

Electromagnetic Transient Training



Alex Shattuck and Lukas Unruh

December 16-18, 2025

Funding Acknowledgement



This Electromagnetic Transient (EMT) course is presented through partnership with [Lawrence Berkeley National Laboratory](#) and the [Interconnection Innovation e-Xchange](#) program which is a **DOE initiative supported by the Office of Critical Minerals and Energy Innovation (CMEI)**

Thank You Texas Reliability Entity



Thank you to **Texas Reliability Entity** for donating this venue.

The donation of this venue keeps registration costs low.

Thanks again!

ESIG Background



1989

UWIG Established

ESIG started as the Utility Wind Interest Group (UWIG) in 1989, a group of six utilities interested in learning more about wind energy

Early 2000's

Understanding Improves

Wind integration understanding rapidly improved, and was helped by consolidation of balancing areas and growth of larger market operators (ISO/RTOs) in early 2000's

2011

UWIG becomes UVIG

Solar energy emerged at scale and with similar integration issues, and UWIG became the Utility Variable Generation Integration Group (UVIG) in 2011

2018

UVIG becomes ESIG

With renewables, storage and decarbonization as mainstream pathways to the future, UVIG merged with the International Institute for Energy Systems Integration (iiESI) and became the Energy Systems Integration Group (ESIG) in March 2018

ESIG Differentiators and Mission



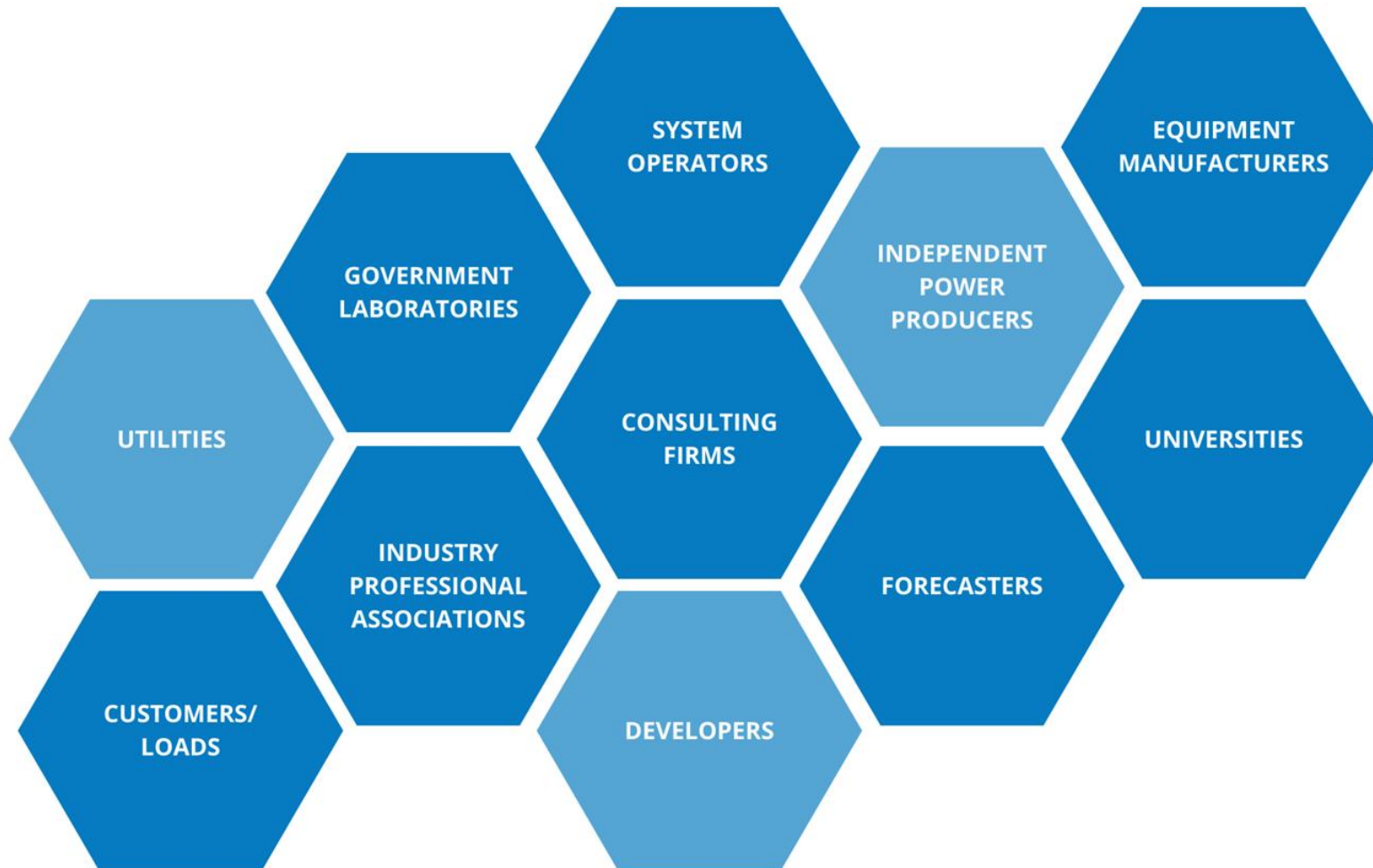
DIFFERENTIATORS

Stellar Technical Reputation | Best in Class, Global Reach | Independent and Trusted

MISSION

- Address the technical challenges for transforming energy systems through collaboration, education and knowledge sharing
- Work with all industries, energy vectors and applications globally
- Forward leaning, but not advocating, keeping everyone at the table
- Working at the cutting edge of the technical pathways toward 100%
- Pragmatically progressive—reliable, economic and sustainable transformation

300+ Members Globally



Welcome!



- **Welcome to the first presentation of ESIG's Electromagnetic Transient Course (supported by CMEI – Thanks again)**
 - **Instructors for the week:**
 - Lukas Unruh – Engineering Manager – Electranix
 - Alex Shattuck – Director of Grid Transformation – ESIG
- **Logistics for the week:**
 - Training will run 9:00a – 5:00p on Tuesday and Wednesday
 - Tuesday lunch presentation by Mehdi Rezvani, ERCOT
 - Training will conclude at **2:30p on Thursday**
 - Happy Hour is Tuesday 6:00p – 8:00p at Meanwhile Brewing

Welcome!



Some questions to kick us off:

- 1. Poll of industry sector**
- 2. What topics are you hoping we cover this week?**
- 3. Poll of experience in industry**
- 4. Poll of experience in modeling**
- 5. Poll of experience in EMT modeling**

Key Takeaways From This Course



- **Align on modeling and study fundamentals**
- **Understanding of the use cases, benefits, and limitations of EMT**
- **Foundation for Model benchmarking, usability, and the right domain and model type**
- **Model quality testing and design evaluation**
- **When, how, and why to perform special studies (SSCI/SSO, Large Loads, Weak Grid, etc.)**

Acknowledgement of Multiple Software Tools



There are multiple commercially available Electromagnetic Transient (EMT) Software available currently

Wednesday and Thursday will include demonstrations in one EMT software but this is not an endorsement of this software, please use the software tool that best aligns with your needs

Throughout this week (and in general in public discussions) please refer to any EMT software tools as "EMT" or similar and try to refrain from using brand names in any discussions

Study Basics for the New Power System Paradigm



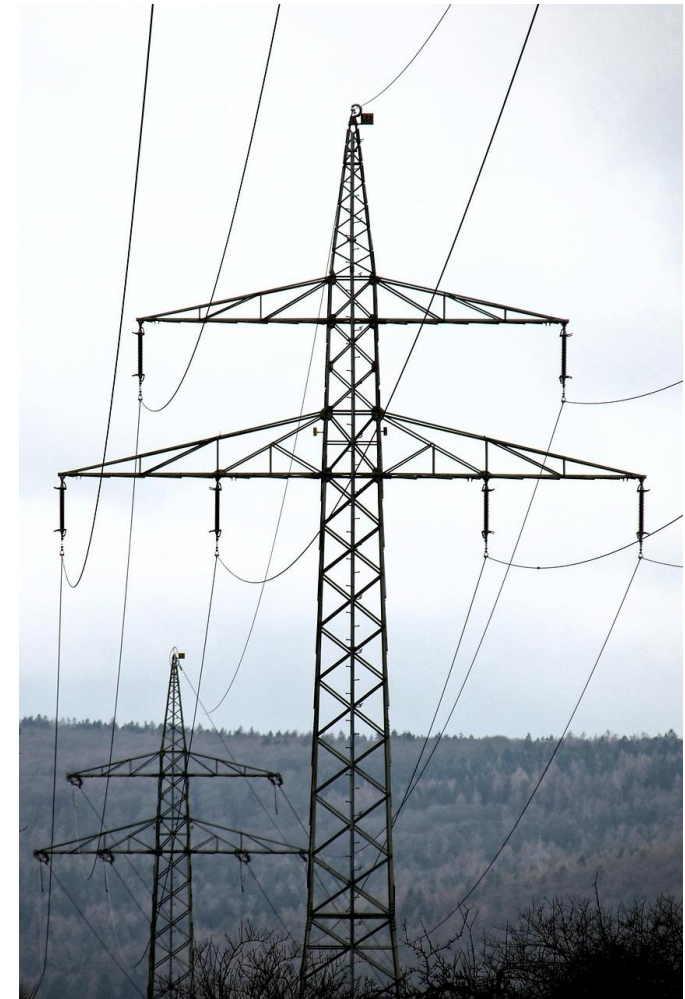
ESIG

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?



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?



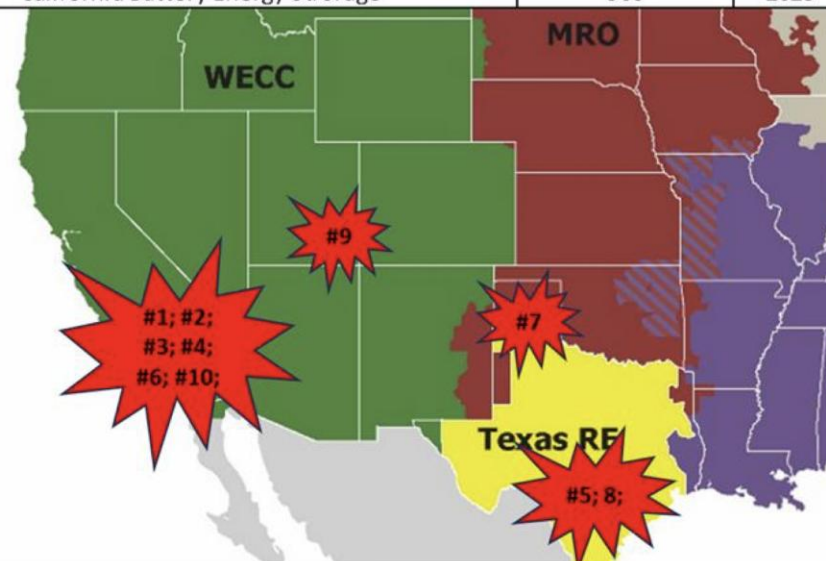
- **Disparate interconnection and planning requirements and processes**
 - The North American power system has diverse electrical characteristics
 - The grid is “transforming” differently everywhere
 - Difficult to determine what the best practice (or sufficient practice) is
- **Heavy reliance on Standard 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 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**

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

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)



Synchronous Machine	Modeling Consideration	Inverter-Based Resource
<ul style="list-style-type: none"> • More mature • Parameters and controls are standardized • Relatively simple plant construction (generator and main power transformer) 	Technology Maturity and Construction	<ul style="list-style-type: none"> • Significantly less mature • Parameters and controls cannot be standardized (<i>performance can</i>) • Relatively more complex plant construction (collector cables, collector transformers, multiple manufacturer plants and hybrid resources)
<ul style="list-style-type: none"> • Largely dictated by the physical behavior of a large spinning mass • Relatively small variations in performance from control parameters 	Technology Performance	<ul style="list-style-type: none"> • 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
<ul style="list-style-type: none"> • 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	<ul style="list-style-type: none"> • 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)



- **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.

What Does NERC Say?



- 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 parameterized² to represent site-specific³ 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.

What Does NERC Say?



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.

What Does NERC Say?



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.

What Does NERC Say?



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

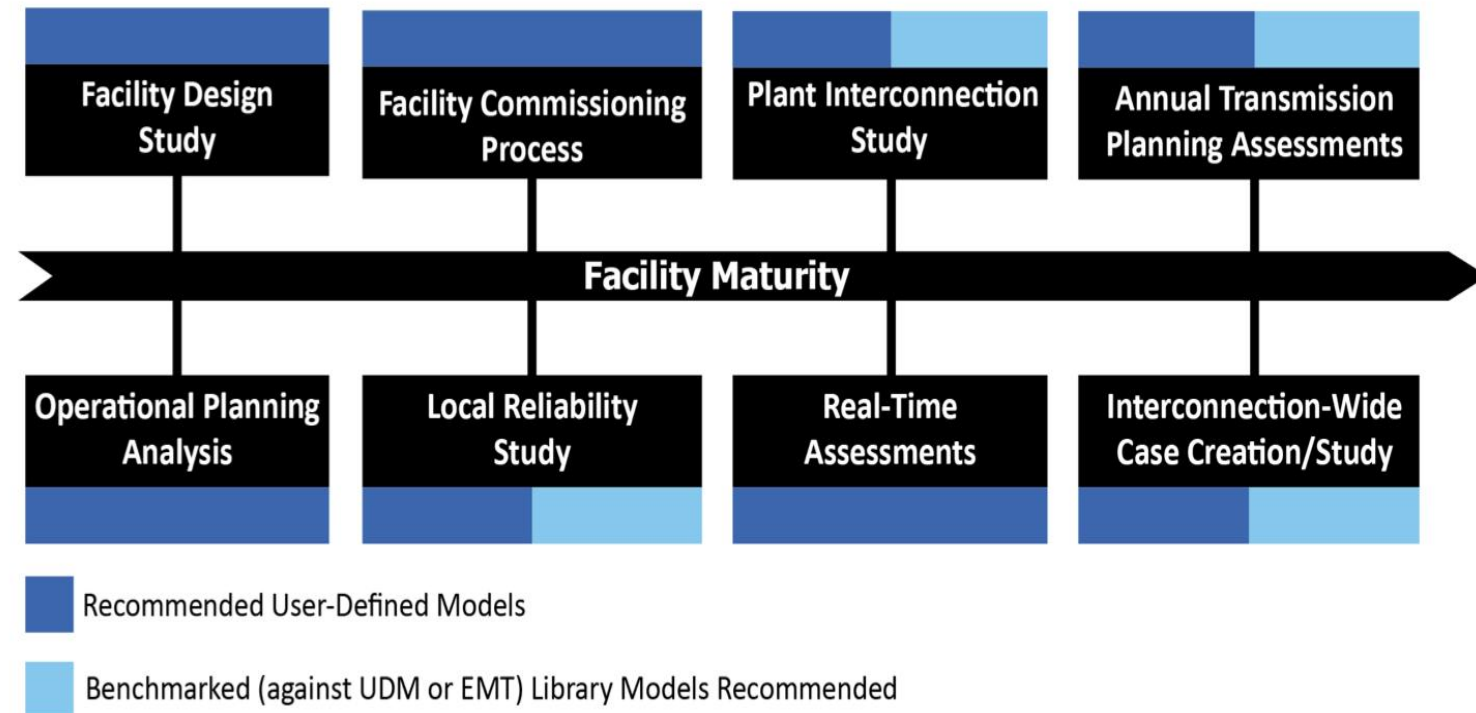
- A model validation report is provided that compares the actual equipment performance against the EMT, positive sequence UDM, and library models.⁷
- A model benchmarking report is provided that compares the response of models across each platform.
- The UDM should include compiled .dll files such that no additional compiling is required by the end-user.
- The UDM should be accompanied by sufficient documentation⁸ 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.

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



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



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

Table 3.1: Solar PV Tripping and Modeling Capabilities and Practices

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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

Why not EMT for everything?

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

Adapted from: [NERC 2022 Odessa Disturbance Report](#)

Grid Reliability is More Than Ridethrough



- 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

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
 - Ride-through 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 ride-through 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

Introduction to Electromagnetic Transient Simulations



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PSPD vs EMT Basics

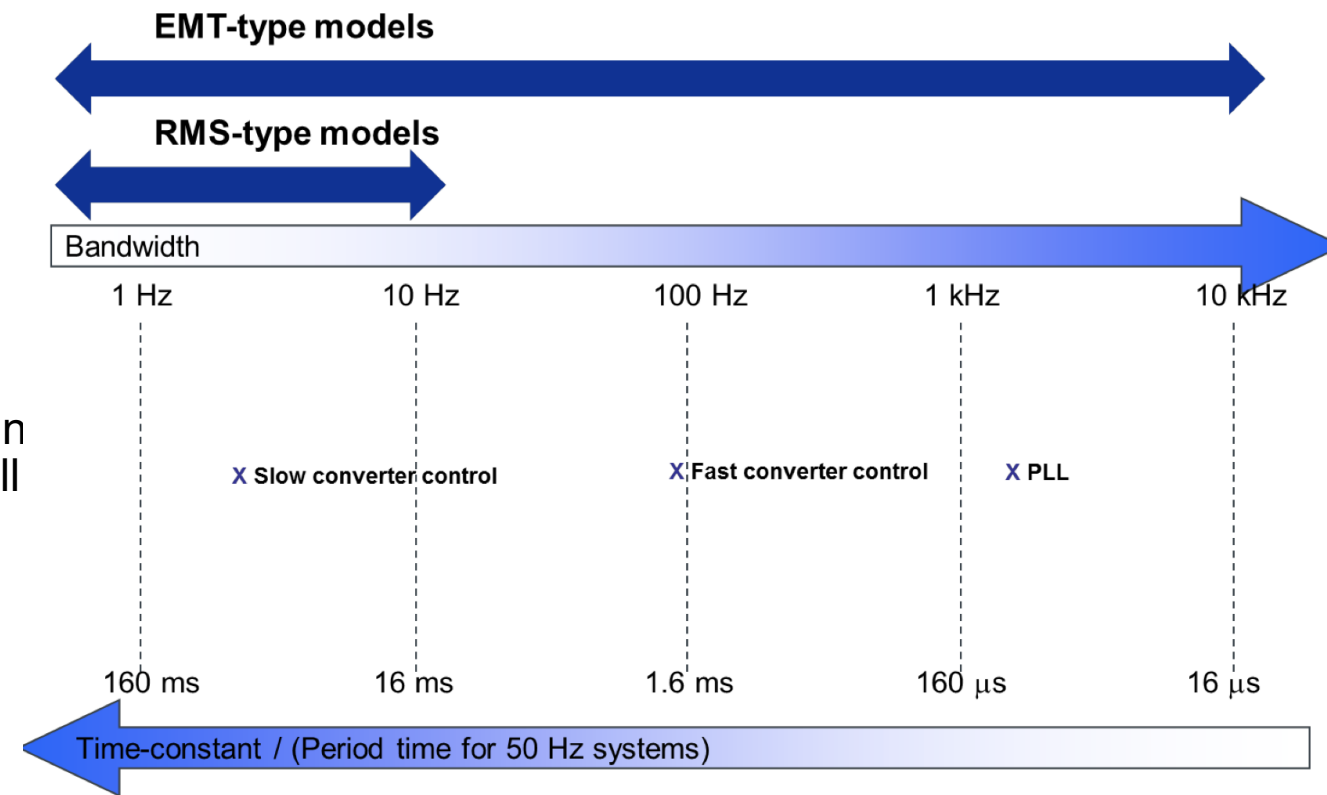
Both PSPD and EMT have great use cases and limitations

- **PSPD:**

- Solution is based on phasor calculations
 - Quick simulation time to provide insight into power flow, voltage, and current
- Assumes a quasi-steady state and sinusoidal balance

- **EMT:**

- Solves differential equations in the time domain and resolves the actual waveform at very small time intervals
- Does not assume sinusoidal balance and captures:
 - Unbalanced faults
 - Very fast control behavior
 - Resonances



Source: [AEMO](#)

PSPD vs EMT Generally



PSPD

Short simulation times

Less detailed and accurate*

“Sledgehammer” of current study paradigm

More Generic/Standard Library than Manufacturer-specific

Can be difficult to map to real-world parameters

Limitations at low “system strength”

EMT

Significantly longer simulation times

More detailed and accurate*

“Scalpel” of current study paradigm

Most often Manufacturer-specific

Often easier to map to real-world parameters

Fewer limitations at low “system strength”

Can be used to study harmonics, SSCI/SSR

How Is The Power System Changing?

- **System inertia or “system strength” is reducing**
 - *All assumptions must change*
- Frequency perturbations will be larger and happen faster (Rate of change of Frequency (ROCOF) increase)
 - Higher ROCOF means its harder to establish and remain within limits
- System voltages will be “less firm”
 - With lower system strength, each change in reactive power will cause a larger change in voltage
- **More complex resources are interconnecting**
 - Hybrid, mixed manufacturer, supplementary controls and devices
- **EMT simulations (and PSPD simulations**) are paramount represent increasingly complex resources on “weakening” system**

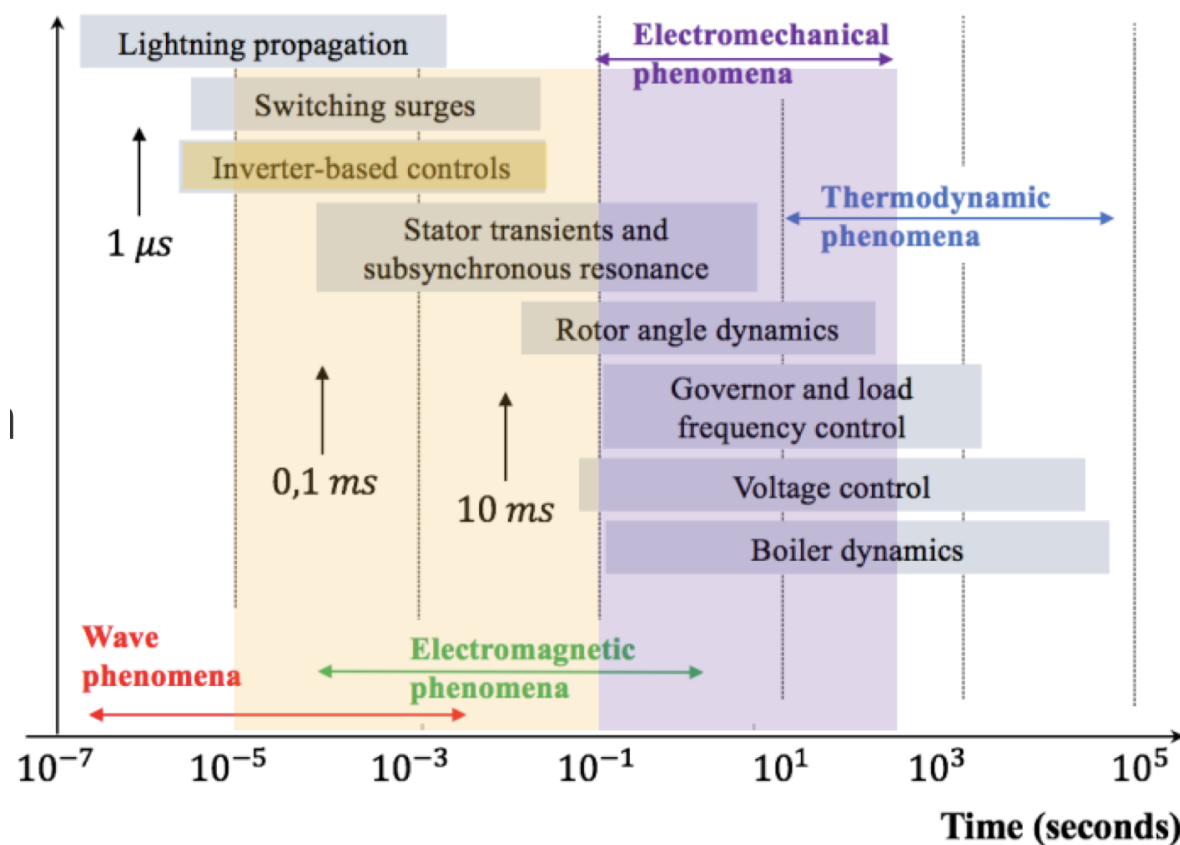
Power System is Changing: Timeframe

- **IBR bring extremely fast controls driven by power electronics and software**
 - Performance is significantly more decoupled from physical behaviors when compared to synchronous machines
 - Software-based controls and power electronics significantly increase the speeds and magnitudes of response
- **IBR controls will get even faster**
 - With increased penetrations of grid forming inverters, overall timeframe will become faster

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

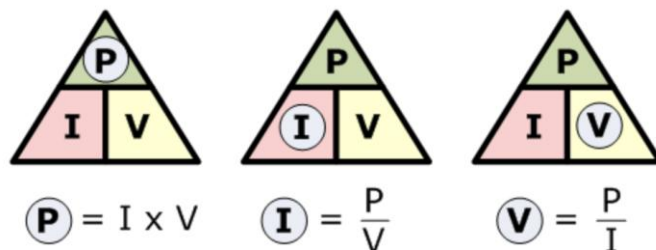
Power System is Changing: Timeframe

- Relevant control and time constants in a synchronous generator-dominated system fall within the electromechanical window
- Relevant controls and time constants for IBR are significantly faster and encompass the **electromagnetic** window
- **As more IBR integrate with the system:**
 - System stability becomes more dependent on faster controls
 - Fast transients and responses to those transients play larger roles in reliability
 - The system response overall becomes faster



Power System is Changing: System Strength

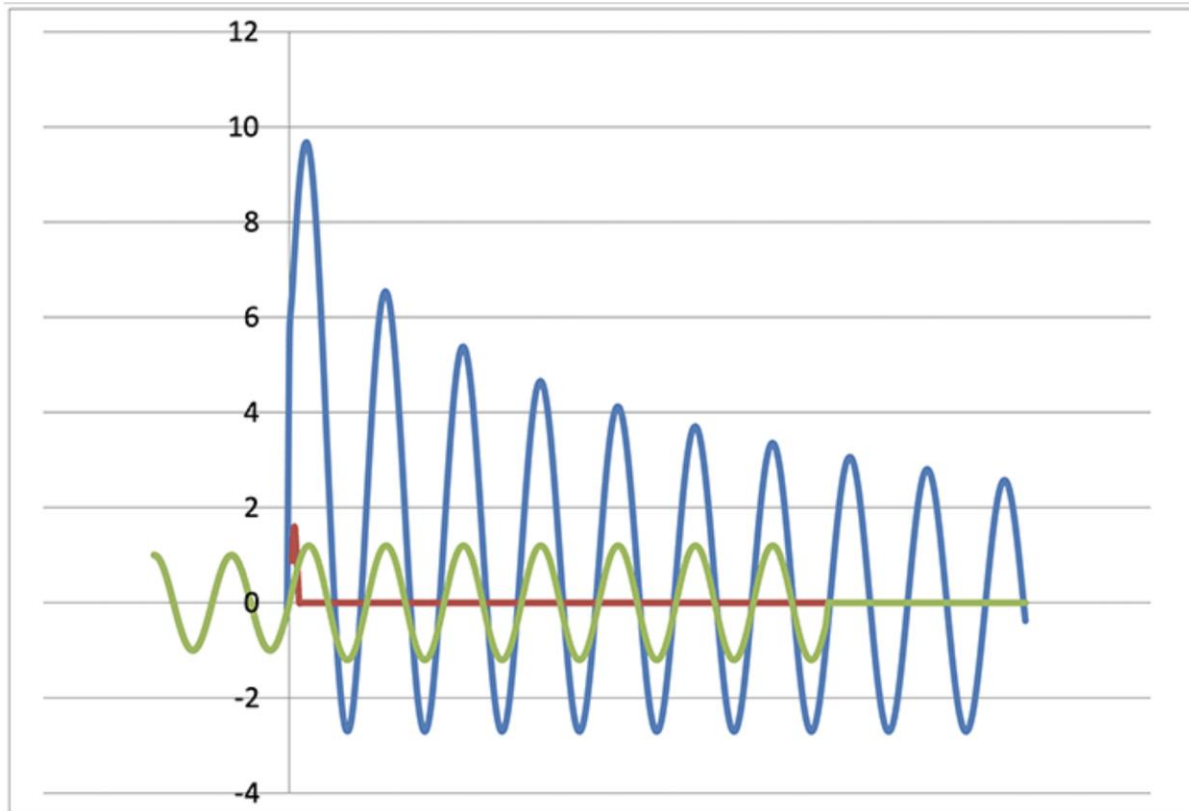
- **Synchronous machines provide inertia to the power system**
 - Large spinning masses have momentum and resist changes
 - Power-electronics resources decouple the mechanics from power injection (type 1-3 wind need consideration)
- **Fault current is provided by this momentum**
 - During system disturbances voltage drops
 - Synchronous generator inertia continues to provide power



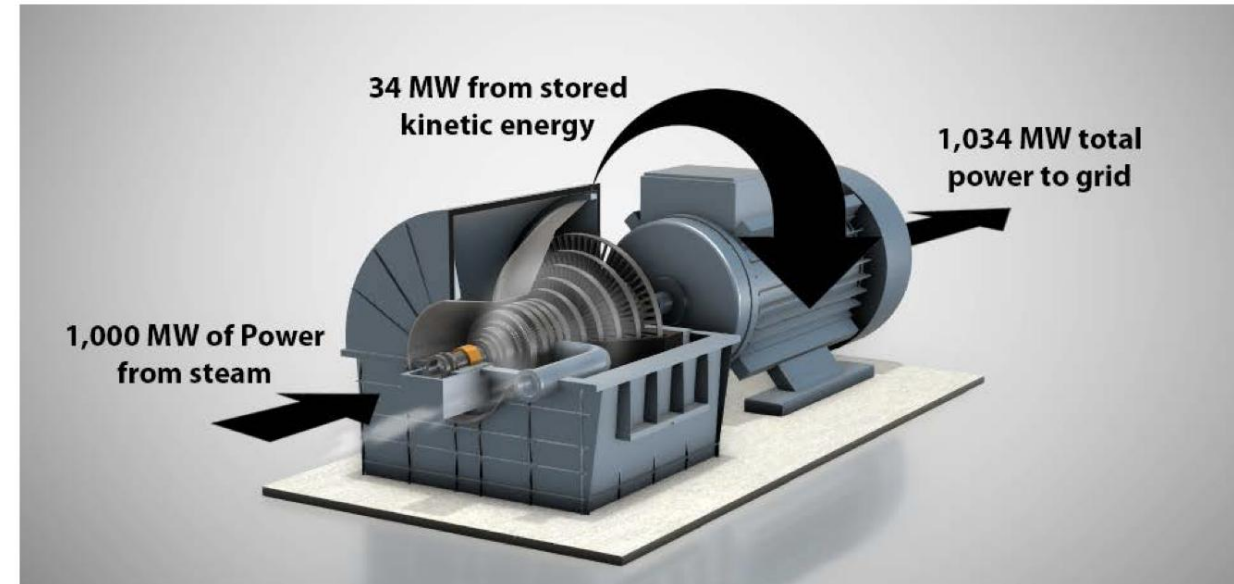
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• Very fast frequency control	• Inherent inertial response
• Minimal plant auxiliary equipment prone to tripping	• Sensitive auxiliary plant equipment
• Dispatchable based on available power	• Fully dispatchable
• Can provide essential reliability services	• Can provide essential reliability services

Short Detour to System Protection

- Detailed and high quality EMT protection models and studies have the potential to help solve this problem

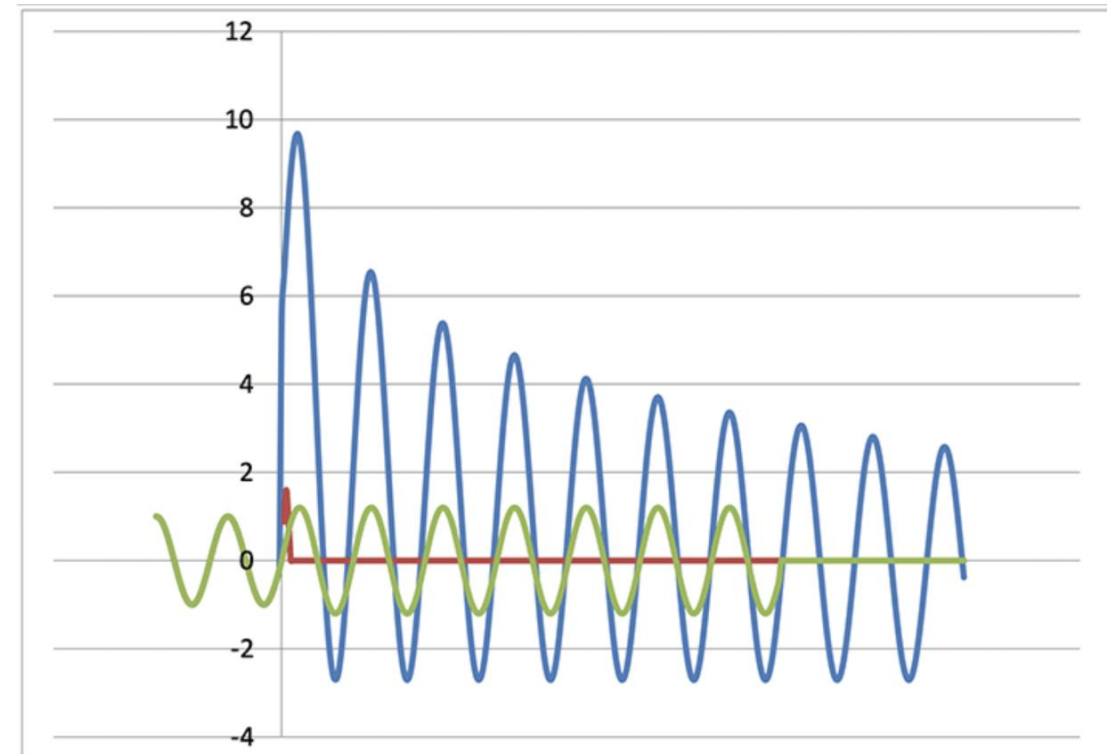


Fault currents for a synchronous generator (blue), an inverter with rapid disconnect (red), and an inverter with ride-through capability (green).



Short Detour to System Protection

- ~6x fault current injection from synchronous machine
- System protections currently use fault current as a primary trigger
 - What happens when protection expects 6x fault current?
 - How can detailed EMT modeling of test systems and protection devices help new solutions?
- Challenges to overcome
 - IBR **do** provide some fault current
 - Fault current injection changes with control changes
 - There is no “one size fits all” for fault current
 - Cannot fit a IBR-sized peg into a synchronous machine-sized hole

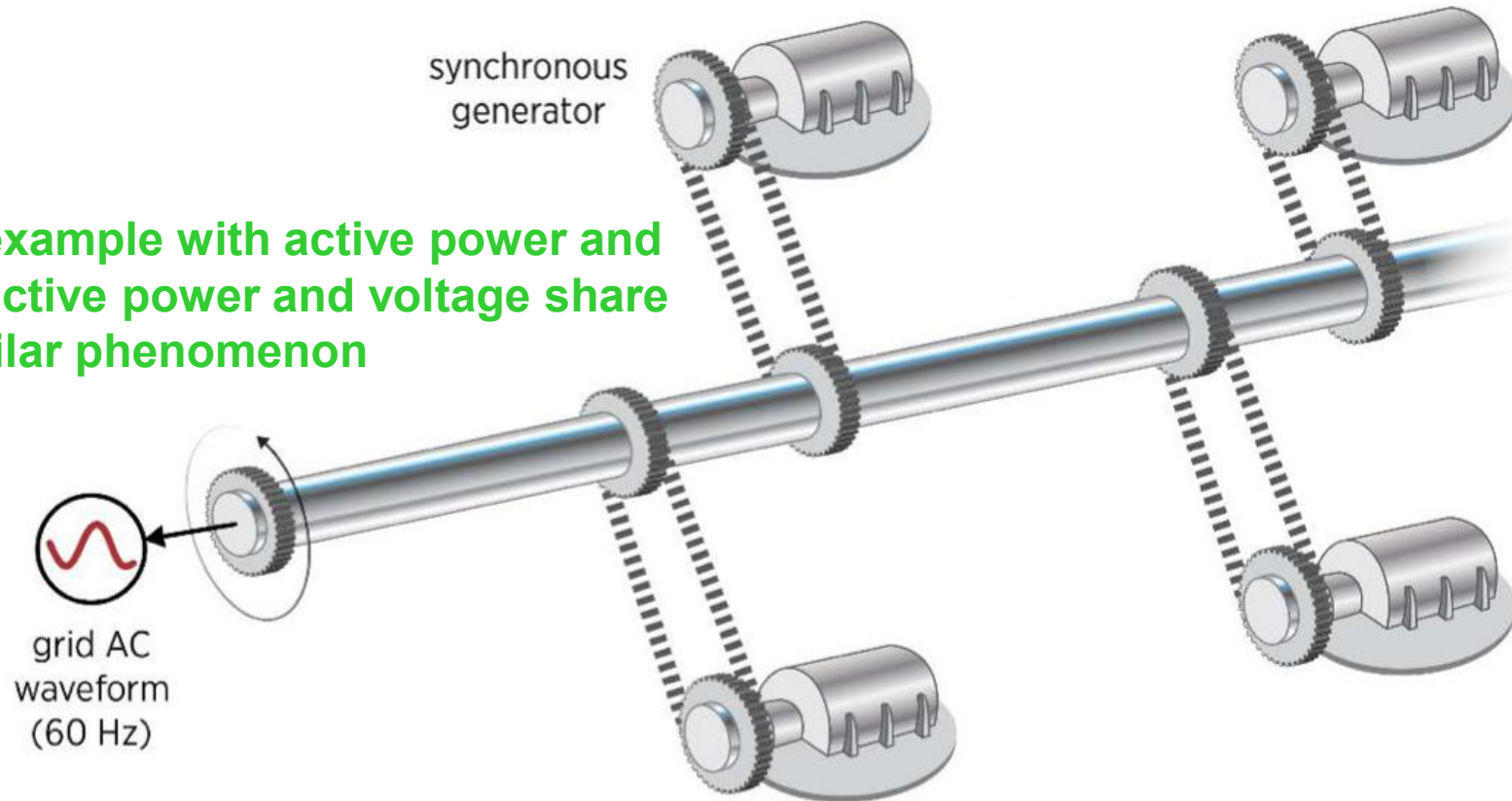


Fault currents for a synchronous generator (blue), an inverter with rapid disconnect (red), and an inverter with ride-through capability (green).

Source: [NREL](#)

Inertia and System Strength: High Level

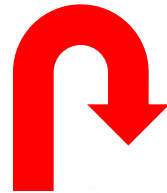
synchronous generator



Note: This is an example with active power and frequency but reactive power and voltage share similar phenomenon

Inertia and System Strength: High Level

System disturbance
causes reduction in
system frequency

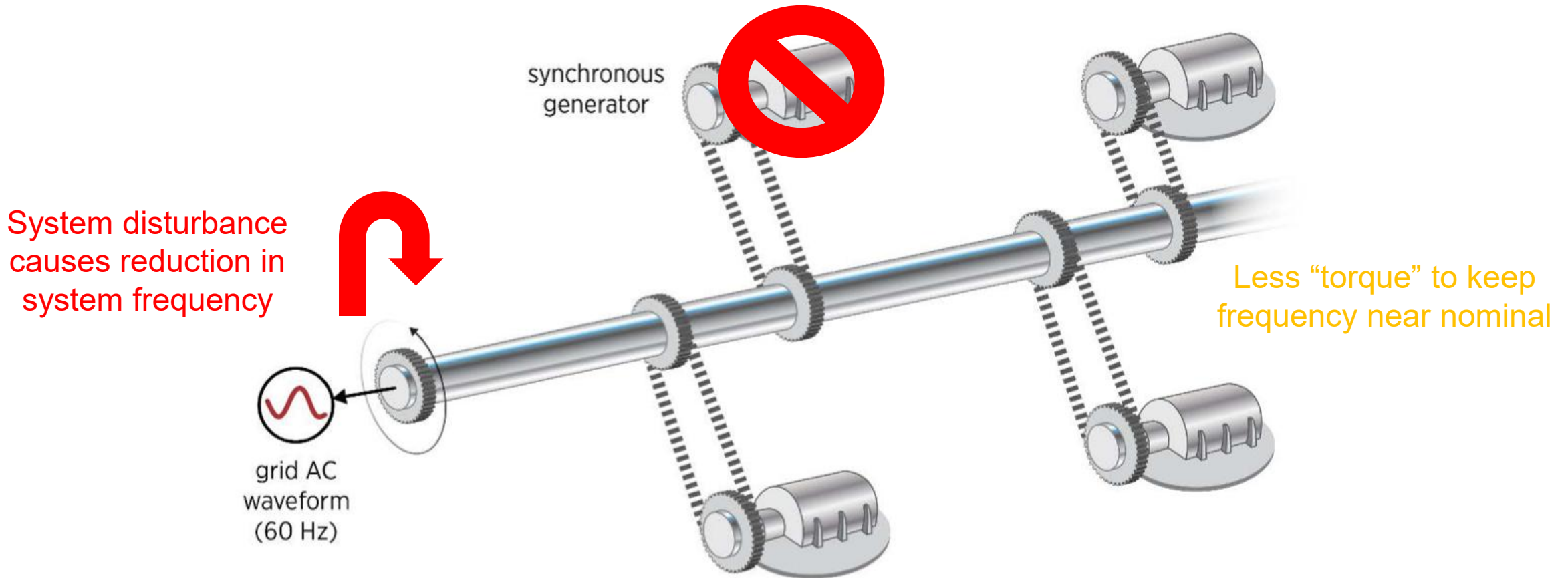


grid AC
waveform
(60 Hz)

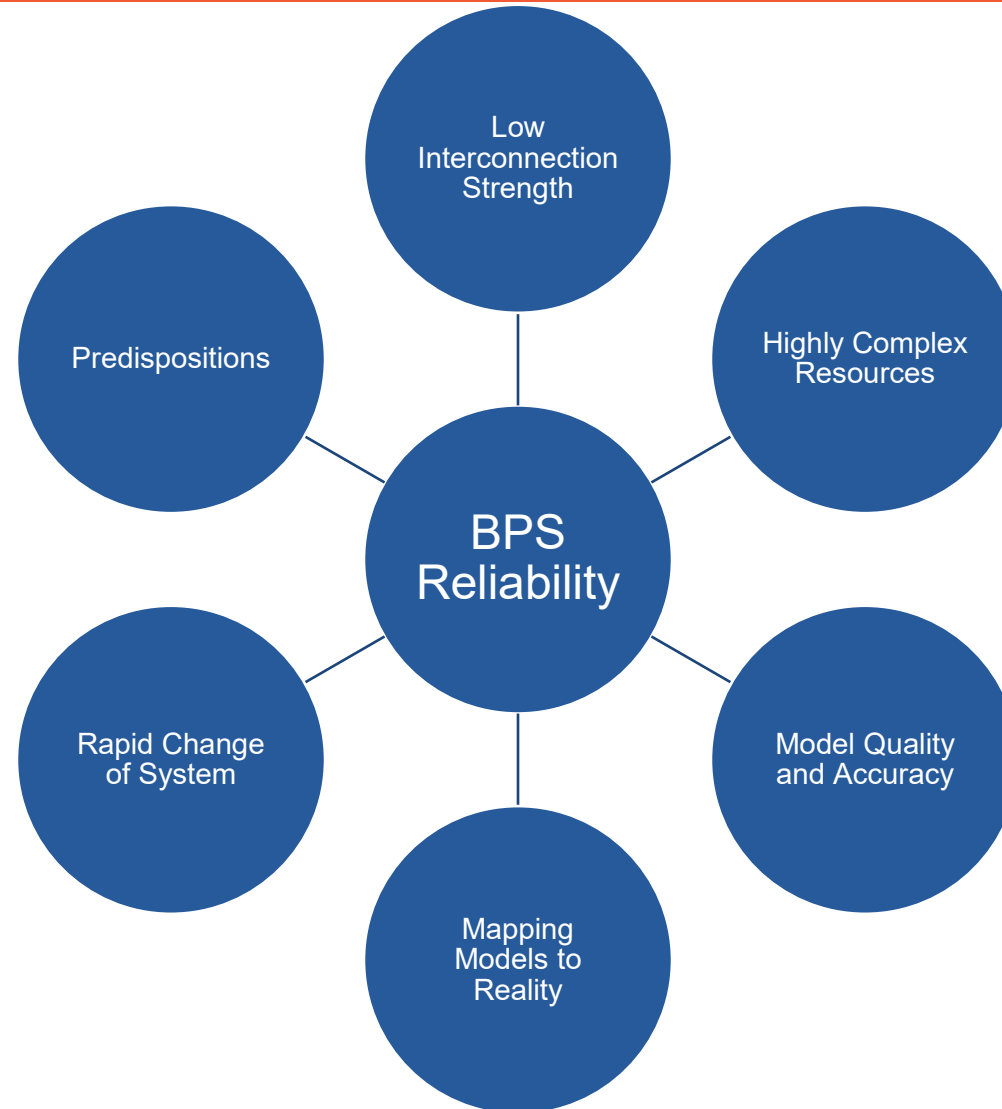
synchronous
generator

Significant “torque” to
keep frequency near
nominal

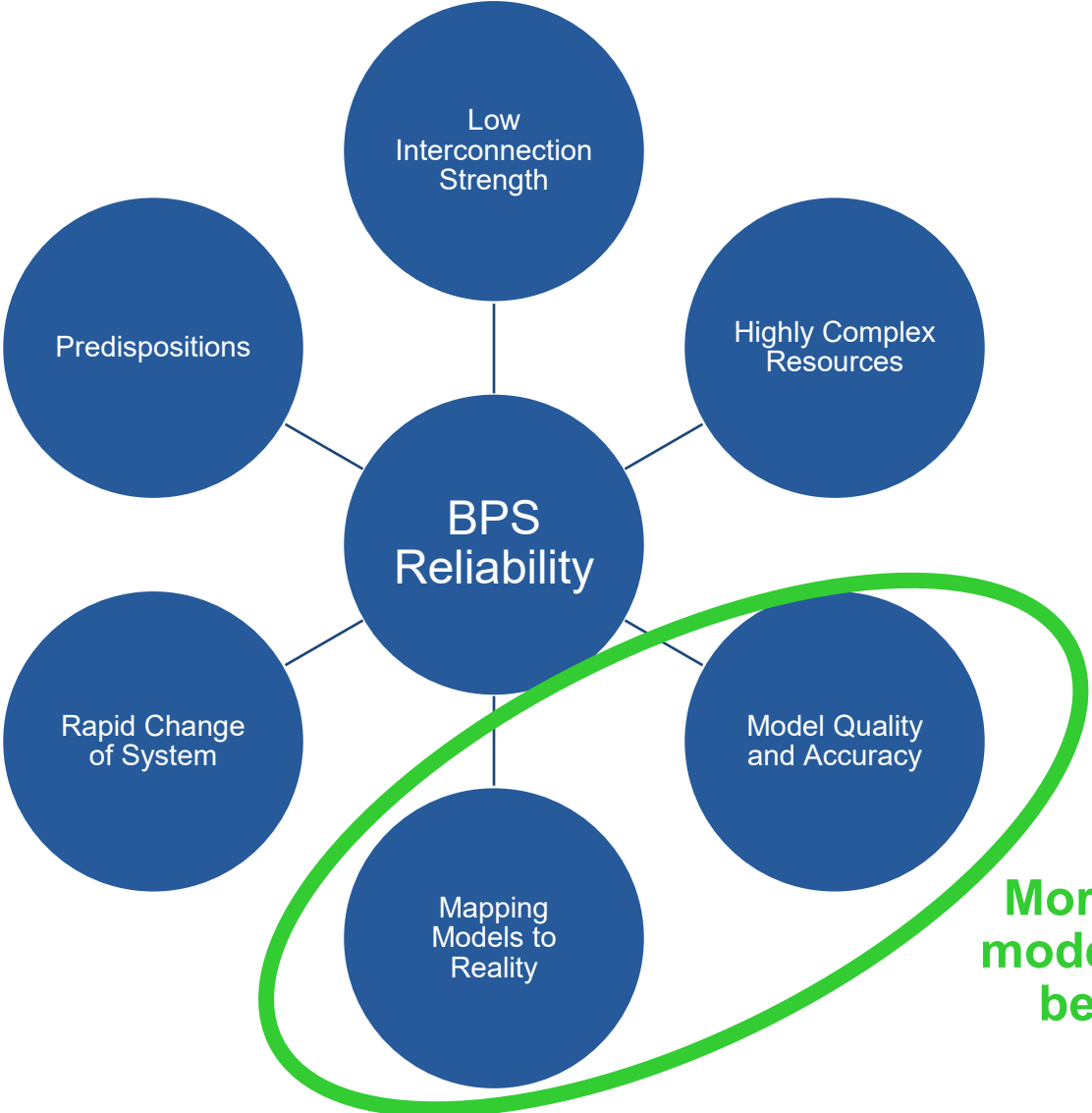
Inertia and System Strength: High Level



Primary Reliability Gaps



Primary Reliability Gaps



More detail in the model creation and benchmarking session

Breaking Predispositions

PSPD:

- PSPD is not obsolete
- PSPD models can be highly accurate*
- PSPD simulations have great use cases

EMT:

- EMT is not the only “right” tool
- EMT models are not accurate just because they are in the EMT domain
- Not everything needs an EMT simulation

System Strength Weakening

PSPD:

- Simulation issues at low short circuit ratios (~3-5)
- Models may not have advanced control features
- Real-world solutions may not map to PSPD models

EMT:

- Capable of simulating in low short circuit ratios (less than 3)
- Models likely include all relevant controls
- Often capable of better mapping between real and modeled parameters

More Complex Resources

PSPD:

- Difficult to model third-party controllers, communication delays, communication protocols, etc.

