Studying the New Power System Paradigm

ESIG
ENERGY SYSTEMS INTEGRATION GROUP

The Current Paradigm Isn’t Working

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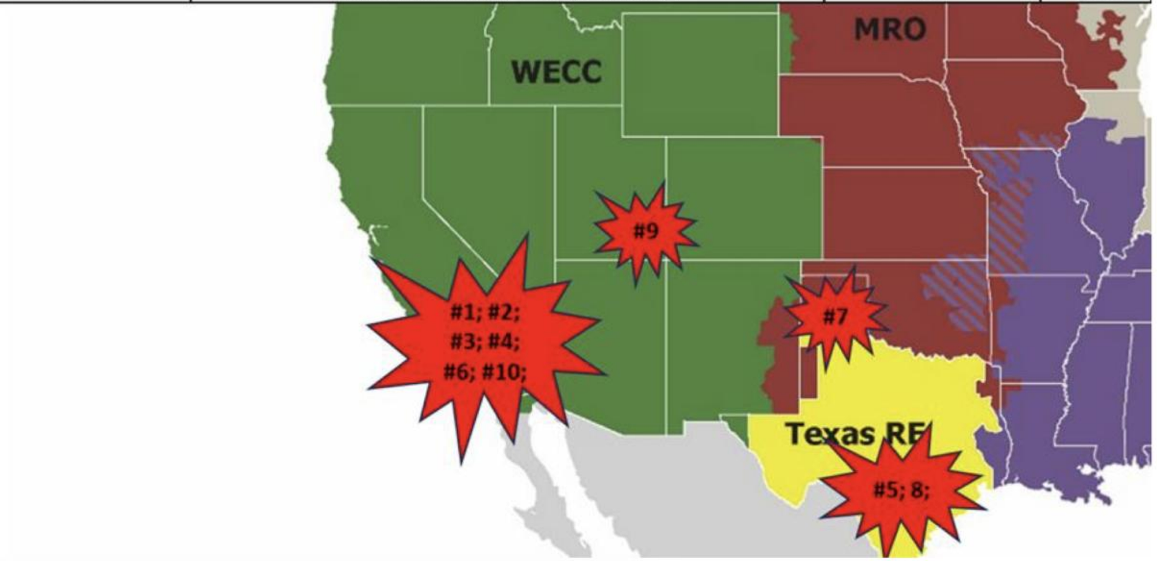
Reliability improvements begin with understanding the results of the current paradigm:

- **10 major disturbances published by NERC since 2016**
  - Totaling ~15,000 MW
  - These are not ALL events, just those classified in NERC procedure for mandatory release
- None of the affected facilities in any of these published reports had models which accurately reflected actual performance
- Motivations for IBR interconnection are not aligned with grid reliability
- Current regulatory structure promotes disparate, misaligned, and sometimes confusing requirements
- Stakeholder-driven processes fail to produce sufficient technical minimum requirements

Reference Number	Disturbance	IBR Reduced (MW)	Year
#1	Blue Cut Fire	1,753	2016
#2	Canyon 2 Fire	1,619	2017
#3	Angeles Forest & Palmdale Roost	1,588	2018
#4	San Fernando	1,205	2020
#5	2021 Odessa	1,112	2021
#6	Victorville & Tumbleweed & Windhub & Lytle Creek Fire	2,464	2021
#7	Panhandle Wind	1,222	2022
#8	2022 Odessa	1,711	2022
#9	Southwest Utah	921	2022
#10	California Battery Energy Storage	906	2023



[Adapted from NERC Ridethrough Technical Conference, Sep. 4 2024]

The Current Paradigm Isn't Working

"This report shows that the voluntary recommendations set forth in NERC Guidelines and other publications are not being implemented."

-Inverter-Based Resource Performance Issues Report, NERC, November 2023

- **Planning a reliable power system depends on accurate modeling of the system and resources connected to it. This includes accurate modeling of IBR performance, as well as protections or**

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices

Cause of Reduction	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Inverter Instantaneous AC Overcurrent	No	Yes
Passive Anti-Islanding (Phase Jump)	Yes[a]	Yes
Inverter Instantaneous AC Overvoltage	No	Yes
Inverter DC Bus Voltage Unbalance	No	Yes
Feeder Underfrequency	No[b]	No[c]
Incorrect Ride-Through Configuration	Yes	Yes

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices

Cause of Reduction	Can Be Accurately Modeled in Positive Sequence Simulations?	Can Be Accurately Modeled in EMT Simulations?
Plant Controller Interactions	Yes[d]	Yes[e]
Momentary Cessation	Yes	Yes
Inverter Overfrequency	No[b]	Yes
PLL Loss of Synchronism	No	Yes
Feeder AC Overvoltage	Yes[f]	Yes
Inverter Underfrequency	No[b]	Yes

Adapted from: NERC 2022 Odessa Disturbance Report

What’s so Different - Technology

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Differences between Inverter-Based Resources and Synchronous Generation	
Inverter-Based Resources	**Synchronous Generation**
• Driven by power electronics and software	• Driven by physical machine properties
• No (or little) inertia	• Large rotating inertia
• Very low fault current	• High fault current
• Sensitive power electronic switches	• Rugged equipment tolerant to extremes
• Very fast and flexible ramping	• Slower ramping
• Very fast frequency control	• Inherent inertial response
• Minimal plant auxiliary equipment prone to tripping	• Sensitive auxiliary plant equipment
• Dispatchable based on available power	• Fully dispatchable
• Can provide essential reliability services	• Can provide essential reliability services

Adapted from: NERC’s An Introduction to Inverter-Based Resources on the Bulk Power System

What's so Different - Technology

- **Software-based IBR add significantly more complexity and uncertainty in both performance and modeling**
  - Need to view IBR performance and modeling with a software-development lens
  - IBR have significant performance flexibility dictated by software parameters
  - Renewable technology is relatively immature and has not been standardized
    - Efforts are being made to standardize IBR performance but intellectual property and patents are large roadblocks
  - Continuity of data and change management is critical throughout the lifecycle of the IBR plant

Differences between Inverter-Based Resources and Synchronous Generation

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What's so Different - Technology

- **Little or no "inertia" and low fault current contribute to the "weakening" of the power system**
  - Advanced grid services can help IBR operate at these weaker, or islanded operating points
- **Much of the current power system has been designed, planned, and operated with the assumption of significant inertia and fault current**
- **Changes in inertia and fault current have ripple effects for:**
  - Protection design and operation
  - Automatic voltage and frequency control
  - Emergency power system operations (i.e UFLS)
  - Standardization of performance and requirements

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What's so Different – Process and Stakeholders

Synchronous Paradigm	IBR Paradigm
Often developed by engineering firms with engineering staff	Often developed by non-engineering firms without engineering staff
Reliability standards are the minimum	Reliability standards are the maximum
Detailed plant information easier to obtain	Detailed plant information more difficult
Detailed information available sooner in the process	Detailed information may not even be available during the interconnection process
Differences between studied and real performance typically smaller	Higher likelihood of large discrepancies in studied and actual performance
As-built information for modeling is easier to obtain	Sometimes difficult to obtain as-built information
Significantly more "operational awareness"	Less "operational awareness"

Why is Modeling IBR So Hard (in general)

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Synchronous Machine	Modeling Consideration	Inverter-Based Resource
• More mature • Parameters and controls are standardized • Relatively simple plant construction (generator and main power transformer)	**Technology Maturity and Construction**	• Significantly less mature • Parameters and controls cannot be standardized (*performance can*) • Relatively more complex plant construction (collector cables, collector transformers, multiple manufacturer plants and hybrid resources
• Largely dictated by the physical behavior of a large spinning mass • Relatively small variations in performance from control parameters	**Technology Performance**	• Rarely dictated by the physical behavior of a spinning mass (i.e., Type 1-3 wind) • Relatively extremely high variation in performance from control parameters
• Majority of parameters are standardized and map 1-1 with the equipment • Relatively few model parameters • 1-1 mapping with measurable quantities reduces the number of tunable parameters and makes site-specific modeling easier	**Model Parameters**	• Few models have 1-1 mapping with the equipment • Thousands of parameters • Lack of mapping reduces quality of study inputs and reduces the ability to implement "tuned" site-specific controls

Why is Modeling IBR So Hard (in North America)

Interconnection and planning requirements in North America do not allow or disincentivize the use of the representative models

- **Vendor equipment-specific models are not allowed to be submitted or are disincentivized with extra scrutiny and costs in most interconnections**
  - This is out of alignment with the NERC Dynamic Modeling Recommendations and FERC Order 2023
- **Manufacturers of IBR equipment do not recommend the use of generic or standard model library models to do site-specific or reliability studies**
  - Standard library and generic models are fine for long term, research, or representing machines far from
- **Developers are not often willing to do perceived “extra” work that could jeopardize interconnection date**

	Generic	Standard Library	Equipment Specific Models
Publicly Available	✓		
Short Time to Market (incl. validated models)			✓
Easy Maintenance			✓
Accuracy			✓
Minimal Tool Implications			✓
Usability	✓	✓	✓
Readiness for hybrid PPs, new technology, etc.			✓
“As-built” configuration for entire modeling portfolio			✓

