Illustrative Examples of Reactive Capability (D-Curves) and Corresponding Compensation under Packages G and E

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Summary of Package E Compensation Metric

Flat rate: a generator's revenue is ***MVAR_Capability****Rate*

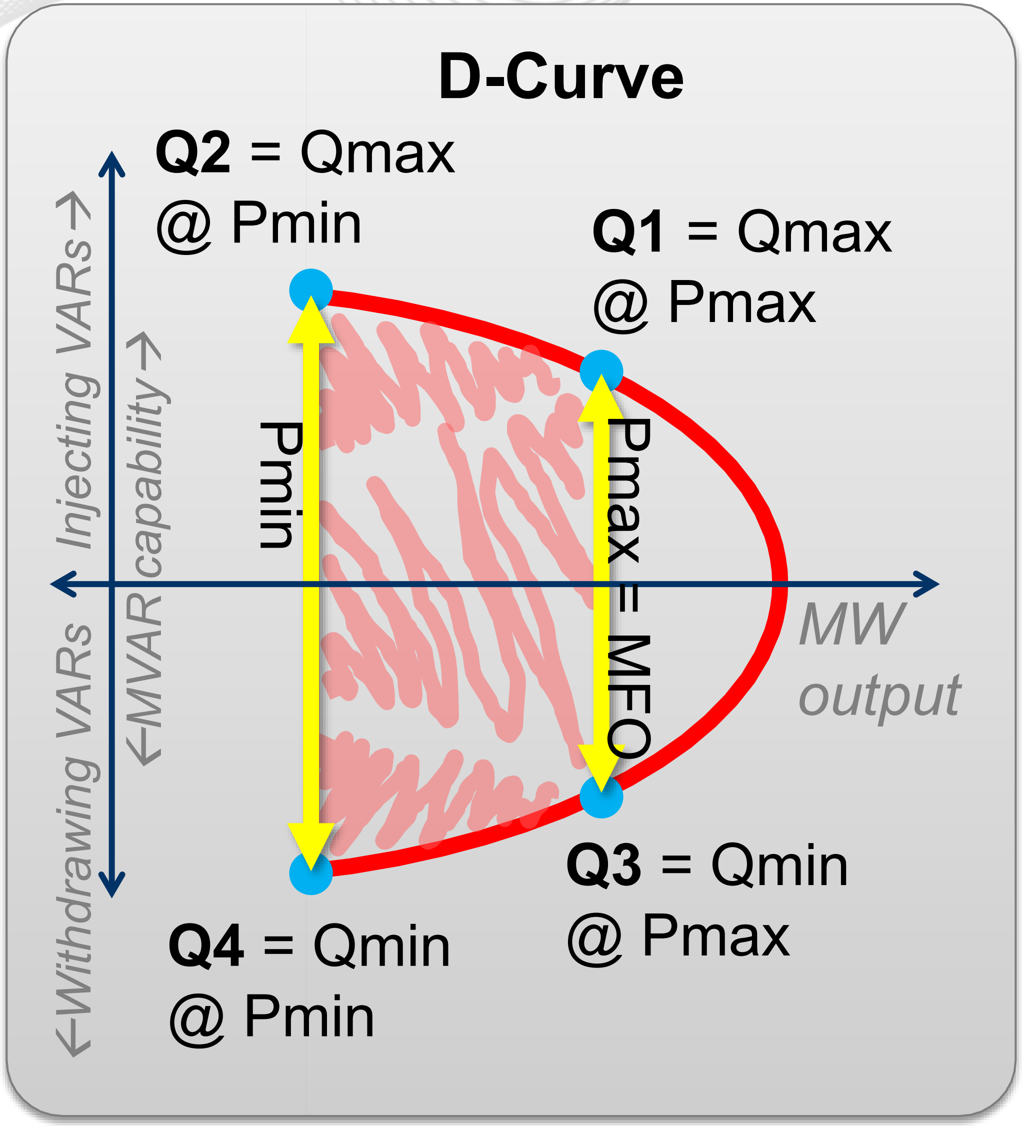
- *For illustration, assume Rate is $1,000/MVAR-yr (hypothetically).*

A generator's **D-curve** shows the maximum reactive capability (both injecting & withdrawing VARs, or "Q") as a function of real power (i.e., MW or "P") output.

- *In general, machine designs mean more MW output means less MVAR capability.*

MVAR_Capability_E is [average of Q1 and Q2] minus [average of Q3 and Q4]. This basically amounts to: ***injecting capability (averaged at Pmax and Pmin) plus withdrawing capability (averaged at Pmax and Pmin).***

- *VAR withdrawal is negative Q, hence the "minus".*
- *Pmin is the lowest power the generator is capable of making while online (not less than zero).*
- *Pmax is Maximum Facility Output or the functional equivalent.*



Summary of Package G Compensation Metric

G

Flat rate: a generator's revenue is ***MVAR_Capability****Rate*

- *For illustration, assume Rate is $1,000/MVAR-yr (hypothetically).*

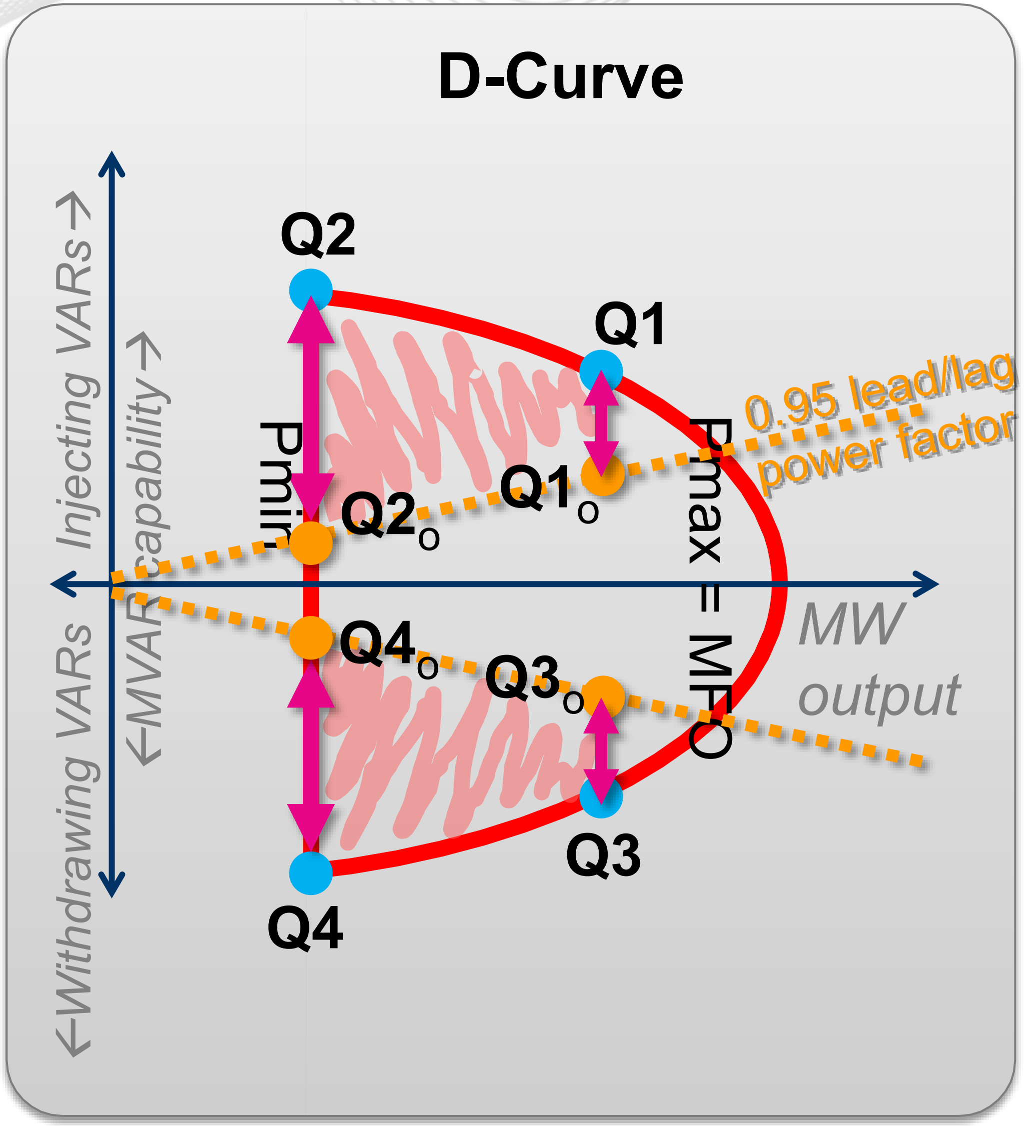
Package G would use precisely the same reactive rate as Package, without adjustment.

MVAR_Capability_G is [average of $Q1-Q1_o$ and $Q2-Q2_o$] minus [average of $Q3-Q3_o$ and $Q4-Q4_o$].