EMT:

- High level of detail makes the modeling of highly complex control system feasible

Mitigating Reliability Needs

PSPD:

- Can be difficult to represent on-site tuning
 - Often do not include advanced controls
- Lack of direct mapping between model and product
 - No mapping in standard library models

EMT:

- Easier to represent on-site tuning
 - Often include advanced controls
- More direct mapping ensures on-site solutions can be tested and studied

Mitigating Reliability Needs

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EMT:

- Easier to represent on-site tuning
 - Often include advanced controls
- More direct mapping ensures on-site solutions can be tested and studied

Critical for the efficient use of the power system



“New” Grid Issues

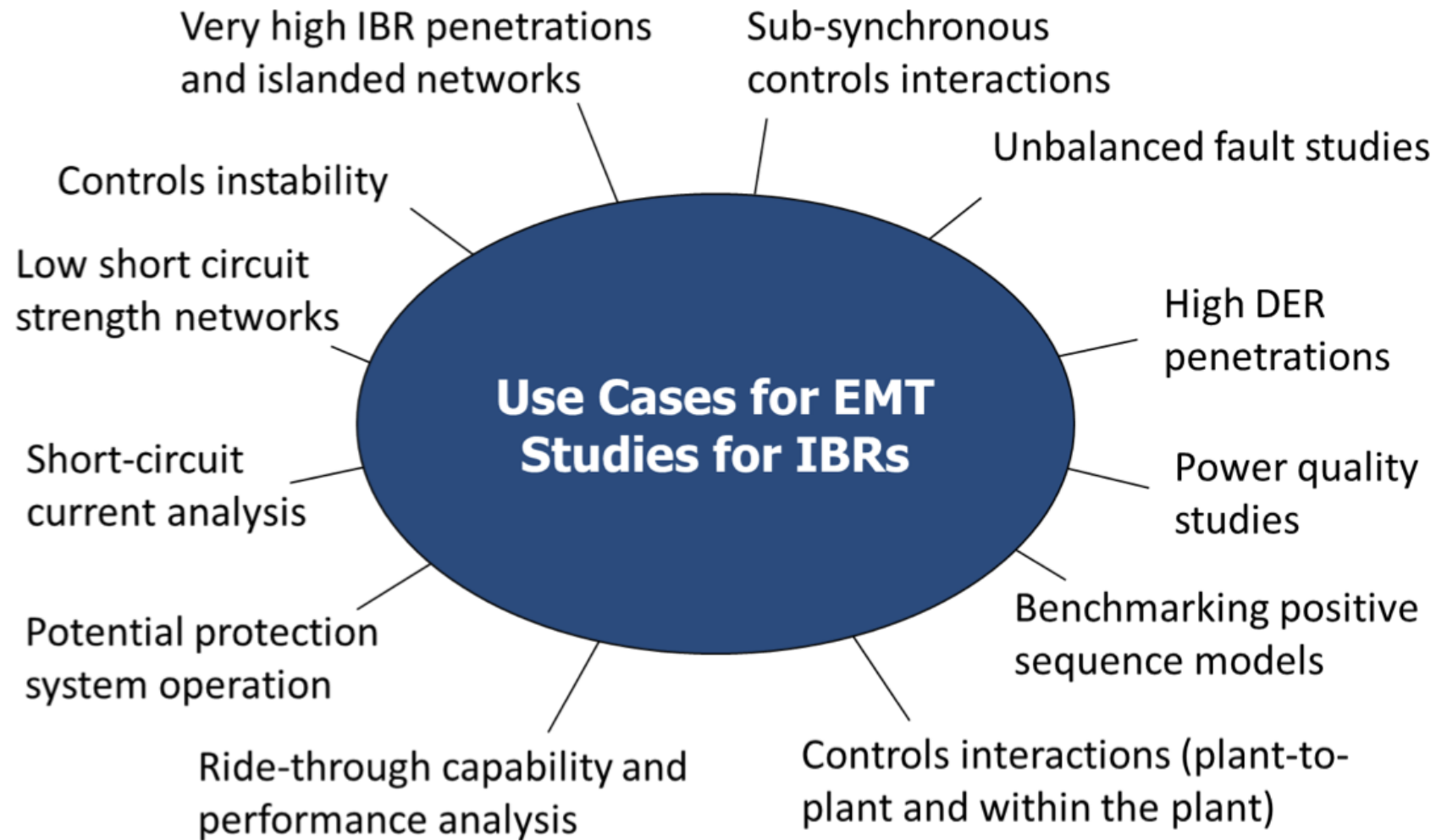
PSPD:

- Not capable of studying sub-synchronous interactions, unbalanced faults, power quality
- Difficulties when studying controller interactions

EMT:

- Capable of studying sub-synchronous interactions, unbalanced faults, etc.
- Added detail helps uncover controller interactions
- Studying effects of changing power system on synchronous mechanics

Use Cases for EMT Studies



Benefits



- Very robust solution engine solving the entire waveform in the time domain
- Able to simulate low system strength conditions
- Able to represent mechanical behaviors
- Often contain real code or highly mapped representations
- Needed to study SSCI/SSR, harmonics, etc.

Limitations



- Extremely high computational burden
- Steeper learning curve (both the tools and the problems)
- EMT models are only as good as their parameterization
- EMT models may not exist for a piece of equipment
- Lack of regulatory clarity

Benefits and Limitations of EMT



Benefits



- Very robust solution engine solving the entire waveform in the time domain
- Able to simulate low system strength conditions
- Able to represent mechanical behaviors
- Often contain real code or highly mapped representations
- Needed to study SSCI/SSR, harmonics, etc.

Extremely capable and important tool

Limitations



- Extremely high computational burden
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Even the best tools need to be used with intention

EMT Simulation Prerequisites



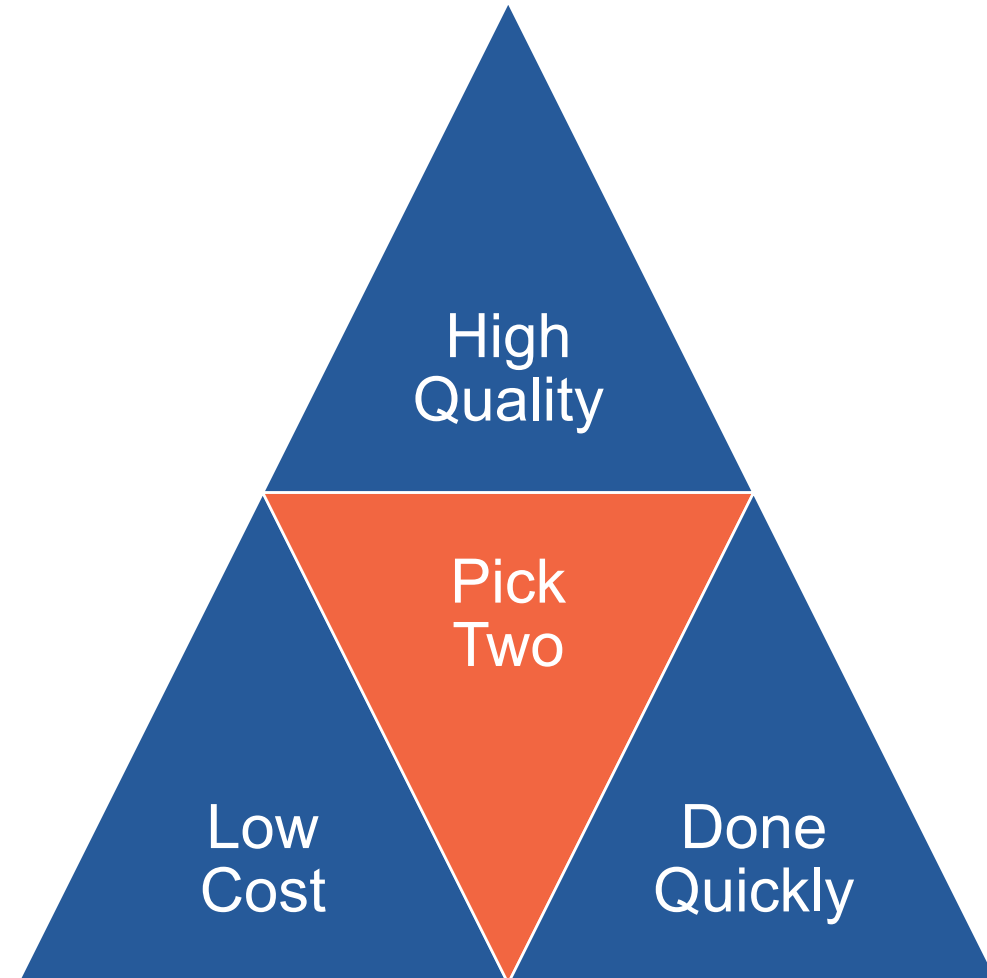
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EMT Simulation Key Considerations



- **EMT Simulations are:**
 - **Difficult**
 - Lack of subject matter expertise world-wide
 - Often used to solve specific problems in specialized studies
 - **Expensive**
 - Subject matter expertise is not cheap
 - EMT models may come at high costs
 - **Time consuming**
 - EMT simulations take much longer to run than PSPD and loadflow
 - Additional simulation detail requires additional data inputs



Does this need an
EMT study?

What am I studying?

Why am I studying it?

Do I have sufficient experience?

Does this need to be studied in EMT?

Can this be studied sufficiently in another way?

Do I have the required data?

- **EMT simulations are not needed for every analysis**
 - Numerous power systems studies can be performed in different software and with different methods
- **EMT simulations *should not be used* for every analysis (generally... for now)**
 - EMT simulations can be overly complex for some reliability needs
 - Attempting to shift paradigm from all PSPD to all EMT can impede incremental progress
- **Many of the principles of good EMT simulation practice apply also to PSPD**
 - Increasing quality, accuracy, and ability to use manufacturer-specific models can increase study accuracy without going “full EMT”
- **Any study is only as good as its inputs**
 - EMT does not automatically equate to correct or accurate
 - Proper model creation, validation, and benchmarking are necessary

Screening!

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What is Screening and Why?



- **Screening (in the context of EMT):**
 - Assessing whether or not an EMT study should be performed
- **Why is screening important:**
 - Resources are limited
 - Time is limited
 - EMT is expensive
 - Some systems and topologies may not see large EMT benefit
- **Screening now may make EMT analysis easier in the future**
 - [FERC Order 2023](#) states: “These modeling requirements include: (...) (3) a validated electromagnetic transient (EMT) model, **if the transmission provider performs an EMT study as part of the interconnection study process.**”
 - Screening for need now can inform requirements for the future

Principles of Screening



- **Screening does not need to be a detailed process, analysis, or dependent on new tools**
 - Screening *can be* as simple as asking the questions in previous slides
 - Screening *can be* as complex as new methods, tools, and processes
- **Screening should be formalized in some way**
 - Study assumptions and methods are good to have in writing
- **Considerations when performing Screening**
 - IBR penetration
 - Series compensation
 - System strength
 - Complexity of interconnecting facilities
 - Grid forming resources



Getting Started With Screening



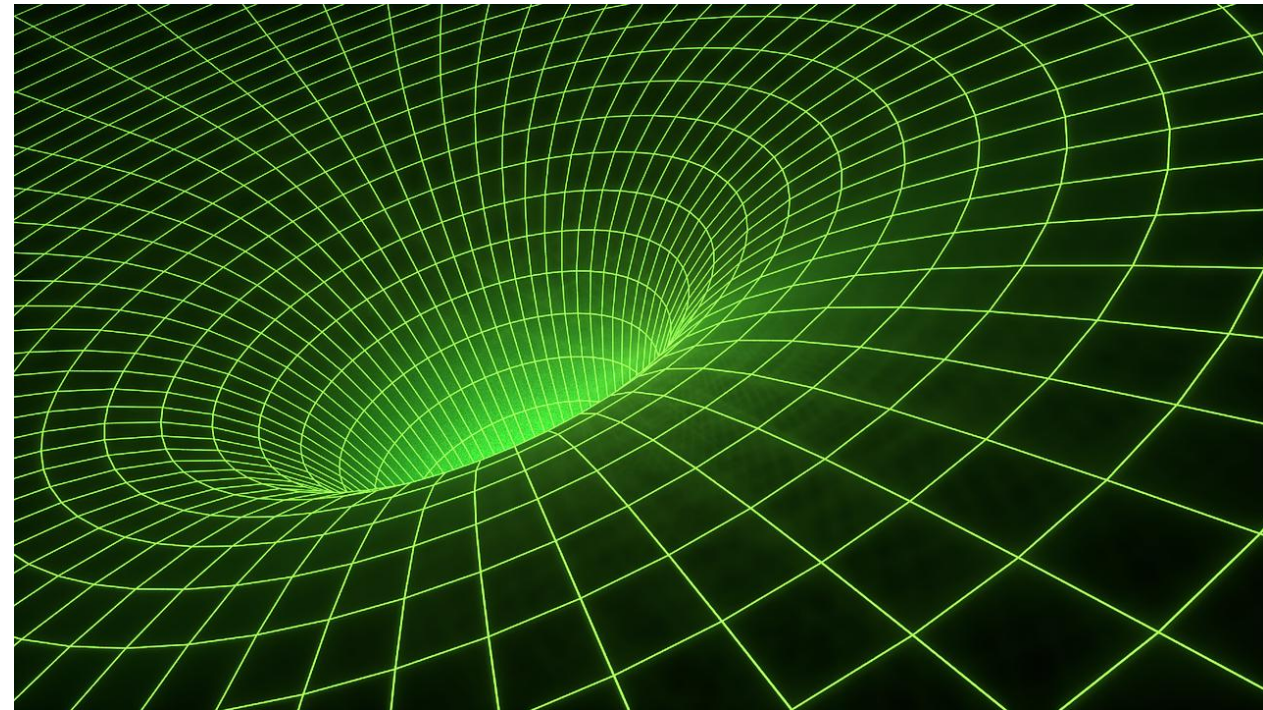
- **Screening metrics, tools, and processes are a hot topic in industry**
 - There are many good examples from the National Labs and industry groups
 - Won't advocate for one method here
 - No one size fits all
 - This are needs further development
- **Metrics for screening need to be thoroughly understood**
 - Many metrics like short circuit ratio (SCR) are misused
 - All metrics have limitations and use cases
- **Look to peers with similar system characteristics**
 - Not every problem needs a novel solution
 - Peer-to-peer learning is critical in the grid transformation
- Andrew Isaacs presented this in ESIG's Interconnection Studies Course
 - [Recording](#)
 - [Slides](#)



So You've Decided to Perform EMT



- **Understand the problem you are solving**
 - Why does the problem exist
 - What performance is needed to be reliable
- **Understand tests needed to confirm solution**
 - Choosing proper tests and success criteria
- **Collect necessary data**
 - Managing stakeholders
- **Avoid doing "the engineer thing"**
 - What is necessary and what is nice to have



Maximizing EMT Simulation Benefit



- **Ensure the use of high quality and representative manufacturer-specific models**
 - EMT is just a simulation domain, bad models exist in all domains
 - For forward-looking and academic purposes different model types have good use cases
- **Ensure that the parameterization you study in EMT matches actual equipment**
 - A perfect EMT study with wrong parameters still results in an incorrect study
- **Ensure sufficient data is available for the study being performed**
 - If data of sufficient detail is not available, EMT simulations may not be “worth it”
- **Ensure that the submitted data is correct**
 - Can be extremely difficult to spot incorrect data
 - Comes through engineering judgement and experience
- **Leverage EMT simulations in addition to other analysis methods**
 - Performing analyses in multiple domains to maximize efficiency

Fundamentals of IBR Plant Model Construction



- **What is the purpose of creating IBR plant models?**
 - **At a high level:** To represent the behavior of the IBR plant during normal and abnormal conditions
 - We need to know how an IBR plant will behave under certain conditions and stimuli
 - **Digging in:** There are numerous ways to represent an IBR plant in EMT including:
 - Aggregate
 - Disaggregate
 - Generic/standard
 - Vendor-specific
 - **Key consideration:** How you represent the IBR plant in the model space should be considered based on the goals and purpose for the study work being conducted
 - **Choose two of the following:** (1) Quick study (time and computation); (2) Accuracy; (3) Cost

Introduction to Plant and Equipment Data

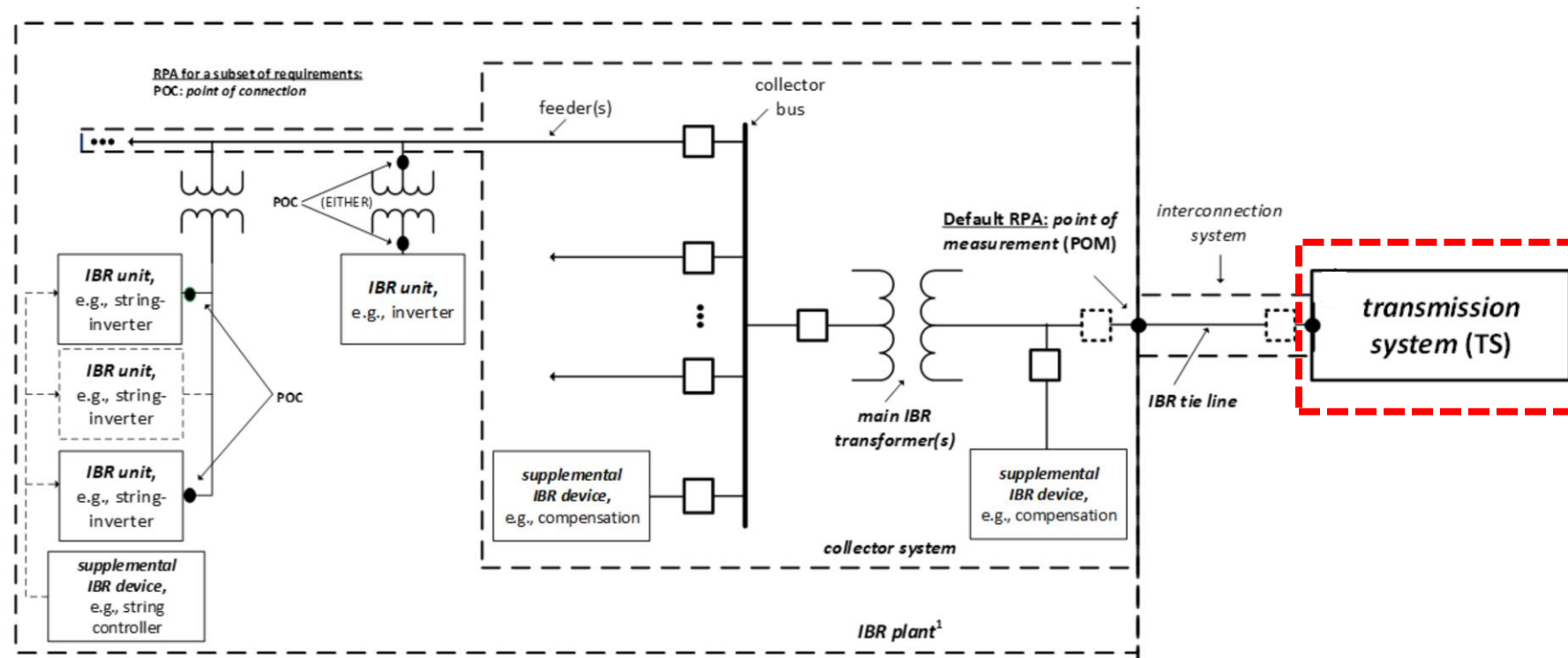


- **A model is only as good as the data that goes into it**
 - A study cannot provide accurate results if the model does not represent the equipment
- **Not all stakeholders involved in the data collection process are technical experts**
 - Modeling and study engineers need to know how to ask for data in the right way to get the right information
 - Engineers also need to build judgement to assess and spot check data
- **Experience in the PSPD processes is transferrable to the EMT space**
 - EMT simulation is an extension of the study process and not an entirely new concept

Components of an IBR Plant – Transmission System

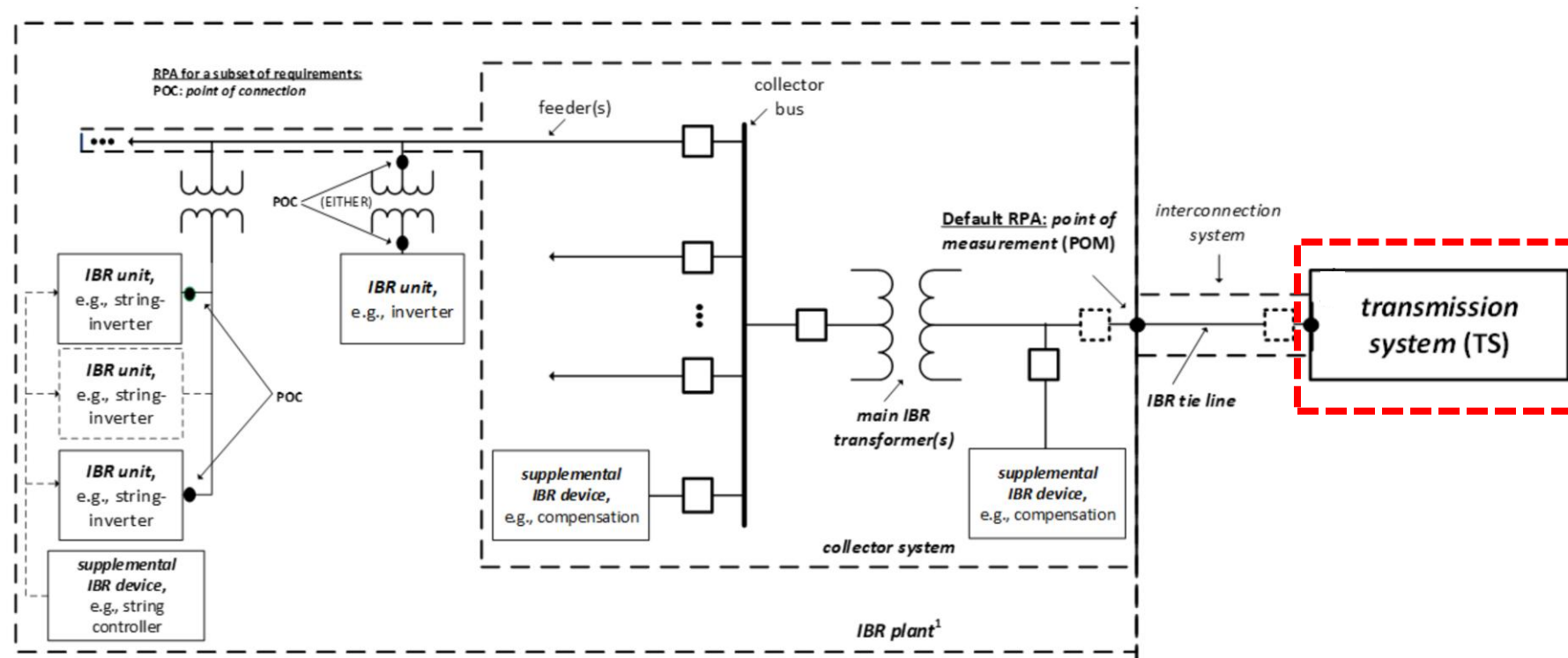
You very likely will NOT get a transmission representation in the EMT domain. (There are a few exceptions)

- Equivalent networks are used in place of the transmission system
- Single machine infinite bus (SMIB) are often used
 - Can be adapted to approximate some TS conditions:
 - SCR
 - X/R ratio
 - System impedance
 - Often represented as a “test bench”



Components of an IBR Plant – Transmission System

You very likely will NOT get a transmission representation in the EMT domain. (There are a few exceptions)

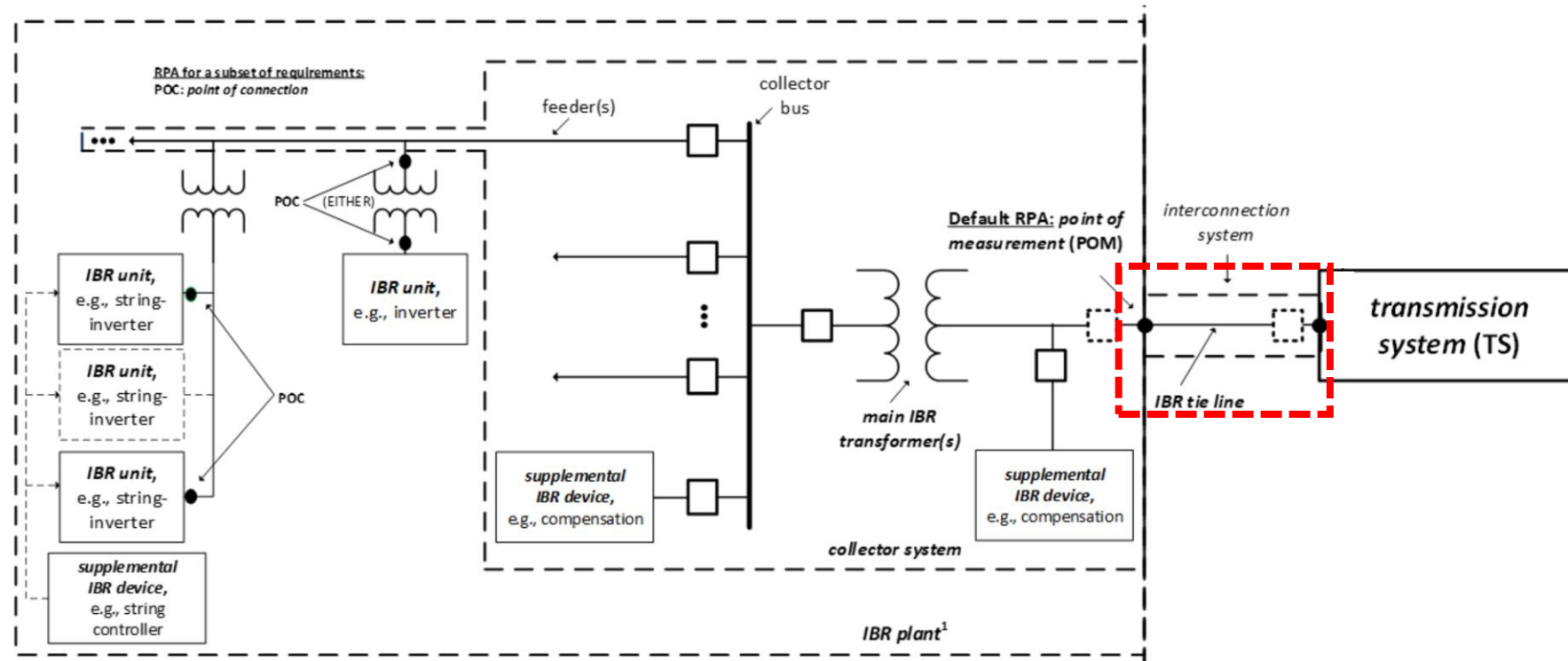


- Strong driver for the need for cross-domain simulation
 - EMT for complex plant analysis, PSPD to "check"
- Co-simulation options exist
 - Not a perfect solution
 - Many technical and practical limitations
- Small portions of the TS may be used with equivalized boundaries

Components of an IBR Plant – IBR Tie Line

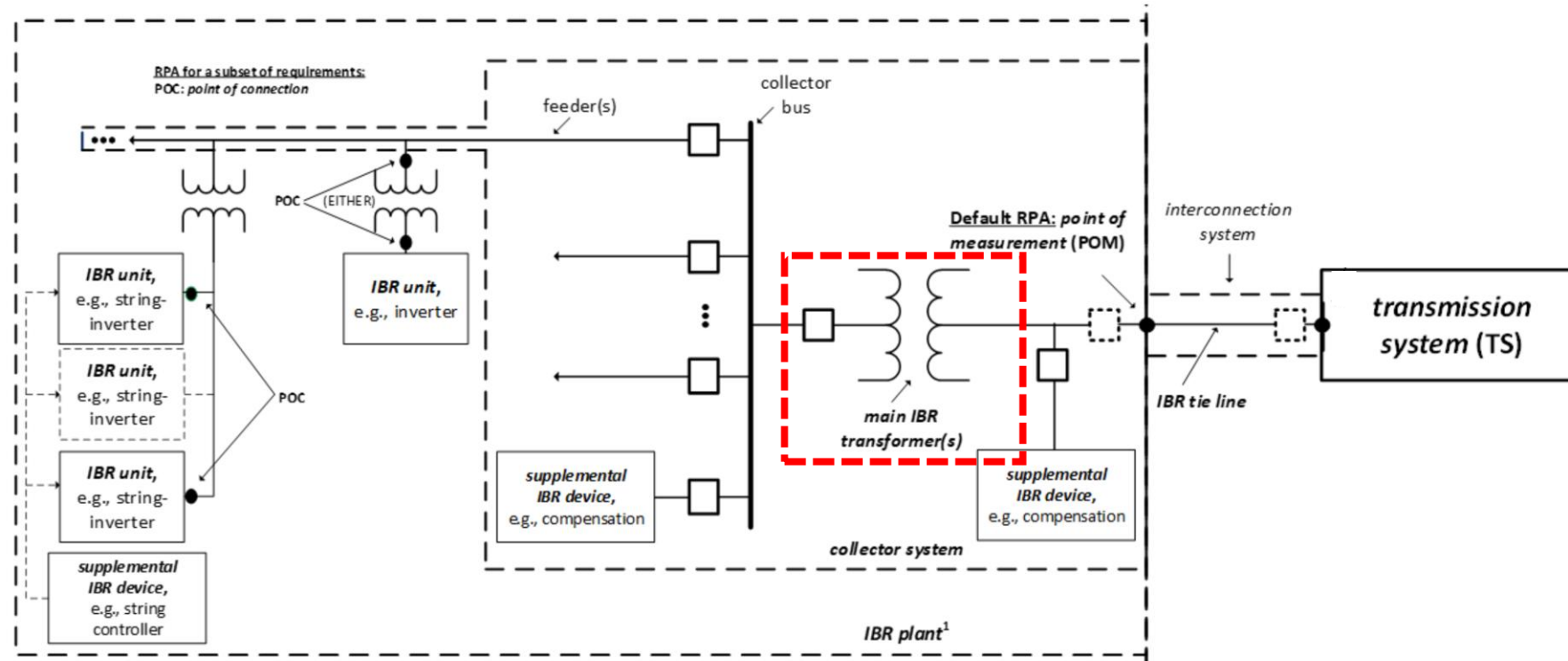
IBR tie lines are often "ignored" due to typically very short lengths

- Many IBR tie lines are extremely short (hundreds of feet) and their impedance is often not included
- Tie lines are important outside of just their impedance
 - Different regional requirements apply at sending or receiving end of tie line
 - Tie lines are often used for controller feedback in the model space
- How much detail do we need in the EMT space?



Components of an IBR Plant – Main Power Transformer

Main IBR transformers: also known as main power transformers (MPT) are frequent causes of incorrect representation

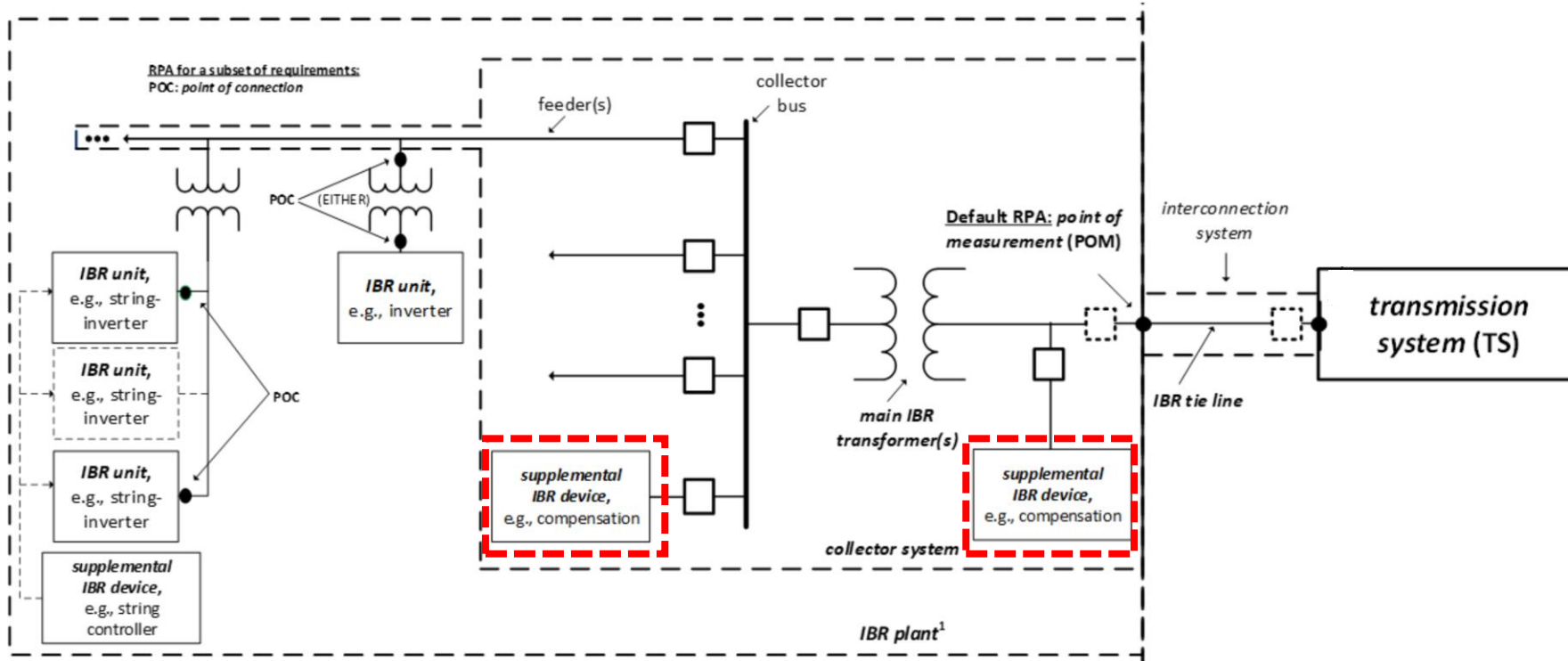


- MPT are important control devices at the IBR Plant
 - Offload tap changers
 - Onload tap changers
 - Deadbands, step size, step number
- Transformer characteristics are crucial
 - Impedance base in the software may be default or specified
 - Transformer documentation can be confusing
 - Prone to data errors when moving between software tools
 - **Some characteristics may not be in test reports**
- Simulations often are not run long enough to incorporate MPT dynamics
- **Very important to confirm parameterization between EMT, PSPD, and data sheets**

Components of an IBR Plant – Supplemental Devices

Supplemental devices are often critical when representing IBR performance and capability

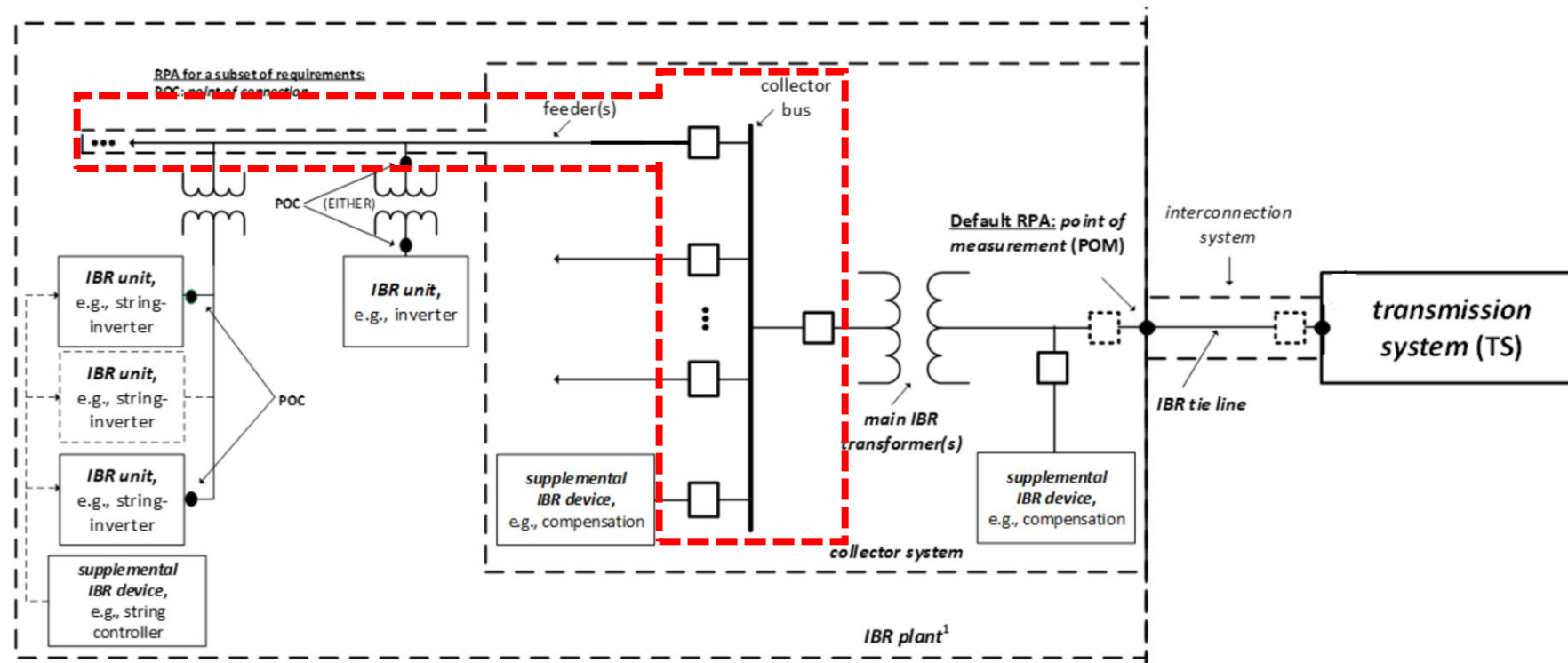
- Supplemental devices add additional capabilities to the IBR Plant design
 - Fixed shunts (capacitors or reactors)
 - Switched shunts
 - Communication devices
- Important to collect this data to maximize EMT benefits
 - Communication protocols
 - Time delays
 - Sample times
- Control hierarchy and communication
 - What is the main controller
 - Does this require additional equipment
- Managing manufacturers, consultants, and developers data security needs



Components of an IBR Plant – Collector System

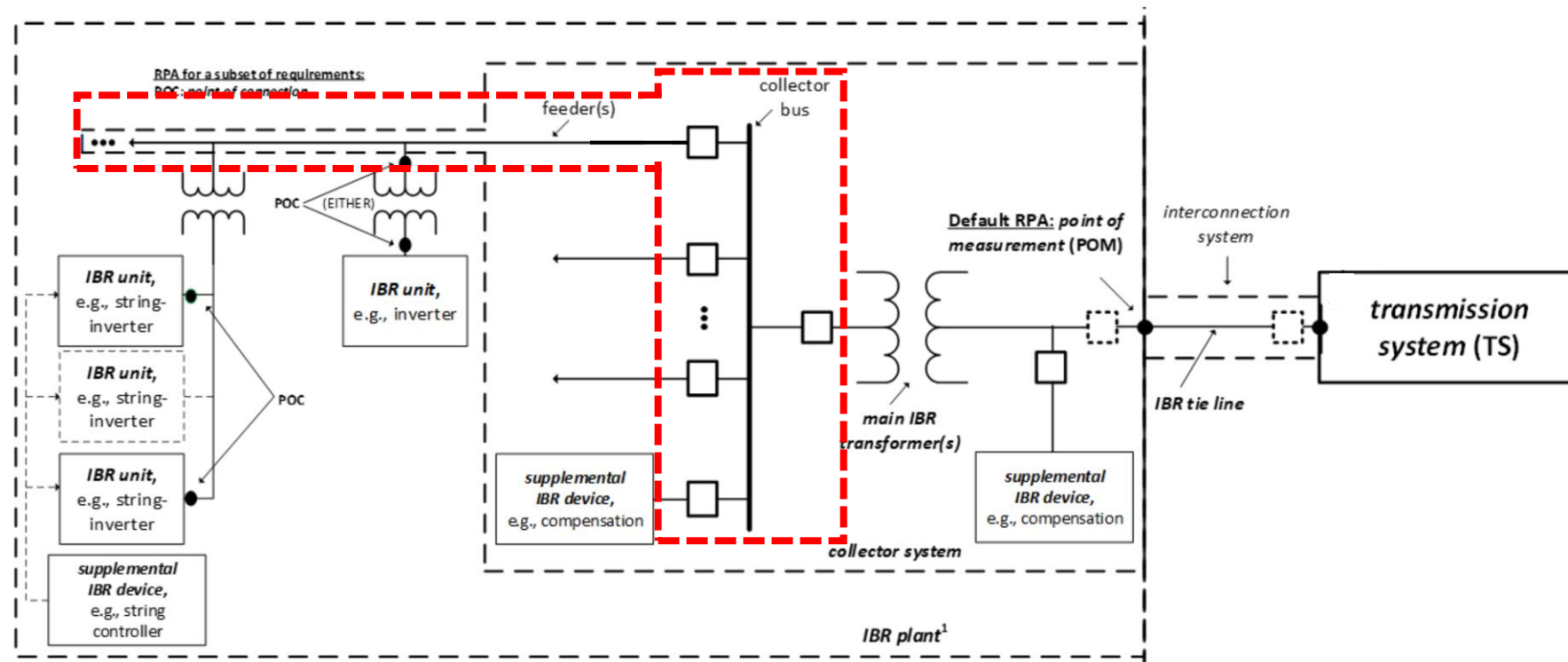
Collector systems vary widely among different types of IBR plants, but general layout is the same

- Composed of numerous components
 - Substation collector buses
 - Cable sections and junctions
 - Protective relays
- With so many components, errors are easy to make
 - Incorrect cable types
 - Incorrect distance data
 - Problems with in-house automation and aggregation



Components of an IBR Plant – Collector System

Cautionary example: Modeling lines in EMT

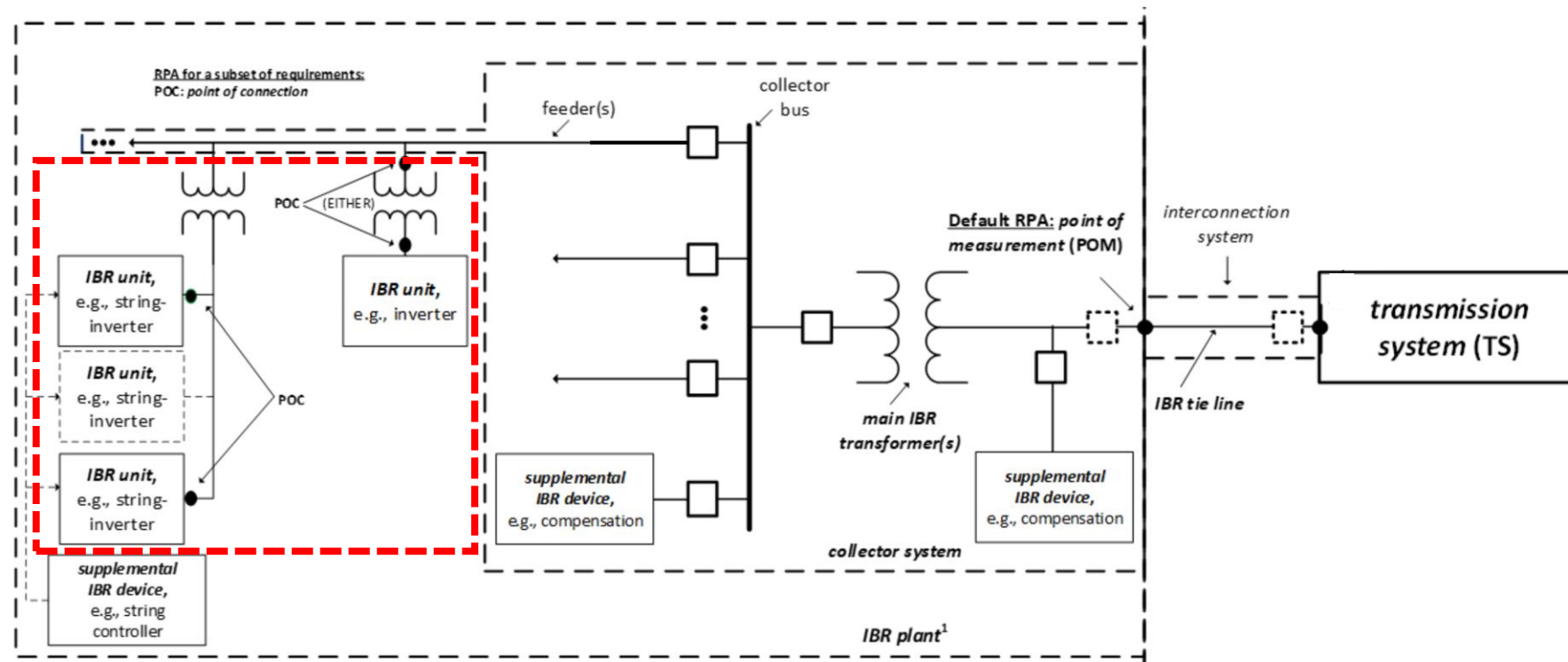


Source: Adapted from IEEE 2800-2022

- Lumped parameter models
 - RL coupled
 - PI-section
- Distributed parameter models
 - Frequency independent
 - Frequency dependent
- **How long are collector lines typically?**
- **What phenomenon are you studying with a plant model?**

Components of an IBR Plant – Inverters

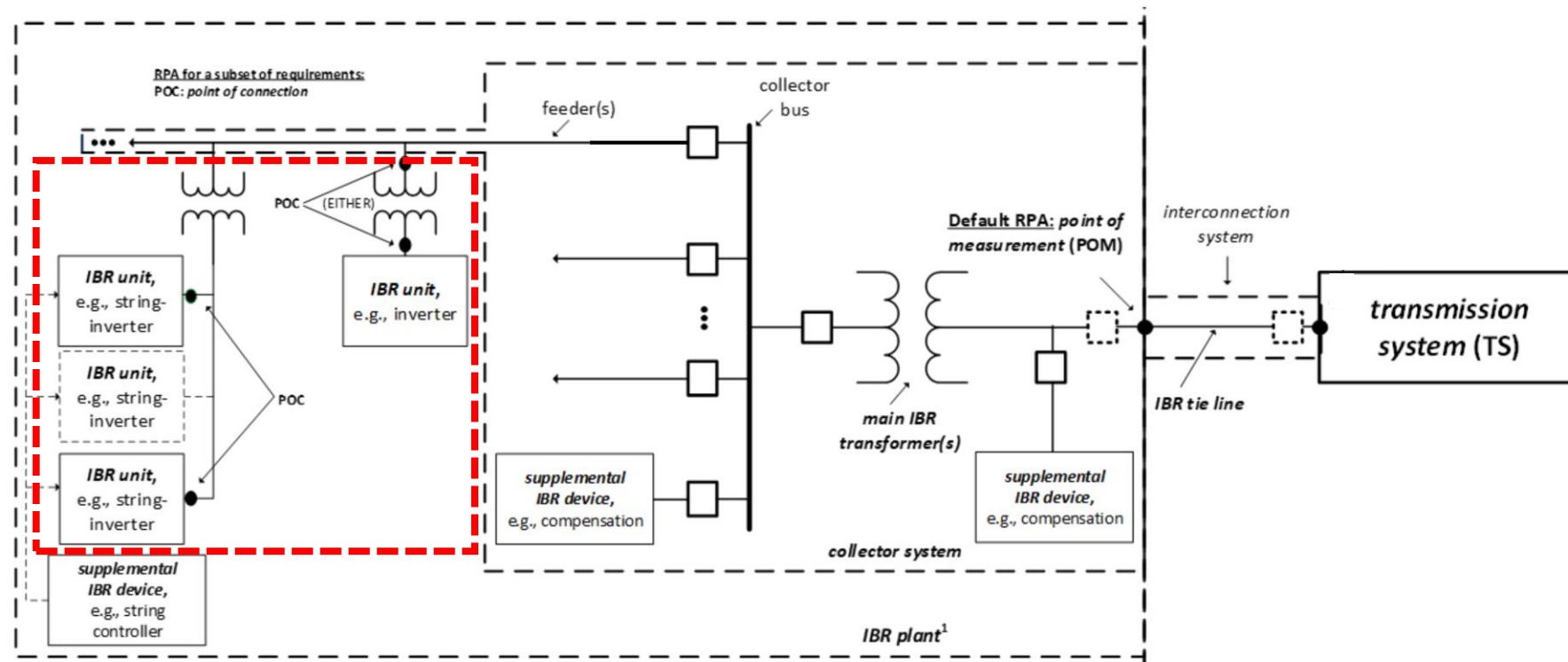
Easy in the steady state, much more difficult in dynamic simulation



- “Inverter” means OEM provided equipment
 - Could include in inverter model and generator step-up transformer (GSU)
 - Could have this information included in one component and connect directly to collector voltage
- In steady state: inverter models are relatively simple and are comprised of easy to transpose data from the OEM
 - Represent capabilities of the inverter
 - Contain the correct data to link to dynamic models
- In dynamics:
 - Actual performance must be represented based on level of detail and type of study

Components of an IBR Plant – Inverters

Easy in the steady state, much more difficult in dynamic simulation

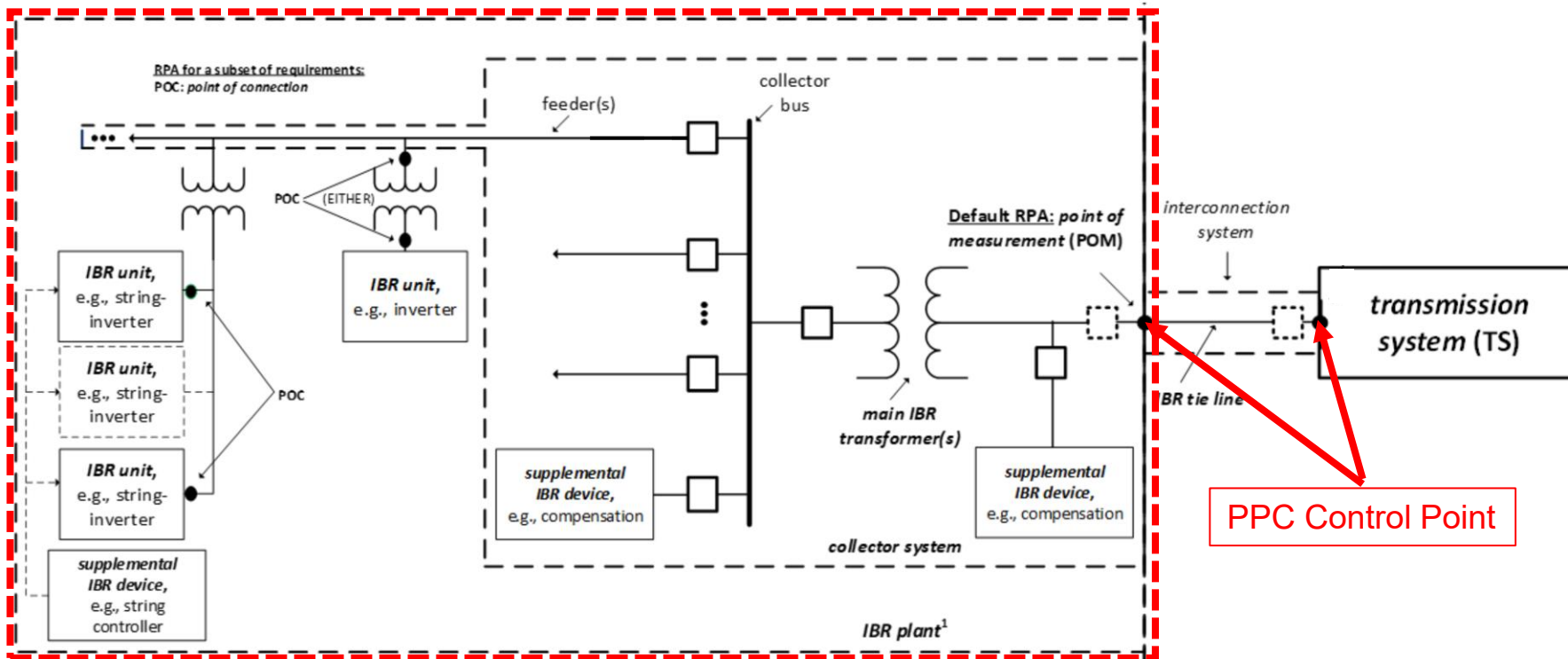


Source: Adapted from IEEE 2800-2022

- Important to know what has been provided in EMT
 - Often models are provided from manufacturer with an “example” collector and parameterization
 - No two plants are identical
- Is the model of the right equipment?
- Is the model the correct software version?
- Does the model include all manufactures as expected?