Source: Vestas

The Modeling Paradigm has Changed (Rapidly)

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- **Modeling IBR is extremely different than modeling synchronous machines**
  - Modeling synchronous machines is “easy”
    - Grounded in physics of spinning masses
    - Relatively simple and highly standardized controls
    - Extremely mature technology
  - Modeling IBR brings significant challenges
    - Performance is almost entirely software-based
    - Complex, not standardized, and often patented control schemes make generic modeling vastly insufficient

The Modeling Paradigm has Changed (Rapidly)

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- **Manufacturer-specific User-defined models deserve their reputation**
  - In the mid 2010's UDM were plagued with:
    - Poor documentation
    - Poor performance (in simulation software i.e. memory leaks)
    - Inaccuracy (in representing their products)
  - This was almost every TSO's first experience with UDM
    - These same people are likely in leadership roles now
- **Industry developed standard library models (i.e. WECC Generic) were a reaction**
  - Industry needed some way to represent IBR and OEM models were insufficient
  - Generic models were developed with OEM input but this input was misconstrued
  - Generic models are being misused as part of common and tariff-directed practice
- **The manufacturer-specific standard library experiment has failed**

The Modeling Paradigm has Changed (Rapidly)

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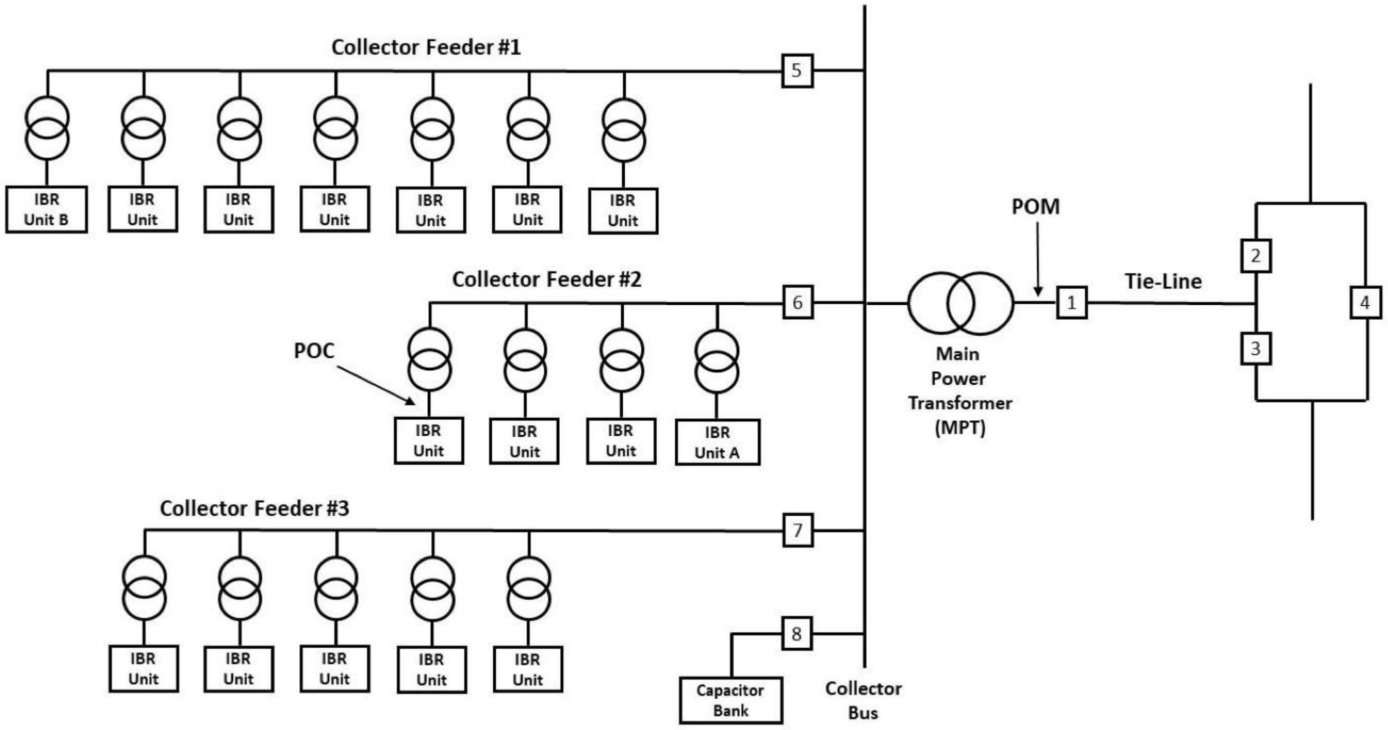
- **Major improvements in the model space driven by international grid codes**
  - The rest of the world has recognized this problem and have come up with different solutions
    - Open-sourced model code
    - High-quality generic models with “hooks”
    - Standardized interfaces (wrappers) for real-code models
    - Model accuracy and validation requirements with high bar for accuracy and model quality
- **Most all of the roadblocks for proper modeling in North America have technical solutions in practice internationally**
- **In order to unlock full capabilities for IBR and ensure reliability, accurate modeling is paramount**

Small Detour Into Steady State Modeling: Aggregation

- **Aggregation is incredibly important…. and incredibly contentious!**
  - Disaggregated models aren't used in large planning cases
    - Can be essential for reliability (and economically prudent) for design evaluation studies
  - Some IBR technology types and layouts benefit much more than others