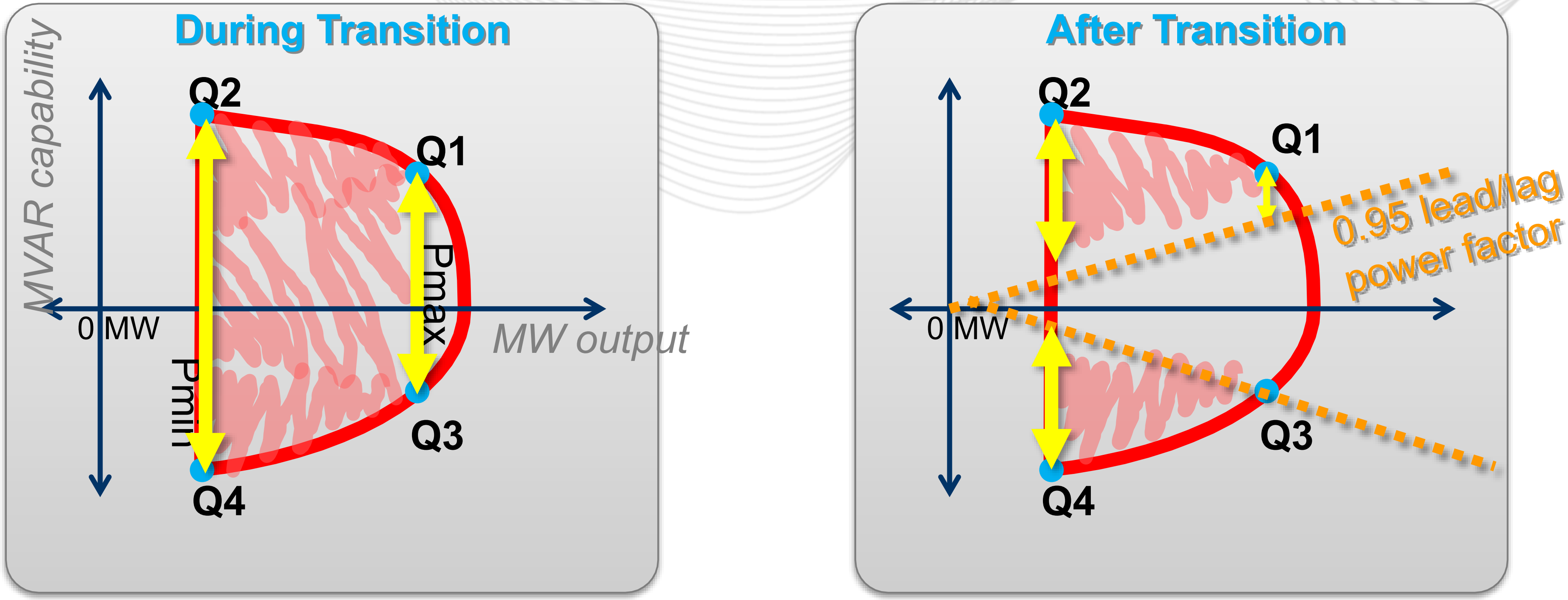
Q_o is the "standard obligation" = 0.95 lead/lag power factor at high side. This amounts to:

injecting capability above obligation (averaged at Pmax and Pmin) *--plus--*
withdrawing capability above obligation (averaged at Pmax and Pmin).

- *VAR withdrawal is negative Q, hence the "minus".*



Package G-PJM-Capability Above Standard Obligation



- Same as Package E during transition period.
- After transition period, same as Package E, except **compensates only capability above standard obligation (i.e., above 0.95 lead/lag power factor)**.

- Transition period is:
  - Option I: 5 years
  - Option II: after 90% of existing Schedule 2 filed rates have rolled off (e.g., only 29 or fewer remain)

Calculating Standard Obligated Capability For Package G

- P is real power, Q is reactive power, S is "apparent power"
- **Obligation is 0.95 Power Factor**
- Power factor is defined as $\mathrm{P/S = 0.95} \rightarrow \mathrm{S = P/0.95}$
- Power systems engineering says: $S^2 = P^2 + Q^2 \rightarrow Q = \sqrt{S^2 - P^2} \rightarrow$
- $Q = \sqrt{\left(\frac{P}{0.95}\right)^2 - P^2} = \left(\sqrt{\left(\frac{1}{0.95}\right)^2 - 1}\right) \times P = \rightarrow$

Obligation: **Q is 32.87% of P**

- Example: obligated reactive capability at 100 MW is 32.87 MVAR (leading and lagging)

Comparative Summary of Compensation Examples (Details for Each Example on Following Slides)

	Package E	Package G
Steam	$81,500	$32,500
CT	$76,500	$17,500
CT w/ Condensing Mode	$81,500	$48,500
Solar	$78,000	$45,000
Solar w/ Condensing Mode	$78,000	$45,000
Battery	$133,000	$100,000
DC-Coupled Hybrid	$78,000	$45,000
New Tech Wind	$78,000	$45,000
Old Tech Wind	$66,000	$33,000
Old Tech Wind Fixed PF	$33,000	$0

Hypothetical rate of $1,000/MVAR-yr

Package G (“Pay Capability in Excess of Standard Obligation”) Examples

Illustrative Example of a 100 MW Steam Generator

VAR injection capability:

- *Q1@Pmax (100 MW) = 40 MVAR*
- *$Q1_o$@Pmax (100 MW) = 33 MVAR*

Difference: 7 MVAR

- *Q2@Pmin (50 MW) = 50 MVAR*
- *$Q2_o$@Pmin (50 MW) = 16 MVAR*

Difference: 34 MVAR

VAR withdrawal capability:

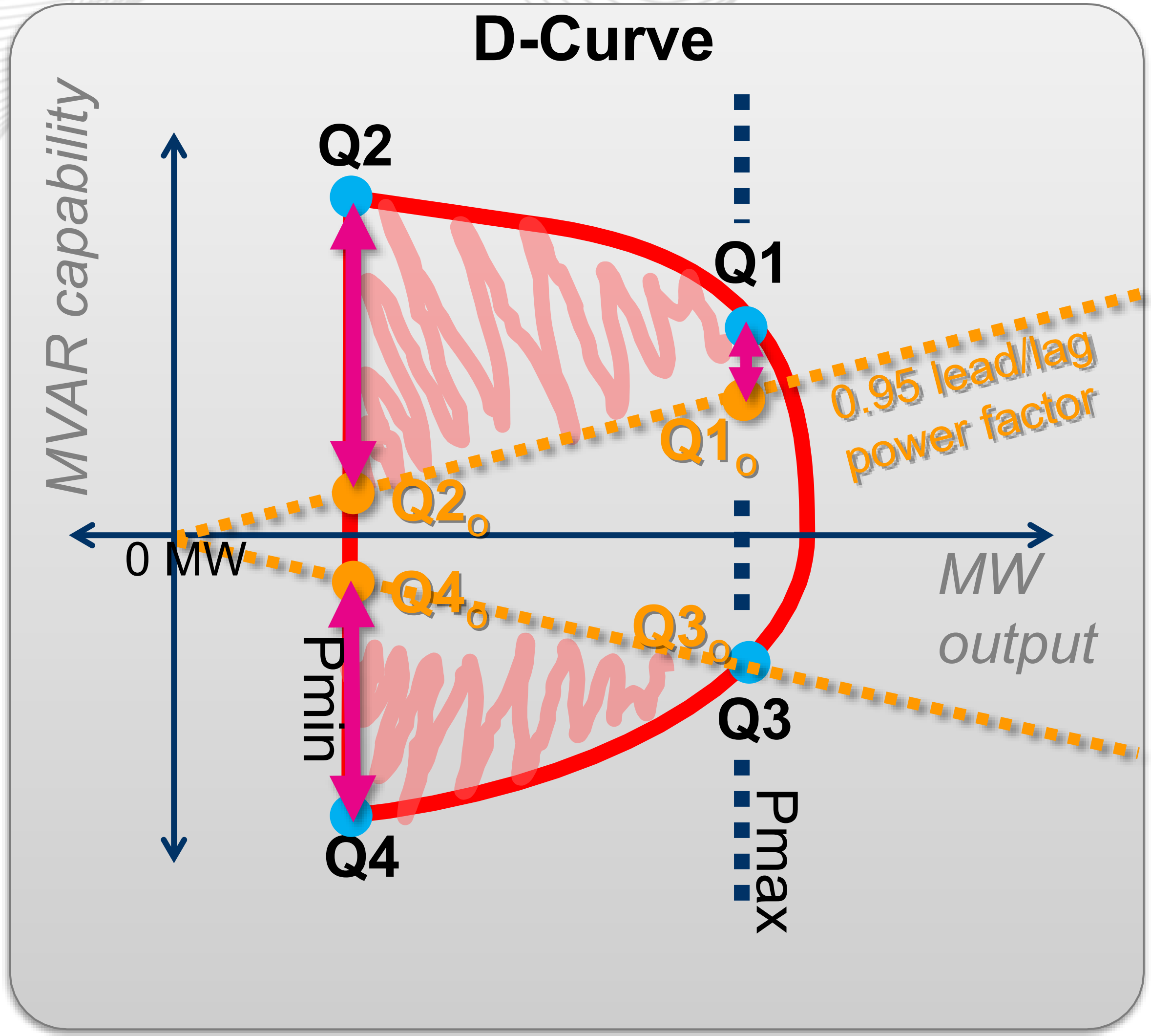
- *Q3 at Pmax = -33 MVAR*
- *$Q3_o$@Pmax = -33 MVAR*

Difference: 0 MVAR

- *Q4 at Pmin = -40 MVAR*
- *$Q4_o$@Pmin = -16 MVAR*

Difference: -24 MVAR

- Average(7,34) - Average(0,-24) = 32.5
- Compensation = $1,000*32.5 = **$32,500/yr**



Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a 100 MW Combustion Turbine

VAR injection capability:

- *Q1@Pmax (100 MW) = 40 MVAR*
- *$Q1_o$@Pmax (100 MW) = 33 MVAR*

Difference: 7 MVAR

- *Q2@Pmin (80 MW) = 45 MVAR*
- *$Q2_o$@Pmin (80 MW) = 26 MVAR*

Difference: 19 MVAR

VAR withdrawal capability:

- *Q3 at Pmax = -33 MVAR*
- *$Q3_o$@Pmax = -33 MVAR*

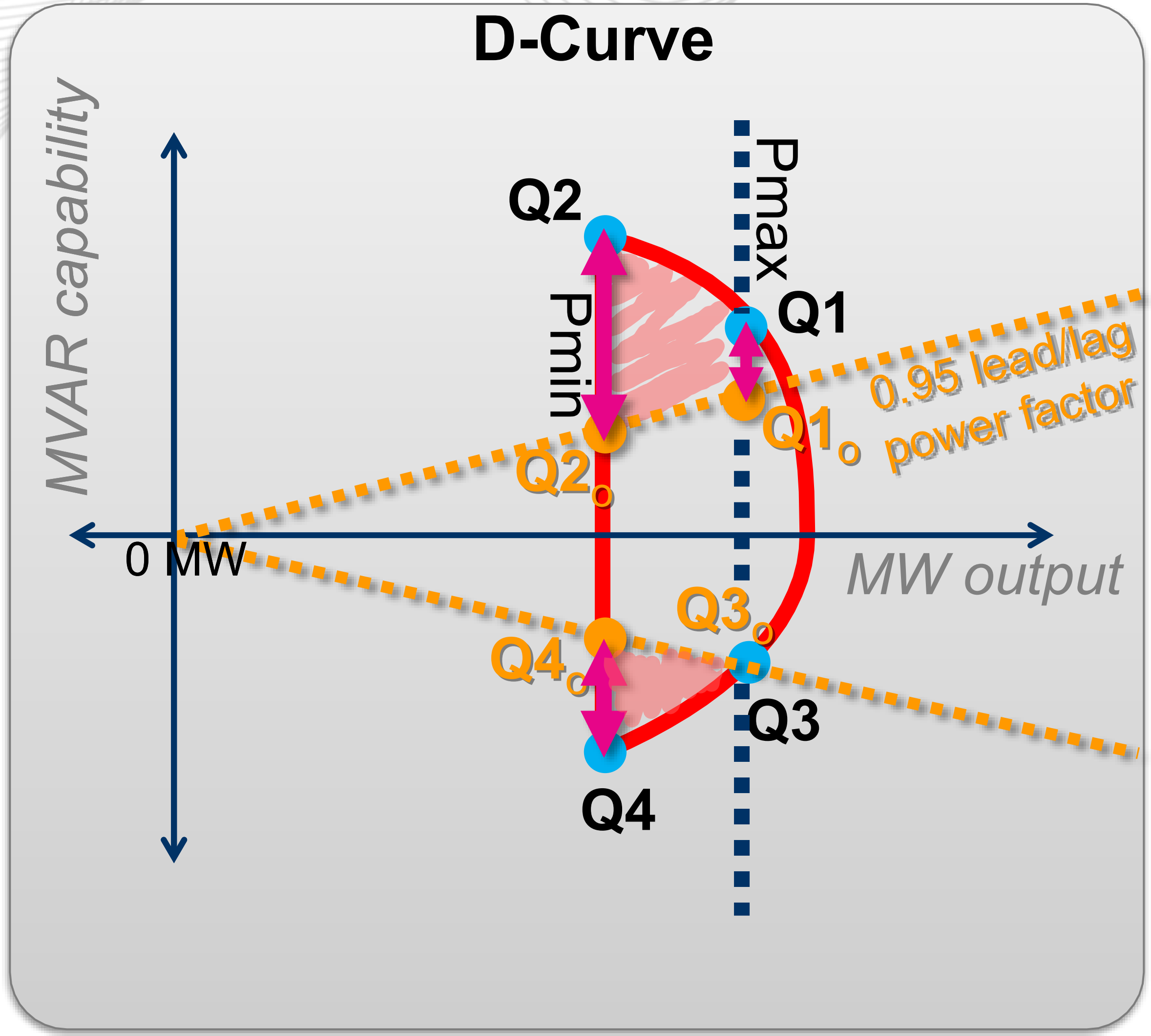
Difference: 0 MVAR

- *Q4 at Pmin = -35 MVAR*
- *$Q4_o$@Pmin = -26 MVAR*

Difference: -9 MVAR

- Average(*7,19*) - Average(*0,-9*) = 17.5
- Compensation = $1,000*17.5 = **$17,500/yr**

Hypothetical rate of $1,000/MVAR-yr



Illustrative Example of a Combustion Turbine
w/ Condensing Mode

G

VAR injection capability:

- *Q1@Pmax (100 MW) = 40 MVAR*
- *$Q1_o$@Pmax (100 MW) = 33 MVAR*

Difference: 7 MVAR

- *Q2@Pmin (0 MW) = 50 MVAR*
- *$Q2_o$@Pmin (0 MW) = 0 MVAR*

Difference: 50 MVAR

VAR withdrawal capability:

- *Q3 at Pmax = -33 MVAR*
- *$Q3_o$@Pmax = -33 MVAR*

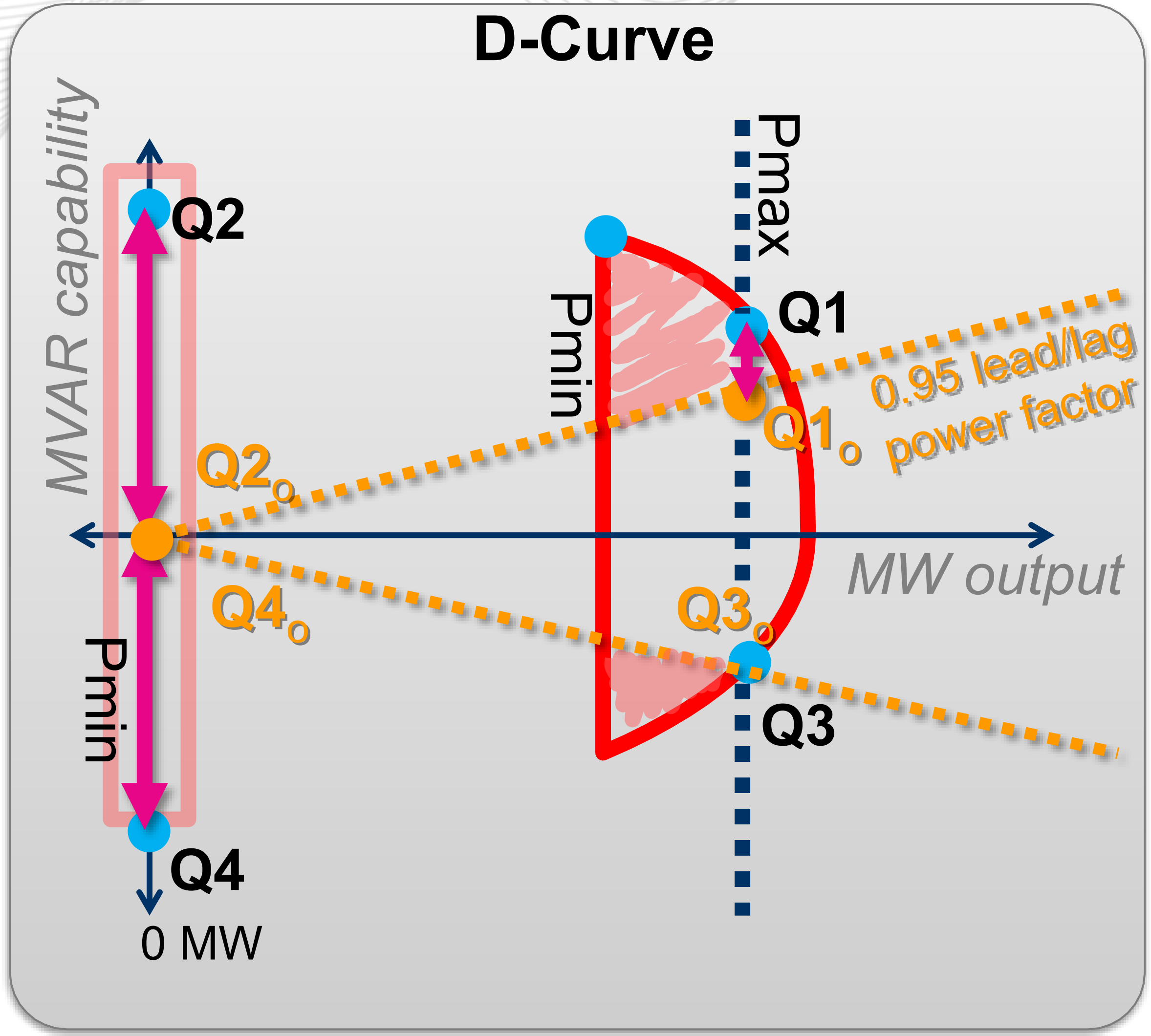
Difference: 0 MVAR

- *Q4 at Pmin = -40 MVAR*
- *$Q4_o$@Pmin = 0 MVAR*

Difference: -40 MVAR

- Average(*7,50*) - Average(*0,-40*) = 48.5
- Compensation = $1,000*48.5 = **$48,500/yr**

Hypothetical rate of $1,000/MVAR-yr



Illustrative Example of a Solar Plant (Same as New Tech Wind and DC-Coupled Hybrid)

G

VAR injection capability:

- *Q1@Pmax (100 MW) = 33 MVAR*
- *$Q1_o$@Pmax (100 MW) = 33 MVAR*

Difference: 0 MVAR

- *Q2@Pmin (0 MW) = 45 MVAR*
- *$Q2_o$@Pmin (0 MW) = 0 MVAR*

Difference: 45 MVAR

VAR withdrawal capability:

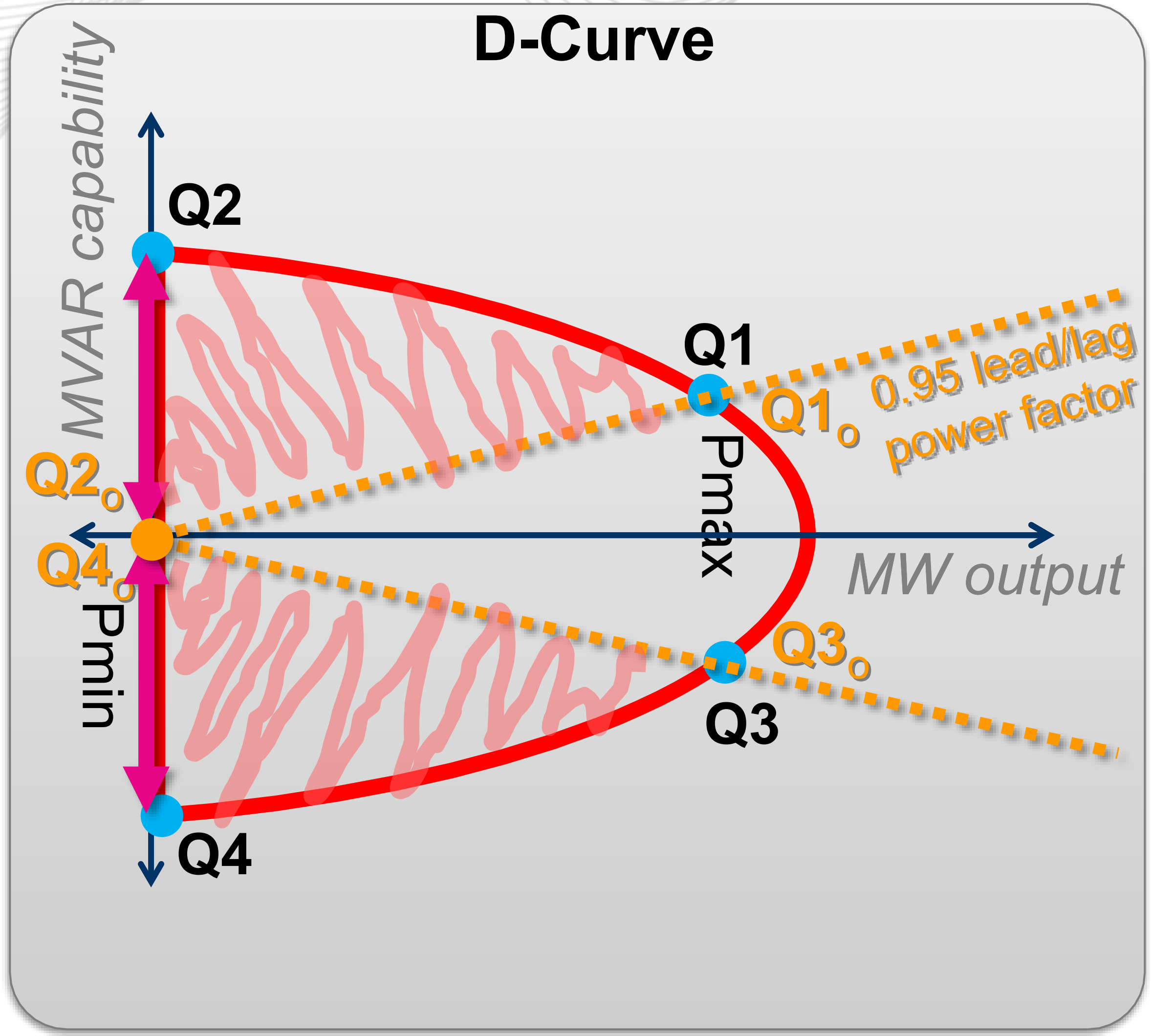
- *Q3 at Pmax = -33 MVAR*
- *$Q3_o$@Pmax = -33 MVAR*