Components of an IBR Plant – Plant Controller(s)

Power plant controller(s) work to operate the IBR plant during normal operations and coordinate plant-wide performance



- Not included in steady state models
- May be standalone controller or part of multiple PPC control scheme
 - Needs to also coordinate with supplemental devices and MPT controls
 - Difficult to manage multiple OEM and control vendors
- **Critical to have high quality documentation**
 - How values are calculated
 - How to set up measurements

Wrap Up and What's Coming Next



- Most important pre-requisite is **if an EMT study is needed**
 - There are many needs and use cases for EMT
 - Stakeholders need to understand their system and trends to prepare for the changing study paradigm
- EMT studies are resource intensive so it's important to maximize benefit
- Data needs (more) scrutiny

What's coming next:

- EMT model creation and model benchmarking



EMT Model Creation and Benchmarking



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Introduction to EMT Model Creation and Benchmarking



- Skipping model validation (for now)
 - Will cover this in the design evaluation session
- EMT model creation is a **critical starting point**
 - Some extra time and scrutiny at this point can save significant time and money later
 - This session will be **most beneficial with group discussion** so please feel free to interject
 - The real knowledge here comes from experience and peers
- Leverage experience and lessons learned from PSPD modeling
- Model **benchmarking adds extra “trust”** in the models
 - Shows that modeled representation is the “same” across simulation domains, software, and time steps
 - This session will assume we are starting with a “validated” and manufacturer-approved EMT model

Step 1: Getting *an* EMT Inverter Model



- **This is not a joke slide**
 - Procuring an EMT model can be extremely difficult
- For **transmission system operators**:
 - May not have requirements for the provision of EMT
 - Many facilities connected currently do not have an EMT model (*available or created*)
 - Very important when considering retroactive requirements
- For **developers**:
 - EMT models after commercial operation date are often expensive (for new-er equipment)
 - Service contract language can help
 - Parts of fleet may be older equipment
 - Retroactive requirements have a huge impact here
 - Can cost hundreds of thousands of dollars and up to 24 months in some cases
 - These models are often “best guesses” and may not have the accuracy of a new model/equipment pair

Step 1: Getting *an* EMT Inverter Model



- For **equipment manufacturers**:
 - There is a time cutoff where equipment and model design practices make the creation of a quality EMT model extremely difficult
 - Grid requirements (retroactive or otherwise) can create “surges” in model creation requests
 - EMT model creation for older facilities are outside of the normal business practices and often come with high prices due to the one-off nature and subject matter experts involved
- **For us all**:
 - Get an EMT model early (before COD is best)
 - Adding in modeling provisions to service contracts can help
 - Keep these thoughts in mind when discussing and creating modeling requirements

Step 1a: Getting *an* EMT Plant Controller(s) Model



- IBR facilities include power plant controllers that need to be modeled
 - Can be provided by the inverter manufacturer
 - Could be written by a third party consultant
 - These may not have actual modeling staff
 - Falls to another party to take the control philosophy and create a model
- Similar process to inverter model acquisition with some additional guiding questions:
 - Does this manufacturer make plant controllers for the region I am studying?
 - What is the *full* control capability of the facility?
 - What devices are communicating, why, and who is in charge
 - What is the communication protocol used?
 - Can these additional devices use this protocol?

Step 2: Getting The Right EMT Inverter and Plant Controller Model(s)



- **Just because the model has an EMT file extension doesn't make it the right model**
- The new paradigm involves many non-technical stakeholders
 - These stakeholders may operate in between technical experts
 - Extremely important to know exactly what you are asking for and ask it in a way that is clear
 - For those receiving requests, confirm understanding and ask follow up questions
- The right EMT model is **site-specific** (for the equipment)
 - Right technology version (and subversions)
 - Correct firmware
- Does the provided model include a site-specific plant representation? (probably not)
 - Manufacturers provide models for their equipment only
 - Some manufacturer-provided models have “generic” balance of plant representations
 - This can be extremely confusing as models change hands throughout study processes

Step 2a: Getting The Balance of Plant Data



- **Inverter models are just one piece of an EMT facility model**
 - Manufacturers often do not know nor have responsibility to build the balance of plant
 - When obtaining an EMT inverter model there is one primary stakeholder
- The balance of plant data comes from **multiple sources**
 - These sources are all working towards the same goal, often in parallel
 - Can create versioning and management of change issues – highly iterative
 - Some pieces of data may be more “final” than others
- Having a standardized checklist of required data can help during this process



Step 2b: Reviewing The Balance of Plant Data



- Similar to the inverter/dynamic models, just because a **piece of data was provided doesn't mean it is correct**
- **Guiding questions:**
 - Did I receive all of the data I asked for?
 - Checklists help – categorizing by “need” and “good to have” helps more
 - Do the values make sense?
 - This comes from engineering judgement and experience
 - Is the data dated/versioned?
 - Helps create a correct “snapshot”
 - Does the balance of plant data match what was used in the PSPD?
 - Not always applicable
 - Have I seen this data before?

Step 3: Putting Major Pieces Together



- Need to determine where the model building responsibility “ends”
 - For the plant model builder, often the point of interconnection
 - For the transmission system operator, much more difficult and study-dependent
- The balance of plant data is used to create the physical representation of the plant
 - Transformers, cables, tie line, etc.
- The inverter and plant controller models and data are connected to the balance of plant where they are designed to
 - Spot checks throughout this process are crucial for efficiency
 - ”solve” as much as possible
 - Does the result make sense?
 - Are losses in line with expectations? Etc.
 - No disturbance runs and other thoughtful checks

Step 4: Site-Specificity and Data



- Putting together the pieces of the model is (a very important) step 1
- **Parameterization** of the model is an equally important step 2
 - A correct model with wrong parameters is the wrong model
- Hinges on model **usability, fidelity, and mapping** to real-world values
- More stakeholders are involved
 - Often developers are responsible for understanding what requirements are needed at the point of interconnection
 - Voltage schedules
 - Frequency deadbands/droops
 - Protection settings
 - Enabled control modes
 - How to manage “telephone game”
 - What should be done when these values don’t make sense
 - Strong foundation of engineering judgement and knowledge is necessary

Step 4a: Representing Site-Specific Controls



- Modeling complex communication systems is a **strong use case for EMT**
- EMT affords the ability to **model in detail many aspects of actual site control that is not possible (or efficient) in other domains**
 - Extremely important to request manuals and documentation from **all vendors**
 - Each vendor model likely has “nuance” that will need to be understood and implemented
- **Hierarchical controls:**
 - Main/secondary schemes
 - Mechanically switched units
 - Plant controllers and supplemental reactive devices
 - Hybrid plants
- **Real-world delays often not modeled (even in EMT):**
 - Communication delays
 - Sample time delays
 - Controller holds
- **Much more! Complexity is always increasing**

In a “perfect world” These have parameters in the model space. In reality, these may need to be manually added.

- **What is model benchmarking?**
 - Simply put: comparing the response of a model to another model or to the performance of the actual equipment
- **Model to measured performance:**
 - Also known as model validation and is part of the type testing process (more on model validation in the design evaluation section)
 - Shows differences between measured response and model response to the same stimulus
 - Some differences will always occur
 - Shows incorrect performance that can then be mitigated
 - **Test benches are few and in high demand**
 - Type testing is thorough but infrequent for any one piece of equipment

Model Benchmarking



Case 1 - TN1.1 - Pref

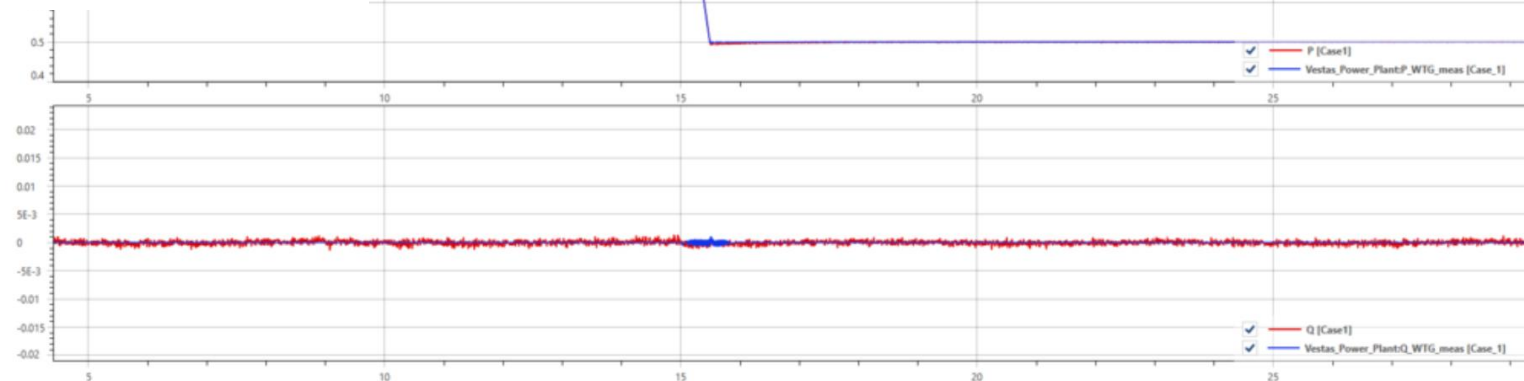
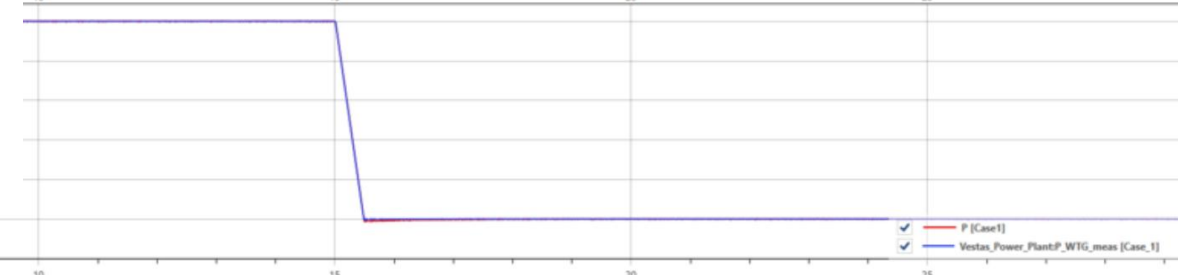
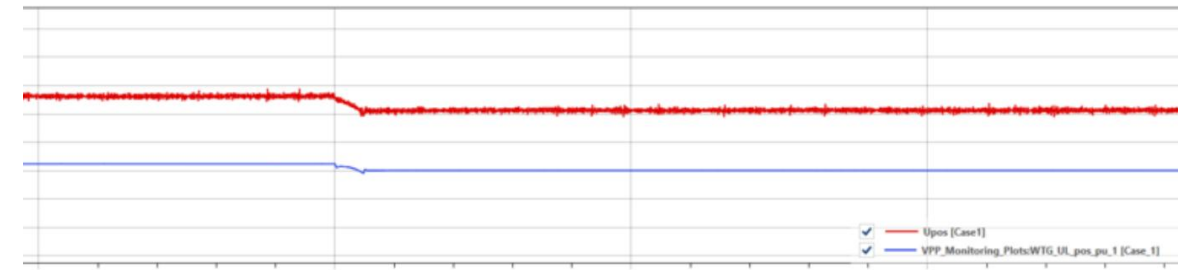
Events

Custom Input

EventType	InputType	RefChangeType
ReferenceChange	CustomInput	Pref

Point Steps Pref

Time	Point
0	1
15	1
15.001	0.5
30	0.5



Source: Vestas

Model Benchmarking



Case 2 - TN1.2 - Qref

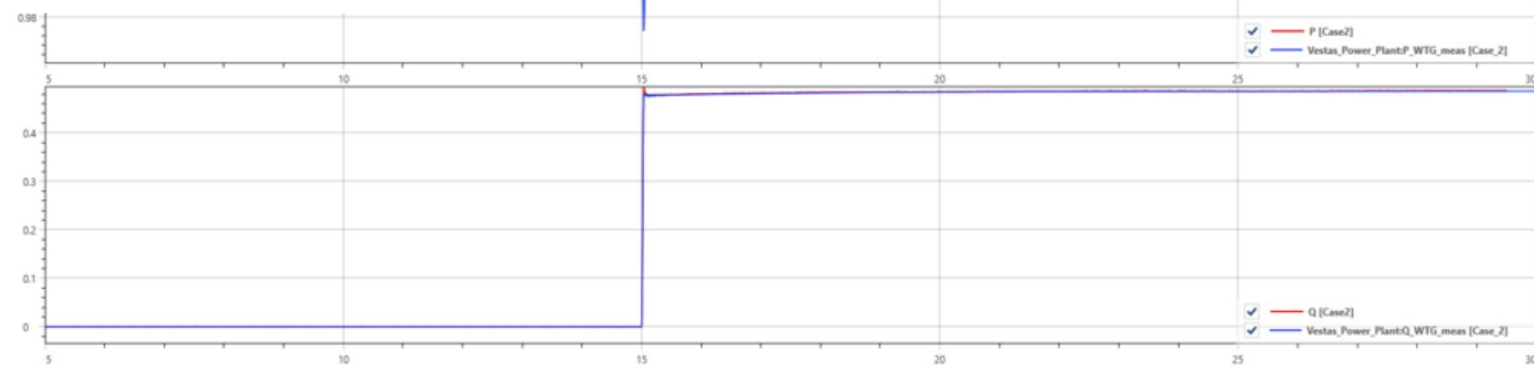
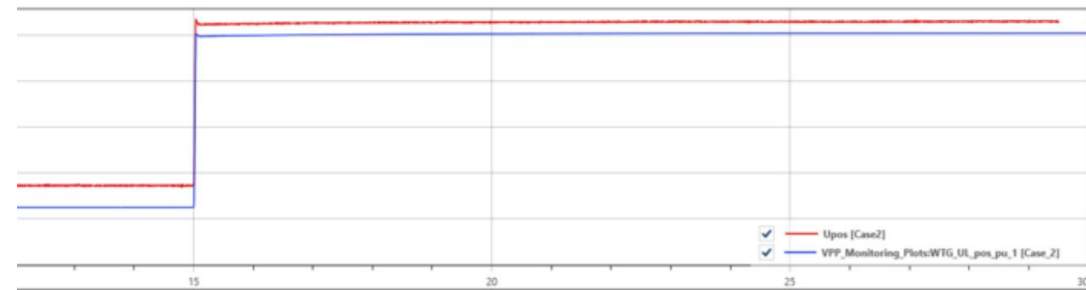
Events

Custom Input

EventType	InputType	RefChangeType
ReferenceChange	CustomInput	Qref

Point Steps Qref

Time	Point
0	0
15	0
15.001	0.5
30	0.5



Source: Vestas

Model Benchmarking



Case 11 - TN4.1 – Phase Jump +30°

Events

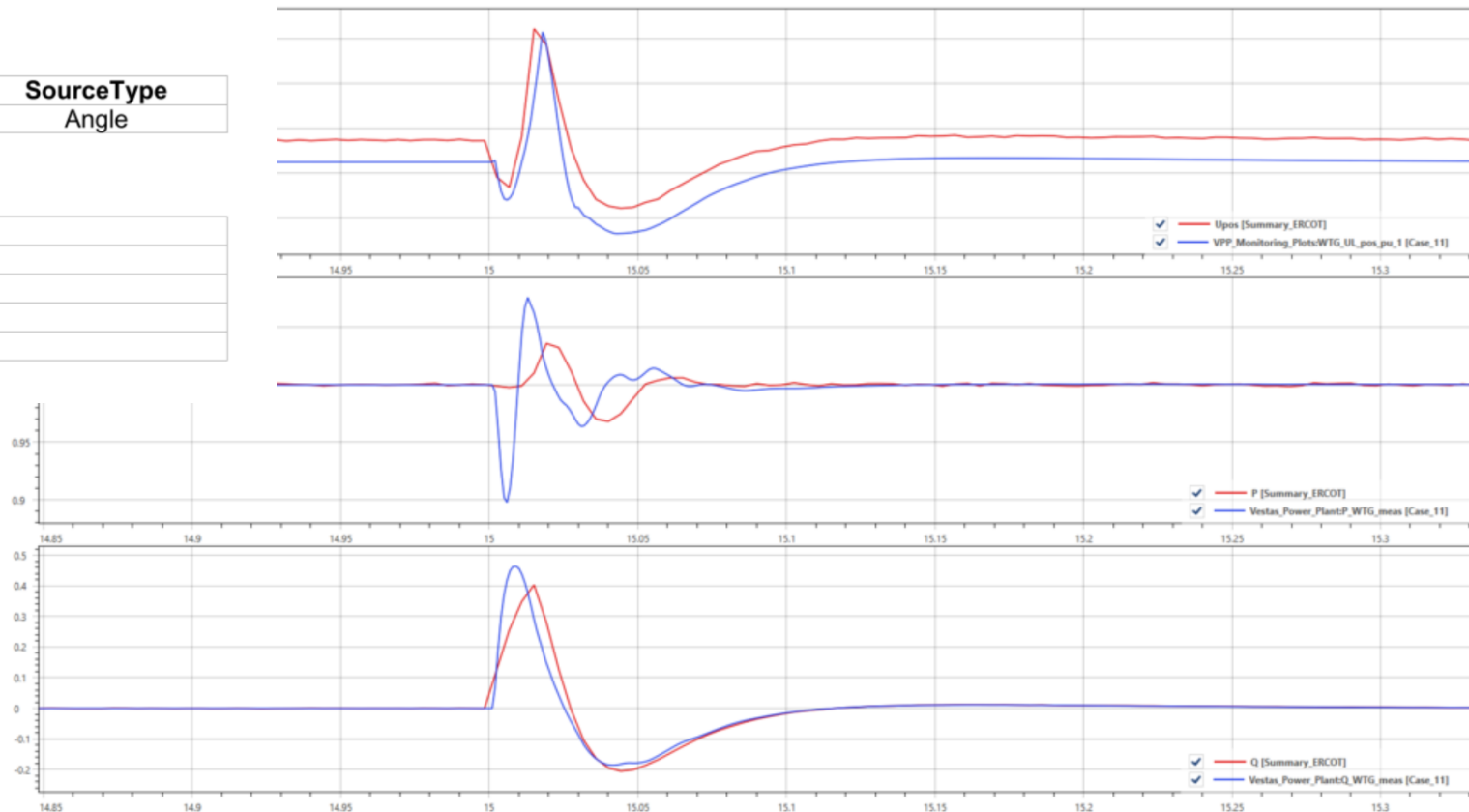
Thevenin Source Change

EventType	FilePath	InputType	SourceType
TheveninSourceChange	---	CustomInput	Angle

PointSteps Angle

Time	Point
0	0
15	0
15.001	30
30	30

Source: Vestas

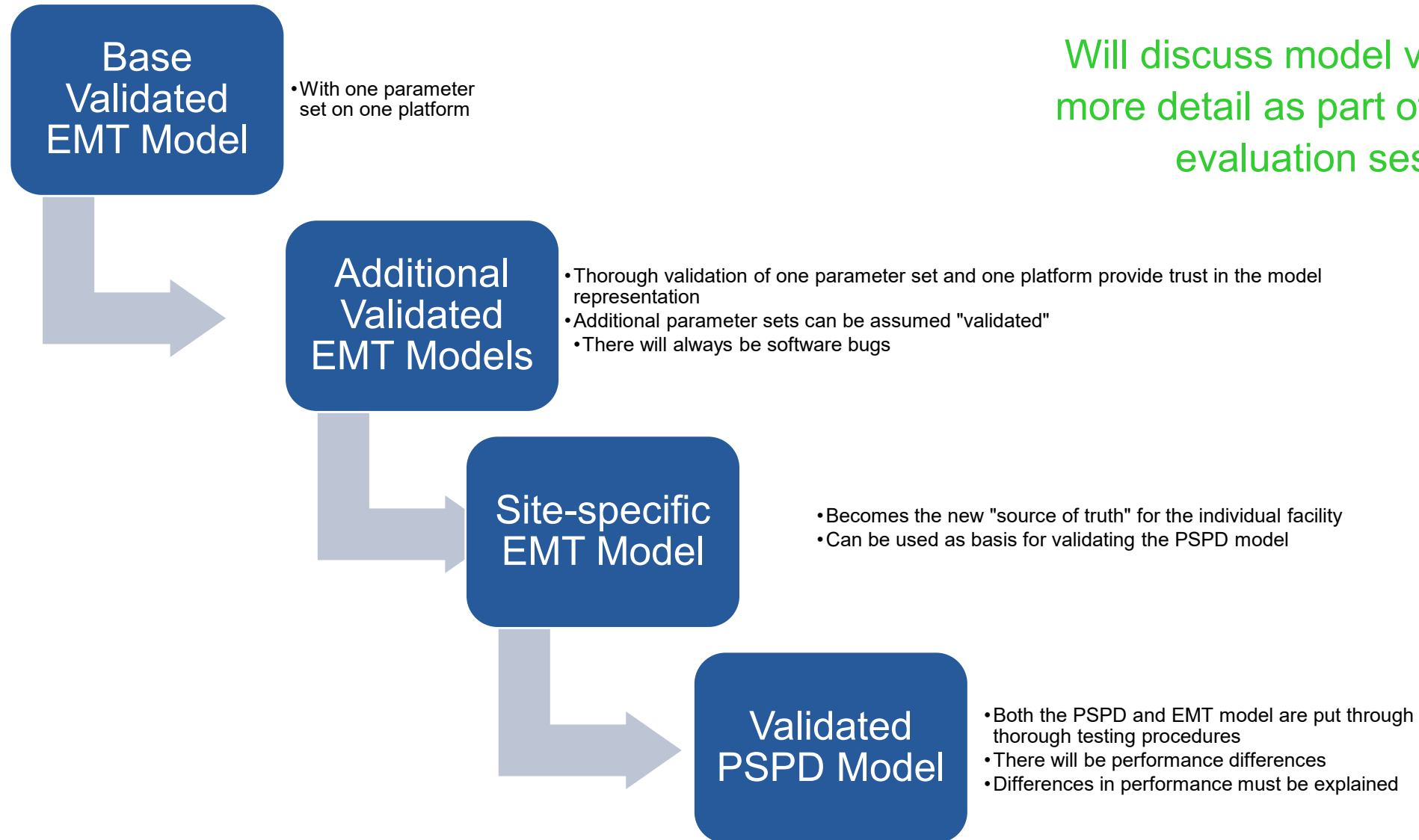


Benchmarking Between PSPD and EMT



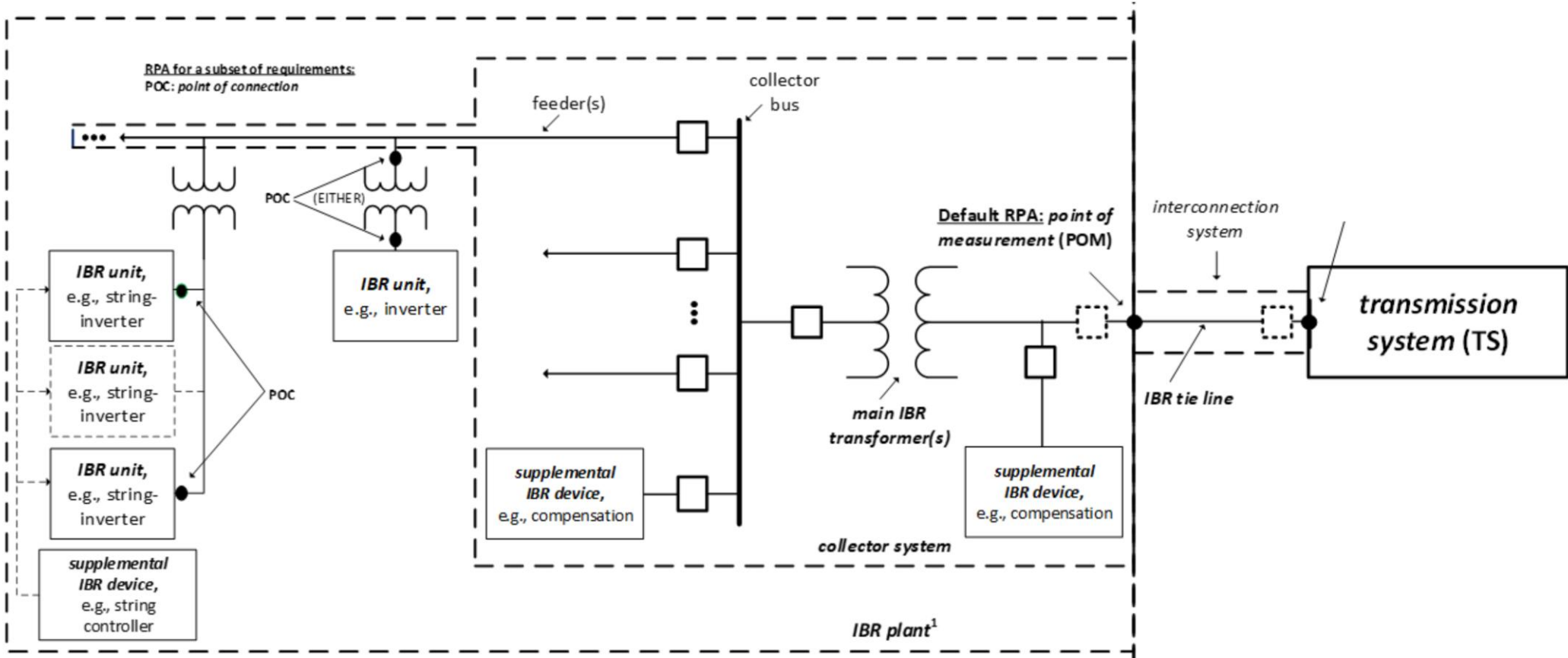
- **Assumption:** The EMT model is validated by the manufacturer
 - **Pro:**
 - The manufacturer performed model validation testing
 - The manufacturer validated the model performance against the test results
 - Differences between model and measurements are explained
 - **Con:**
 - The validation was done on one specific "platform"
 - The validation was done with one specific parameter set
- **Need:** Site-specific parameterized model in both the PSPD and EMT domains

Benchmarking Between PSPD and EMT – Inverter and Plant Controller



Will discuss model validation in more detail as part of the design evaluation session

Benchmarking Between PSPD and EMT Balance of Plant



Source: Adapted from IEEE 2800-2022

Success Story of Quality Model Practices



- Case Study: (Source [Vestas](#))
 - IBR facility showed instability in operations that was not seen in the study space
 - Facility was immediately curtailed to ~50% output
 - Proposed solution was multiple transmission assets
- **Old paradigm:**
 - The models in the process are the best we have
 - Pay for the transmission upgrades
- **New paradigm:**
 - Leverage principles in this training
 - Perform detailed analysis with highly representative models
 - Avoid transmission upgrades, install tuned controls

Success Story of Quality Model Practices



CONFIDENTIAL

What Was The Problem?

A Vestas Site was curtailed and facing significant proposed transmission upgrades

Stability modelling showed severe adverse response including re-triggering of voltage ride through mode

- This caused ~20% voltage swings at the Project POI
- Grid SCR at the POI was <1.75

The proposed solutions were costly and came with significant lead times

- Substation re-configuration
- New 138 kV Transmission line
- Grid Side - SVC/STATCOM/Synchronous Condenser
- Project curtailment for many prior outages



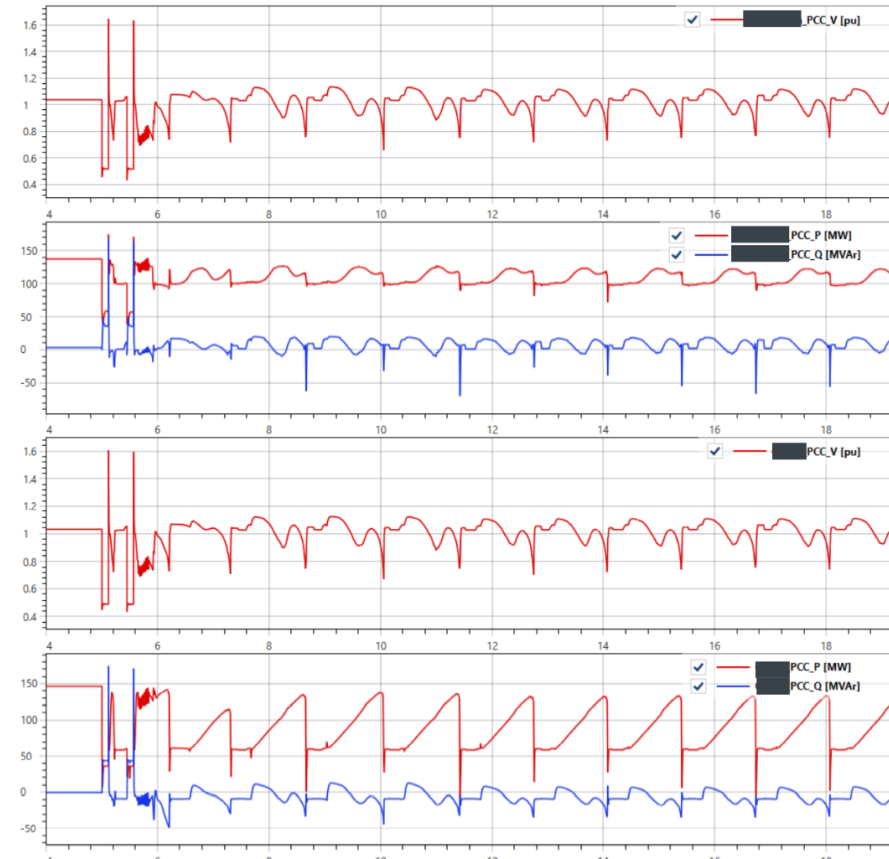
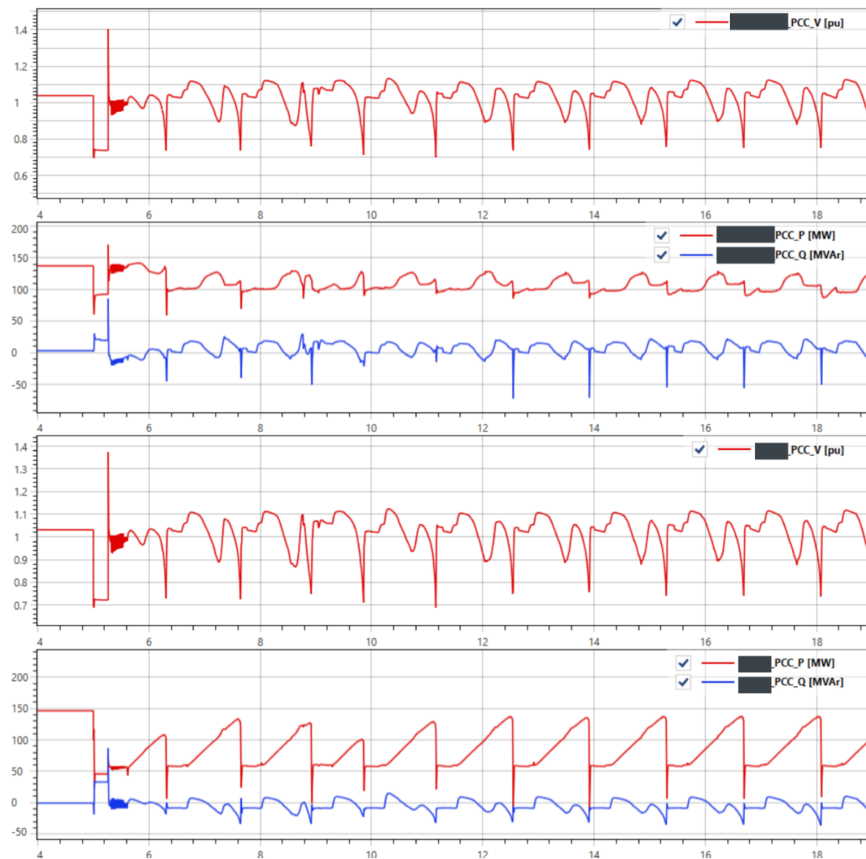
Success Story of Quality Model Practices



CONFIDENTIAL

Vestas Plant Results for two Severe Planning Contingencies

Both show significant retriggering and typical weak grid response



Success Story of Quality Model Practices



CONFIDENTIAL

Study Groundwork and Setup

Vestas needed to work internally, with the Customer, Regional Entities, and their consultants

Work with Customer

- Several meetings with Customer to explain the situation and how site controller tuning could be an alternative solution to the transmissions upgrades

Work with Regional Entities

- Detailed collaboration to discuss the previous study process and to understand the problem grid conditions and contingencies
- Provide technical justification to re-perform two worst planning contingencies in the EMT domain with confirmation in RMS by the consultant
- Work through necessary NDA and process for proper data handling

Vestas Internal Work

- Access and download the Projects' Power Plant Controller and WTG settings
 - Create as-left models to use as tuning starting point
- Recreate a small region of the Grid in PSCAD
 - All other non-Vestas Generators were netted out
 - The fault response was benchmarked against the RMS study



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Success Story of Quality Model Practices



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Vestas Internal EMT Study

The two worst planning events were studied in the EMT domain and the Vestas controllers were tuned

- Changes were made to both the Plants' Power Plant Controllers and WTG control parameters
- The new parameters showed stability in the EMT domain for the two worst contingencies
- Parameters from the EMT model were transferred exactly to the RMS models and these models were studied and approved for all planning contingencies under Regional Entity procedure
- In parallel, the parameters were studied internally to ensure they would not damage the WTG or reduce the WTG lifespan
- After internal and external approval of the parameters they were installed on-site with exact mapping to the studied parameters



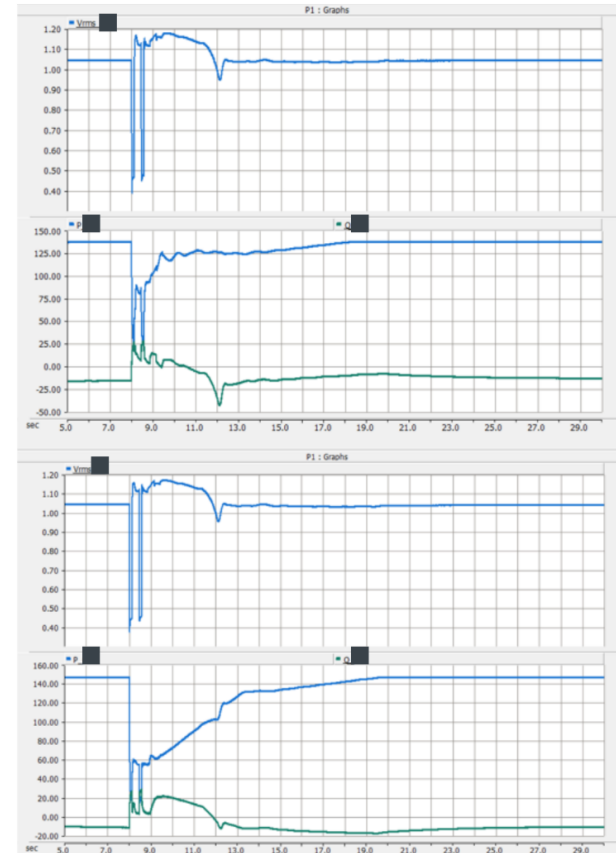
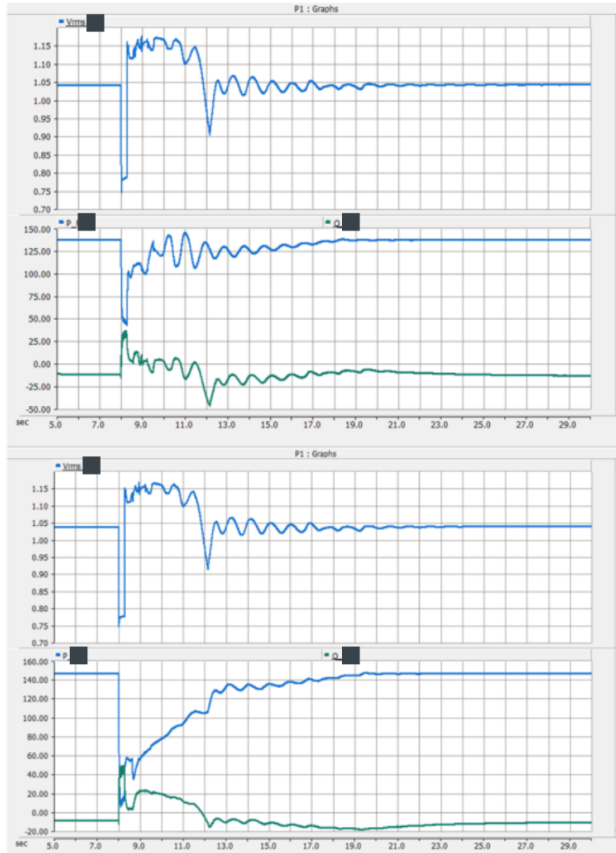
Success Story of Quality Model Practices



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Vestas Plant Results for Two Severe Planning Contingencies

Both show stable post-fault response within Regional Entity Criteria



Key Takeaways



- **”Extra” work now pays itself back later (usually)**
 - Models are the building blocks of analysis
 - Small mistakes made early on are extremely difficult to track down
 - Or worse – the mistakes give reasonable, but wrong performance
- Ensuring one thoroughly vetted “Source of truth” is critical
 - Always have a reference for expected performance
 - Enables cross-domain analysis
- While many PSPD modeling principles can inform EMT work, added details and specialized use cases underscore the importance of engineering judgement and experience
 - Also underscores the need for mentorship within organizations

Introduction to Design Evaluation



ESIG

ENERGY SYSTEMS
INTEGRATION GROUP

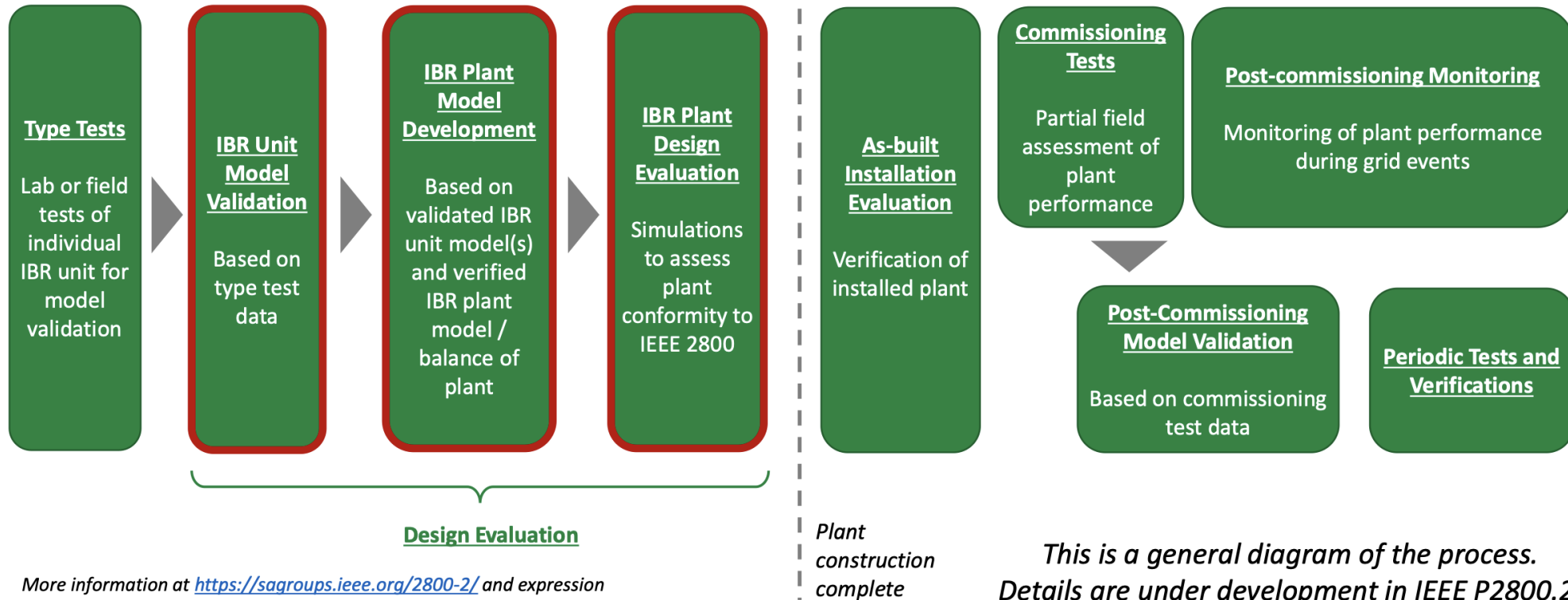
Design Evaluation: Introduction



- Design evaluation is a term with specific meanings in specific contexts
- **Generally:** Design evaluation is exactly what it sounds like, confirming that the site as designed and modeled conforms with the performance requirements at the point of interconnection
- Requires **validated** equipment and **verified** plant models
- **Disclaimer:**
 - I have been heavily involved at a leadership level in the P2800.2 process and have many (many) opinions on design evaluation and validation/verification
 - Some of these opinions differ from the consensus language in the currently approved P2800.2 draft

Design Evaluation: Introduction

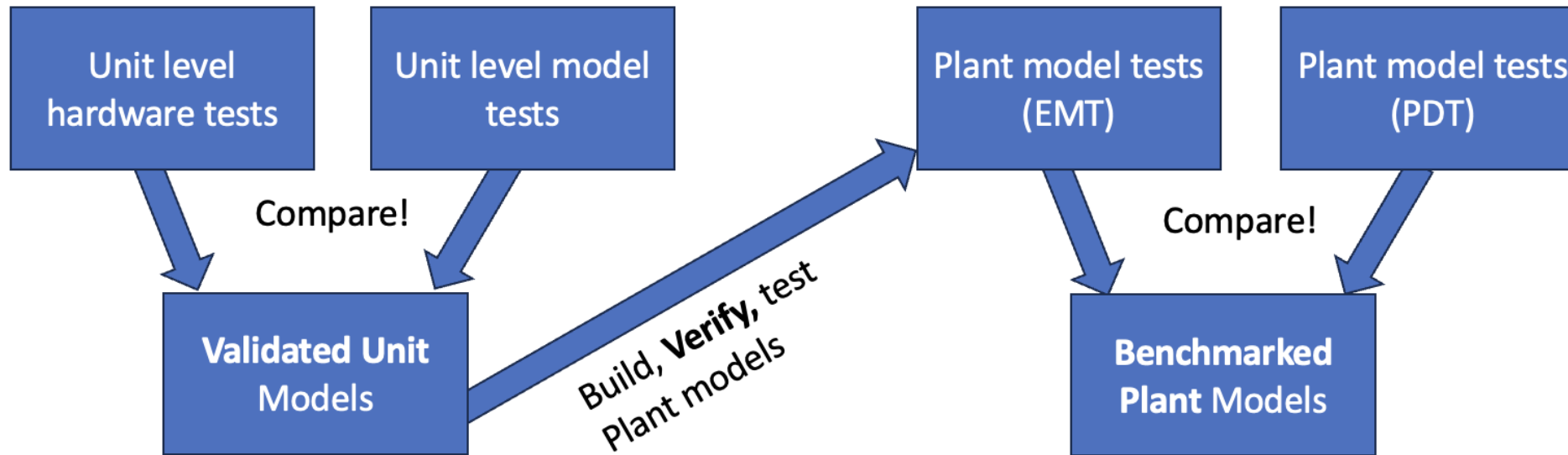
Overview of conformity assessment steps in IEEE P2800.2, *Recommended Practice for Test and Verification Procedures for IBRs Interconnecting with Bulk Power Systems*



More information at <https://sagroups.ieee.org/2800-2/> and expression of interest to participate [here](#).