Source: NERC



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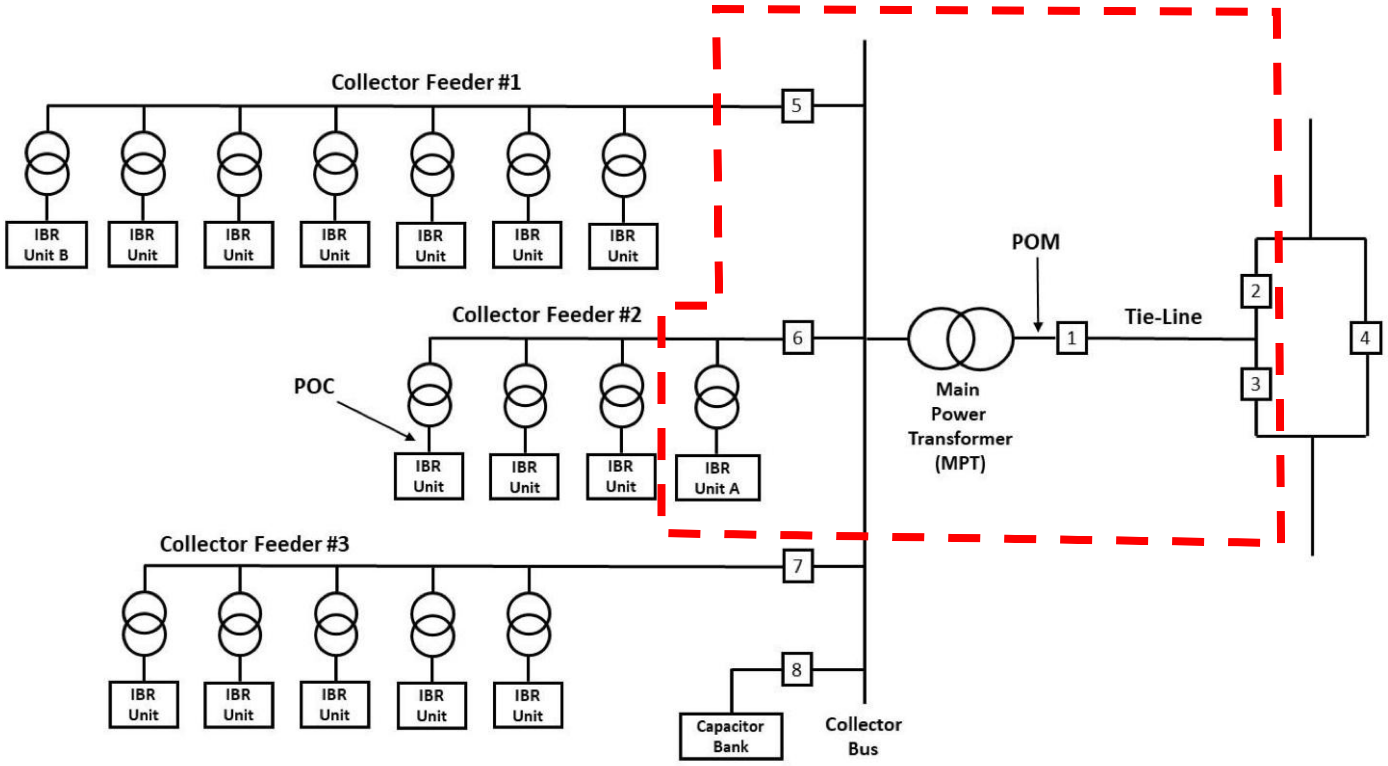
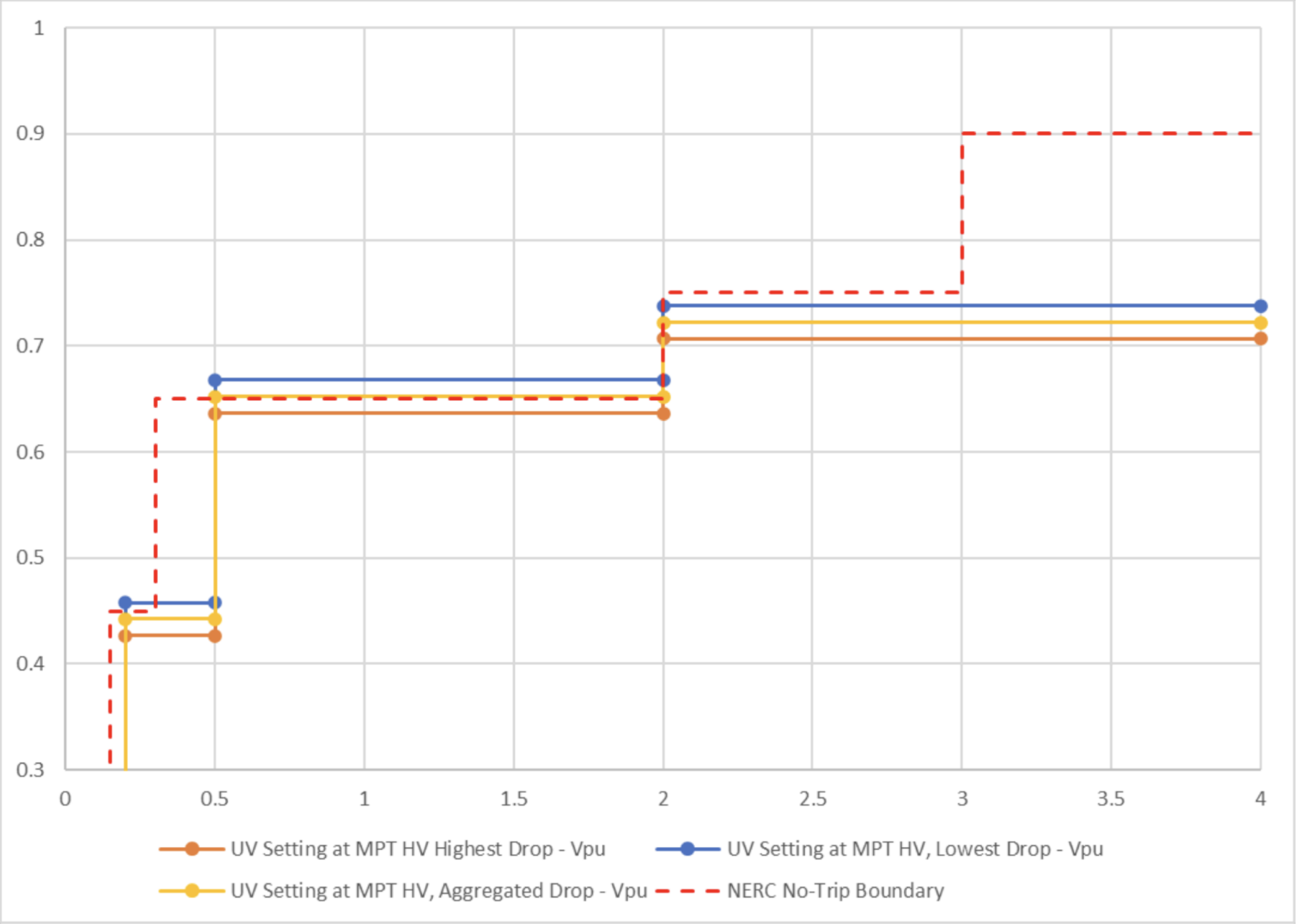


Considerations For Aggregation

- **Not every IBR facility or technology type gain substantial benefits from disaggregated studies**
  - IBR technologies with small (short) collector systems see limited benefits
- **Making both an aggregated and disaggregated steady state model is easier than it sounds**
  - Many common practices involve building some sort of disaggregated representation as part of the aggregate model build
- **Simulation domain and study purpose matters**
  - Massive considerations for compute time when considering EMT
  - Not all assessments benefit from being performed in the disaggregate
- **Potential benefits of disaggregated study work (keeping in mind the above)**
  - Demonstrate partial tripping and actual ridethrough capability (major observation from NERC event reports)
  - Site reactive power compensation sizing and capability
  - Working with voltage-dependent IBR technologies

Aggregation Examples

(...) it can be observed that the difference in voltage drop between the two extreme IBR units can be significant. - NERC



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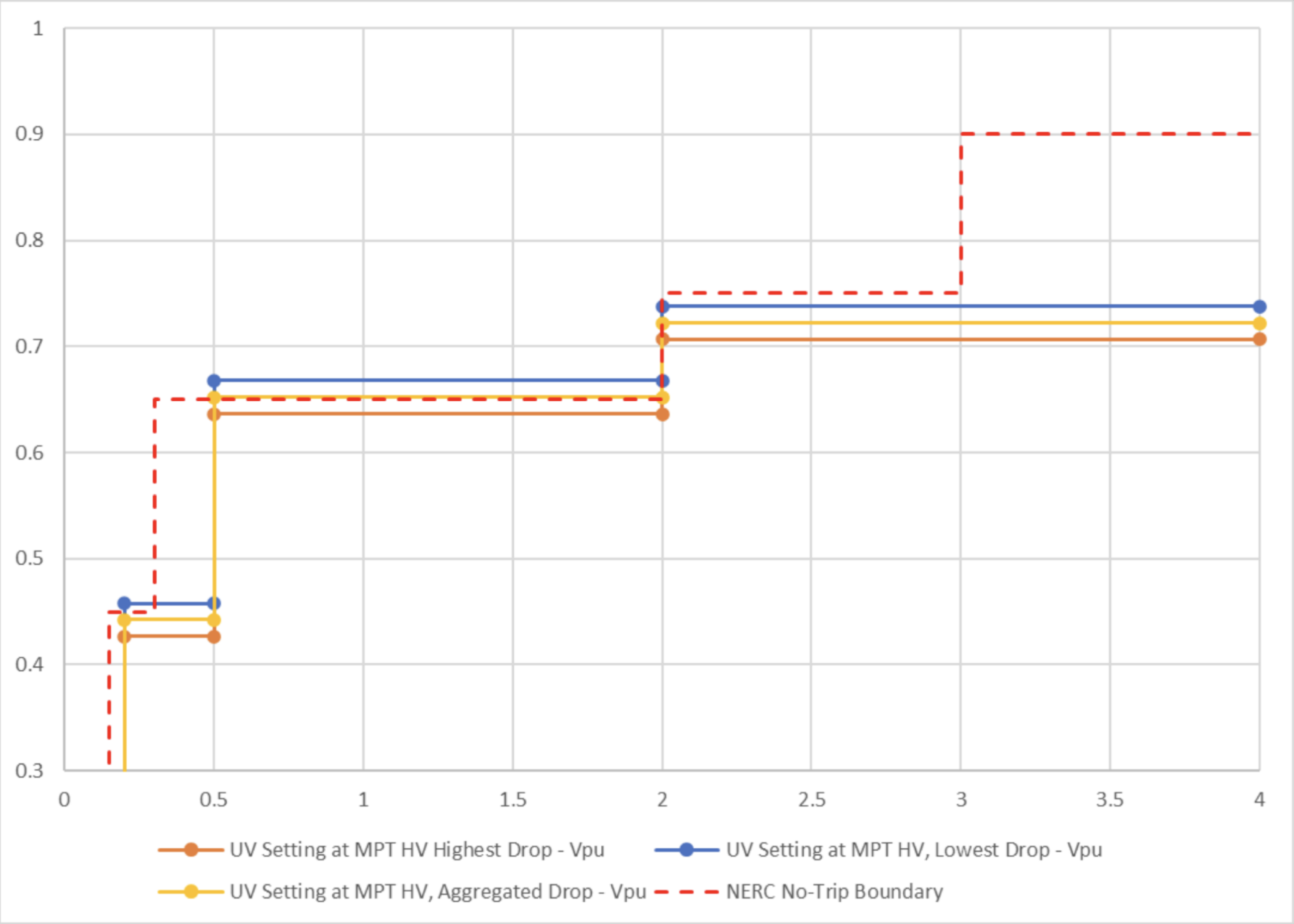
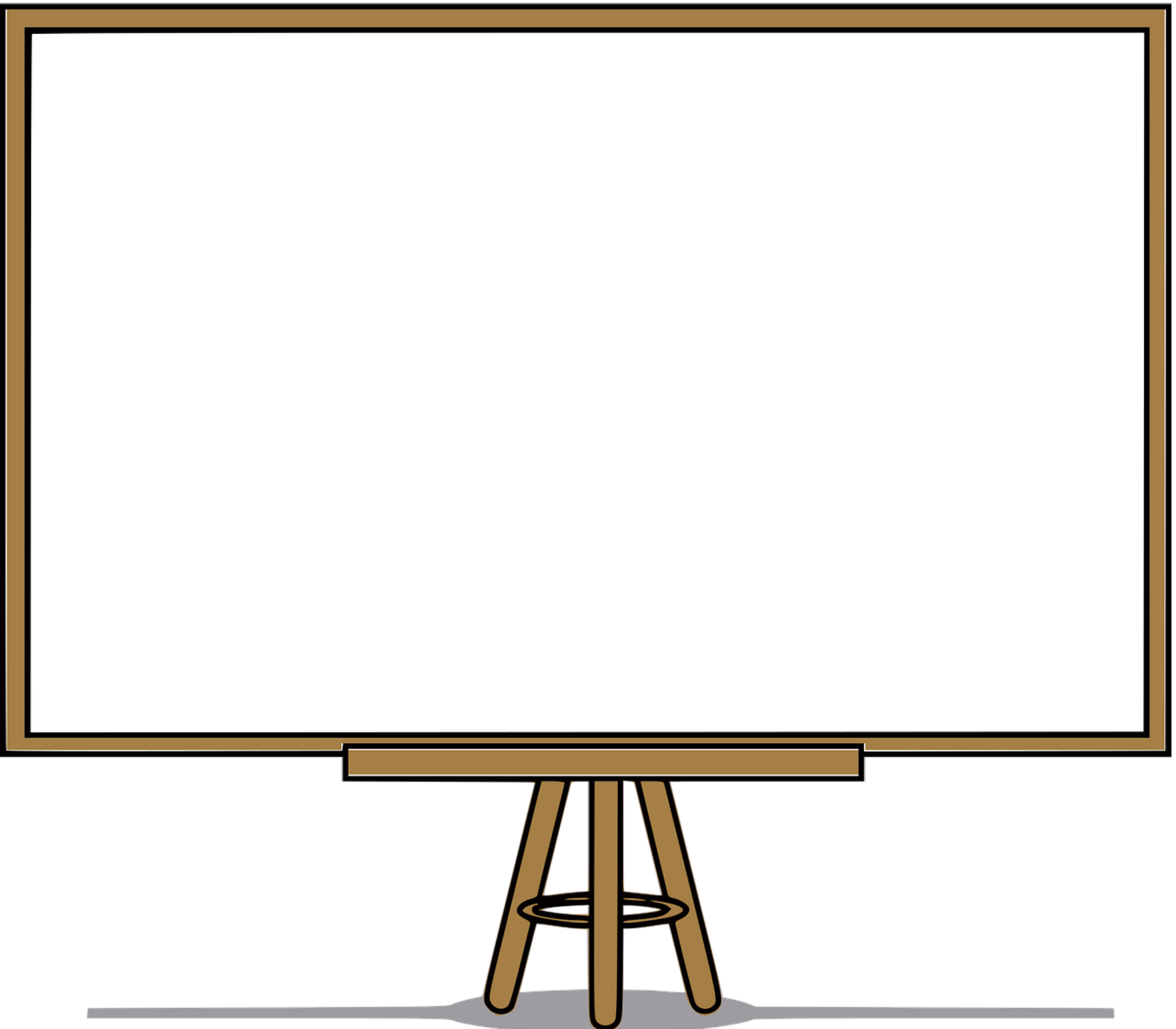


Source: [NERC]

Generic Standard Library and Equipment-Specific Modeling – Thought Examples



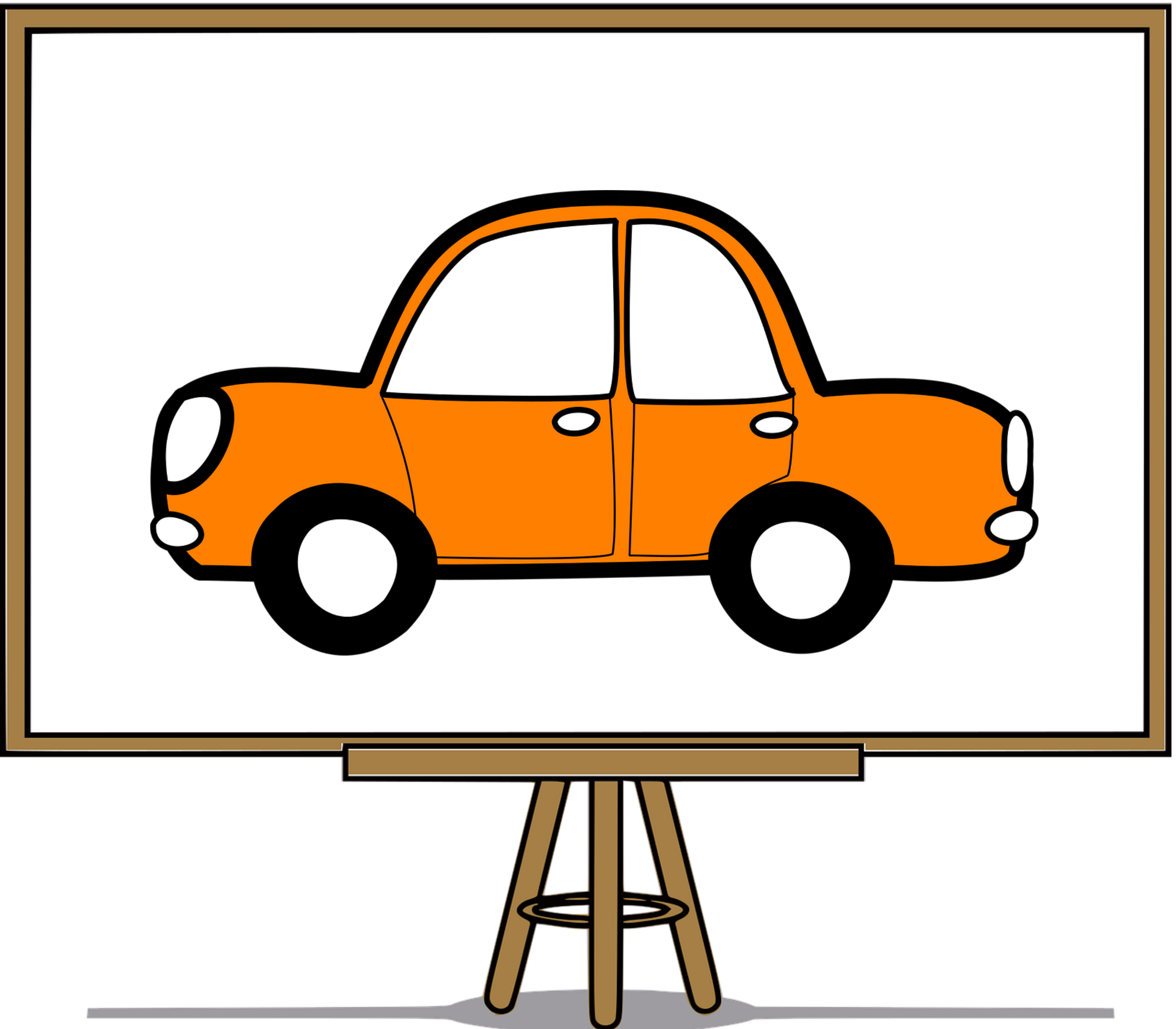
Task: Paint a picture of a vehicle

(represent an IBR plant in general)

Generic or Standard Library Model

Equipment Specific Model

Generic Standard Library and Equipment-Specific Modeling – Thought Examples



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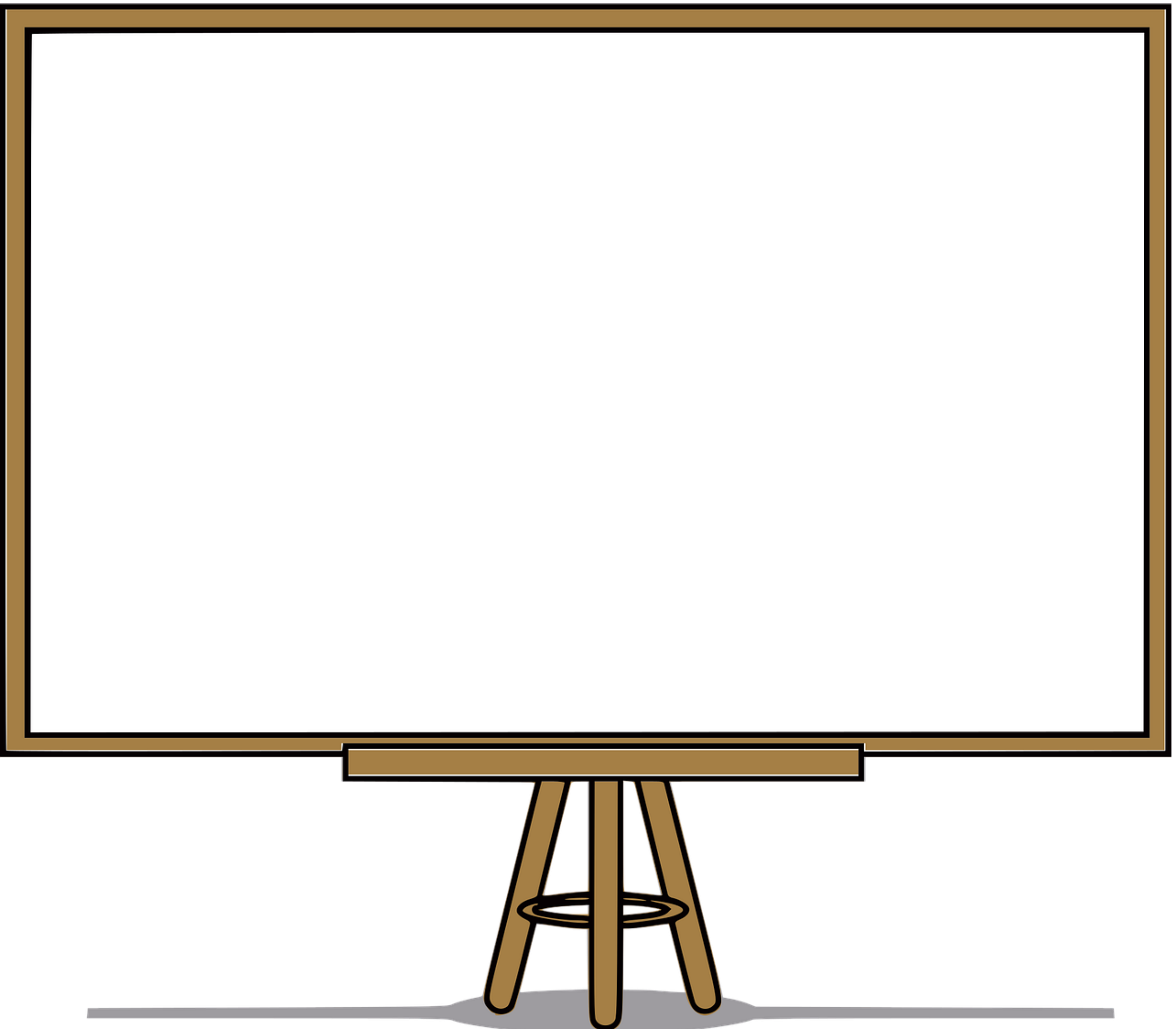

Task: Paint a picture of a van

(represent an IBR plant of a specific type)

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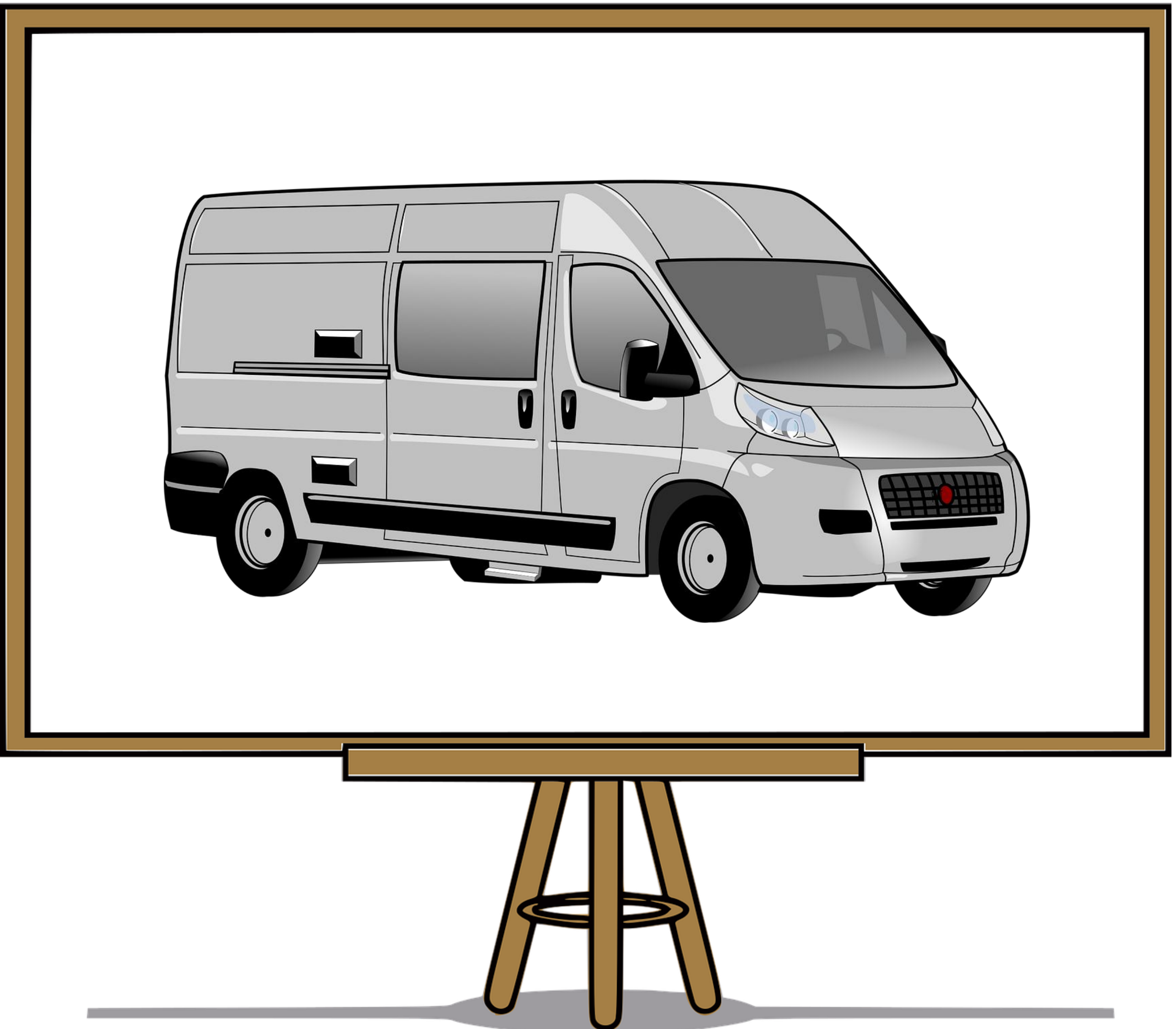

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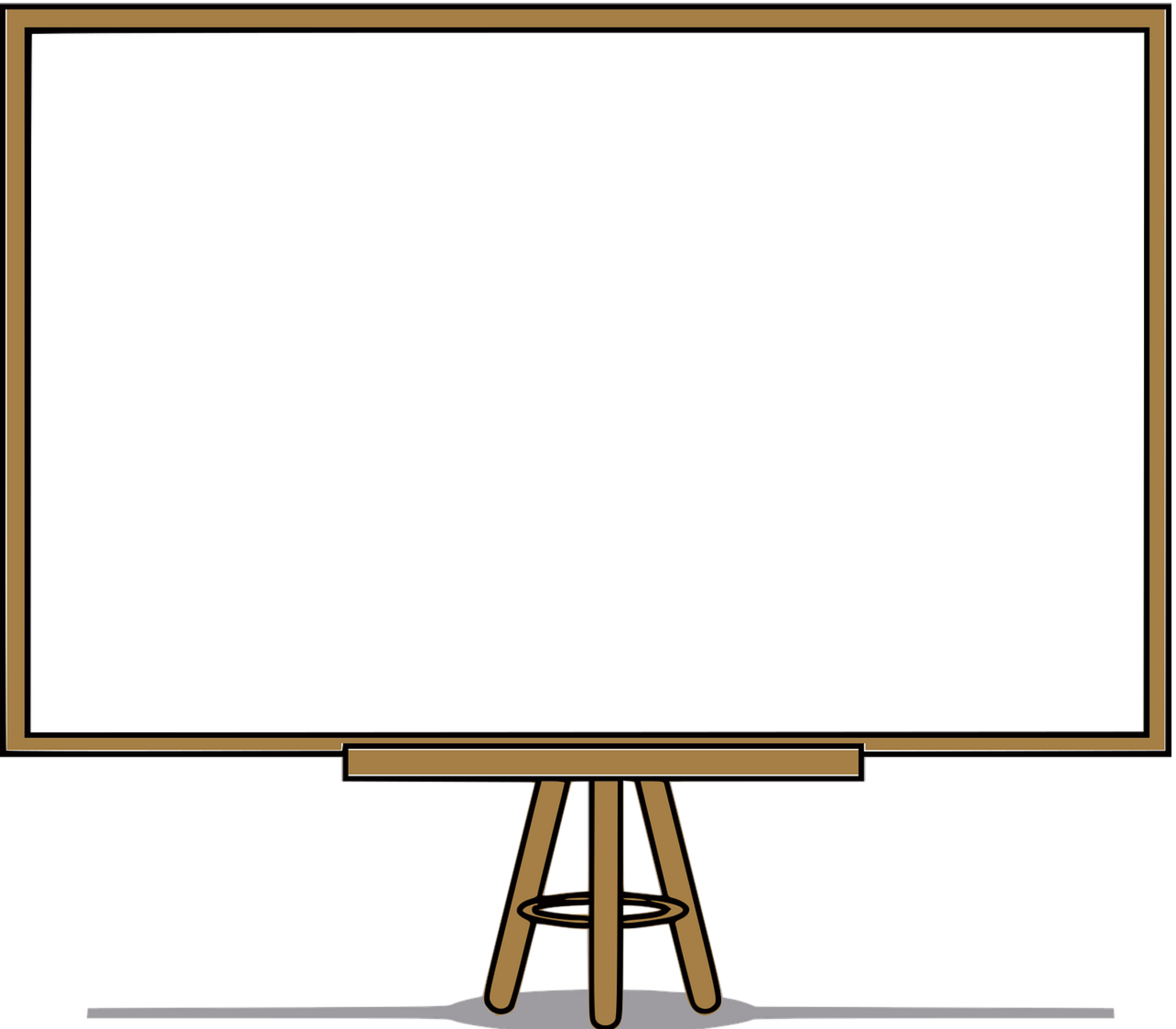