Difference: 0 MVAR

- *Q4 at Pmin = -45 MVAR*
- *$Q4_o$@Pmin = 0 MVAR*

Difference: -45 MVAR

- Average(*0,45*) - Average(*0,-45*) = 45
- Compensation = $1,000*45 = **$45,000/yr**



Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Battery

G

VAR injection capability:

- ***Q1*@Pmax (100 MW) = *33* MVAR**
- ***$Q1_o$*@Pmax (100 MW) = *33* MVAR**

*Difference: **0** MVAR*

- ***Q2*@Pmin (0 MW) = *100* MVAR**
- ***$Q2_o$*@Pmin (0 MW) = *0* MVAR**

*Difference: **100** MVAR*

VAR withdrawal capability:

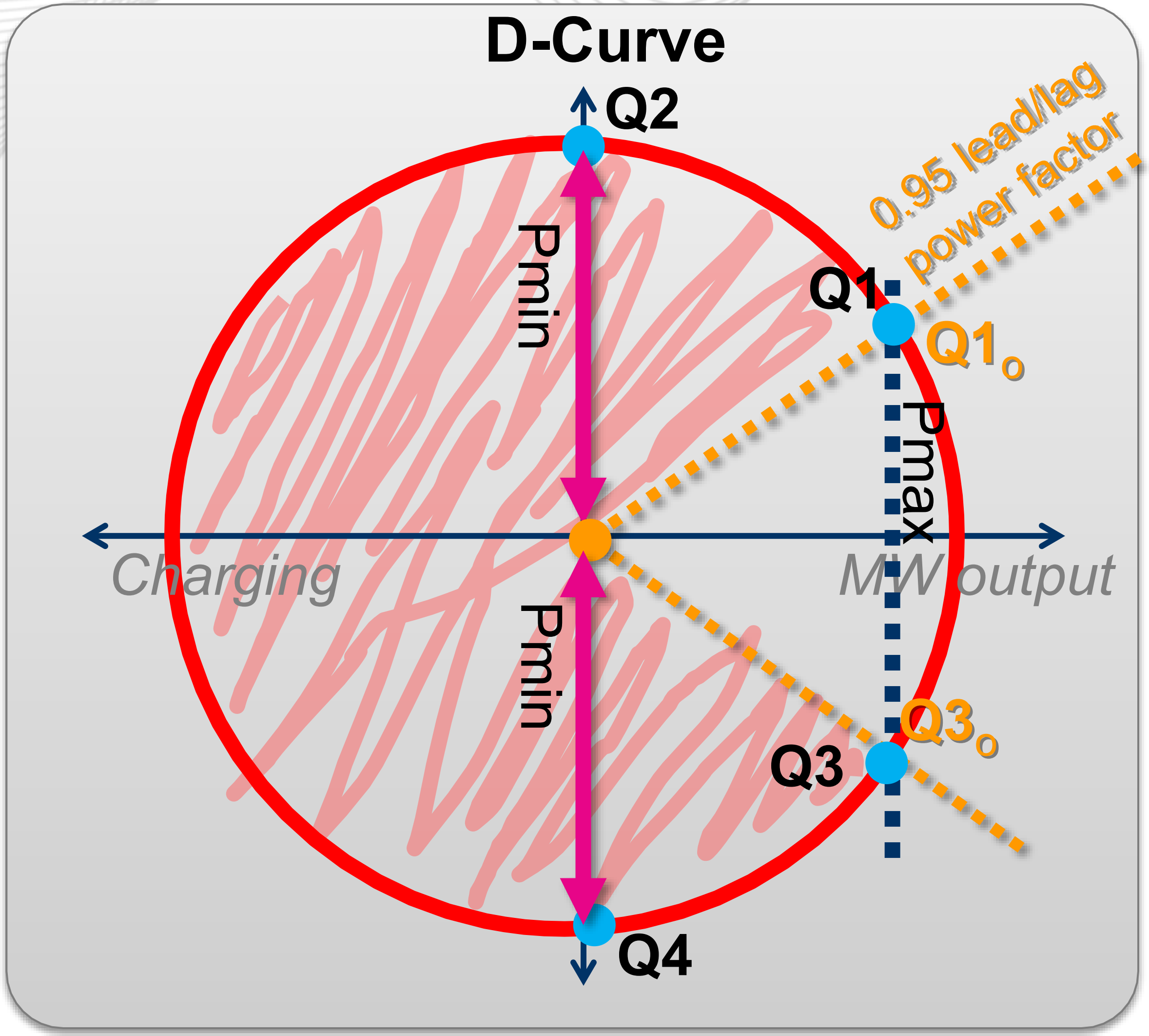
- *Q3 at Pmax = -**33** MVAR*
- ***$Q3_o$*@Pmax = -*33* MVAR**

*Difference: **0** MVAR*

- *Q4 at Pmin = -**100** MVAR*
- ***$Q4_o$*@Pmin = *0* MVAR**

*Difference: -**100** MVAR*

- Average(**0,100**) - Average(**0,-100**) = 100
- Compensation = $1,000*100 = **$100,000/yr**

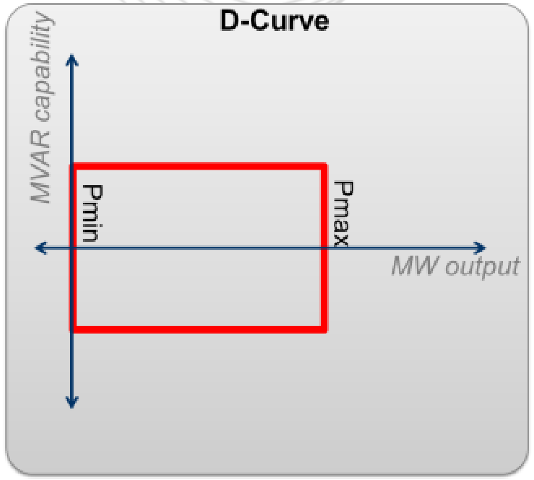


Hypothetical rate of $1,000/MVAR-yr

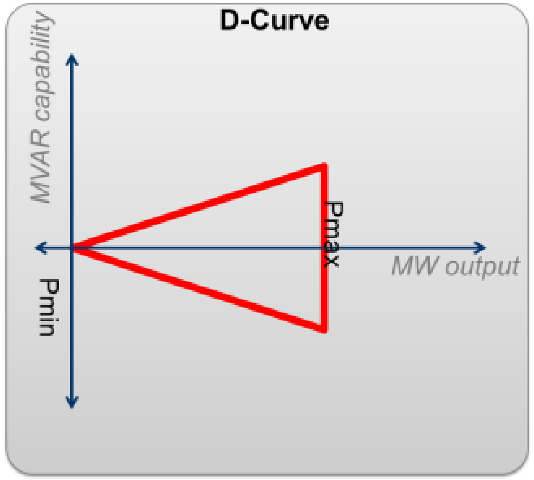
Illustrative Example of Old-Technology Wind Plants

G

- Old tech with full capability fixed at +/-33 MVAR regardless of power:
  - 0 excess at Pmax, 33 MVAR excess lead and lag at Pmin → $33,000



- Old tech with controller set to only provide 0.95 lead/lag capability:
  - 0 excess capability above obligation → $0