*This is a general diagram of the process.
Details are under development in IEEE P2800.2.
Some variations permitted.*

IBR Unit Model Validation



Source: IEEE ©2024

What will be validated? (models compared against type tests)

1. Voltage and reactive power control modes – Clause 5.7.4
2. Primary Frequency response – Clause 5.9.4
3. Fast Frequency response – Clause 5.9.4
4. Voltage disturbance ride through – Clause 5.11.4 to 5.11.8
5. Frequency disturbance ride through – Clause 5.13
6. Limitation of overvoltage over one fundamental frequency period – Clause 5.14.4
7. PPC Testing – Clause 5.17
8. Frequency Scanning
9. Protections – Clause 5.15
 - a. Frequency protection
 - b. ROCOF protection
 - c. Voltage protection
 - d. AC overcurrent protection
 - e. Unintentional islanding protection

IBR Unit Model Validation Challenges



- **How do you evaluate what is an “acceptable” match?**
 - This topic delayed IEEE P2800.2 by months (sorry)
 - Incredibly difficult to gain consensus
- **Different manufacturers have different modeling standards**
 - Some manufacturers have highly detailed and mapped models, others may not have the same level of accuracy
- **Intent of IEEE standards**
 - Some manufacturers have trouble committing to accuracy percentages
 - How is error calculated
 - Fear that requirements will be copy/pasted with no nuance
- **Is the difference in performance real or due to measurement errors in the test bench?**
 - While measurement errors should be minimized, IEEE 2800-2022 measurement tolerances add up

IBR Unit Model Validation Challenge #1



- **Quantitative vs Qualitative** (single most contentious issue in the design evaluation subgroup)
- **Quantitative**
 - **Pro:**
 - Can standardize model quality
 - Helps automate screening
 - Informs engineering judgement
 - **Con:**
 - Poorly determined error bands can let bad models through and overly constrain good models
 - If there is no qualitative component, it is very easy to fall into automation traps

IBR Unit Model Validation Challenge #1

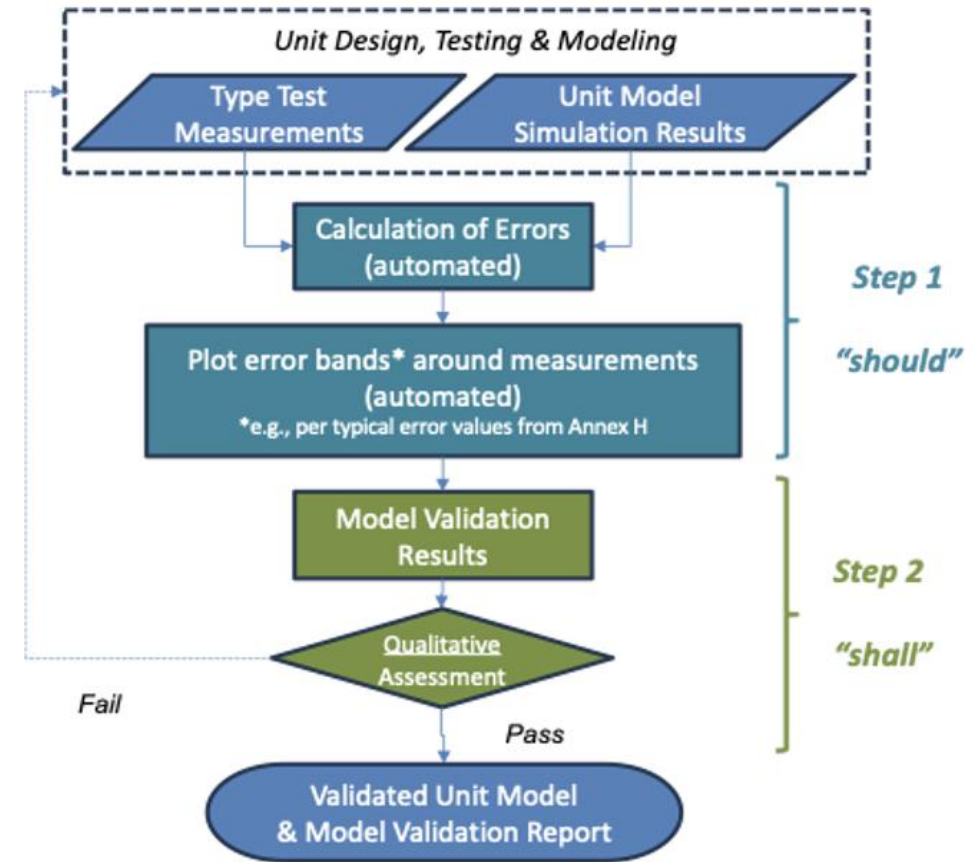


- **Quantitative vs Qualitative** (single most contentious issue in the design evaluation subgroup)
- **Qualitative**
 - **Pro:**
 - Experienced engineers have more freedom to assess model performance and ask nuanced questions
 - If done well, can effectively identify important errors
 - **Con:**
 - There aren't enough experienced engineers to do this work
 - Hard to automate, can lead to fatigue
 - Doesn't help standardize model accuracy, can lead to variance in "acceptable" performance

IBR Unit Model Validation Recommendations



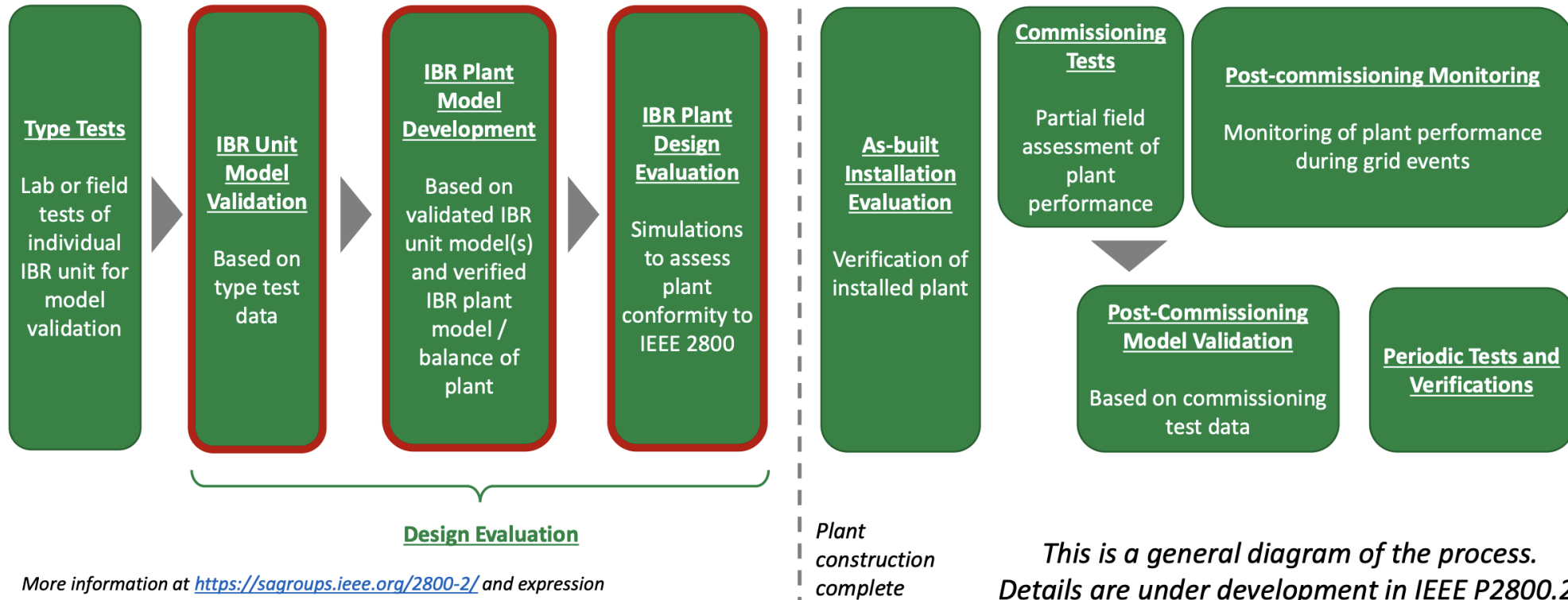
- **Push this work to the manufacturer**
 - Create a validation report that:
 - Uses both quantitative and qualitative methods
 - Engineering review for any differences outside of determined bands
 - And other oddities
- **Lowers burden on other industry stakeholders**
 - Other stakeholders would review the validation report
 - Validation reports are done only by the equipment-level experts



Source: IEEE ©2024

IBR Plant Design Evaluation

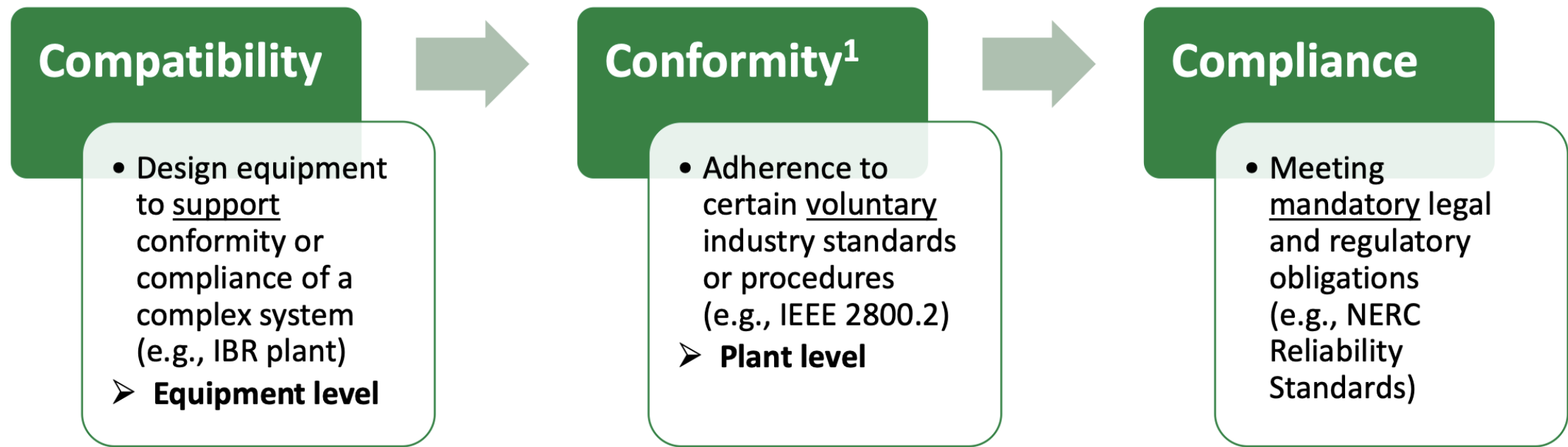
Overview of conformity assessment steps in IEEE P2800.2, Recommended Practice for Test and Verification Procedures for IBRs Interconnecting with Bulk Power Systems



More information at <https://sagroups.ieee.org/2800-2/> and expression of interest to participate [here](#).

*This is a general diagram of the process.
Details are under development in IEEE P2800.2.
Some variations permitted.*

Another Terminology Break



¹ The term “conformance” is depreciated and should not be used any longer.

Conformity does ensure grid stability!

Design Evaluation: Scope and Procedures



Requirement	RPA where requirement applies	Design evaluation	Procedure type	IBR Plant Representation Detail and Data ^a
<i>Clause 4 General interconnection technical specifications and performance requirements</i>				
4.2 Reference points of applicability (RPA)	POM (default)	R	IBR plant design documentation	Disaggregated single line diagram
4.4 Measurement accuracy	POC and POM	R	OEM documentation	IBR unit(s) and supplemental IBR device(s)
4.5 Operational measurement and communication capability	POM	R	OEM documentation	IBR unit(s) and supplemental IBR device(s)
4.6 Control capability requirements	POM	R	OEM Documentation	IBR unit(s) and supplemental IBR device(s)
4.6.1 Execution of mode or parameter changes	POM	R	OEM Documentation	IBR unit(s) and supplemental IBR device(s)
4.6.2 Ramping for control parameter change	POM	R	OEM Documentation	IBR unit(s) and supplemental IBR device(s)
4.7 Prioritization of IBR responses	POM	R	IBR plant design documentation	IBR unit(s) and supplemental IBR device(s)
4.8 Isolation device	POM	R	IBR plant design documentation	Disaggregated single line diagram
4.9 Inadvertent energization of the TS	POM and POC	R	Protocol Documentation between GO and TO	[TBD]
4.10 Enter service	POM	R	Protocol Documentation between GO and TO	IBR unit(s) and supplemental IBR device(s)
4.11 Interconnection integrity	POM	R	OEM documentation	IBR unit(s) and supplemental IBR device(s)
4.12 Integration with TS grounding	POM	R	IBR plant design documentation	Aggregated single line diagram

^[1] Refer to footnote 38 for examples of OEM documentation and to footnote 39 for examples of IBR plant design documentation.

^[2] In this version of the document, representing the IBR plant with a non-aggregated model may be limited to steady-state power flow and short-circuit, and [fundamental-frequency stability dynamic modeling] domains. The development and use of a non-aggregated IBR plant model in electromagnetic transient (EMT) modeling domain may be computational burdensome and time-consuming with limited benefits—a good compromise may be to use a partially aggregated EMT model in special cases and where justified. For more information about differentiating between applicability of simulation domains and inverter mathematical models in these domains refer to [B23].

Design Evaluation: Scope and Procedures



Requirement	RPA where requirement applies	Design evaluation	Procedure type	IBR Plant Representation Detail and Data ^a
<i>Clause 5 Reactive power—voltage control requirements within the continuous operation region</i>				
5.1 Reactive power capability	POM	R	IBR plant design documentation, OEM documentation and steady-state power flow or [positive-sequence] modeling	Aggregated model or Disaggregated model subject to [7.2.4.1]
5.2 Voltage and reactive power control modes	POM	R for capability	OEM documentation	IBR unit(s) and supplemental IBR device(s)
		R for performance of 5.2.2	Positive-sequence modeling or EMT modeling	Aggregated model
<i>Clause 6 Active-power—frequency response requirements</i>				
6.1 Primary frequency response (PFR)	POC and POM	R	Positive-sequence and EMT modeling	Aggregated model
6.2 Fast frequency response (FFR) ¹	POC and POM	R	Positive-sequence and EMT modeling	Aggregated model

Design Evaluation: Scope and Procedures



Requirement	RPA where requirement applies	Design evaluation	Procedure type	IBR Plant Representation Detail and Data ^a
Clause 7 Response to TS abnormal conditions				
7.2.2 Voltage disturbance ride-through requirements	POC	R	OEM documentation on capability	IBR unit(s) and supplemental IBR device(s)
			EMT Modeling	
	POM	R	Positive-sequence and EMT modeling	Aggregated model
7.2.3 Transient overvoltage ride-through requirements	POM	R	IBR plant design documentation and OEM documentation	As appropriate
7.3.2 Frequency disturbance ride-through requirements	POM	R	Positive-sequence and EMT modeling	[Aggregated model]
7.4 Return to service after IBR plant trip	POM		Refer to line entries for 4.10	
Clause 8 Power quality				
8.1.2 Rapid voltage changes (RVC)	POM	R	[TBD]	[TBD]
8.1.3 Flicker	POM	NR	[TBD]	[TBD]
8.2.1 Harmonic current distortion	POM	R	[TBD]	[TBD]
8.2.2 Harmonic voltage distortion	POM	D	[EMT modeling or Frequency Domain]	[TBD]
8.3.1 Limitation of cumulative instantaneous overvoltage	POM	R	[TBD]	[TBD]
8.3.2 Limitation of overvoltage over one fundamental frequency period	POM	R	[TBD]	[TBD]

^[1] Refer to footnote 38 for examples of OEM documentation and to footnote 39 for examples of IBR plant design documentation.

^[2] In this version of the document, representing the IBR plant with a non-aggregated model may be limited to steady-state power flow and short-circuit, and [fundamental-frequency stability dynamic modeling] domains. The development and use of a non-aggregated IBR plant model in electromagnetic transient (EMT) modeling domain may be computational burdensome and time-consuming with limited benefits—a good compromise may be to use a partially aggregated EMT model in special cases and where justified. For more information about differentiating between applicability of simulation domains and inverter mathematical models in these domains refer to [B23].

Design Evaluation: Scope and Procedures



Requirement	RPA where requirement applies	Design evaluation	Procedure type	IBR Plant Representation Detail and Data ^a
<i>Clause 9 Protection</i>				
9.1 Frequency protection	POC and POM	R	Applicable <i>IBR plant</i> design documentation on [...], Applicable OEM documentation on [...], and validated <i>IBR unit</i> and <i>supplemental IBR device</i> models	<i>IBR unit(s)</i> and <i>supplemental IBR device(s)</i> , <i>collector system</i> , <i>main IBR transformer</i> , any other <i>IBR plant</i> equipment
9.2 Rate of change of frequency (ROCOF) protection	POC and POM	R		
9.3 Voltage protection	POC and POM	R		
9.4 AC overcurrent protection	POC and POM	R		
9.5 Unintentional islanding protection	POC and POM	D		<i>IBR unit(s)</i> and <i>supplemental IBR device(s)</i>
9.6 Interconnection system protection	POM	R		<i>main IBR transformer</i> , <i>intertie line</i>
<i>Clause 10 Modeling Data</i>				
10 Modeling data	POC and POM	R	OEM documentation	<i>IBR unit(s)</i> and <i>supplemental IBR device(s)</i> , <i>collector system</i> , <i>main IBR transformer</i> , any other <i>IBR plant</i> equipment

Verified Plant Models: EMT Reality



Simulation Domain / Model Detail	Non-aggregated model	Aggregated model		Notes ^a
		Partially aggregated model	Fully aggregated model	
steady-state power flow model	Yes ^a	n/a	Yes	In cases where aggregation provides limited benefit (for example battery systems with no substantial collector grid, or for very small plants), aggregated models may be used.
steady-state short-circuit model	Yes	n/a	Yes	
Fundamental-frequency phasor-domain (PDT) model (user-defined model and/or generic model)	[Maybe ^a]	Maybe ^a (maximize non-aggregation based on model limitations)	Yes	A non-aggregated stability model may inform proper coordination between IBR Unit protection, voltage protection, and voltage ride-through capability specified at the point of measure.. In cases where aggregation provides limited benefit (for example battery systems with no substantial collector grid, or for very small plants), aggregated models may be used.
electromagnetic transient (EMT) models	No ^a	Maybe ^a	Yes	Computing a non-aggregated EMT model may be overly burdensome and not add sufficient value in most cases.

^a Refer to subclause 7.2.4.1 for guidance on potential benefits and costs of aggregated and disaggregated IBR plant models.

Source:
IEEE

^[1] Refer to footnote 38 for examples of OEM documentation and to footnote 39 for examples of IBR plant design documentation.
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Verified Plant Models: EMT Reality



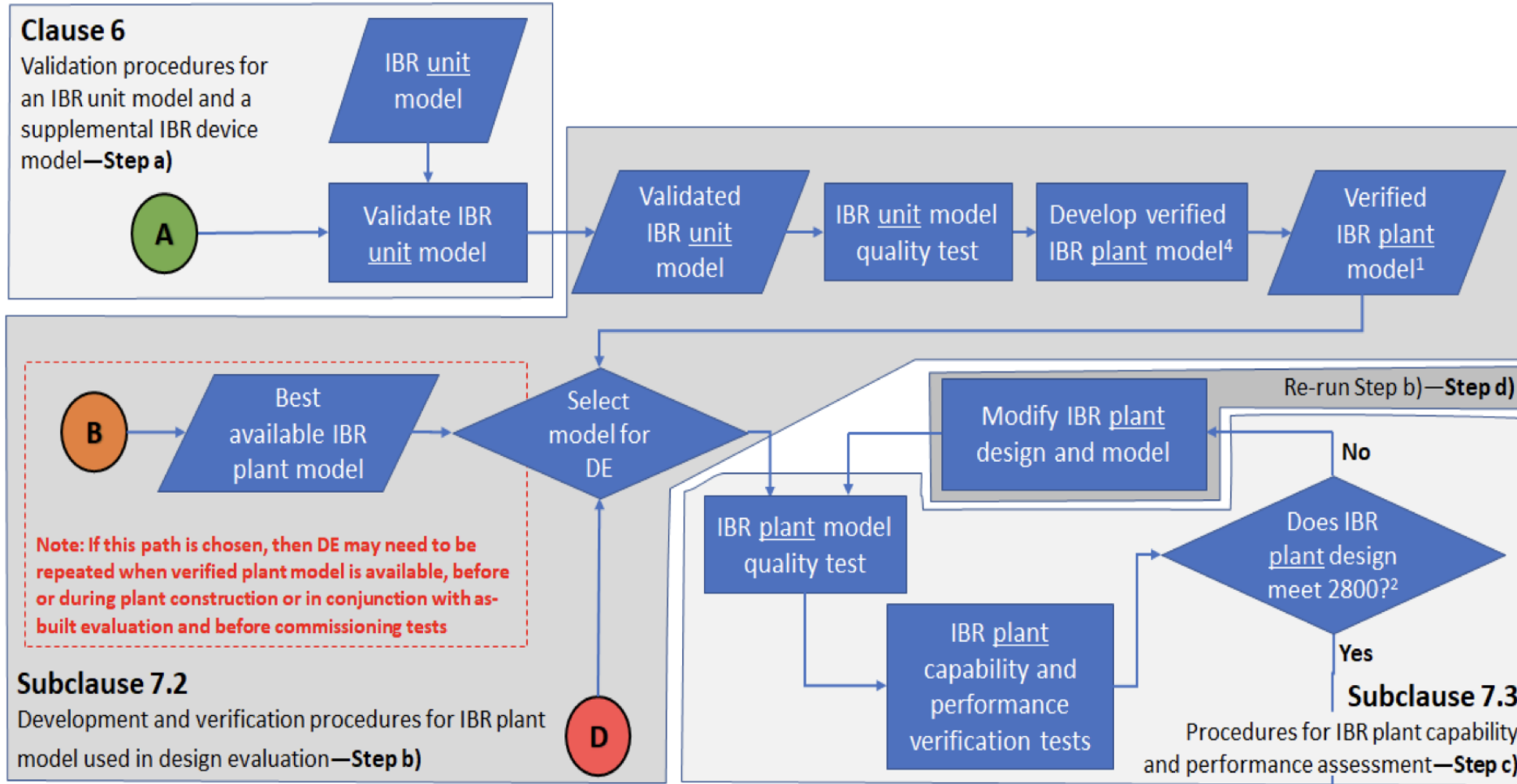
Simulation Domain / Model Detail	Non-aggregated model	Aggregated model		Notes ^a
		Partially aggregated model	Fully aggregated model	
steady-state power flow model	Yes ^a	n/a	Yes	In cases where aggregation provides limited benefit (for example battery systems with no substantial collector grid, or for very small plants), aggregated models may be used.
steady-state short-circuit model	Yes	n/a	Yes	
Fundamental-frequency phasor-domain (PDT) model (user-defined model and/or generic model)	[Maybe ^a]	Maybe ^a (maximize non-aggregation based on model limitations)	Yes	A non-aggregated stability model may inform proper coordination between IBR Unit protection, voltage protection, and voltage ride-through capability specified at the point of measure.. In cases where aggregation provides limited benefit (for example battery systems with no substantial collector grid, or for very small plants), aggregated models may be used.
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Putting It All Together



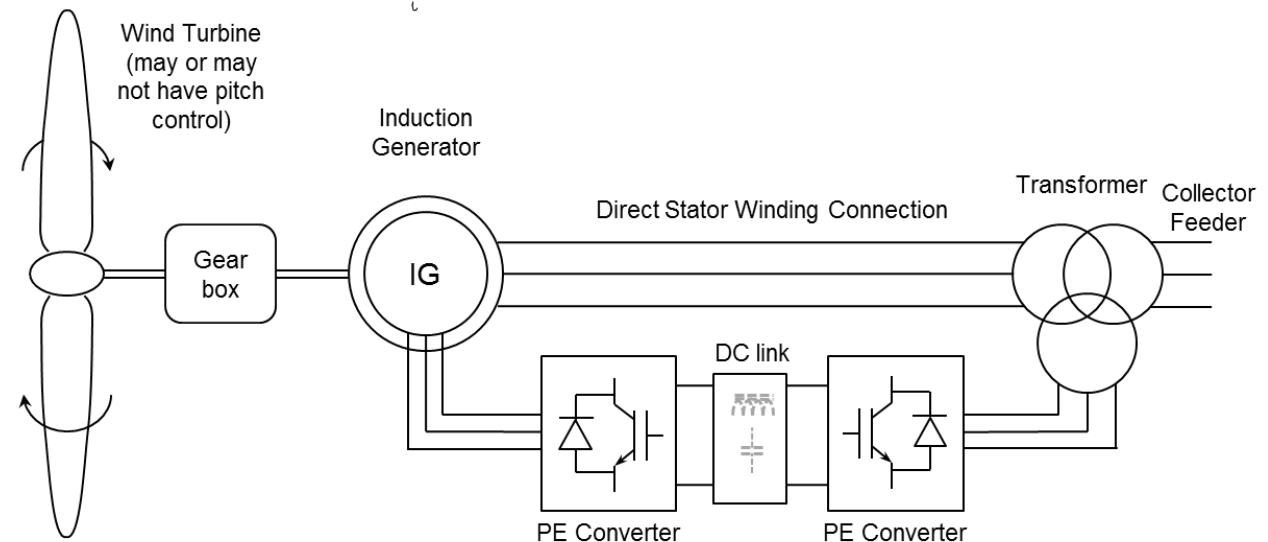
IBR Controls Review

IBR Controls?

- Understanding IBR controls is important to:
 - Understand how device will act on the system
 - Understand what “expected behaviour” may be
 - Understanding nature of inverter-related instability
 - Diagnose / debug EMT model issues
 - Facilitate constructive conversations with OEMs / developers
 - Understand difference in types of controls for wind / PV / BESS / GFM

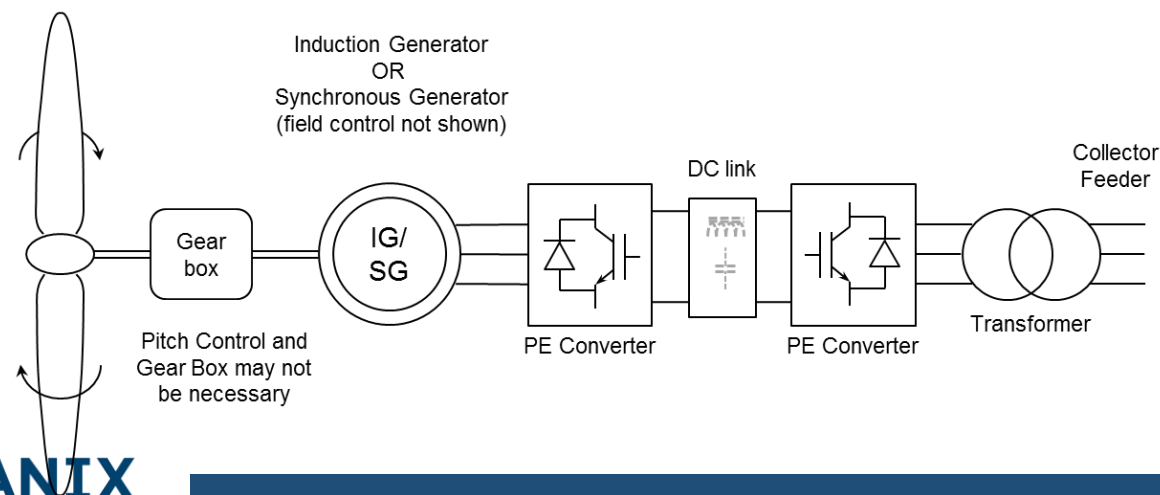
Wind Turbine – Type 3

- *Type 3: Doubly Fed Asynchronous Generator*
 - *Wound rotor connected through a converter to the grid.*
 - *Converters rated to approximately 30% of machine rating*
 - *Rotor speed can vary +/- 30% of synchronous speed*
 - *Much improved energy harvesting compared to older fixed-speed designs*
 - *Independent P/Q control*

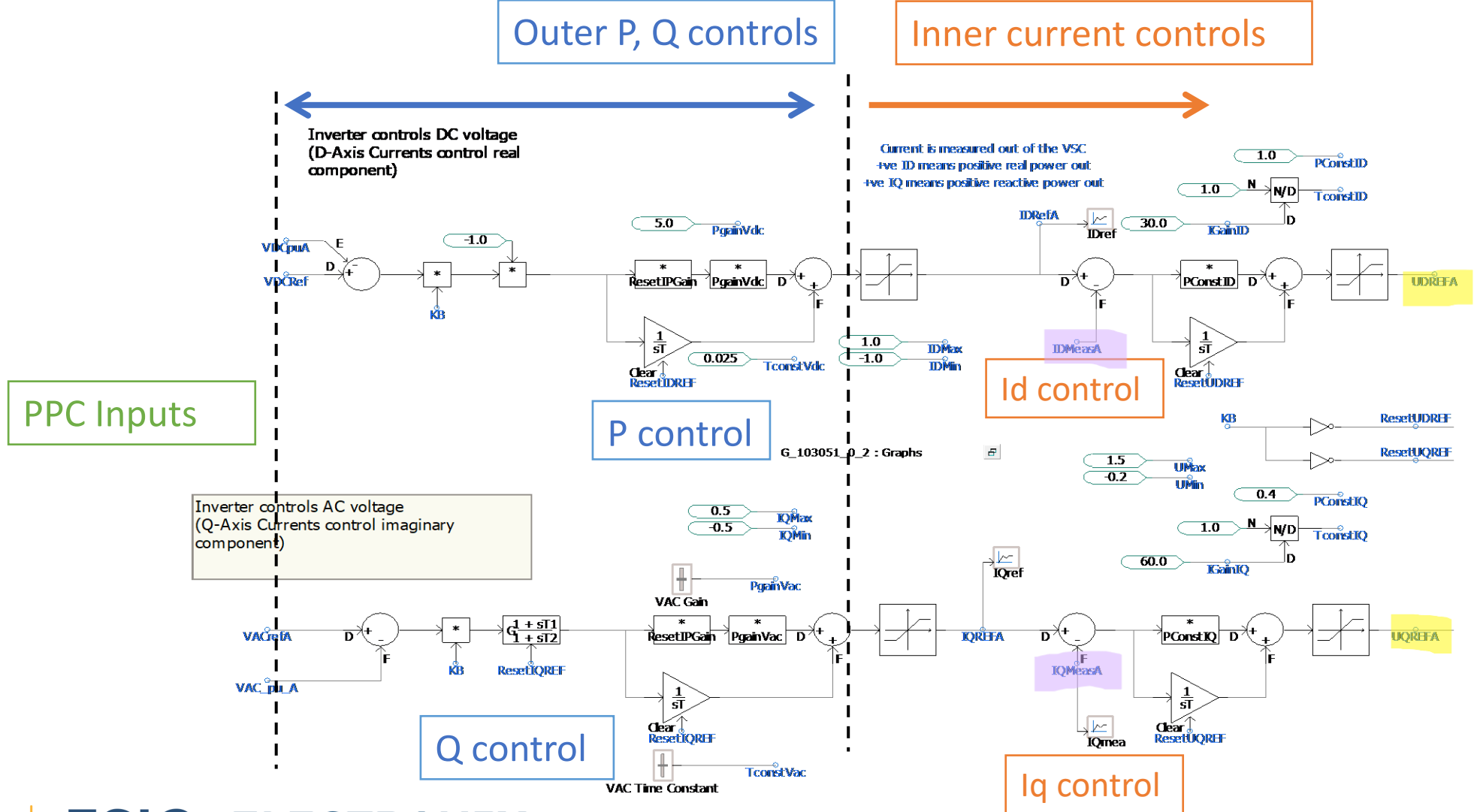


Full Converter

- *Type 4 WTG: Generator connected through fully rated converters*
 - *Can use induction or synchronous generators*
 - *Generator speed is decoupled from grid frequency*
 - *Gearbox optional*
- *PV Inverter:*
 - *Interface similar to Type 4 (full converter), with fewer mechanical constraints (e.g. can reduce power from PV immediately, no crowbar needed)*
- *BESS Inverter:*
 - *Similar to PV, plus fast bi-directional power flow*

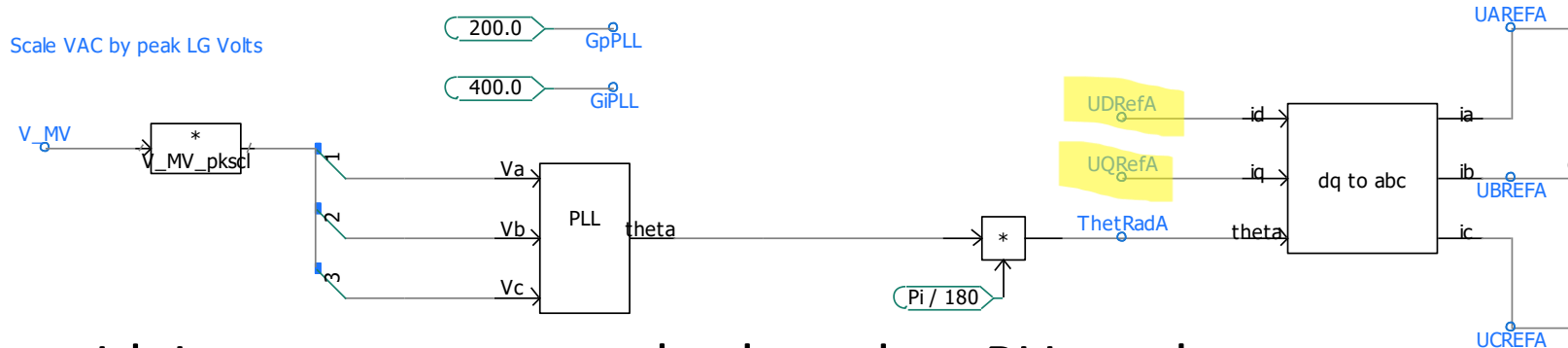


Outer and Inner Controls

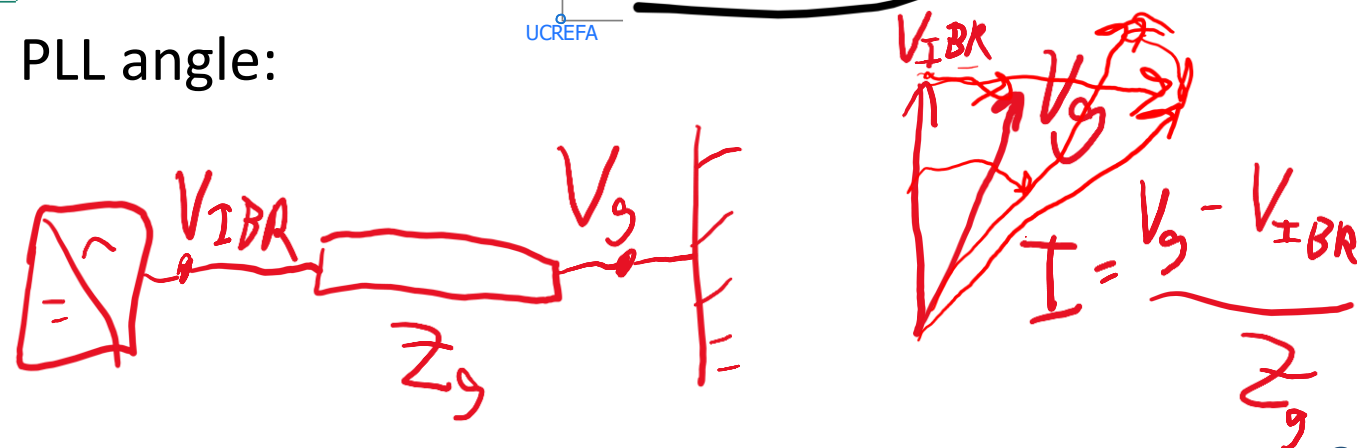
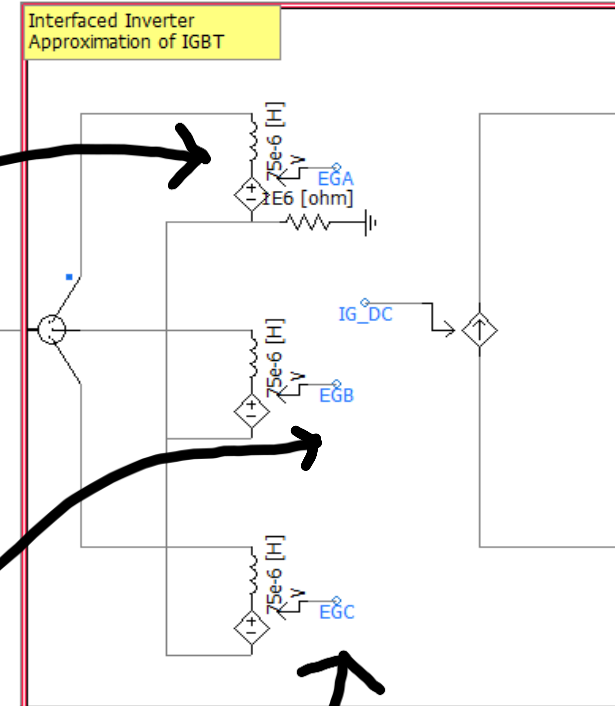
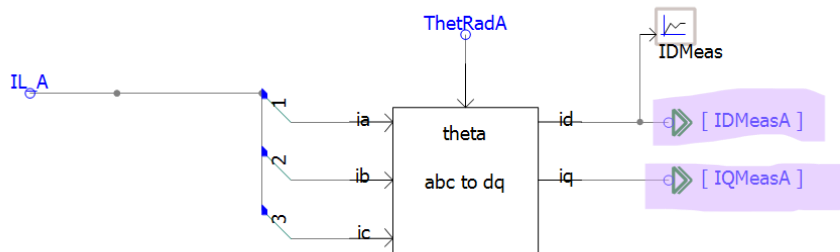


PLL and firing controls

- Simplified voltage source approximation of IGBT bridge (average source model):

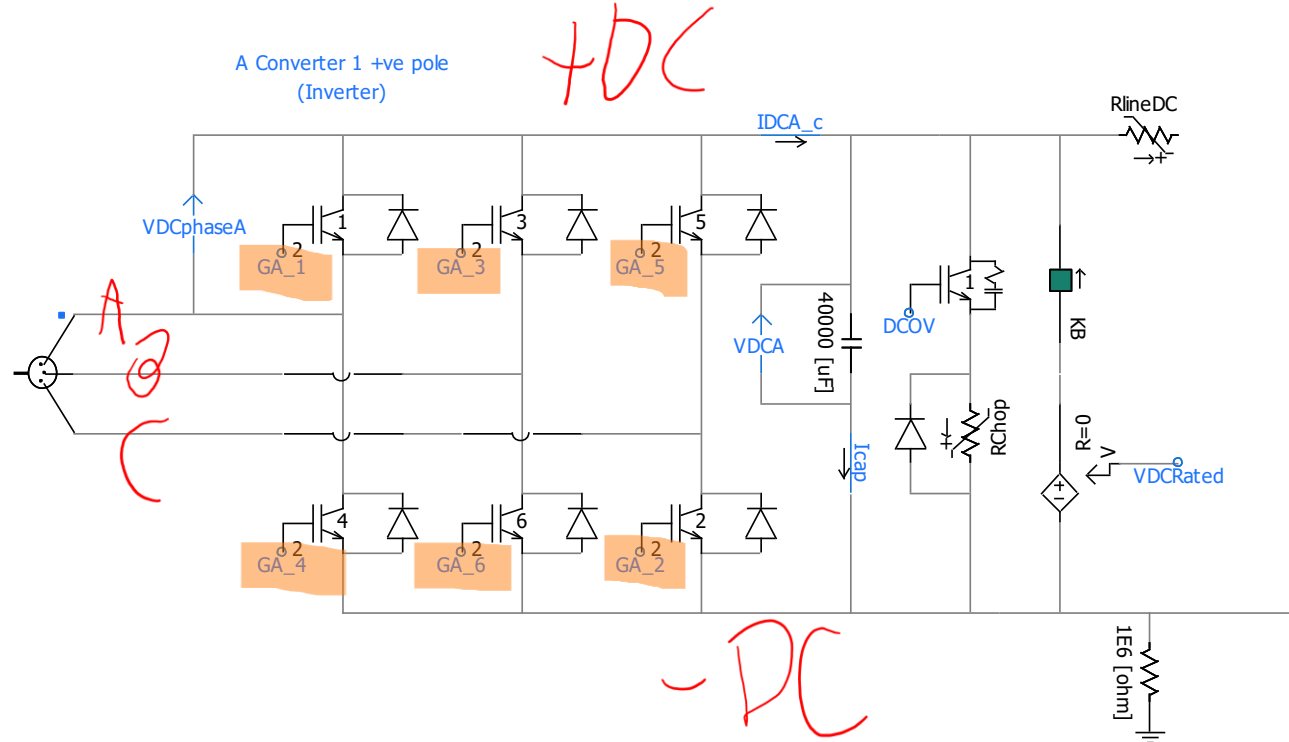


- Id, Iq measurements also based on PLL angle:



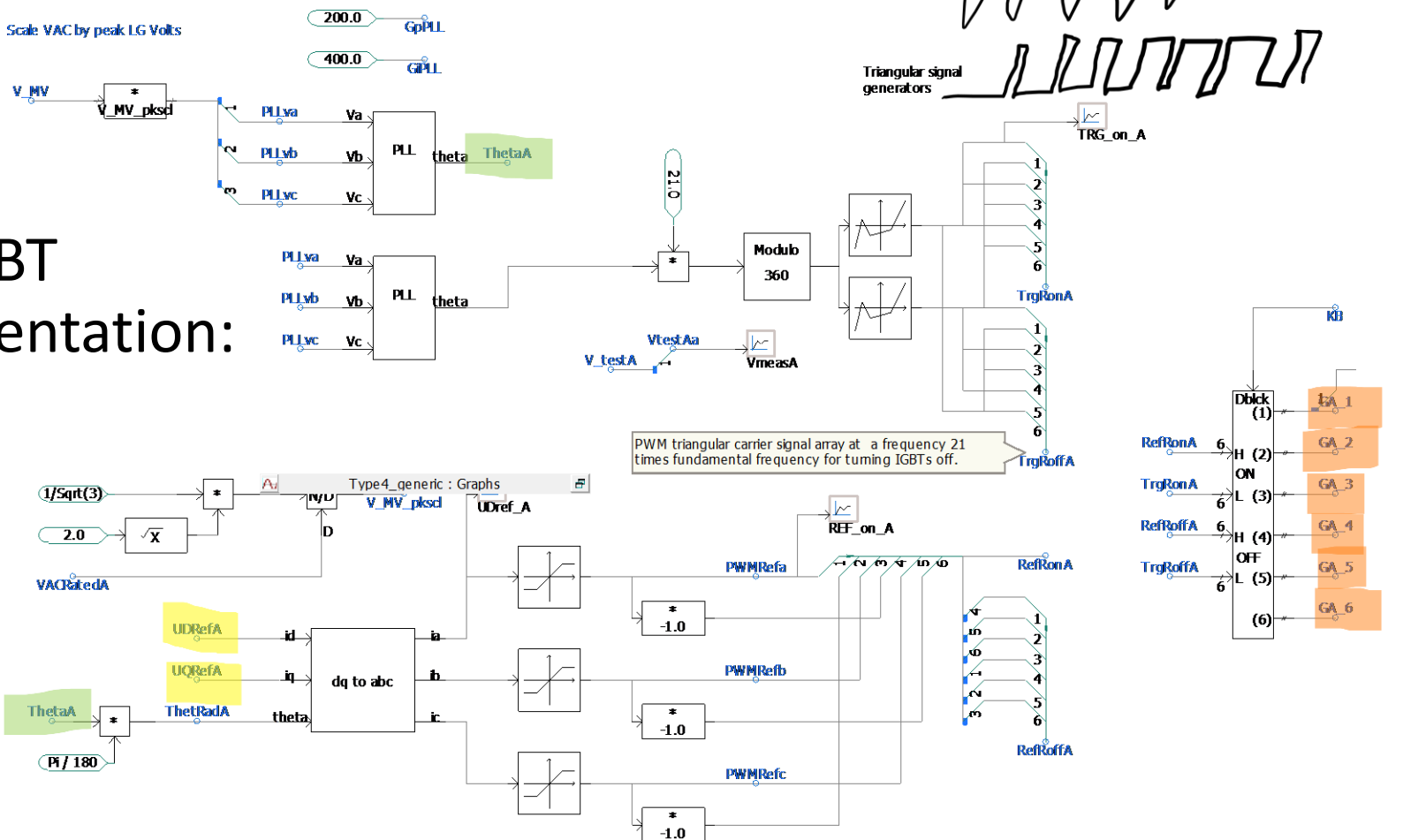
PLL and firing controls

- Full IGBT representation:



PLL and firing controls

Full IGBT representation:



EMT Model Testing & Intake

EMT Model Intake

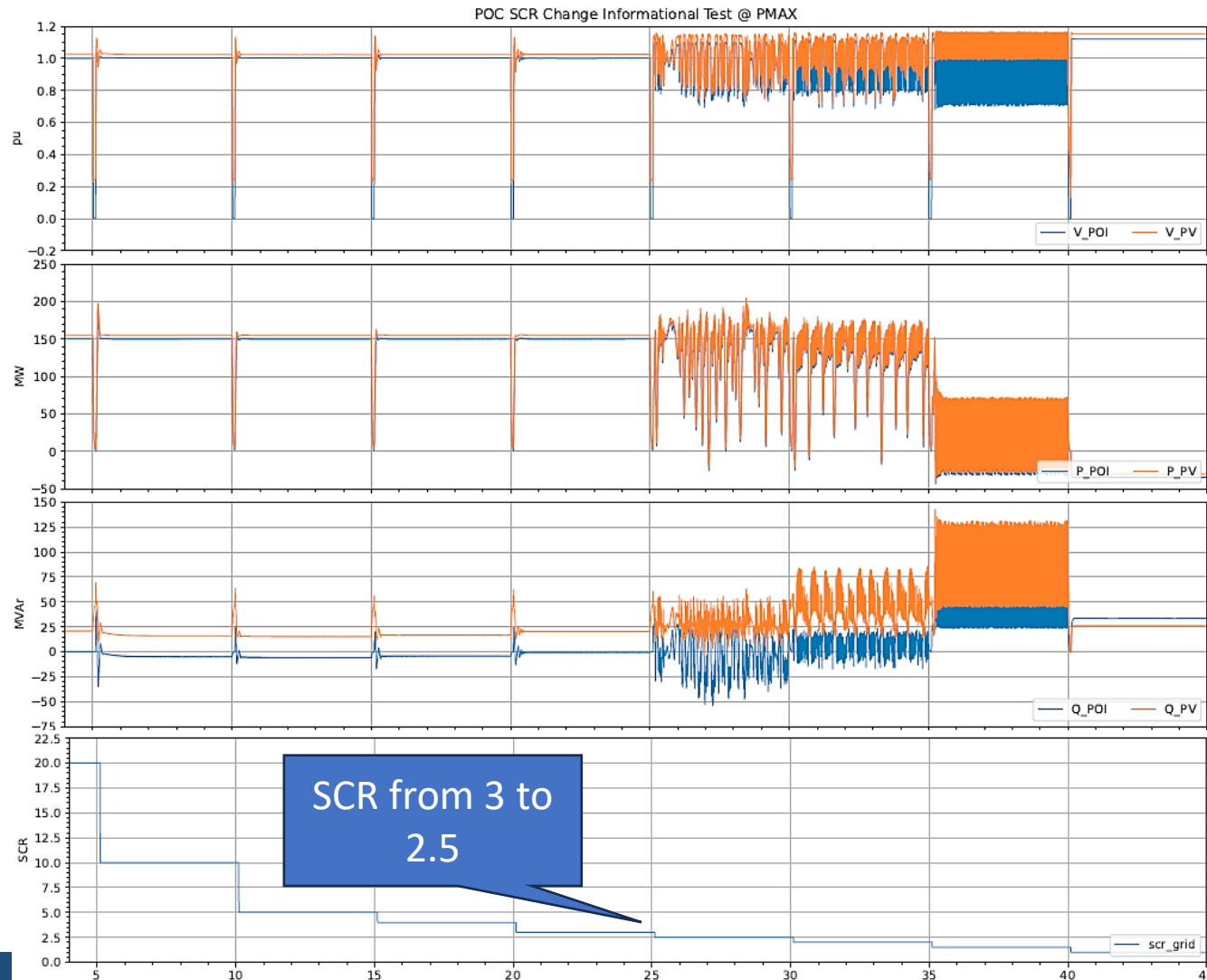
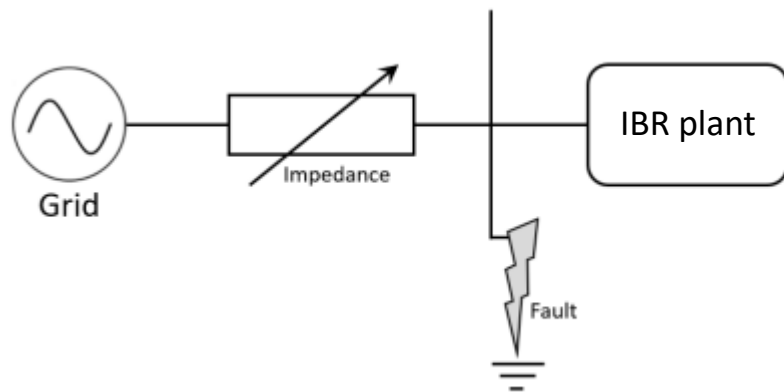
- Why collect and check EMT models?
 - High quality, well verified models needed for EMT studies
 - Lack of usability - > challenging or impossible to use in study
 - Lack of accuracy -> inaccurate studies (limited value)
 - Lack of basic performance -> likely won't work well in a system study
- Should you collect models for all plants, even if not under study?
 - Yes! insurance for when you need to include that plant in a future study
 - difficult to get accurate models for plants after COD

EMT Model Intake – Model Requirements

- Process that must include:
 - EMT model requirements
 - **Accuracy**: Is it detailed and correct? Validated?
 - **Usability**: Does it function within a study context?
 - **Site-specific**: Does it represent the equipment being used?
 - Documentation
 - **Performance Testing**: Is the plant likely to conform with basic performance needs for the system? (Note that usually a full study is the final arbiter of “acceptable performance”)
 - Documentation
- May include:
 - Benchmarking between EMT and RMS models
 - Testing of specific capability (e.g. GFM)

EMT Model Intake – Performance Testing

- Tests may include:
 - Fault ride-through and recovery
 - Voltage / Frequency, Phase-jump, and RoCoF ride-through
 - Voltage / Frequency support verification
 - Weak-system performance testing
 - Specific capability testing (e.g. GFM)



Terminology & timelines note

- Late 2000's – present: Electranix Model Requirements (EMR)
 - Earlier versions emphasis on model accuracy & usability, with basic performance tests (i.e. check 3LG FRT at SCR 3) added later
 - Rev 13 (2025) performance tests roughly match proposed 2800.2 SG3 (~50 tests)
- 2020: ERCOT MQT (Model Quality Testing)
 - Accuracy emphasis plus some ERCOT-specific performance requirements
- 2022: IEEE 2800-2022 Appendix G EMT Dynamic Modelling Requirements
- Draft IEEE 2800.2 Terminology:
 - Design Evaluation: Tests plant model against many IEEE 2800 performance requirements. Should not replace EMT interconnection study (if warranted), but likely the only EMT study that most plants get
 - MQT: Preliminary check on model accuracy and basic performance
- Many others along the way
- Today's Landscape?