Task: Paint a picture of a Mercedes sedan

(represent an IBR plant of a specific type by a specific manufacturer)

Generic or Standard Library Model

Equipment Specific Model

Generic Standard Library and Equipment-Specific Modeling – Thought Examples

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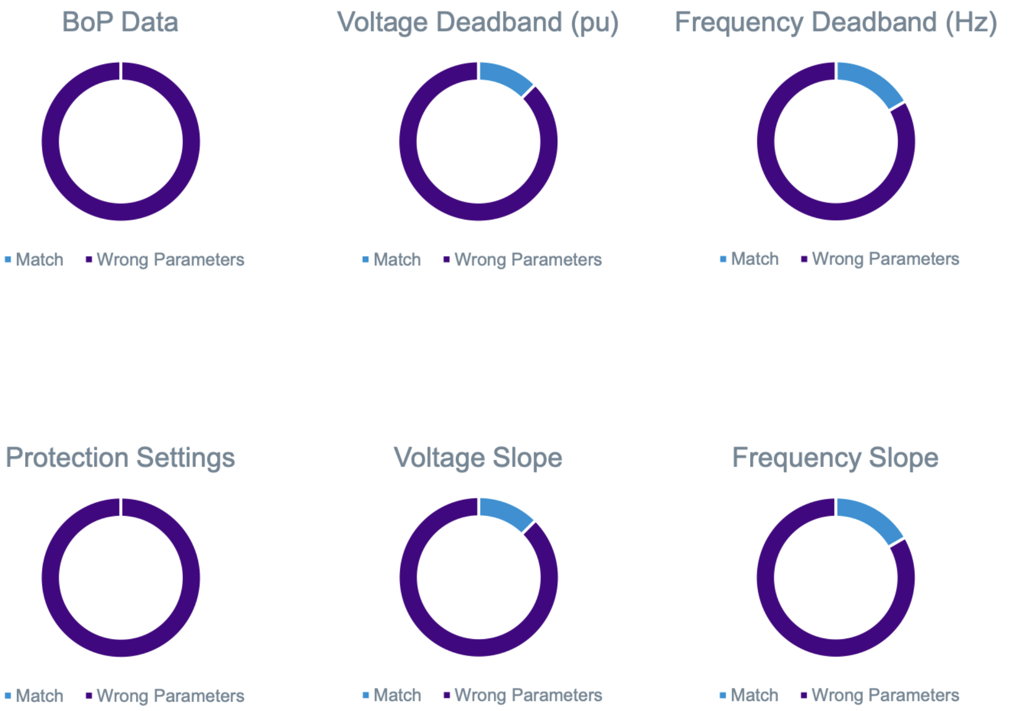
Generic or Standard Library Model

Equipment Specific Model

Generic vs. Equipment Specific – Real World

Vestas Case Study – Comparing Models Used in the Planning and Interconnection Process to Site-Specific Equipment-Specific Models



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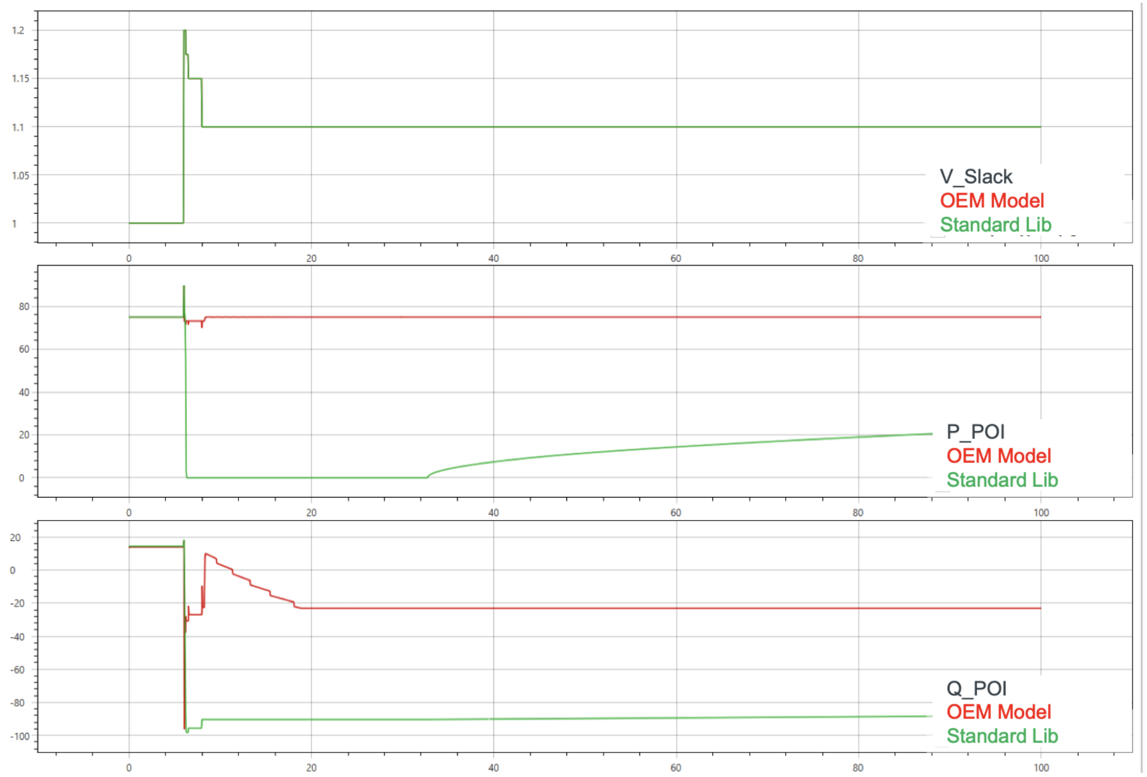


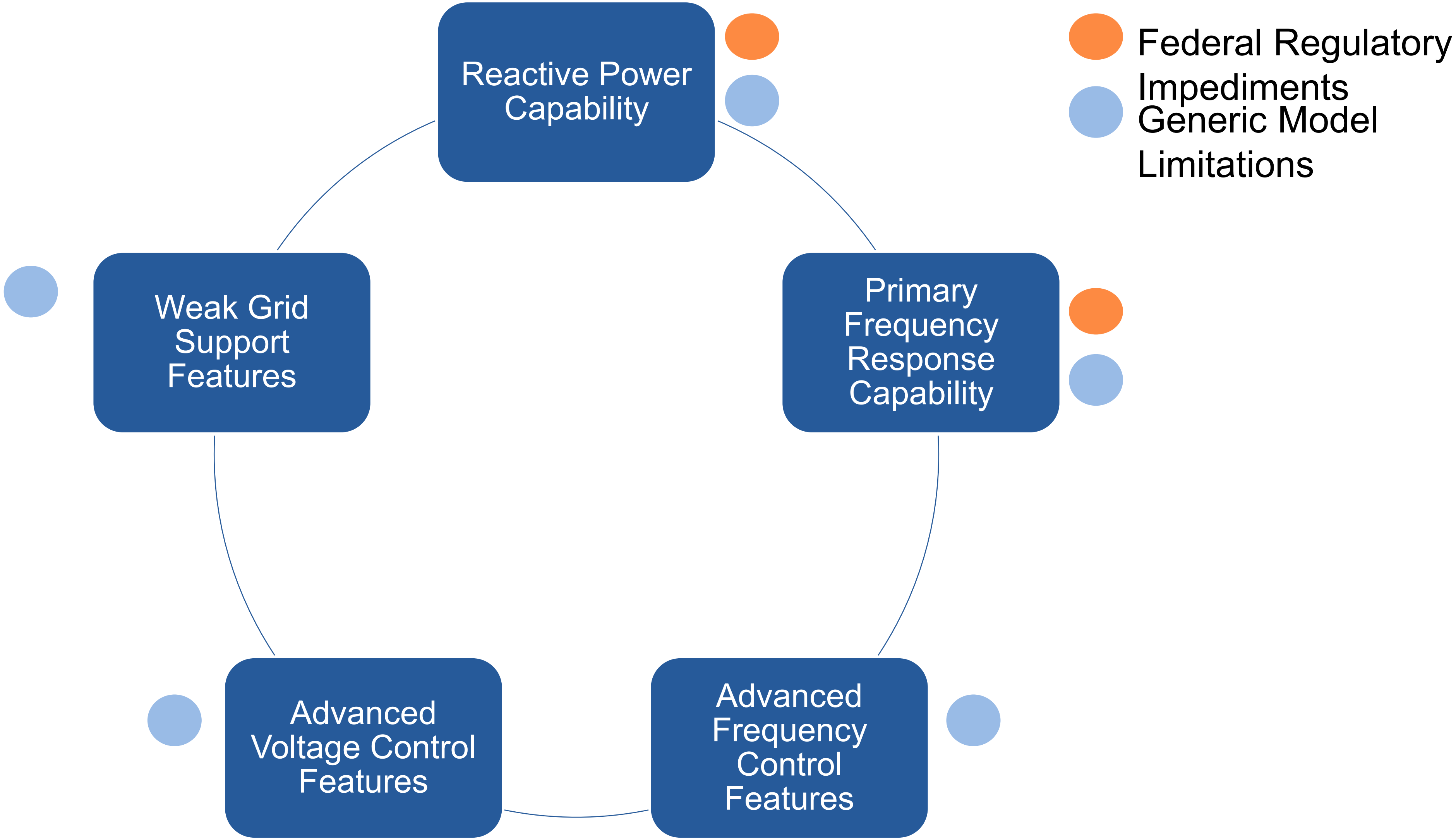
The "Standard Lib" represents NERC MOD validated models used in current reliability processes

Source: Vestas

Why is IBR Modeling Detail So Important?

- **The power system is evolving rapidly, and the current stability margin is being reduced by current IBR interconnection and planning processes**
- **Transmission enhancements are on a significantly slower time scale than IBR interconnections**
- **IBR have significantly underutilized capabilities**
  - Enabling these capabilities (which are only available in equipment-specific models) is essential to the efficient use of the current power system and to inform efficient future grid enhancements
- **Utilizing "advanced" IBR capabilities will be essential to maintaining grid reliability and avoiding erroneous transmission upgrades**
- **Reliance on generic and standard library models ensures that interconnection and planning studies will always be wrong when compared to actual performance**
  - "Wrong" in this case is neither conservative nor optimistic
  - Generic and standard library models give both false positives and negatives

What is Being Underutilized?



Federal Regulatory Impediments – An Example

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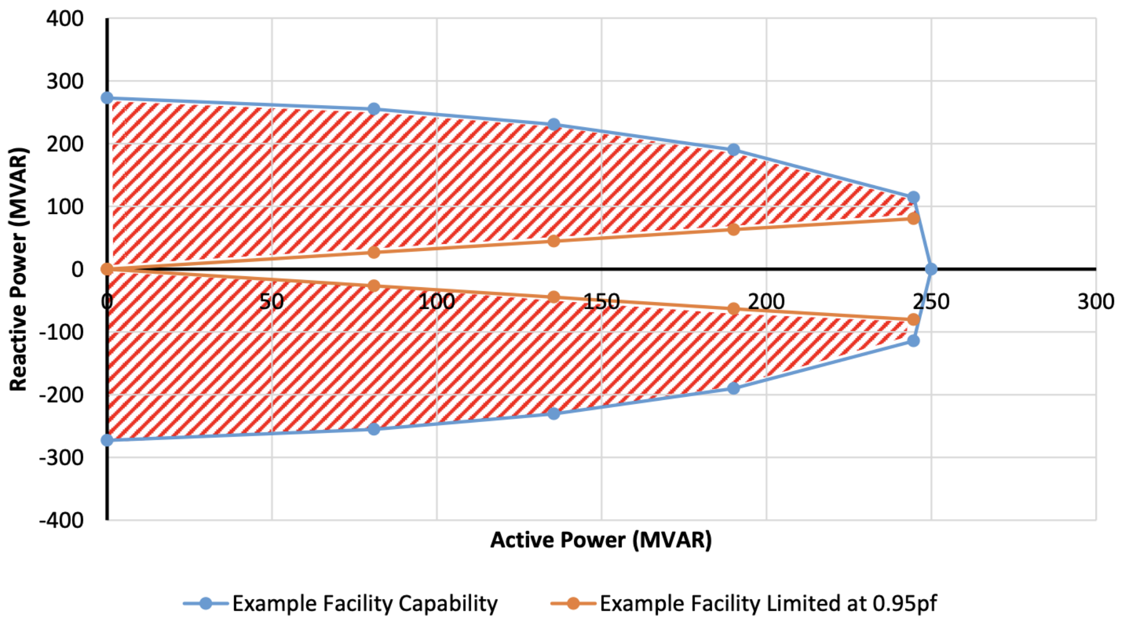
Language with unexpected interpretations in FERC Order 827 limits reactive power capability

- FERC Order 827 states to "(…) maintain a composite powe delivery at continuous rated power output at the high-side c the generator substation within the range of 0.95 leading and 0.95 lagging, unless the Transmission Provider has established a different power factor range (…)"
- This is similar, but not identical, to the IBR operating points that contributed to the Iberian blackout
  - IBR were operated at a fixed power factor
    - No matter the grid condition, the plant will deliver a fixed reactive power for a given active power
  - FERC Order 827 dictates a power factor limited operation
    - The direction of reactive power (leading or lagging) may change, but is still limited to +/- 0.95



NERC Level 2 Alert data shows 35% of the currently installed IBR are operating in this limited mode

Grid Forming Inverters – Added Complexity to an Unprepared Paradigm

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- Grid forming inverters are extremely similar to grid following inverters
- Grid forming controls add complexity on top of the complexity of studying and planning grid following resources
  - Industry shows evidence of reliability issues tied to grid following, these may exacerbate with grid forming
- Integration of grid forming technology in North America is disjointed
  - Little to no Federal guidance on whether to require, incentivize, or even integrate GFM
- Every battery energy storage resource that is connected without grid forming capabilities increases the opportunity cost of adding it later
  - Many BESS can implement GFM with simple software changes
  - Not every IBR needs to be GFM

Reliability Consideration	Grid Following	Grid Forming
Technology Maturity	Immature compared to synchronous	Immature compared to GFL
Software-based	Susceptible to IBR performance and ridethrough issues	
Power Electronic-Connected		
Model Parameters	Similar complexity and difficulties	
Grid Impact	”Passive” grid participant	“Active” grid participant
Modeling and Study Risks	Insufficient accuracy can lead to self tripping of an IBR and cause local reliability issues	In addition to GFL, insufficient accuracy can create improper references and control interactions

