PJM Manual M14D R71 and Voltage Support

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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.

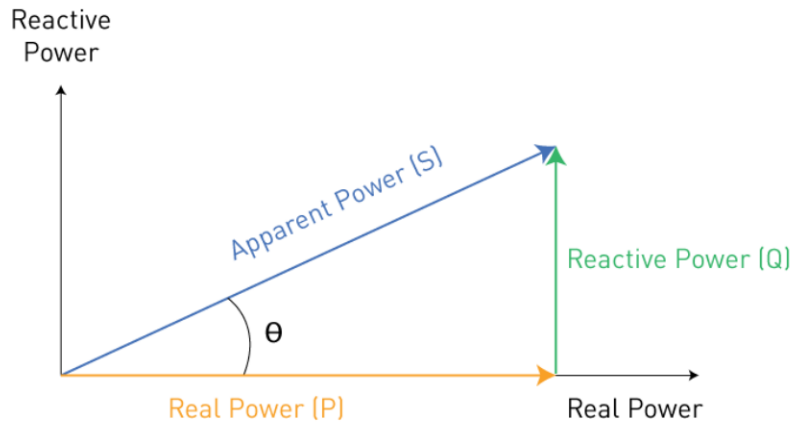
Presentation Order

Progression

1. **Context and Related History**
2. Applicable Existing Standards
3. Manual Edits
4. Enforcement

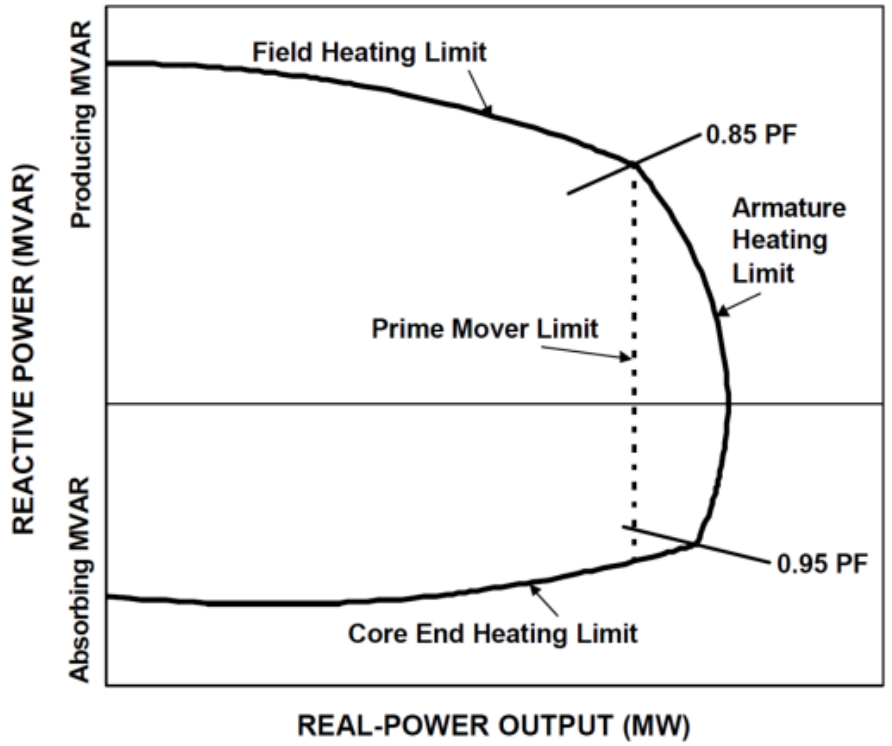
Quick VAR Refresher

- MW do work. MVAR support voltage and energize motor (inductive) loads.
- MW can be transmitted long-distances at high voltages. MVARs are more local.
- VARs are produced by traditional gens (i.e. d-curve), inverters (with proper config.), cap banks and synchronous condensers.



Quick VAR Refresher

- Gens are inherently optimally located to provide VARs.
- A gen under-performing in volt support creates more ‘work’ for other nearby gens, or long-term create need for additional voltage supporting grid devices.
- VAR control has minor cost to a gen – max MW limits, internal losses, internal wear.



Recent Historical Context

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.

Presentation Order

Progression

1. Context and Related History
2. **Applicable Existing Standards**
3. Manual Edits
4. Enforcement

Applicable Regulatory Text Highlights

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.”

Applicable Regulatory Text Highlights

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."

PJM M14D 7.1.2 Voltage and Reactive Control

- “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

Presentation Order

Progression

1. Context and Related History
2. Applicable Existing Standards
3. **Manual Edits**
4. Enforcement

PJM M14D Edits

- 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 D-curve submittals.

7.1.2 AVR Modes

Being in any AVR mode other than voltage control 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.
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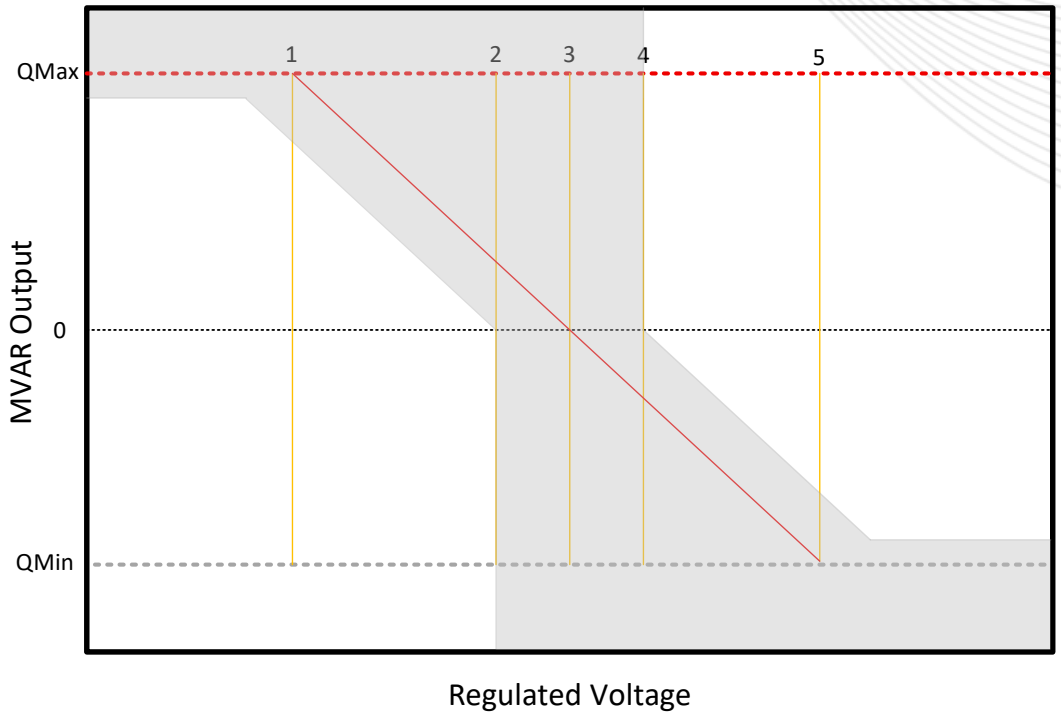
7.1.2 Volt-Var Boundaries