Electranix Model Requirements Walkthrough

Model Accuracy Features

For the model to be sufficiently accurate, it must:

- A. *Represent the full detailed inner control loops of the power electronics.* The model cannot use the same approximations classically used in transient stability modeling, and must fully represent all fast inner controls, as implemented in the real equipment. Models which embed the actual hardware code into a PSCAD component are currently wide-spread, and this is the required type of model.^{2,3}
- B. *Represent all control features pertinent to the type of study being done.* Examples include external voltage controllers, customized PLLs, ride-through controllers, SSCI damping controllers and others. As in point A, actual hardware code is required to be used for most control and protection features.
- C. *Represent plant level control.* Power Plant Control (PPC) representation must be included which represents the specific controllers used in the plant. Plant controllers must be represented in sufficient detail to accurately represent short term performance, including transitions into and out of ride-through modes, settable control parameters or options, and any other specific implementation details which may impact plant behaviour. *Generic PPC representations are not acceptable unless the final PPC controls are designed to exactly match the generic PPC model.* If multiple plants are controlled by a common controller, or if the plant controller is controlling multiple types of resources (eg. Hybrid BESS/PV), this must be included in the plant control model. If supplementary or multiple voltage control devices (eg. STATCOM) are included in the plant, these should be coordinated with the PPC. *All plant level communication delays should be included in the model, including transport delays, measurement delays, delays due to bus (eg. MODBUS) communication, sample and hold logic at the inverter or the PPC, and any other delay that may influence overall plant response in the time-frame of the study.*

Electranix Model Requirements Walkthrough

- D. *Represent all pertinent electrical and mechanical configurations.* This includes any filters and specialized transformers (including grounding transformers). Mechanical features such as gearboxes, pitch controllers, PV panel dynamics, DC bus controllers, must be modelled if they impact electrical performance within the timeframe and electrical purview of the study. An infinite voltage source on the DC side is generally not acceptable. Battery resources must include the capability to represent the full range of state-of-charge levels. PV and wind resources must have capability to represent full range of active power availability. Any control or dynamic features of the actual equipment which may influence behaviour in the simulation period which are not represented or which are approximated must be clearly identified.
- E. *Have all pertinent protections modeled in detail for both balanced and unbalanced fault conditions.* Typically this includes various OV and UV protections (individual phase and RMS), frequency protections, DC bus voltage/current protections, converter overcurrent protections, and often other inverter specific protections. Any protections which can influence dynamic behaviour or plant ride-through in the simulation period must be included. If there are mechanical limits which influence ride-through, such as thermal protection of wind turbine crowbar functions, these should be included in the model. Actual hardware code is recommended to be used for these protection features.
- F. *Be configured to match expected site-specific equipment settings.* Any user-tunable parameters or options must be set in the model to match the equipment at the specific site being evaluated, as far as they are known. Default parameters are not appropriate unless these will match the configuration in the installed equipment.

Electranix Model Requirements Walkthrough

Model Usability Features

In order to allow study engineers to perform system analysis using the model, the PSCAD model must:

- G. *Have control or hardware options which are pertinent to the study accessible to the user.* Although plant must be configured to match site specific settings as far as they are known (see point F above), parameters pertinent to the study must be accessible for use by the model user. Examples of this could include protection thresholds, real power recovery ramp rates, frequency or voltage droop settings, voltage control response times, or SSCI damping controllers.⁴ *Diagnostic flags (eg. flags to show control mode changes or which protection has been activated) should be visible to aid in analysis.*
- H. *Be accurate when running at a simulation time step of 10 μ s or higher.* Often, requiring a smaller time step means that the control implementation has not used the interpolation features of PSCAD, or is using inappropriate interfacing between the model and the larger network. Lack of interpolation support introduces inaccuracies into the model at larger simulation time-steps. In cases where the power transistor (eg. IGBT) switching frequency is so high that even interpolation does not allow accurate switching representation at 10 μ s (eg. switching frequency greater than 40 kHz), an average source approximation of the inverter switching may be used to allow a larger simulation time step².
- I. *Operate at a range of simulation time steps.* The model must not be restricted to operating at a single time step, but must be able to operate within a range (eg. 10 μ s – 20 μ s)
- J. *Include documentation and a sample implementation test case.* Test case models must be configured according to the site-specific real equipment configuration up to the Point of Interconnection. This would include (for example): aggregated generator model, aggregated generator transformer, equivalent collector branch, main plant transformers, gen tie line, power plant controller, and any other static or dynamic reactive resources. Test case must use a single machine infinite bus representation of the system, configured with an appropriate representative SCR⁵. Access to technical support engineers is desirable. Additional detail on required documentation and test case is described in PSCAD Model Test Checklist (Appendix A).

Electranix Model Requirements Walkthrough

- K. *Have an identification mechanism for configuration.* The model documentation must provide a clear way to identify the specific settings and equipment configuration which will be used in any study, and tie these model parameters to as-left hardware settings at commissioning. This may be control revision codes, settings files, or a combination of these and other identification measures.
- L. *Accept external reference variables.* This includes real and reactive power ordered values for Q control modes, or voltage reference values for voltage control modes. Model must accept these reference variables for initialization, and be capable of changing these reference variables mid-simulation, ie. dynamic signal references.
- M. *Be capable of initializing itself.* Once provided with initial condition variables, the model must initialize and ramp to the ordered output without external input from simulation engineers. Any slower control functions which are included (such as switched shunt controllers or power plant controllers) must also accept initial condition variables if required. Note that during the first few seconds of simulation (eg. 0-2 seconds), the system voltage and corresponding terminal conditions may deviate from nominal values due to other system devices initializing, and the model must be able to tolerate these deviations or provide a variable initialization time.
- N. *Have the ability to scale plant capacity.* The active power capacity of the model must be scalable in some way, either internally or through an external scaling component. This is distinct from a dispatchable power order, and is used for modeling different capacities of plant or breaking a lumped equivalent plant into smaller composite models.

EMR Performance Tests

- Based on IEEE 2800 requirements
- Recommend using a moderately weak SCR (e.g. 2.5) for most tests

⁵ Representative SCR should reflect approximate N-1 interconnection SCR where possible, especially if the system is expected to be weak. If the system strength is not known, using a relatively low SCR in the test system, such as 2.5, may help to avoid issues during study phases.

Performance Tests

- Initialization (flat run)
 - Check that plant can initialize correctly for all considered initial conditions
 - Check Pmax, Pmin, possibly Qmax, Qmin

EMR

Table 1: Initialization Tests

Test #	Test Description				Success Criteria
	Test duration [s]	Test Type	Active Power	Reactive Power	
1-1	20	Flat Run	Pmax ¹⁷	0	Reach steady state within 5s
1-2	20	Flat Run	Pmin	0	Reach steady state within 5s

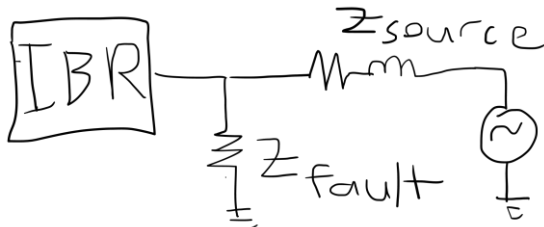
Performance Tests

Low-voltage ride through (fault tests)

- Option 1: zero-impedance infinite bus, play in ride-through curve
 - Tests exact limits, but grid model unrealistic



- Option 2: use source impedance and fault impedance as voltage divider
 - Less precise POI voltage, allows for testing with non infinite source



$V_{IBR} \sim = 0.5$ when $Z_{source} = Z_{fault}$

EMR

Table 11—Voltage ride-through requirements at the RPA for IBR plants with auxiliary equipment that cause ride-through limitations⁸⁹

Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
$V > 1.20$	May ride-through or may trip	NA
$V > 1.10$	Mandatory operation	1.0
$V > 1.05$	Continuous operation ⁹⁰	1800
$V < 0.90$	Mandatory operation	3.00
$V < 0.70$	Mandatory operation	2.50
$V < 0.50$	Mandatory operation	1.20
$V < 0.25$	Mandatory operation	0.16
$V < 0.10$	Permissive operation ⁹¹	0.16

Table 12—Voltage ride-through requirements at the RPA for IBR plants without auxiliary equipment that cause ride-through limitations

Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
$V > 1.20$	May ride-through or may trip	NA
$V > 1.10$	Mandatory operation	1.0
$V > 1.05$	Continuous operation ⁹⁰	1800
$V < 0.90$	Mandatory operation	6.00
$V < 0.70$	Mandatory operation	3.00
$V < 0.50$	Mandatory operation	1.20
$V < 0.25$	Mandatory operation	0.32
$V < 0.10$	Permissive operation ⁹¹	0.32

Table 2: Balanced Fault Ride-through Tests

Test #	Test Description					Success Criteria
	Fault duration [s]	Fault type	Fault impedance Z_f	Active Power	Reactive Power	
2-1	0.16	3PHG	$Z_f=0$	P_{max}^{17}	0	Ride Through
2-2	0.16	3PHG	$Z_f=0$	P_{max}^{17}	Q_{min}	Ride Through
2-3	0.16	3PHG	$Z_f=0$	P_{max}^{17}	Q_{max}	Ride Through
2-4	2.50	3PHG	$Z_f=Z_s$	P_{max}^{17}	0	Ride Through
2-5	2.50	3PHG	$Z_f=Z_s$	P_{max}^{17}	Q_{min}	Ride Through
2-6	2.50	3PHG	$Z_f=Z_s$	P_{max}^{17}	Q_{max}	Ride Through

Table 3: Unbalanced Fault Ride-Through Tests

Test #	Test Description					Success Criteria
	Fault duration [s]	Fault type	Fault impedance Z_f	Active Power	Reactive Power	
3-1	0.16	2PHG	$Z_f=0$	P_{max}^{17}	0	Ride Through
3-2	0.16	2PHG	$Z_f=0$	P_{max}^{17}	Q_{min}	Ride Through
3-3	0.16	2PHG	$Z_f=0$	P_{max}^{17}	Q_{max}	Ride Through
3-4	0.16	1PHG	$Z_f=0$	P_{max}^{17}	0	Ride Through
3-5	0.16	1PHG	$Z_f=0$	P_{max}^{17}	Q_{min}	Ride Through
3-6	0.16	1PHG	$Z_f=0$	P_{max}^{17}	Q_{max}	Ride Through

Performance Tests

Low-voltage ride through (fault tests)

- Response during low-voltage:

Table 13—Voltage ride-through performance requirements

Parameter	Type III WTGs	All other IBR units
Step response time ^{b, c, d}	NA ^a	≤ 2.5 cycles
Settling time ^{b, c, d}	≤ 6 cycles	≤ 4 cycles
Settling band	-2.5%/+10% of IBR unit maximum current	-2.5%/+10% of IBR unit maximum current

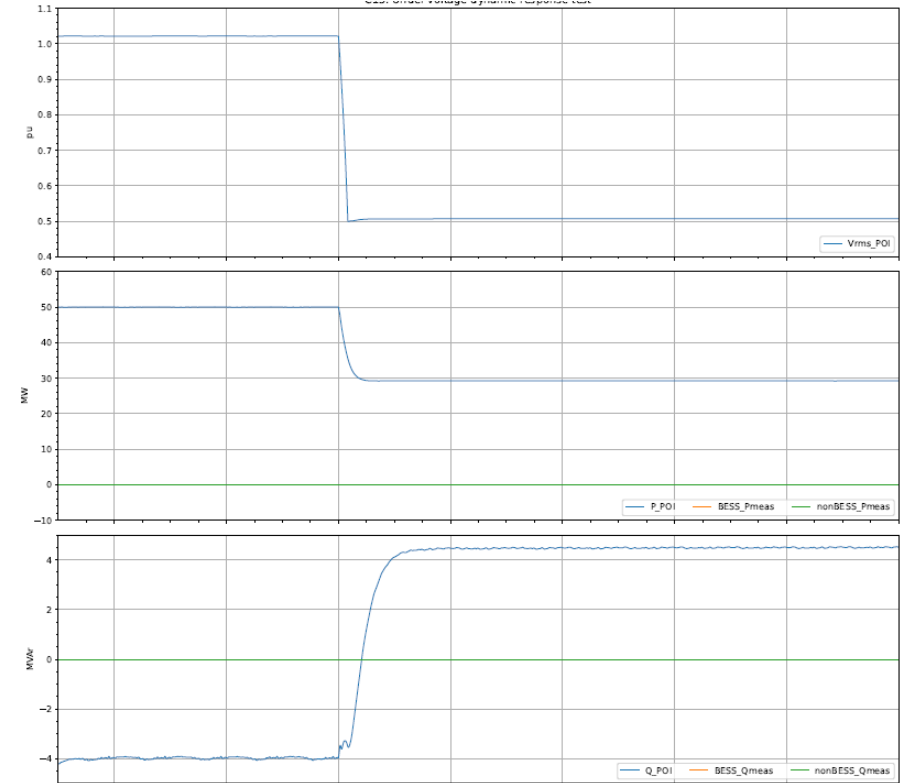
^a The initial response from the type III WTG is driven by machine characteristics and not the control system. DC component, if present, has an impact on response, which is driven by machine parameters and time of fault occurrence. Even though the control system takes an action, it cannot control machine's natural response. As such, defining response time for type III WTGs is not necessary.

^b System conditions may require a slower response time, or IBR units may not be able to meet response times noted in this table for certain system conditions. If so, greater response time and settling time are allowed with mutual agreement between an IBR owner and the TS owner.

^c The DFT with a one-cycle moving average window is used to derive phasor quantities such as active, reactive, positive-sequence, negative-sequence currents, etc. The time delay required for the DFT measurements is included in the step response time and settling time specified in this table.

^d The specified step response time and settling time applies to both 50 Hz and 60 Hz systems.

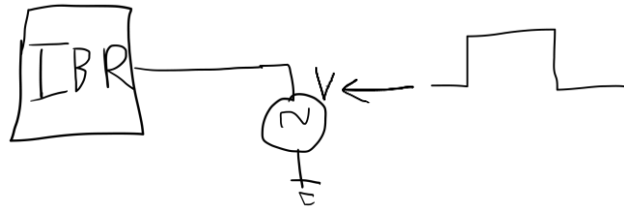
IEEE 2800:



Performance Tests

High-voltage ride through

- Infinite bus play-in ride-through curve



- Alternatives?

Table 11—Voltage ride-through requirements at the RPA for IBR plants with auxiliary equipment that cause ride-through limitations⁸⁹

Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
$V > 1.20$	May ride-through or may trip	NA
$V > 1.10$	Mandatory operation	1.0
$V > 1.05$	Continuous operation ⁹⁰	1800
$V < 0.90$	Mandatory operation	3.00
$V < 0.70$	Mandatory operation	2.50
$V < 0.50$	Mandatory operation	1.20
$V < 0.25$	Mandatory operation	0.16
$V < 0.10$	Permissive operation ⁹¹	0.16

Table 12—Voltage ride-through requirements at the RPA for IBR plants without auxiliary equipment that cause ride-through limitations

Applicable voltage (p.u.) at the RPA	Operating mode/response	Minimum ride-through time (s) (design criteria)
$V > 1.20$	May ride-through or may trip	NA
$V > 1.10$	Mandatory operation	1.0
$V > 1.05$	Continuous operation ⁹⁰	1800
$V < 0.90$	Mandatory operation	6.00
$V < 0.70$	Mandatory operation	3.00
$V < 0.50$	Mandatory operation	1.20
$V < 0.25$	Mandatory operation	0.32
$V < 0.10$	Permissive operation ⁹¹	0.32

EMR

Table 4: Over-Voltage Ride-Through Tests

Test #	Test Description				Success Criteria
	Duration [s]	Grid Voltage at POI (use infinite source at POI)	Active Power at POI	Initial Approx. Reactive Power at POI	
4-1	1	1.2 pu	Pmax	0	Ride Through
4-3	1	1.2 pu	Pmax	Qmax	Ride Through

Performance Tests

Steady-State Voltage Response Test

IEEE 2800:

Table 5—Performance target range

Parameter	Performance target	Notes
Reaction time	< 200 ms	
Maximum step response time	As required by the TS operator	The slowest response shall be tuned based on the TS operator requirements for response time and stability given the anticipated range of grid strength, other local voltage control devices, and overshoot requirements. The step response time may typically range between 1 s and 30 s. Any switched shunts or LTC transformer tap change operation needed to restore the dynamic reactive power capability in Figure 8 shall respond within 60 s.
Damping	Damping ratio of 0.3 or higher	Damping ratio, indicative of control stability, depends on grid strength.

Table 5: Voltage Reference Step Change Tests

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
5-1	Relative V (or Q or PF) ¹ reference change as per Figure 1	P _{max}	0	Step Response < 10s
5-2	Relative V (or Q or PF) ¹ reference change as per Figure 1	P _{min}	0	Step Response < 10s

¹ Will be based on reactive power control method

EMR

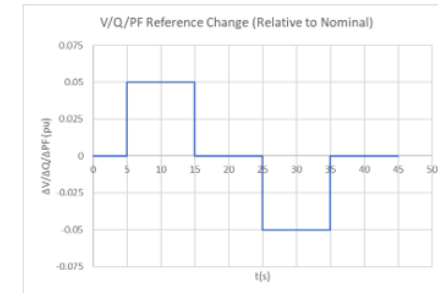
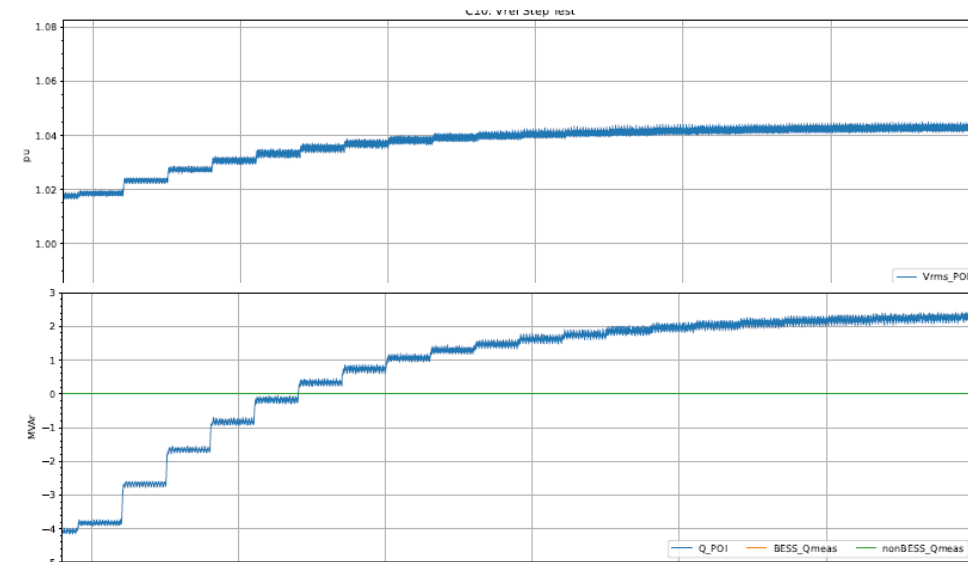


Figure 1: Relative voltage reference step change



Performance Tests

Power Reference Step Test

EMR

Table 6: Active Power Reference Step Change Tests

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
6-1	Active Power controller reference change as per Figure 2	Pmax	0	Plant Responds Appropriately

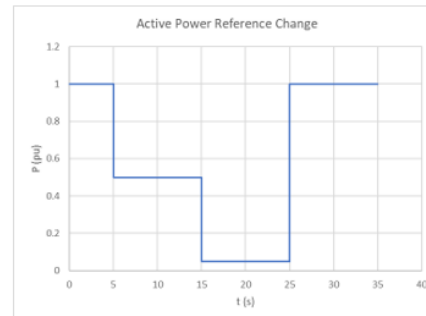


Figure 2: Active power reference step change

No time requirement in IEEE 2800

Performance Tests

Grid Frequency Response Test

IEEE 2800:

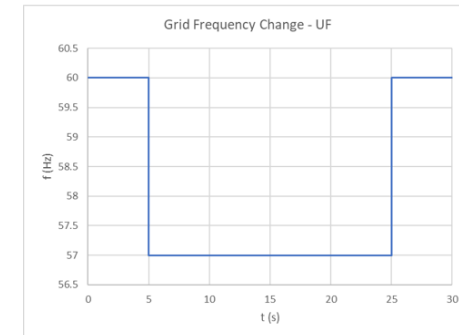
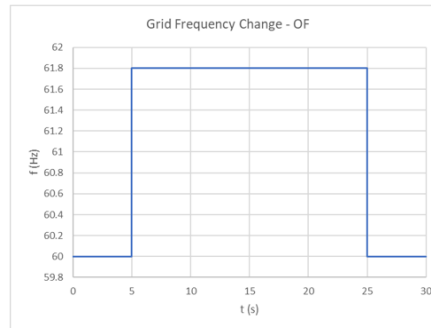
Table 8—Parameters of active power-frequency response dynamic performance for IBR plant

Parameter	Units	Default value	Ranges of available settings	
			Minimum	Maximum
Reaction time	Seconds	0.50	0.20 (0.5 for WTG)	1
Rise time	Seconds	4.0	2.0 (4.0 for WTG)	20
Settling time	Seconds	10.0	10	30
Damping ratio	Unitless	0.3	0.2	1.0
Settling band	% of change	Max (2.5% of change or 0.5% of ICR)	1	5

EMR

Table 7: Grid Frequency Response and Ride-through Tests

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
7-1	Grid Frequency Change as per Figure 3	Pmax	0	Ride-through, Appropriate response per IEEE 2800 Table 8
7-2	Grid Frequency Change as per Figure 3	Pmin	0	Ride-through, Appropriate response per IEEE 2800 Table 8
7-3	Grid Frequency Change as per Figure 4	Pmax	0	Ride-through, Appropriate response per IEEE 2800 Table 8
7-4	Grid Frequency Change as per Figure 4	Pmin	0	Ride-through, Appropriate response per IEEE 2800 Table 8



Performance Tests

Grid Phase Angle Step Tests

7.3.2.4 Voltage phase angle changes ride-through

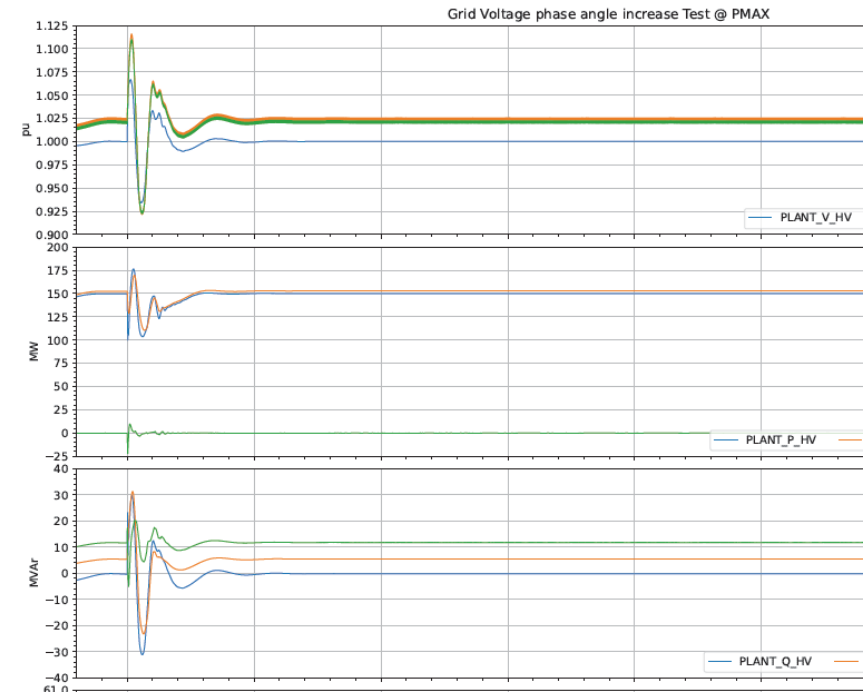
IEEE 2800:

The *IBR plant* shall ride through positive-sequence phase angle changes within a sub-cycle-to-cycle time frame of the *applicable voltage* of less than or equal to 25 electrical degrees.¹¹⁶

EMR

Table 9: Grid Voltage Phase Angle Change Ride-through Tests

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
9-1	Grid voltage angle change equal to +25°	Pmax	0	Ride Through
9-2	Grid voltage angle change equal to -25°	Pmax	0	Ride Through
9-3	Grid voltage angle change equal to +25°	<u>Pmin</u>	0	Ride Through
9-4	Grid voltage angle change equal to -25°	<u>Pmin</u>	0	Ride Through



Performance Tests

SCR Change Test (informational, to a degree)

EMR

Table 10: POC SCR Change Informational Tests

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
10-1	Short Circuit Ratio (SCR) of the plant at POC is changed as per Figure 6. 3LG Z=0 fault is applied at each SCR transition. Time between transitions may be extended to allow stabilization.	Pmax	0	For informational purposes only (not pass/fail). Plant should show stable operation until SCR = 2.5 and is unlikely to show stable operation as SCR approaches 1 ¹

¹ valid only for grid following inverters

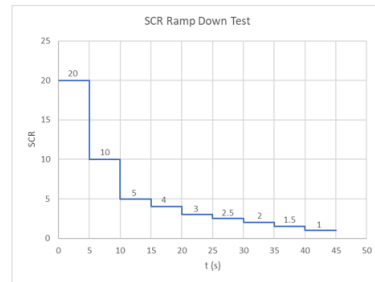
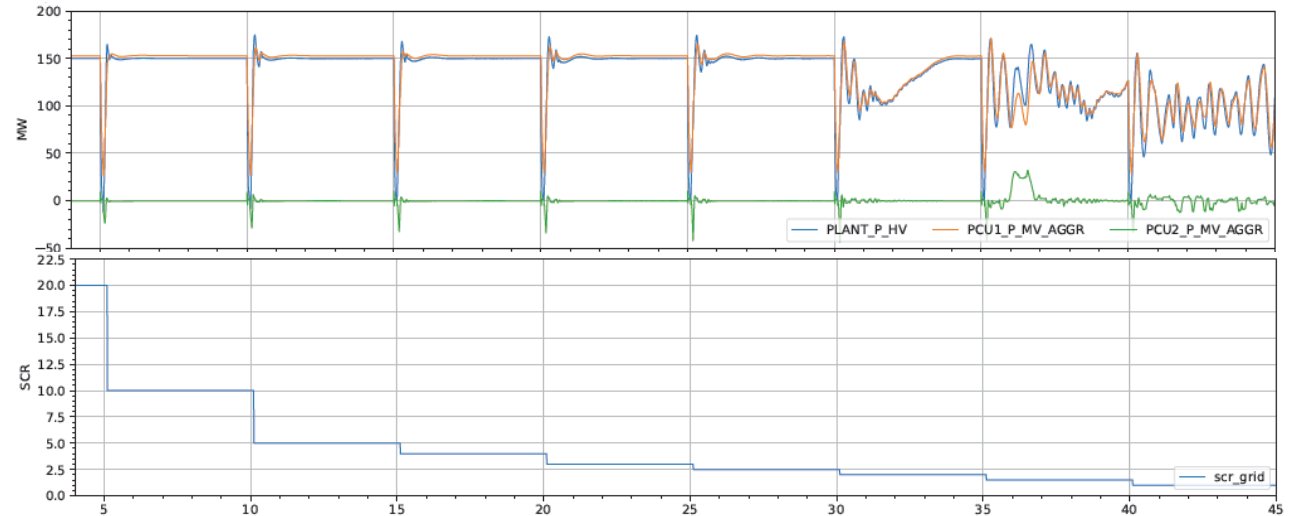


Figure 6: POC SCR change



No such requirement in IEEE 2800

Protection Inclusion Test

EMR

Table 12: Voltage Protection Inclusion Tests (Note that these tests only indicate that the model has protection included, and may vary according to equipment capability)

Test #	Test Description			Success Criteria
	Event	Active Power at POI	Initial Approx. Reactive Power at POI	
12-1	Grid Voltage step as per Figure 9	Pmax	0	Inverter Trips
12-2	Grid Voltage step as per Figure 10	Pmax	0	Inverter Trips

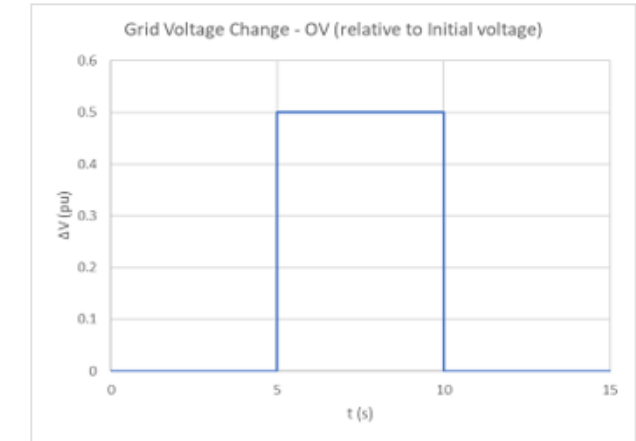


Figure 9: Grid voltage change - OV

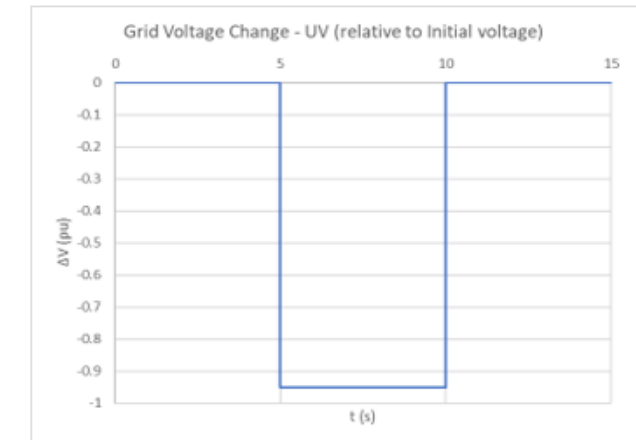
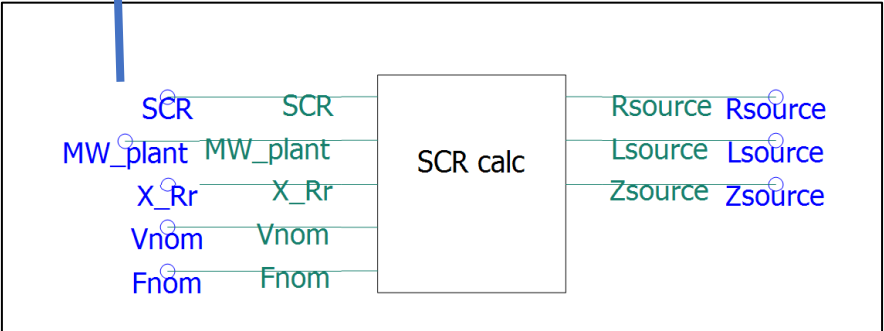
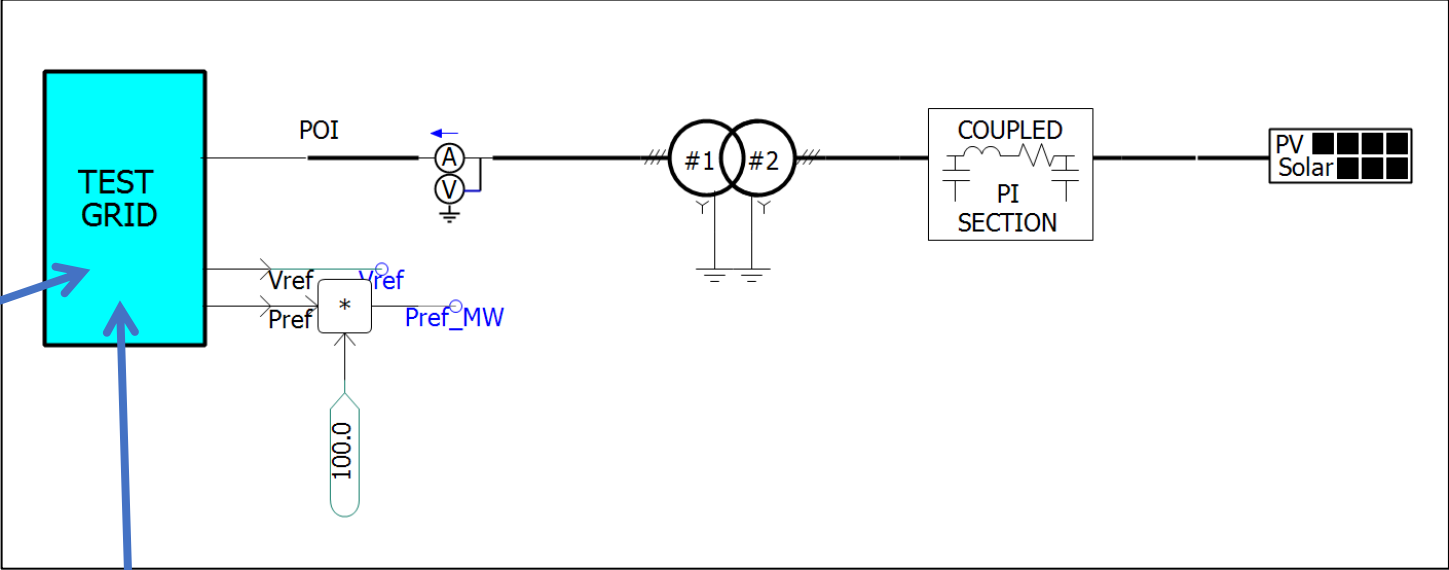
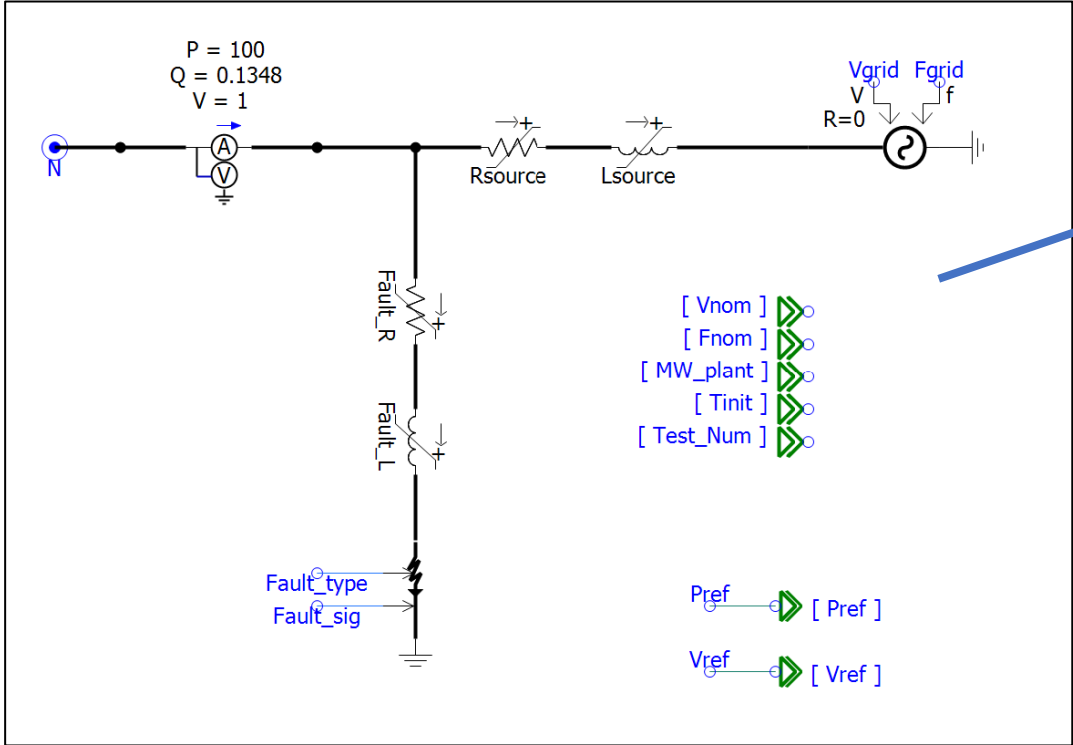


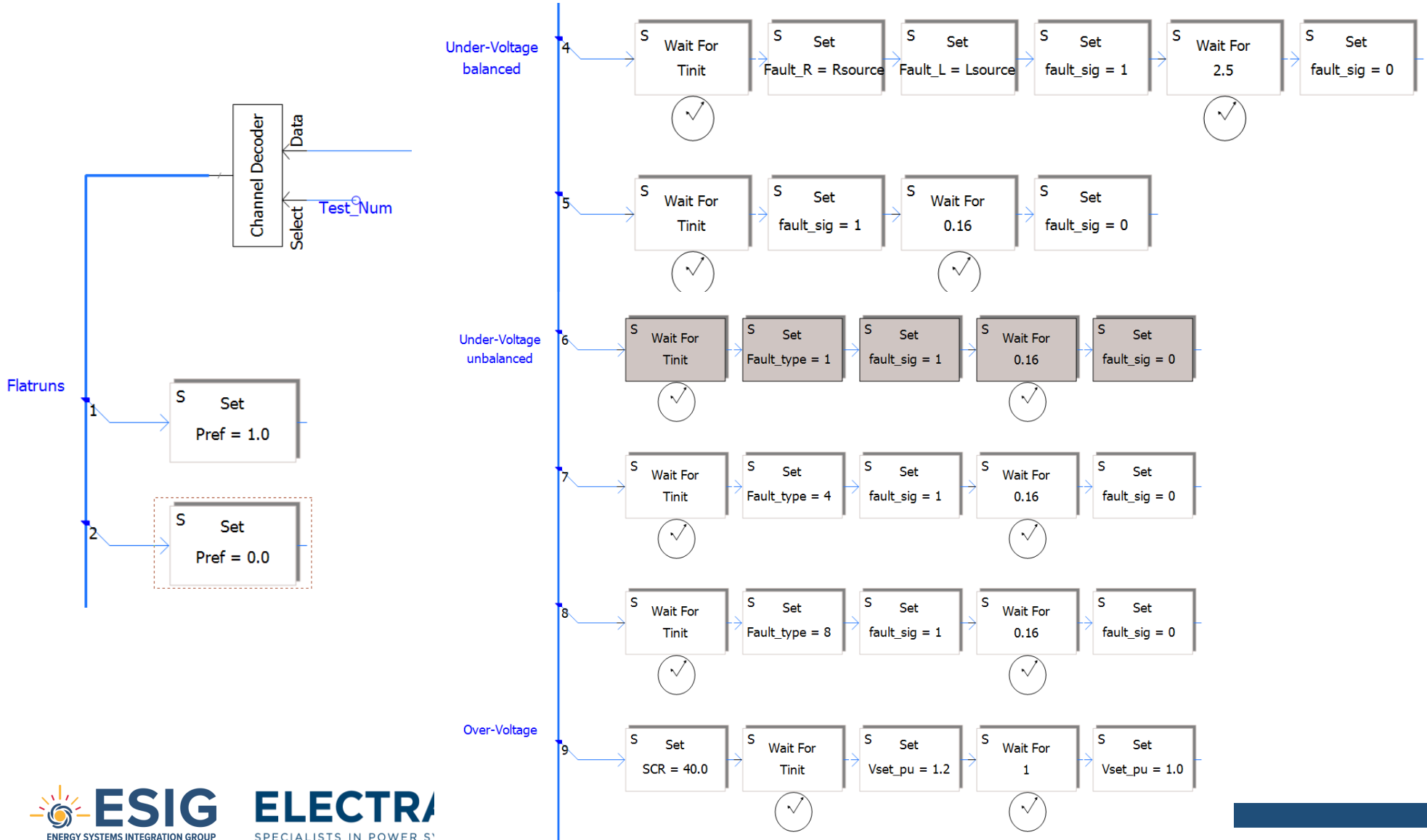
Figure 10: Grid voltage change - UV

No such requirement in IEEE 2800

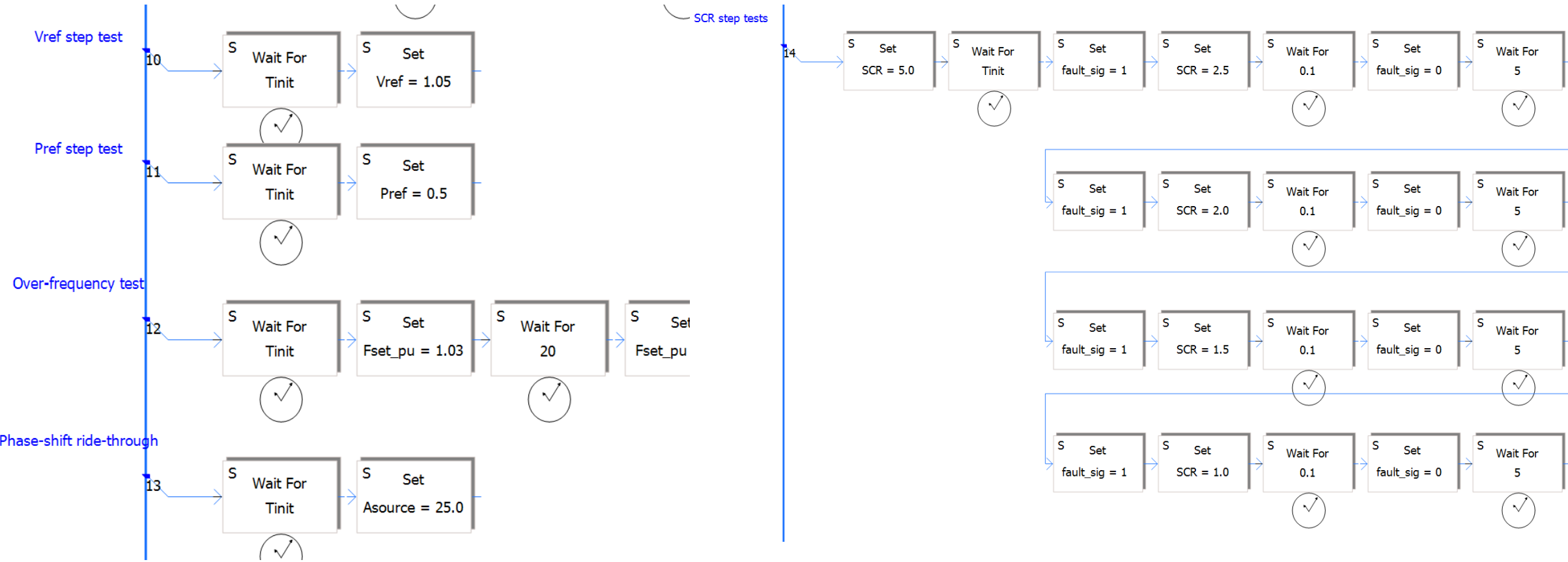
Basic Test Component



Basic Test Component



Basic Test Component



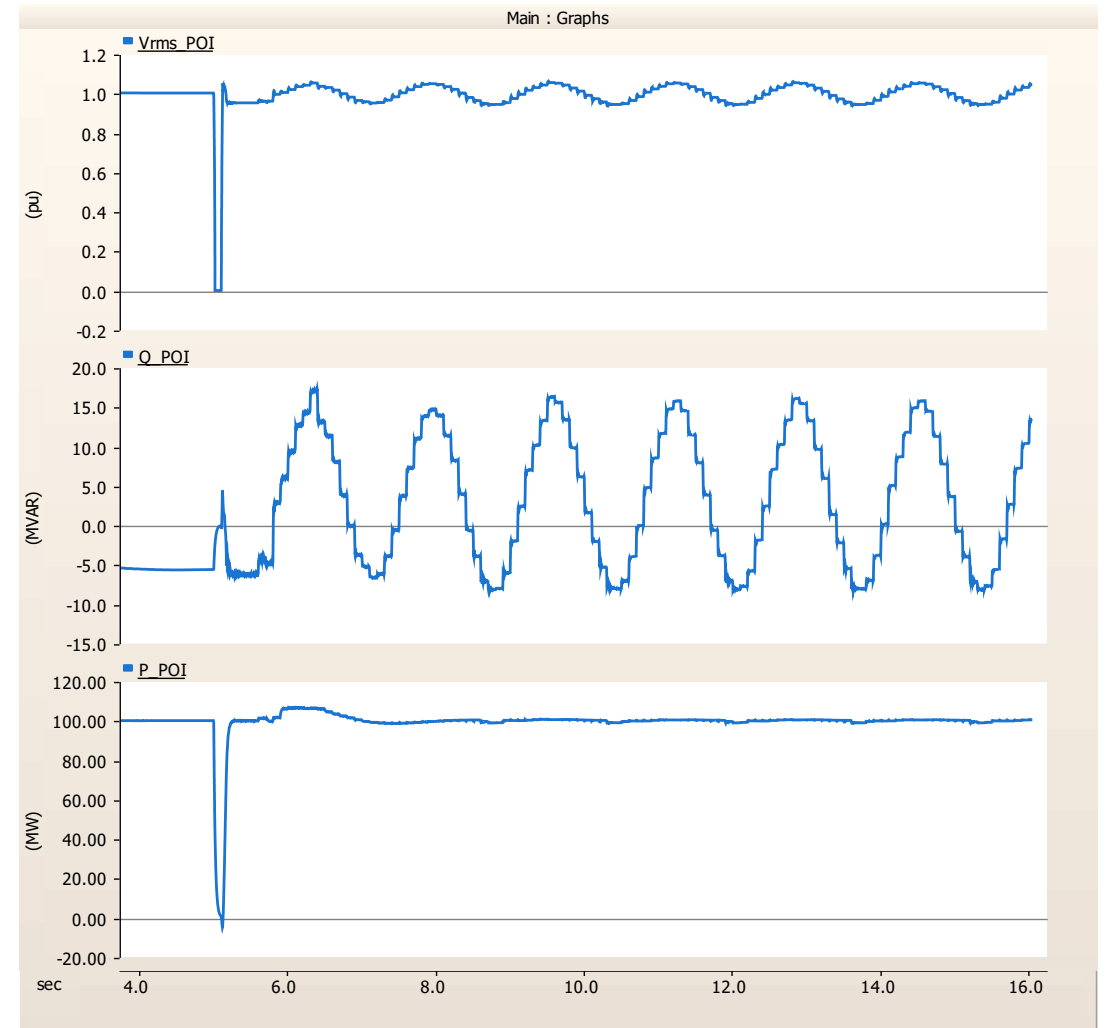
Basic Test Component – Add More Detail?

- Initialization
 - Back calculate voltage source V , angle based on P , Q , V at POI
 - Calculate V_{ref} needed for a given POI V , Q
 - Use fast tap-changer to properly initial tap (if no load-flow solution available)
- Standardized and detailed plotting
 - Terminal and POI quantities
 - Various sequence components, harmonic components, etc.
- Dedicated external automation. May include automated post-processing for success criteria (reporting), automated benchmarking with other simulation platforms, etc.

