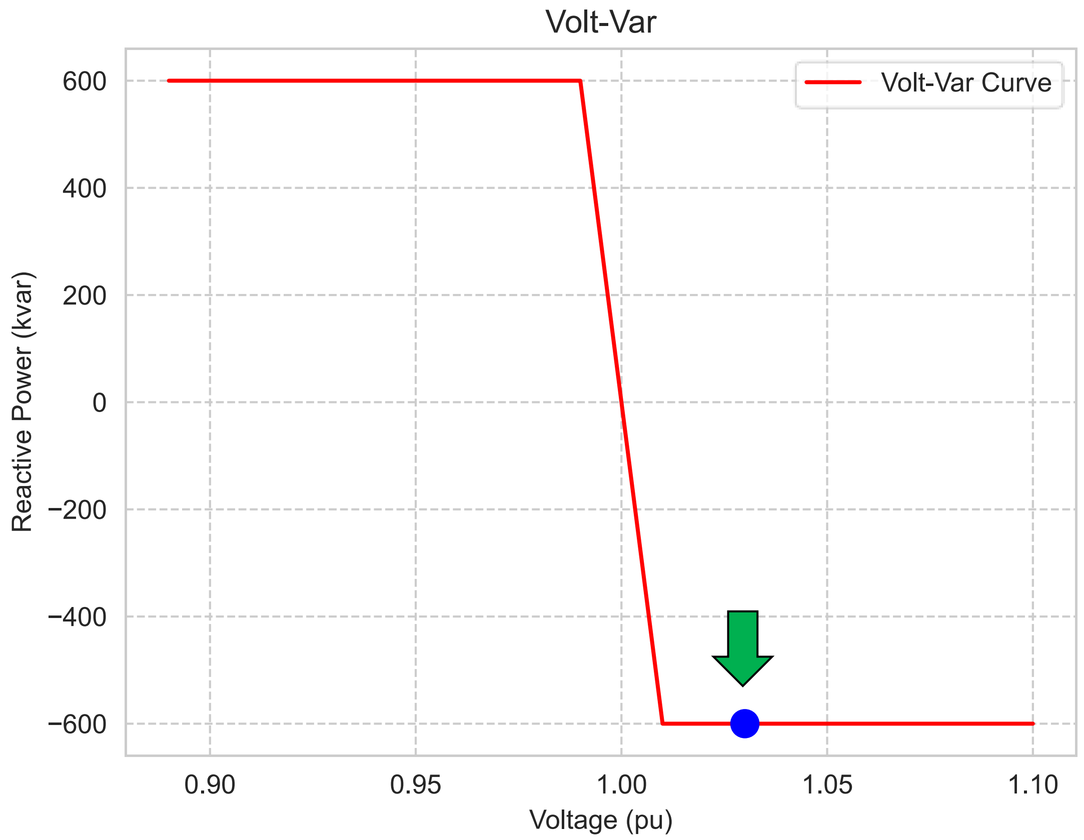

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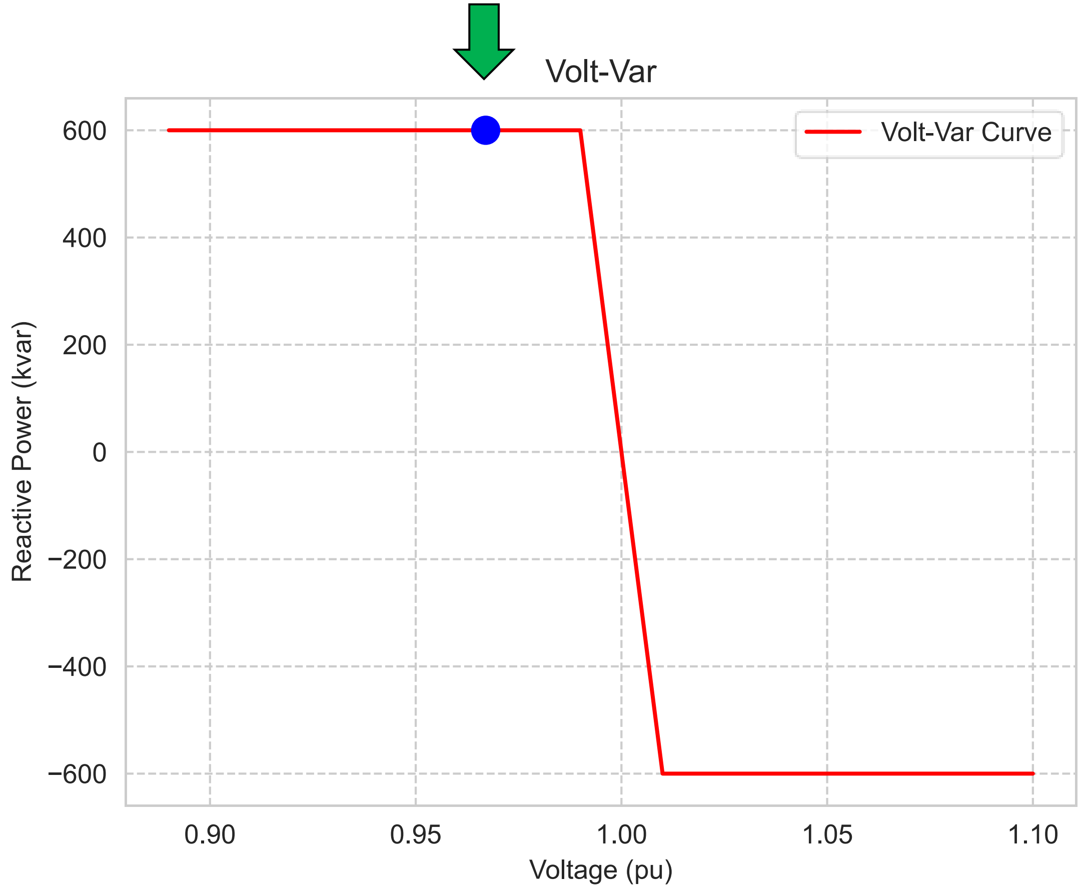