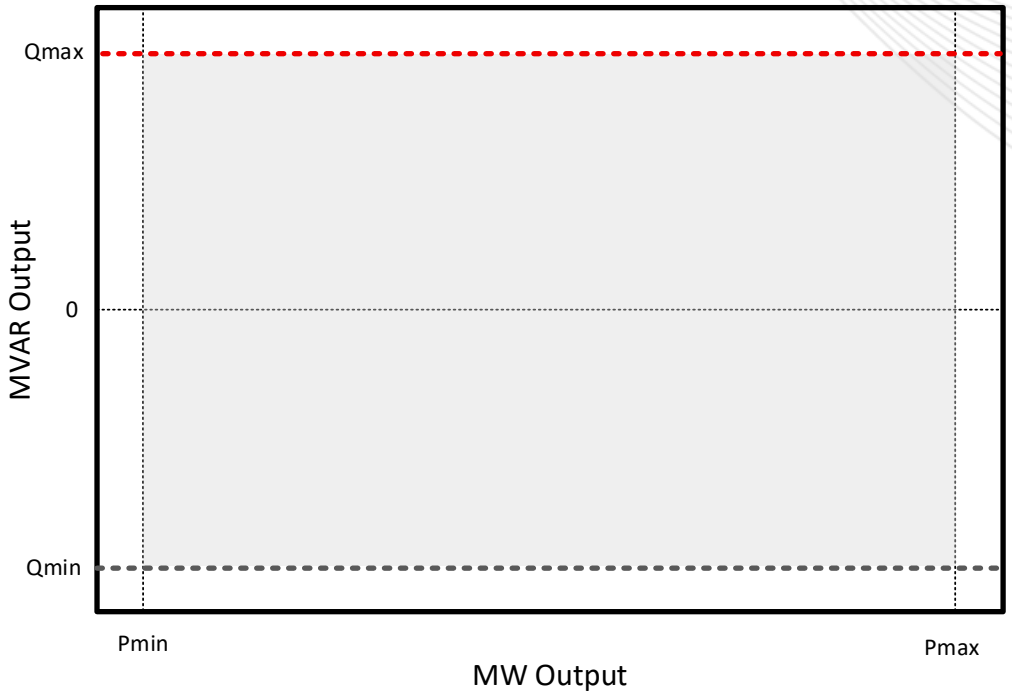


Legend

---	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

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

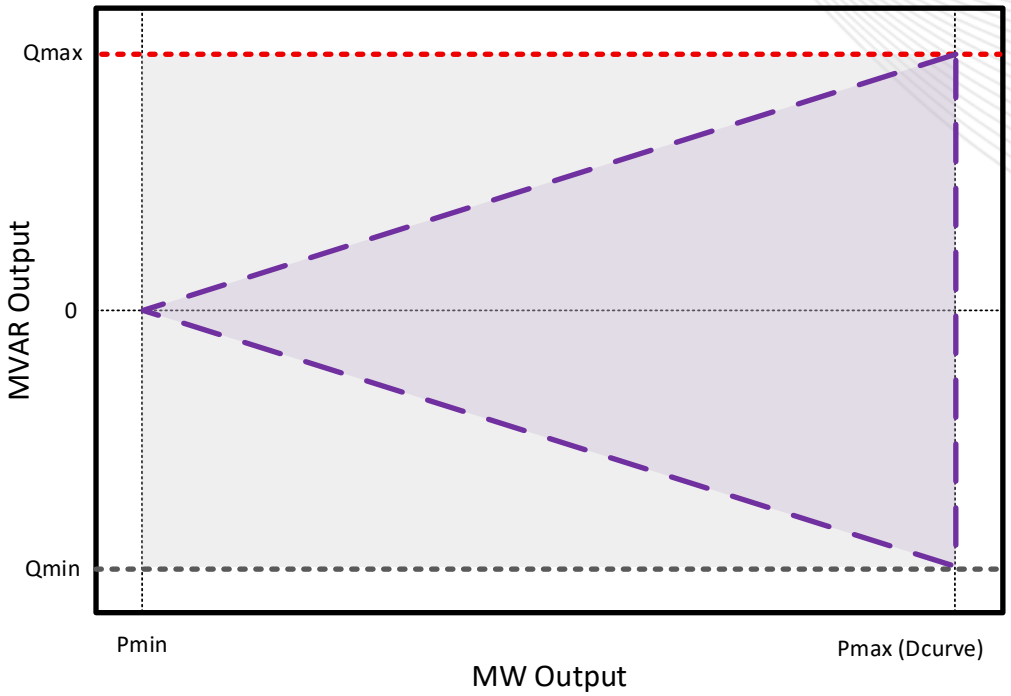
7.1.2 VAR Control Range Boundaries



	Expected MVAR Range
Pmin	Unit Minimum MW Output Capability
Pmax	MFO (Max Facility Output) from Unit ISA or GIA
- - -	Qmax = Pmax * 0.3287
- - -	Qmin = Pmax * (0.3287) * (-1)

- Defines acceptable reactive control range per MW output.

7.1.2 VAR Control Range Boundaries



	Expected MVAR Range
Pmin	Unit Minimum MW Output Capability
Pmax	Max MW Value on Dcurve in PJM eDART
- - -	Qmax = Pmax * 0.3287
- - -	Qmin = Pmax * (0.3287) * (-1)
◁	Incorrect Reactive Range - Don't do this

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

Attachment D: Gen. Reactive Capability Curve Spec.

Two new required “curve data”:

- The “Maximum AVR capable MW Output” provided to the system, as measured at the low-side of the unit step-up transformer, excluding any station service load fed off the unit terminal bus, consistent with the PJM EMS model. This is the maximum MW output at which MVAR capability range converges to zero, and beyond which more MW output may be possible but without any MVAR control range. The "Maximum AVR capable MW Output" is a limit of the AVR subsystem of the genset or inverter and may exceed the MW capability (Maximum Facility Output) of the generator (or solar panels, etc.) itself.

Attachment D: Gen. Reactive Capability Curve Spec.

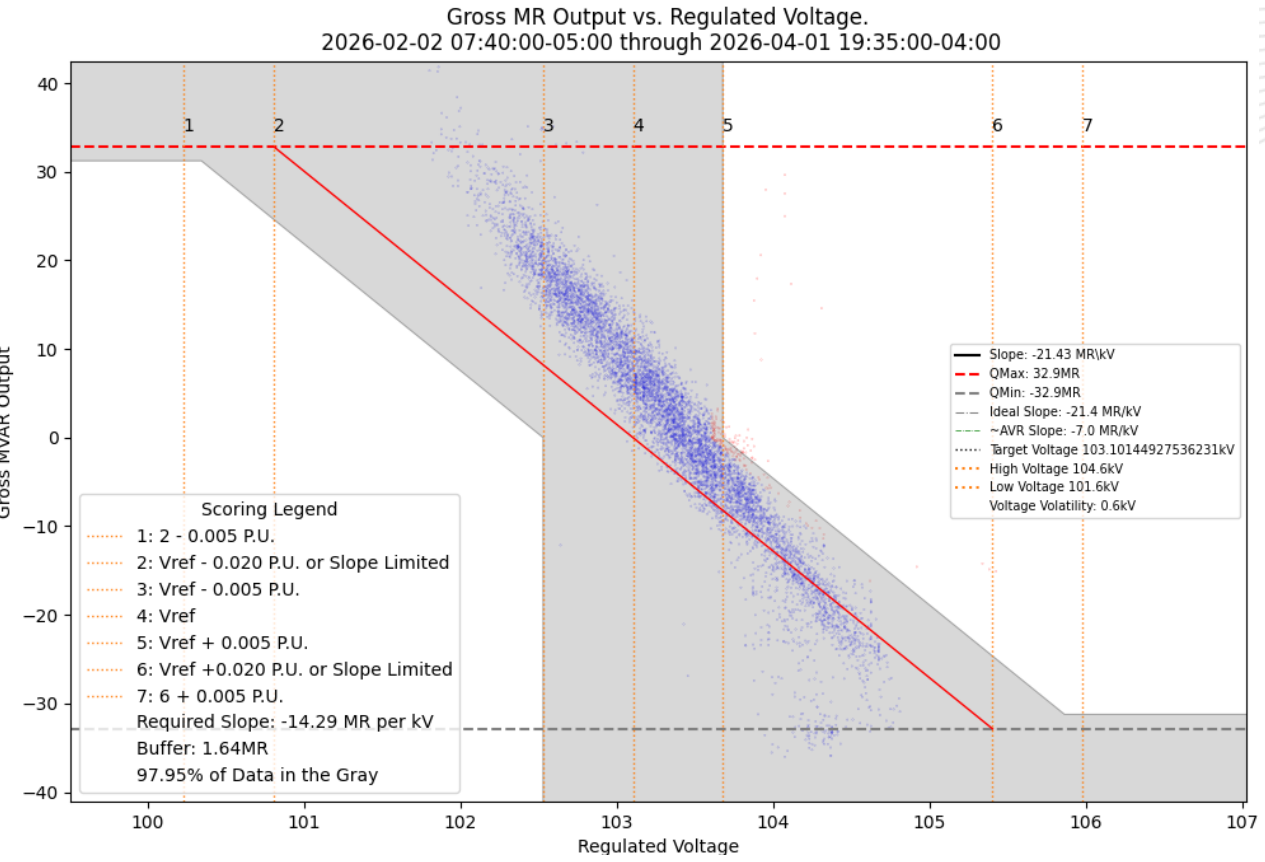
- The "Unit Minimum MW Output with Reactive Control", as measured at the low-side of the unit step-up transformer, excluding any station service load fed off the unit terminal bus consistent with the PJM EMS model. This is the minimum MW the unit can sustain while still providing MVAR support, below which less MW output is possible but without any MVAR control range.

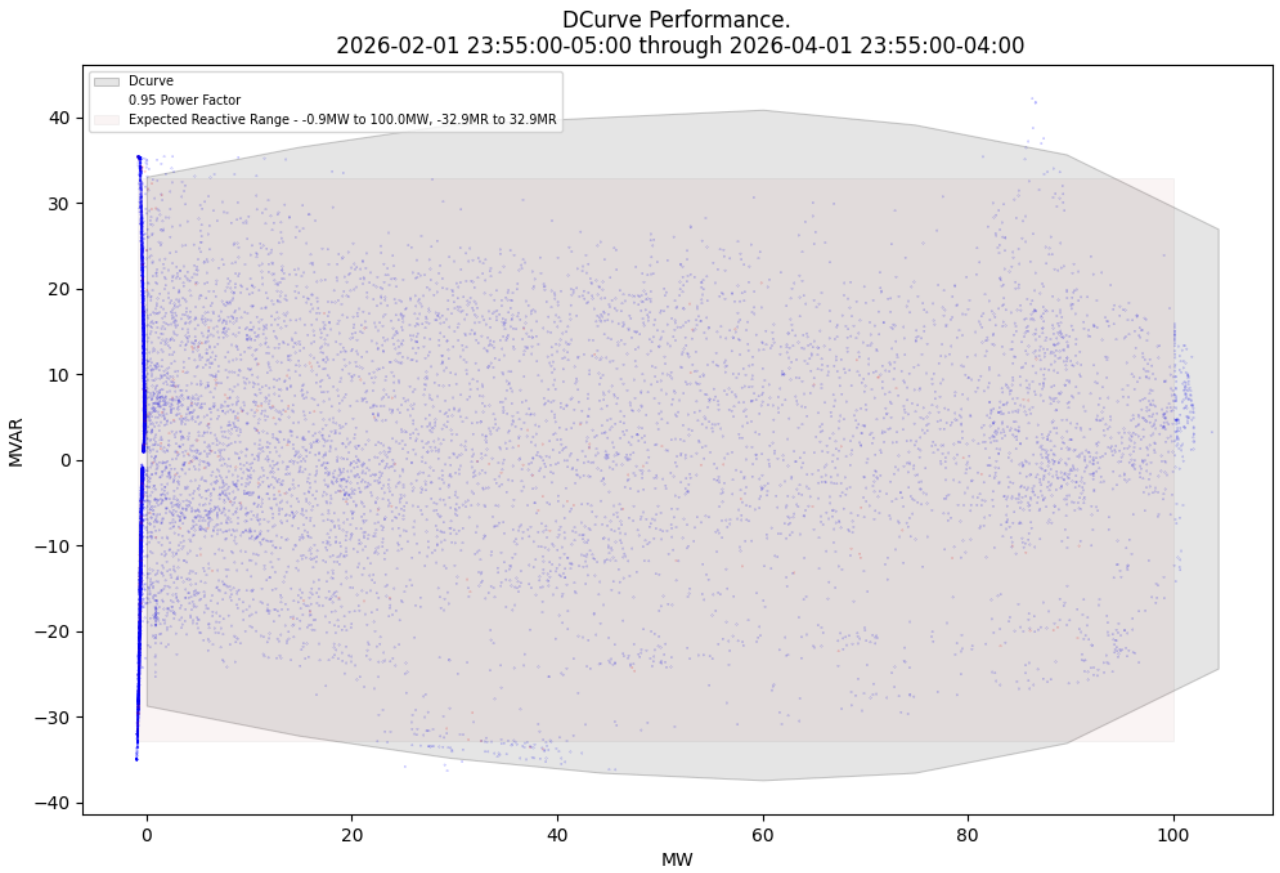
Presentation Order

Progression

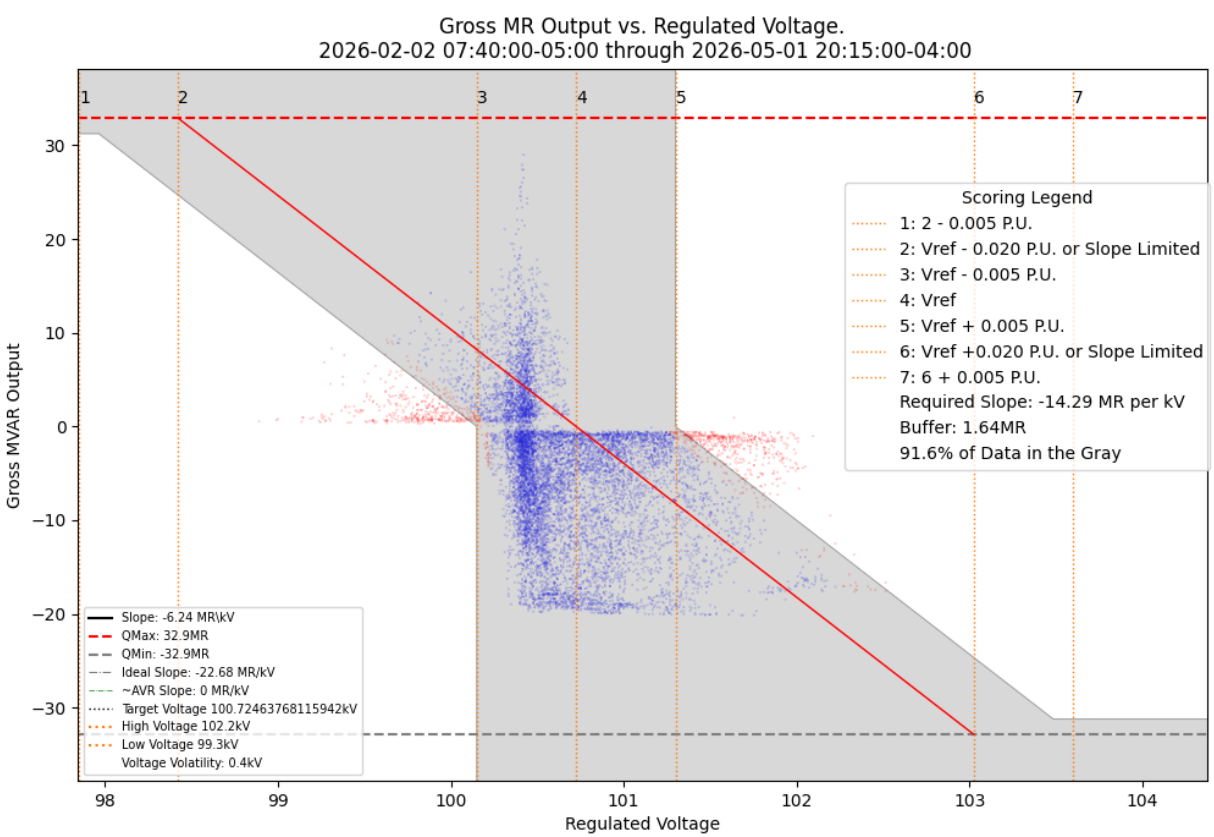
1. Context and Related History
2. Applicable Existing Standards
3. Manual Edits
4. **Enforcement**

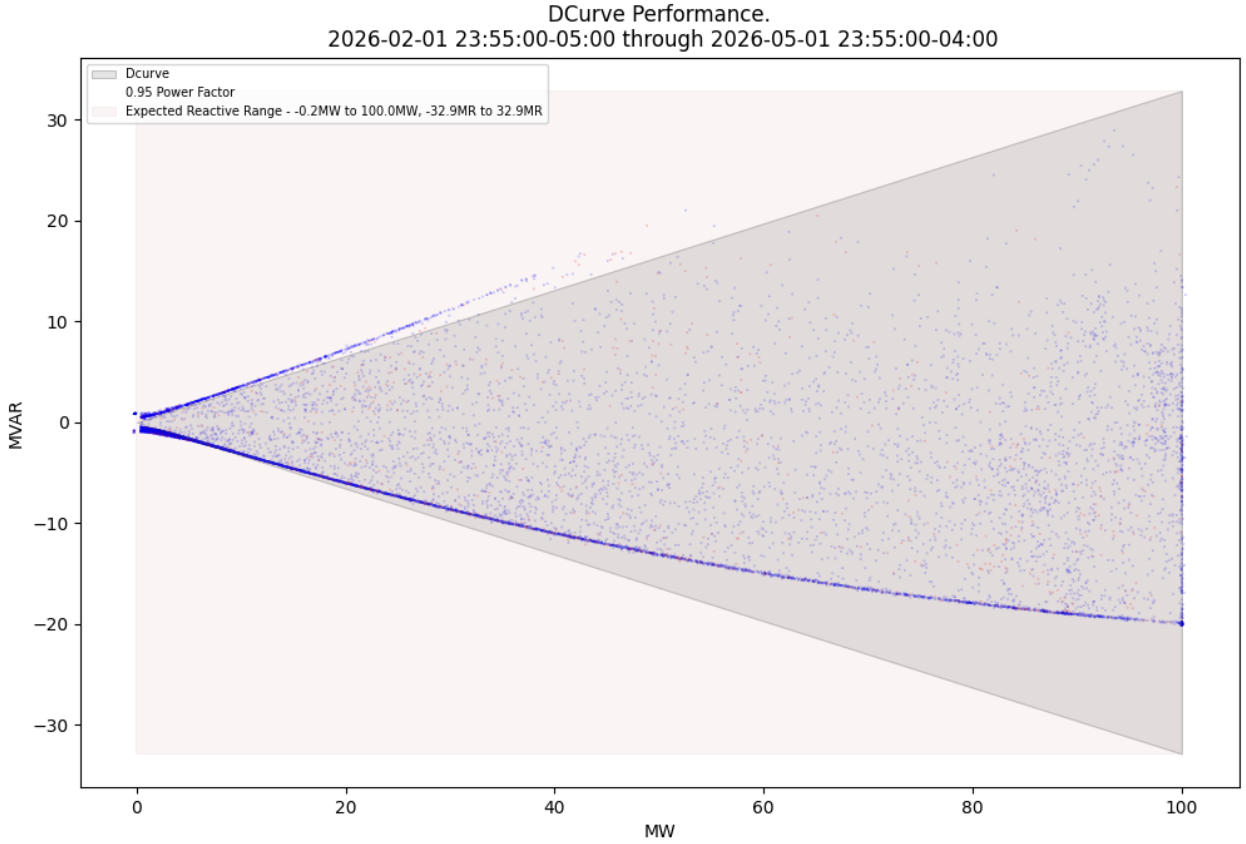
Example 1: Exemplary Performance



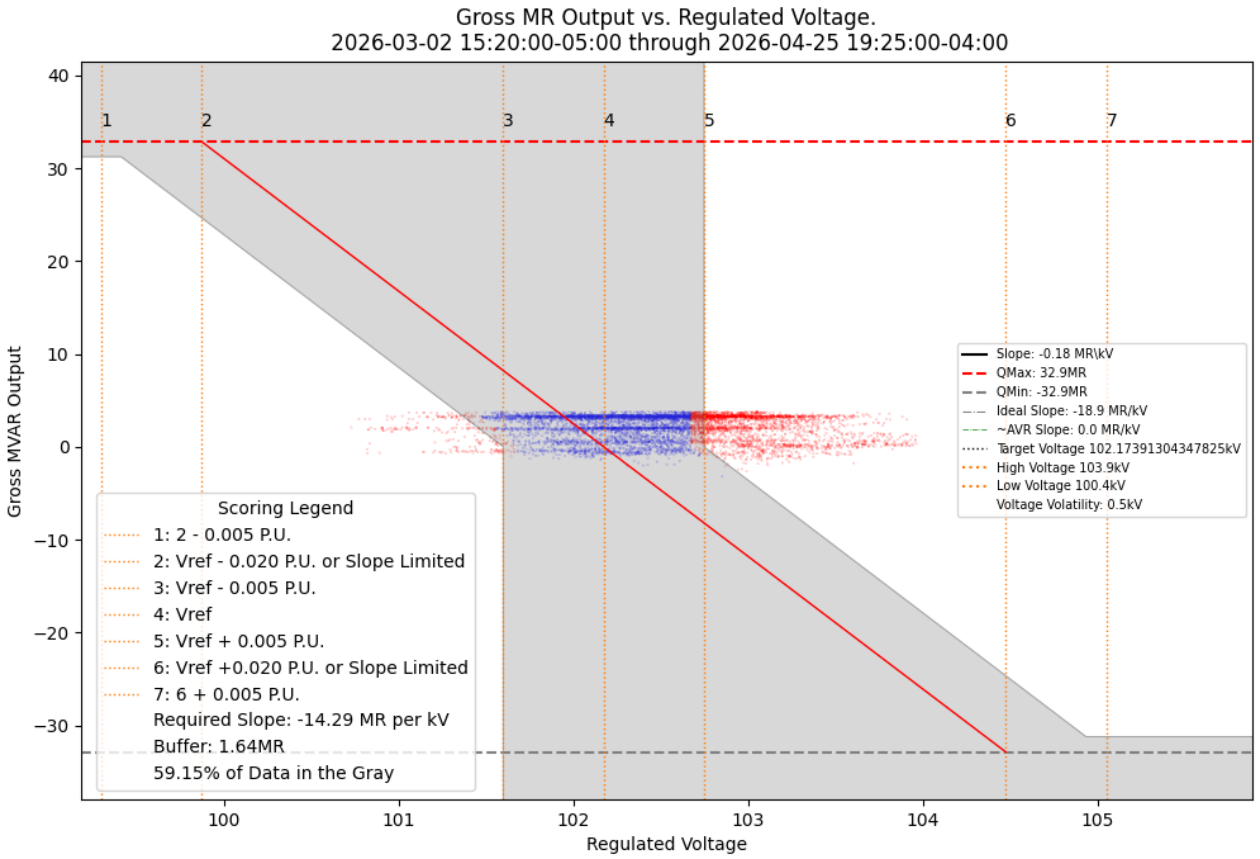


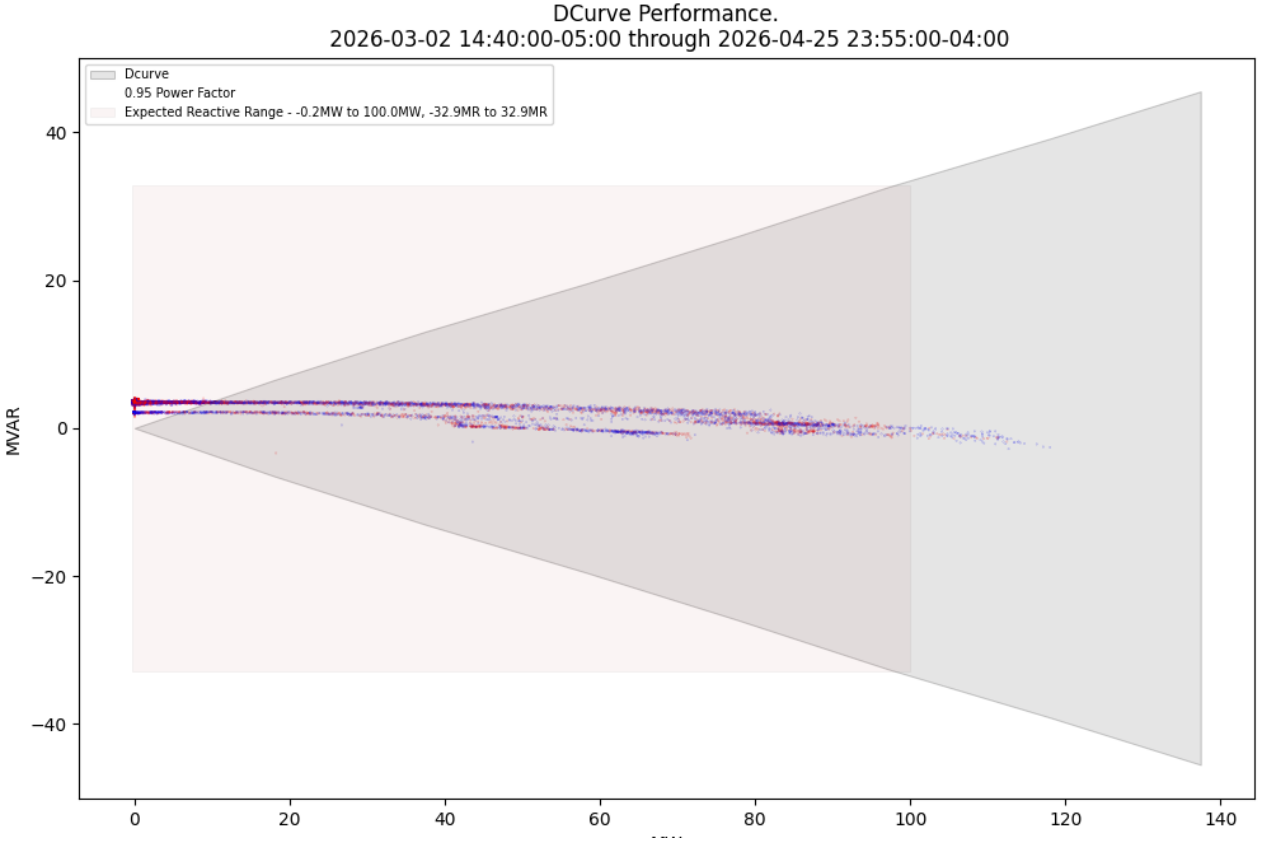
Example 2: Power Factor Clamping



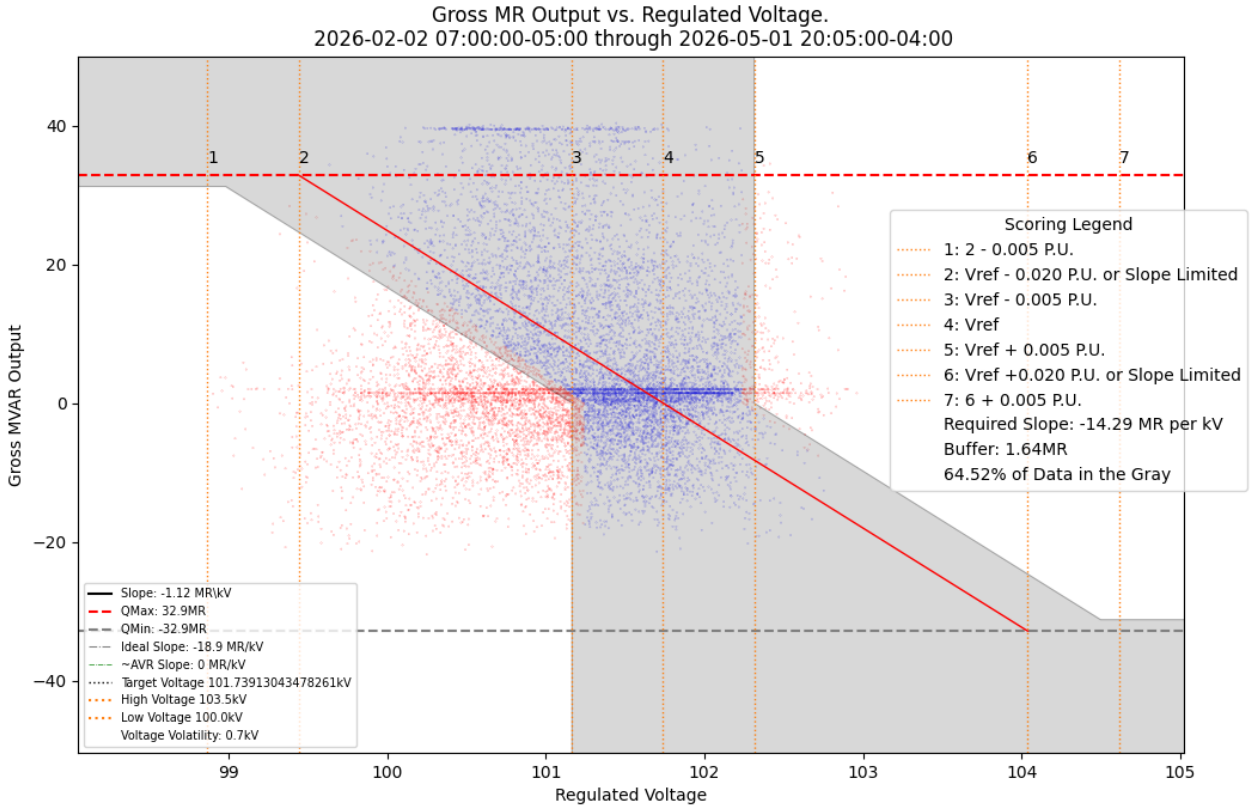


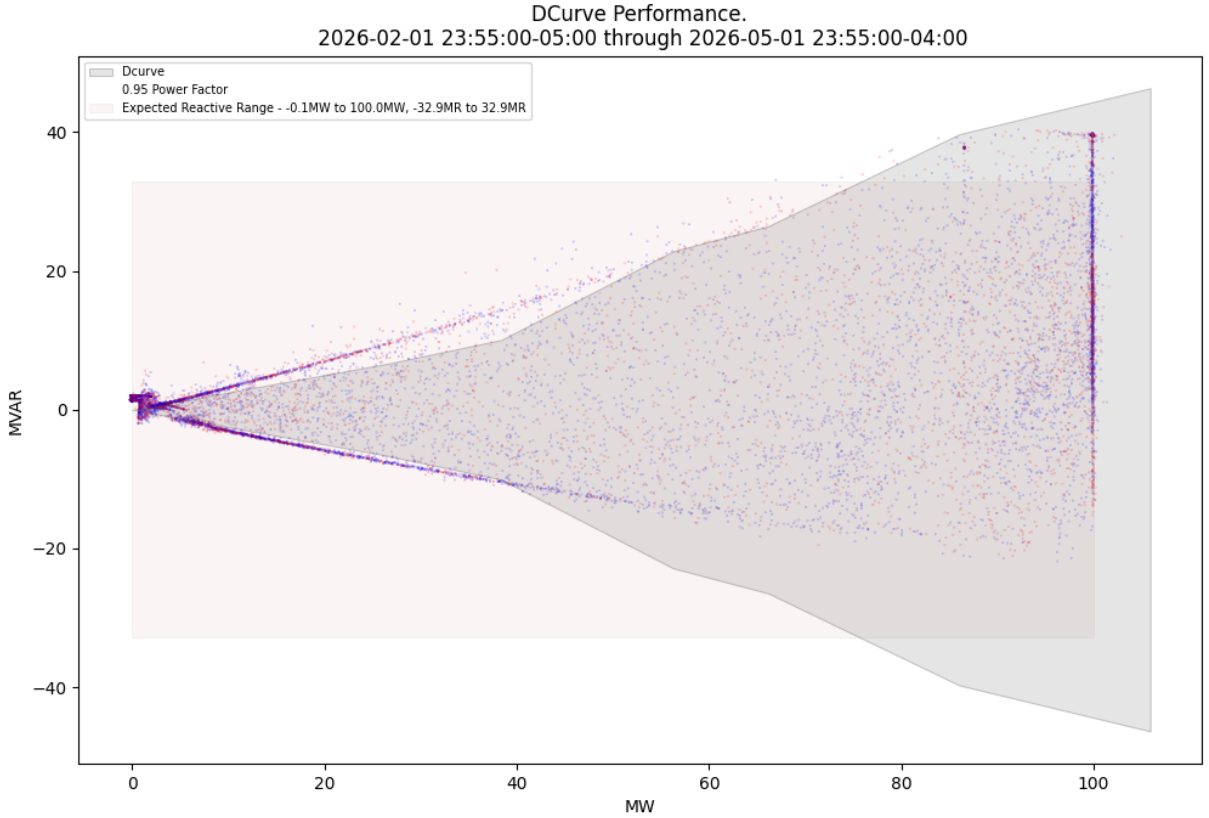
Example 3: Constant MVAR Mode



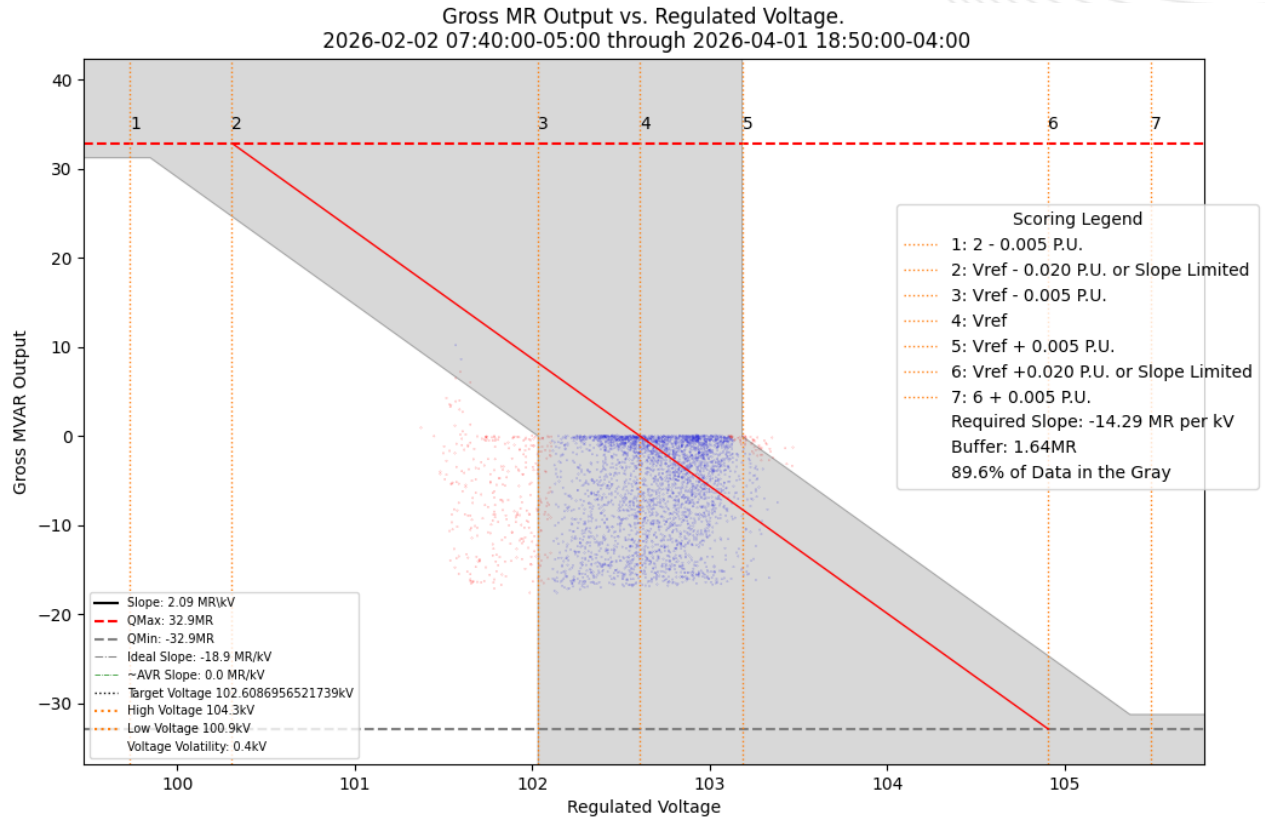


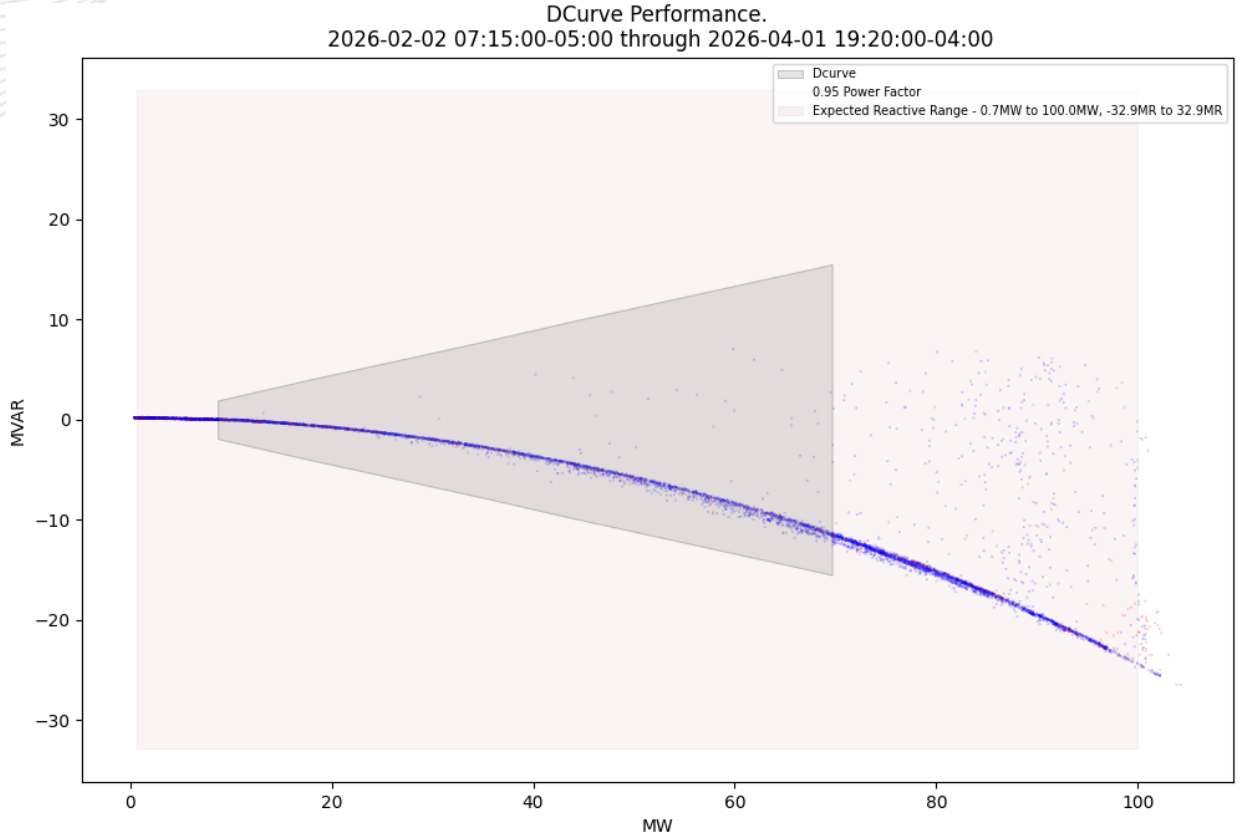
Example 4: Mixed



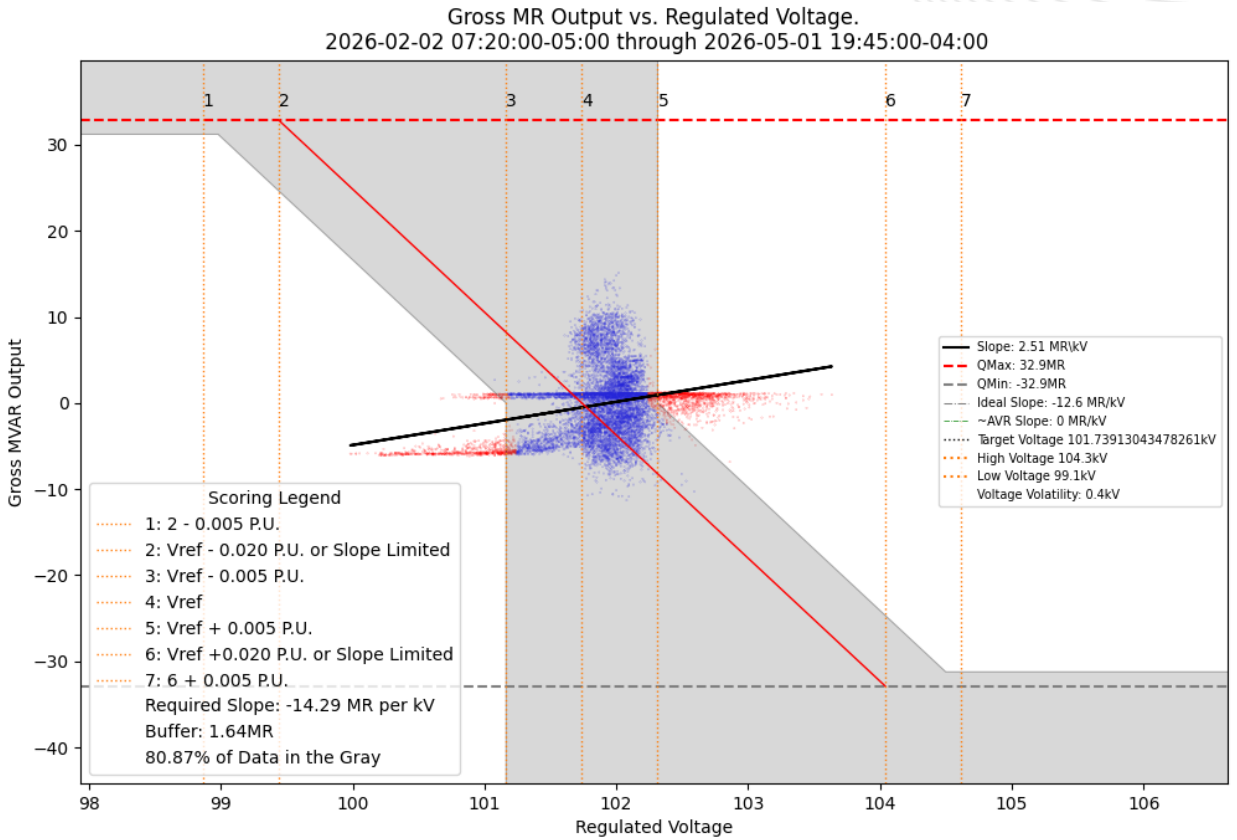


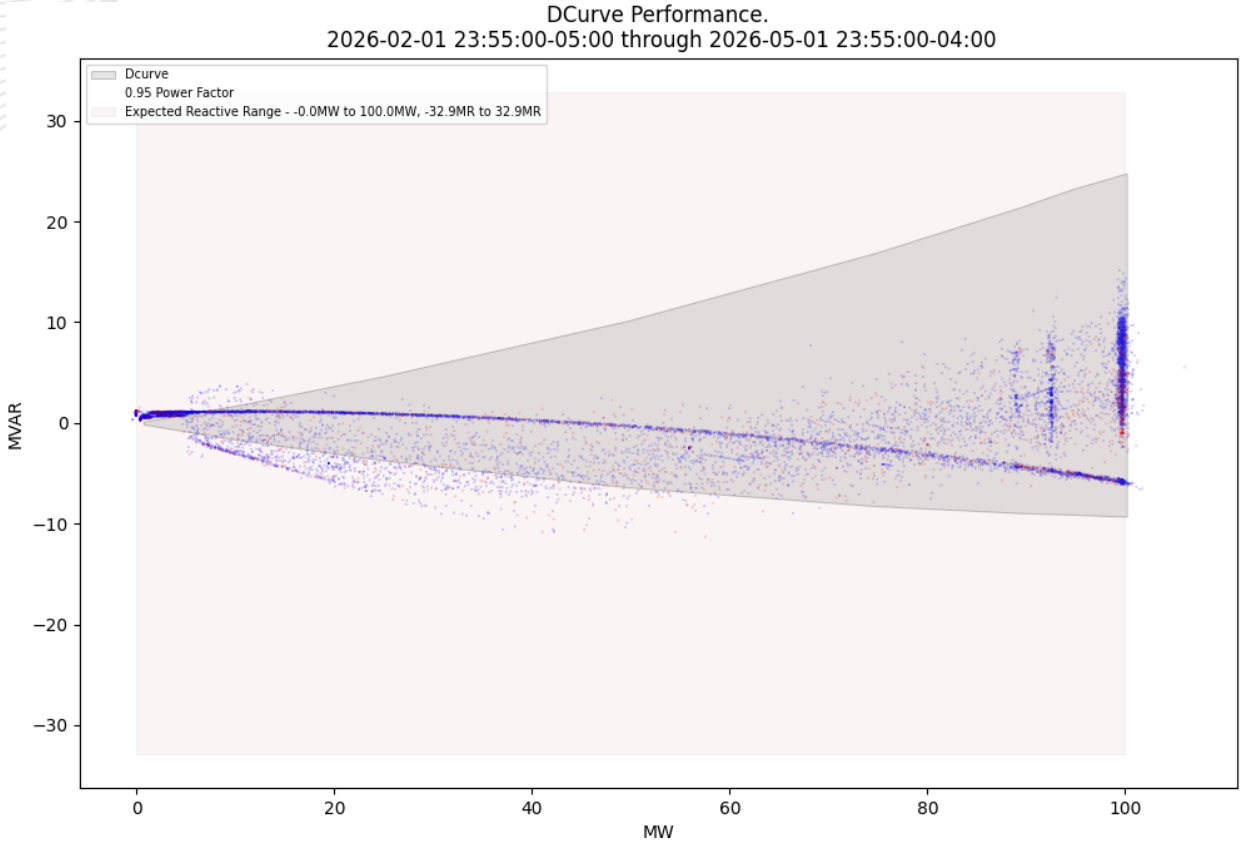
Example 5: Purely Inductive





Example 6: Inverse Slope





7.1.2 Investigative Process

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)

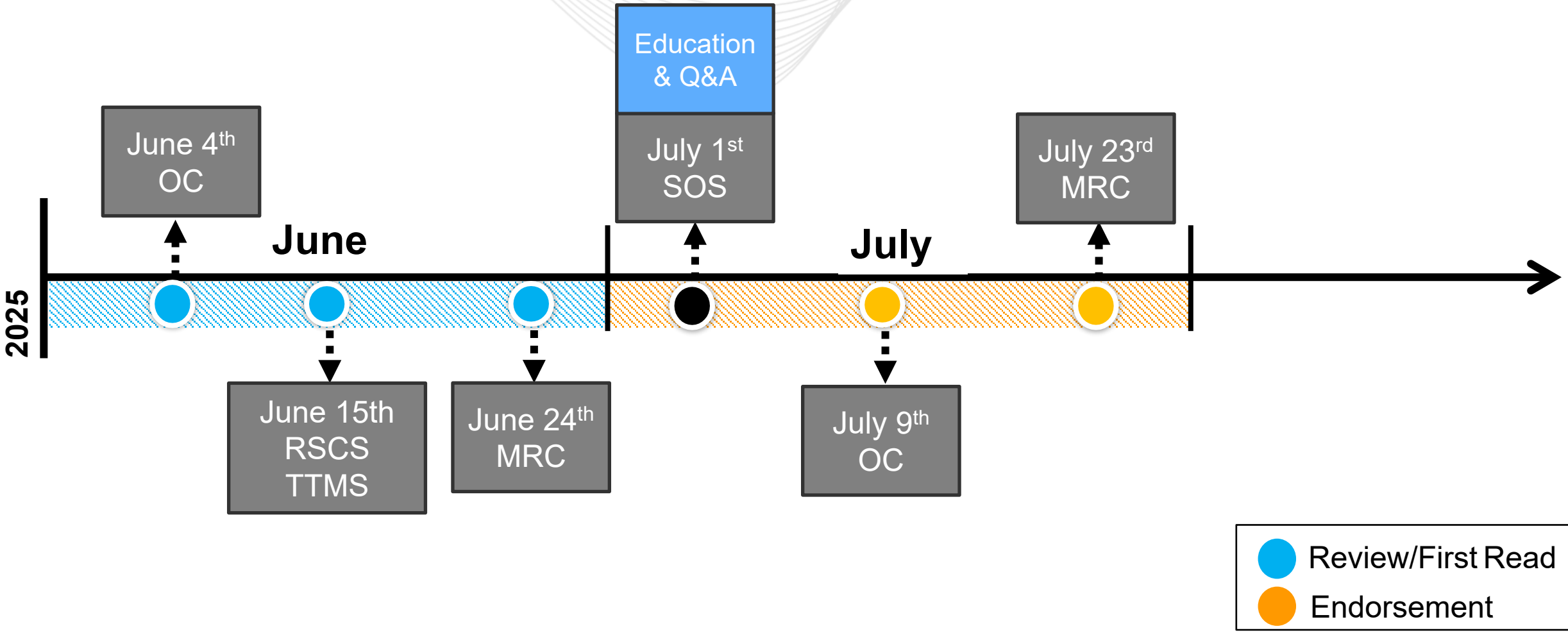
PJM may ultimately direct generators to alter their reactive controls, including AVR settings or inverter settings, and work with the gen owners/operators to confirm successful resolution before closing the analysis. Critical issues that cannot be resolved via the investigative process may be referred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

Key Takeaways

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.

Review/Endorsement Timeline



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Manual 14D: Revision 71

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Appendix

PJM VAR Support Team

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- Matt Wharton
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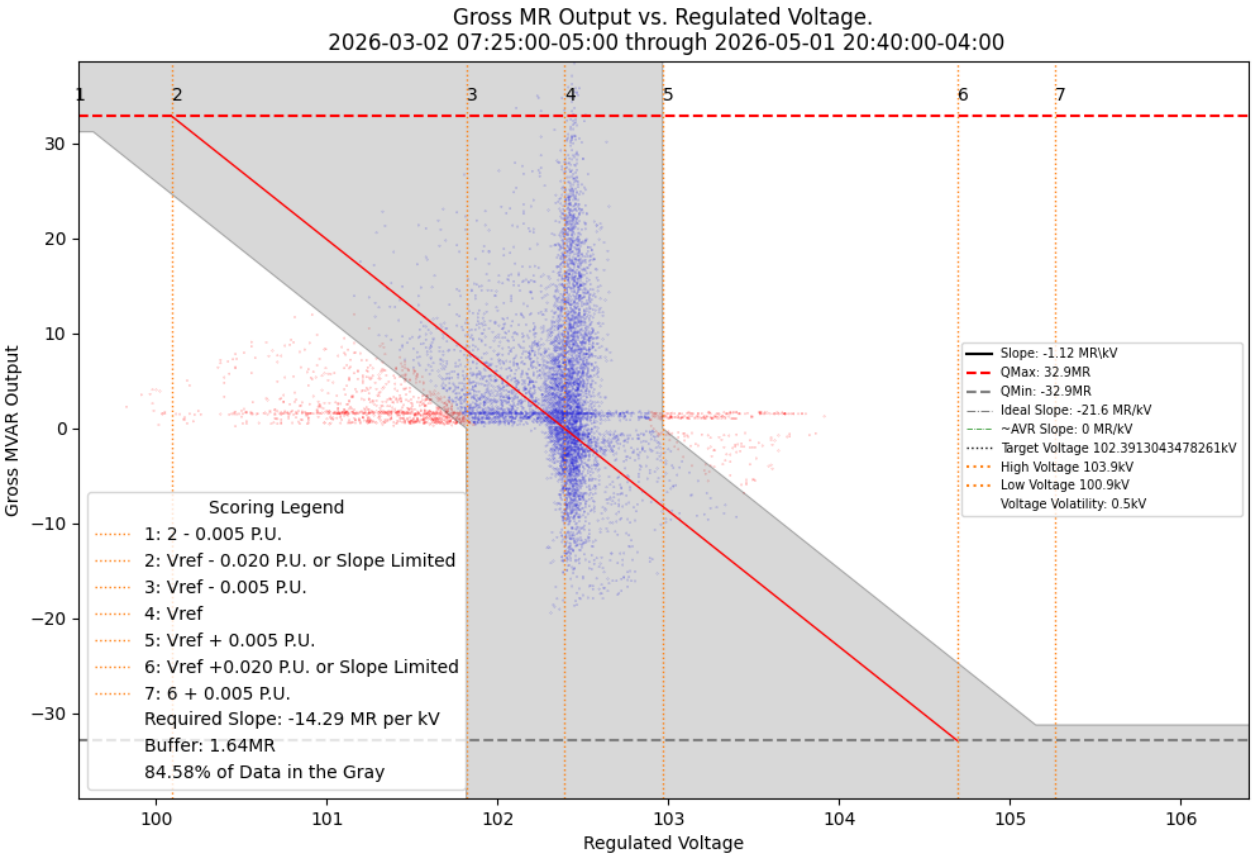
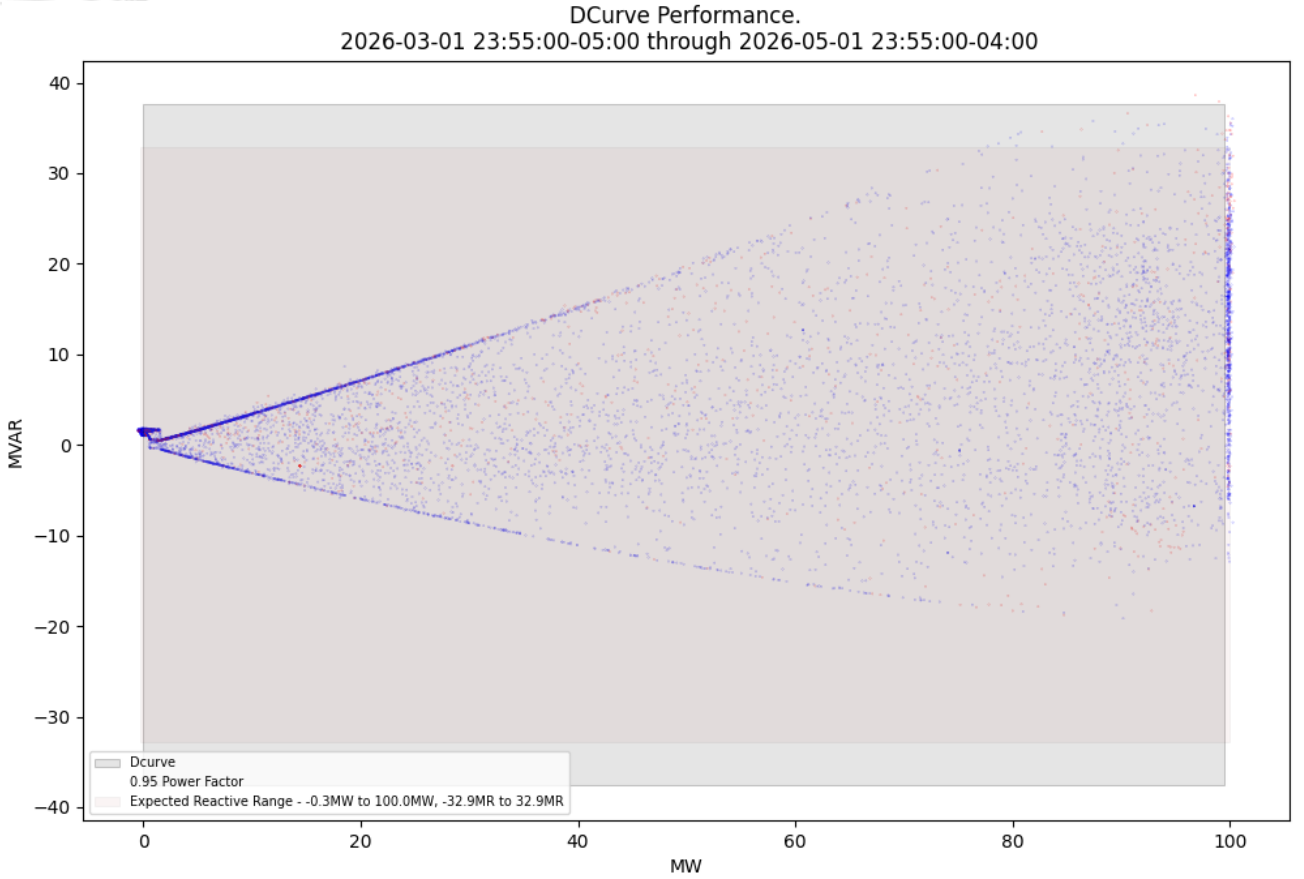
Example: AVR MVAR Mode





Committee for the Analysis of the Electricity Crisis:
MAIN CONCLUSIONS

The Committee's analysis of the incident leads to the conclusion that the power outage had a multifactorial origin, in which three elements converged:

1. The system exhibited insufficient voltage control capacity for two reasons. First, on the 27th, prior to the incident, the System Operator scheduled the operation of 10 synchronous power plants capable of regulating voltage on the 28th, according to its instructions. The final number of synchronous power plants engaged was the lowest since the beginning of the year.

And second, several of the power plants capable of regulating voltage – and specifically compensated for this, having been programmed by technical constraints for this purpose – did not respond adequately to the System Operator's instructions to reduce it; some even produced reactive power, the opposite of what was required, contributing to increasing the problem.

- **Insufficient voltage control capacity**
- One of the report's most decisive findings is the confirmation that the grid lacked sufficient dynamic voltage control capacity on the day of the blackout. This shortfall was not due to a structural lack of resources, but to the low operational availability of synchronous power plants.
- Of the ten units scheduled by the System Operator (Red Eléctrica de España) to provide voltage control—three nuclear and seven combined-cycle plants—one was declared unavailable on 27 April due to a fault and was not replaced, reducing effective capacity at a critical time. These units were activated outside of the day-ahead electricity market, via remunerated technical restrictions, and were tasked with supplying or absorbing reactive power to regulate voltage across different parts of the country. Despite this programming, the report reveals that some units failed to respond correctly to operating commands. In one case, reactive power was injected when absorption was required, increasing voltage instead of stabilizing it.

PJM is responsible for the overall coordination of the Bulk Electric System voltage scheduling. In general, since voltage schedules have a significant effect on local voltages PJM authorizes the Local Transmission Control Center to establish and adjust generator voltage schedules after gaining PJM approval. Whenever the voltage schedule impacts the overall PJM economic/reliable operation, **PJM shall exercise its operational control and direct changes to the generation voltage/reactive schedules, capacitor/reactor schedule/status, and transformer LTC operation for the overall reliable/economic operation of PJM**.

M03 Section 3.11 (excerpts)

	PJM Default Generator Voltage Schedules								
Voltage Level (kV)	765	500	345	230	161	138	115	69	**66**
Schedule (kV)	760.0	525.0	350.0	235.0	164.0	139.5	117.0	70.0	67.0
Bandwidth (+/- kV)	+/-10.0	+/- 8.0	+/- 7.0	+/- 4.0	+/- 4.0	+/- 3.5	+/- 3.0	+/- 2.0	+/- 1.5

PJM Transmission Owners must supply and communicate voltage schedules and a low and high bandwidth or the PJM default voltage schedule as noted in the above table to all Generation Owners and PJM in the zone for applicable generators meeting the following criteria:

- Individual generating units greater than 20 MVA.
- Generators that aggregate to 75 MVA or greater connected to a common bus.
- Black start generators.
- Any other Generation Owner that request a voltage schedule

M14D 7.1.2 Voltage and Reactive Control (excerpts)

The reactive output of the generator must be regulated in the manner specified by PJM and/or the Transmission Owner.

A Transmission Owner wishing to exempt an applicable generator from following a voltage schedule shall submit an exemption request via the eDART Voltage Schedule application, including the engineering basis such as, but not limited to, stability limitations, generator limitations etc. for such exemption. PJM, in coordination with the affected Transmission Owner, must review the request and provide approval (or denial) based on their analysis, before the change can go into effect.

M14D 7.1.2 (cont.) Voltage and Reactive Control (excerpts)

Generation Owners shall comply with the assigned voltage schedule in automatic voltage control mode (AVR in service and controlling voltage). Generation Owners are required to maintain the same voltage schedule if an AVR is out of service unless directed otherwise. PJM allows for 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

4.6.1.1.1 New Facilities:

For all new Generating Facilities to be interconnected pursuant to the Tariff, other than wind-powered and other non-synchronous generation facilities, the Generation Project Developer shall design its Generating Facility to maintain a composite power delivery at continuous rated power output at a power factor of at least 0.95 leading to 0.90 lagging. For all new wind-powered and other non-synchronous generation facilities the Generation Project Developer shall design its Generating Facility with the **ability to maintain a composite power delivery at a power factor of at least 0.95 leading to 0.95 lagging across the full range of continuous rated power output**. For all wind-powered and other non-synchronous generation facilities that submitted a New Services Request on or after November 1, 2016, the power factor requirement shall be measured at the high-side of the facility substation transformers. This power factor range standard shall be dynamic and can be met using, for example, power electronics designed to supply this level of reactive capability (taking into account any limitations due to voltage level, real power output, etc.) or fixed and switched capacitors, or a combination of the two.

4.6.1.2 Obligation to Supply Reactive Power:

Project Developer agrees, as and when so directed by Transmission Provider or when so directed by the Transmission Owner acting on behalf or at the direction of Transmission Provider, to operate the Generating Facility to produce reactive power within the design limitations of the Generating Facility pursuant to voltage schedules, reactive power schedules or power factor schedules established by Transmission Provider or, as appropriate, the Transmission Owner. **Transmission Provider shall maintain oversight over such schedules to ensure that all sources of reactive power in the PJM Region, as applicable, are treated in an equitable and not unduly discriminatory manner.** Project Developer agrees that Transmission Provider and the Transmission Owner, acting on behalf or at the direction of Transmission Provider, may make changes to the schedules that they respectively establish as necessary to maintain the reliability of the Transmission System.

4.6.1.2 Obligation to Supply Reactive Power:

Project Developer agrees, as and when so directed by Transmission Provider or when so directed by the Transmission Owner acting on behalf or at the direction of Transmission Provider, to operate the Generating Facility to produce reactive power within the design limitations of the Generating Facility pursuant to voltage schedules, reactive power schedules or power factor schedules established by Transmission Provider or, as appropriate, the Transmission Owner. **Transmission Provider shall maintain oversight over such schedules to ensure that all sources of reactive power in the PJM Region, as applicable, are treated in an equitable and not unduly discriminatory manner.** Project Developer agrees that Transmission Provider and the Transmission Owner, acting on behalf or at the direction of Transmission Provider, may make changes to the schedules that they respectively establish as necessary to maintain the reliability of the Transmission System.

Tariff, Part IX, Subpart B (GIA)

- 4.6.1.3 Deviations from Schedules:

- In the event that operation of the Generating Facility or Merchant Transmission Facility of a Project Developer causes the Transmission System or the Transmission Owner's facilities to deviate from appropriate voltage schedules and/or reactive power schedules as specified by Transmission Provider or the Transmission Owner's operations control center (acting on behalf or at the direction of Transmission Provider), or that **otherwise is inconsistent with Good Utility Practice and results in an unreasonable deterioration of the quality of electric service to other customers of Transmission Provider or the Transmission Owner**, the Project Developer shall, **upon discovery of the problem or upon notice from Transmission Provider** or the Transmission Owner, acting on behalf or at the direction of Transmission Provider, **take whatever steps are reasonably necessary to alleviate the situation at its expense, in accord with Good Utility Practice and within the reactive capability of the Generating Facility or Merchant Transmission Facility**. In the event that the Project Developer does not alleviate the situation within a reasonable period of time following Transmission Provider's or the Transmission Owner's notice thereof, the Transmission Owner, with Transmission Provider's approval, upon notice to the Project Developer and at the Project Developer's expense, may take appropriate action, including installation on the Transmission System of power factor correction or other equipment, as is reasonably required, consistent with Good Utility Practice, to remedy the situation cited in Transmission Provider's or the Transmission Owner's notice to the Project Developer under this section.

B. Requirements and Measures

R1. The Generator Operator shall operate each generator connected to the interconnected transmission system in the automatic voltage control mode (with its automatic voltage regulator (AVR) in service and controlling voltage) or in a different control mode as instructed by the Transmission Operator.

R2. Unless exempted by the Transmission Operator, each **Generator Operator shall maintain the generator voltage or Reactive Power schedule** (within each generating Facility's capabilities) provided by the Transmission Operator, or otherwise shall meet the conditions of notification for deviations from the voltage or Reactive Power schedule provided by the Transmission
Operator.

NERC VAR-002-4.1

VAR-002-4.1 — Generator Operation for Maintaining Network Voltage Schedules

R #	Time Horizon	VRF	Violation Severity Levels			
			Lower VSL	Moderate VSL	High VSL	Severe VSL
R2	**Real-time Operations**	**Medium**	N/A	N/A	The Generator Operator did not have a conversion methodology when it monitors voltage at a location different from the schedule provided by the Transmission Operator.	The Generator Operator did not maintain the voltage or Reactive Power schedule as instructed by the Transmission Operator and did not make the necessary notifications required by the Transmission Operator. OR The Generator Operator did not have an operating AVR, and the responsible entity did not use an alternative method for controlling voltage. OR The Generator Operator did not modify voltage when directed, and the responsible entity did not provide any explanation.

NERC VAR-002-2b (superceded by 4.1)

Appendix 1, Interpretation of Requirements R1 and R2, Request:
Requirement R1 of Standard VAR-002-1 states that Generation Operators shall operate each generator connected to the interconnected transmission system in the automatic voltage control mode (automatic voltage regulator in service and controlling voltage) unless the Generator Operator has notified the Transmission Operator. Requirement R2 goes on to state that each Generation Operator shall maintain the generator voltage or Reactive Power output as directed by the Transmission Operator. The two underlined phrases are the reasons for this interpretation request.
Most generation excitation controls include a device known as the Automatic Voltage Regulator, or AVR. This is the device which is referred to by the R1 requirement above. Most AVR's have the option of being set in various operating modes, such as constant voltage, constant power factor, and constant Mvar. In the course of helping members of the WECC insure that they are in full compliance with NERC Reliability Standards, **I have discovered both Transmission Operators and Generation Operators who have interpreted this standard to mean that AVR operation in the constant power factor or constant Mvar modes complies with the R1 and R2 requirements** cited above. Their rational is as follows:

- The AVR is clearly in service because it is operating in one of its operating modes
- The AVR is clearly controlling voltage because to maintain constant PF or constant MVAR, it controls the generator terminal voltage
- R2 clearly gives the Transmission Operator the option of directing the Generation Operator to maintain a constant reactive power output rather than a constant voltage.

Other parties have interpreted this standard to require operation in the constant voltage mode only. Their rational stems from the belief that the purpose of the VAR-002-1 standard is to insure the automatic delivery of additional reactive to the system whenever a voltage decline begins to occur. The material impact of misinterpretation of these standards is twofold.

- First, misinterpretation may result in reduced reactive response during system disturbances, which in turn may contribute to voltage collapse.
- Second, misinterpretation may result in substantial financial penalties imposed on generation operators and transmission operators who believe that they are in full compliance with the standard.

In accordance with the NERC Reliability Standards Development Procedure, I am requesting that a formal interpretation of the VAR-002-1 standard be provided. Two specific questions need to be
answered.

- First, does AVR operation in the constant PF or constant Mvar modes comply with R1?
- Second, does R2 give the Transmission Operator the option of directing the Generation Owner to operate the AVR in the constant Pf or constant Mvar modes rather than the constant voltage mode?

NERC VAR-002-2b (superceded by 4.1)

Interpretation:

1. First, 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. This answer is predicated on the assumption that the generator has the physical equipment that will allow such operation and that the Transmission Operator has not directed the generator to run in a mode other than constant voltage.

2. Second, does R2 give the Transmission Operator the option of directing the Generation Owner (sic) to operate the AVR in the constant Pf or constant MVAR modes rather than the constant voltage mode?

Interpretation: Yes, 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.

NERC Links

NERC VAR-002-4.1

https://www.nerc.com/globalassets/standards/projects/2016-epr-02/var_002_4_1_errata_clean_07072017.pdf

NERC VAR-002-2b (superceded by 4.1)

https://www.nerc.com/globalassets/standards/projects/2014-01/var-002-2b-redlined-to-ferc-approved.pdf

ERO Enterprise CMEP Practice Guide

https://www.nerc.com/globalassets/programs/registration/registration-documentation/cmep-practice-guide---application-of-the-registration-criteria-for-category-2-generator-owner-and-generator-operator-inverter-based-resources-2.pdf

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