Workshop – IBR Performance Issues

Example #1

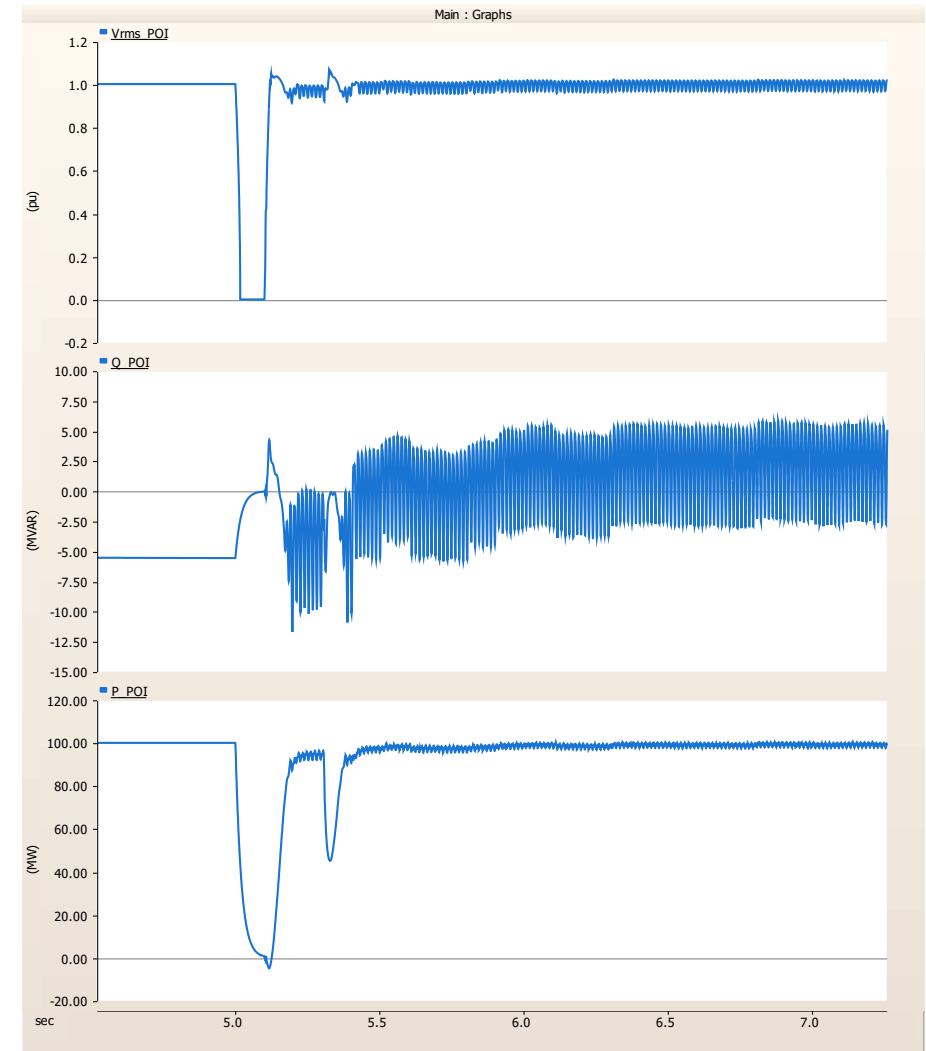
- Root Cause?
- Fix?



Workshop – IBR Performance Issues

Example #2

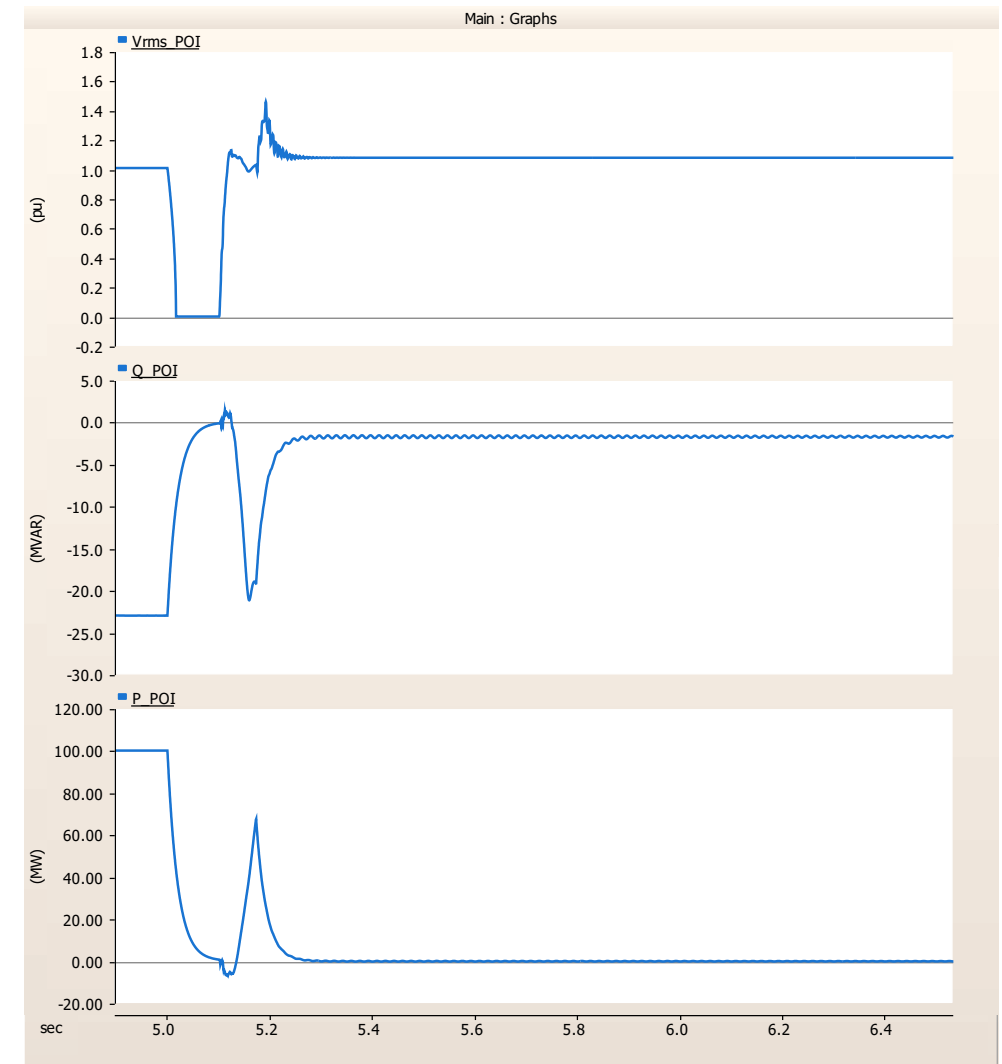
- Root Cause?
- Fix?



Workshop – IBR Performance Issues

Example #3

- Root Cause?
- Fix?



EMT System Modelling

System Model Construction and Quality Assurance

Consider:

1. How big?
2. What detailed models to include?
3. How to construct the model?
4. Can we validate it?

Keep in mind:

- Practical vs Accurate (assumptions!)
- Data availability, timelines, budgets



Kept System Selection

- Not feasible to include full interconnect
- What are you looking for? Fast phenomena -> small system, slow phenomena -> larger system
- Selecting is part science, part art! Mix and match as appropriate...



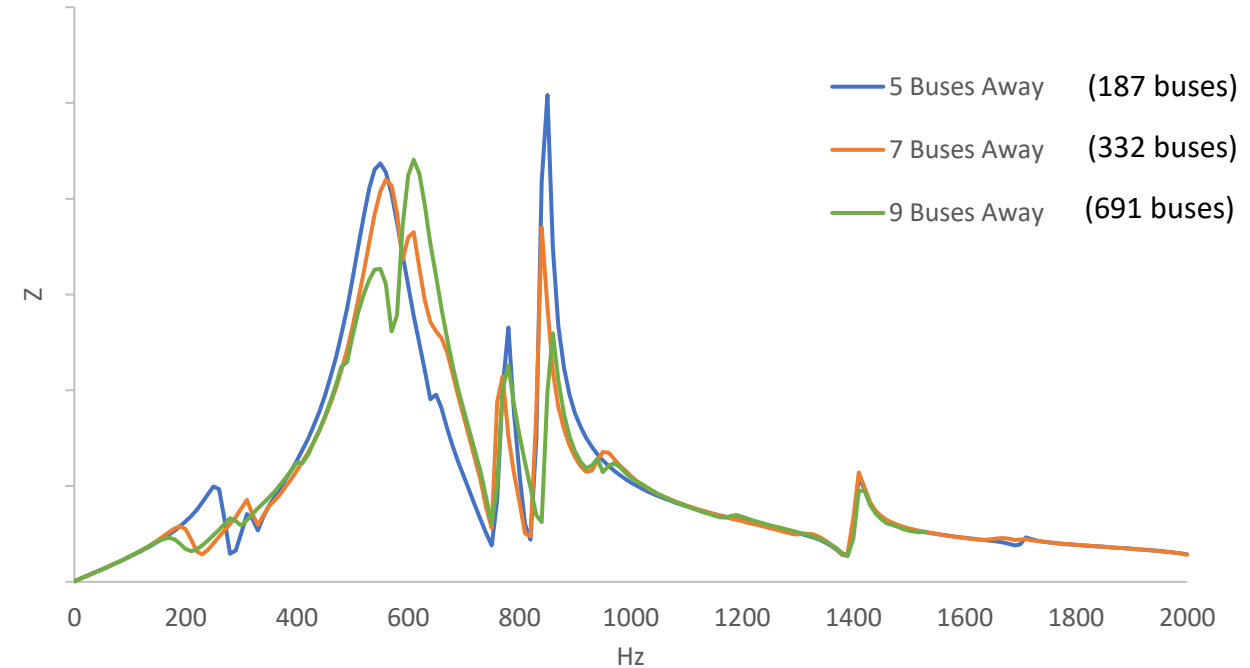
-Missing key device dynamics (machines, HVDC, etc.)
-Network Equivalents having outsized impact on dynamics
-System capacitance cancelled-out in equivalent

-Dynamics de-coupled by strong bus? (“boundary of strength”)
-Frequency response?
-Keep distribution?
Engineering judgement & experience!

-Slow simulation
-Modelling burden
-less “usable” model

Kept System Selection: Frequency Response

- Ideally, model a large enough system to get a valid electromagnetic response from system
- Shunt capacitors and long transmission lines dominate the electrical frequency response (remainder is inductive)



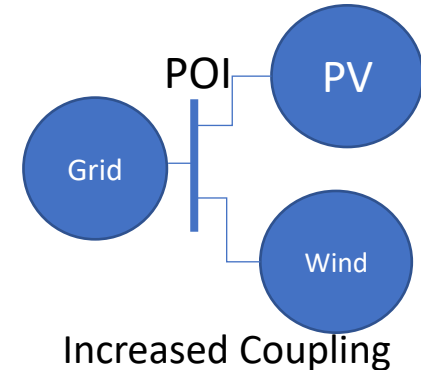
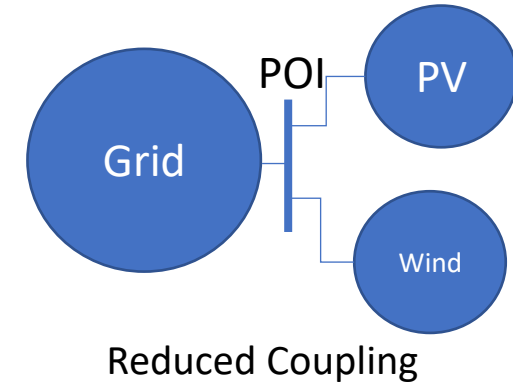
Detailed Models to Include: Nearby IBRs

Impact of Nearby Inverter-Based Resources

- Wind plants, solar plants, STATCOMs, SVCs, HVDC
- Interaction risk is strongly dependent on controls & tuning
- Screening methods are limited, but coupling between inverters (and risk of interaction) is stronger on weak grids
- Unable to assess interactions without EMT models

Technical References

- CIGRE “Connection of Wind Farms to Weak AC Networks” B4.62, Technical Brochure 671
- ERCOT [Panhandle Renewable Energy Zone Study Report](#)

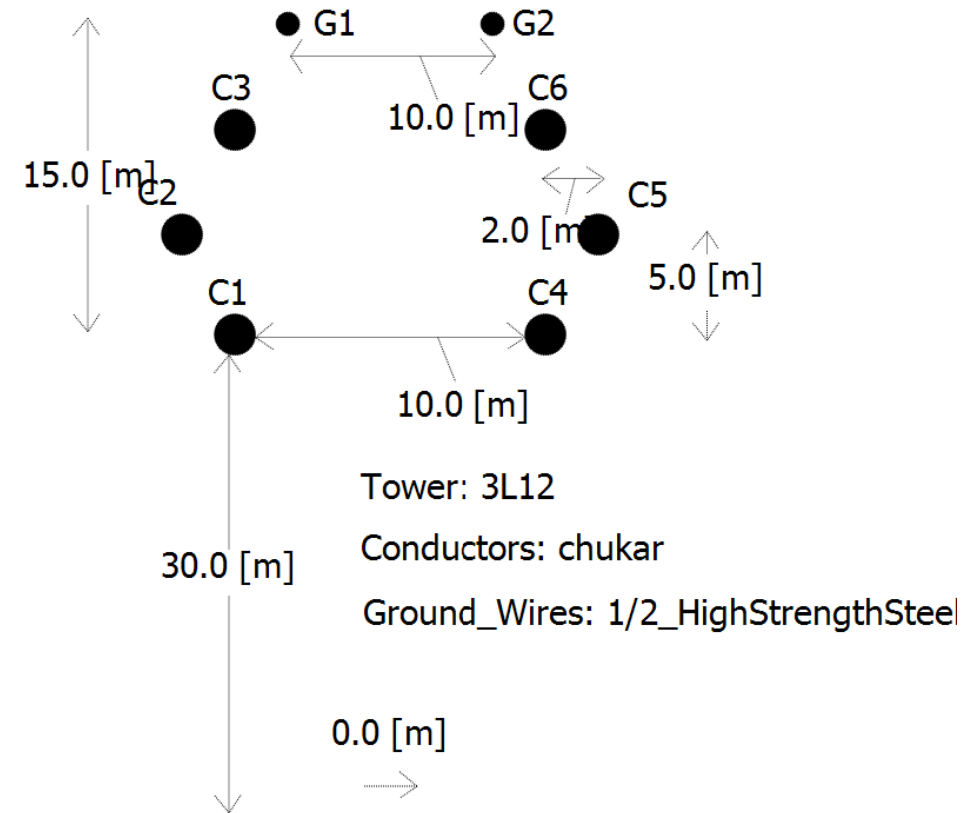


Detailed Models to Include: Transmission Lines

- “Detailed” relative to loadflow-derived data
- Where does it matter?
 - “focus area” vs boundary region
- Transmission lines: Pi-section vs Bergeron vs frequency dependent, mutual coupling
- Transformers: Winding Configuration, Saturation, multi-limb vs 3-phase bank
- Loads: ZIP vs CLOD / CMLD style vs non-generic
- non-IBR generation: standard library models

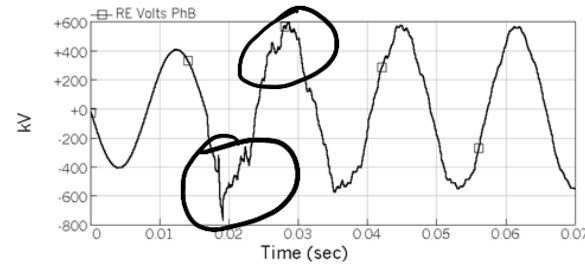
Detailed Models to Include: Transmission Lines

- Load-flow derived models
 - select based on simulation timestep and travel time
 - Travel time > Time Step: Bergeron Traveling Wave Model
 - Travel time < Time Step: Coupled PI Model
- Detailed T-lines:
 - More modelling detail needed
 - Conductor type, tower geometry, sag, grounding, bundling, etc.

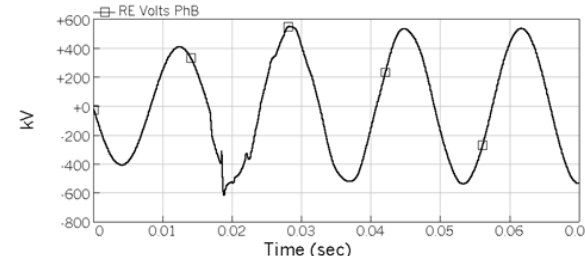


Detailed Models to Include: Transmission Lines

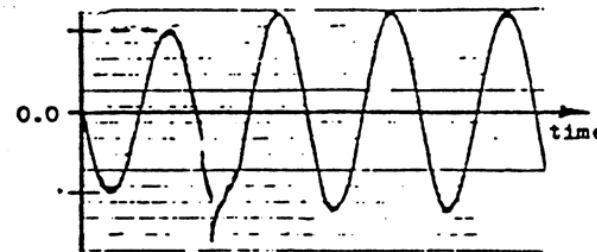
Bergeron model



Frequency dependent (phase) model



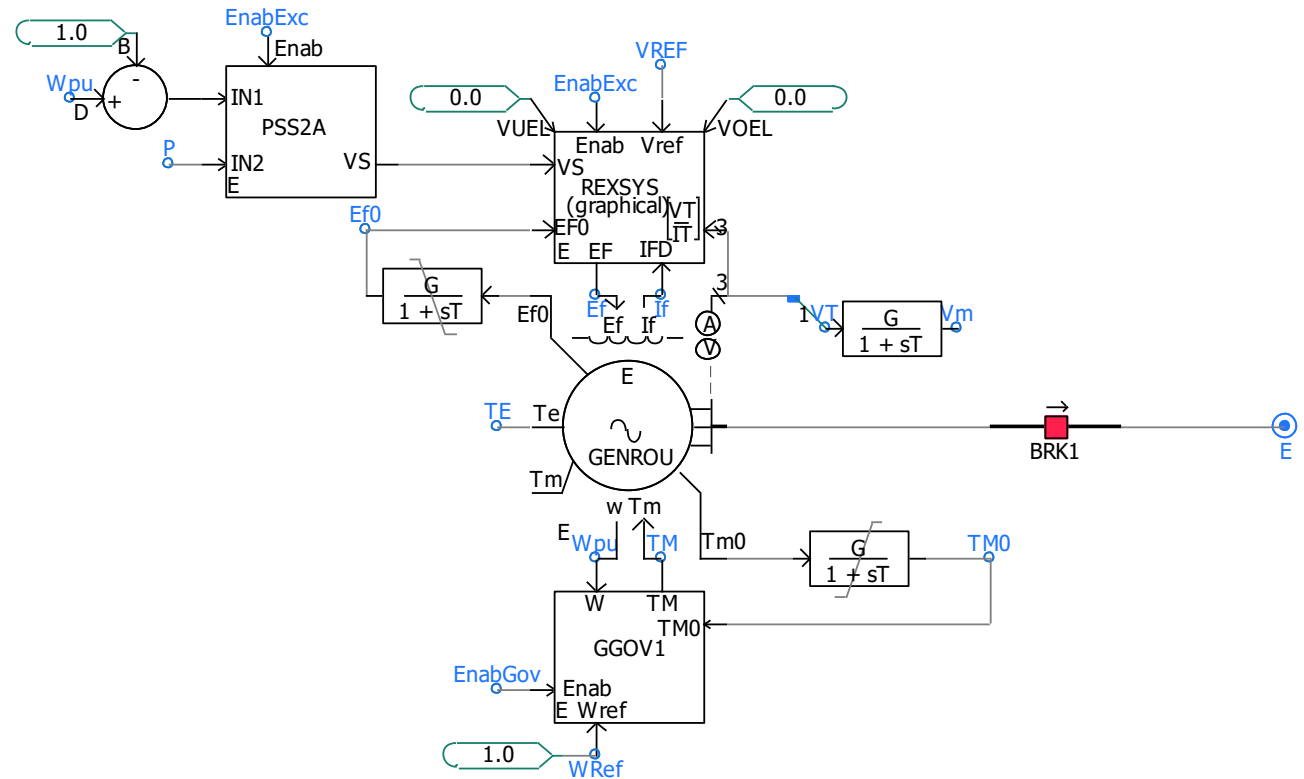
Field test measurement



Full System Model Construction

Generator Model Example

Can construct using PSPD machine dynamic data:

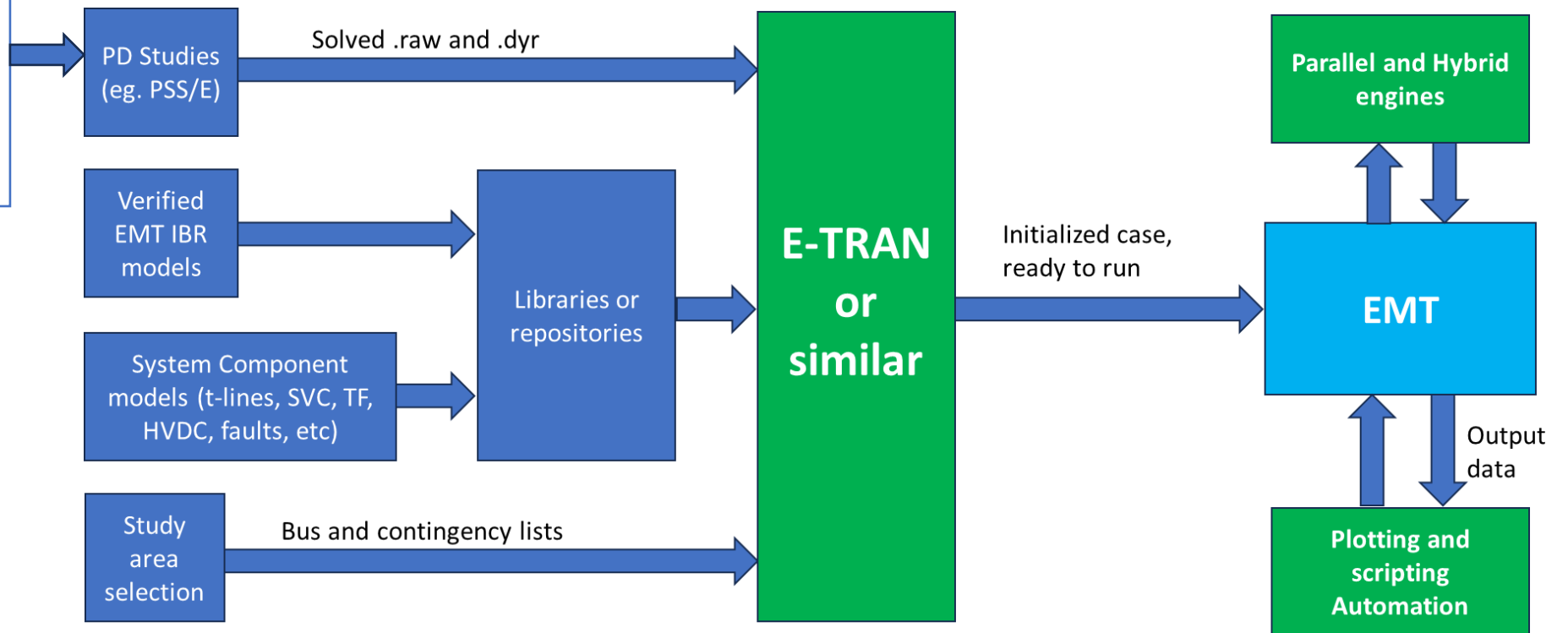


EMT Studies – Building System Model

- EMT type study normally deals with relatively small or medium size power systems
- Main challenges of building system models for large systems:
 - Large amount of data entry (model building) is a challenge and time-consuming
 - Easy to make errors
 - Difficult to select appropriate kept and equivalent subsystems
 - Difficult to use available load flow type data (PSS/E, PSLF and etc) maintained by most power utilities

System Model Construction (Electranix Approach)

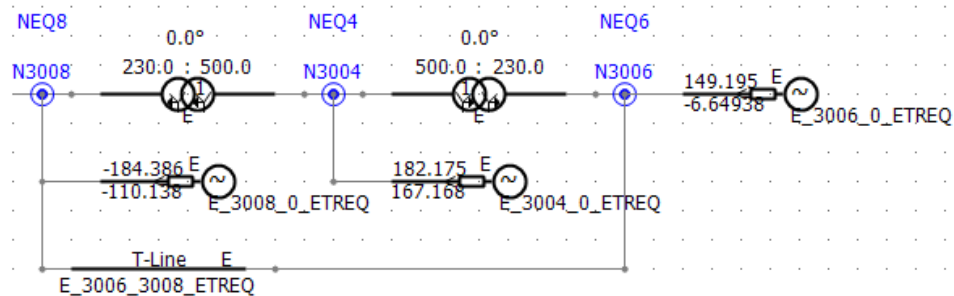
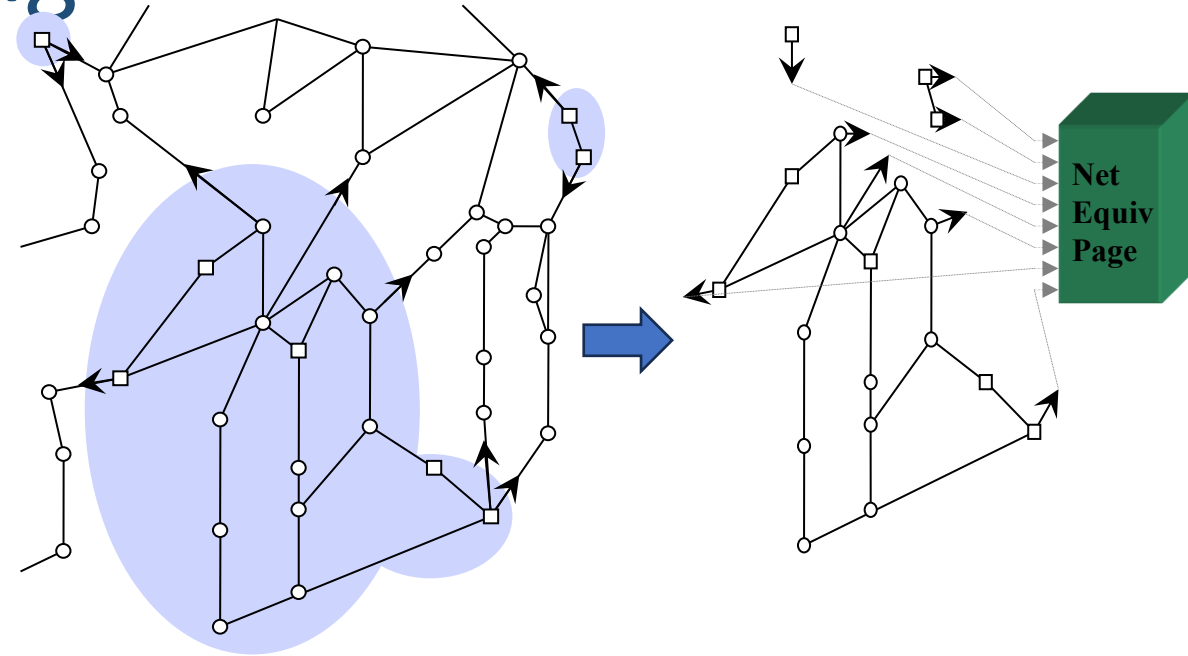
Many PDT runs can be done to identify worst cases, understand wide area dynamics



Full System Model Construction

External System Modelling

- External network typically modelled as $N \times N$ admittance matrix with voltage sources behind impedance at N boundary points
- Voltage source can be passive, (fixed magnitude and angle), or dynamic (co-simulation)
- Custom network equivalents which imitate machine dynamics of external system also possible, but not easy



Is this a dynamic Interface	No (Constant Source)	<input type="checkbox"/>
Name for Source Current	No (Constant Source)	<input type="checkbox"/>
	Yes (Dynamic Source)	<input type="checkbox"/>

Full System Model Construction

Checking Accuracy

- How do we know the model is right?
- Steady state benchmark against loadflow solution
 - Should be very close. Precise alignment is possible
- Short-circuit benchmark
 - Beware of differences in IBR current contributions
- Dynamic benchmark against transient stability
 - Best used to check local electro-mechanical response (inter-area modes may be missing in EMT)
 - Won't match if individual models (especially IBR) are not well benchmarked
 - Consider inherent differences between tools
- Frequency Response Comparisons
- Field validation
 - High speed recordings needed

Special Studies – SSO/SSCI

Type of SSO

Distinguish between terms...

- “SSR”: Sub-Synchronous Resonance
 - Interaction between the mechanical/torsional masses in a generator (or wind turbine) and the electrical resonance from a series capacitor.
 - “SSTA”: Torque Amplification: Increase in peak shaft torques leading to higher fatigue.
- “SSTI”: Sub-Synchronous Torsional Interaction
 - Interactions between the mechanical/torsional masses in a generator (or wind turbine) and a power electronic device (such as an HVDC link, SVC, IBR etc...).
- “SSCI”: Sub-Synchronous Control Instability
 - Interactions between a power electronic device (such as an HVDC link, SVC, IBR etc...) and a series compensated system.
- “SSFR”: Sub-Synchronous Ferro Resonance
 - Interactions between a saturated transformer and a series compensated system.

	Series Cap	Power Electronics	Gas Turbine	Transformer
Series Cap	--	SSCI	SSR	SSFR
Power Electronics	SSCI	Control Interaction	SSTI	--
Gas Turbine	SSR	SSTI	--	--
Transformer	SSFR	--	--	--

Real World SSCI Events

(IEEE transaction on power systems: Yunzhi Cheng et al :[Real-World Subsynchronous Oscillation Events in Power Grids with High Penetrations of Inverter-Based Resources](#))

1. (2007) A SSO event occurred in south central Minnesota when a 100-MW type-3 wind power plant (WPP) was inadvertently left radially connected to a 345-kV series compensated transmission line.
2. (2009) Tripping of a transmission line left multiple type-3 WPPs radially connected to a series compensated 345-kV transmission line in South Texas. Large 20-30 Hz overcurrent appeared within 150 ms, causing severe damage to the series capacitor and WPPs. **Wind controller was modified.**
3. (2010) Oklahoma Gas & Electric (OG&E) observed 13-Hz oscillations at two nearby WPPs. The oscillations occurred when wind farm output was above 80 percent of its rated level and the magnitude of oscillation reached 5% of the 138-kV voltage.: **Wind controller was modified.**
4. (2011) 4-Hz oscillations were observed at a type-4 WPP in Texas region after a transmission line tripped.
5. (2011-2014) Since 2011, oscillations were observed by BPA during high wind generation conditions. A 450MW type-4 WPP located in Oregon was identified as the source. **Voltage controller was modified.**
6. (2011-2012) OG&E reported two wind oscillation events, one in December 2011 and another one in December 2012. Both were triggered due to line outage. For the 2012 event, 3-Hz oscillations appeared at a 60-MW WPP after a line outage. **Wind controller was modified.**
7. (2012-2013) During the one-year period, more than 58 oscillation events were reported in North China with oscillation frequency of 6-9 Hz. The oscillations occurred due to interaction between type-3 WPPs and 500-kV double circuit series compensated transmission lines connecting Guyuan station with Inner Mongolia and North China grids. **SSCI**
8. (2014-2015) 30-Hz oscillations appeared when type-4 WPPs located in Xinjiang China with connection to a 750 kV system started to export power. The oscillations spread to the main grid and caused the subsynchronous resonance (SSR) protection relay of a 600-MW thermal power plant located 48 km away to trip the power plant. Initial research indicated that such oscillations are triggered due to interaction between WPPs with weak grid interconnection. **SSR, SSTI and SSCI**
9. (2015) Poorly damped 20-Hz oscillations were observed in root mean square (RMS) voltage of a 44-kV distribution feeder in Hydro One, Canada after the energizing of a 30 MVar shunt capacitor at the substation. **Weak system**

- 10.(2016) In November 2016, PMUs captured oscillations for multiple days at a solar farm in AEP.
- 11.(2017) 37-Hz and 63-Hz oscillations were observed in instantaneous voltages and currents at a 600-MW type-3 WPP (300 turbines, each 2 MW) connected to a 220 kV grid in northwest China.
- 12.(2017) 7-Hz oscillations in real power, reactive power, and RMS voltage appeared in a First Solar's solar farm in California. **Weak system and PV controller was modified.**
- 13.(2017) Three separate SSO events occurred in South Texas. The frequency range is 22-26 Hz in instantaneous currents. **Wind controller was modified.**
- 14.(2015-2019) 7-Hz voltage oscillations were observed in Australia's West Murray zone under low system strength and high penetrations of IBRs. **Weak system**
- 15.(2018-2019) 3.5-Hz oscillations were observed in real power and reactive power measurement for two 230 kV type-4 WPPs in Hydro One after a planned 230-kV bus outage. The outage caused a significant reduction in system strength viewed from the WPPs. A nearby 150 kV solar PV also reported undamped reactive power oscillations. **Weak system**
- 16.(2019): 9-Hz oscillations were observed 10 minutes before the August 2019 Great Britain (GB) power system disruption . Weak grid oscillations were later identified as the reason why an 800-MW offshore WPP went to the de-loading stage. The WPP vendor upgraded the control software afterwards. **Weak system and wind controller was modified**
- 17.(2020) 7-Hz oscillations, 17-19 Hz voltage oscillations were reported for the Southeast Australia region including Victoria, New South Wales, etc. **Weak system**
- 18.(2021) 22-Hz oscillations in RMS voltage related to a solar PV farm were reported by Dominion Energy in eastern U.S.. In instantaneous currents and voltages, 38-Hz and 82-Hz components were observed.
- 19.(2021-2022) South Africa

When SSO studies are Required

- SSO event occurs, leading to sustained oscillations or the tripping of multiple plants and potential equipment damage.
- High concentration of inverter-based resources (IBRs) located near series-compensated lines.
- Installation of new series-compensated transmission lines in proximity to existing IBRs or synchronous generators.
- Adding non-series-compensated lines in proximity to existing series-compensated infrastructure.
- Integration of IBRs or large loads close to synchronous generation.
- Adding SVCs, STATCOMs and HVDC near series compensation or synchronous generators.

Types of SSO Analysis

1. Screening Studies

- SSR/SSCI: Harmonic Impedance Scans (dynamic and passive)
- SSTI: Unit Interaction Factor/ Radiality factor: based on short circuit calculations

2. Advanced Screening Studies

- System wide eigen-analysis which uses curve-fitting of frequency scans to represent state equations of black-box models

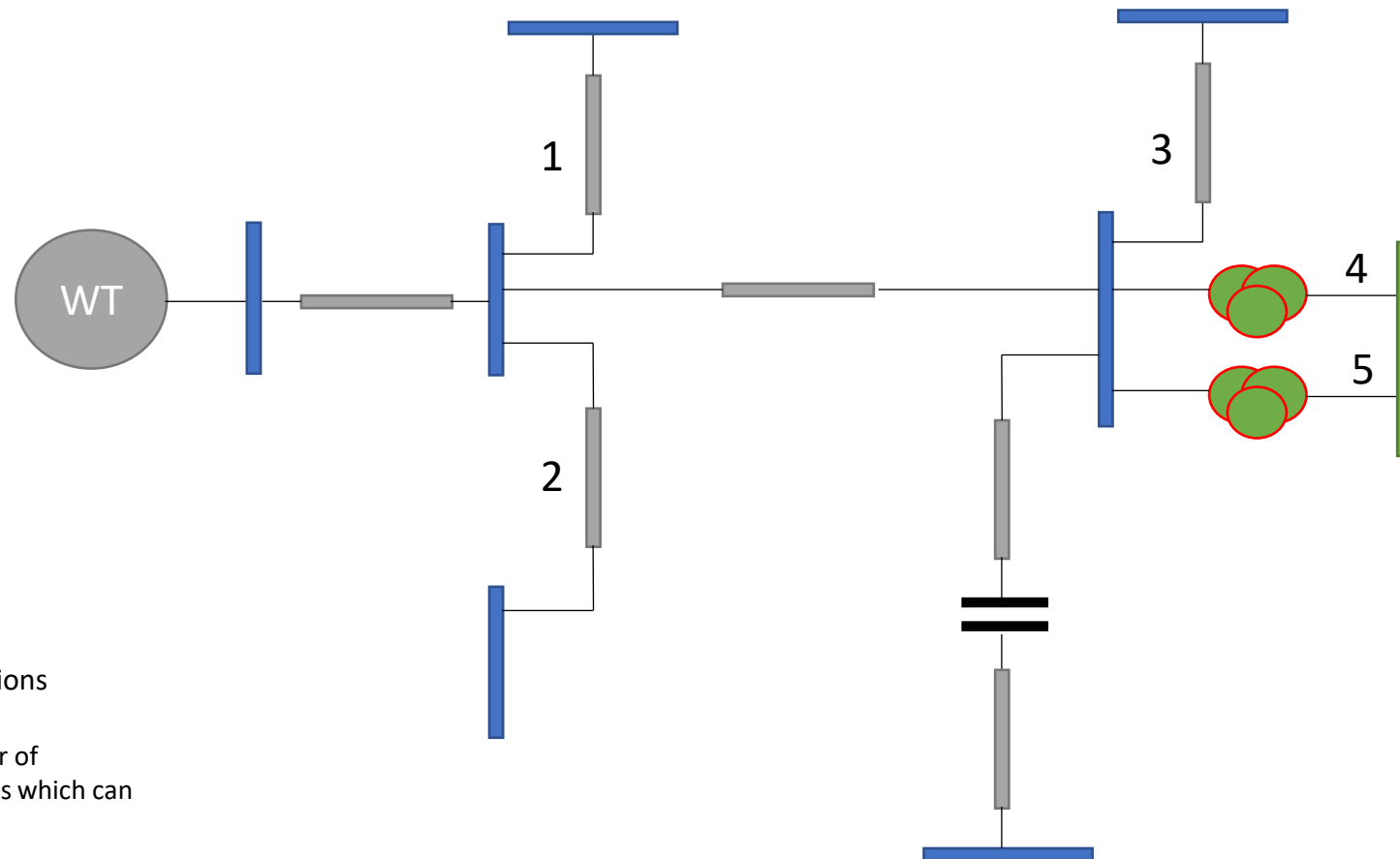
3. Perturbation Analysis/combined impedance analysis

- SSR/SSTI: Used to evaluate generator electrical damping vs frequency
- SSCI: Used to evaluate Effective Dynamic Impedance of a power electronic device

4. Full Detailed Time Domain Analysis

- SSR/SSTI/SSCI/SSFR/SSTA: Uses fully detailed models of all devices

SSCI Risk : Screening Network Scans



$2^5 = 32$ combinations

2^n (where n is number of
transmission elements which can
be taken as outages)

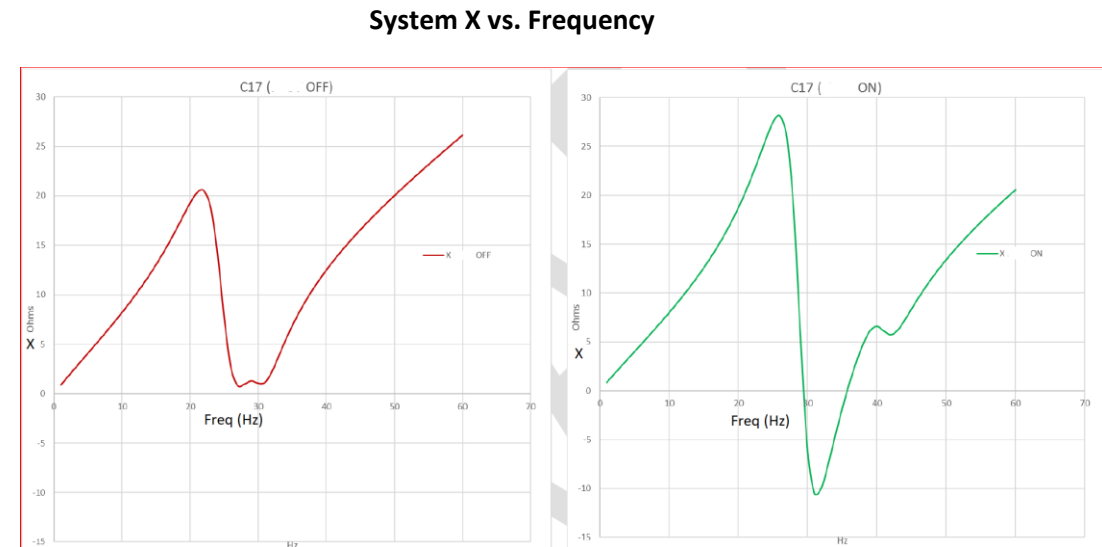
SSCI Risk : Screening

Passive System scanning and identifying SSCI risk at each IBR location with and without upgrade

Contingency			Passive Scan at [REDACTED]					
			[REDACTED] OFF			[REDACTED] ON		
			Percent Dip	Resonant Frequency (Hz)	Xcross @ Resonance F?	Percent Dip	Resonant Frequency (Hz)	Xcross @ Resonance F?
1	C16	N-1	55	30	False	99	36	True
2	C32	N-1	53	30	False	89	36	True
3	C17	N-2	75	33	False	188	36, 42	True, False
4	C96	N-2	72	29	True	124	35	True
5	C25	N-3	108	33	True	265	36, 42	True, False
6	C28	N-3	86	30, 32	True, False	157	36	True
7	C29	N-4	916	33	True	1722	36, 42	True, False
8	C93	N-5	916	32	True	1716	36, 41	False, True
9	C125	N-6	913	32	True	1693	40	True
10	C1055	N-6	916	33	True	1720	36, 42	False, True

Check for

- Increase in resonant frequency
- Increase in percentage inductance dip
- Whether inductance cross the X axis at resonance

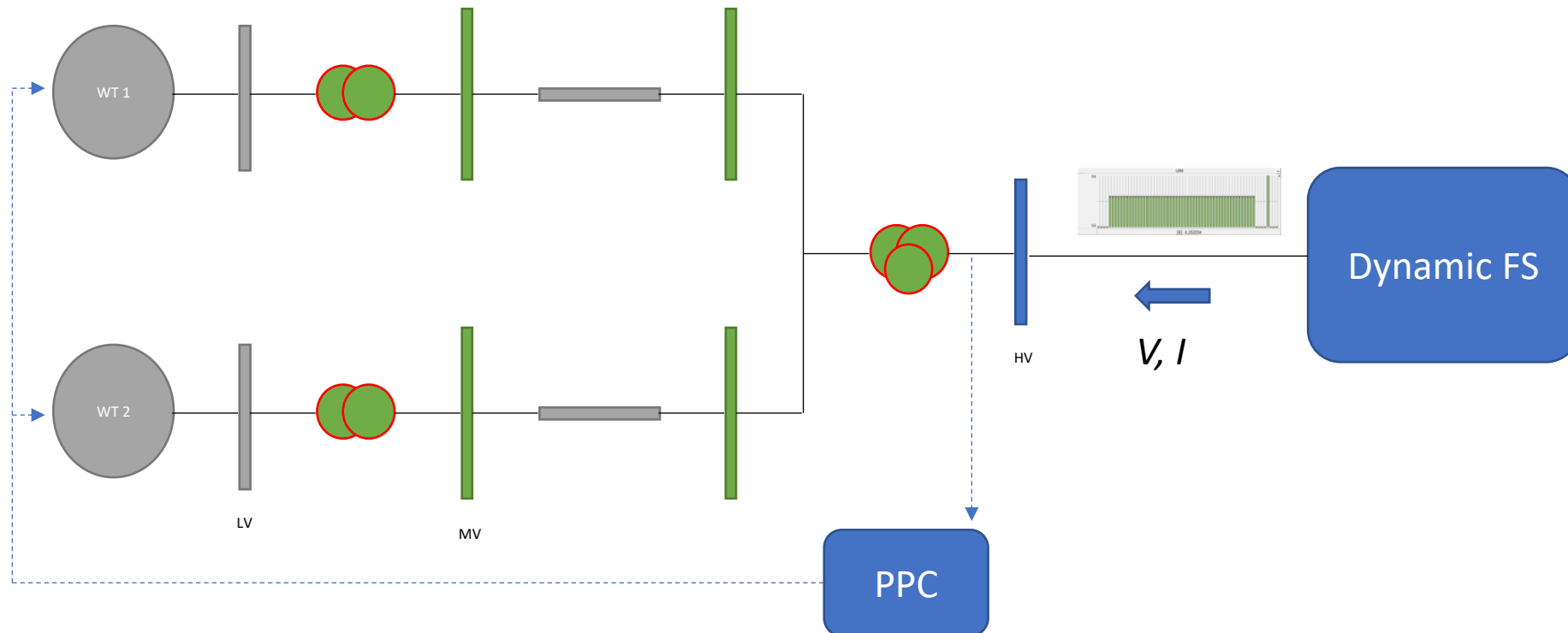


Pre - upgrade

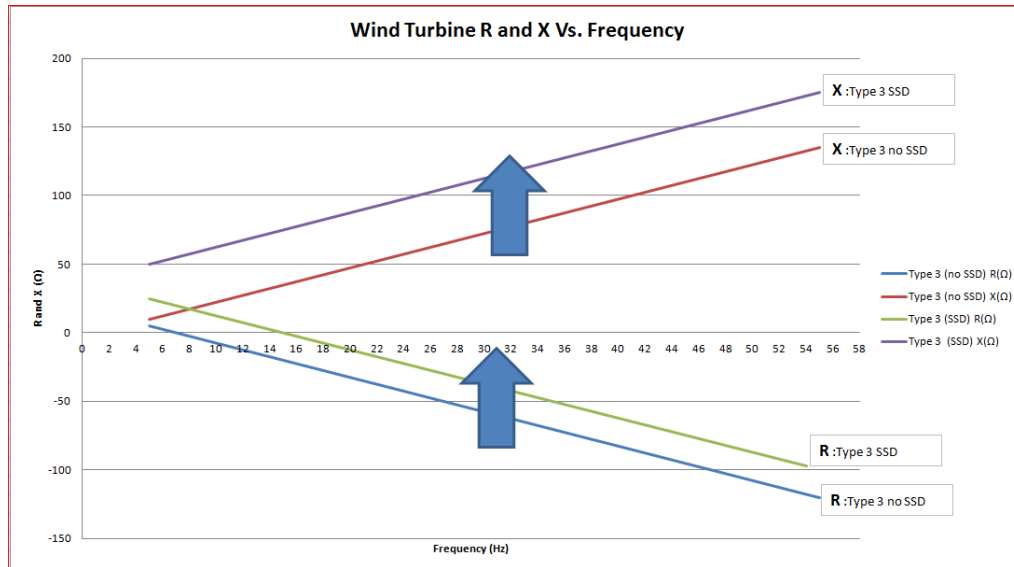
Post - upgrade

Requires further detailed investigation

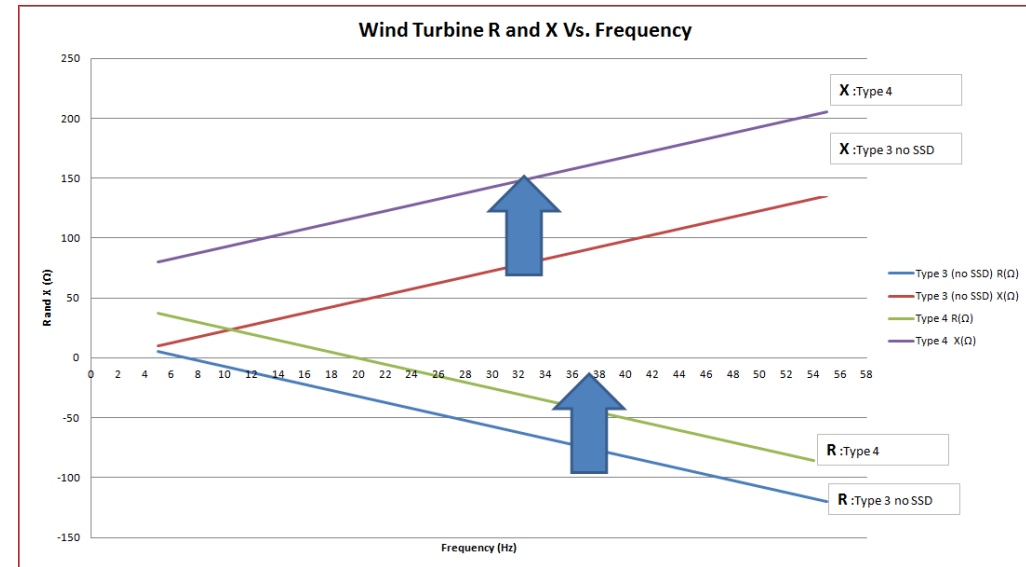
SSCI Risk: Screening Dynamic Frequency Scan