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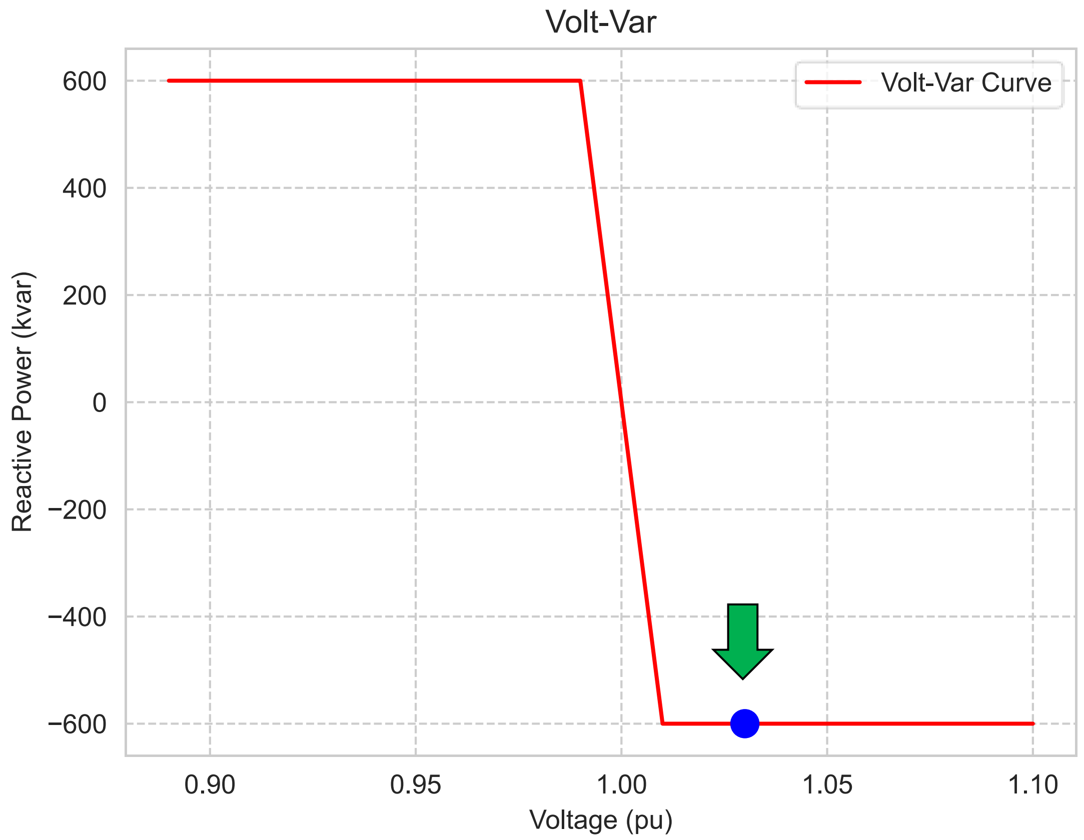
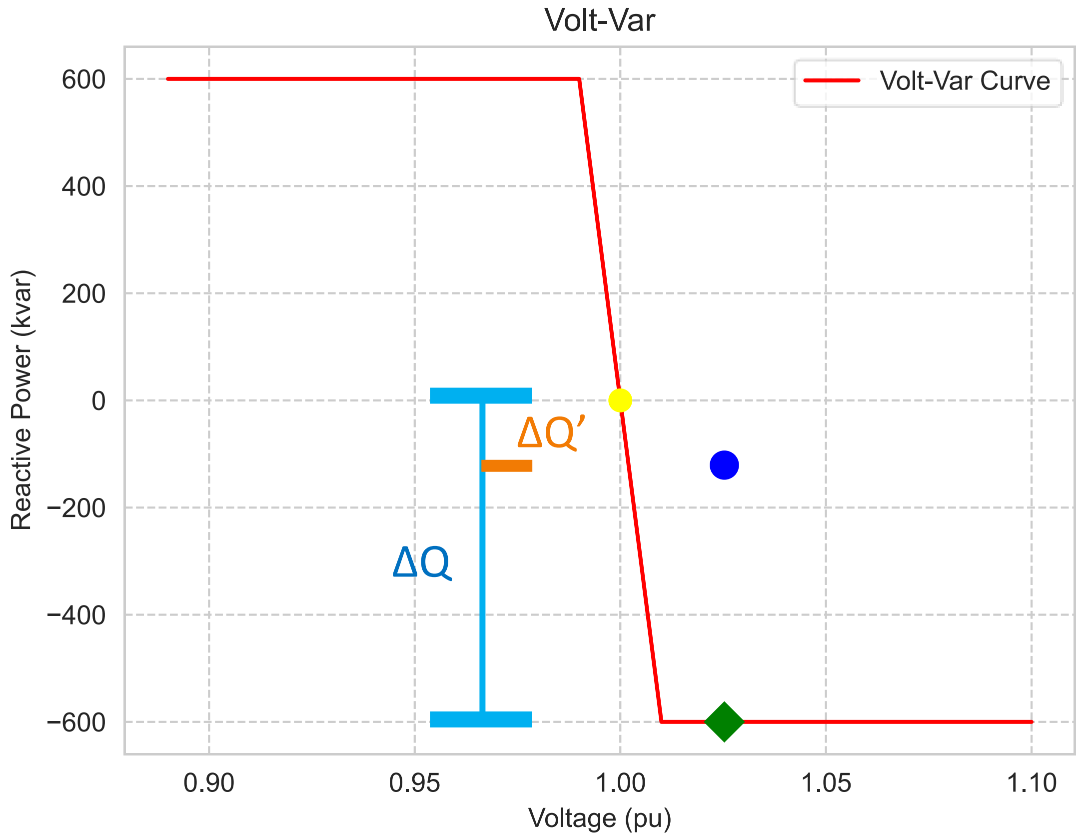


# How the convergence process works

| Control Iteration (i) | Voltage vi | Reactive power Qi | Desired Reactive power |
|---|---|---|---|
| 1 | 1.0253 | -120.8 | -600 |
| 2 | 1.019 | -216.64 | -600 |
| 3 | 1.014 | -293.31 | -600 |
| 4 | 1.0099 | -353.47 | -594 |
| 5 | 1.0059 | -353.65 | -354 |

