

Generator Reactive Performance

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System Operations Subcommittee

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Disclaimer: While materials are current at the time of publishing, applicable requirements may change. PJM Governing Documents control.

Voltage and Reactive Control for Reliability and Fairness

- To ensure safe stable voltage for the grid, and fairness and compliance for all generators, PJM seeks to increase clarity and detail of minimum acceptable generation VAR performance.
 - Effort founded on existing NERC requirements and guidance, PJM Manuals, and Tariff.
 - Adds content and clarity to M14D reactive control requirements.
 - Education on PJM's analysis and enforcement approach.

Compliance Change

- NERC ERO Enterprise CMEP Practice Guide came into effect on May 15th, 2026, lowering IBR registration threshold down to 20 MVA/60 kV, bringing more IBRs under NERC Reliability Standards. (“Category 2 GO”)
- In current industry context, existing M14D language has opportunity for improvement to better align with NERC standards.
- Urgent need to proceed efficiently and increase quality of reactive control given present and increasing operational risks.

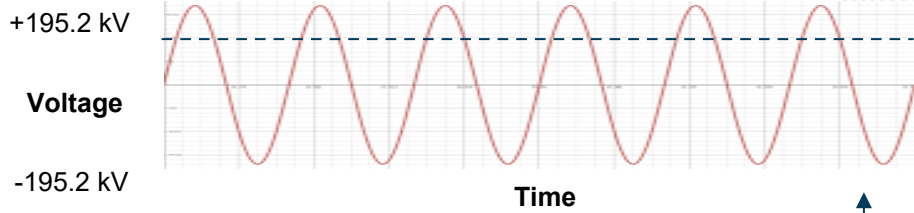
2025 Spain Blackout

- Main finding: insufficient voltage control, from not enough synchronous gens, and inadequate gen reactive response.
- Up to \$1B in economic loss.
- 8 deaths attributable.

Emerging PJM Risk

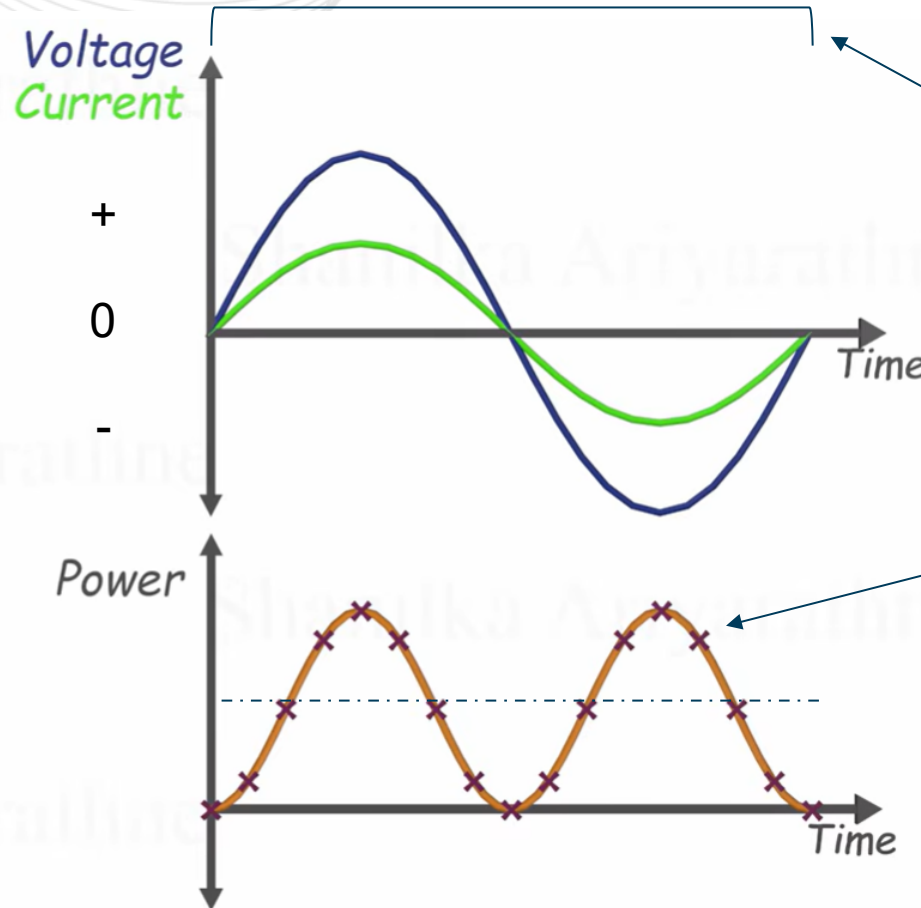
- Quickly increasing load to v-regulating gen ratio.
- Capacity constraints increase overall transmission, losses, and voltage collapse risks.
- Specific areas have increasing low voltage constraints.

- Clarify that only one AVR mode, automatic controlling voltage, is acceptable without documented exception.
- Define acceptable boundaries of volt-var control.
- Define acceptable range of var control to MW output.
- Define an investigative process for reactive control performance issues.
- Amend and clarify reactive capability curve submittals.



$$\text{RMS Voltage} = \frac{195.2}{\sqrt{2}} = 138\text{kV}$$

- Voltage and Current are Waves
- The spinning rotors inside of generators produce an oscillating voltage and current. Inverter's internal logic acts similarly.
- AC grids carry these oscillating waves from station to station, from each power plant to every home.

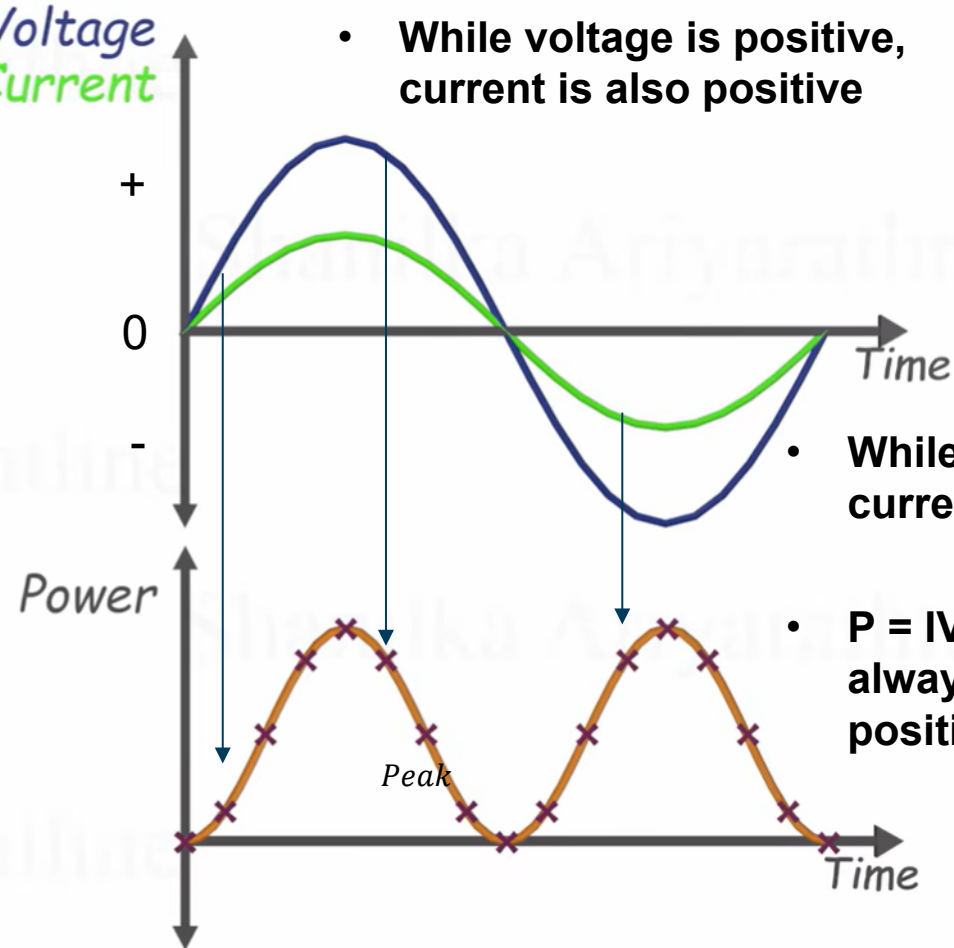


1 cycle. Generators create 60 cycles per second on the eastern interconnection

$P = I * V$ This is "complex power". Physicists often prefer S instead of P because P sometimes implies just Watts

- Power is always positive in this example
- We call “positive” power MW’s, sometimes called “active power” or “real power”
- This example has no “reactive” power. Sometimes called “imaginary power”
- **This is not common in reality**
- **Current and voltage are RARELY perfectly aligned like this**