SSCI Risk: Screening Dynamic Frequency Scan Results



Type 3 with and without SS damping controller

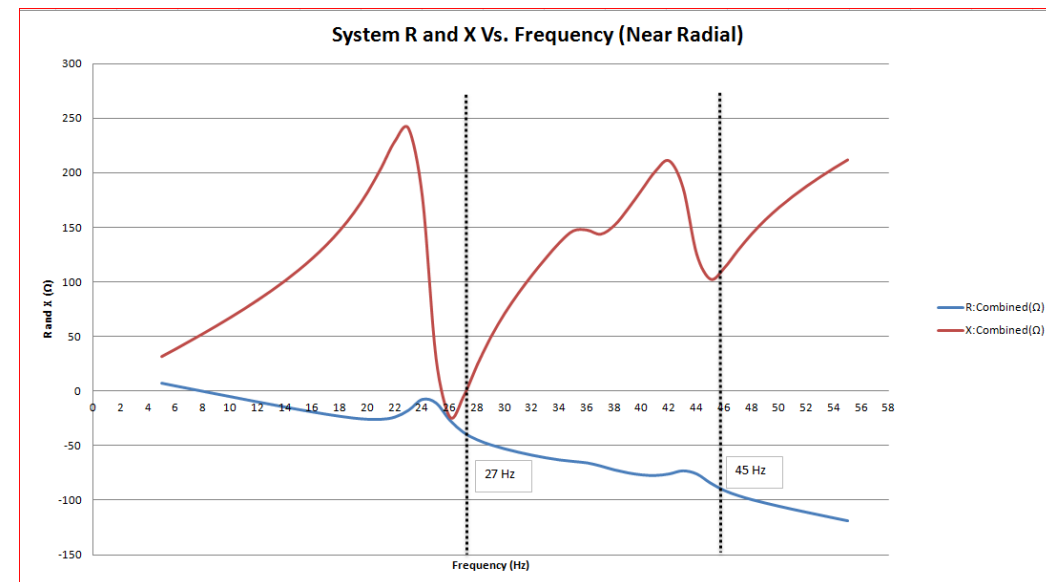
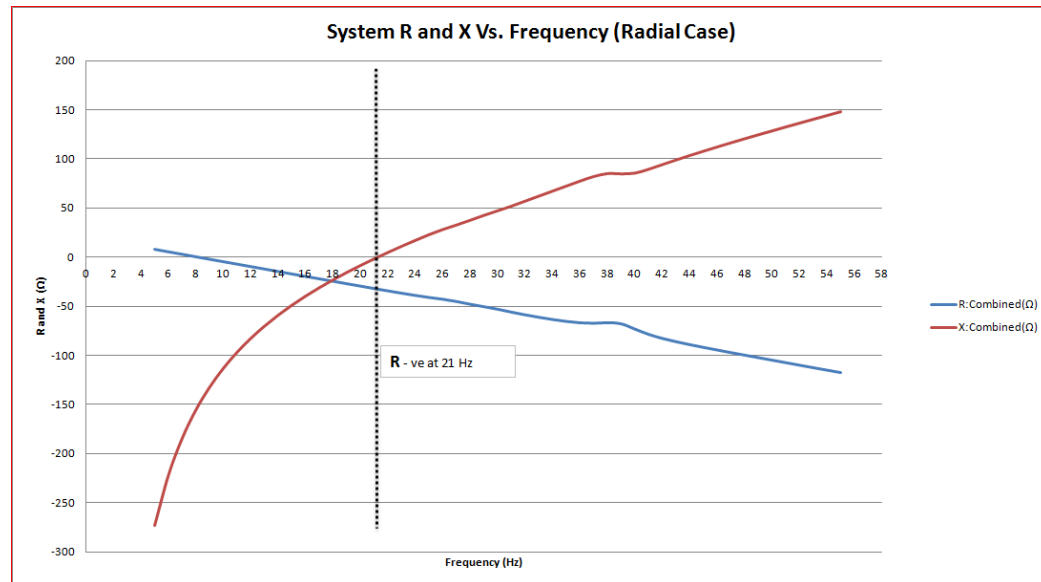


Type 3 and Type 4

SSCI Risk: Screening

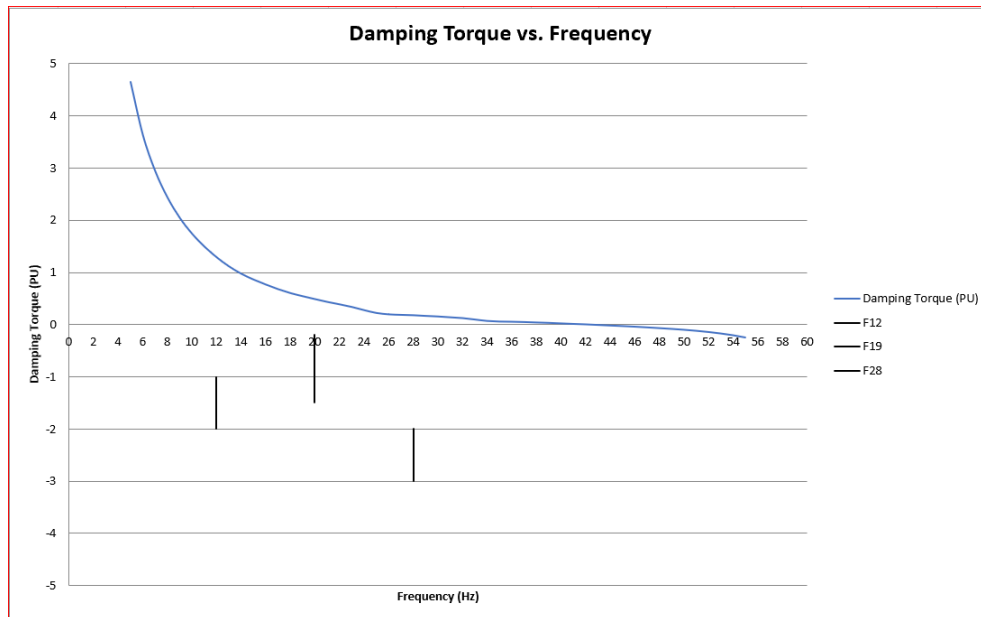
Adding Dynamic and Passive Scan Results

- Dynamic impedance scans of the inverters and system impedances can be added together to estimate the overall damping and resonant frequencies for critical contingencies. (Caution is required, there are approximations built into this!). It is important to note that these are screening techniques. **All final conclusions must be based on fully detailed time domain simulations of critical contingencies.**

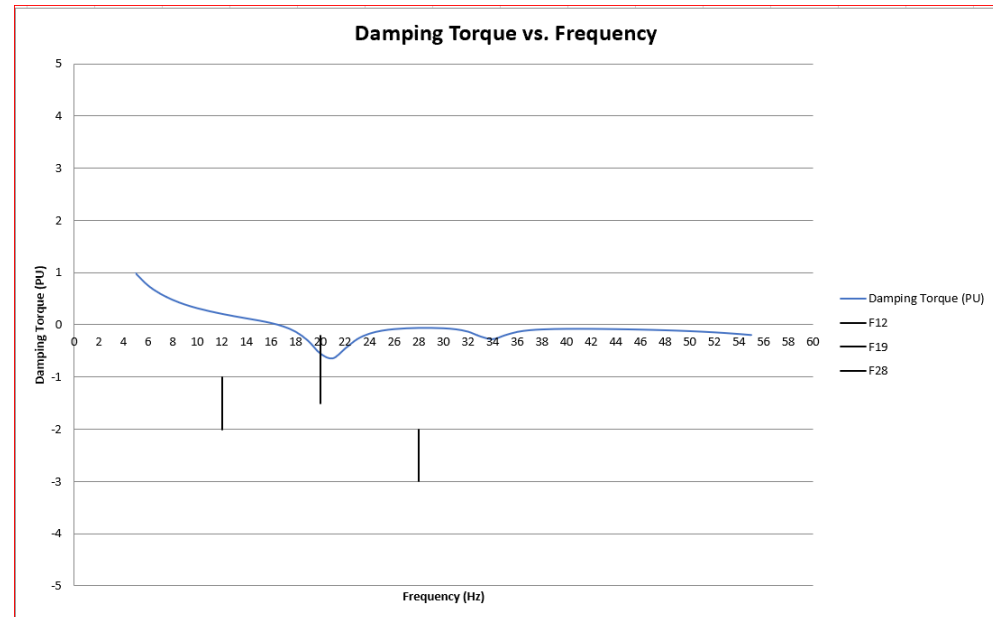


SSR Risk : Screening

Damping calculation of synchronous generators compared against mechanical damping



Pre - upgrade



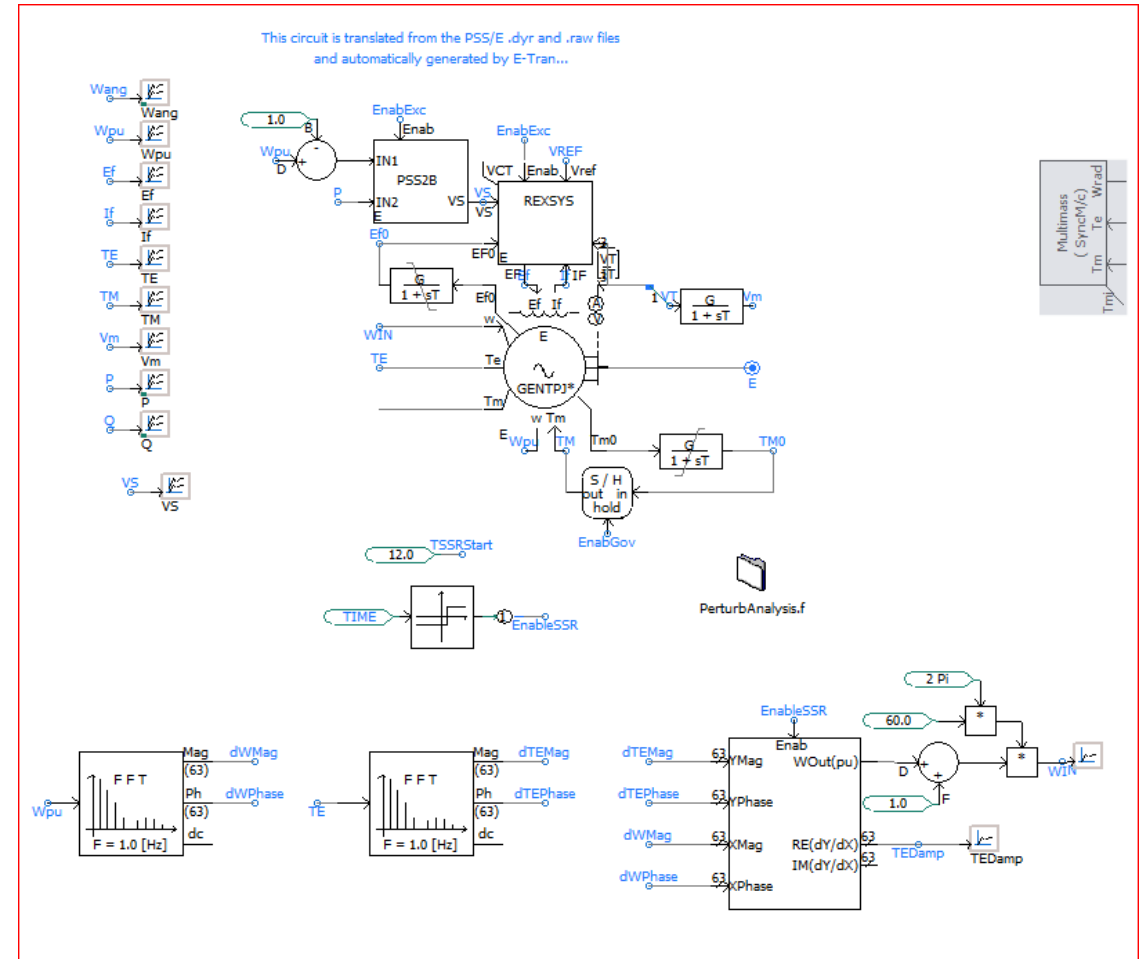
Post - upgrade

Requires further detailed investigation

SSR Risk:

Dynamic Frequency Scans (Perturbation)

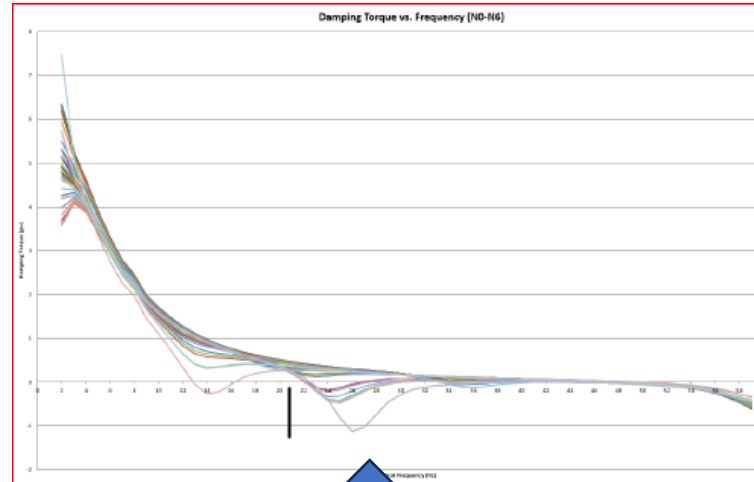
- Force the speed to be 1 pu plus a small oscillation at 5-55 Hz
- Measure the relative magnitude and angle between the electrical torque and delta W
- The electrical damping is the real part of dTe/dW



SSTI Risk : Screening

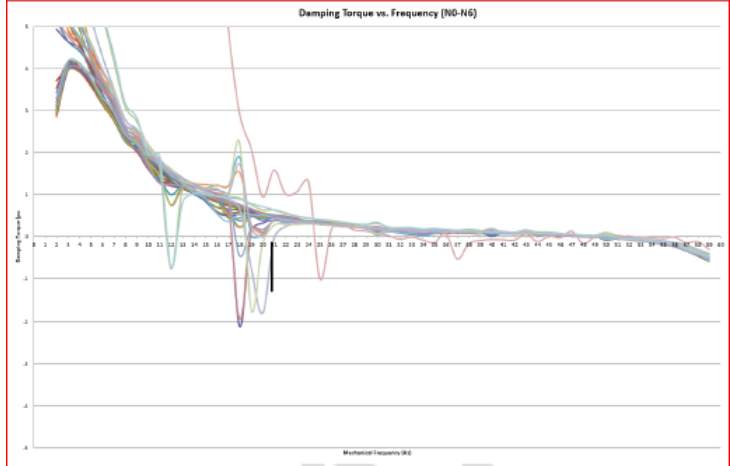
Perturbation Analysis of synchronous generators with detailed IBR plants

- Installing IBRs near synchronous generators may lead to increased negative damping at the generator terminals and shift the negatively damped regions toward the torsional mode range



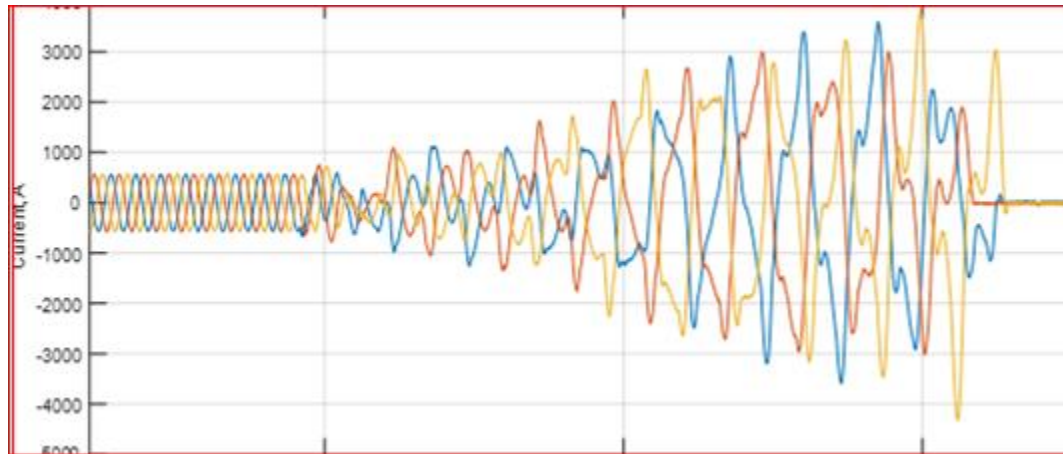
Synchronous generator Damping plots with IBR **not** in service

Synchronous generator Damping plots with IBR in service

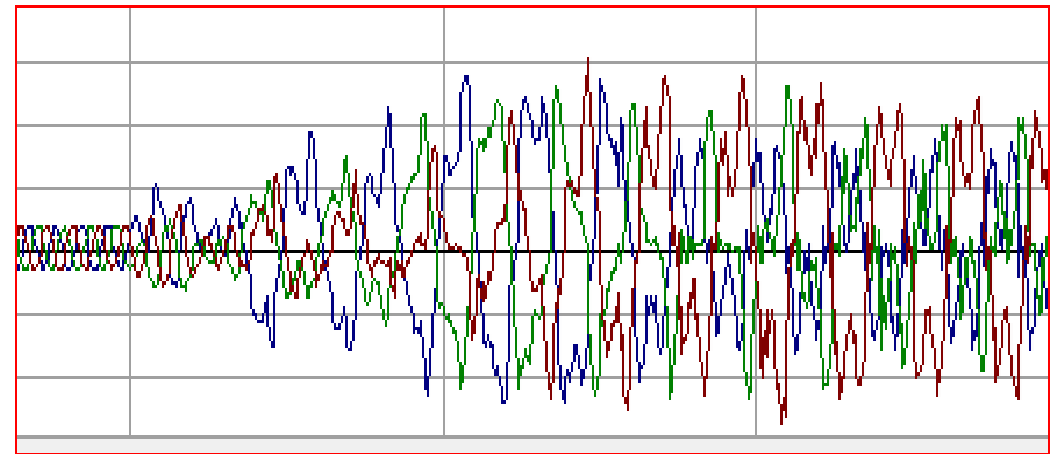


SSFR Risk

- A saturated plant transformer can oscillate with a series capacitor, leading to undamped oscillations that may require either tripping the plant or bypassing the series capacitor to stop them.
- The situation worsens when multiple plants are connected in close proximity to the series capacitors.



Field Measurement- Current

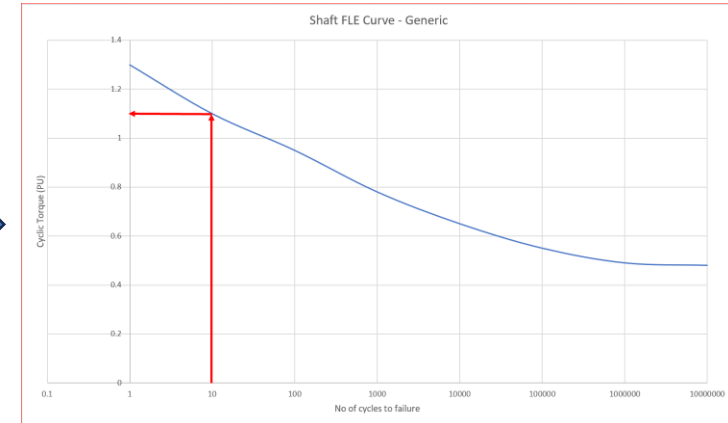


EMT Simulation - Current

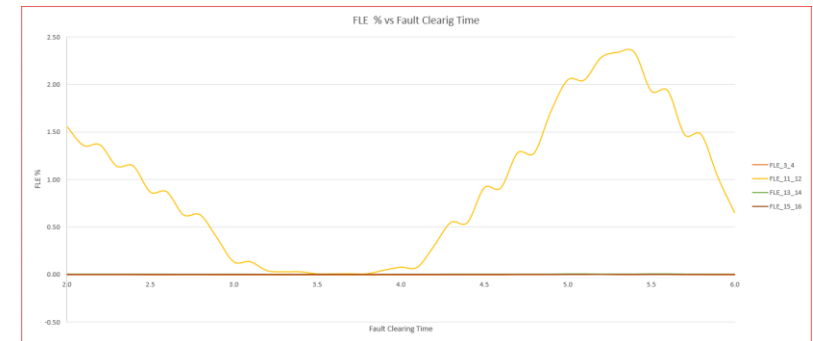
SSTA Risk : Detailed Study

- Fatigue curve / S-N Curve
- FLE : Fatigue Life Expenditure
- Generally, FLE = 1% for a fault is acceptable
- Introducing series compensation can elevate the torque experienced by the generator shaft, potentially causing mechanical failure
- Depends on fault clearing time

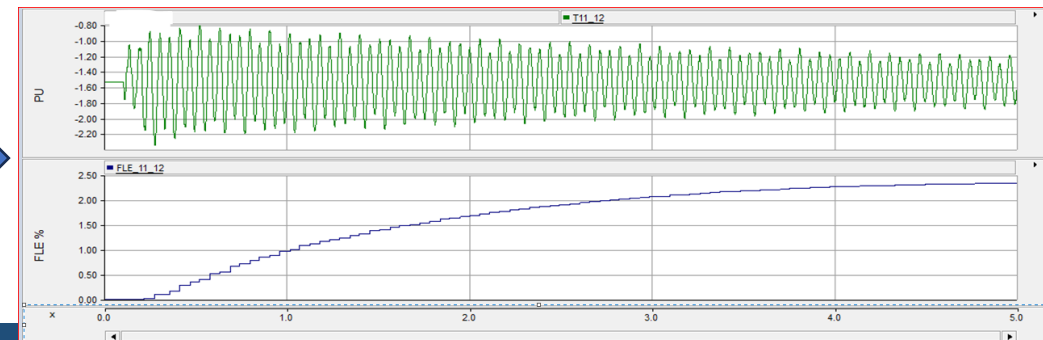
shaft fails after 10 occurrences of 1.1 per unit torque : FLE = 100%



FLE % sensitivity to fault clearing duration



Sample Cyclic Torque Event and Percentage of FLE Utilized - Cumulative



Data Requirement at Each Stage of SSO Studies

Study Stage	Screening Studies			Detailed EMT Studies		
	High Level system Screening for SSCI and SSR	Detailed SSCI Screening	Detailed SSR Screening	SSFR	SSTI	SSTA
Power flow case and dynamic data records	Yes	Yes	Yes	Yes	Yes	Yes
Detailed IBR EMT model		Yes		Yes	Yes	
Synchronous generator torsional model			Yes		Yes	Yes
Torsional mechanical damping			Yes		Yes	Yes
Detailed system model				Yes	Yes	Yes

Potential Mitigation and Protection Measures for SSO Issues

SSO Issue	Mitigation and protection schemes						
SSCI	IBR inverter and PPC tuning	Addition of GFM BESS with positive damping	RAS schemes				SS relay
SSR			RAS schemes	SSDCs on excitation systems	Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)
SSFR			RAS schemes			Switchable Arresters	SS relay
SSTI	IBR inverter and PPC tuning	Addition of GFM BESS with positive damping	RAS schemes		Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)
SSTA			RAS schemes		Passive damping Filters /Blocking Filters		Torsional Stress Relay (TSR)

Challenges in SSO Studies

- **Detailed System Modeling:** Includes accurate representations of series compensation and frequency-dependent transmission line models.
- **Accurate IBR EMT Models:** Must be consistent with the actual field firmware to accurately reflect dynamic behavior and requires OEM-provided models.
- **Synchronous Generator Shaft Modeling:** Requires torsional models with mechanical damping data, along with FLE/S-N curves. (Nearly impossible to get from OEMs)
- **Multi-Stakeholder Coordination:** Involves collaboration among OEMs, TOs, and ISOs : and complex NDAs.
- **Time-Intensive EMT Simulations:** EMT studies are complex and require significant time, knowledge and computational resources.
- **Mixed SSR and SSCI Interactions:** Systems may exhibit a combination of SSR and SSCI, which can be difficult to isolate and analyze.
- **Numerous Operating Scenarios:** A large number of possible network conditions and concurrent transmission projects increase the scope and complexity of the study.

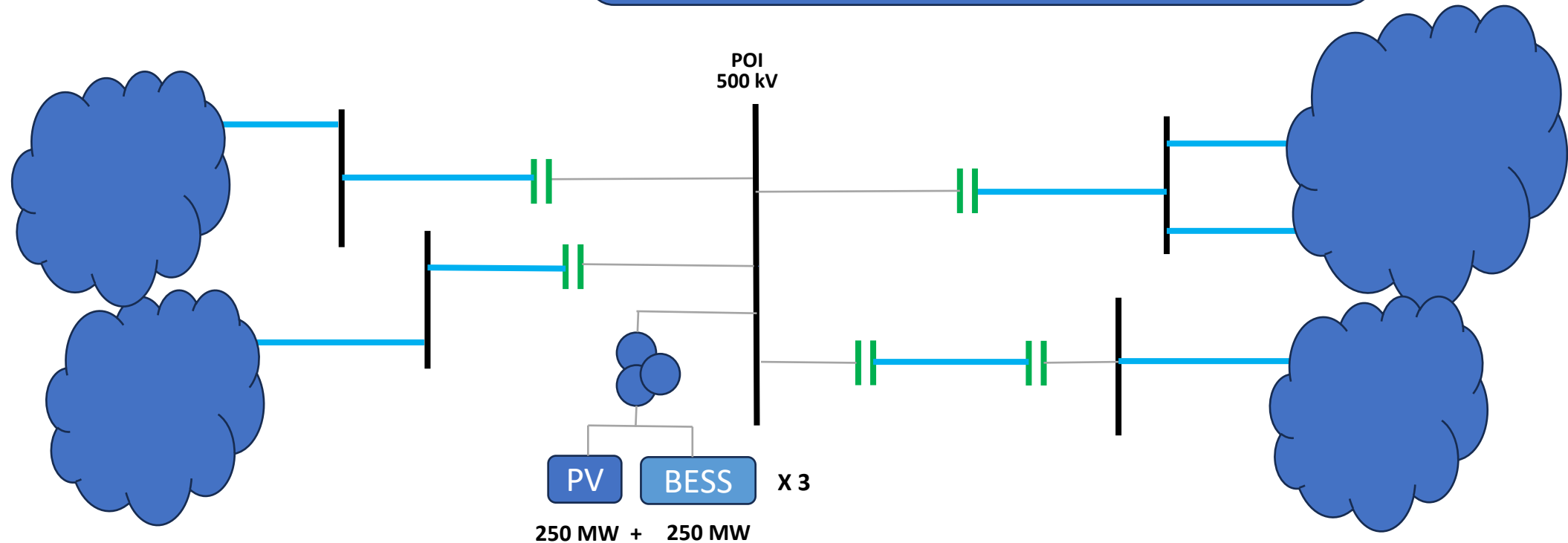
SSO/SSCI Example study

750 MW PV + 750MW GFM BESS Project
Heavily series compensated system

Network Topology

- 500 kV System

Presence of multiple series resonance modes within the 15 Hz to 48 Hz range



Detailed System and Plant EMT Model

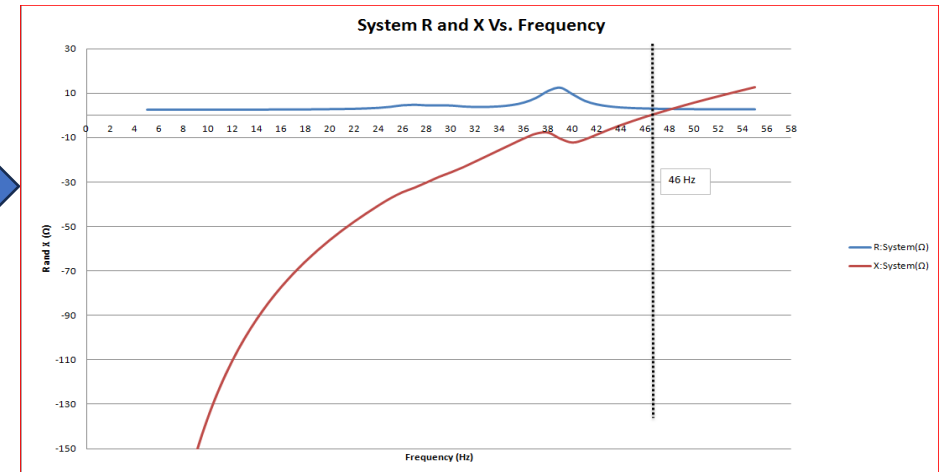
- Three equivalent feeders with 250 MW each (750 MW)
- Equivalent collector systems
- Detailed custom tuned OEM PV inverter and GFM BESS Inverter
- Detailed custom tuned OEM PPC to site conditions
- Transformer Neutral Grounding Reactors (NGR)
- Plant HV and MV arresters
- Transformer Saturation
- Series Capacitors with MOV and protection
- Detailed transmission line models

Screening: Passive Frequency Scan

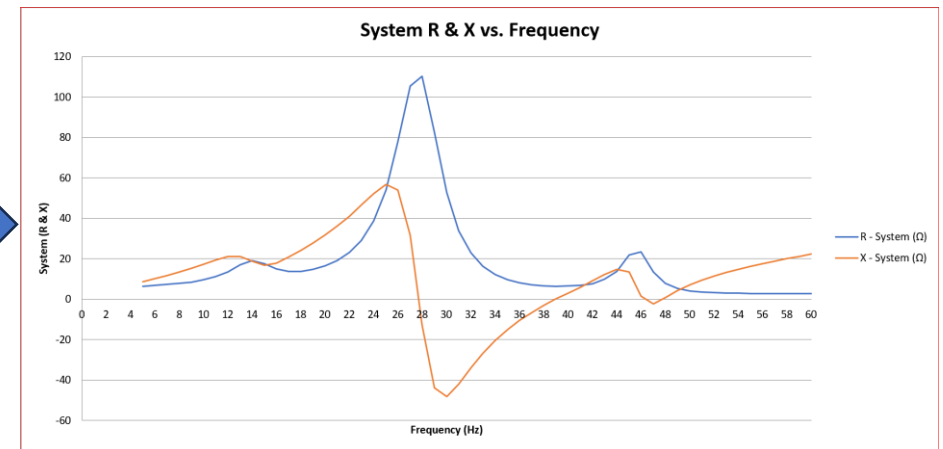
System side

- The passive frequency scanning method looks for electrical resonances in the system in the range of 2 Hz to 55 Hz.
- Series system resonances can be observed when a series compensated line is radially or near radially connected to a generator.
- If a generator is radial to a series compensated line then the system inductance is negative at lower frequencies and turns positive above the series resonance frequency.
- If a generator is connected to a series compensated line parallel with other lines (or shunt devices), then a dip in the reactance can be observed.

Radial
Case to
series
capacitor



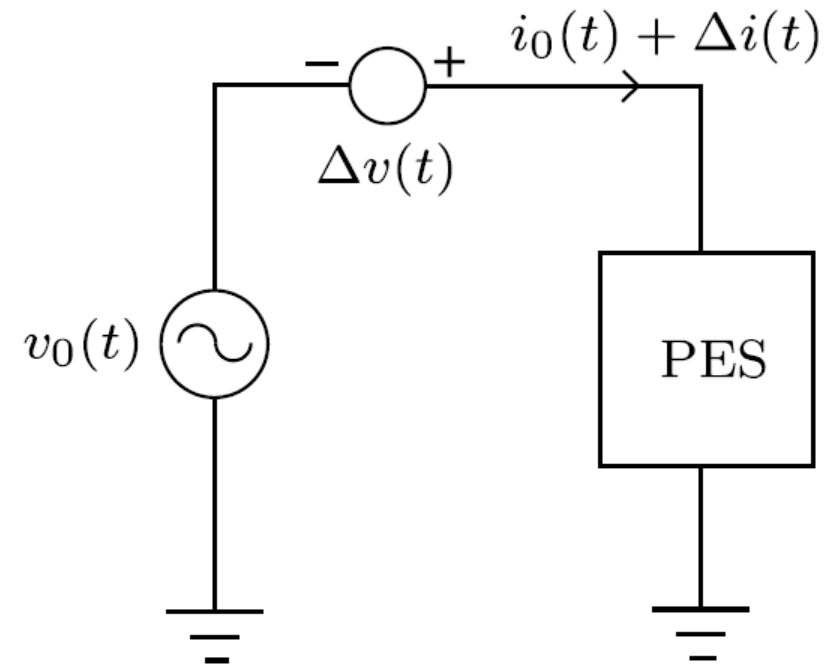
Near
Radial
Case to
series
capacitor



Screening : Dynamic Frequency Scan

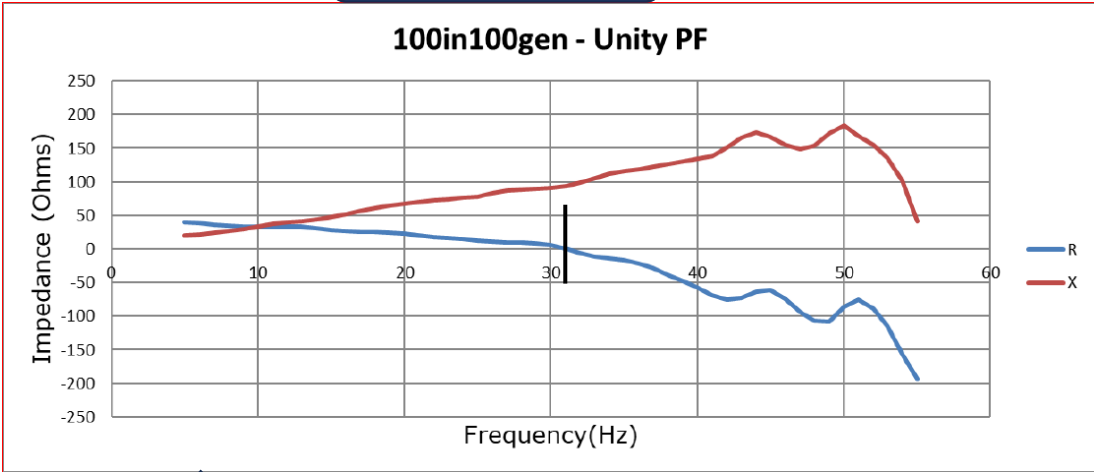
IBR Side

- Small magnitude voltage harmonics are injected to the fundamental waveform at the POI of an IBR plant at a range of sub-synchronous frequencies.
- R and X values are calculated at the IBR plant terminal for each sub-synchronous frequency.



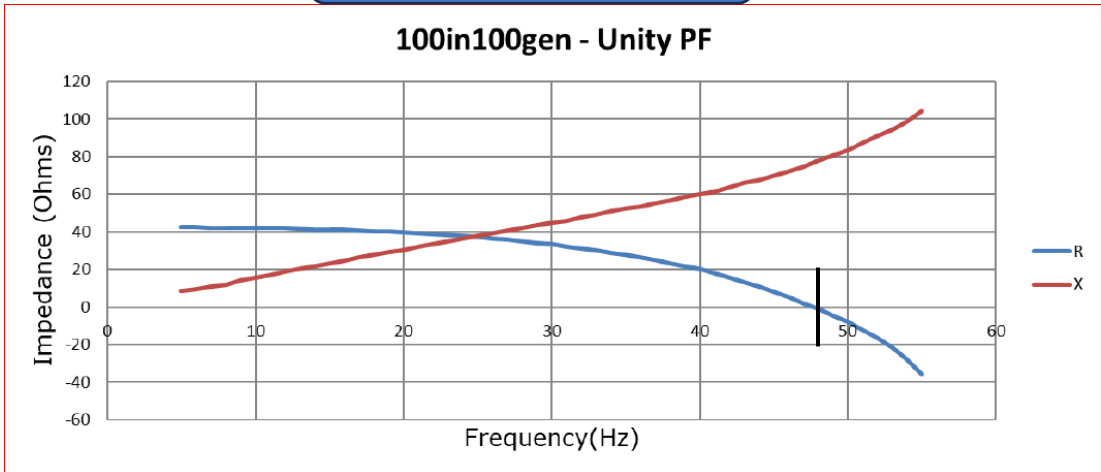
Dynamic Frequency Scan Results

750 MW PV



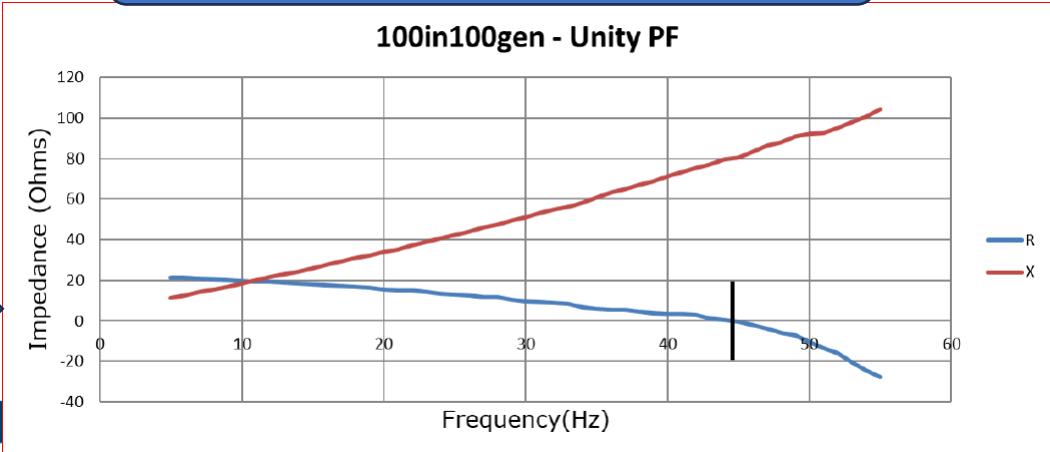
R becomes negative at 32 Hz

750 MW GFM BESS



R becomes negative at 48 Hz

750 MW PV + 750 MW GFM BESS

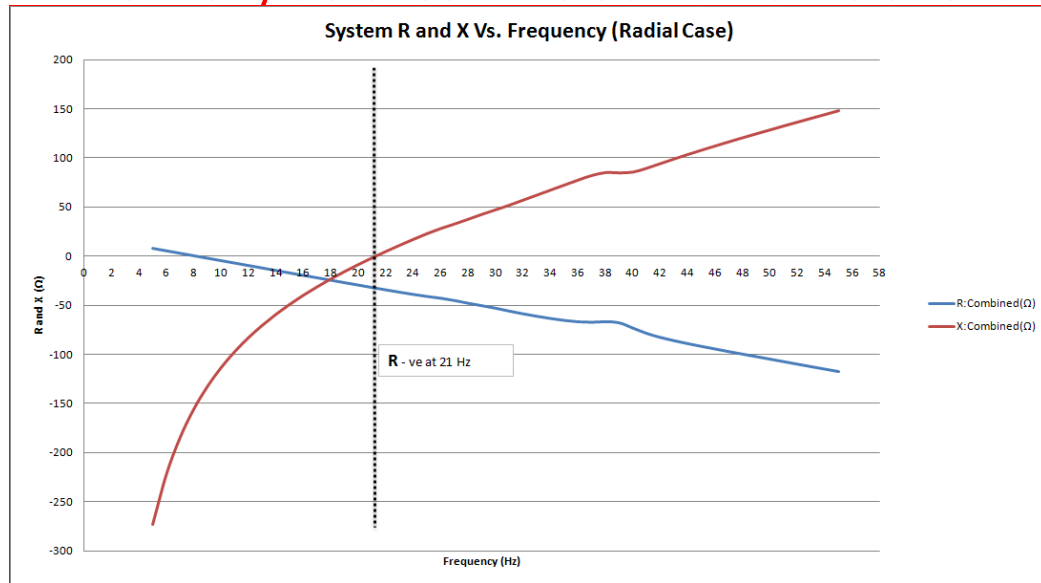


R becomes negative at 45 Hz

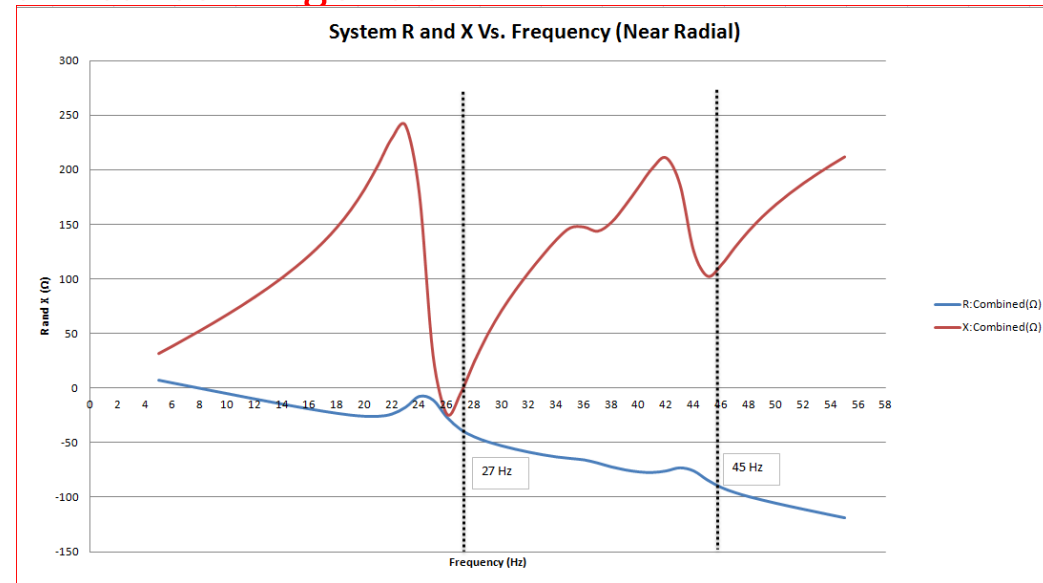
Contingency Selection

Adding Dynamic and Passive Scan Results

- Dynamic impedance scans of the inverters and system impedances can be added together to estimate the overall damping and resonant frequencies for critical contingencies. (Caution is required, there are approximations built into this!).
- It is important to note that these are screening techniques. All final conclusions must be based on fully detailed time domain simulations of critical contingencies.



Unstable SSCI



Unstable SSCI

What are the Worst-Case Contingencies ?

Resonant Frequency

$$f_r = \frac{1}{2\pi\sqrt{LC}} \text{ (Hz)}$$

L : Total inductance
C : Total Capacitance

- Adding more generation
- Additional network expansion



- Unstable SSCI Frequency range

- Adding more series Compensation in **Series**



- Unstable SSCI Frequency range

- Adding more series Compensation in **Parallel**



- ?

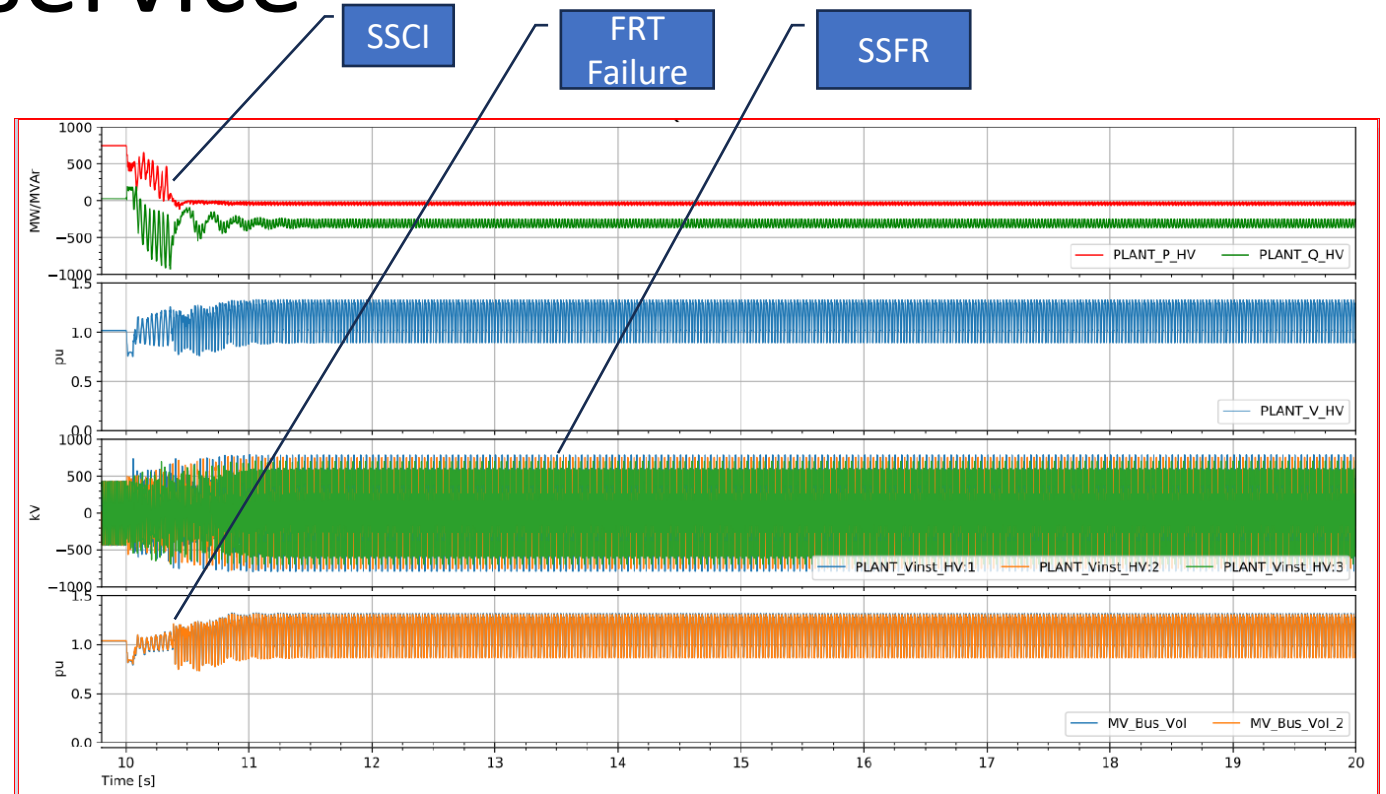
Screening Analysis Results

- Having all series capacitors in service does not represent the worst-case scenario for SSCI – **Location and topology specific**
- The most severe resonance and highest negative damping occur when the system is radial to a single series capacitor – **Location and topology specific**

Detailed Time-Domain Results

750 MW PV Only in-service

- Post fault SSCI and subsequent ride-through failure under N-3 conditions caused by phase overvoltage
- SSFR concerns under N-3 conditions: It was recommended to install and properly tune a sub-synchronous detection relay to disconnect the plant during SSFR events.
- The plant's inability to ride through faults masks underlying SSCI issues associated with the PV system.