Grid Forming vs. Grid Following – In Depth

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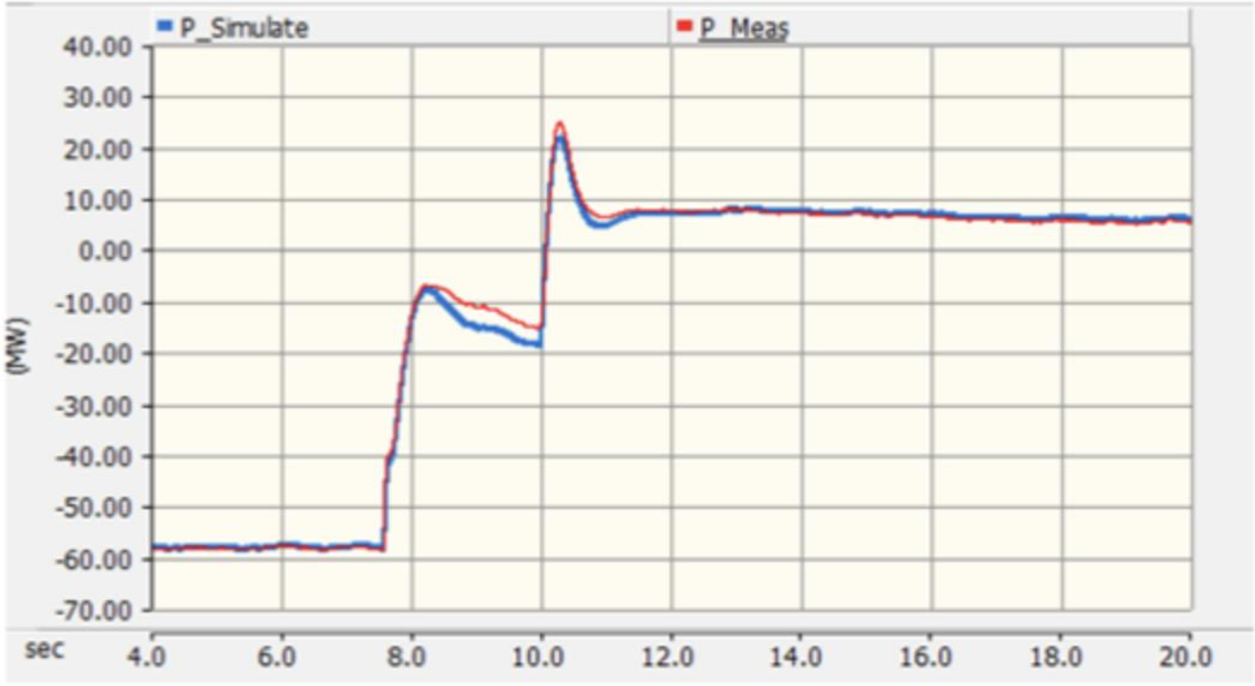
Inverter Attribute	Grid-Following Control	Grid-Forming Control
Reliance on grid voltage	Relies on well-defined grid voltage, which the control assumes to be tightly regulated by other generators (including GFM inverters and synchronous machines)	Actively maintains internal voltage magnitude and phase angle
Dynamic behavior	Controls current injected into the grid (appears to the grid as a constant current source in the transient time frame)	Sets voltage magnitude and frequency/phase (appears to the grid as a constant voltage source in the transient time frame)
Reliance on PLL for synchronization	Needs phase-locked loop (PLL) or equivalent fast control for synchronization	Does not need PLL for tight synchronization of current controls, but may use a PLL or other mechanism to synchronize overall plant response with the grid.*
Ability to provide black start	Not usually possible	Can self-start in the absence of network voltage. When designed with sufficient energy buffer and over-current capability, it can also restart the power system under blackout conditions. (Only a limited number of generators on a system need to be black start–capable.)
Ability to operate in low grid strength conditions	Stable operation range can be enhanced with advanced controls, but is still limited to a minimum level of system strength	Stable operation range can be achieved without a minimum system strength requirement, including operation in an electrical island. (GFM IBRs will not, however, help to resolve steady-state voltage stability for long-distance high-power transfer.)
Field deployment and standards	Has been widely used commercially. Existing standards and standards under development define its behavior and required functionalities well.	Has been deployed in combination with battery storage primarily for isolated applications. Very limited experience exists in interconnected power systems. Existing standards do not yet define its behavior and required functionalities well.

* A GFM inverter also needs a synchronization mechanism when it has reached its current or energy buffer limits. If it reaches these limits, it will temporarily fall back to grid-following operation and will need to track the grid voltage phasor.

- Grid forming is a spectrum
- Different methods for implementing GFM
    - Virtual synch machine
    - Droop control

How does GFM Help – Operating Example

- Grid forming controls provide extremely fast response times
  - These are controlled responses, even in extreme grid conditions
  - Can stabilize weak grids or provide voltage and frequency references in the absence of synchronous machines
- If there is sufficient additional energy (like in BESS) these stabilizing responses can sustain for long periods of time
- Kapolei Energy Storage:
  - Response to extreme underfrequency disturbance
  - Plant responded within 250ms to arrest the frequency drop
  - Sustained this grid forming response for 30 minutes while the system recovered



Source: Hawaiian Electric Company.

How to unlock GFM – Need to Break the Cycle

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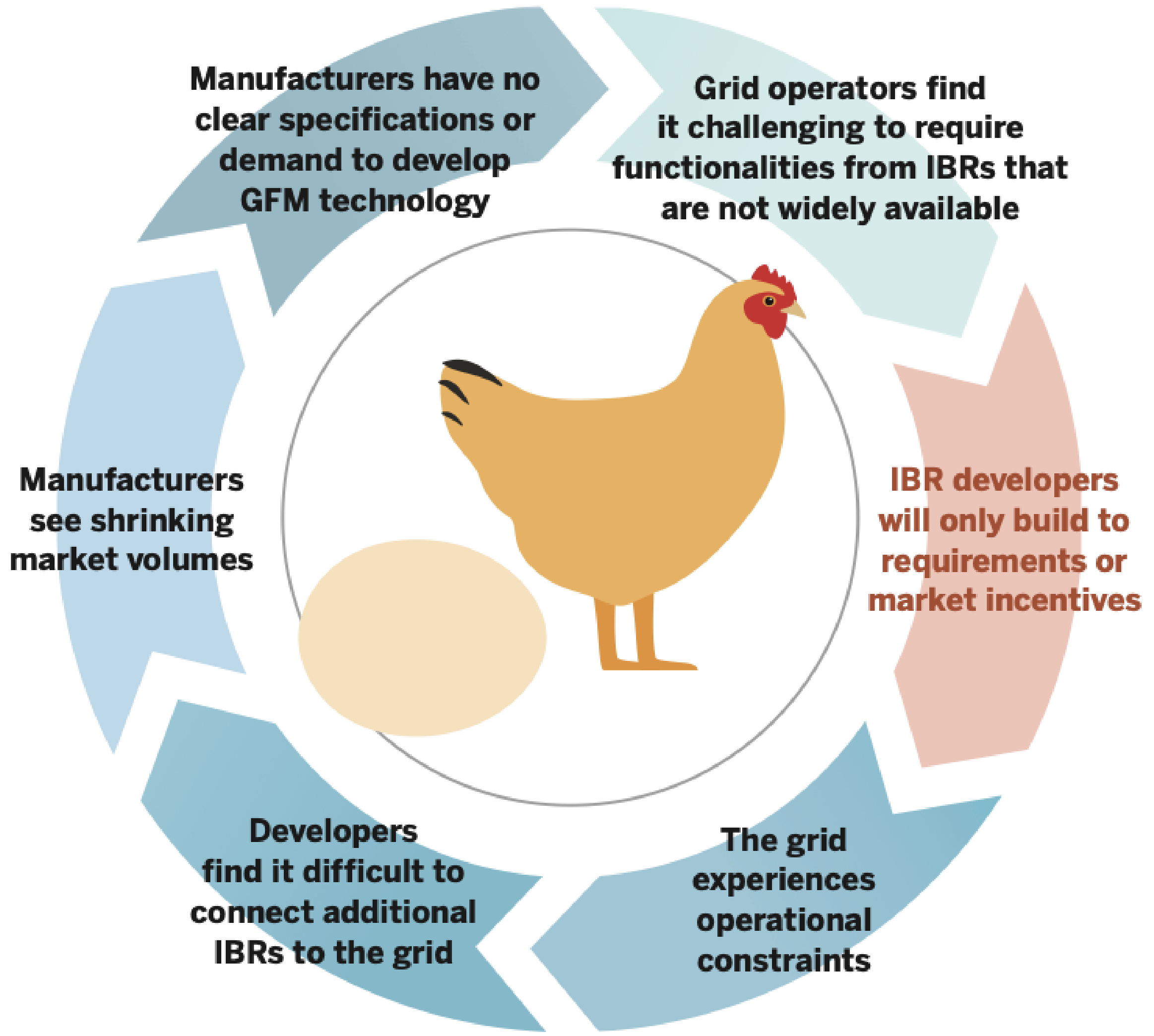

How to unlock GFM

In the proposed process for deploying new GFM capabilities to serve system needs, the outer circle follows steps 1 through 9 as discussed in the text, while the three inner elements show how the nine steps relate to IBR equipment manufacturers and project developers and owners. Steps 1 through 9 are not set in stone and will likely need to be an iterative loop as systems and technologies continue to evolve.

- Need to move with urgency
- System operators need to clearly define what they *want and need* from GFM resources
  - Studies defining quantitative needs are not currently widespread
  - System operators have difficulty mandating the interconnection of GFM
- Specification and details for how system operators will test for and confirm performance are necessary ASAP
  - Few system operators currently have GFM testing specifications
- Manufacturers take these grid needs, and develop equipment that can meet the grid needs and system operator requirements
  - Little to no international guidance on GFM performance specifications
  - Adds extreme difficulty when procuring resources to develop new technologies

Conclusions

Regulatory enhancements are needed to close gaps and enhance North American system reliability

- Major events comprised of unexpected IBR tripping show that the current modeling paradigm is insufficient
- Many of the modeling challenges have solutions internationally
- There is strong best practice available for IBR modeling in North America
  - This best practice is often at odds with current regulatory processes
- Regulatory processes need enhancements to allow stakeholders to perform best practice
- Process enhancements must have strong industry consensus technical foundation (i.e. IEEE 2800-2022, P2800.2, etc.)
- Stakeholder driven processes need enhancement to prevent gaming, lobbying, and misinformed comments and ballots

ERO Members -- Transmission Owners

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Conclusions

Modeling IBR is hard, data and evidence shows the current paradigm is insufficient, and logic continues that added complexities of GFM will exacerbate these insufficiencies

- Grid forming inverters have many of the same reliability issues as discussed for GFL in numerous NERC disturbance reports
- There is insufficient understanding of how much GFM is needed, where it is needed, and what types of GFM resources can be connected
- There are not many incentives for installing GFM resources
- Grid forming resources are very important to high renewable penetration goals
- There are significant lessons that can be learned from GFL mistakes
- Standardization efforts are underway (much sooner than for GFL)

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