Voltage
Current

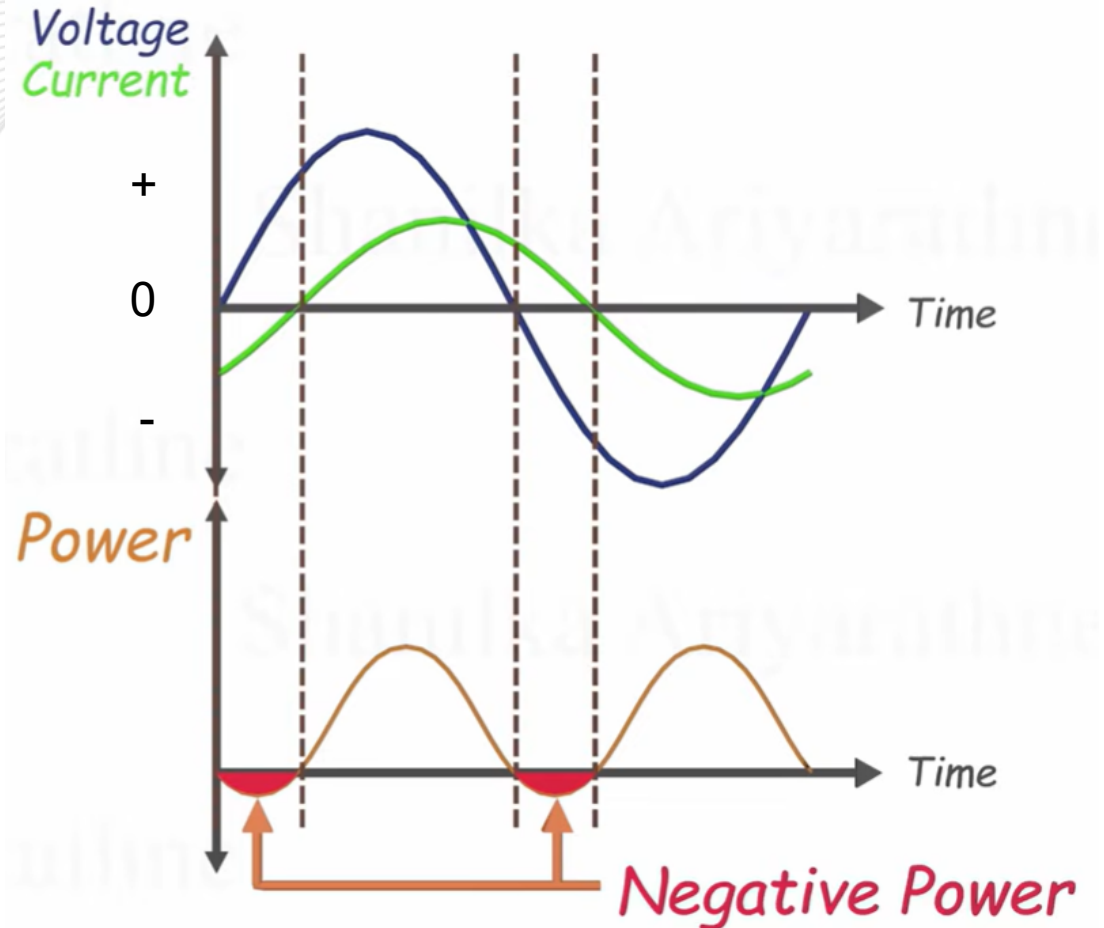


- While voltage is positive, current is also positive

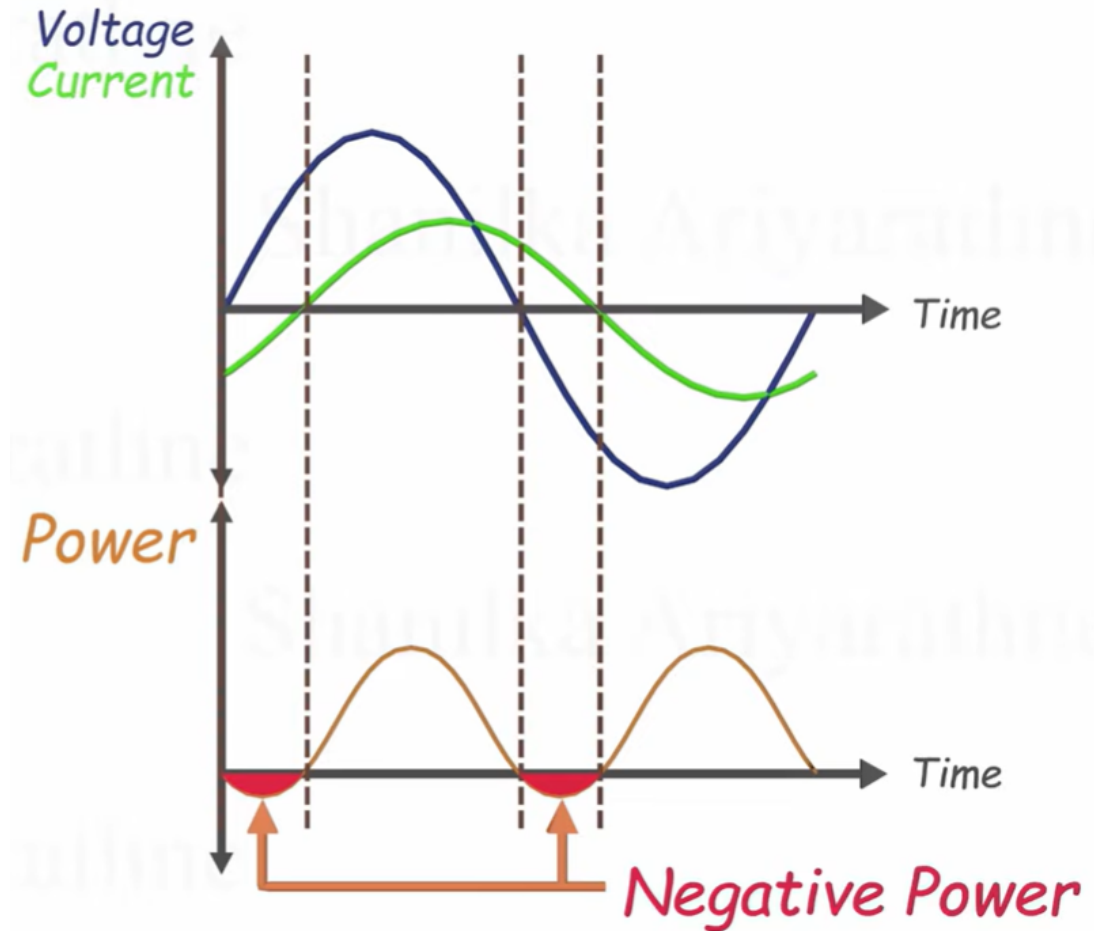
- While voltage is negative, current is also negative

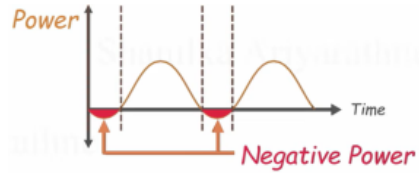
- $P = IV$ at any point always yields positive power

- This is more common
- **Main Takeaway: Current and voltage are rarely perfectly aligned**
- They often oppose each other in some portion of every cycle (60 cycles per second)
- A negative current multiplied by a positive voltage = Negative Power. Vice Versa
- What is negative power? And why aren't they aligned?



- Why aren't they aligned?
- Some power produced doesn't make it to the load
- It gets stored in electric fields (capacitive) or magnetic fields (inductive) in wires, transformers, other grid equipment
- Storage takes time, knocks current and voltage out of alignment
- Those same electric / magnetic fields immediately discharge power when they fill up, returning it to the grid. This happens 120x per second
- **Main Takeaway: The load can't use this power but it's still power**
- 'Negative Power' represents the storing and discharging of power (120x per second) that can't be used by the load.





Same power curve, lets move to 2 cycles



Engineers don't like the single power curve so they use math to represent the top graph in components

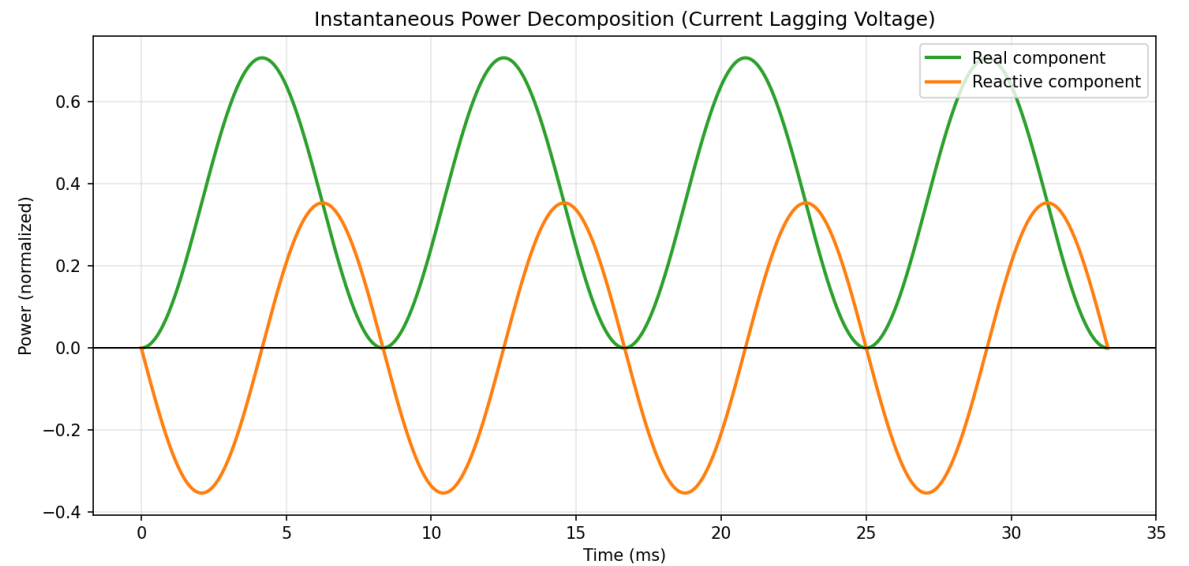
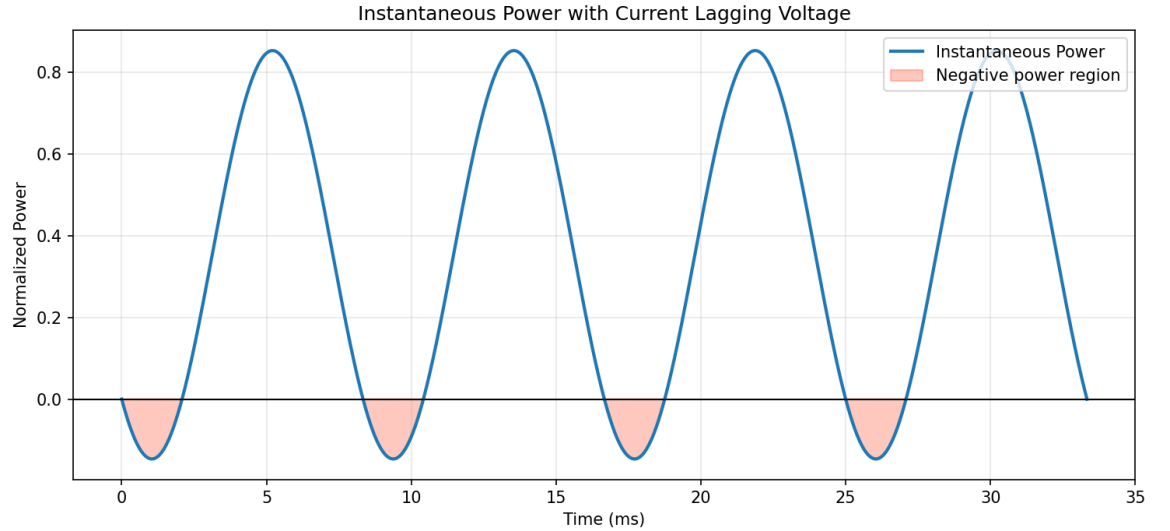
They represent it as two waves:

1. Green. A wave that stays completely positive. This is the power delivered to the load that "performs work". MW's.

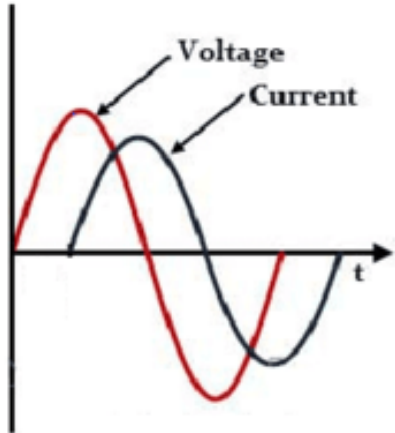
2. Orange. A wave whose average is 0. This is **MVAR's**.

mega Volt-Ampere reactive (MVAR) are the storing and discharging of power (120x per second) that can't be used by the load. This "reactive power" is required to maintain the system voltage.

