

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

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

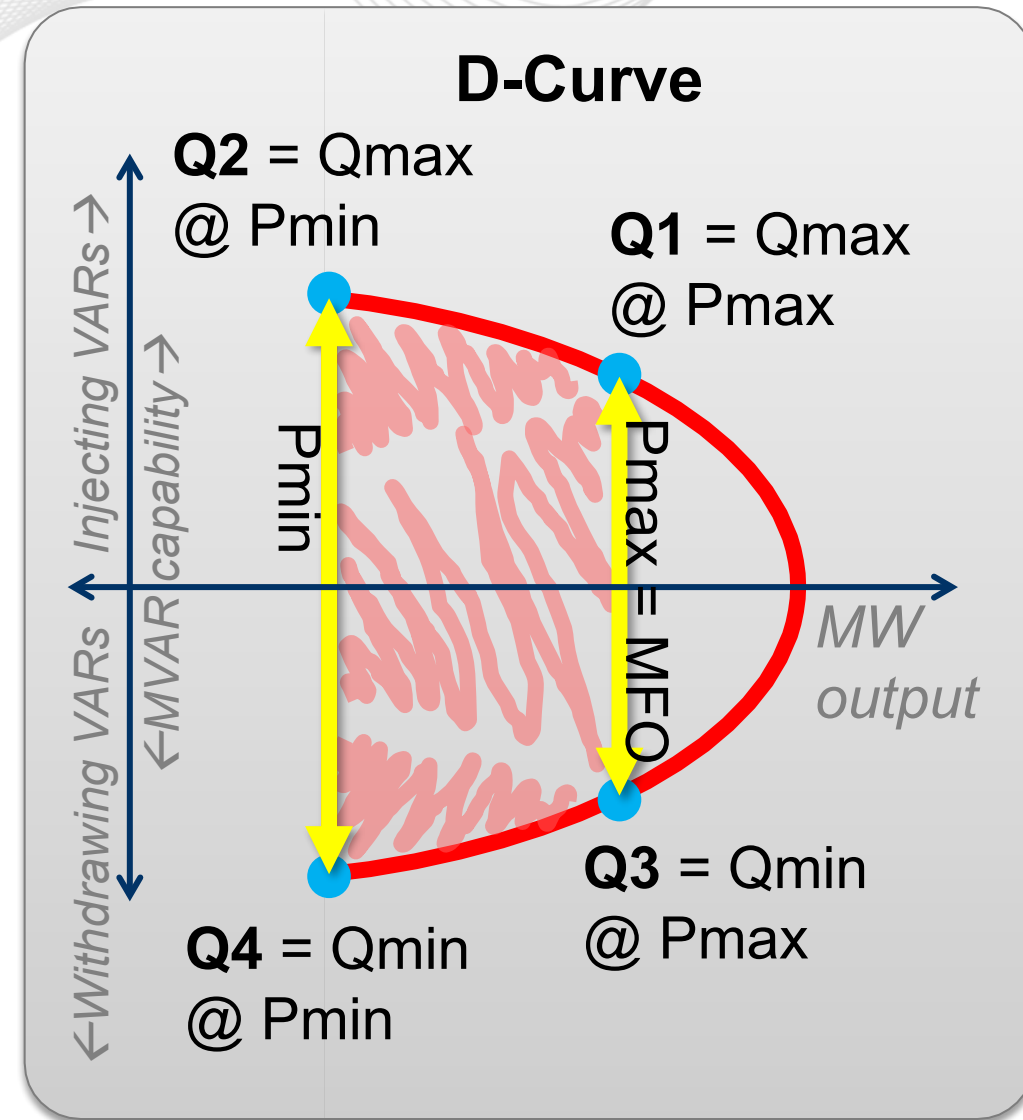
- For illustration, assume Rate is \$1,000/MVAR-yr (hypothetically).

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.



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

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

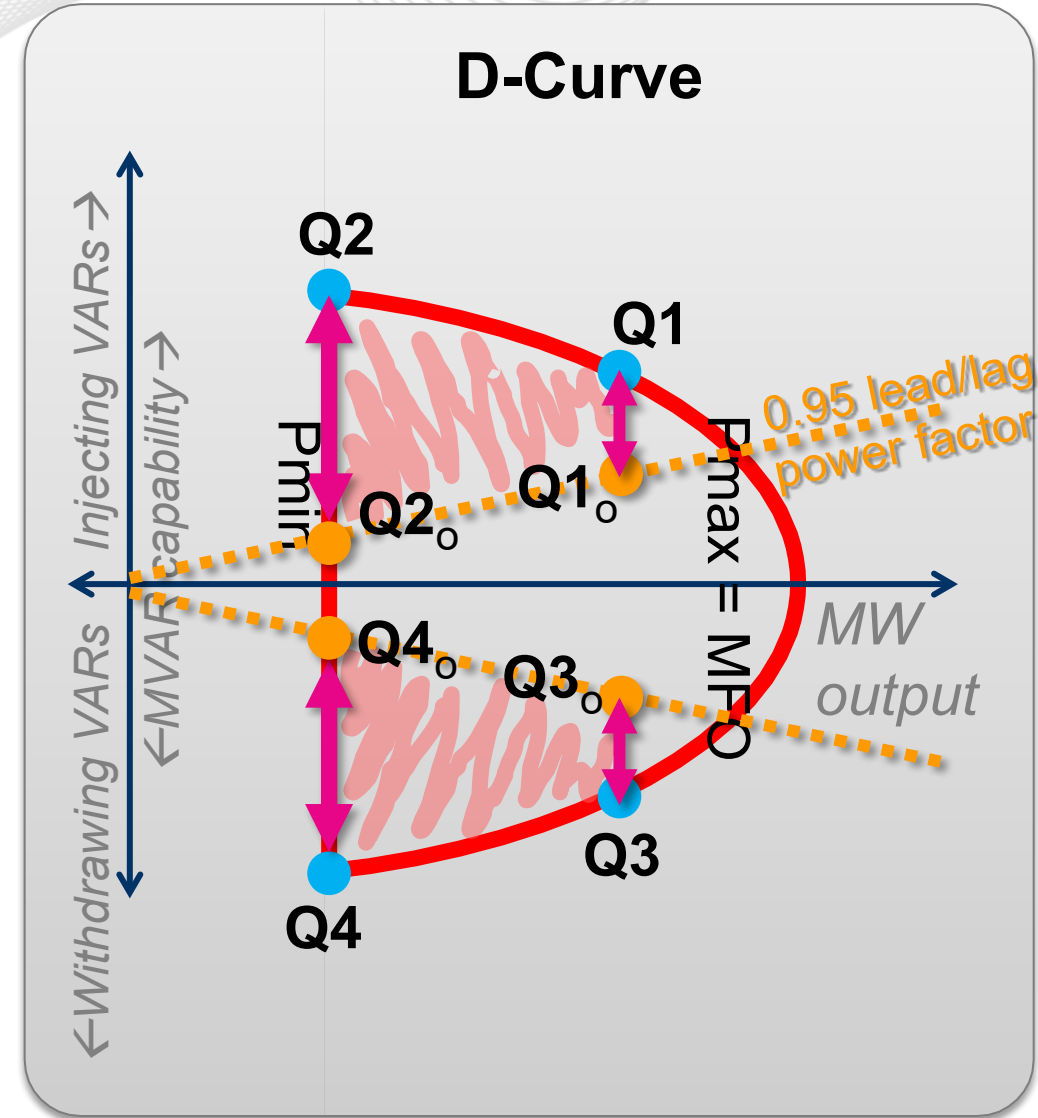
Package G would use precisely the same reactive rate as Package, without adjustment.