Hypothetical rate of $1,000/MVAR-yr

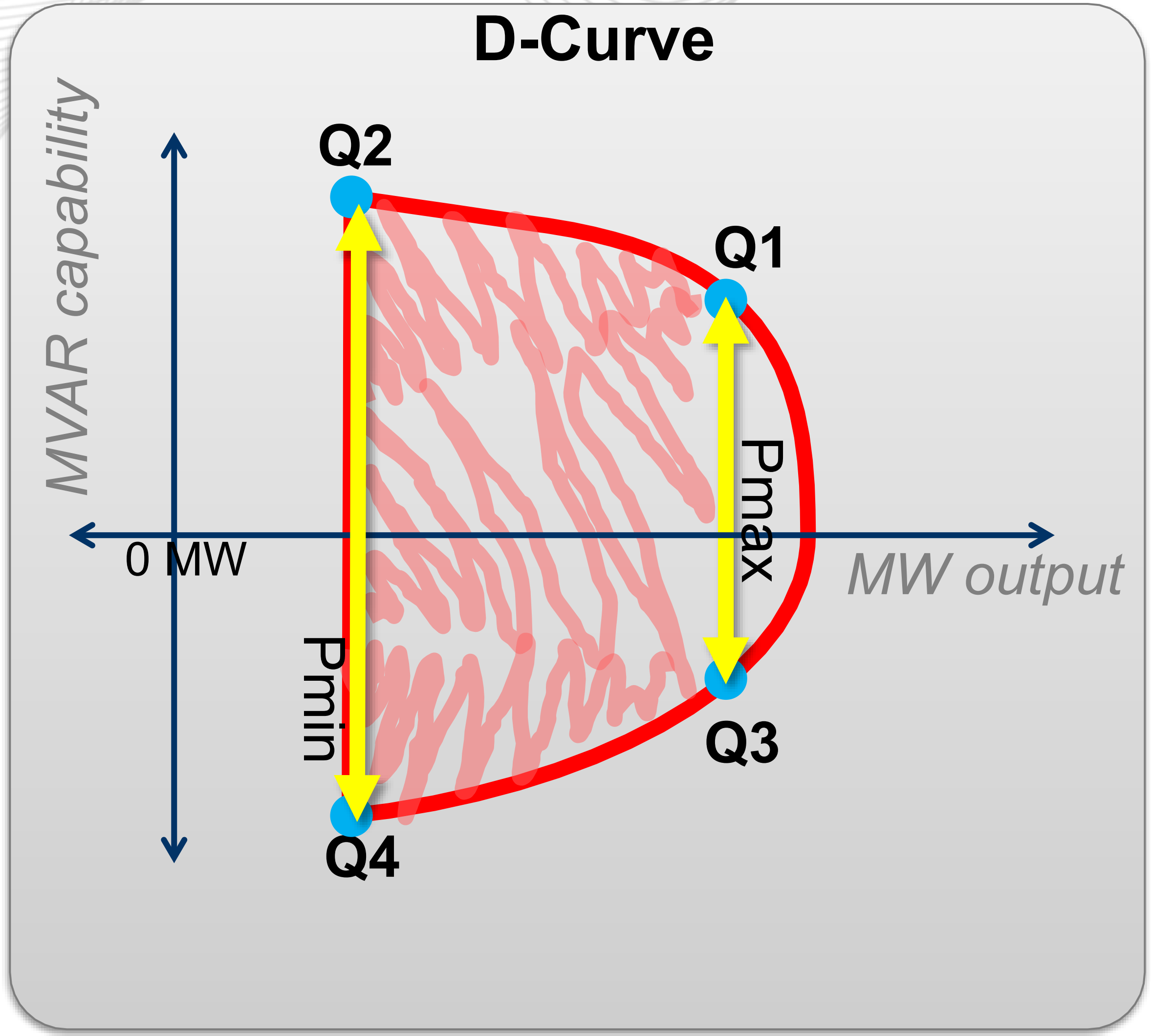
Package E (“Pay Full Capability”) Examples (Same As Prior Meeting)

Illustrative Example of a 100 MW Steam Generator

- VAR injection capability:
  - Q1 at Pmax (100 MW) = **40** MVAR
  - Q2 at Pmin (50 MW) = **50** MVAR
- VAR withdrawal capability:
  - Q3 at Pmax = **-33** MVAR
  - Q4 at Pmin = **-40** MVAR
- Average(**40,50**) - Average(**-33,-40**) = 81.5
- Compensation = $1,000*81.5 = **$81,500/yr**

Typical interconnection agreements require a minimum reactive capability that amounts to roughly 1/3d of MFO. In theory, the "nose" of the D-curve is typically not available.

Synchronous machine designs generally have lower VAR withdrawal capability than injection capability.



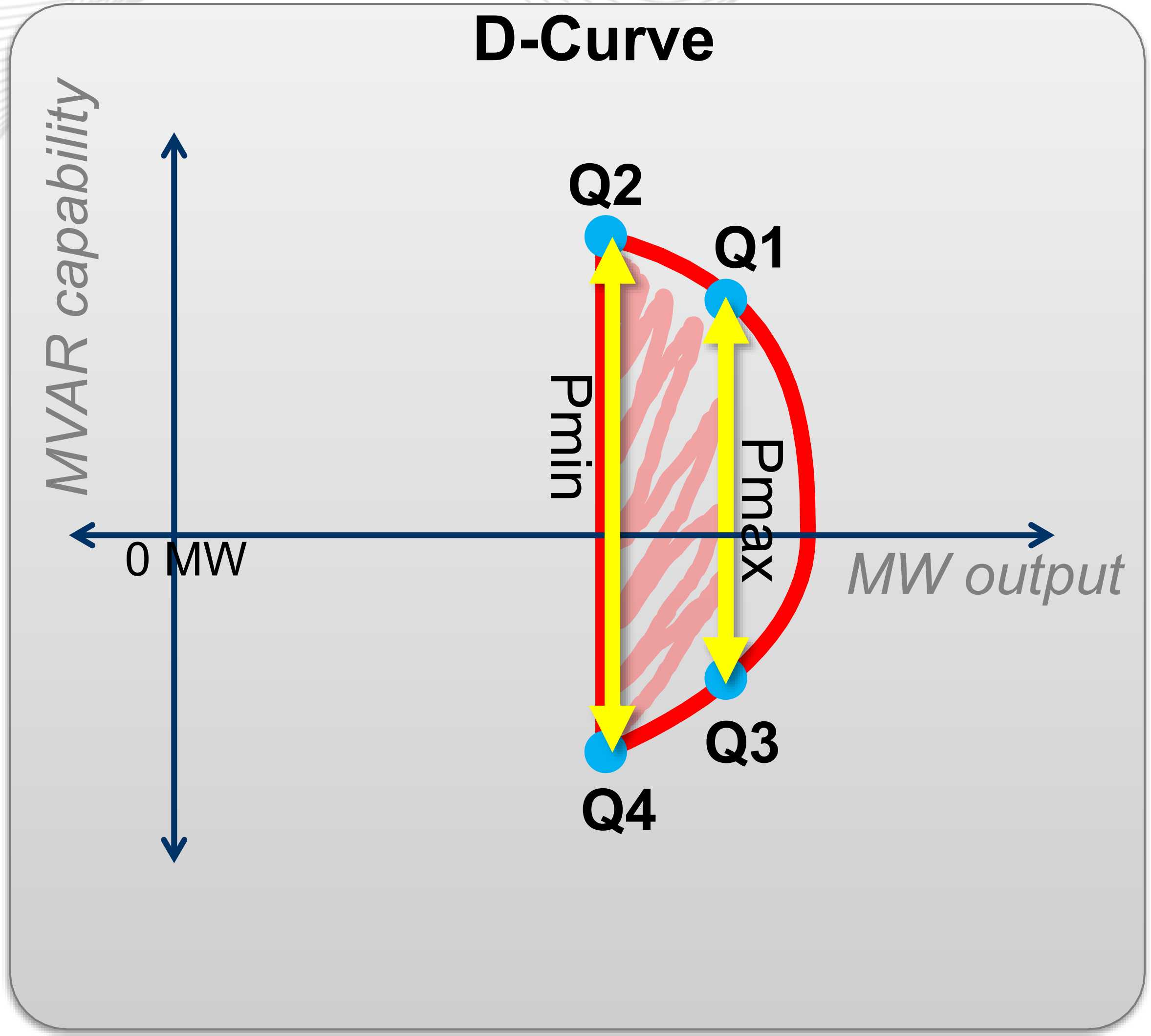
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a 100 MW Combustion Turbine

E

- VAR injection capability:
  - *Q1 at Pmax (100 MW) = **40** MVAR*
  - *Q2 at Pmin (80 MW) = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 at Pmax = **-33** MVAR*
  - *Q4 at Pmin = **-35** MVAR*
- Average(***40,45***) – Average(***-33,-35***) = 76.5
- Compensation = $1,000*76.5 = **$76,500/yr**

A CT might have a narrower dispatchable range than a steam generator, which might reduce the reactive capability available to PJM.

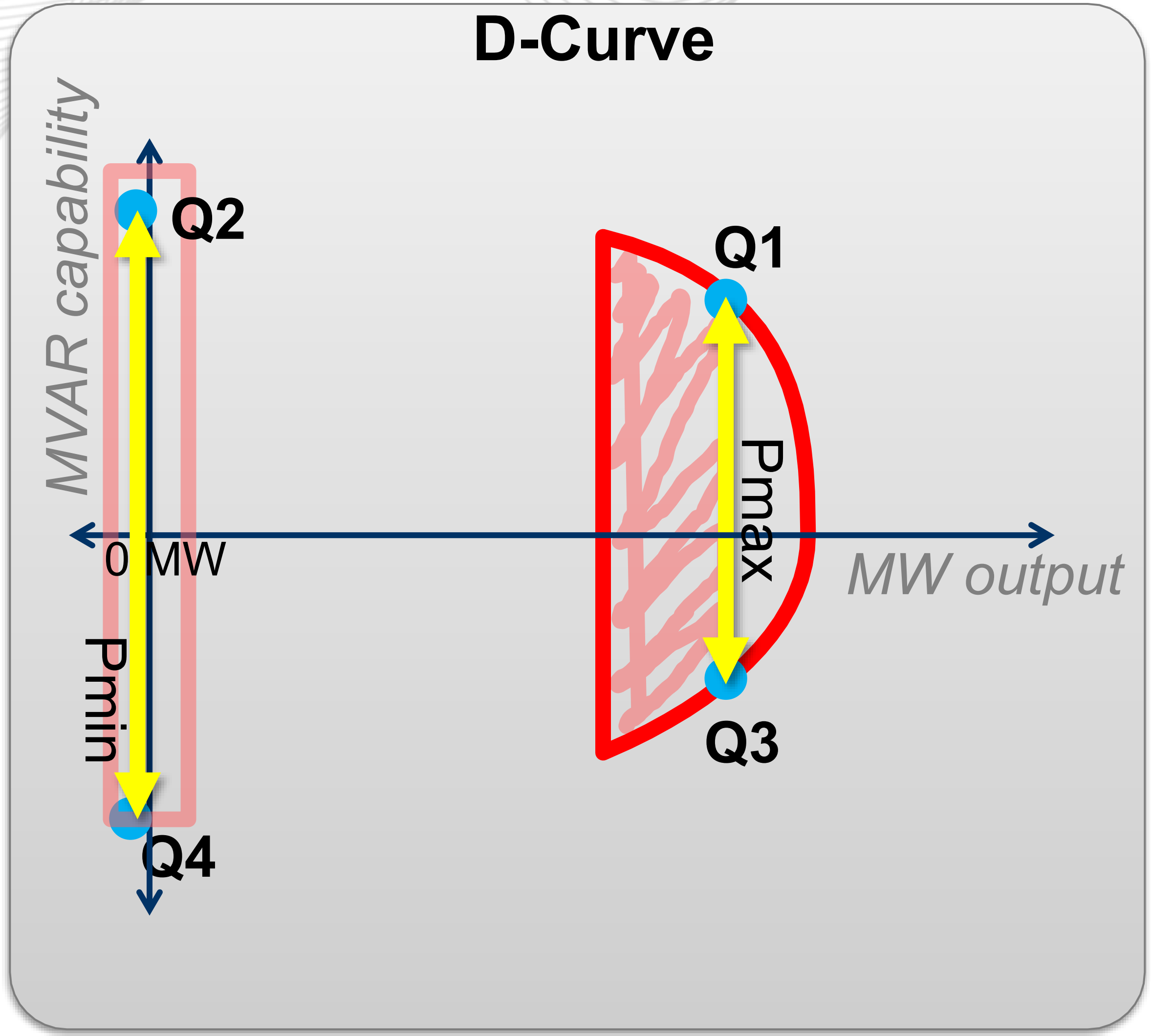


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Combustion Turbine
w/ Condensing Mode

A synchronous machine generator with "condensing mode" can operate at 0 MW.

- VAR injection capability:
  - *Q1 = **40** MVAR*
  - *Q2 = **50** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-40** MVAR*
- Average(***40,50)*** – Average(***-33,-40***) = 81.5
- Compensation = $1,000*81.5 = **$81,500/yr**

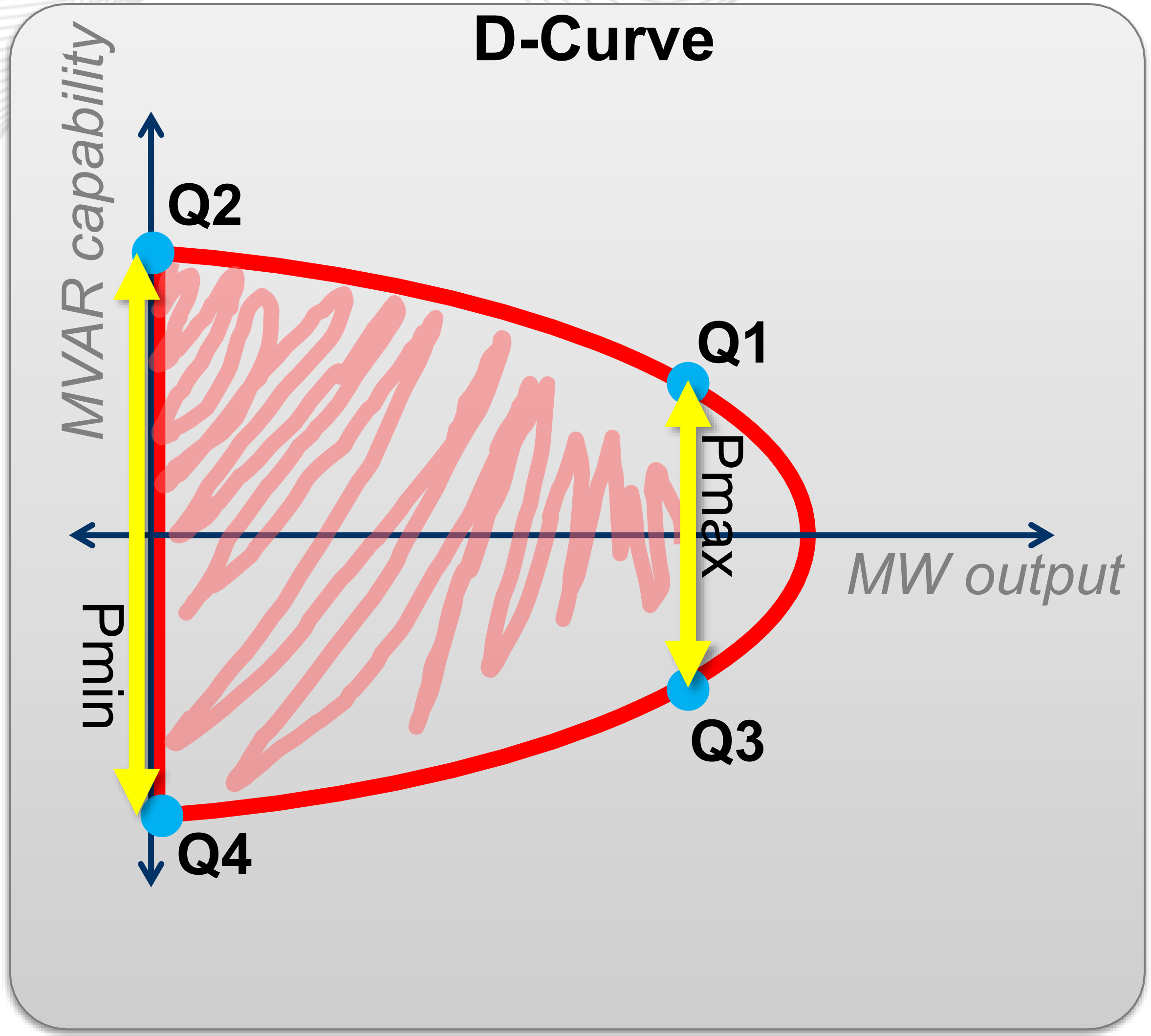


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar Plant

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

Inverter reactive capability matches power capability (they have a circular D-curve at the inverter terminals), however high impedance between PJM and large solar farm inverters reduces the reactive capability.



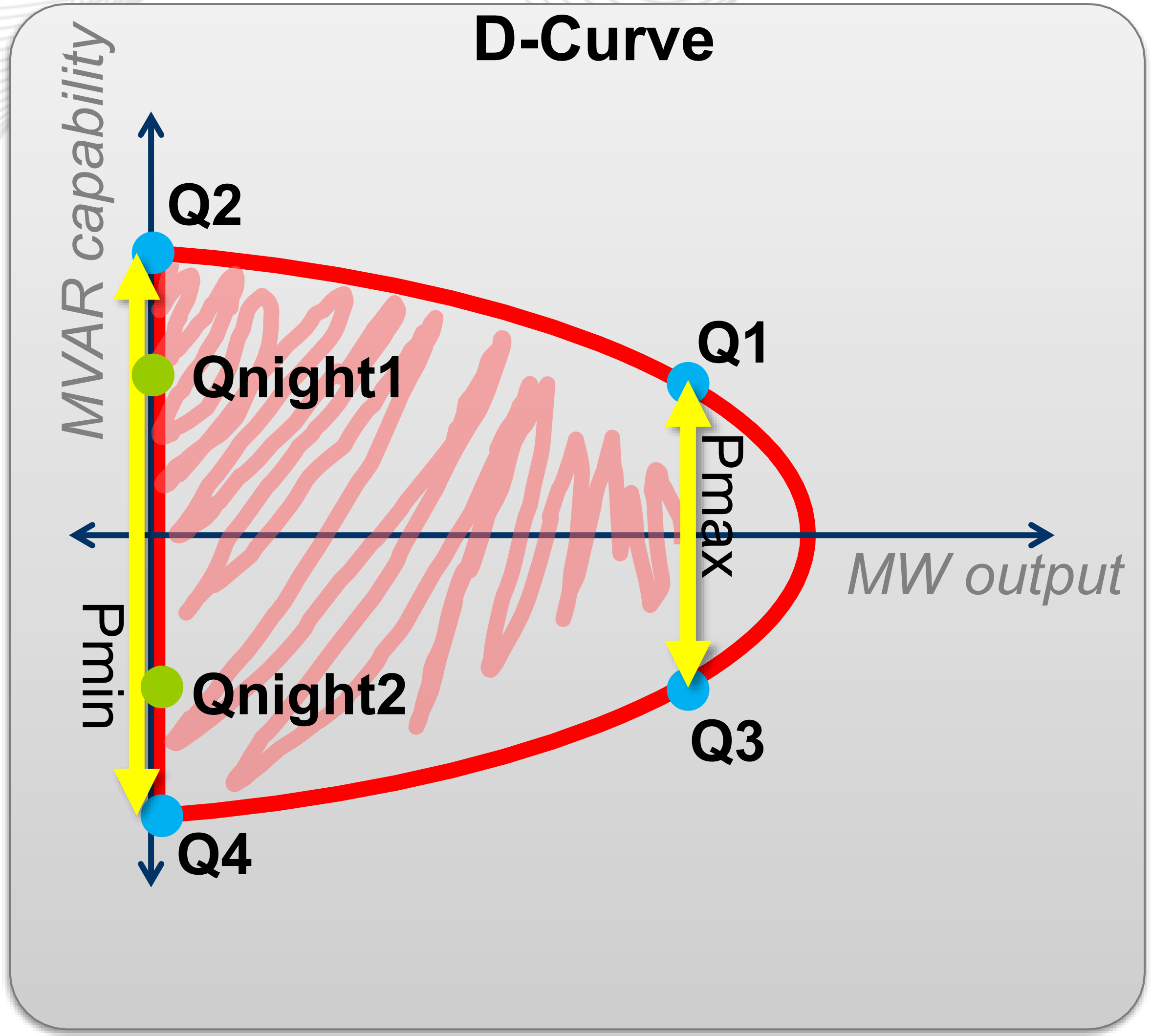
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar Plant *w/ Reactive at Night Capability*

E

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

Reactive capability at 0 MW at night might be lower than capability at 0 MW during the day (i.e., when dispatched to 0 MW). Therefore, no change vs. previous example.