Green Wave + Orange Wave = Top Blue Wave

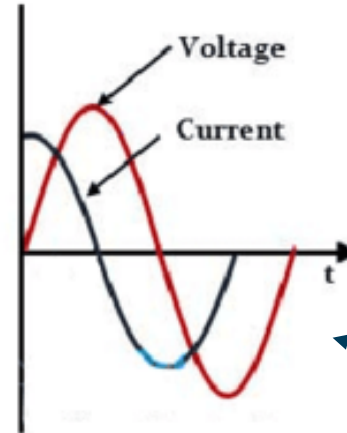


- How to avoid voltage drops? Sacrifice some MW's



- INDUCTIVE
- Current peaks behind voltage in cycle
- 'Absorbing vars' or 'Negative MVAR Output'
- Lagging power factor

- **DROPS VOLTAGE**



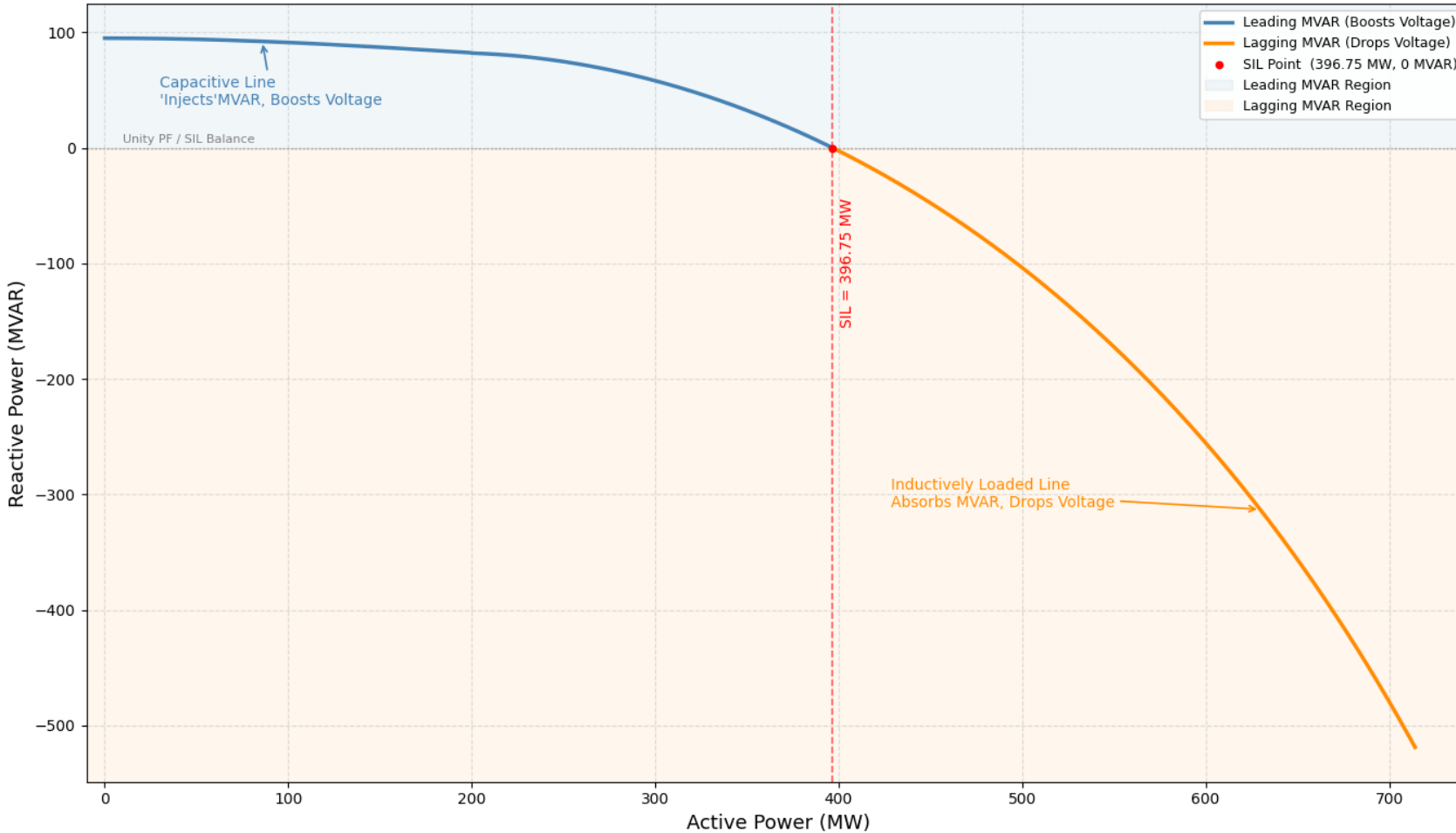
- CAPACITIVE
- Current peaks before voltage
- 'Generating vars' or 'Positive MVAR Output'
- Leading power factor

- **RAISES VOLTAGE**

- Your generator (rotor OR inverter programming) should be able to adjust it's current to lead or lag its voltage.
- **Both modes of operation are required to maintain stable system voltages**

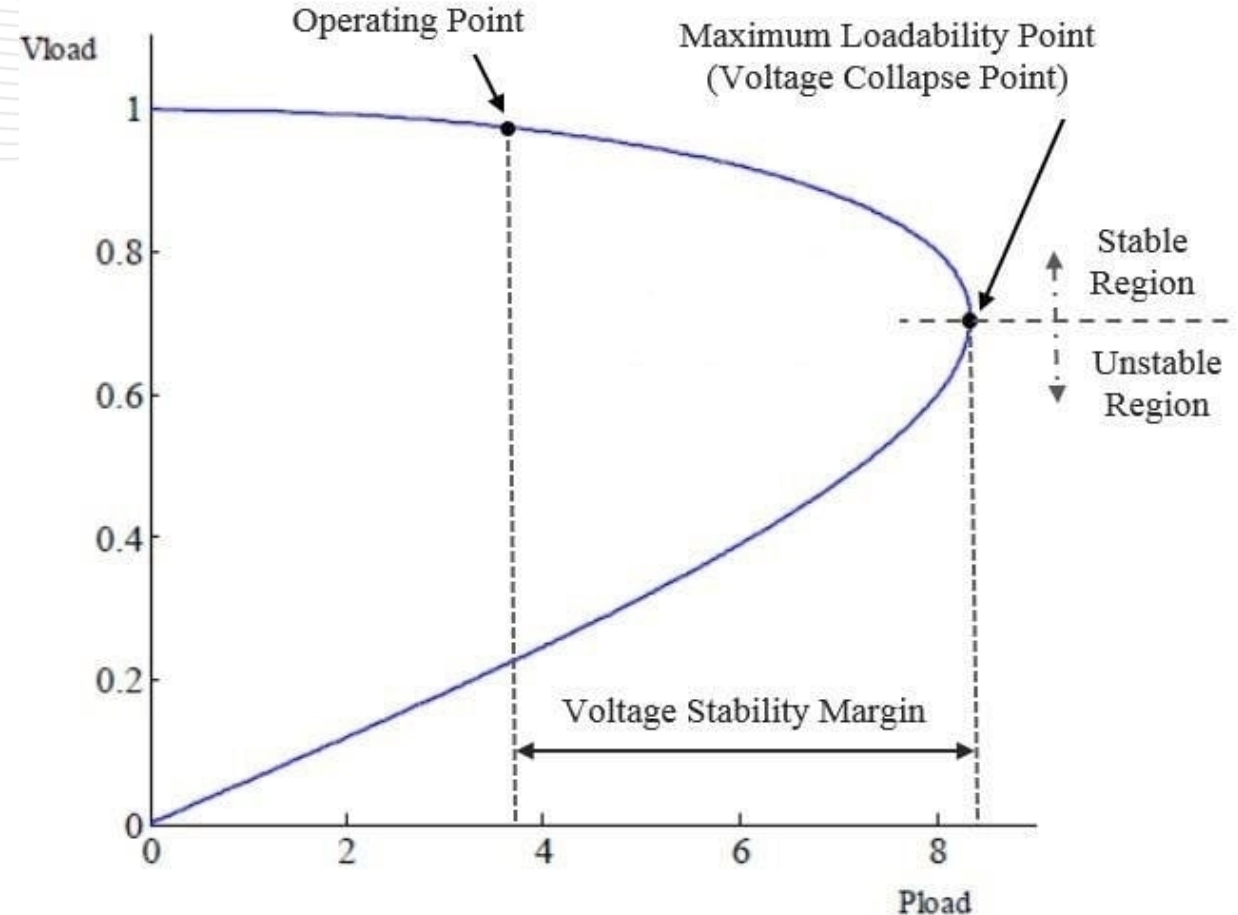
A transmission grid without any MW's on it is capacitive, generating reactive power like a giant capacitor when an AC current is applied

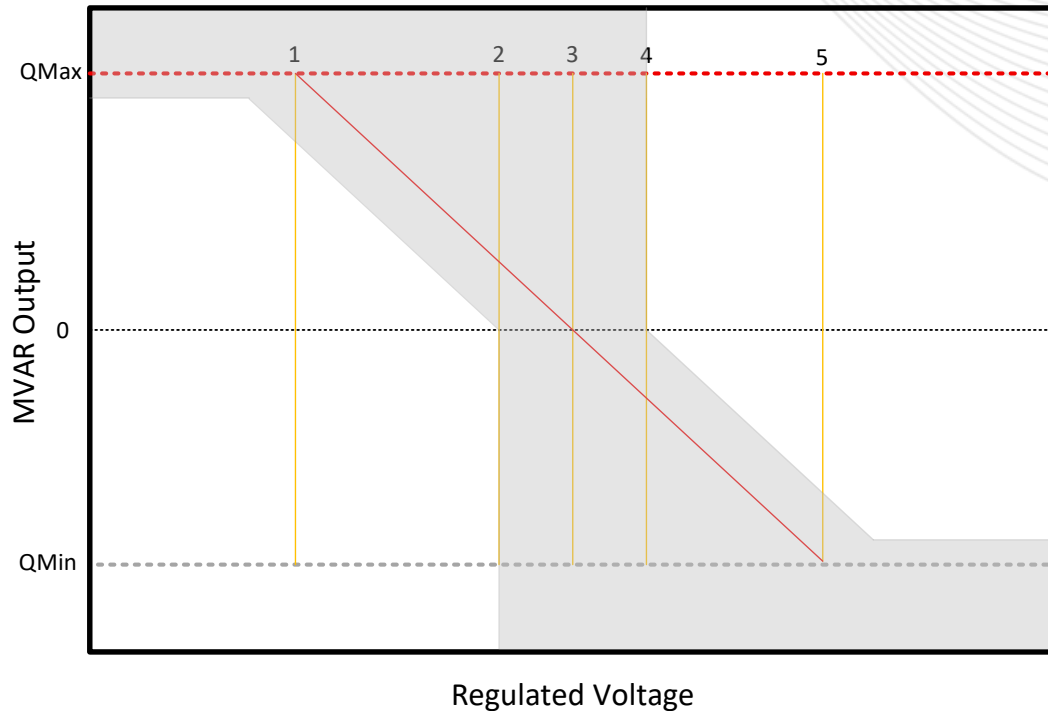
MW vs. MVAR — Surge Impedance Loading Curve
 345 kV Line | $Z_c = 300 \Omega$ | SIL = 396.75 MW



- This representation is for a single line but can also be thought of as a “Thevenin Equivalent” between a generator and the rest of the grid.
- Lots of wires suspended in the air are naturally capacitive when unloaded
- As loading increases, they become increasingly inductive

- This is also true for transfer interfaces across our footprint. The larger the MW transfer, the more voltage support (reactive support) is required to facilitate that transfer.
- As power transferred increases, system voltage drops and the need for MVAR's increases.
- **If the voltage drops too much we could cross into the unstable region causing the entire system to collapse.**
- We maintain a “Voltage Stability Margin” at all times across key transmission corridors. These are PJM’s IROL’s.