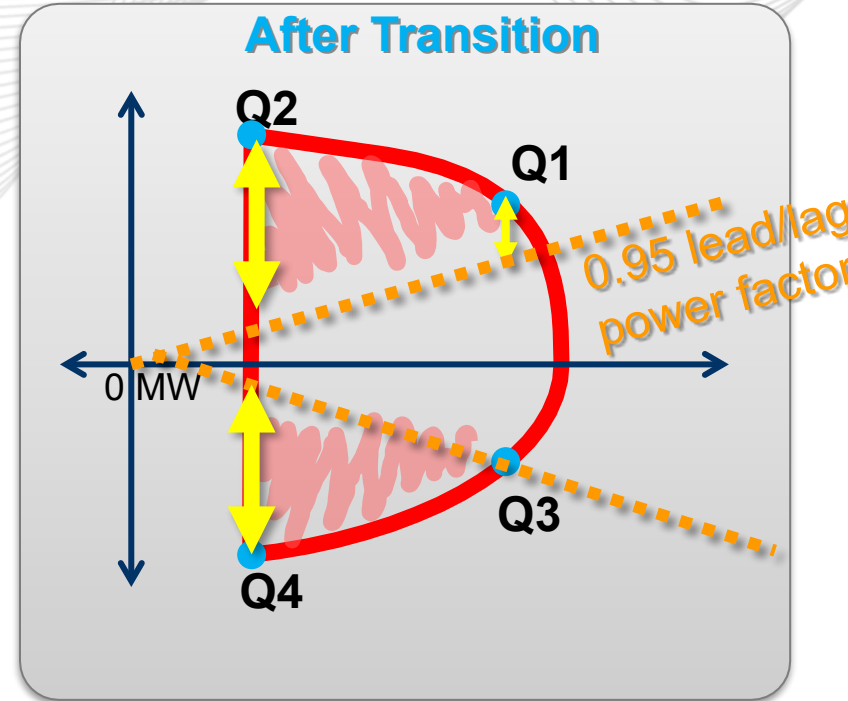
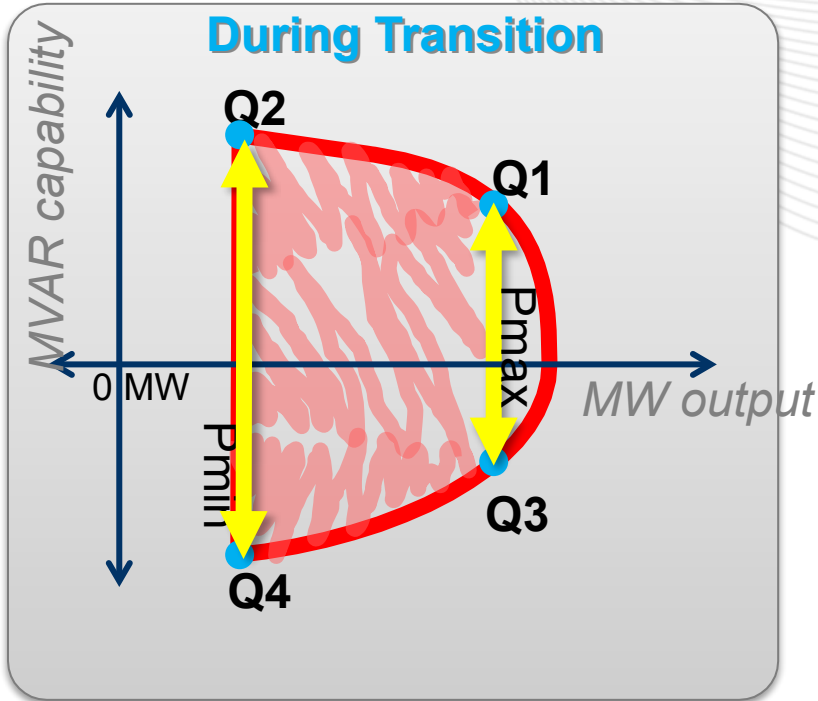
$MVAR_Capability_G$ is [average of $Q1-Q1_o$ and $Q2-Q2_o$] minus [average of $Q3-Q3_o$ and $Q4-Q4_o$].

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

injecting capability above obligation (averaged at P_{max} and P_{min}) --plus--
withdrawing capability above obligation (averaged at P_{max} and P_{min}).

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





- 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)

- P is real power, Q is reactive power, S is “apparent power”
- **Obligation is 0.95 Power Factor**
- Power factor is defined as $P/S = 0.95 \rightarrow S = P/0.95$
- 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

VAR injection capability:

- **Q1**@Pmax (100 MW) = **40** MVAR Difference: **7** MVAR
- **Q1_o**@Pmax (100 MW) = **33** MVAR

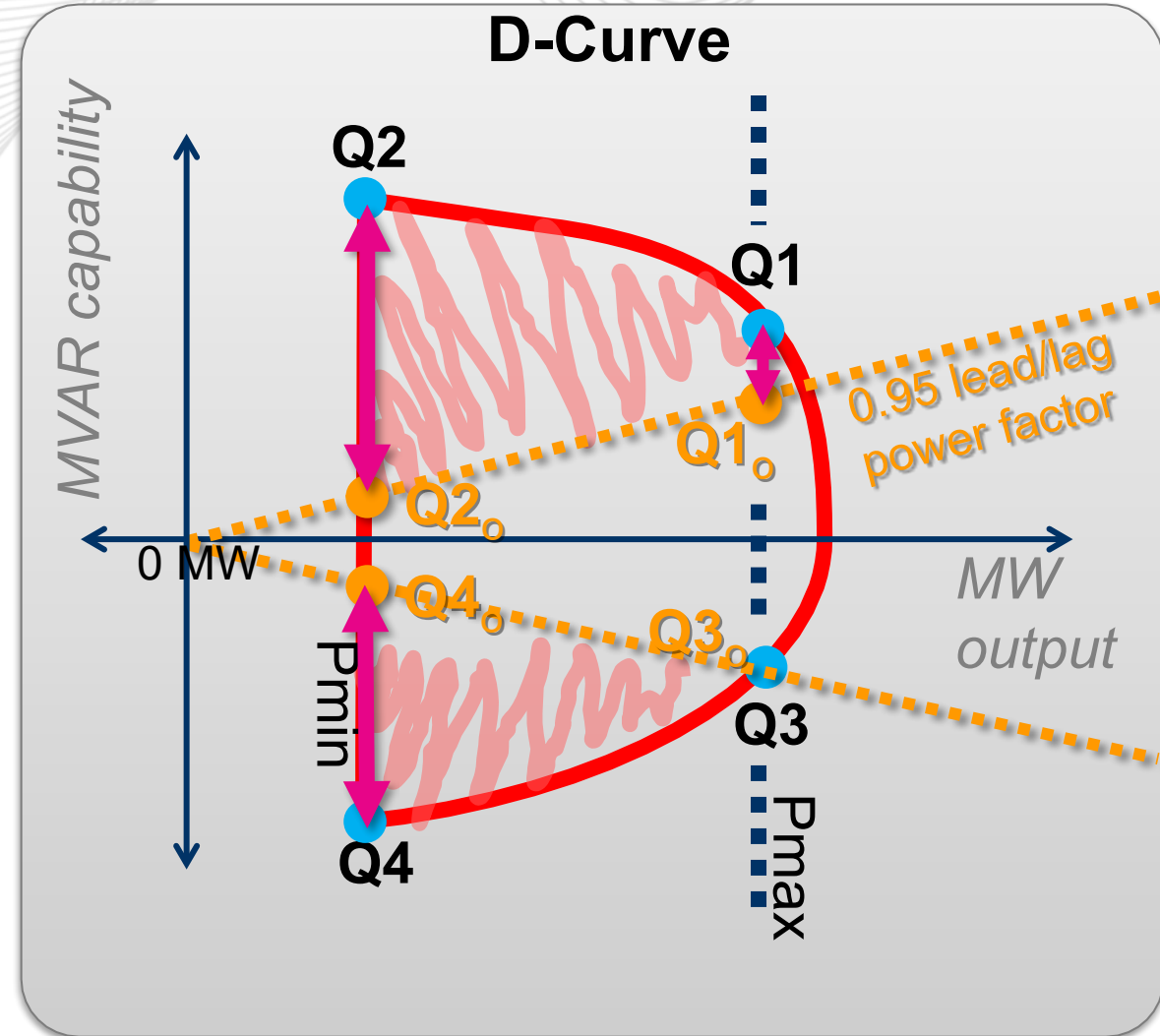
- **Q2**@Pmin (50 MW) = **50** MVAR Difference: **34** MVAR
- **Q2_o**@Pmin (50 MW) = **16** MVAR

VAR withdrawal capability:

- Q3 at Pmax = **-33** MVAR Difference: **0** MVAR
- **Q3_o**@Pmax = **-33** MVAR

- Q4 at Pmin = **-40** MVAR Difference: **-24** MVAR
- **Q4_o**@Pmin = **-16** MVAR

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



Hypothetical rate of \$1,000/MVAR-yr

VAR injection capability:

- **Q1**@Pmax (100 MW) = **40** MVAR Difference: **7** MVAR
- **Q1_o**@Pmax (100 MW) = **33** MVAR

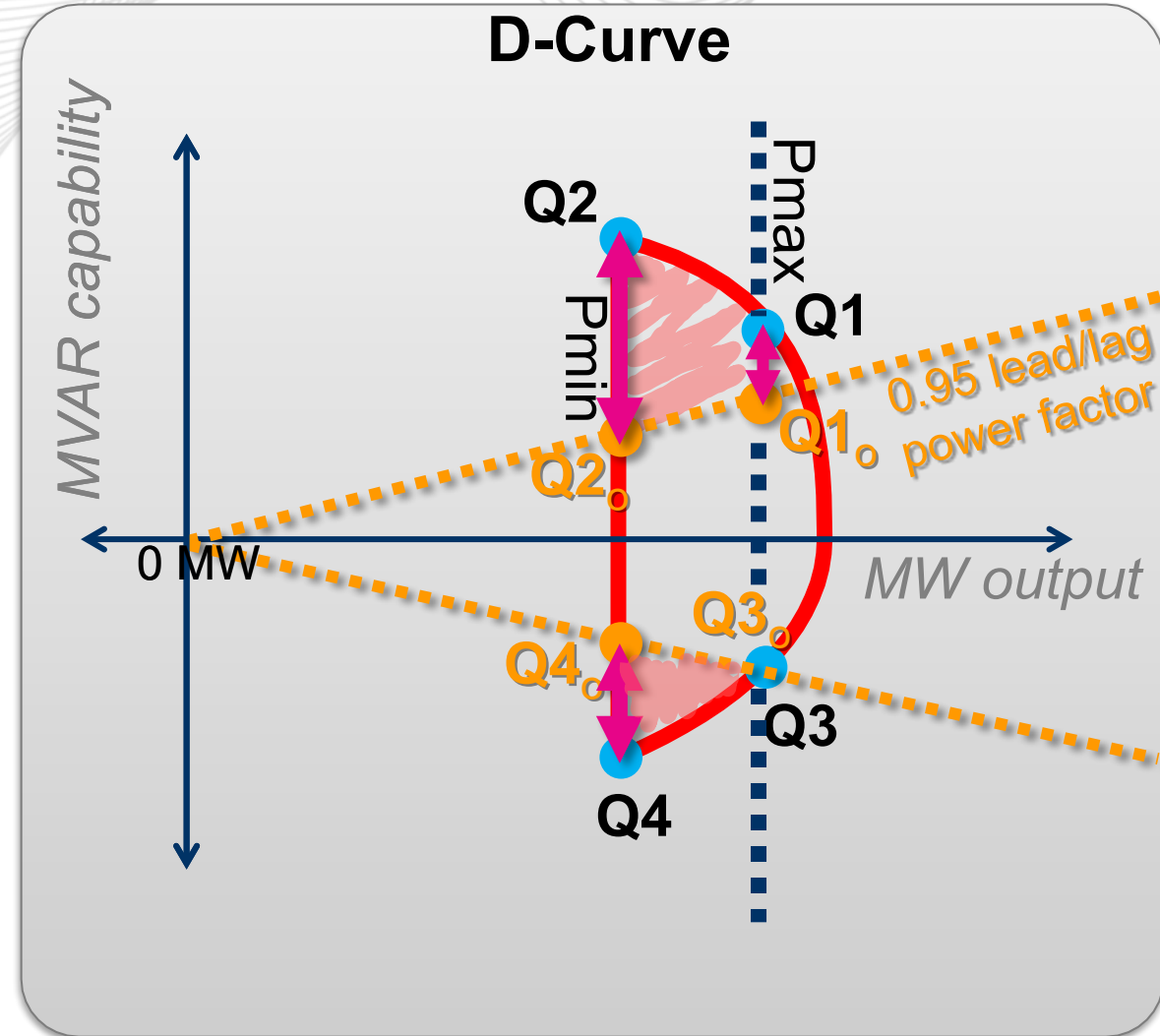
- **Q2**@Pmin (80 MW) = **45** MVAR Difference: **19** MVAR
- **Q2_o**@Pmin (80 MW) = **26** MVAR

VAR withdrawal capability:

- Q3 at Pmax = **-33** MVAR Difference: **0** MVAR
- **Q3_o**@Pmax = **-33** MVAR

- Q4 at Pmin = **-35** MVAR Difference: **-9** MVAR
- **Q4_o**@Pmin = **-26** MVAR

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



Hypothetical rate of \$1,000/MVAR-yr

VAR injection capability:

- **Q1**@Pmax (100 MW) = **40** MVAR Difference: **7** MVAR
- **Q1_o**@Pmax (100 MW) = **33** MVAR

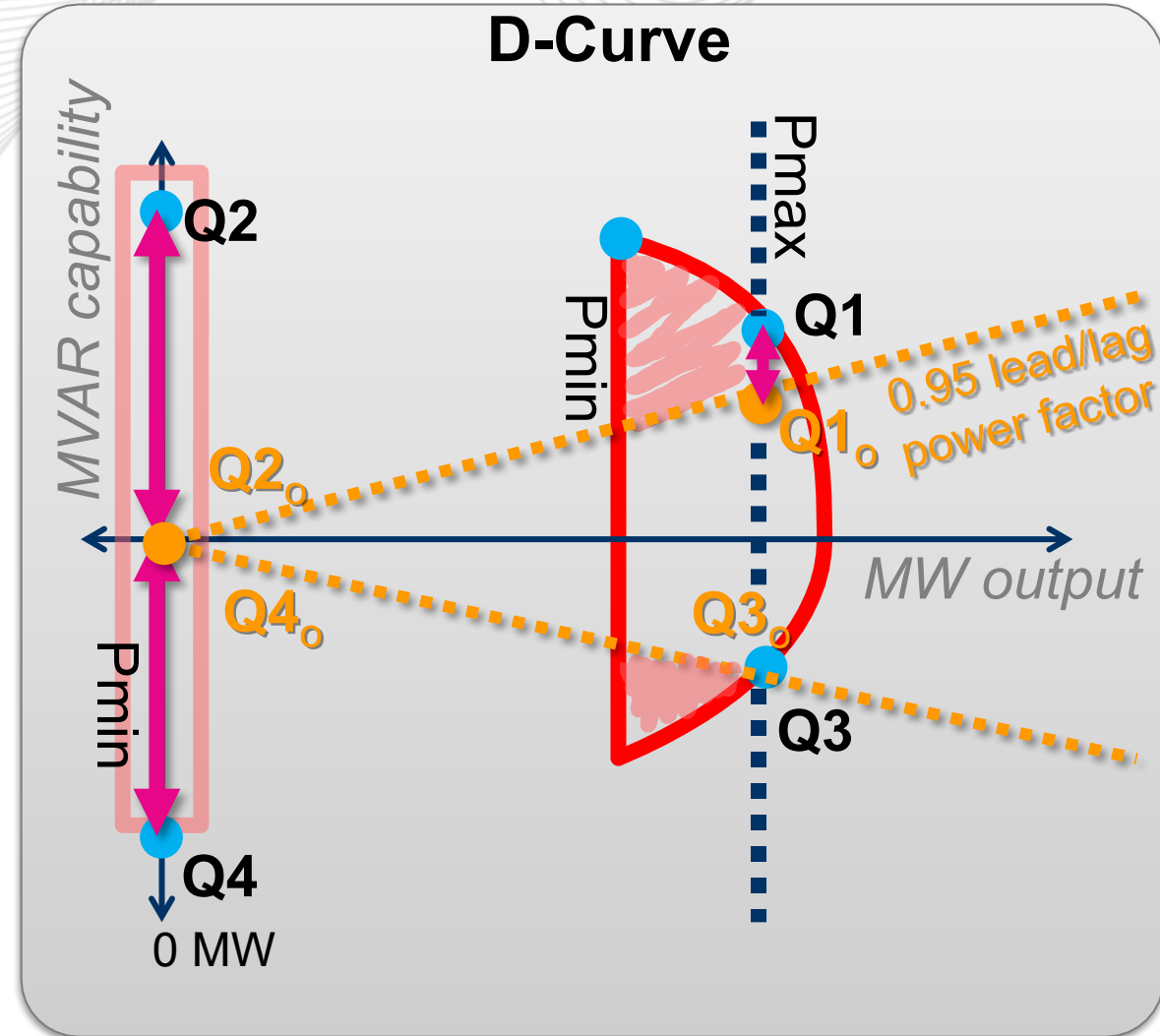
- **Q2**@Pmin (0 MW) = **50** MVAR Difference: **50** MVAR
- **Q2_o**@Pmin (0 MW) = **0** MVAR

VAR withdrawal capability:

- Q3 at Pmax = **-33** MVAR Difference: **0** MVAR
- **Q3_o**@Pmax = **-33** MVAR

- Q4 at Pmin = **-40** MVAR Difference: **-40** MVAR
- **Q4_o**@Pmin = **0** MVAR

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



Hypothetical rate of \$1,000/MVAR-yr

VAR injection capability:

- **Q1**@ P_{max} (100 MW) = **33** MVAR Difference: **0** MVAR
- **Q1_o**@ P_{max} (100 MW) = **33** MVAR

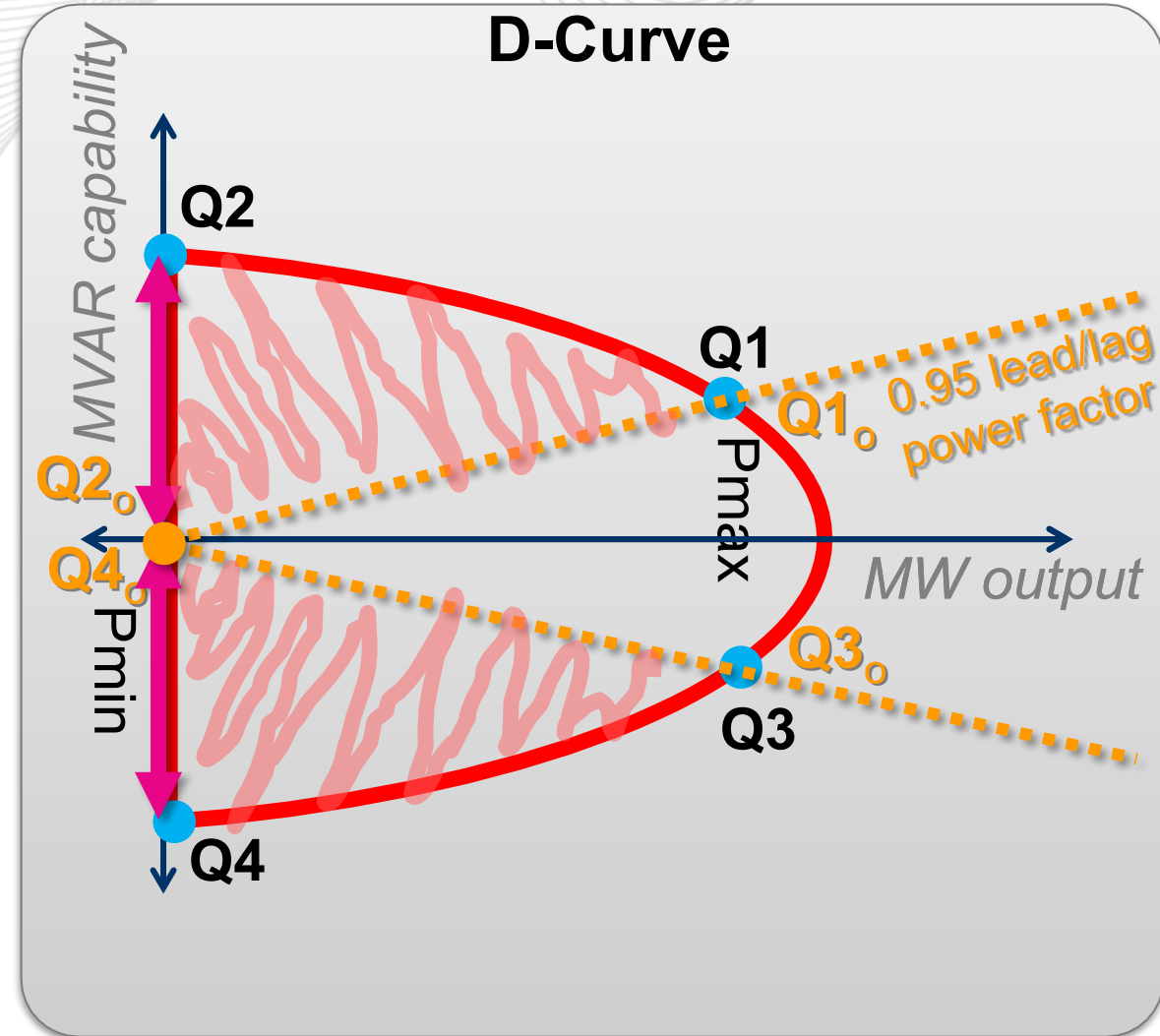
- **Q2**@ P_{min} (0 MW) = **45** MVAR Difference: **45** MVAR
- **Q2_o**@ P_{min} (0 MW) = **0** MVAR

VAR withdrawal capability:

- Q3 at P_{max} = **-33** MVAR Difference: **0** MVAR
- **Q3_o**@ P_{max} = **-33** MVAR

- Q4 at P_{min} = **-45** MVAR Difference: **-45** MVAR
- **Q4_o**@ P_{min} = **0** MVAR

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



Hypothetical rate of \$1,000/MVAR-yr

VAR injection capability:

- $Q1@Pmax (100 MW) = 33 MVAR$ Difference: 0 MVAR
- $Q1_o@Pmax (100 MW) = 33 MVAR$

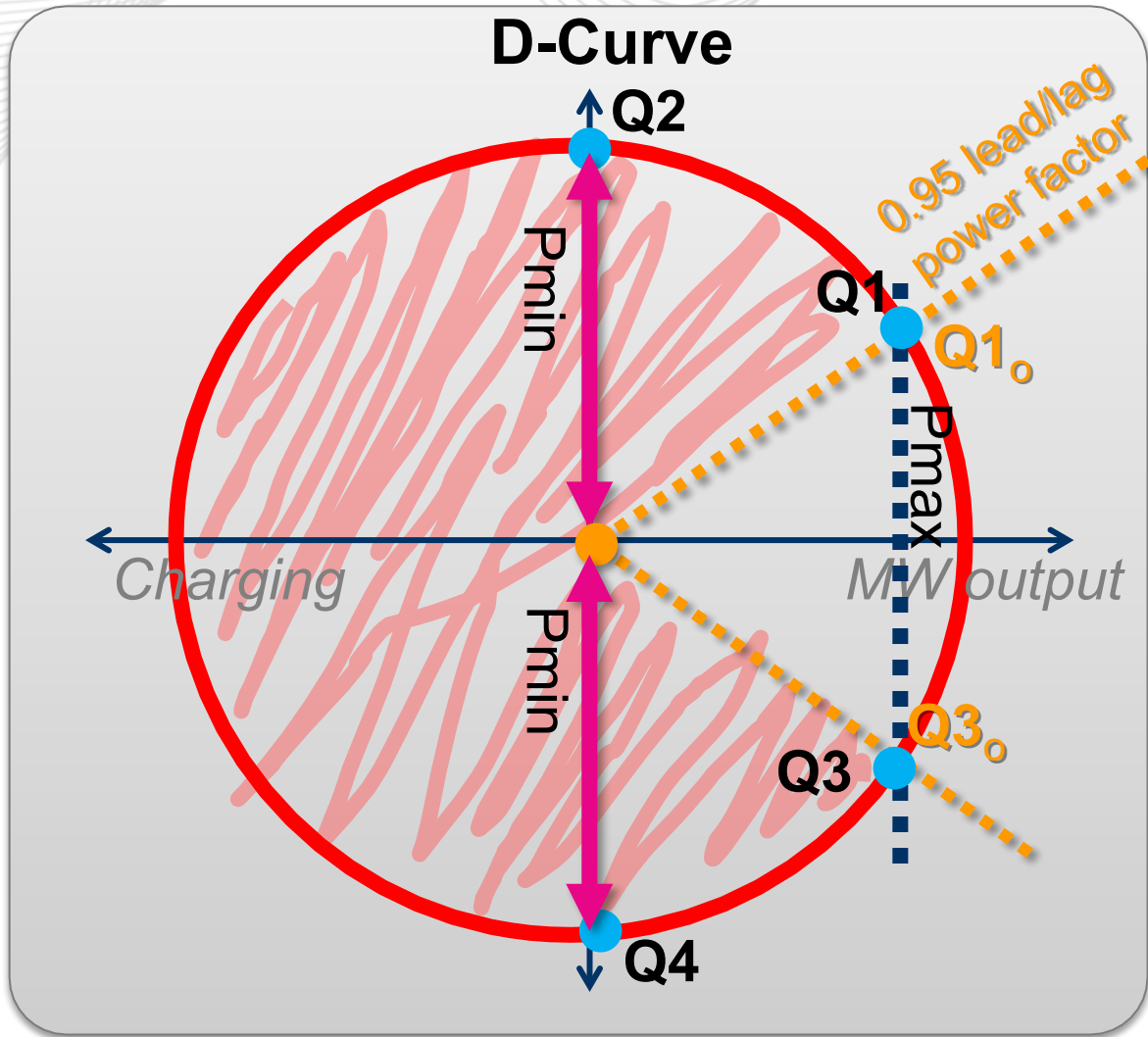
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- $Q2@Pmin (0 MW) = 100 MVAR$ Difference: 100 MVAR
 - $Q2_o@Pmin (0 MW) = 0 MVAR$

VAR withdrawal capability:

- $Q3 at Pmax = -33 MVAR$ Difference: 0 MVAR
- $Q3_o@Pmax = -33 MVAR$

-
- $Q4 at Pmin = -100 MVAR$ Difference: -100 MVAR
 - $Q4_o@Pmin = 0 MVAR$

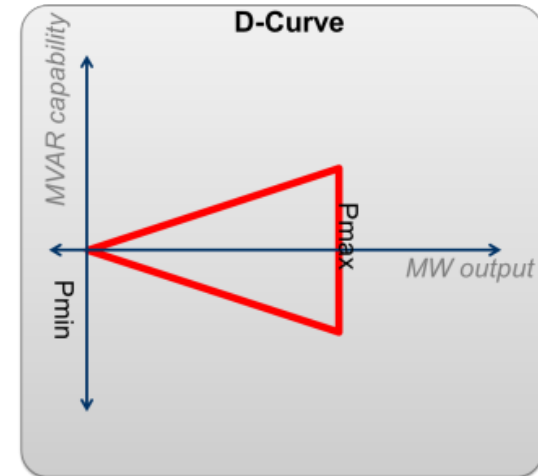
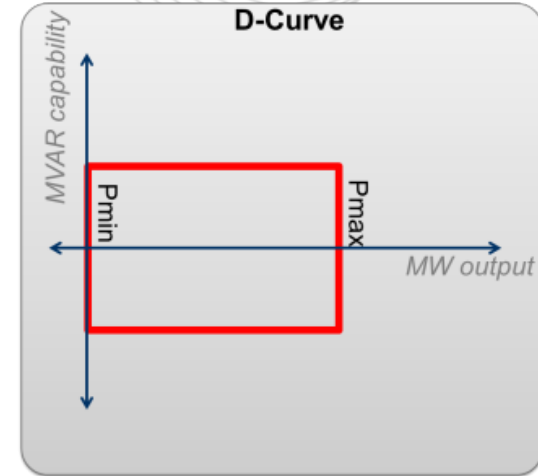
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- $Average(0, 100) - Average(0, -100) = 100$
 - $Compensation = \$1,000 * 100 = \underline{\$100,000/yr}$



Hypothetical rate of \$1,000/MVAR-yr

- 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



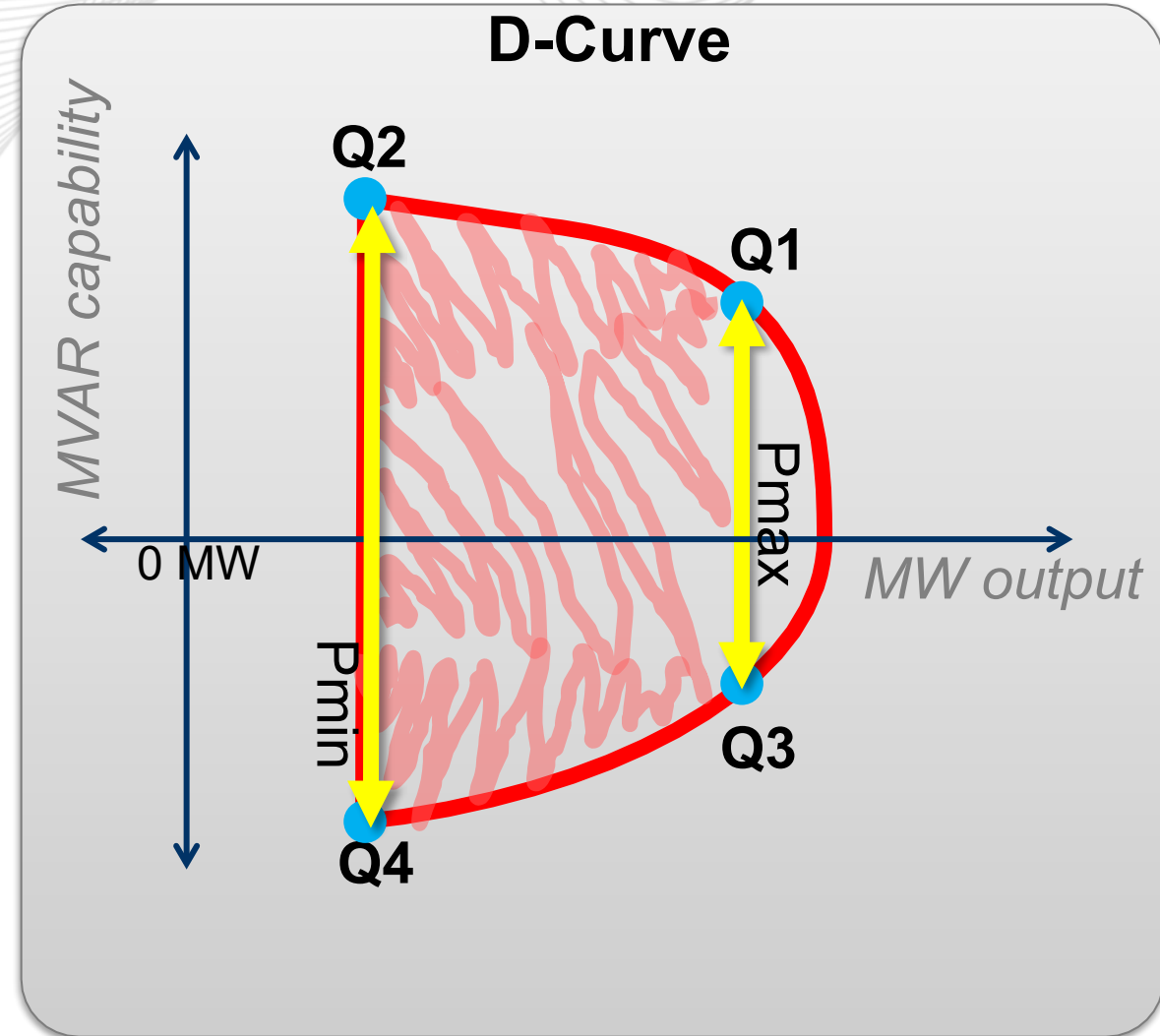
Hypothetical rate of \$1,000/MVAR-yr

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

- 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.

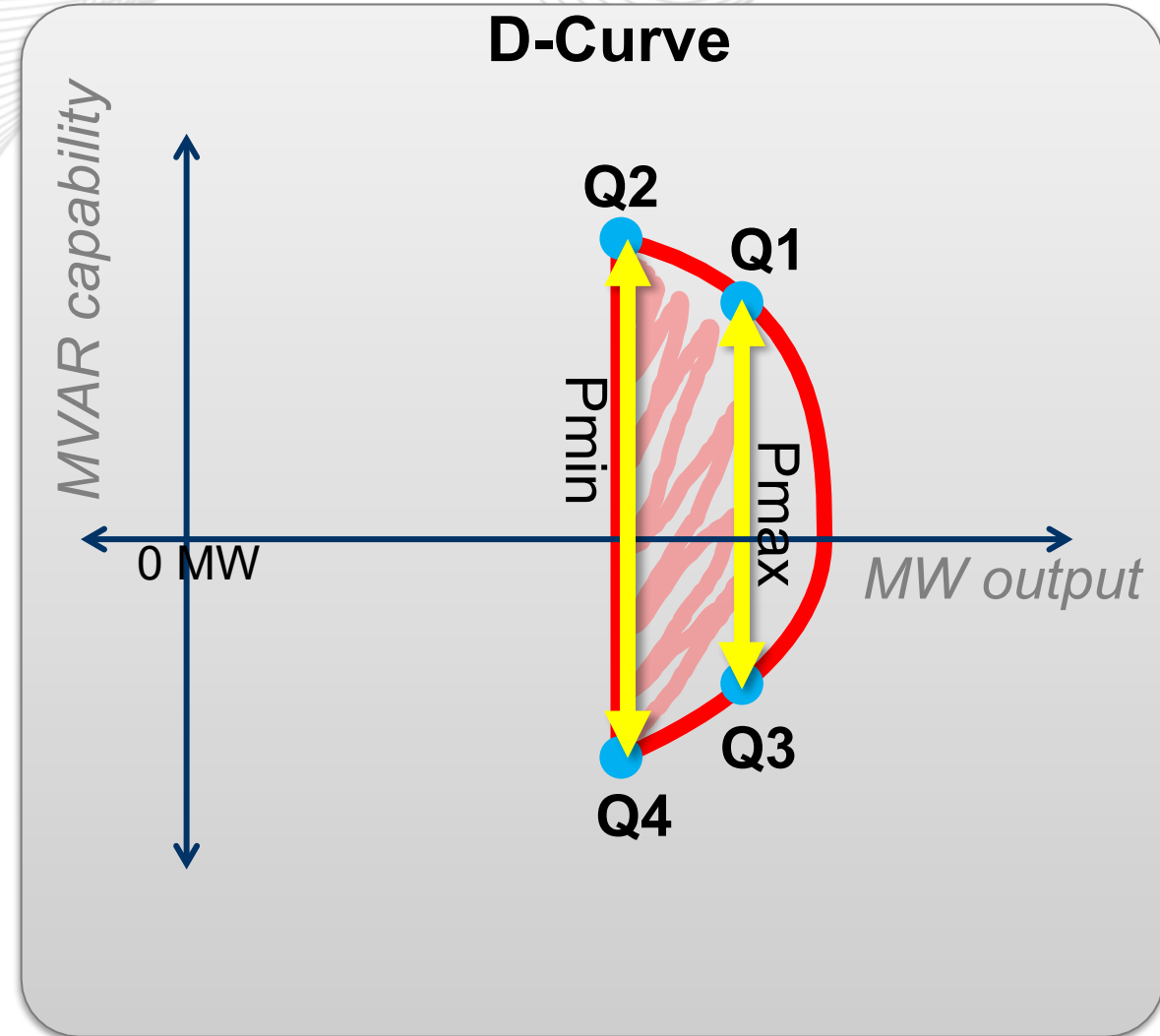
Synchronous machine designs generally have lower VAR withdrawal capability than injection capability.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

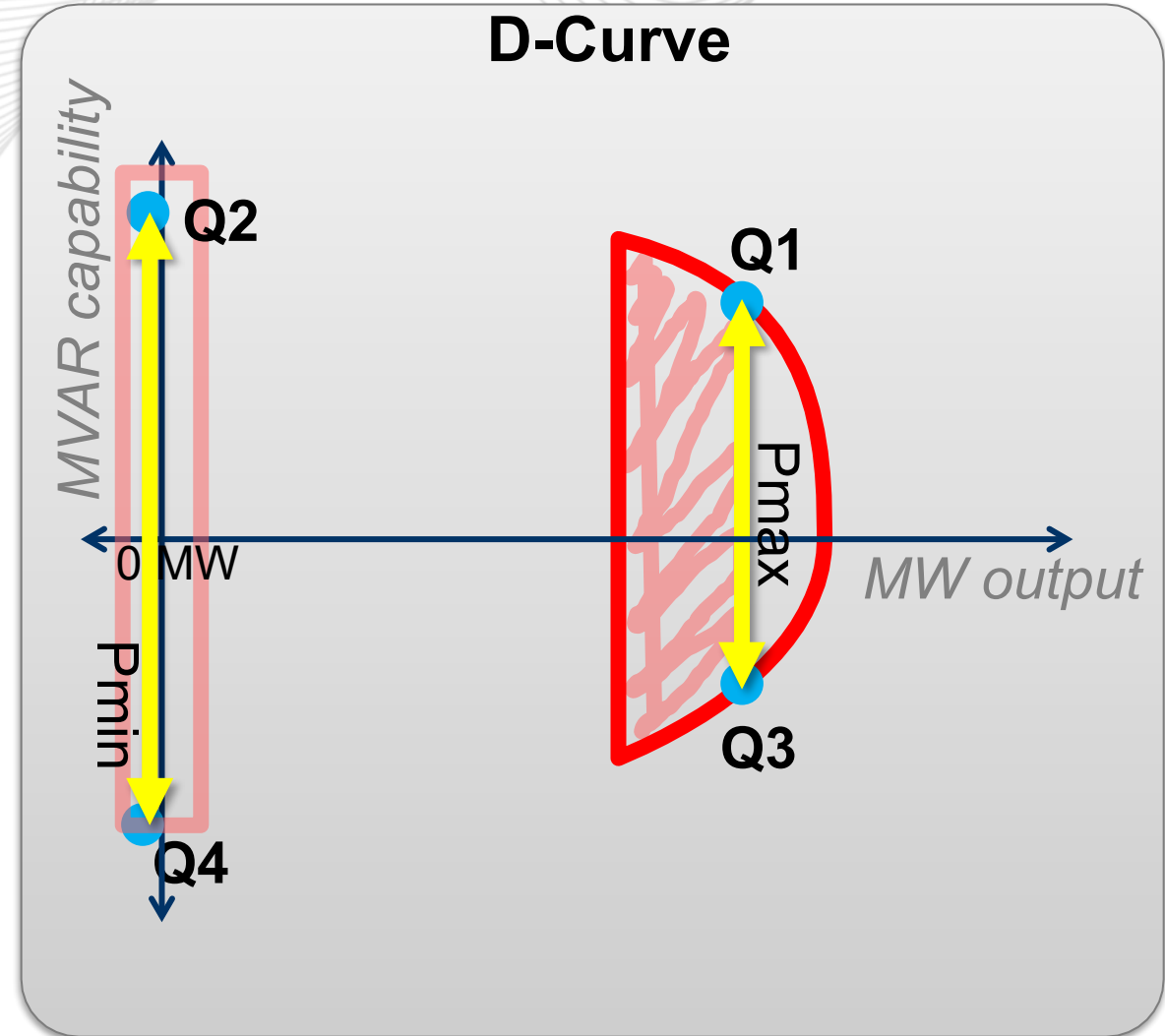
A CT might have a narrower dispatchable range than a steam generator, which might reduce the reactive capability available to PJM.



Hypothetical rate of \$1,000/MVAR-yr

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

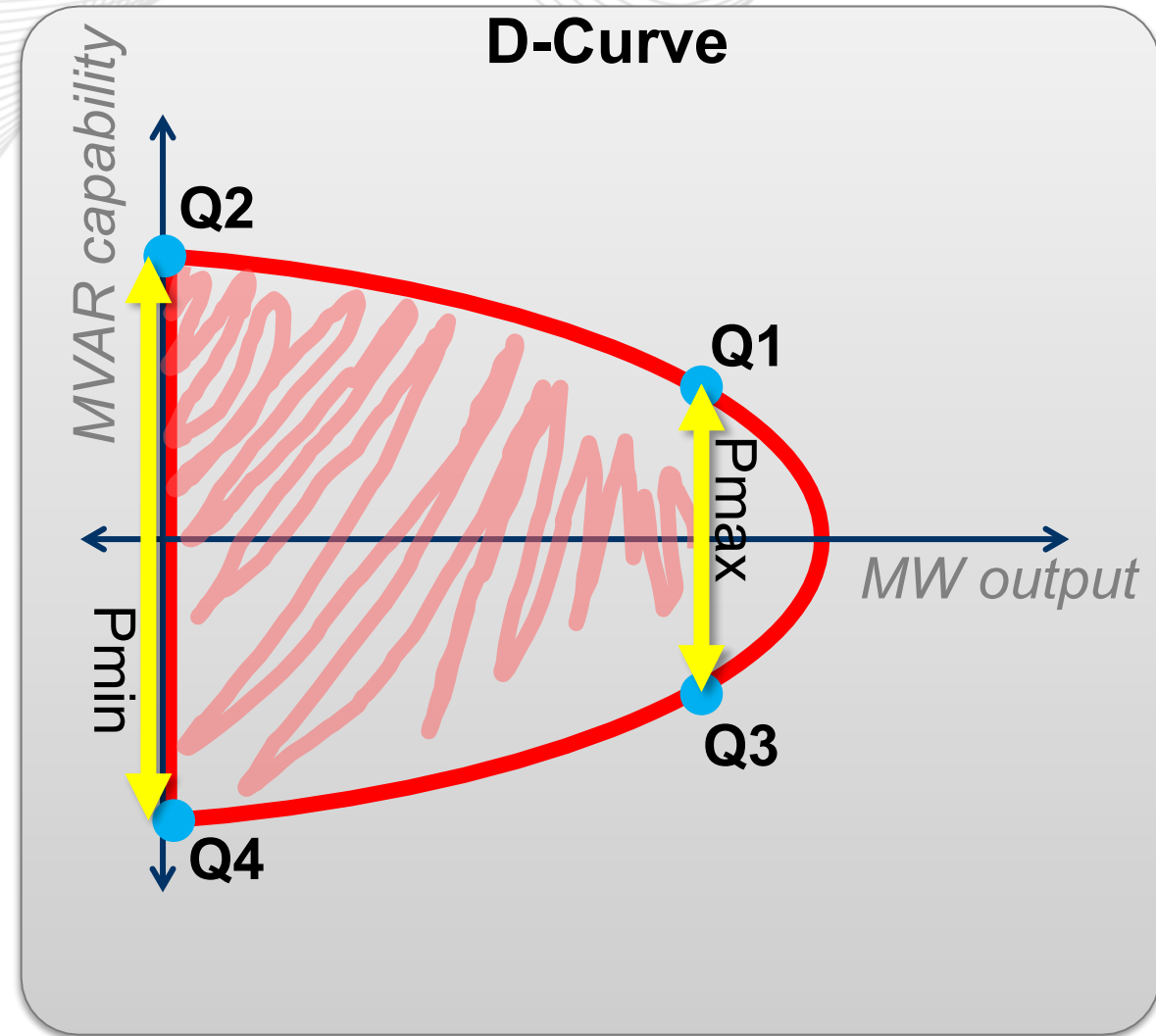
- VAR injection capability:
 - Q1 = **40** MVAR
 - Q2 = **50** MVAR
- VAR withdrawal capability:
 - Q3 = **-33** MVAR
 - Q4 = **-40** MVAR
- Average(**40,50**) – Average(**-33,-40**) = 81.5
- Compensation = \$1,000*81.5 = **\$81,500/yr**



Hypothetical rate of \$1,000/MVAR-yr

- 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**

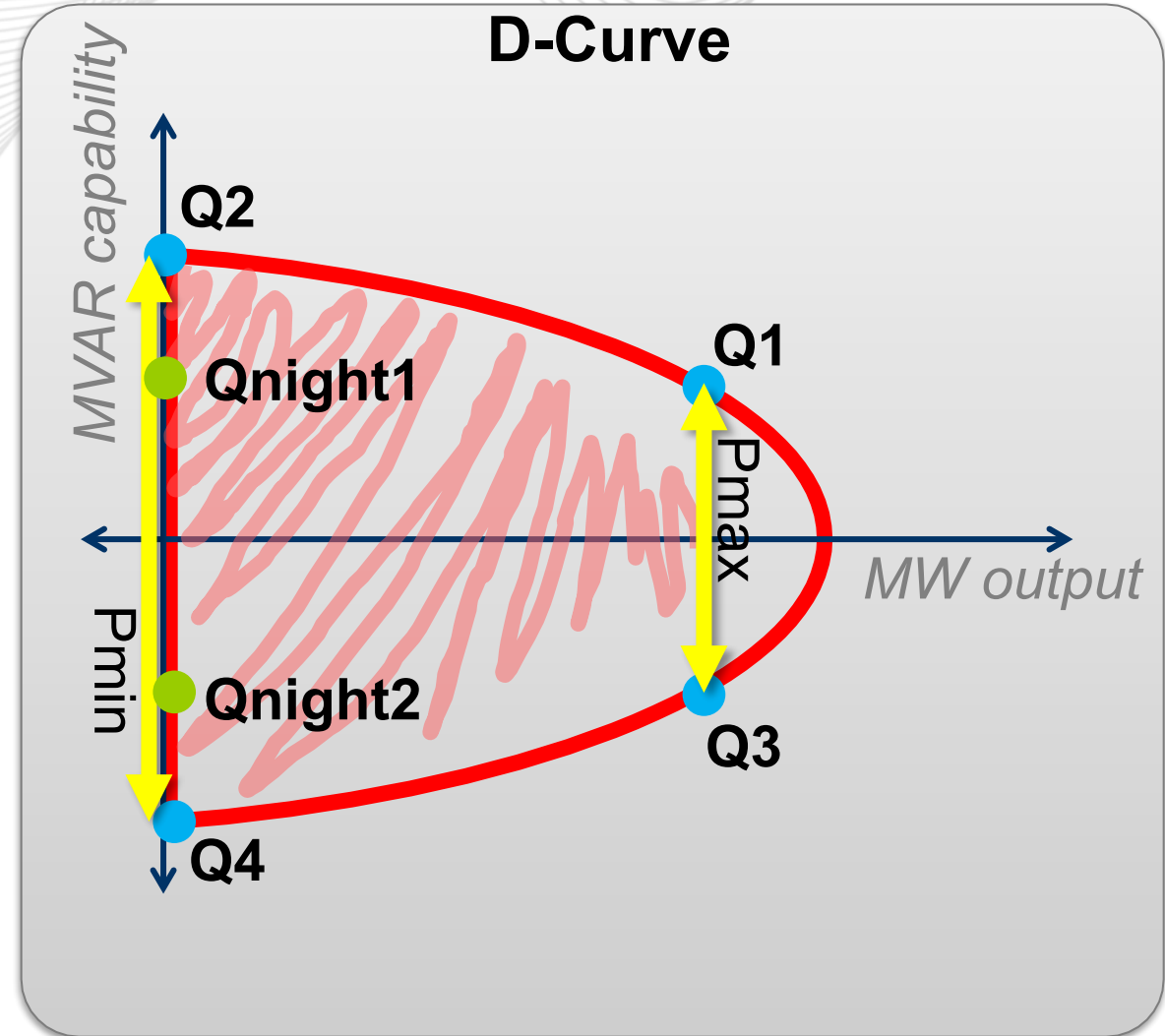
Inverter reactive capability matches power capability (they have a circular D-curve at the inverter terminals), however high impedance between PJM and large solar farm inverters reduces the reactive capability.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

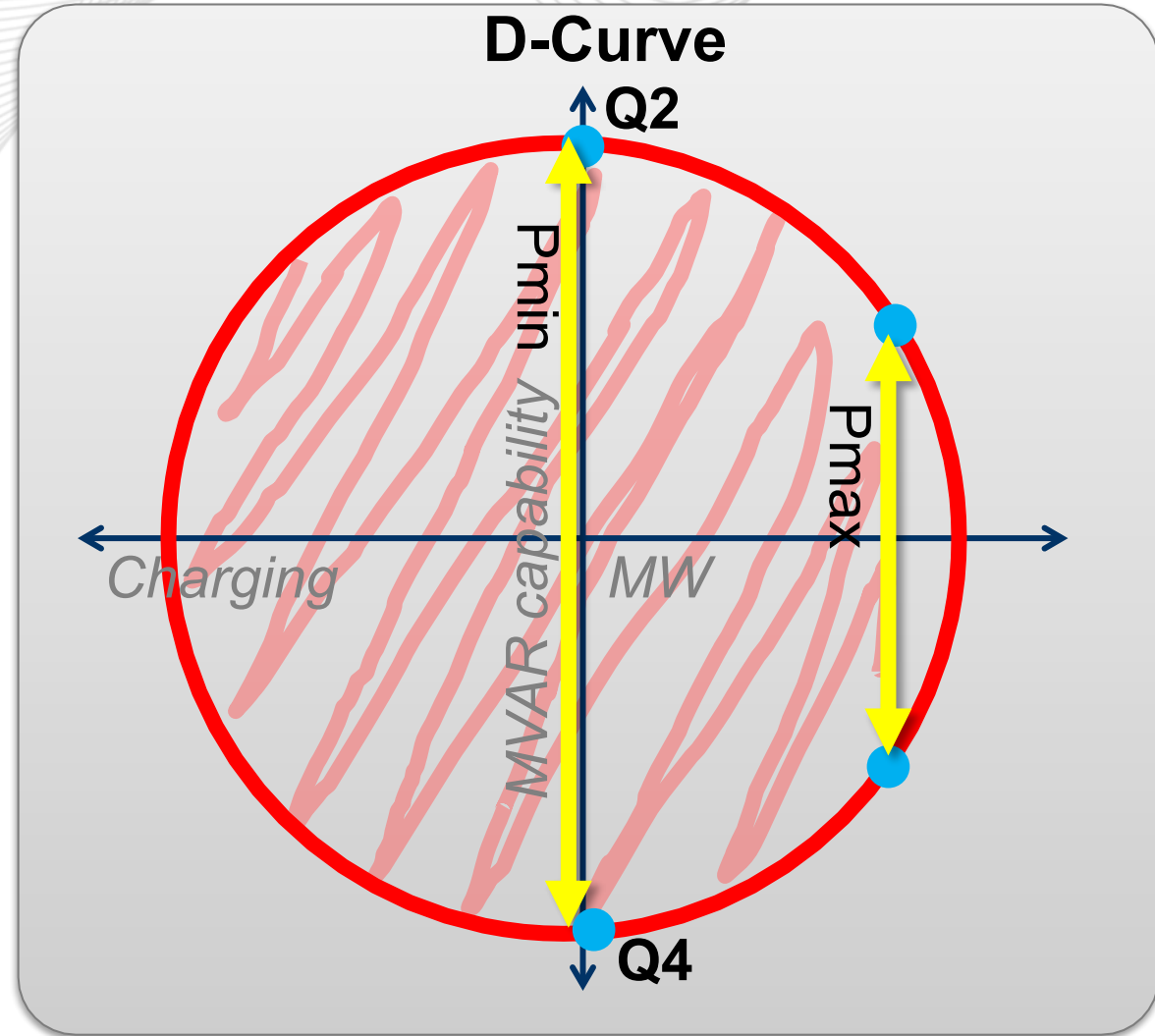
Reactive capability at 0 MW at night might be lower than capability at 0 MW during the day (i.e., when dispatched to 0 MW). Therefore, no change vs. previous example.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

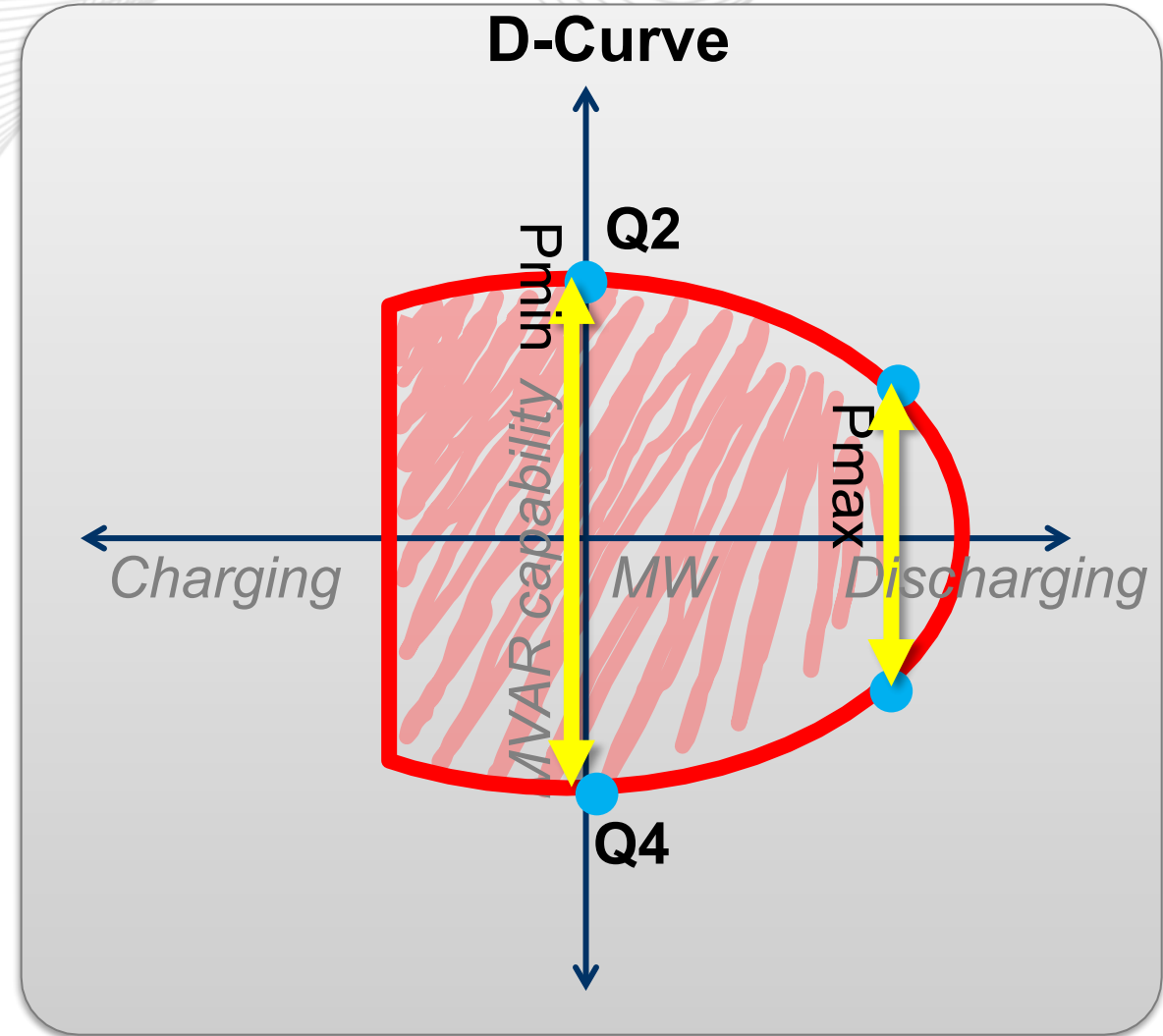
Battery inverters would be located close to the POI, with little impedance to PJM. The full circular inverter capability is therefore available to PJM.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

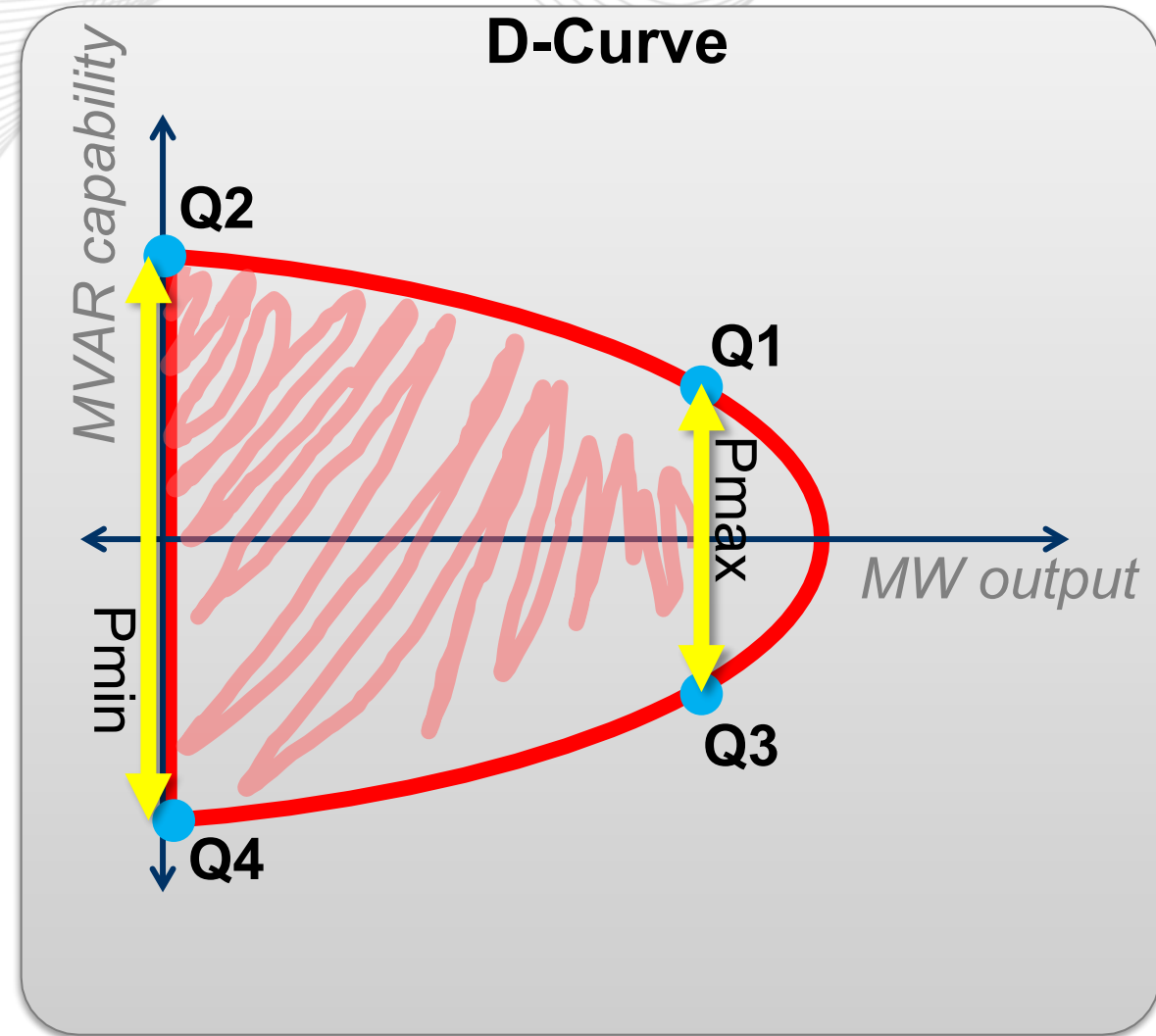
This hypothetical solar-battery hybrid uses the solar inverters to operate the batteries. It is the same as the standalone solar example, except also has charging MW.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

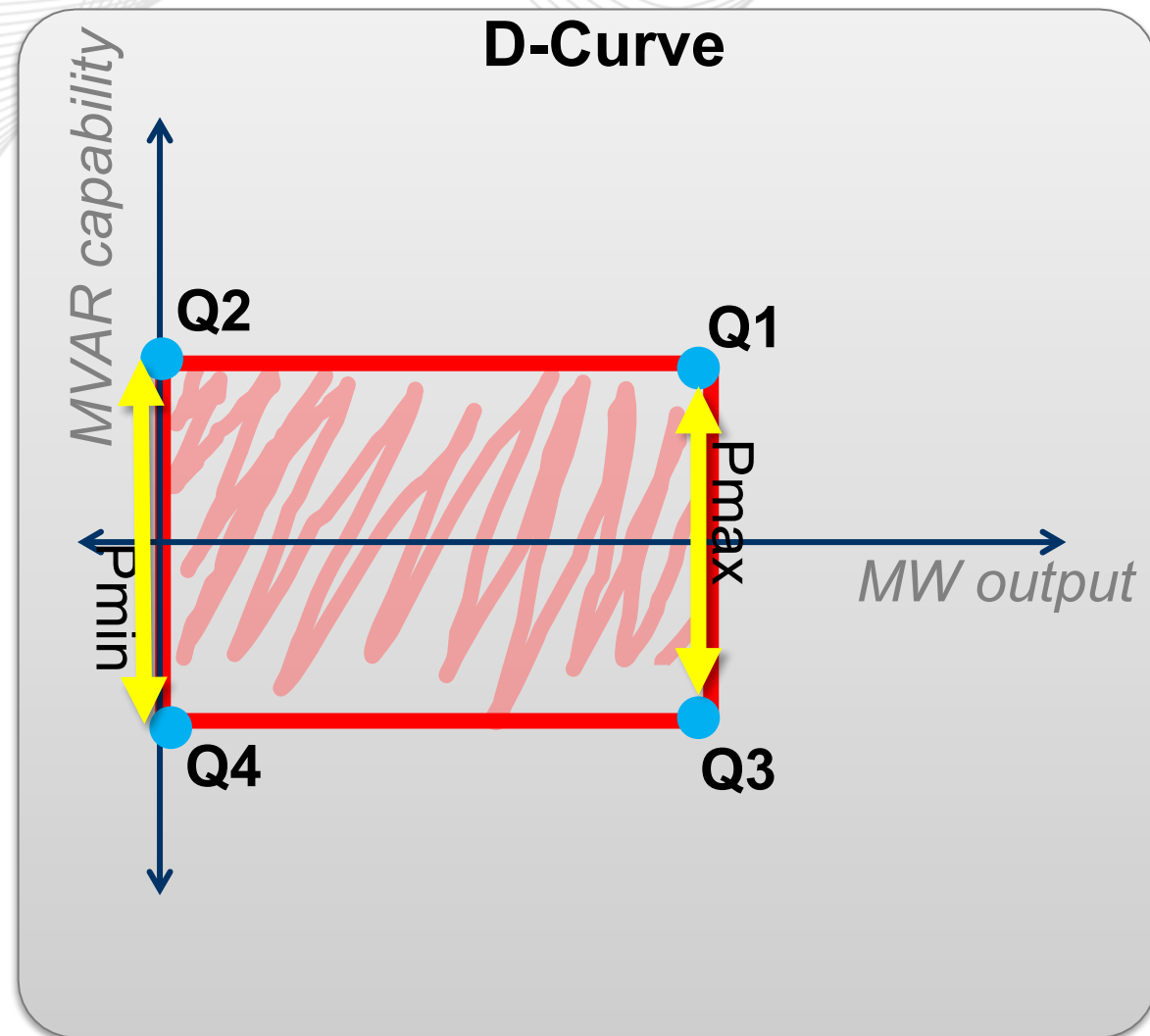
New wind generator technology is fully inverter-based, similar to solar. This result is the same as the solar example.



Hypothetical rate of \$1,000/MVAR-yr

- 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**

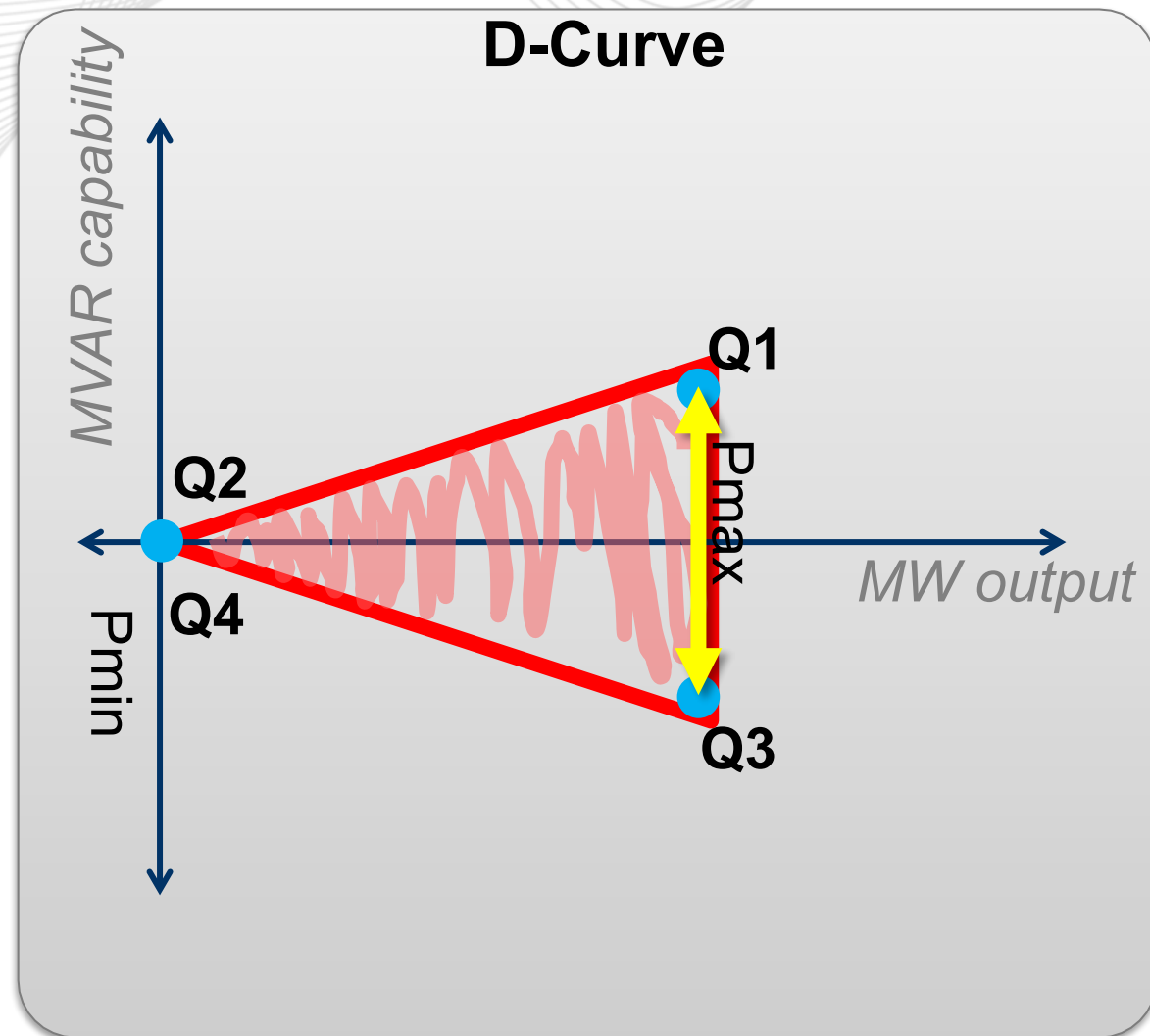
Old wind generator technology is only partly inverter based. They don't use the generators for reactive, instead using dedicated equipment that doesn't vary with power output..



Hypothetical rate of \$1,000/MVAR-yr

- 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