- Desired Reactive Power
- Reactive Power $Q_i$
- Reactive Power $Q_{i-1}$




$\Delta Q$ = Desired Reactive Power - Reactive Power $Q_{i-1}$

$\Delta Q'$ = deltaq_factor * $\Delta Q$

deltaq_factor = 0.2

**Convergence.dss**

# How the convergence process works

| Control Iteration (i) | Voltage vi | Reactive power Qi | Desired Reactive power |
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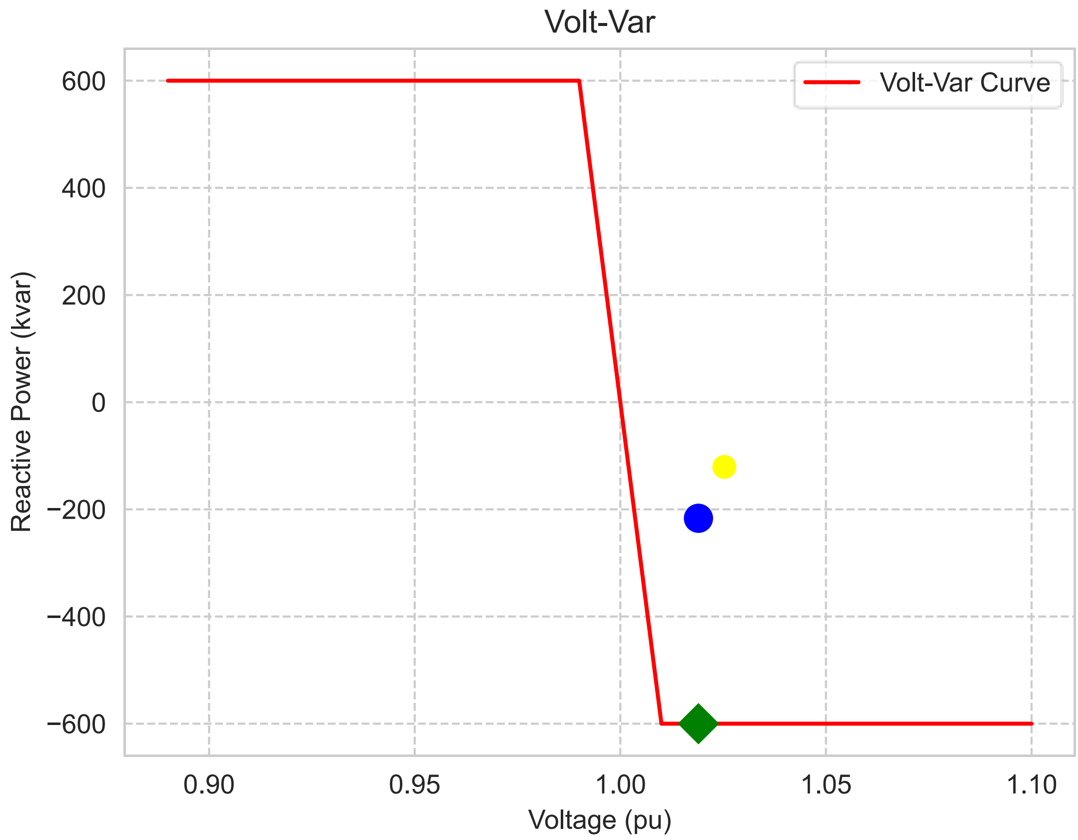
Desired Reactive Power

Reactive Power $Q_i$

Reactive Power $Q_{i-1}$



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| Control Iteration (i) | Voltage vi | Reactive power Qi | Desired Reactive power |
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| 2 | 1.019 | -216.64 | -600 |
| 3 | 1.014 | -293.31 | -600 |
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Desired Reactive Power

Reactive Power $Q_i$

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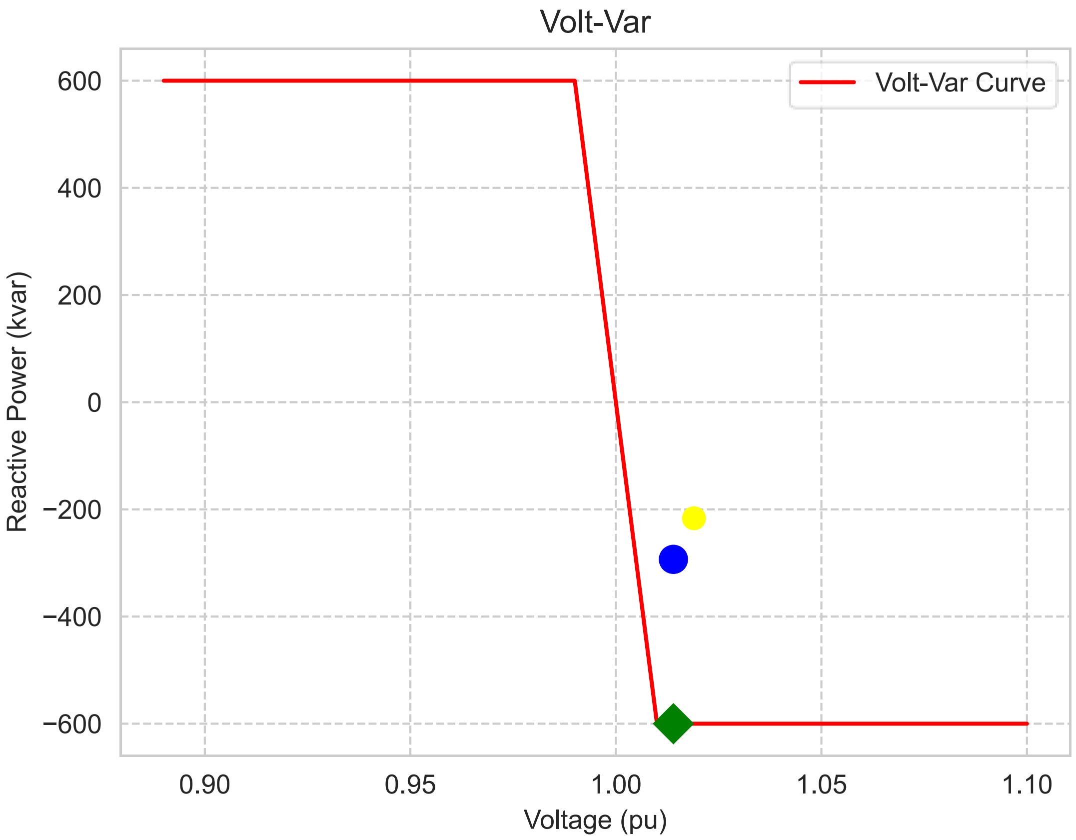

# How the convergence process works

| Control Iteration (i) | Voltage vi | Reactive power Qi | Desired Reactive power |
|---|---|---|---|
| 1 | 1.0253 | -120.8 | -600 |
| 2 | 1.019 | -216.64 | -600 |
| 3 | 1.014 | -293.31 | -600 |
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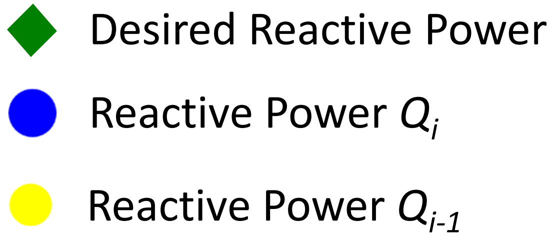


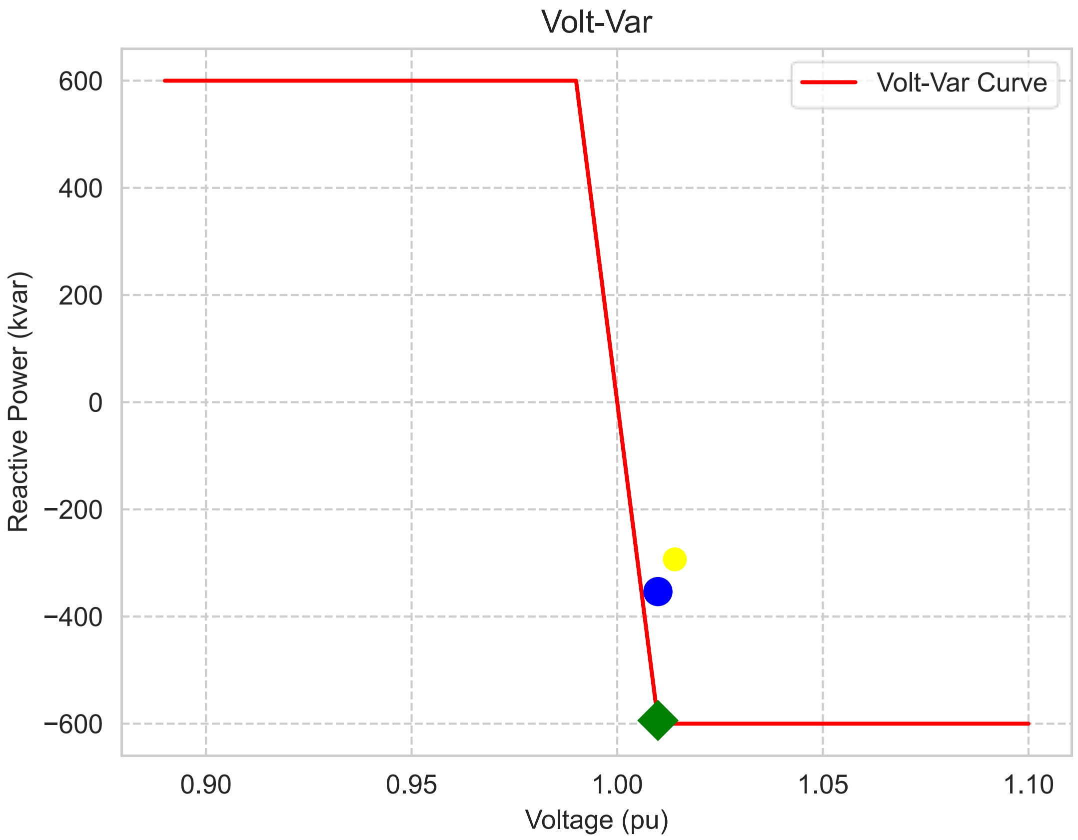

# How the convergence process works

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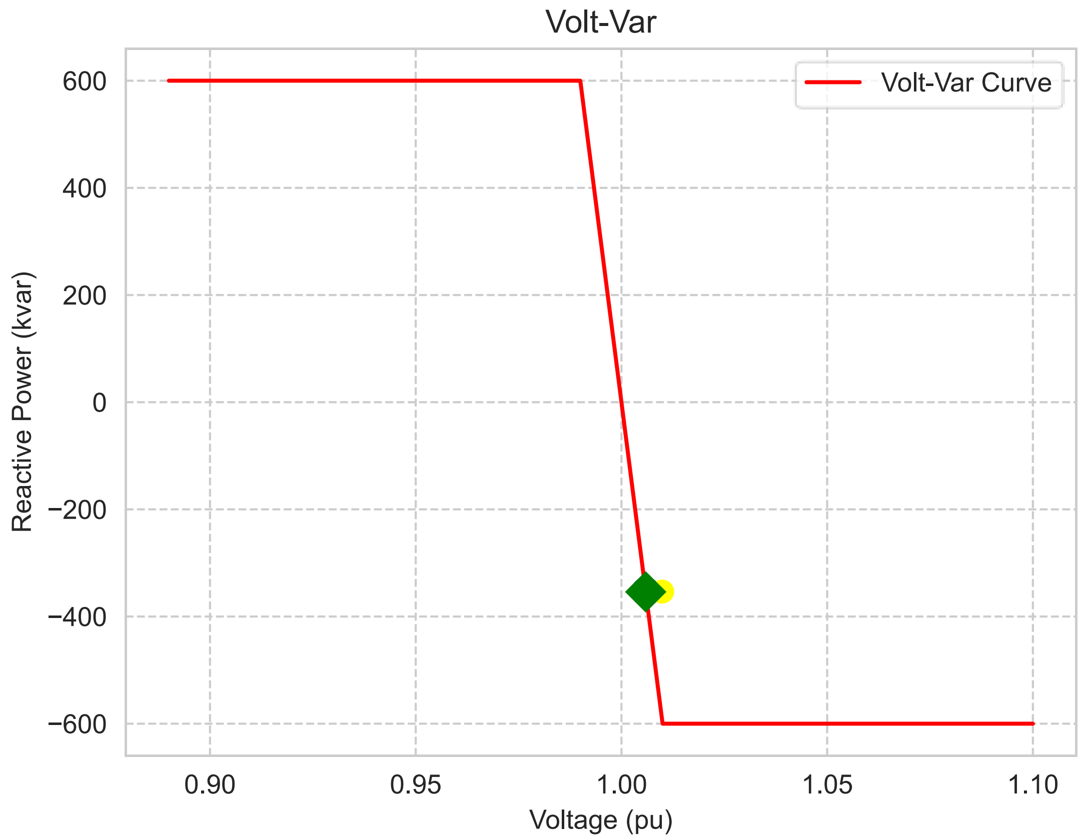
| 5 | 1.0059 | -353.65 | -354 |

- Desired Reactive Power
- Reactive Power $Q_i$
- Reactive Power $Q_{i-1}$




It converges when:

- $|v_i - v_{i-1}| < VoltageChangeTolerance$
- $|Q_i - \text{Desired } Q_i| < VarChangeTolerance$

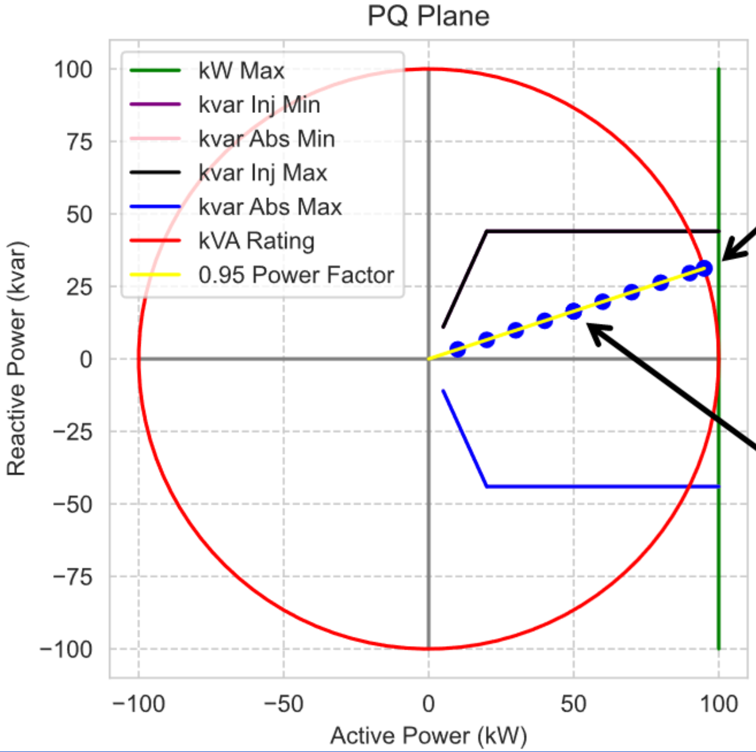
**https://publicdownload.epri.com/PublicAttachmentDownload.svc/AttachmentId=74500**

# A Few Examples of Smart Inverter Functions According IEEE Std 1547-2018

# Example # 1 Constant Power Factor

```
New PVSystem.PV phases=3 bus1=A Pmpp=100 kV=13.8 kVA=100 %Pmpp=100 pf=0.95 irradiance=P_pu
~ kvarMax=44 kvarMaxAbs=44 pfpriority=Yes
```

P_pu = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]




P and Q curtailed
Constant power factor setting fulfilled

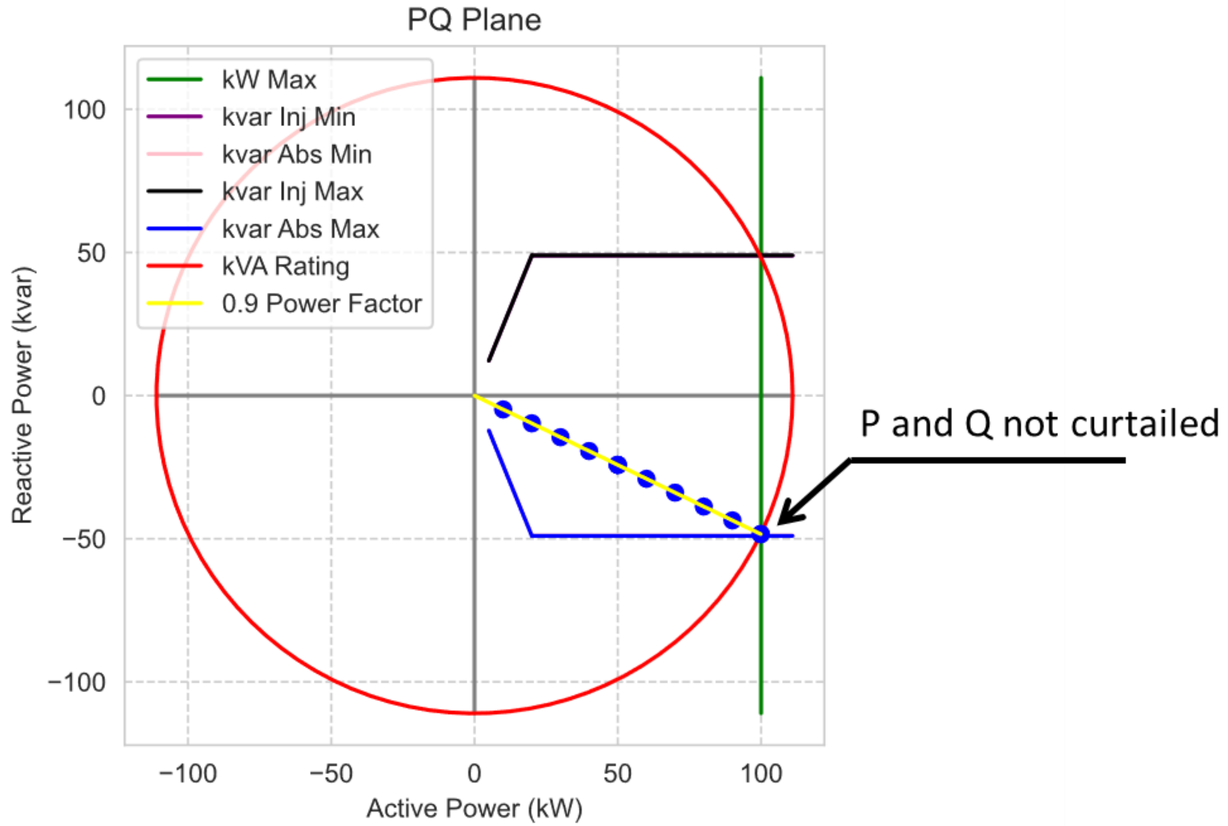
Voltage variation should not impact P and Q output

**Example1.py**

# Example # 2 Constant Power Factor

```
New PVSystem.PV phases=3 bus1=A Pmpp=100 kV=13.8 kVA=112 %Pmpp=100 pf=-0.9 irradiance=P_pu
~ kvarMax=44 kvarMaxAbs=44 pfpriority=Yes
```

P_pu = [0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0]

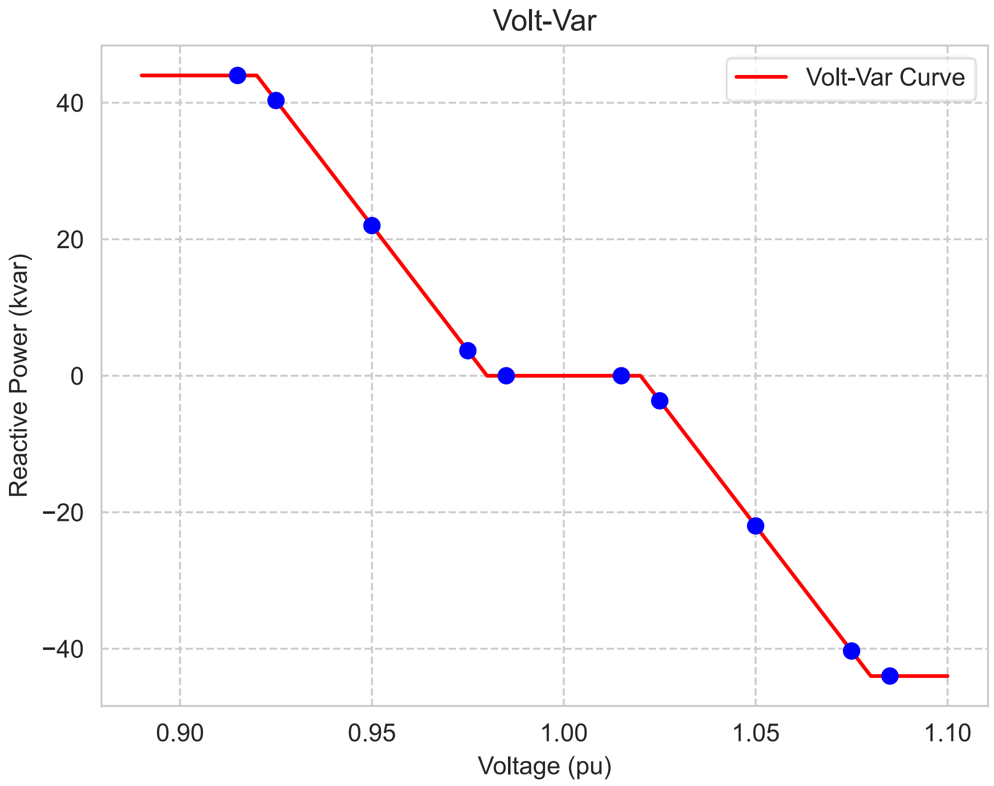


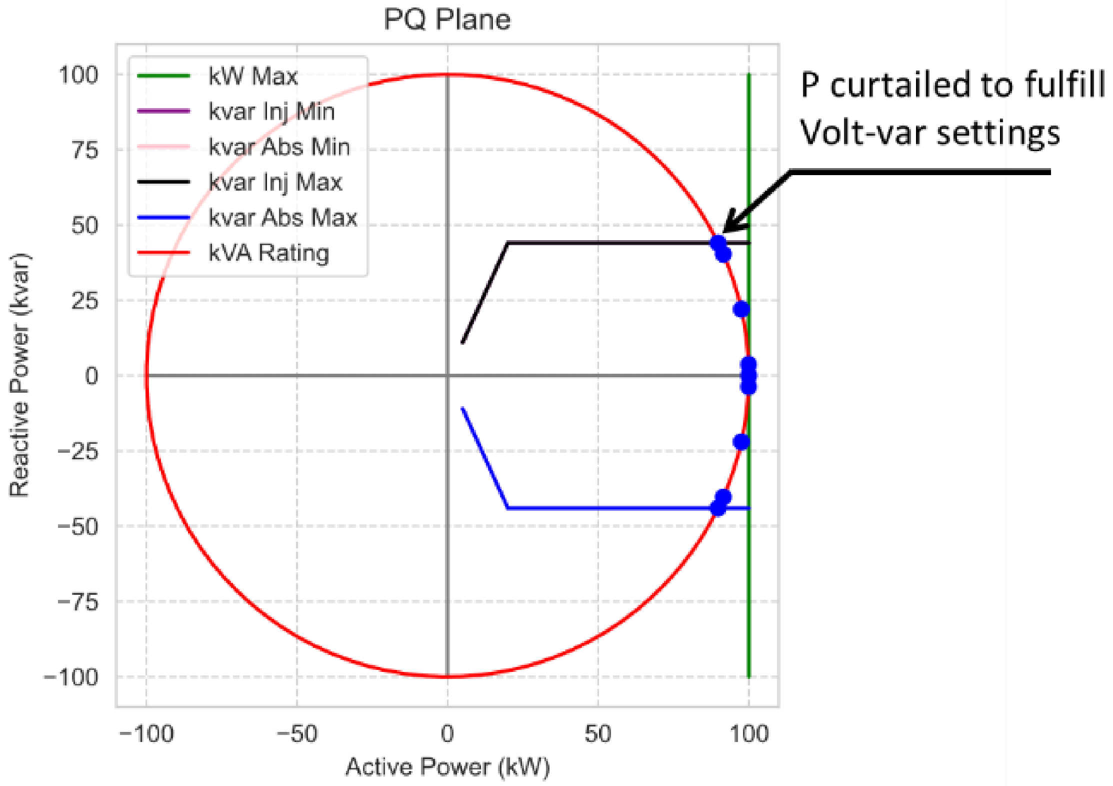

**Example2.py**

# Example # 3 Volt-Var (Example3.py)

```
New PVSystem.PV phases=3 bus1=A Pmpp=100 kV=13.8 kVA=100 %Pmpp=100 irradiance=1 kvarMax=44 kvarMaxAbs=44 wattpriority=No
New XYcurve.generic npts=5 yarray=[1 1 0 -1 -1] xarray=[0.5 0.92 1.0 1.08 1.5]
New InvControl.VoltVar mode=VOLTVAR voltage_curvex_ref=rated vvc_curve1=generic RefReactivePower=VARMAX
```

v_pu = [0.915, 0.925, 0.95, 0.975, 0.985, 1.015, 1.025, 1.05, 1.075, 1.085]

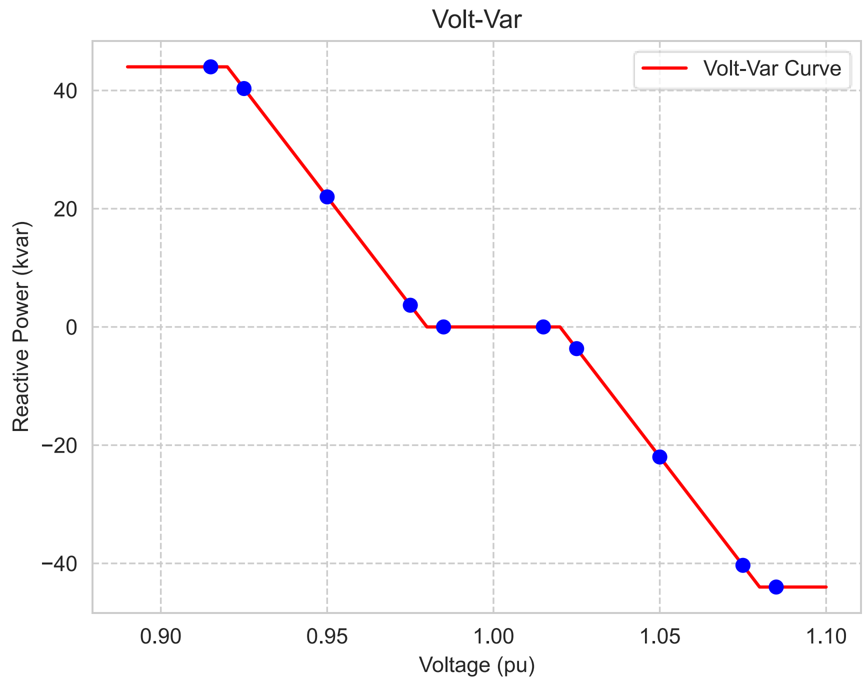


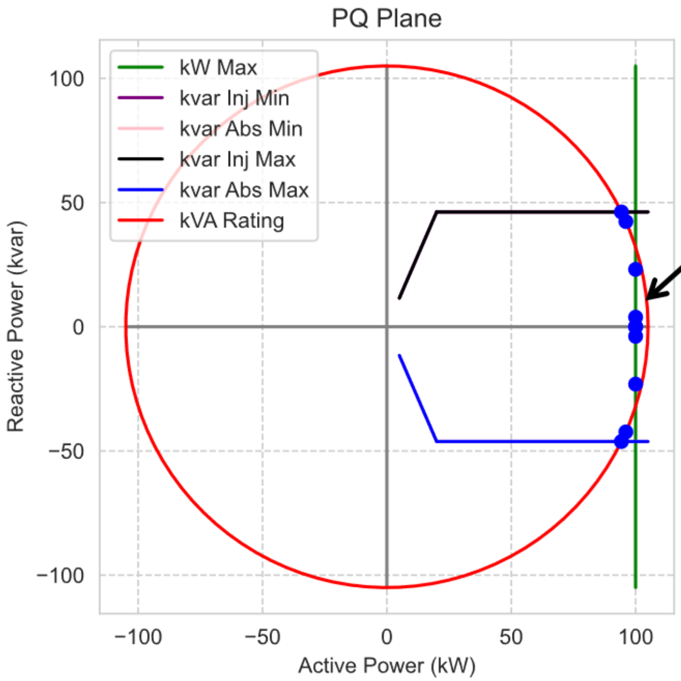



# Example # 4 Volt-Var (Example4.py)

```
New PVSystem.PV phases=3 bus1=A Pmpp=100 kV=13.8 kVA=105 %Pmpp=100 irradiance=1 kvarMax=44 kvarMaxAbs=44 wattpriority=No
New XYcurve.generic npts=5 yarray=[1 1 0 -1 -1] xarray=[0.5 0.92 1.0 1.08 1.5]
New InvControl.VoltVar mode=VOLTVAR voltage_curvex_ref=rated vvc_curve1=generic RefReactivePower=VARMAX
```

v_pu = [0.915, 0.925, 0.95, 0.975, 0.985, 1.015, 1.025, 1.05, 1.075, 1.085]




DER model has different kW and kVA rating.

P limited by its rating







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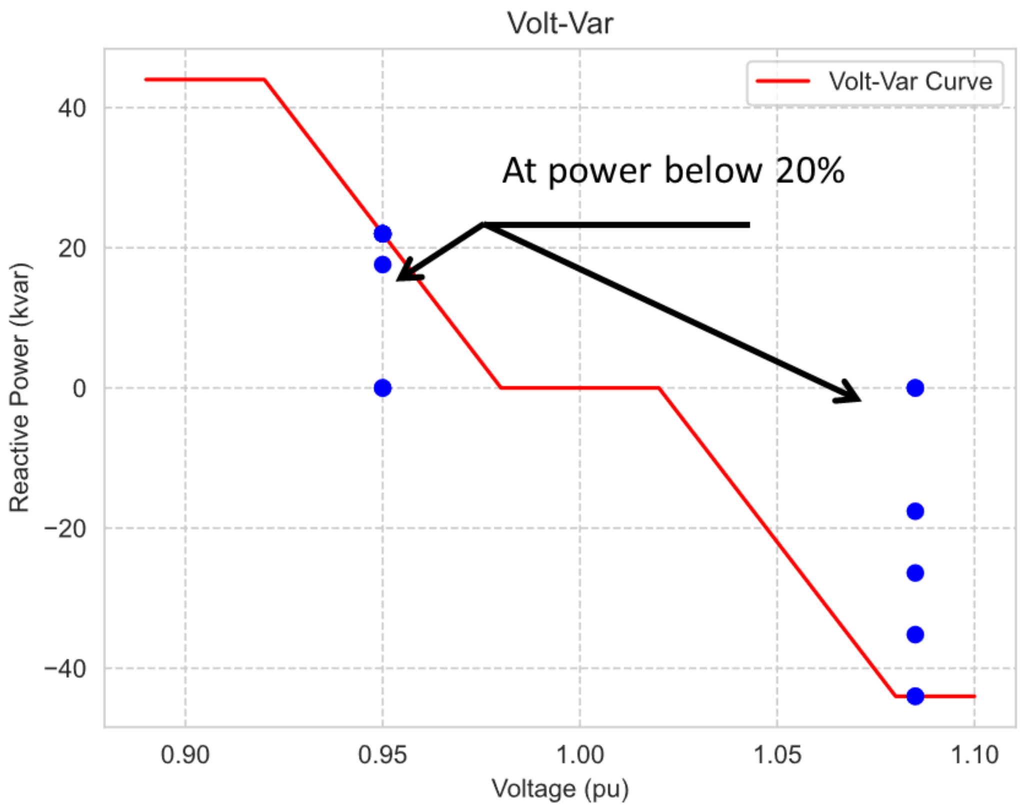
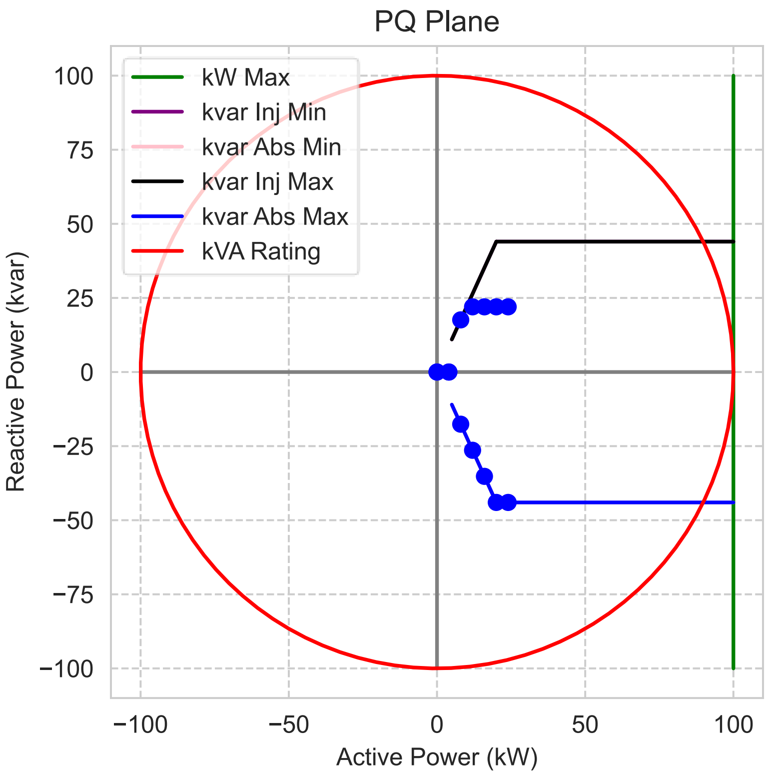
# Example # 5 Volt-Var (Example5.py)

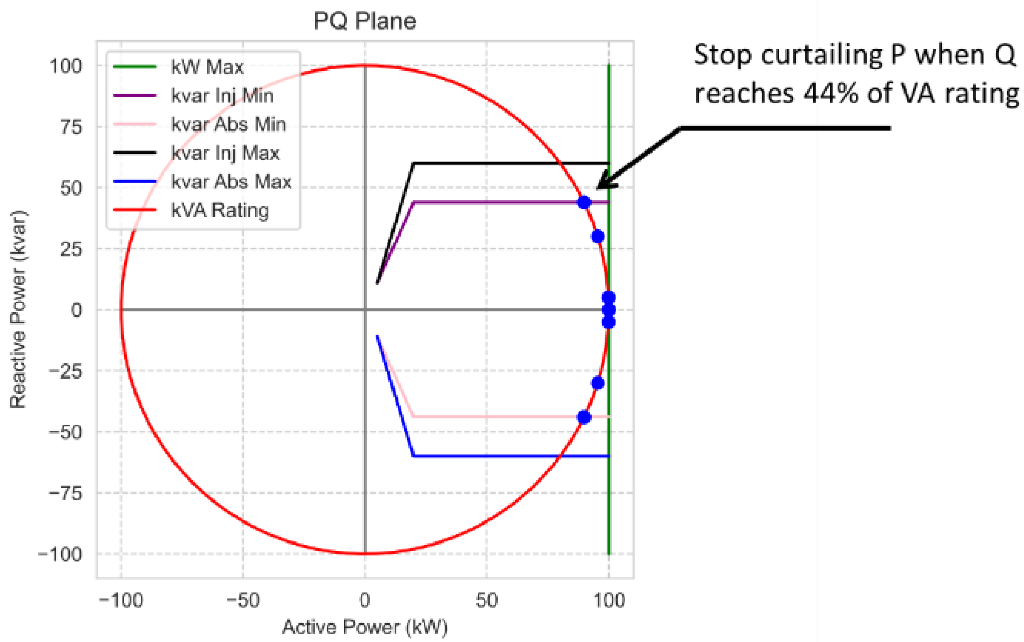
```
New PVSystem.PV phases=3 bus1=A Pmpp=100 kV=13.8 kVA=100 %Pmpp=100 irradiance=1 kvarMax=44 kvarMaxAbs=44 wattpriority=No
~ %PminNoVars=5 %PminkvarMax=20
New XYcurve.generic npts=5 yarray=[1 1 0 -1 -1] xarray=[0.5 0.92 1.0 1.08 1.5]
New InvControl.VoltVar mode=VOLTVAR voltage_curvex_ref=rated vvc_curve1=generic RefReactivePower=VARMAX
```

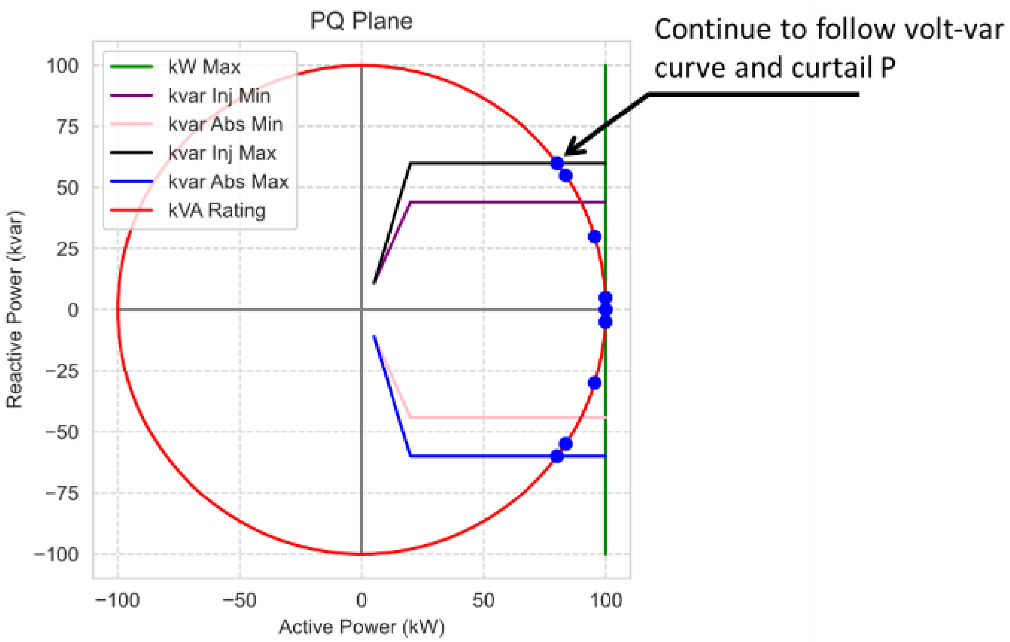


# Model Limitations

- OpenDSS can’t use positive sequence component voltage value for the applicable voltage as required in IEEE Std 1547-2018 Clause 4.6.3.
- OpenDSS can’t model inverters with capabilities greater than reactive power minimum requirements specified in IEEE Std 1547-2018.



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