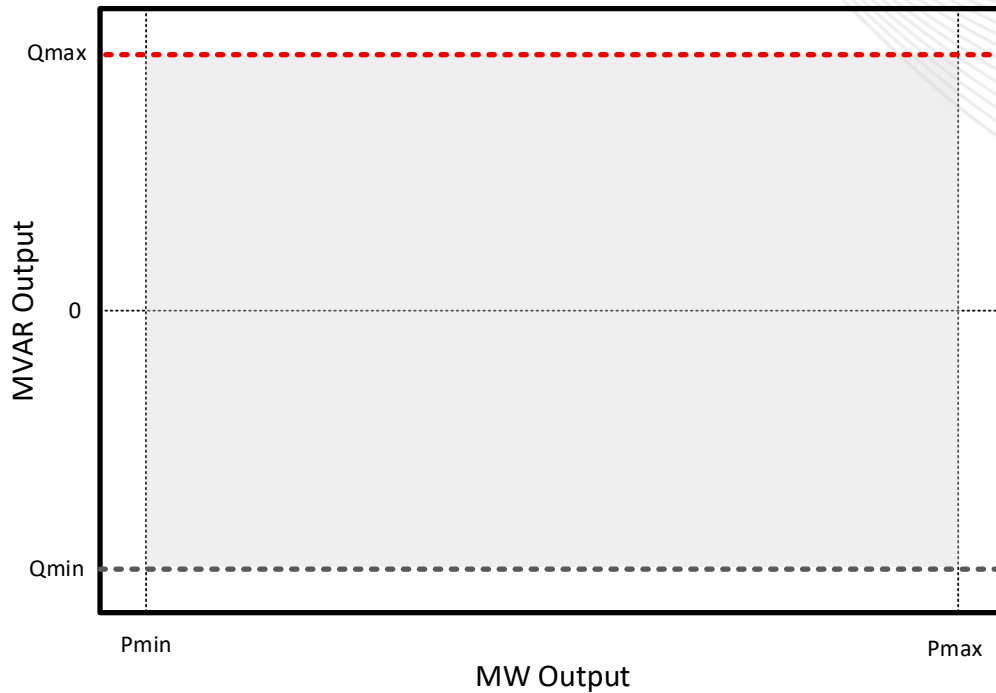


- Defines acceptable range of VAR output at any voltage.
- Gray area is acceptable.
- 32.87% relates to the standard .95 pf capability standard.




Legend

---	Max Reactive Output (Qmax) 32.87% of Max MW
---	Min Reactive Output (Qmin) -32.87% of Max MW
1	Vref - 0.020 Per Unit
2	Vref - 0.005 Per Unit
3	Target Voltage a.k.a Voltage Reference (Vref)
4	Vref + 0.005 Per Unit
5	Vref + 0.020 Per Unit

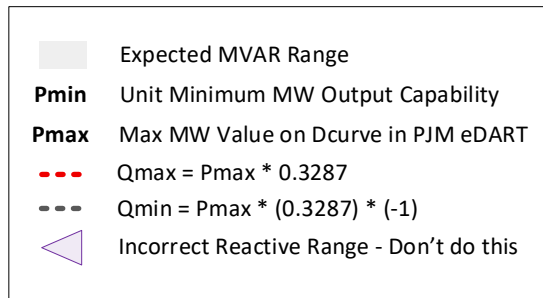
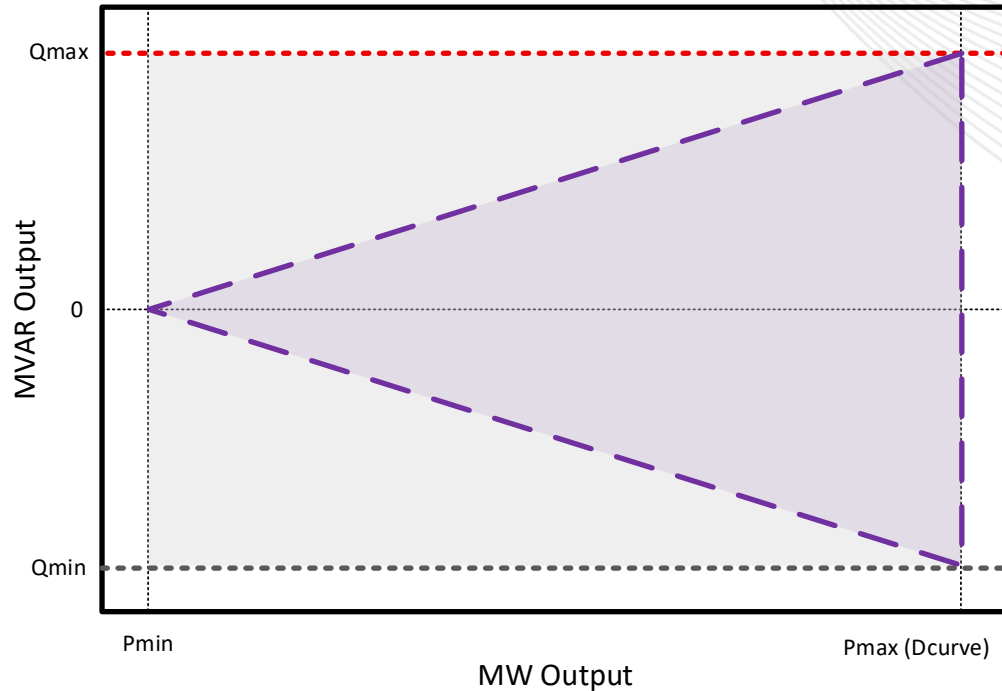
7.1.2 VAR Control Range Boundaries



- Defines acceptable reactive control range per MW output.

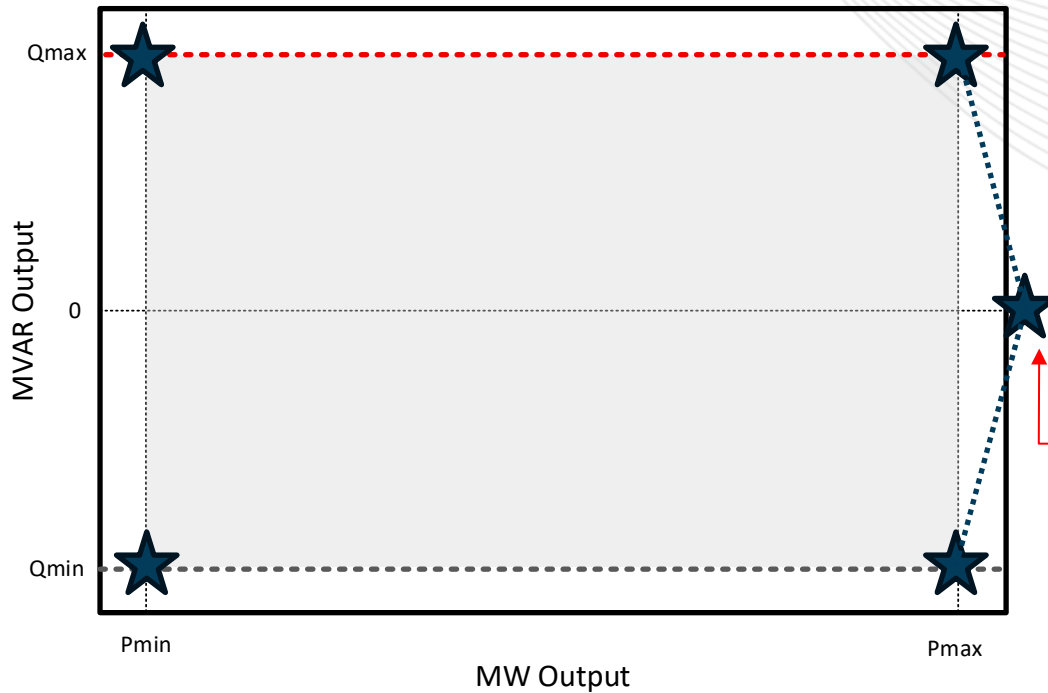
	Expected MVAR Range
Pmin	Unit Minimum MW Output Capability
Pmax	MFO (Max Facility Output) from Unit ISA or GIA
	$Q_{max} = P_{max} * 0.3287$
	$Q_{min} = P_{max} * (0.3287) * (-1)$




7.1.2 VAR Control Range Boundaries



- Commonly made *incorrect* assumption or interpretation of reactive control range per MW output.
- Shown as a counter-example.

Required Reactive Capability Curve Points



	Expected MVAR Range
Pmin	Unit Minimum MW Output Capability
Pmax	MFO (Max Facility Output) from Unit ISA or GIA
	$Q_{max} = P_{max} * 0.3287$
	$Q_{min} = P_{max} * (0.3287) * (-1)$

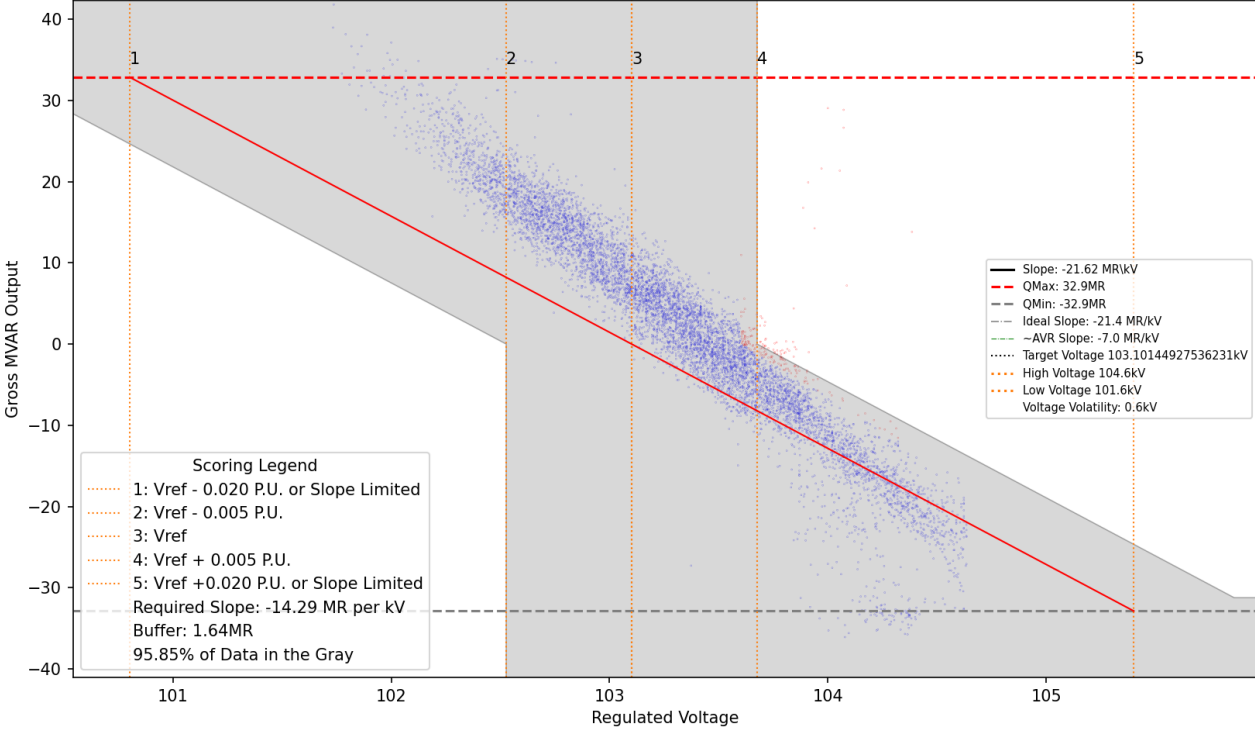
- Minimum required points cover capability at Pmin and Pmax as well as...
- PJM needs to know the “nose” of the curve. **Generators regularly exceed MFO MW**
- At what point does your generator produce 0 MVAR while maximizing its MW output
- Pmin is the minimum MW where AVR is functional

- **Real Examples**

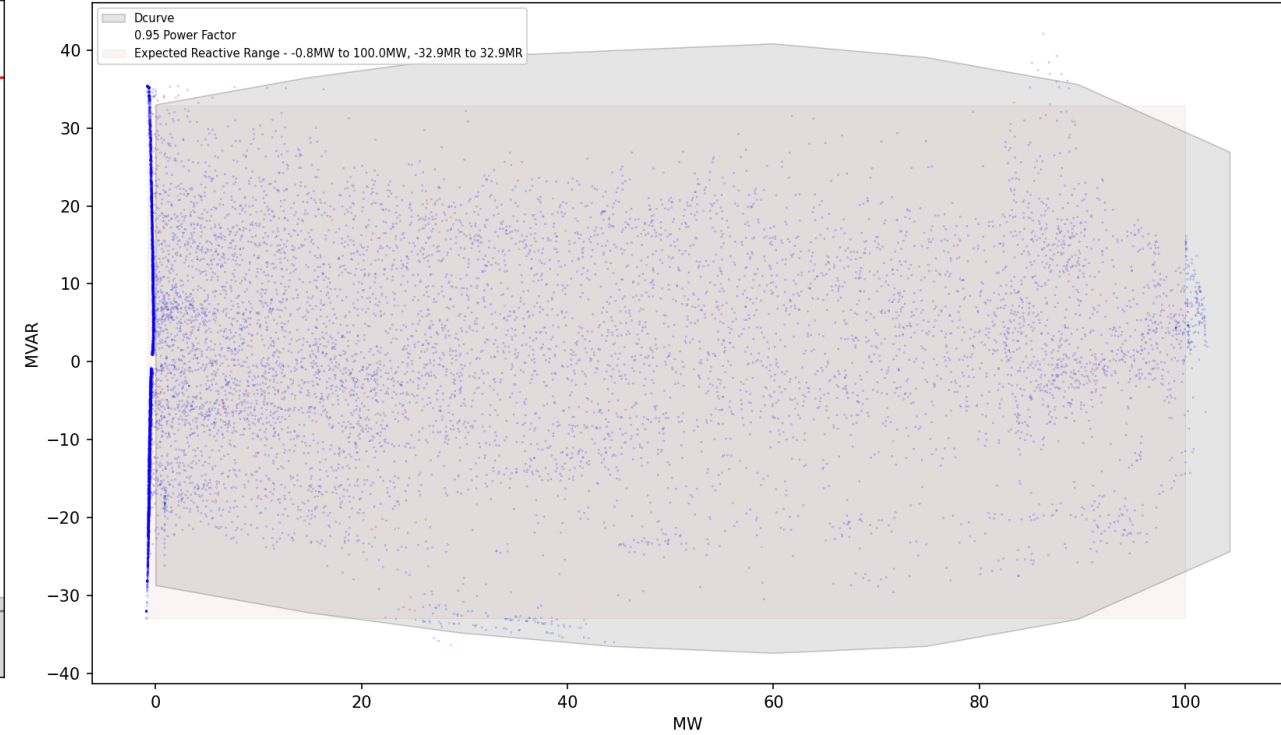
- Sourced from real-time telemetered data
- Excludes reported reactive testing, reported AVR outages, and reported changes in setpoint
- Generation inside PJM footprint
- High side voltage and low side vars are used
- All examples are “normalized” to 100 MW P_{MAX} with a 100 KV high side voltage. For example for an 800 MW generator on the 500 KV, all MW and MVAR numbers are divided by 8 and all voltages are divided by 5.

- Exemplary Performance**

Gross MR Output vs. Regulated Voltage.
2026-02-02 07:38:00-05:00 through 2026-04-01 19:38:00-04:00

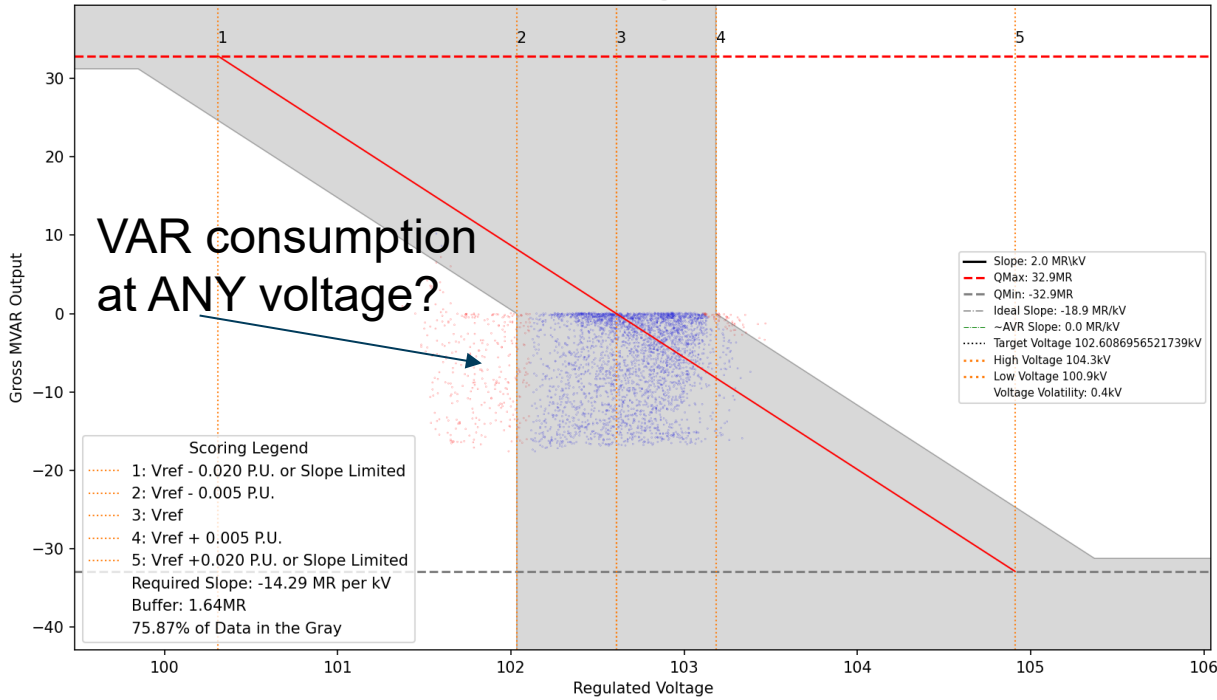


DCurve Performance.
2026-02-01 23:58:00-05:00 through 2026-04-01 23:58:00-04:00

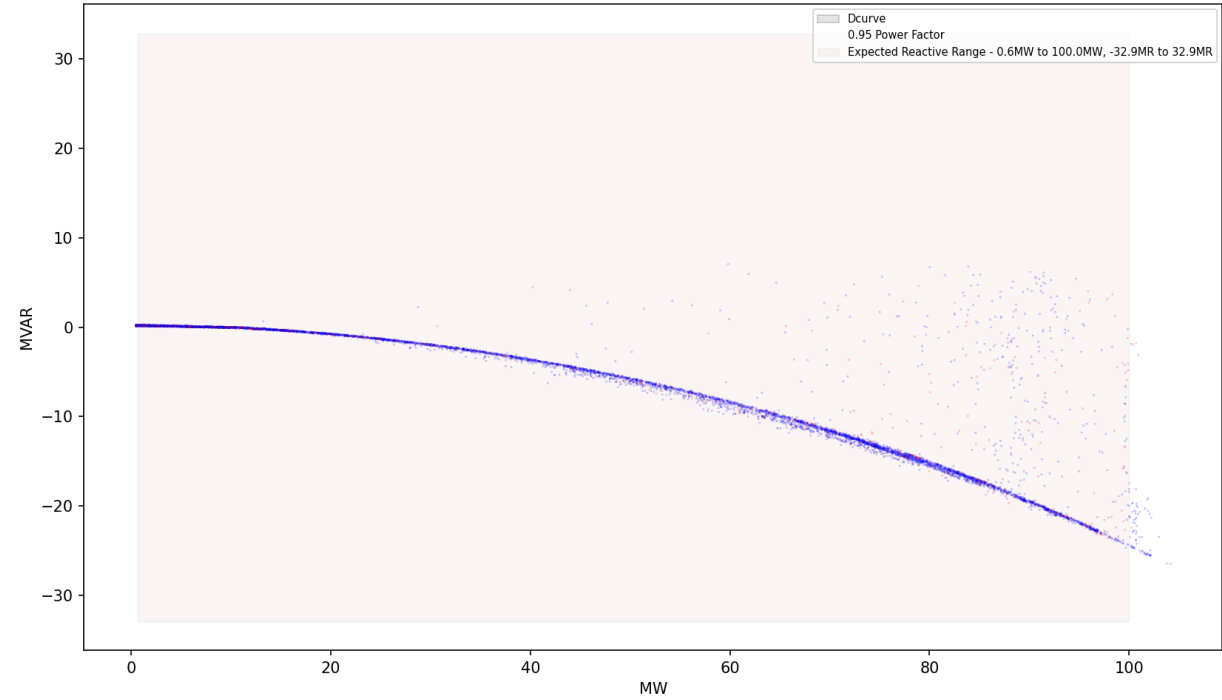


- **Purely inductive machine**
- Relies on MVAR output from neighbors and infrastructure to support its MW generation

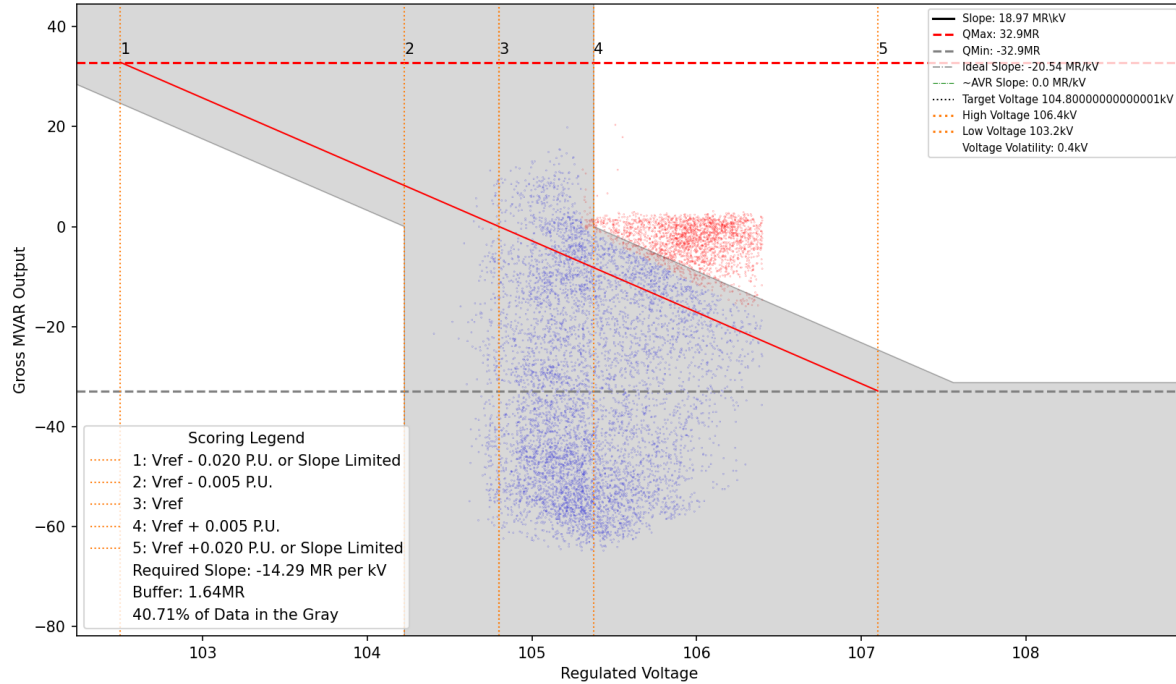
Gross MR Output vs. Regulated Voltage.
2026-02-02 07:40:00-05:00 through 2026-04-01 18:50:00-04:00



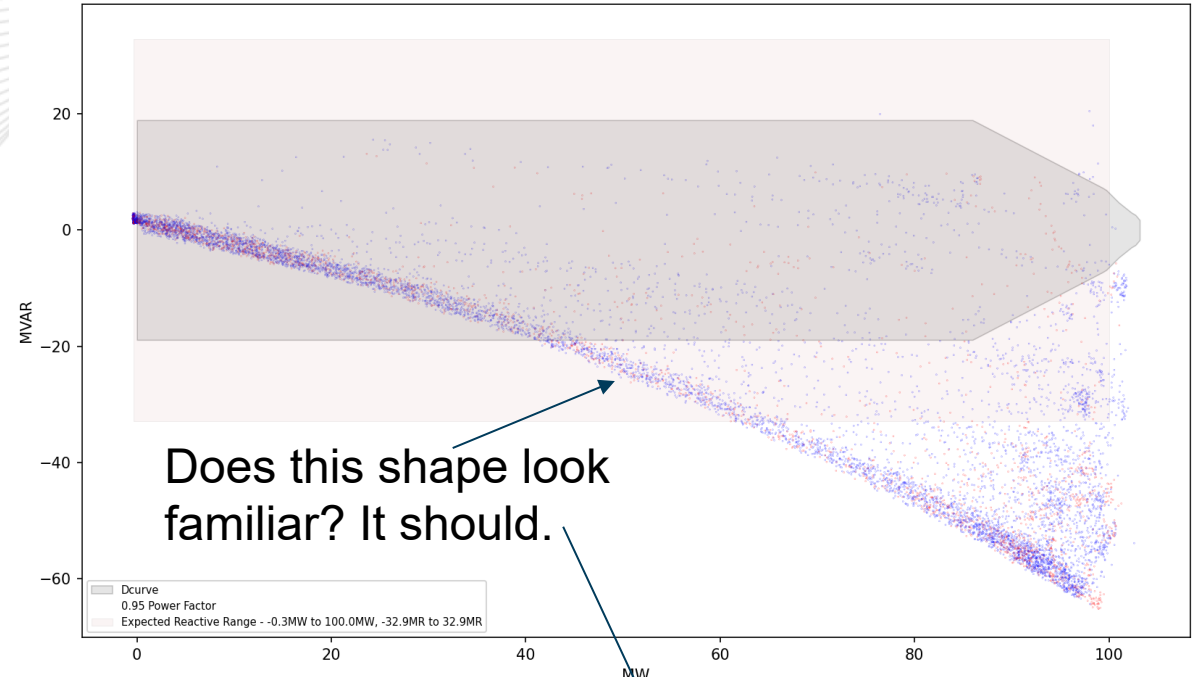
DCurve Performance.
2026-02-02 07:15:00-05:00 through 2026-04-01 19:20:00-04:00



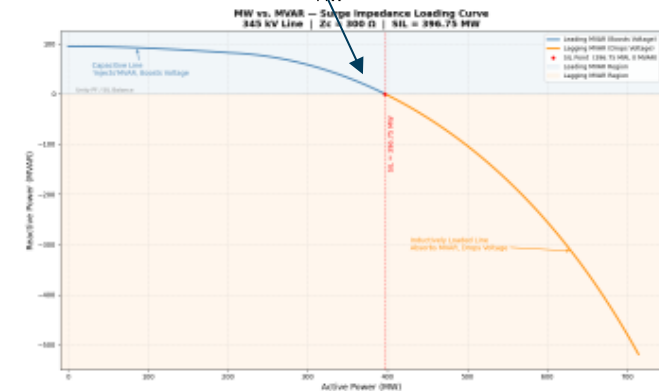
Gross MR Output vs. Regulated Voltage.
2026-04-02 07:13:00-04:00 through 2026-06-01 19:38:00-04:00



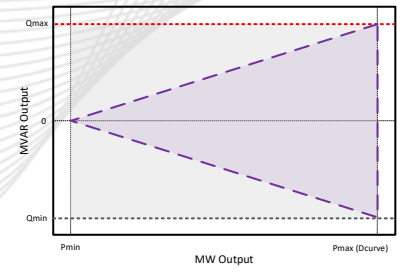
Dcurve Performance.
2026-04-01 23:58:00-04:00 through 2026-06-01 23:58:00-04:00



- Pulling MVARs from the grid. Other sources are producing extra MVARs (spending more \$\$) to compensate.
- Those not following the rules are doing so at the cost of those who are following the rules

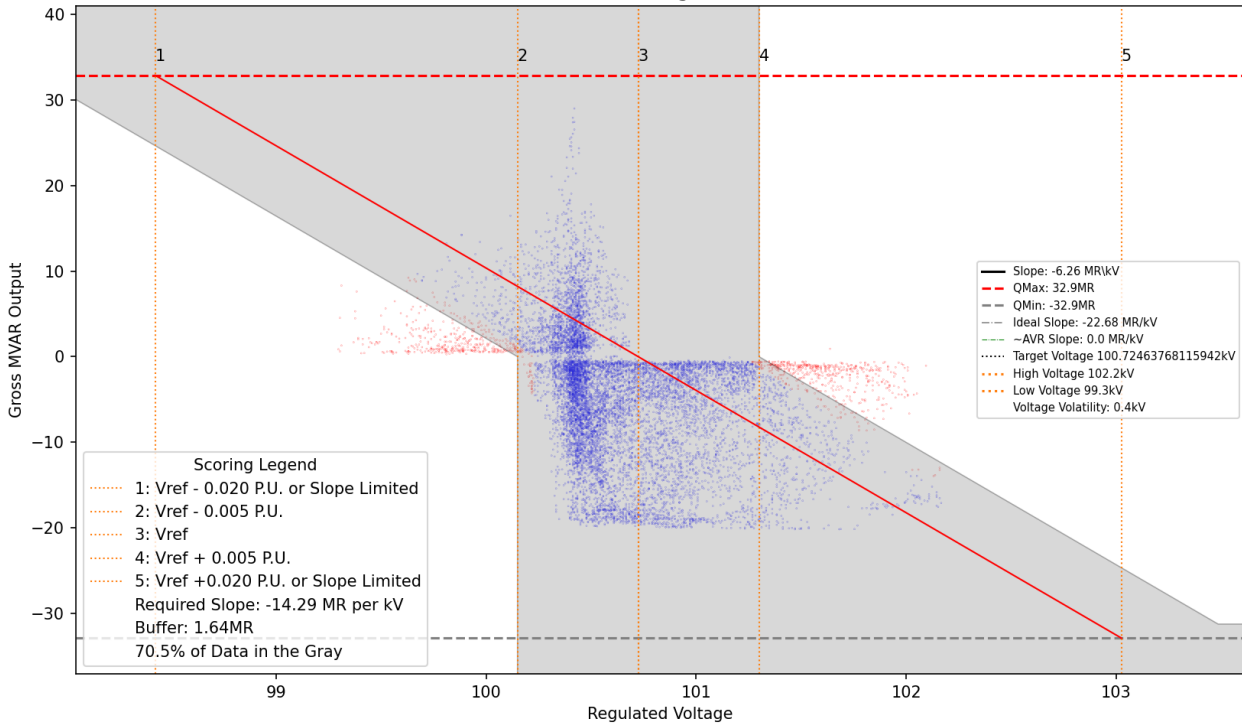


- **Power Factor clamping**

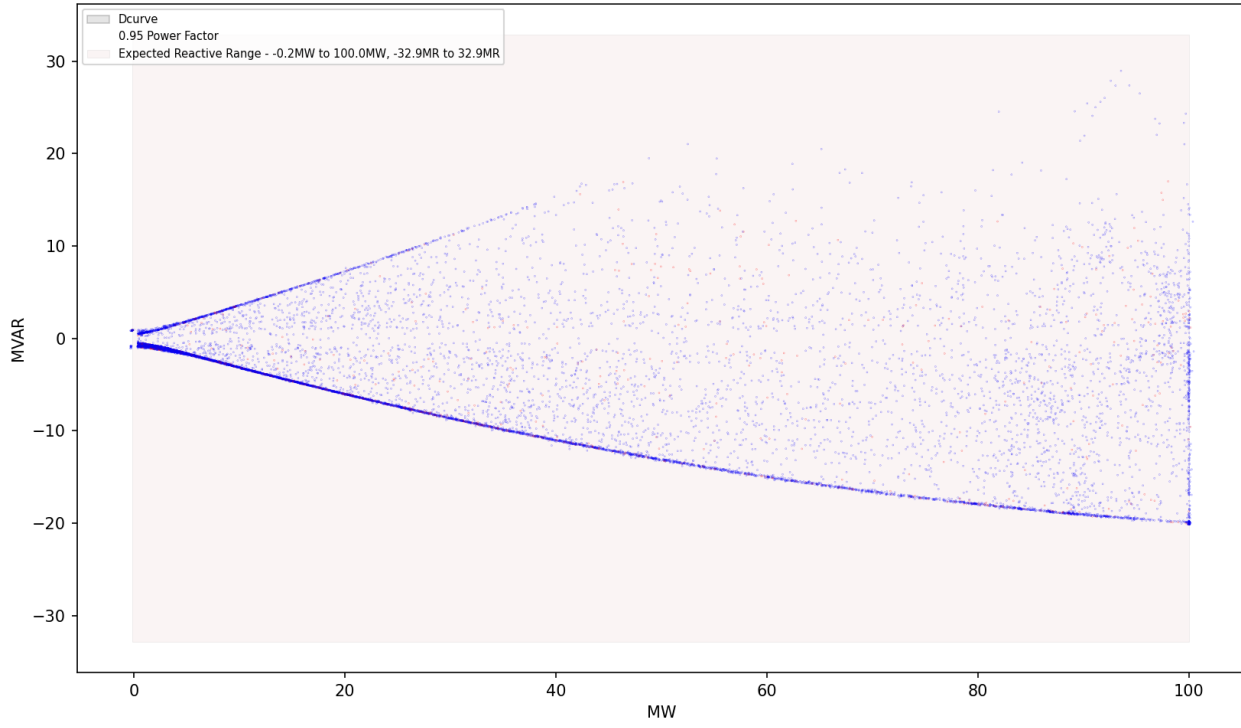


Remember Purple = "Don't do this"

Gross MR Output vs. Regulated Voltage.
2026-02-02 07:40:00-05:00 through 2026-05-01 20:15:00-04:00



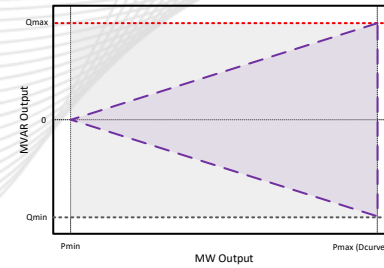
Dcurve Performance.
2026-02-01 23:55:00-05:00 through 2026-05-01 23:55:00-04:00



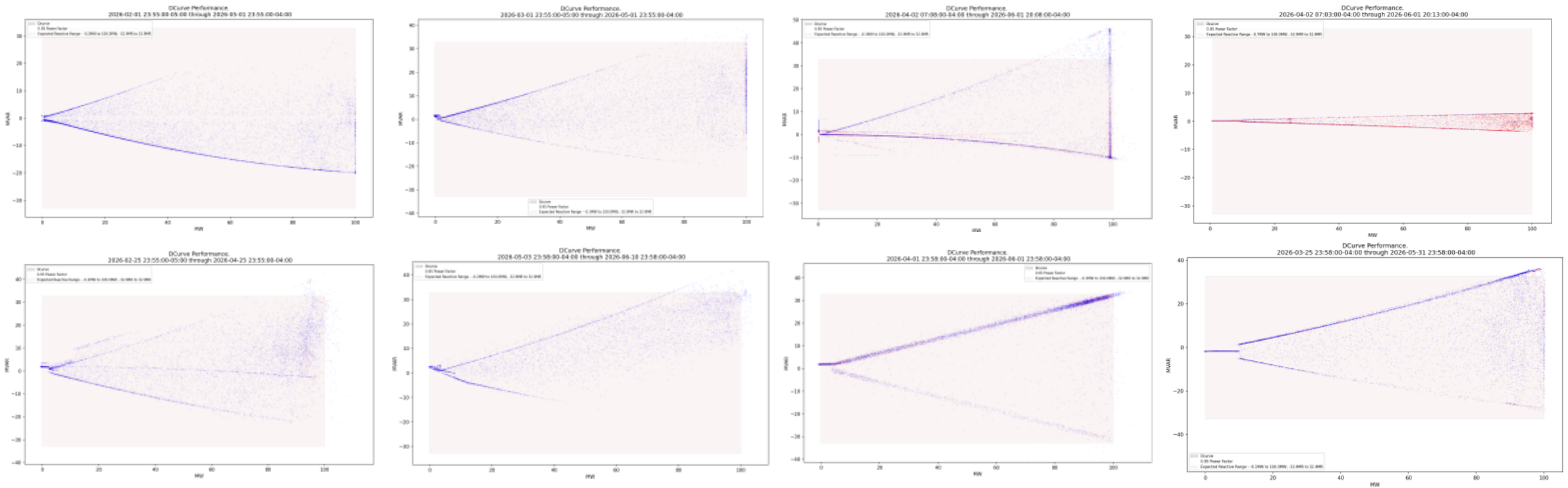


What is Reactive Performance

- **Power Factor clamping**
- These are all different units. Different owners. Data from March - June

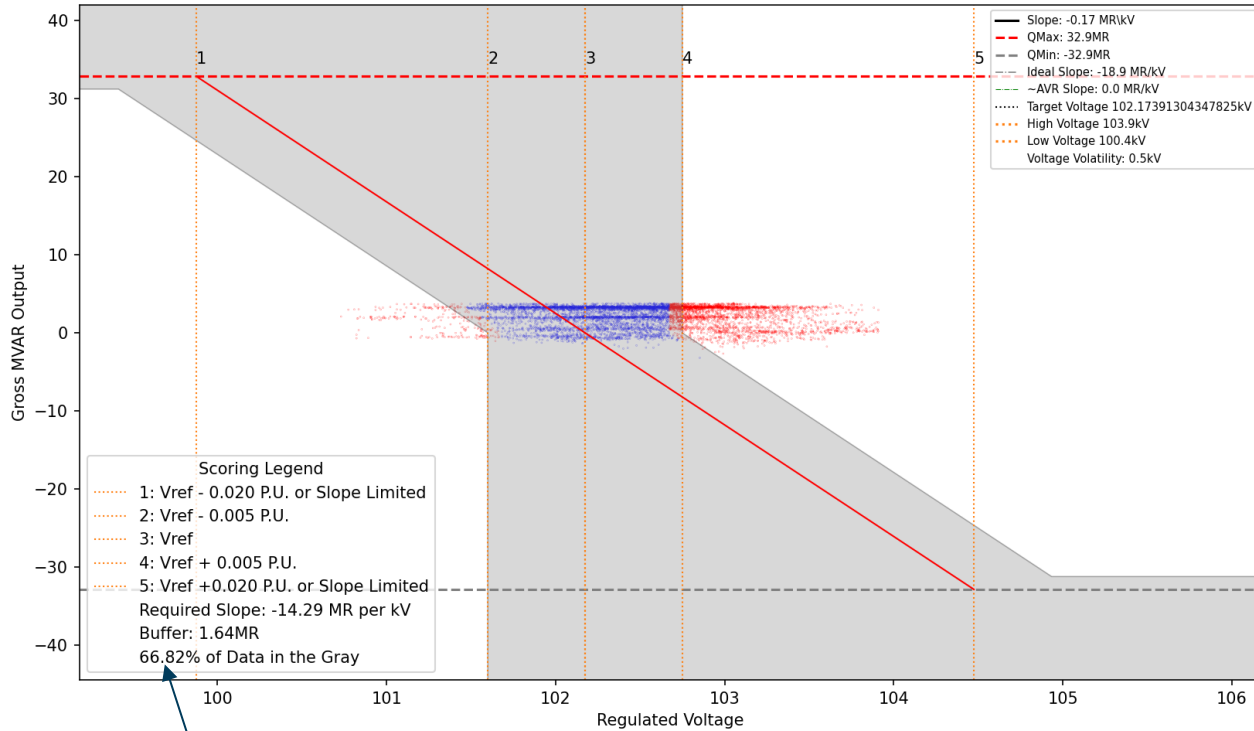


Remember Purple = “Don’t do this”

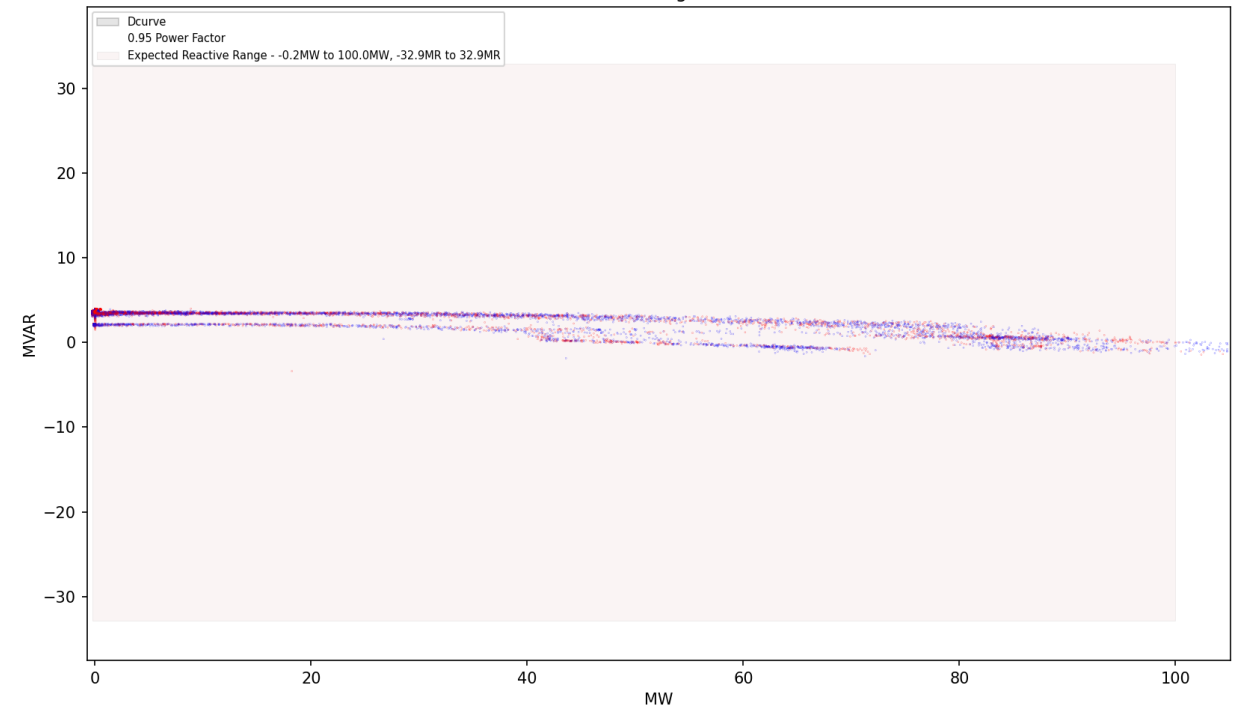


- **Constant MVAR Mode**

Gross MR Output vs. Regulated Voltage.
2026-03-02 15:20:00-05:00 through 2026-04-25 19:25:00-04:00