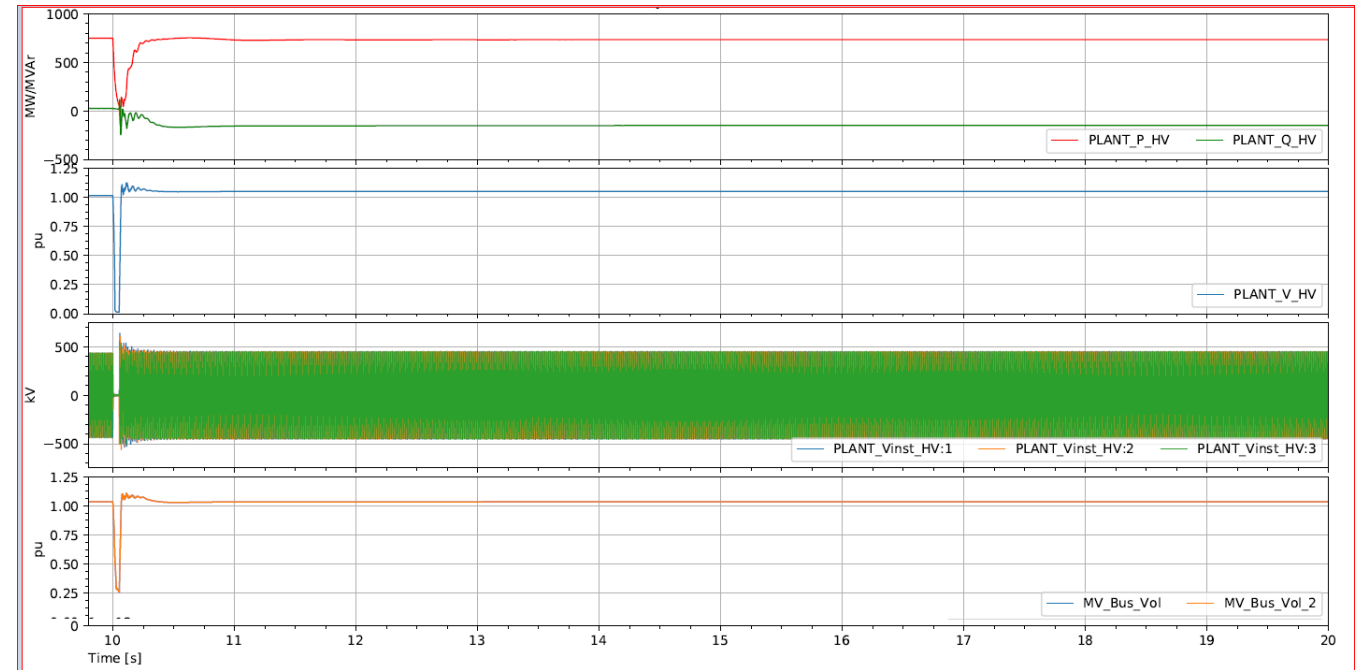
Post fault SSCI and subsequent ride through failure and SSFR Oscillations

Unacceptable

Detailed Time-Domain Results

750 MW BESS Only in-service

- Post fault ride-through failure under N-3 conditions caused by phase overvoltage : Acceptable under IEEE - P2800
- SSFR concerns under N-3 conditions: It was recommended to install and properly tune a sub-synchronous detection relay to disconnect the plant during SSFR events.
- No SSCI Oscillations

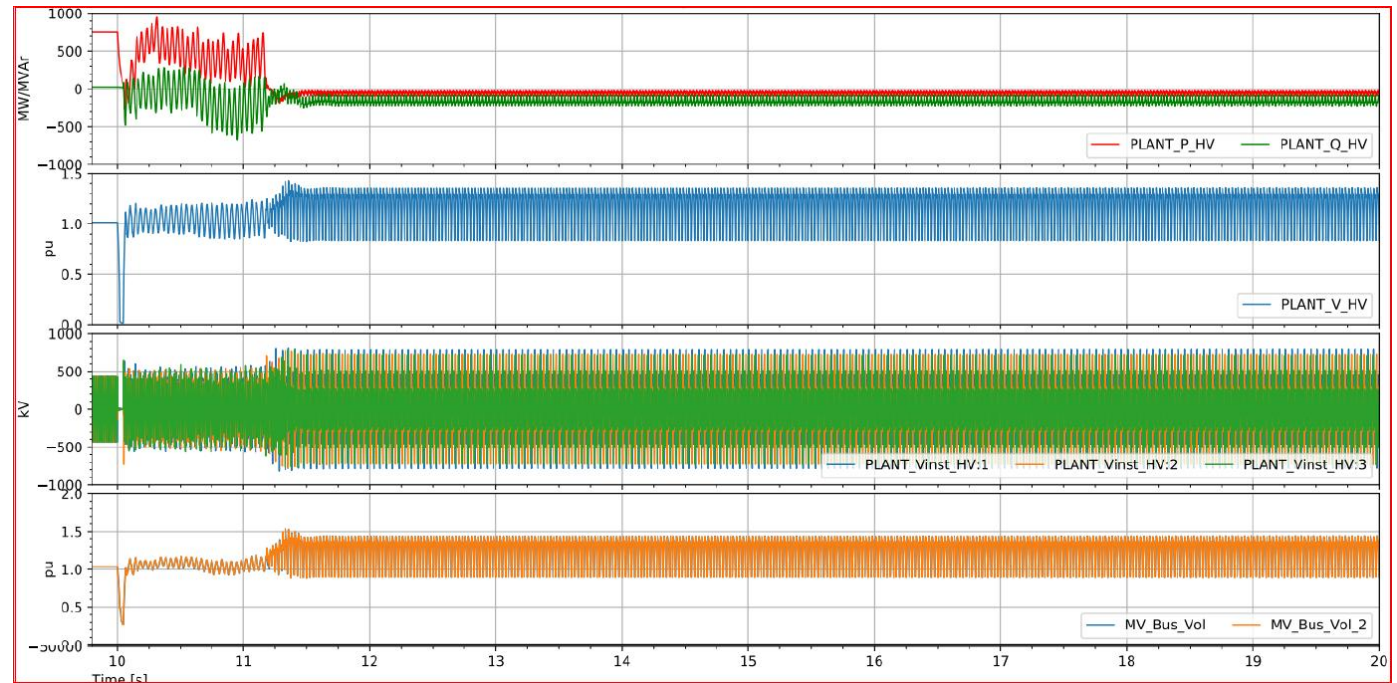


Acceptable

Detailed Time-Domain Results

750 MW PV + 187 MW GFM BESS (25% units) in service

- Post fault SSCI and subsequent ride-through failure under N-3 conditions caused by phase overvoltage
- SSFR concerns under N-3 conditions: It was recommended to install and properly tune a sub-synchronous detection relay to disconnect the plant during SSFR events.
- The plant's inability to ride through faults masks underlying SSCI issues associated with the PV system.



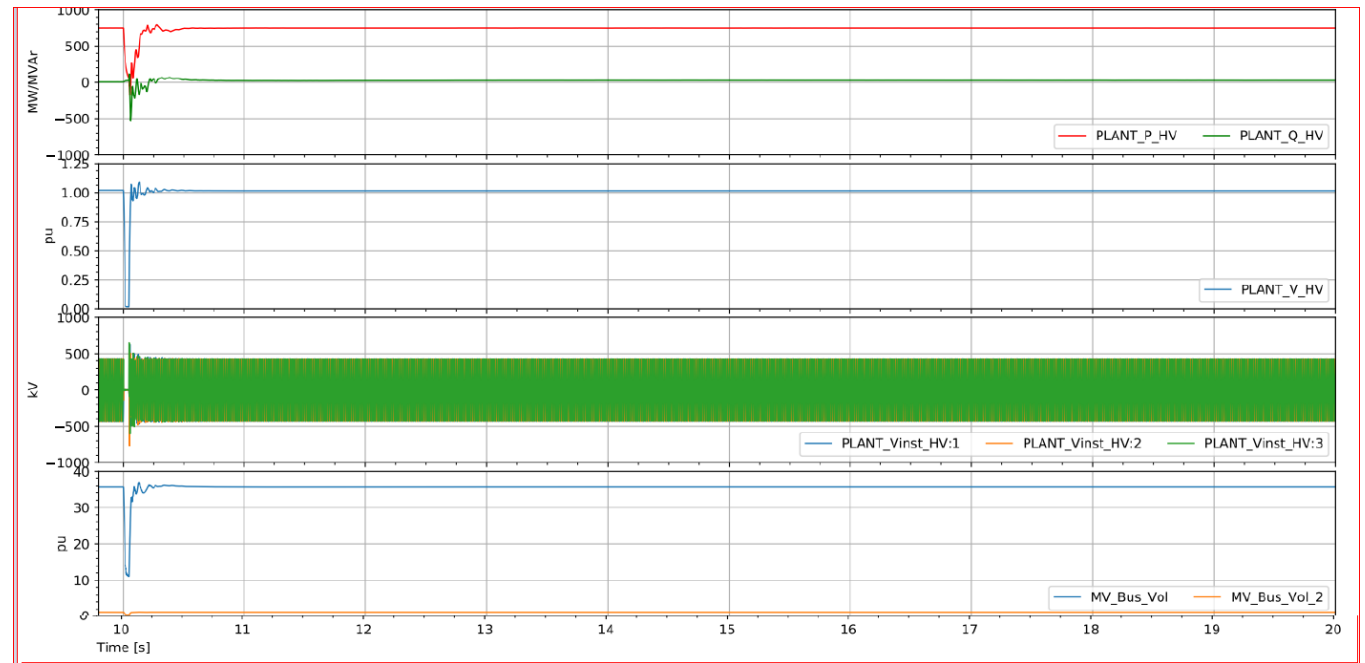
Post fault SSCI and subsequent ride through failure and SSFR Oscillations

Unacceptable

Detailed Time-Domain Results

750 MW PV + 375 MW GFM BESS (50% units) in service

- Successful plant Ride Through for all selected contingencies
- No SSFR Oscillations
- No SSCI oscillations



Acceptable

Recommendations

- To ensure SSCI stability under current system conditions, at least 50% of the BESS GFM inverters must remain in operation.
- It is recommended to install and accurately tune a sub-synchronous detection relay to trip the plant during SSFR events.
- Enhance the SSCI performance of the PV inverter through additional tuning .
- It is strongly recommended to update the inverter firmware to reflect the parameters of the tuned EMT model.
- Perform a cluster-based SSCI EMT study that includes other nearby plants in the interconnection queue.

Large Data Center Load Study Considerations

Types of Large Loads: Hyperscale Cloud

- Purpose: IT resources for shared use across the internet.
- Owned by: Cloud service providers (CSPs)
- Size: 10's to 100's of MW
- Examples:
 - Amazon Web Service (AWS), Google Cloud Platform, Microsoft Azure
 - Netflix, Amazon shopping, Office 365, Google search, etc.
- Interface Hardware:
 - Cooling by Variable Speed Drive, sometimes with active filter
 - IT infrastructure behind distributed power distribution, behind UPS
 - Office lighting and admin computing
 - Diesel generator backup

Types of Large Loads: Crypto Mining

- Purpose: Calculation of Bitcoin, Ethereum, and other Cryptocurrency tokens.
- Owned by: Private developers
- Interface Hardware:
 - Cooling by natural wind or forced air
 - IT infrastructure behind small power supplies (no UPS)
 - No generator backup

Types of Large Loads: AI Inference

- Purpose: Distributed user requests to access trained models.
- Owned by: Private developers or Hyperscale AI
- Size: 100's MWs to >1GW
- Examples:
 - Google gemini search, GPT user requests, etc.
- Interface Hardware:
 - Similar to hyperscale cloud computing, but potentially lower reliability requirement (eg. may use UPS)

Types of Large Loads: AI Training

- Purpose: Training major AI models for use in inference.
- Owned by: Private Developers or Hyperscale AI
- Size: 100's MWs to >1 GW (in aggregate up to 5 GW)
- Examples:
 - Microsoft, Oracle, xAI, Amazon, Meta
- **Key Feature: Variable active power output.**
- Interface Hardware:
 - Same as AI Inference

Background: Large Load Characteristics

- AI training processes can exhibit fast variation in active power.
- Data center loads are not designed to ride through system events (UPS doesn't count)
- Loads are a mix of types of converter based interfaces

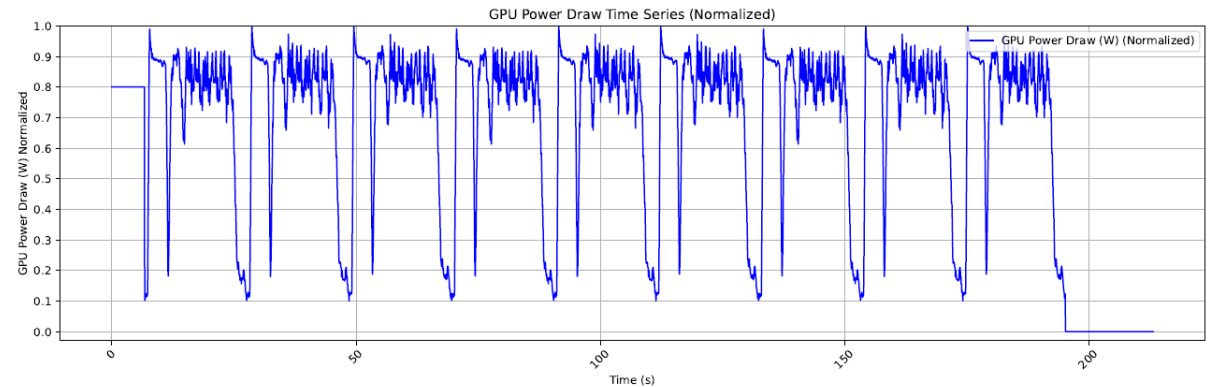


Fig. 1. Power readings from an at-scale training job on DGX-H100 racks.

Power Stabilization for AI Training Datacenters

Esha Choukse, Brijesh Warriar, Scot Heath, Luz Belmont, April Zhao, Hassan Ali Khan, Brian Harry¹,
Matthew Kappel, Russell J. Hewett¹, Kushal Datta, Yu Pei, Caroline Lichtenberger, John Siegler,
David Lukofsky¹, Zaid Kahn¹, Gurpreet Sahota, Andy Sullivan, Charles Frederick, Hien Thai,
Rebecca Naughton¹, Daniel Jurnove, Justin Harp¹, Reid Carper, Nithish Mahalingam,
Sri Varkala, Alok Gautam Kumbhare, Satyajit Desai, Venkatesh Ramamurthy,
Praneeth Gottumukkala, Girish Bhatia, Kelsey Wildstone, Laurentiu Olariu,
Ileana Incorvaia, Alex Wetmore, Prabhat Ram, Melur Raghuraman
Mohammed Ayna, Mike Kendrick, Ricardo Bianchini
Microsoft

Aaron Hurst, Reza Zamani, Xin Li, Michael Petrov, Gene Oden, Rory Carmichael
OpenAI

Tom Li, Apoorv Gupta, Pratikumar Patel, Nilesh Dattani, Lawrence Marwong, Rob Nertney,
Hirofumi Kobayashi, Jeff Liott, Miro Enev, Divya Ramakrishnan, Ian Buck, Jonah Alben
NVIDIA

Summary of reliability risk categories

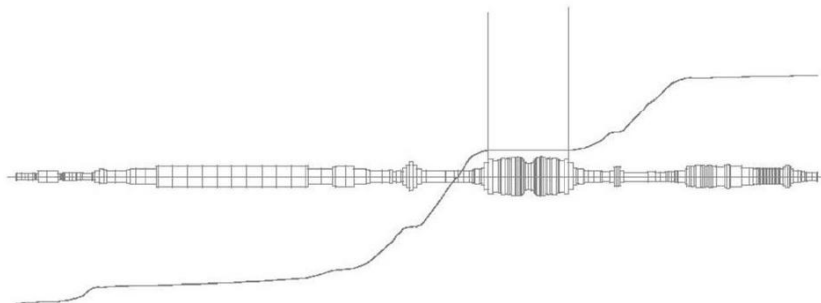
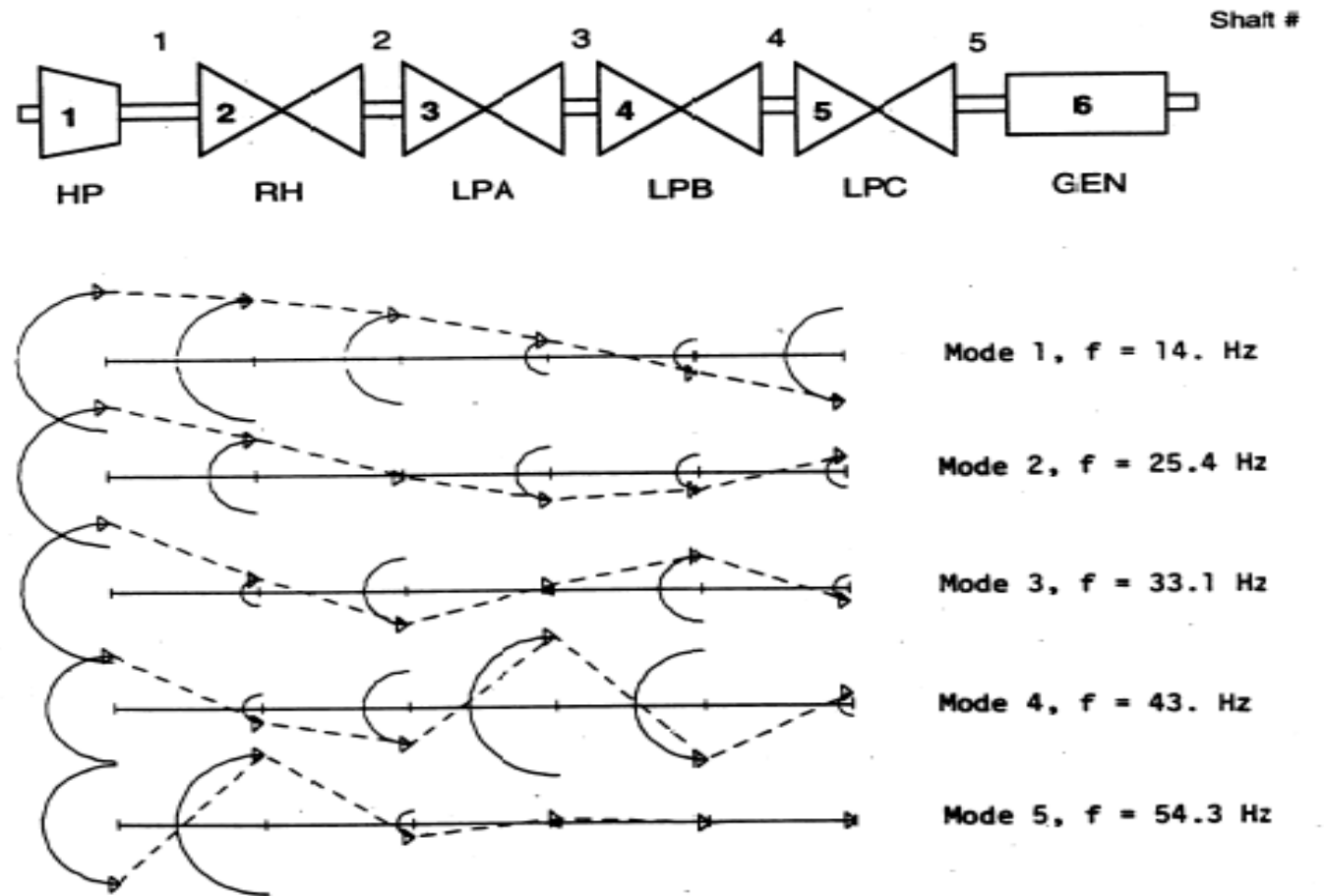
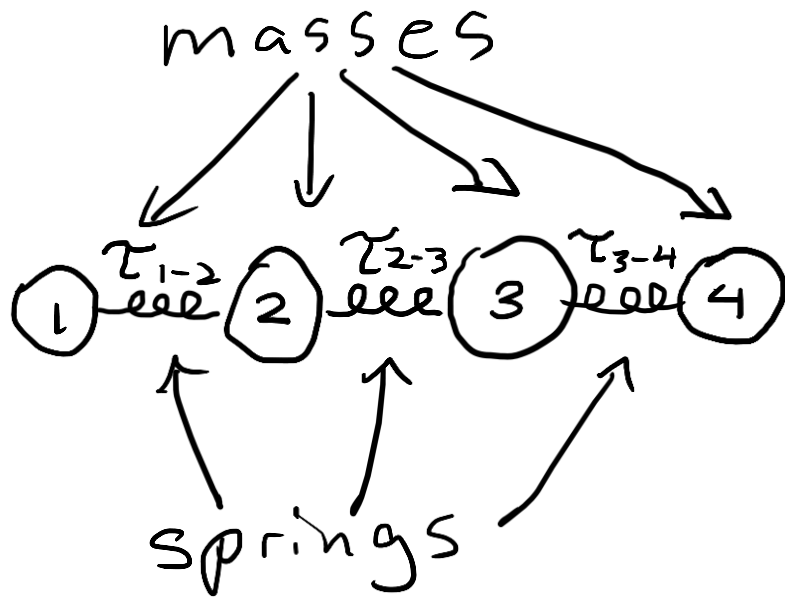
- The following are categories of risk that may drive requirements and/or studies:
 - **Basic powerflow considerations**
 - **Active power variation**
 - Synchronous generator damage
 - Flicker
 - Machine mode oscillations
 - Interarea oscillations
 - **Ride-through failure**
 - Load rejection overvoltage
 - VAR adequacy
 - Resource adequacy
 - **Passive damping**
 - SSCI instability

Basic Powerflow Studies:

- **Ensure the following:**

- Sufficient generation exists (careful with “imports will handle it”)
- Can serve the full load under outage conditions
- VARs available to control the voltage for various transfer scenarios
- VARs available for fast changes in load

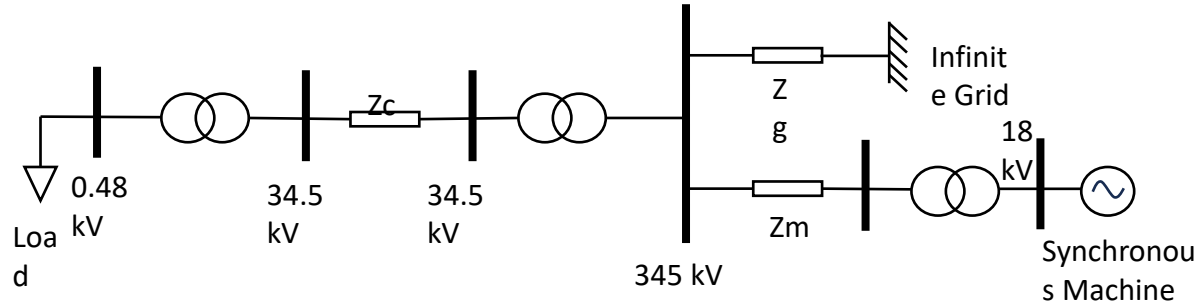
Reminder... Synchronous Generator Shaft



Active Power Variation Studies:

- **Synchronous generator damage risk evaluation:**
 - EMT simulation is required
 - Model detail of synchronous machine shaft system
 - Use various load profiles to force oscillations into the grid, including components of torsional frequencies
 - Measure generator shaft torques and terminal active power variation
 - Compare the torque and active power against machine long term capabilities
 - **Alternative: compare load output power against variation criteria.**
- **Data Required:**
 - Synchronous machine shaft models
 - Range of potential load profiles
 - Detailed grid model
 - **Mechanical and electrical limit data for machines**, or requirement criteria

Example (ERCOT study)



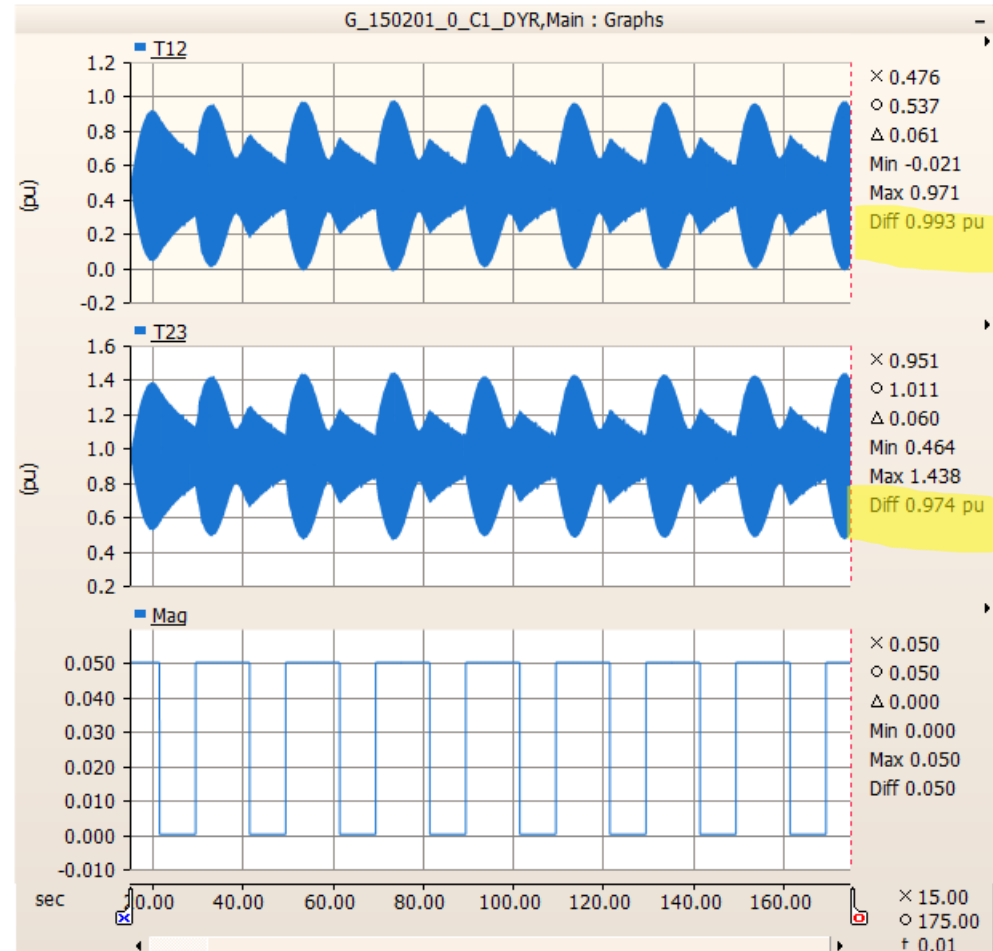
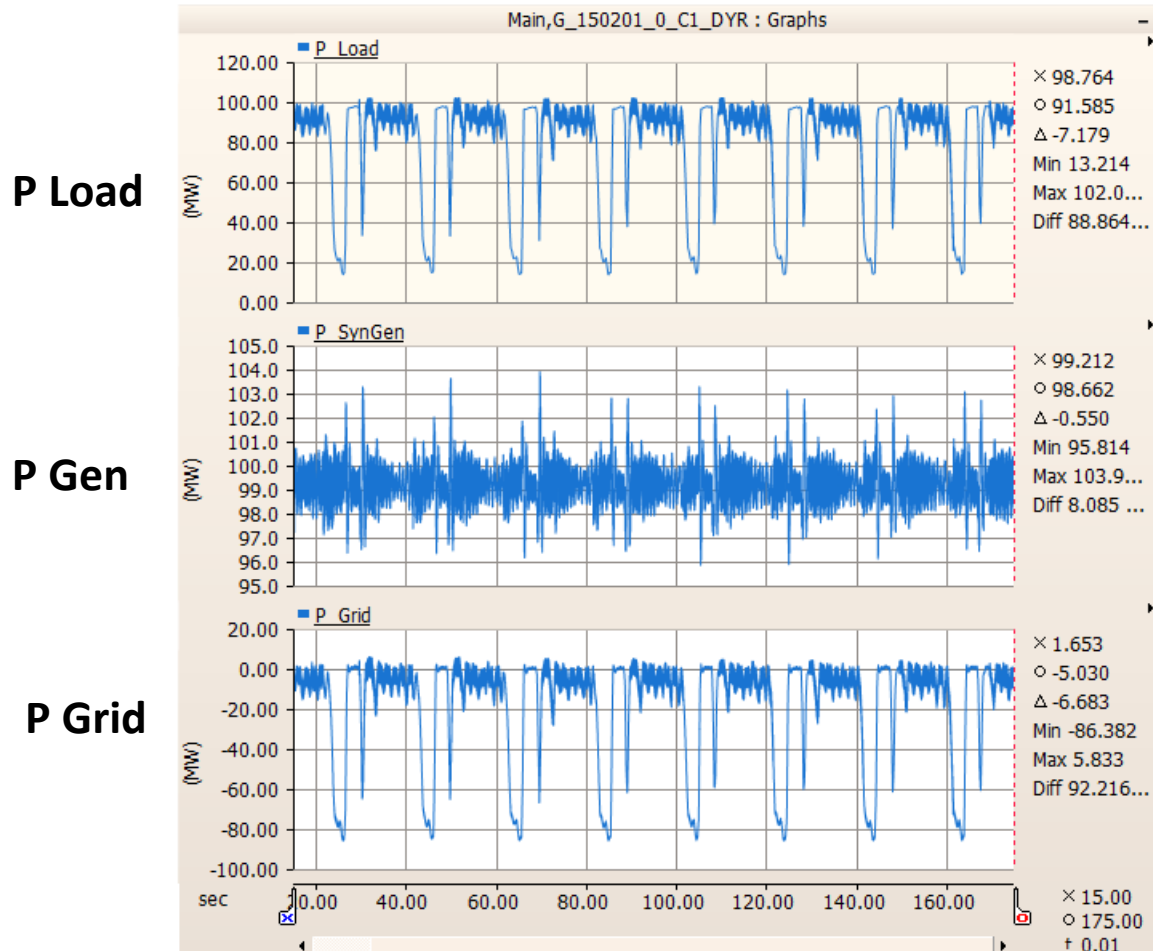
Key Parameters:

- Machine Rating = 100 MW
- Synchronous machine key torsional mode: 12 Hz**
- Load profiles:
 - Profile 1 (S1 – S8): Fixed frequency square wave varying between 25 MW and 100 MW with a ramp rate of 10 MW/1ms
 - Profile 2 (S9 – S16): Proxy waveform mimicking measured AI training load profile

Scenario No.	Load Variation	Max Pk-Pk Active Power Variation* (Generator electrically close: $Z_m = 0$)			Alternating Torque	
		At the Load	At the Machine	At the Grid	Tau12 (pu)	Tau23 (pu)
	Hz	MW	MW	MW		
S1	Load profile 1 at 2 Hz	76.81	32.98	77.81	0.233	0.234
S5	Load profile 1 at 12 Hz	77.61	11.89	82.55	5.124	5.028
S9	Load profile 2	85.55	6.21	87.44	0.042	0.042
S13	Load profile 2 with 12 Hz oscillations	88.86	8.09	92.22	0.993	0.974

*Note: Split of active power between machine and grid is initially determined by impedance split, and the final variation will depend on the frequency of the variation and other machine characteristics over time. Ref. ERCOT LLWG October 24 meeting:

Load profile 2 with 12 Hz – Scenario S13 (similar to paper on slide 6) 1pu Torque... strong Torque Amplification!



Torque 12

Torque 23

Per unit 12 Hz Component

Some additional study challenges

- Data is **very hard** to get for load
 - Limits on load variation
 - Harmonic profiles
 - Sufficiently detailed models to quantify damping
 - Ride-through capability
- Data is **very hard or impossible** to get for synchronous machines
 - Multi-mass data
 - Physical design limits
- Studies require specialist skills (EMT experts with special training)

Active Power Variation Studies: Flicker

- **Flicker:**

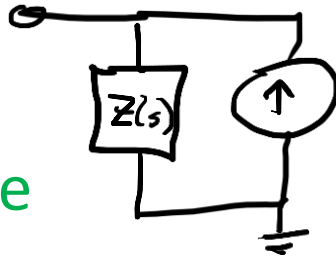
- EMT simulation may be required
- Flicker can be evaluated simply using powerflow tools (worst case)
- Flicker can be more precisely quantified using simulated flicker meters

- **Data Required:**

- Synchronous machine shaft models
- Range on load profiles, particularly ramp rates, magnitudes, and frequency content limits
- Measurements are useful

What about harmonics?

- Some events were recorded of large harmonics associated with data centers...
- What is needed is a frequency dependent Norton equivalent source
- Perturbation techniques can be used to derive impedances, and currents can be measured in strong testbeds (EMT and/or site measurement)



Study!

- Frequency-dependent impedance characterization is done for the external system under many operating conditions
- Harmonic sources are added
- *Multi-port* harmonic “powerflow” is calculated to create a family of possible voltage amplifications, add existing measured background harmonic voltage distortion, and check harmonic voltage distortion, and harmonic current ratings of equipment

Active Power Variation Studies:

- **Machine mode oscillations and interarea oscillations :**

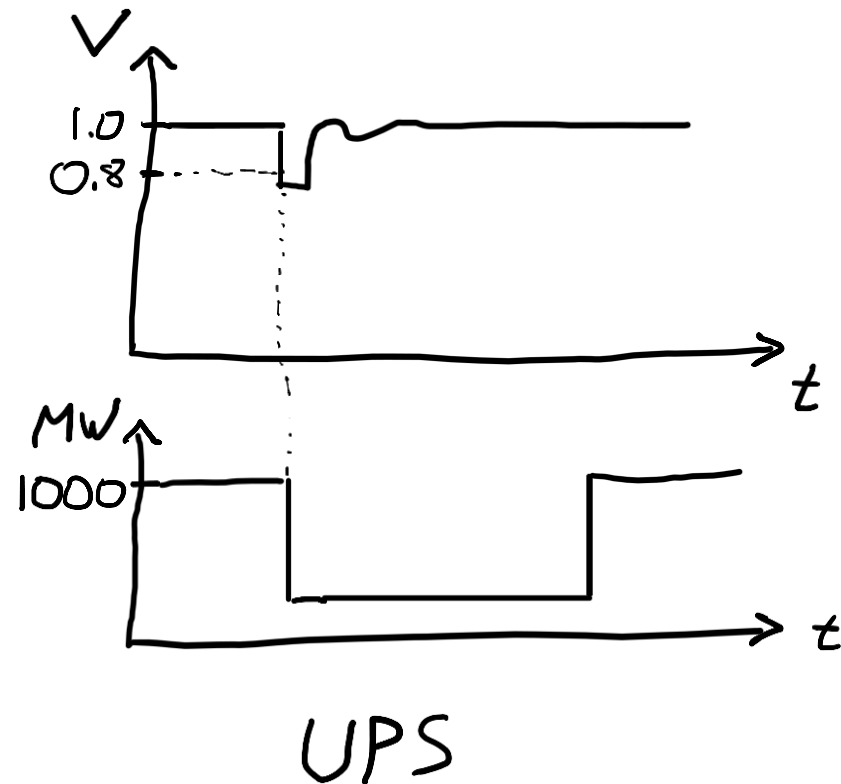
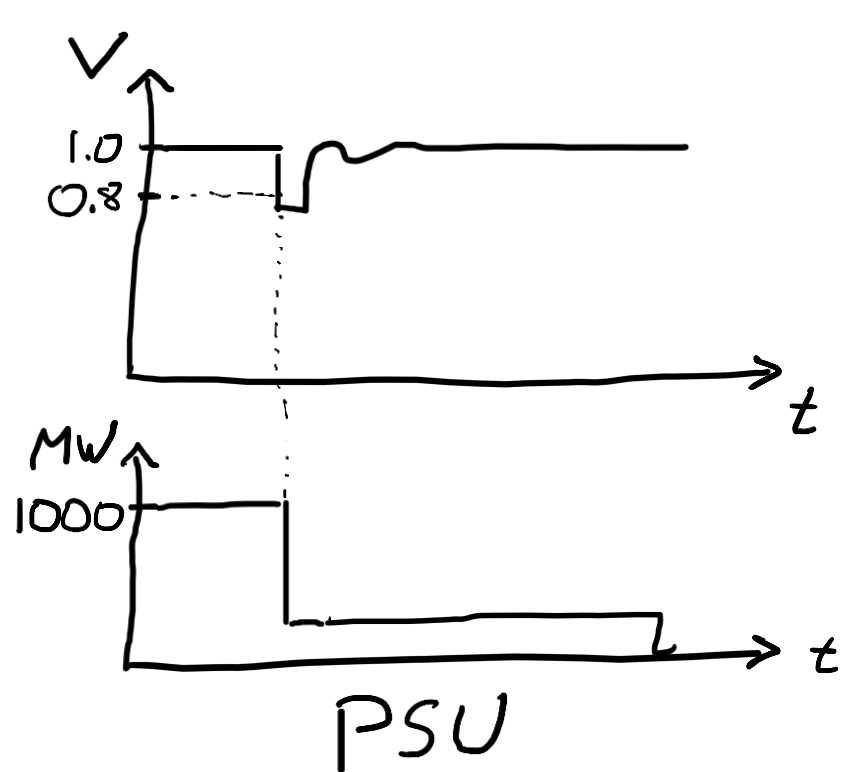
- Phasor domain (transient stability) tools are used to force the load at key machine or system modes

- **Special data required:**

- Transient stability models for load with flexible variation profiles
- Range on load profiles
- Detailed grid model
- Data on machine mode frequencies
- Data on interarea mode frequencies and drivers for oscillations (if interarea oscillations are being studied)

Ride-through background...

- Small voltage depressions may lead to load disconnections...

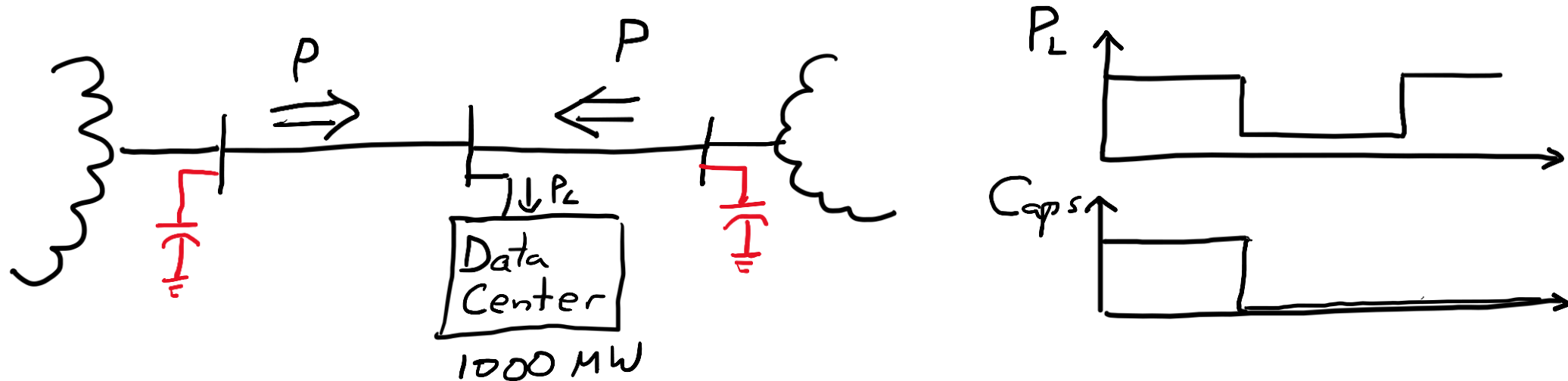


Ride-Through Impact Studies

- Need to ensure that bulk regional disconnection and reconnection (or not) of load will not:
 - Cause load-rejection temporary overvoltage
 - Results in IBR or STATCOM tripping
 - Cause problems with VAR adequacy or dynamic voltage problems
 - Adversely impact frequency of the grid
 - Impact generator resource commitment or create dispatching problems.
 - Study tools may be a mix of Phasor Domain and EMT
- **Special data required:**
 - Ride-through characteristics of the load
 - Ride-through characteristics of nearby devices in the system

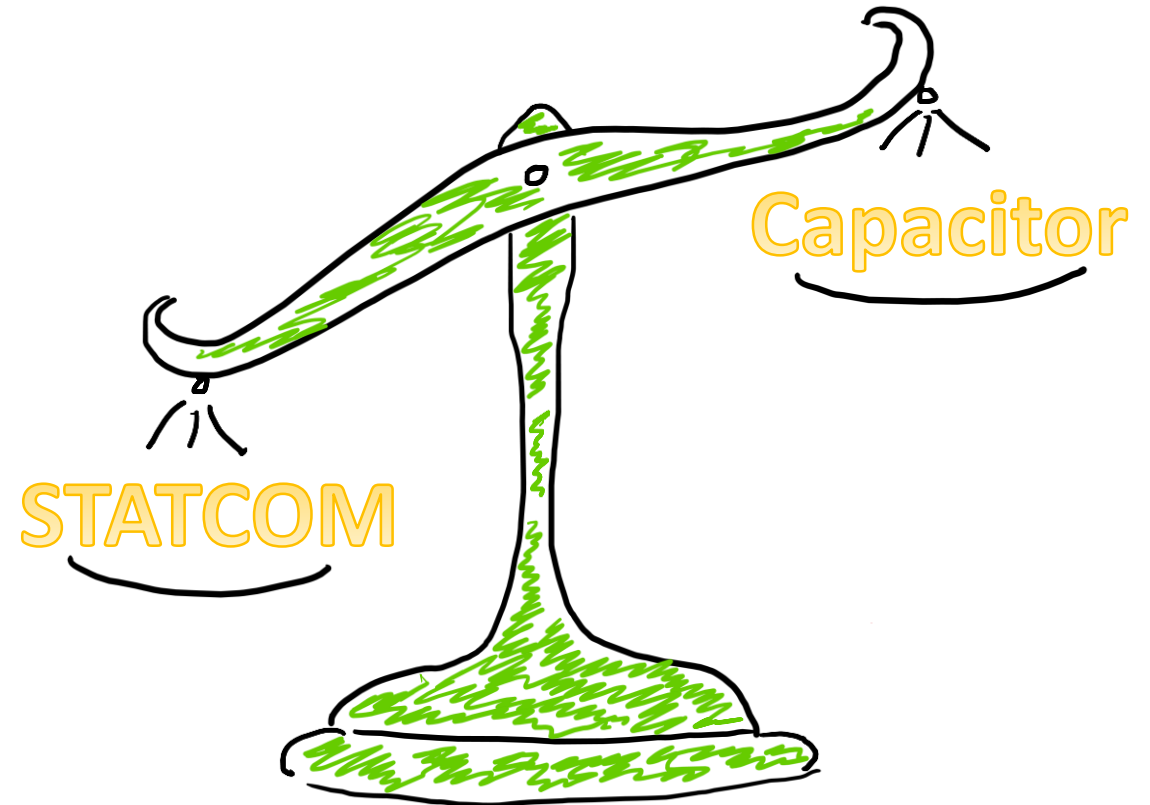
Thinking about dynamic VARs!

- Steady state voltage studies (powerflow) are usually used to determine VAR requirements. Shunt caps are the preferred option to regulate load transfers because they are cheap, and traditionally load doesn't move too fast. Dynamic VARs are often used for load when voltage recovery is problematic (eg. induction motor loads). But...



What is the problem with switched Caps?

1. Caps can be switched off, but not immediately switched on (without special designs). Large, fast load changes will drive large, fast voltage changes!
2. Switching caps causes transients on the system, and wear and tear on breakers.
3. Caps weaken the power system by increasing effective 60 Hz impedance.
4. Caps increase the likelihood of problematic harmonic resonances in the system.
5. **STATCOM solves all of the above, but requires money and time!**

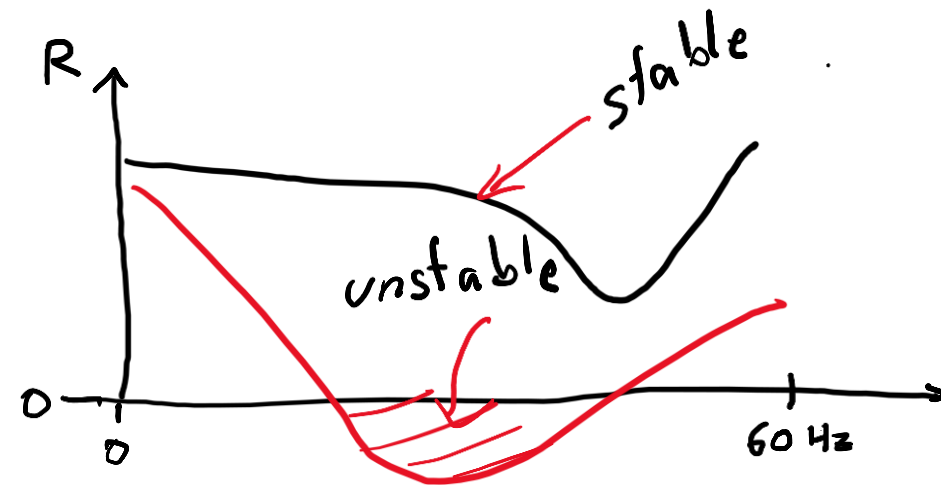


Passive Damping Studies

- SSCI and SSTI are well known phenomena whereby power electronic controls add to or remove damping from the grid.
- If damping becomes negative at an electrical resonance point (eg. Series caps) or at a mechanical resonance point (eg. Machine torsional), instability can occur.
- Study is performed in EMT using very detailed models

Special data required:

- Dynamic impedance characteristics of the load
- Dynamic model of the rest of the grid



What kind of models do you need?

- As always, it depends on what kind of study you're doing...
- You need to collect the appropriate models for the type of concern you are evaluating!

EMT model \neq EMT model

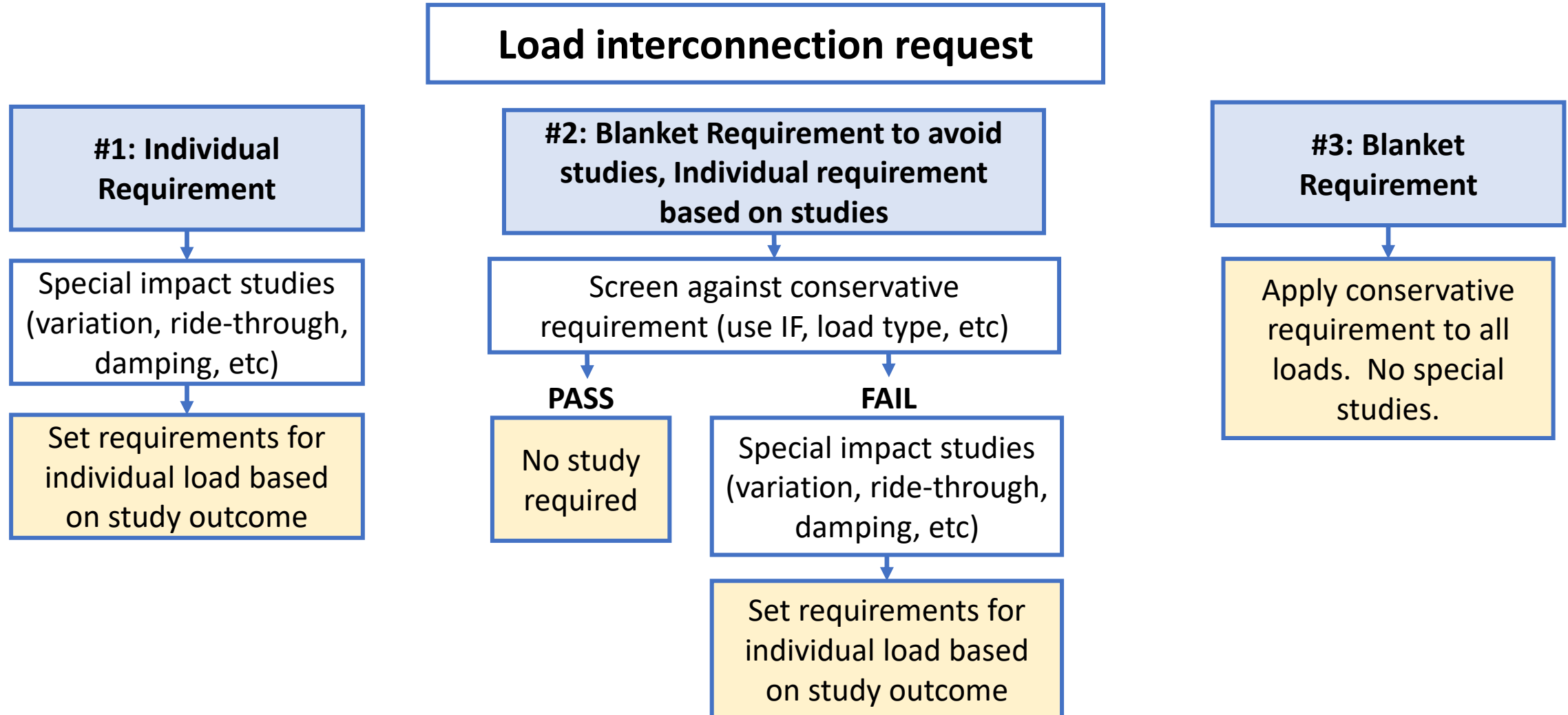
PDT model \neq PDT model

Draft study/model matrix...

Concern	EMT Model with protection (OEM specific)	EMT Model including switching circuitry (OEM specific)	EMT Model including grid-facing control representation (OEM specific)	EMT Model with software cycling (OEM agnostic)	OEM Specific Harmonic Model (Norton Source)	Powerflow Model	PDT Model with software cycling	PDT Model without software cycling
SSTI screening (eg. UIF)	No	No	No	No	No	Yes	No	No
SSTI due to software cycling	No	No	No	Yes	No	No	No	No
Torque impact due to fast changes in load	No	No	No	Maybe	No	Maybe	Maybe	No
SSTI due to control damping	No	No	Yes	No	No	No	No	No
SSCI due to control damping	No	No	Yes	No	No	No	No	No
Harmonic model creation	No	Yes*	Yes*	No	No	No	No	No
Harmonic evaluation	Maybe	Maybe	Maybe	Maybe	Yes	No	No	No
Flicker evaluation	No	No	No	Maybe	No	Yes	No	No
Ride-through sensitivity	Yes*	No	Yes*	No	No	No	No	No
Ride-through impact	Maybe	No	Maybe	No	No	No	No	Maybe
Frequency impact	Maybe	No	No	No	No	No	No	Maybe
IBR/FACTS interaction impact	Maybe	No	Maybe	Maybe	No	Maybe	Maybe	Maybe
Machine mode oscillations due to software cycling	No	No	No	Maybe	No	No	Yes	No
Interarea oscillations	No	No	No	No	No	No	Yes	No
Resource balancing due to ramping	No	No	No	No	No	Yes	No	No
Steady state constraints	No	No	No	No	No	Yes	No	No
Dynamic VAR margin	No	No	No	No	No	Yes	No	Yes

*Alternative to EMT modeling could be detailed laboratory testing on OEM specific equipment

Competing Philosophies for Requirements:



Requirement Philosophy Pros and Cons:

#1: Individual Requirement

Pros:

- Maximum load flexibility

Cons:

- Very heavy study burden
- Re-study may be needed if grid or load changes
- You may find yourself with zero margin

#2: Blanket Requirement to avoid studies, Individual requirement based on studies

Pros:

- Expedited time frames for remote projects over alternative #1

Cons:

- Study burden still heavy
- Re-evaluation may be needed if grid or load changes
- Possibility to miss issues depending on screening approach
- You may find yourself with zero margin again

#3: Blanket Requirement

Pros:

- No study required.
- