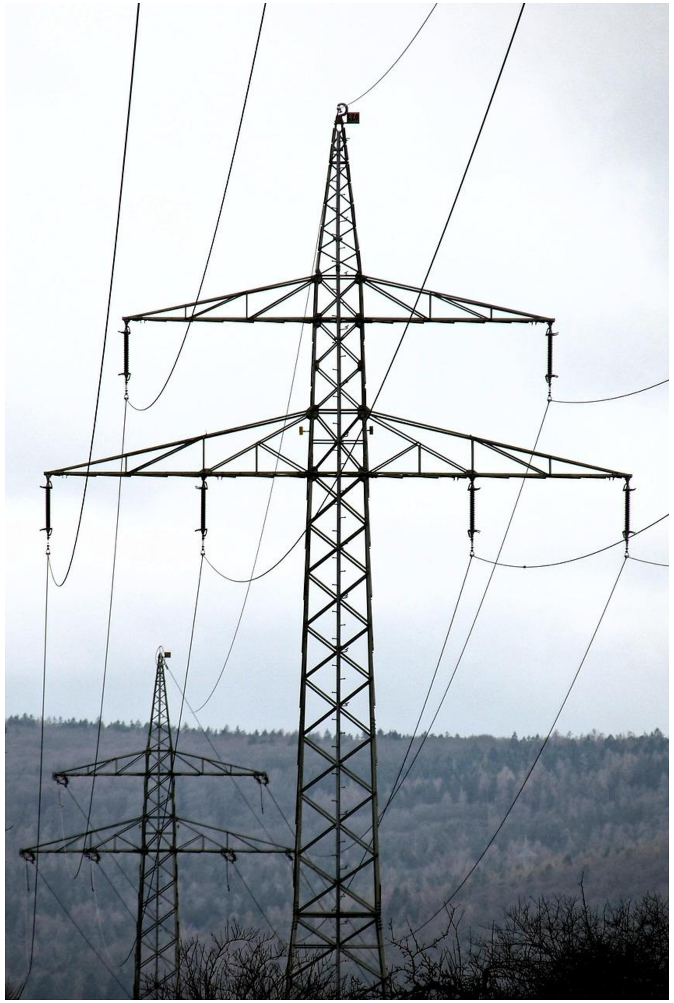
Study Basics for the New Power System Paradigm

ESIG
ENERGY SYSTEMS
INTEGRATION GROUP

Brief Stop for Terminology

- **Electromagnetic Transient or "EMT"** are the terms that will be used when discussing electromagnetic transient models, domain, studies, etc.
- **Positive Sequence Phasor Domain (PSPD)** is the term that will be most commonly used throughout this training course and is a consensus term used in the IEEE 2800 series of standards and can also be referred to as:
  - **RMS**
  - **Positive sequence**
  - **Transient stability**
  - **Phasor domain**
  - **Many more**



Why Are Power System Studies Performed?

ESIG

In a perfect world: Represent the **system** behavior **before** it happens

- Accurate modeled representations are critical
  - Study results are only as good as their inputs
- Grid reliability depends on the ability to **represent, understand, and mitigate** changing grid characteristics
- Energy affordability is linked directly to study accuracy
  - Inaccurate models are **neither conservative nor optimistic**

What is the Current Study Paradigm?