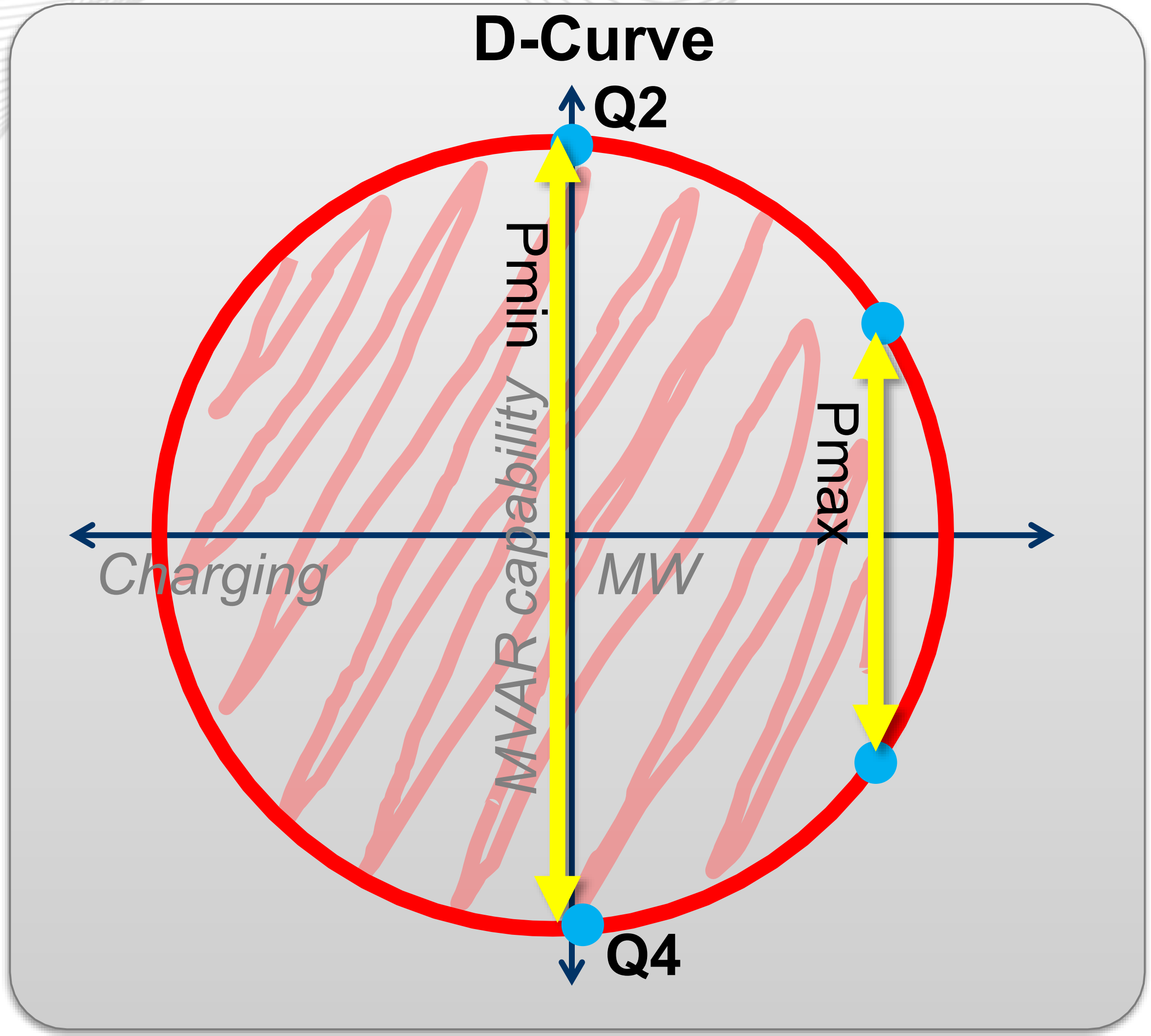
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Battery

E

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **100** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-100** MVAR*
- Average(***33,100***) – Average (***-33,-100***) = 133
- Compensation = $1,000*133 = **$133,000/yr**

Battery inverters would be located close to the POI, with little impedance to PJM. The full circular inverter capability is therefore available to PJM.



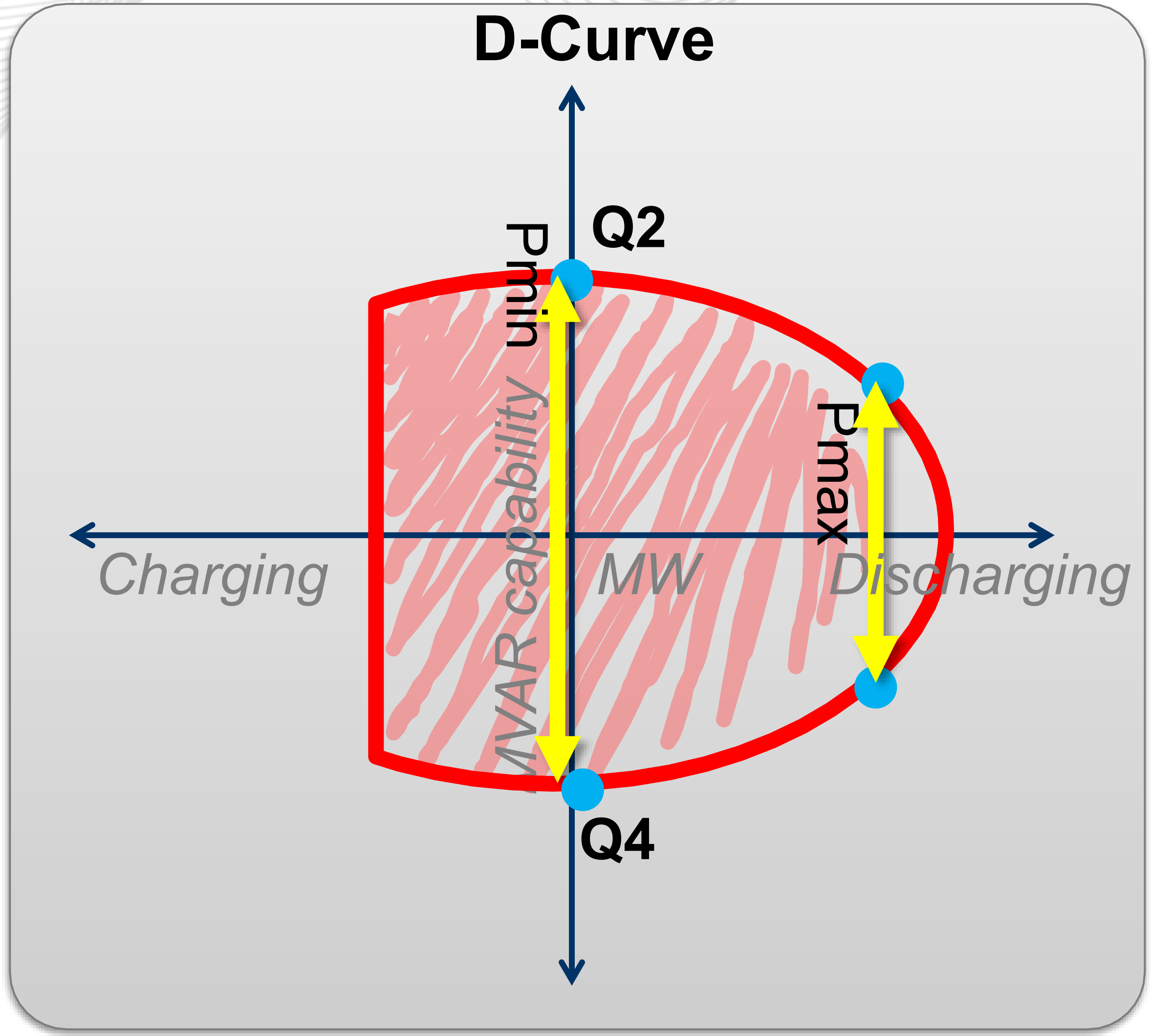
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of a Solar-Battery Hybrid
(Shared Inverters)

E

- VAR injection capability:
  - *Q1 =* ***33*** *MVAR*
  - *Q2 =* ***45*** *MVAR*
- VAR withdrawal capability:
  - *Q3 =* ***-33*** *MVAR*
  - *Q4 =* ***-45*** *MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

This hypothetical solar-battery hybrid uses the solar inverters to operate the batteries. It is the same as the standalone solar example, except also has charging MW.

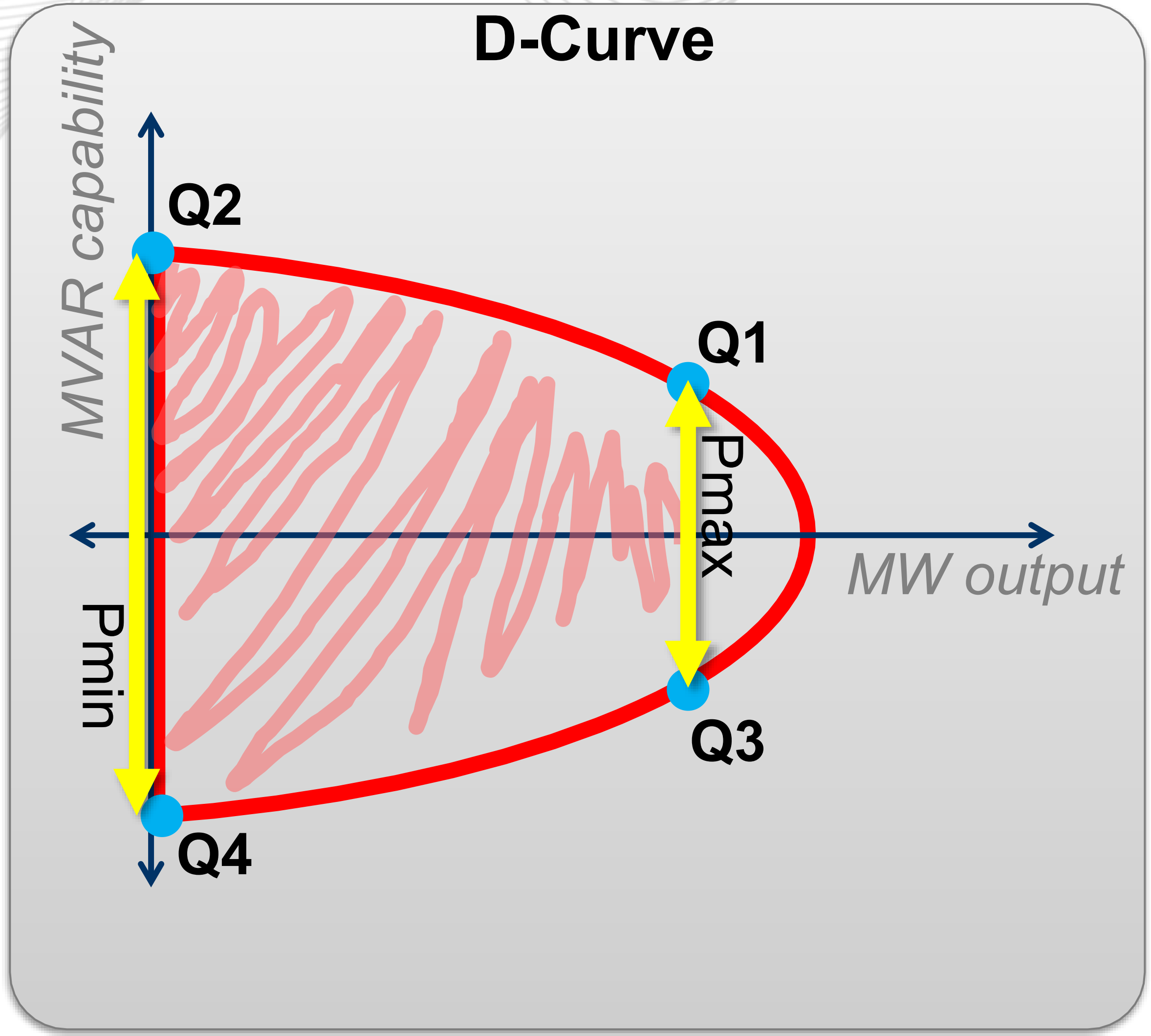


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of New-Technology Wind Plant

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **45** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-45** MVAR*
- Average(***33,45***) – Average (***-33,-45***) = 78
- Compensation = $1,000*78 = **$78,000/yr**

New wind generator technology is fully inverter-based, similar to solar. This result is the same as the solar example.

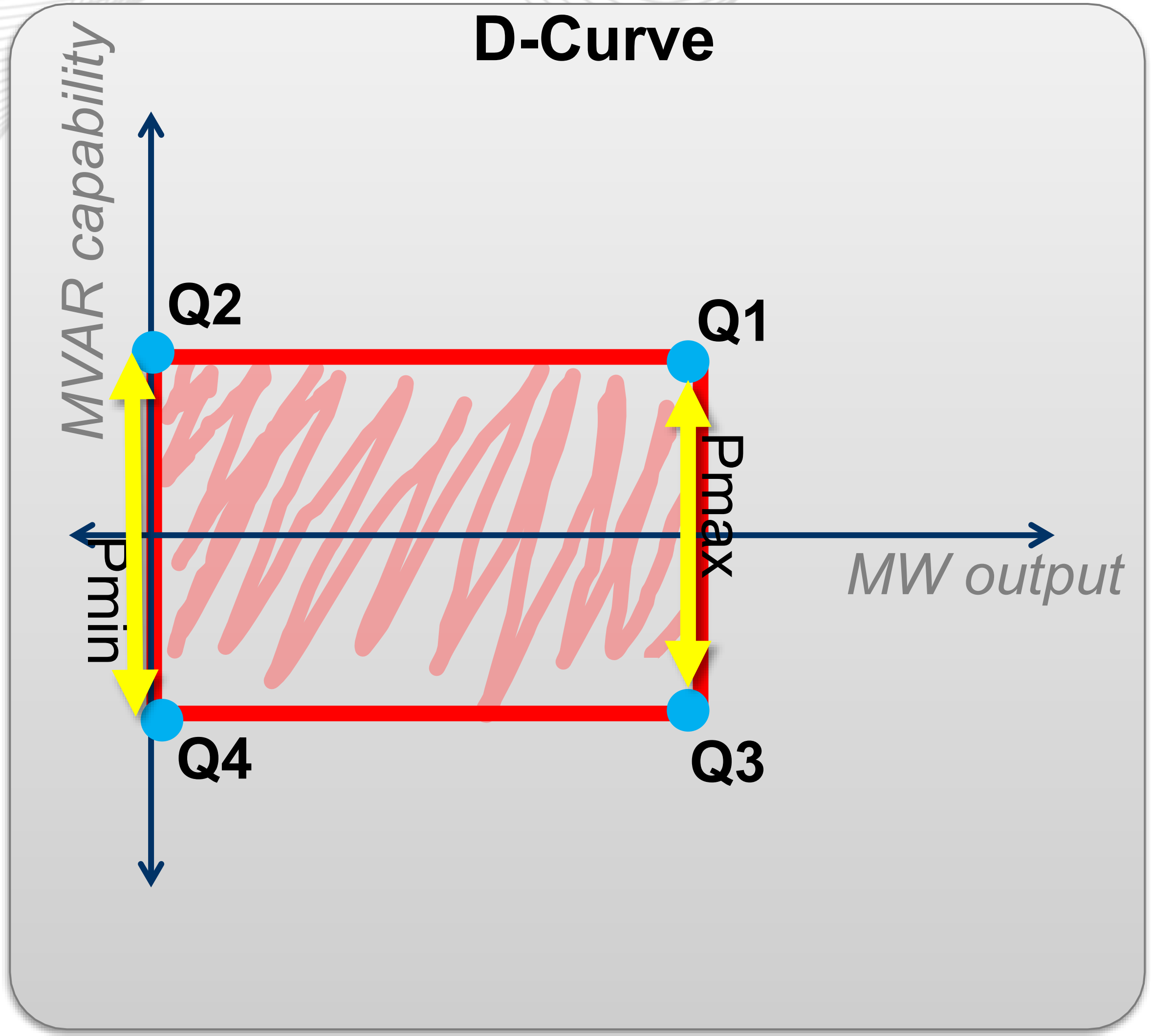


Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of Old-Technology Wind Plant
w/ Full Reactive Capability at All Times

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **33** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-33** MVAR*
- Average(***33,33***) – Average (***-33,-33***) = 66
- Compensation = $1,000*66 = **$66,000/yr**

Old wind generator technology is only partly inverter based. They don't use the generators for reactive, instead using dedicated equipment that doesn't vary with power output..



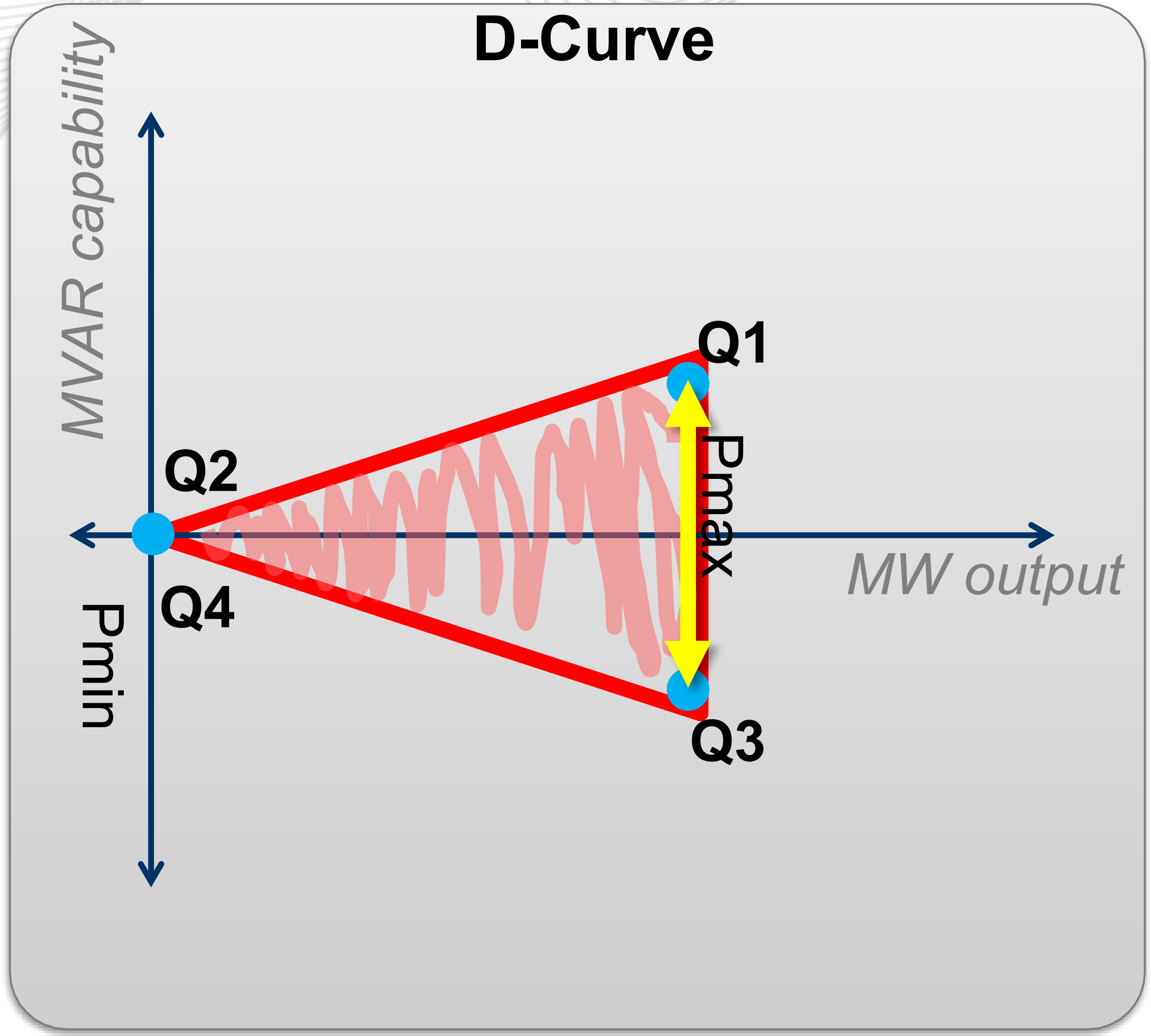
Hypothetical rate of $1,000/MVAR-yr

Illustrative Example of Old-Technology Wind Plant
w/ Fixed Power Factor Control Only as-per ISA

E

- VAR injection capability:
  - *Q1 = **33** MVAR*
  - *Q2 = **0** MVAR*
- VAR withdrawal capability:
  - *Q3 = **-33** MVAR*
  - *Q4 = **-0** MVAR*
- Average(***33,0***) – Average (***-33,-0***) = 33
- Compensation = $1,000*33 = **$33,000/yr**

This example's dedicated VAR equipment was programmed to only provide reactive capability required by the ISA, which is a fixed power factor that drops with lower MW. This is consistent with the ISA power factor obligation, but does not provide the full capability of the equipment.



Hypothetical rate of $1,000/MVAR-yr