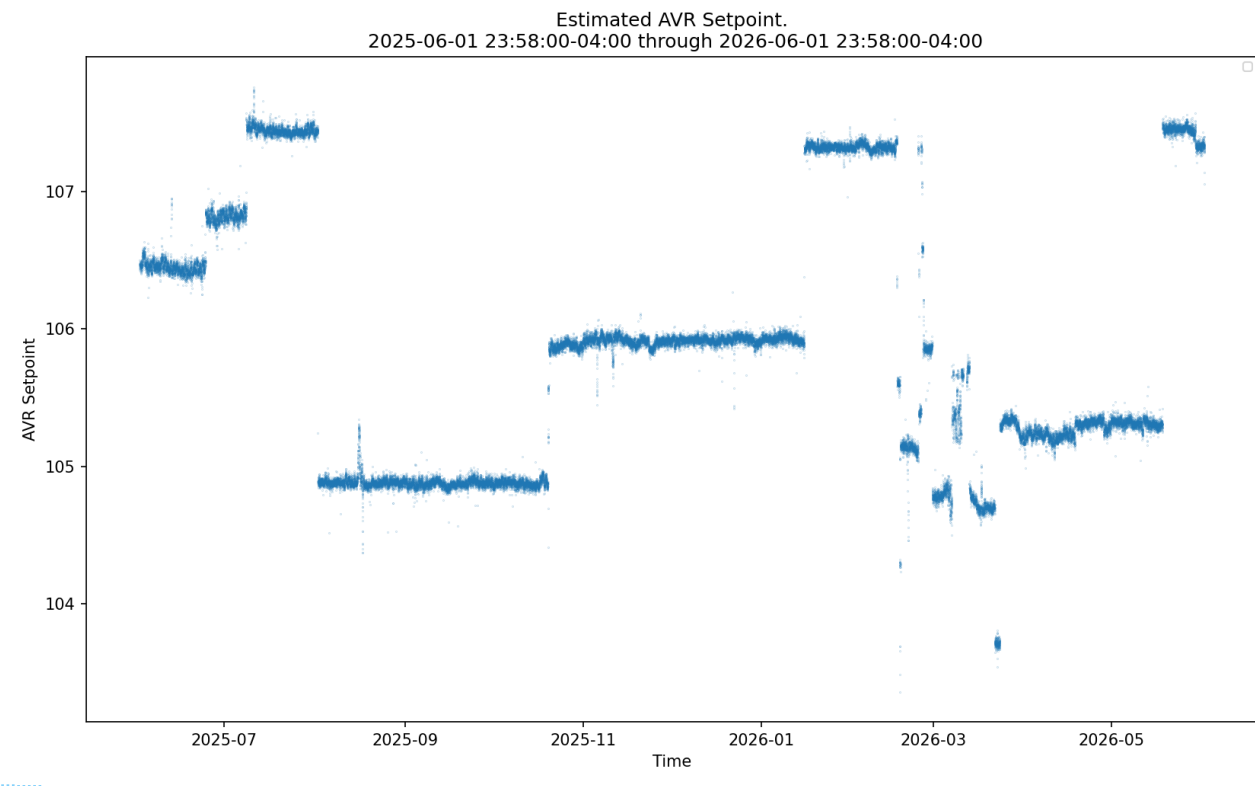
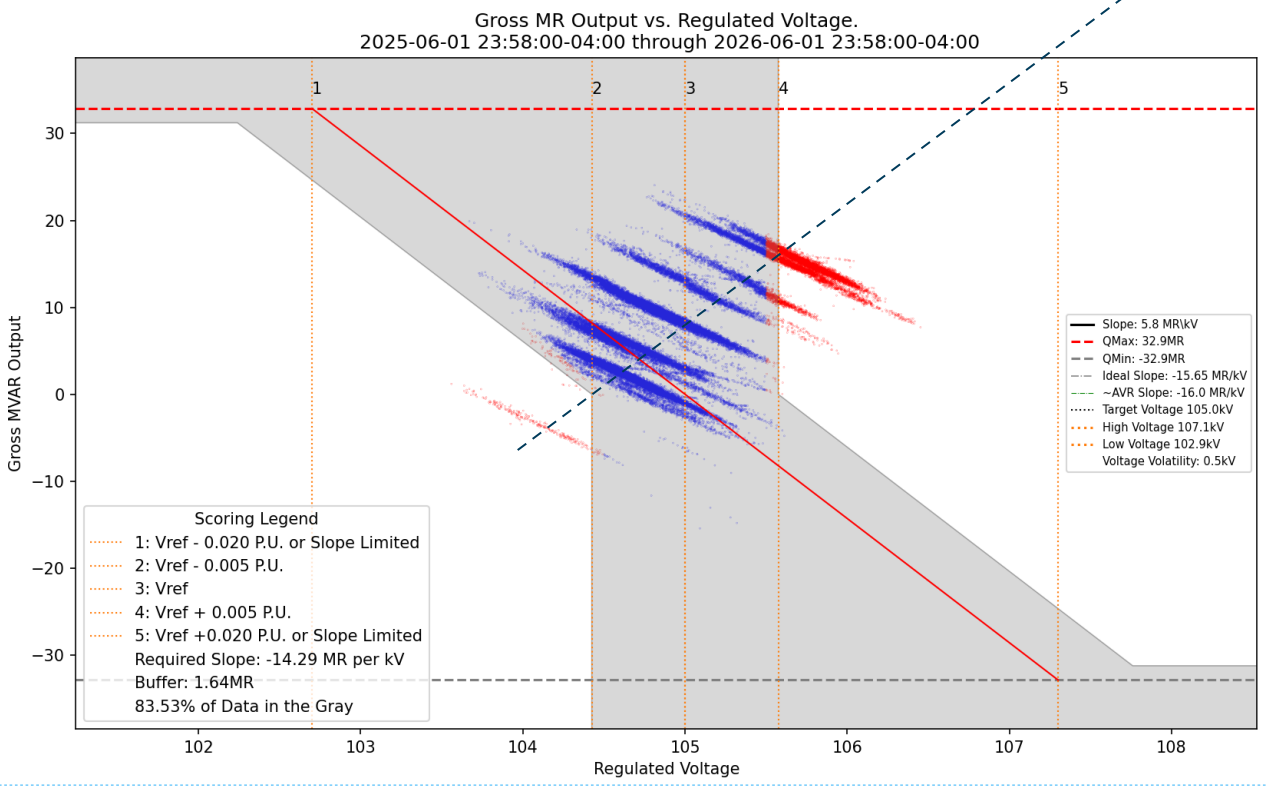
Dcurve Performance.
2026-03-02 14:40:00-05:00 through 2026-04-25 23:55:00-04:00



That's an alarming percentage of time!

- Moving Setpoint**

Trying hard to move AGAINST!? the grid?



PJM may initiate a three-party investigation – between relevant TO/EDC, Gen Owner/Operator, and PJM – of apparent reactive control issues for any given gen unit. Although PJM may systematically analyze the reactive performance of the entire generation fleet, many factors must be considered before reaching conclusions, necessitating a case-by-case analysis approach. Those factors may include:

- AVR or other gen equipment limitations, short or long-term
- Voltage schedule exceptions (which may be requested by the TO and must be entered in eDART)
- ISA or GIA that deviates from the standard Tariff template
- Other documented exceptions (ex. legacy units that predate relevant standards)

PJM may ultimately direct generators to alter their reactive controls, including AVR settings or inverter settings, and work with the gen owners/operators to confirm successful resolution before closing the analysis. Critical issues that cannot be resolved via the investigative process may be referred to the appropriate governing entity, such as NERC or PJM legal, for further review.

PJM M14D

7.1.2

- “The reactive output of the generator must be regulated in the manner specified by PJM and/or the Transmission Owner.”
- “Generation Owners shall comply with the assigned voltage schedule in automatic voltage control mode”

Tariff, Part IX, Sub. B

Gen Inter. Agreement

- “Proj. Dev. agrees... when so directed by [PJM]... to operate the Gen Facility to produce reactive power... pursuant to voltage schedules... established by [PJM]”
- “[PJM] shall maintain oversight... to ensure that all sources of reactive power in the PJM Region... are treated in an equitable and not unduly discriminatory manner.”

NERC VAR-002-4.1

- Gen Op shall operate each gen connected to the transmission system in the automatic voltage control mode
- Gen Op shall maintain the generator voltage or Reactive Power schedule provided by the Transmission Operator

NERC VAR-002-2b

- “...does AVR operation in the constant PF or constant Mvar modes comply with R1? Interpretation: No, only operation in constant voltage mode meets this requirement.”
- “...if the Transmission Operator specifically directs a Generator Operator to operate the AVR in a mode other than constant voltage mode, then that directed mode of AVR operation is allowed.”

- “Generation Owners shall comply with the assigned voltage schedule in automatic voltage control mode (AVR in service and controlling voltage).”
- “PJM allows for different voltage control modes of operation for generators (voltage, reactive power, and power factor) which are described in the following section.”
- Four modes of AVR control defined.

AVR Operating Mode	Expected Generator Response
Automatic controlling voltage (voltage schedule)	Reactive output varies based on the grid system needs to maintain the reference voltage within the assigned voltage schedule's bandwidth up to the reactive capabilities of the generator. This is the standard voltage control operating mode for most generators in PJM.
Automatic controlling MVARs (MVAR schedule)	Reactive output remains steady based on scheduled MVARs
Automatic controlling power factor (power factor schedule)	Reactive output varies based on the real power output of the generator to maintain a constant ratio of real power versus apparent power (constant power factor)
Manual	Reactive output varies based on the manual adjustments made by the plant operator

Being in any AVR mode other than automatic controlling voltage mode must be documented in eDART and approved by PJM and the TO. PJM ~~allows~~ categorizes the different voltage control modes of operation for generators (voltage, reactive power, and power factor) which are described in the following section.

AVR Operating Mode	Expected Generator Response
Automatic controlling voltage (voltage schedule)	Reactive output varies based on the grid system needs to maintain the reference voltage within the assigned voltage schedule's bandwidth up to the reactive capabilities of the generator. This is the standard voltage control operating mode for most generators in PJM.
Automatic controlling MVARs (MVAR schedule)	Reactive output remains steady based on scheduled MVARs
Automatic controlling power factor (power factor schedule)	Reactive output varies based on the real power output of the generator to maintain a constant ratio of real power versus apparent power (constant power factor)
Manual	Reactive output varies based on the manual adjustments made by the plant operator

Reactive Controls

- 1. NERC has lowered the threshold of registered generation, newly including mid-sized IBRs in reliability standards.**
- 2. PJM has present and increasing low-voltage concerns that must be addressed.**
- 3. PJM has existing authority and responsibility to ensure adequate system voltage**
- 4. Consistent analysis and improved Manual guidance and requirements will allow PJM, TOs and GOs to work together and address emerging risk, fairly and efficiently, both case-by-case and systematically.**

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Manual 14D: Revision 71

Voltage vs. Active Power 345 kV Line | Voltage Boosted Sub-SIL, Sags Super-SIL