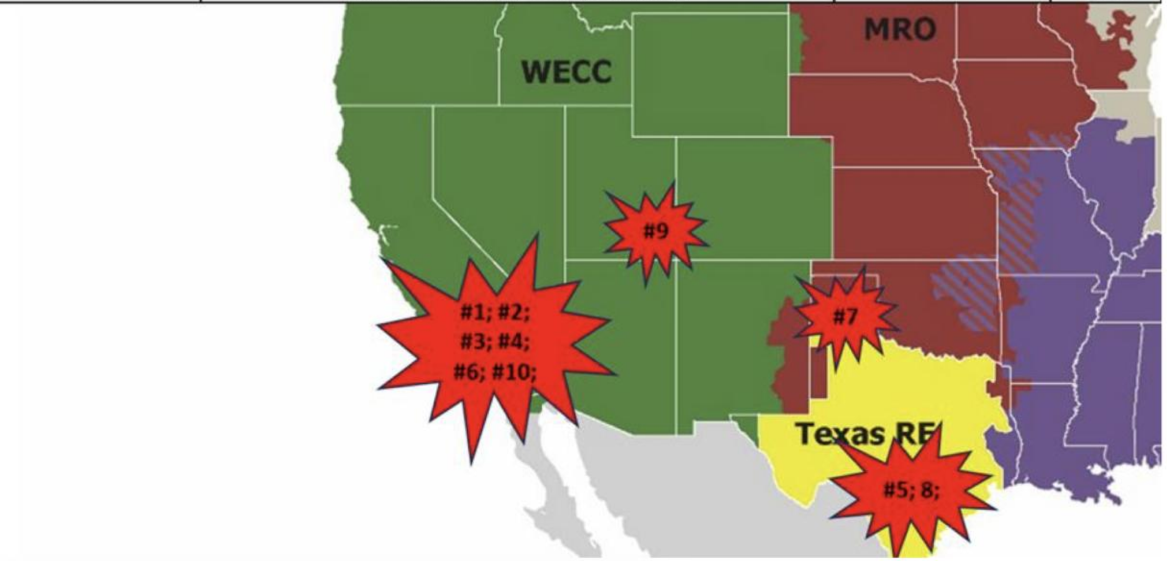
- **Disparate interconnection and planning requirements and processes**
  - The North American power system has diverse electrical characteristics
  - The grid is “transforming” differently everywhere
  - Difficult to determine what the best practice (or sufficient practice) is
- **Heavy reliance on Standard Library (or generic) models for reliability studies**
  - In much of North America, Standard Library models are required with manufacturer-specific models either not allowed or disincentivized (FERC Order 2023 can help)
  - Against NERC, FERC, and MMWG Guidance
- **Strong focus on speed and cost**
  - Less focus on reliability
  - Recommended practices are not being implemented (read the IBR-related NERC Alerts)

The Current Paradigm Isn't Working

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**
- **Four** additional events in 2024 totaling **~3200MW**
- **EMT can't close these gaps without an overhaul in study and modeling mindset**

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 Strorage	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

Why is Modeling IBR So Hard (in general)

ESIG

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
  - All but a small handful of the plants affected in the NERC-reported disturbances used generic models
- **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 Needs Change (Rapidly)

ESIG

- **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 Current Paradigm Makes Sense

- **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**

Much Has Changed

- **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
    - Model accuracy and validation requirements with high bar for accuracy and model quality
    - Model usability requirements
    - Model quality requirements
    - Open-sourced model code
    - High-quality generic models with "hooks"
    - Standardized interfaces (wrappers) for real-code models
- **Most all of the technical 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**

What Does NERC Say?

Recommended Dynamic Modeling Practices

NERC strongly recommends the following framework for dynamic models used in BPS reliability studies:

- All models should be detailed and accurate representations of expected or as-built facilities on the BPS, including during interconnection studies and throughout the lifecycle of a project.
- It is the responsibility of each TP and PC to establish clear, consistent, sufficiently detailed, and comprehensive modeling requirements. These requirements should include model quality checks and updates when needed.
- It is the responsibility of each project developer and GO to meet the modeling requirements established by the TP and PC and to provide adequate proof of conformance to the requirements. It is the responsibility of each GO to maintain an accurate model throughout the lifecycle of the project. GOs shall notify the TP and PC of any expected changes or updates (per NERC FAC-002) for in-service equipment and submit updated models accordingly.

Source: NERC

What Does NERC Say?

ESIG

- All TPs and PCs should require all of the following for each generator connected (or seeking interconnection) to the BPS to ensure that sufficient models and supporting documentation are provided:
  - A positive sequence library model that is on the list of unacceptable models found in **Appendix A** should not be provided. This model is often used by the MOD-032 designee for Interconnection-wide base case creation, and it is often used in studies to represent facilities outside of the TP/PC study area.
  - A positive sequence user-defined model (UDM)[1] should be used for system impact studies during the interconnection process and for local stability studies within the TP or PC footprint.
  - An electromagnetic transient (EMT) model is used to study specific BPS reliability issues in detail, specifically the interconnection of inverter-based resources. These types of analyses are becoming increasingly prevalent and necessary for systems with increasing levels of inverter-based resources.
  - All of the aforementioned models should be verified by the OEM to be accurately parameterized[2] to represent site-specific[3] controls, settings, and protections with supporting documentation and attestations. They should also be validated against actual product performance according to NERC Reliability Standards and local TP and PC requirements.[4]
  - A model benchmarking report should be prepared that compares all the aforementioned models against each other and documents any discrepancies across the models, including those due to software platform limitations. The benchmark reports should be available among neighboring PCs.

Source: NERC

What Does NERC Say?

ESIG

Positive Sequence Library Models

Library models should generally not be used for detailed reliability studies, particularly in and around the study area due to a lack of model accuracy and fidelity to represent the actual equipment controls and protections. Unique situations may exist where equipment manufacturers attest that the library models sufficiently represent the actual installed equipment controls and protections; however, most equipment manufacturers advocate that UDMs are more appropriate for these detailed studies. This is particularly applicable for BPS-connected inverter-based resources.

Library models are often used by the MOD-032 designees to create the Interconnection-wide base cases, so TPs and PCs should require submittal of a positive sequence library model in conjunction with a UDM for all facilities. The models should be benchmarked by the GO against actual facility or site-specifically parameterized EMT or UDM model. Models used as the benchmark for the library should be parameterized to match the commissioned facility such that the resulting benchmarked library model is as representative of the facility as possible. Gaps between the library model and UDM performance should be documented and mitigated if possible.

Source: NERC

What Does NERC Say?

ESIG

Positive Sequence User-Defined Models

Accurately parameterized, manufacturer-verified, and user-defined models should be used for detailed reliability studies, such as during interconnection system impact studies, as references during the facility commissioning process and local reliability studies. For example, a PC modeling the resources in their footprint during their TPL-001 annual planning assessment should use the more detailed UDMs in their area (and neighboring footprint(s)) while the rest of the Interconnection would be represented with library models from the Interconnection-wide base case. UDMs should be used for any studies or parts of the network that require accuracy and fidelity and that are not available in library models.

Equipment manufacturers should provide both UDM and library models for the equipment installed or to be installed at a facility. Included in the model packages, the equipment manufacturers should clarify the differences across models in terms of model accuracy and fidelity as well as to provide justification regarding when each model should be used. With both model types available as well as a detailed description of the limitations and best uses of each model, GOs, TPs, and PCs should have enough information to use engineering judgement to determine which model is most appropriate for each study. Additionally, once a facility is accurately represented with a UDM, the library model can then be benchmarked against the site-specific UDM performance by the GO or their third-party consultant.

Source: NERC

What Does NERC Say?

A UDM should only be considered acceptable by a TP and PC if the following usability requirements are met:

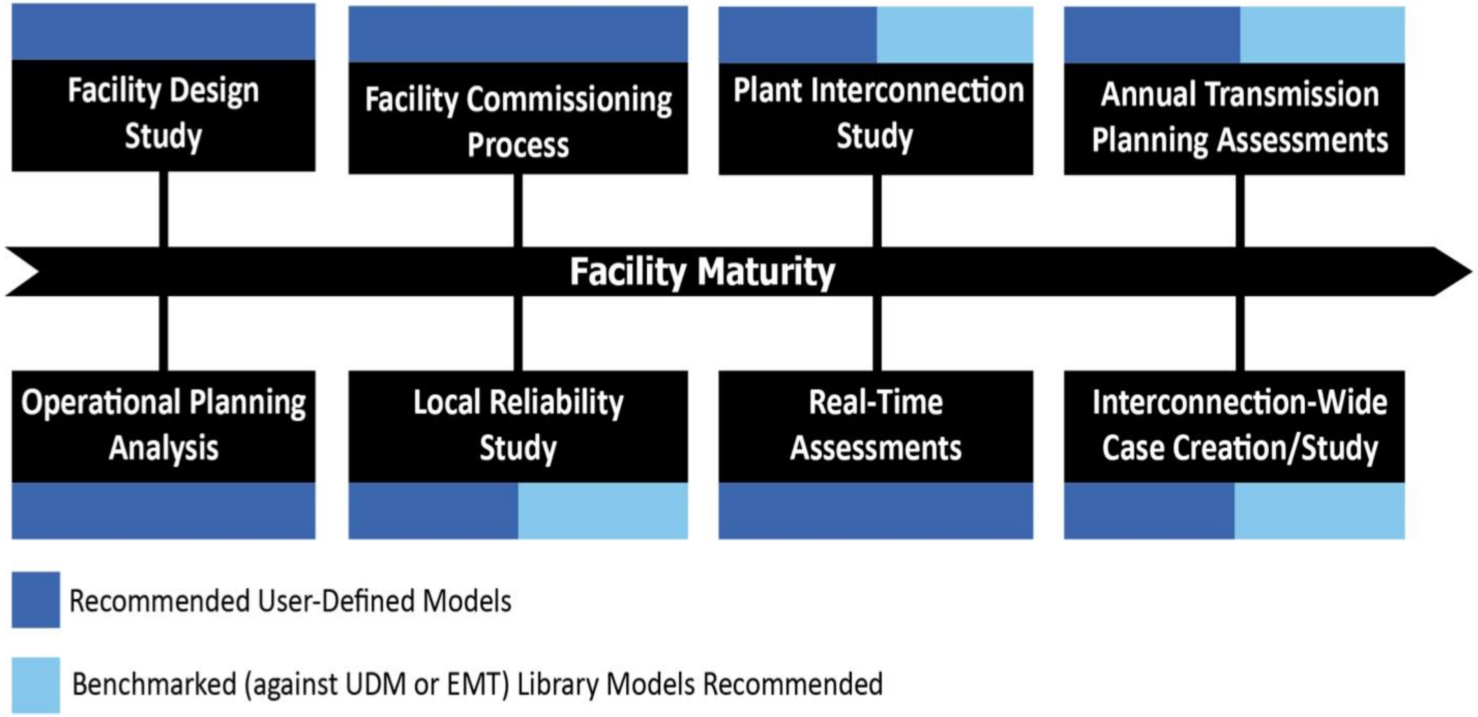
- A model validation report is provided that compares the actual equipment performance against the EMT, positive sequence UDM, and library models.[7]
- A model benchmarking report is provided that compares the response of models across each platform.
- The UDM should include compiled .dll files such that no additional compiling is required by the end-user.
- The UDM should be accompanied by sufficient documentation[8] for the TP and PC:
  - Properly integrate the facility model(s) into network model
  - Understand control modes and applicable parameter functions
  - Understand the facility ratings and capabilities
  - Initialize models appropriately in reliability studies

Portions of UDM may be "black boxed" to protect intellectual property. This is generally considered acceptable so long as sufficient documentation is provided and applicable control settings are exposed to the end-user so that they can be parameterized appropriately.

Source: NERC

Intersection of Recommendations and Reality

- **Why** should I follow these recommendations when:
  - I don’t have to
  - I have high profile interconnection deadlines
  - More complexity means more time and money
- **How** can I follow these recommendations when:
  - I don’t know what equipment I will use
  - I don’t know final parameters
  - I don’t have a representative model



Source: NERC

Model Types and Simulation Domains

- Model type considerations (Standard Library/Generic vs. User-defined/Manufacturer-specific) **remain regardless of simulation domain**
- A poorly constructed EMT model is **just as ”wrong”** as a poorly constructed PSPD model
  - At both the manufacturer and end-user level
- Just because a model is provided in the EMT domain doesn’t mean it is inherently accurate
  - Similarly, PSPD models aren’t insufficient by virtue of simulation domain
  - It is possible for significant overlap between the accuracy of “good” PSPD models compared to manufacturer-specific EMT models and actual product performance
- **Enhancements to PSPD** modeling in addition to an **increase in EMT requirements, studies, and understanding** is essential for a reliable grid transformation
  - Enhancements to PSPD modeling can help close reliability gaps as EMT knowledge builds

Capturing Known Issues by Simulation Domain

ESIG

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

- The current modeling and study paradigm is phasor domain and steady state driven and leaves **gaps**
- **EMT simulations** can represent many of the causes of reduction that are not possible in phasor domain simulations

Why not EMT for everything?

- Grid reliability needs
- Simulation differences
- Process and technological limits

Adapted from: NERC 2022 Odessa Disturbance Report

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

Grid Reliability is More Than Ridethrough

ESIG

- NERC disturbance reports tell the **very last chapter of the story**
  - Easy to categorize all risks as ridethrough
- **Normal operation** controls and plant response to small disturbances is also critical
  - These often do not "need" and EMT model
  - Requires high quality PSPD models
- Normal and abnormal (ridethrough) operations require **both control systems to work as intended and hand off**
  - **EMT simulations are required to help mitigate some reliability risks but are excessive for others**

Table 1.1: Causes of Solar PV Active Power Reductions

Cause of Reduction	Odessa 2021 Reduction [MW]	Odessa 2022 Reduction [MW]
Inverter Instantaneous AC Overcurrent	–	459
Passive Anti-Islanding (Phase Jump)	–	385
Inverter Instantaneous AC Overvoltage	269	295
Inverter DC Bus Voltage Unbalance	–	211
Feeder Underfrequency	21	148*
Unknown/Misc.	51	96
Incorrect Ride-Through Configuration	–	135
Plant Controller Interactions	–	146
Momentary Cessation	153	130**
Inverter Overfrequency	–	–
PLL Loss of Synchronism	389	–
Feeder AC Overvoltage	147	–
Inverter Underfrequency	48	–
Not Analyzed	34	–

* In addition to inverter-level tripping (not included in total tripping calculation.)
** Power supply failure

Adapted from: NERC 2022 Odessa Disturbance Report

Reliability Need: Maintaining System Voltage and Frequency

- **Maintaining system voltage and frequency is critical for power system reliability:**
  - Power quality
    - Ensuring quality is sufficient to minimize adverse effects
  - Ridethrough and normal operations
    - Keeping system frequency and voltage within specified bounds is essential for "normal operations"
    - Remaining near nominal quantities provides extra "margin" during system disturbances
- In **system steady state** (normal operation) slow controls take precedence
  - Automatic voltage regulation or primary frequency response, for example
- In **system dynamic state** (abnormal operation) fault ridethrough and fast controls take precedence

There are many other reliability needs!

Active Power Controls at 30,000 ft

- **Active Power Setpoint Change**
  - Active power reference signal is input into the controller, and the controller moves to the new setpoint
- **Response to grid frequency disturbance**
  - **Primary Frequency Response**
    - Immediate and proportional change in active power injection in response to frequency disturbances – should move in grid-stabilizing direction
  - **Fast Frequency Response***
    - Similar to PFR in that active power injection will change in response to frequency disturbances
      - Acts on significantly faster timeframes to PFR. Capable of providing full response in ~30 cycles

Reactive Power Controls at 30,000 ft

- **Reactive Power Setpoint**
  - Reactive power setpoint is given to the controller, and the reactive power injection moves to that setpoint
- **Power Factor Setpoint**
  - The plant operates at one specified power factor at all times. Reactive power varies with active power
- **Automatic Voltage Regulation**
  - Changes reactive power injection as a function of voltage.
  - Can be **open** or **closed loop** controllers
    - **Open loop** controllers do not incorporate any feedback
      - May be unstable in most grid conditions
    - **Closed loop** controllers incorporate feedback to minimize large swings in output and controller interactions

Ridethrough Controls at 30,000 ft

- **Ridethrough Modes:**
  - Occurs when measured voltage crosses a high or low threshold (outside of “normal”)
  - Controls operate significantly faster than “normal operation” controls
    - Primary purpose is to protect equipment while maximizing grid connection stability
- **Detailed considerations:**
  - At the extremes of both equipment capability and simulation methods
    - Very fast and high magnitude changes in simulation quantities
  - Requires “hand off” between power plant controller and individual inverters
  - Sampling time, communication delays and protocols, and actual equipment limits dramatically change performance
  - **The differences between EMT and PSPD emerge clearly in ridethrough analysis**

Key Takeaways

- The modeling and study **paradigm must change** to maintain reliability through the grid transition
- There is significant room **for improvement within current practices**
  - Requires practice above the compliance "floor"
  - Can be good practice to hone fundamentals needed for EMT analyses
  - Important not to let the next new thing hinder mastery of the current state of the art

Key Takeaways

- **PSPD simulations will remain a mainstay in reliability studies**
  - Computational burden
  - Lack of EMT models for many grid-connected resources
  - Not all studies need EMT
    - Verifying performance of automatic voltage regulation can be performed in PSPD while a sub-synchronous oscillation study must be performed in EMT
- **”Over engineering”** is a real concern
  - Engineering first instinct is to model all details possible
  - **What study is being performed, for what reason, time, and cost** should inform simulation domain
- **Efficient mitigation of current reliability issues requires a thorough understanding of both PSPD and EMT domains**
  - This understanding will inform engineering judgment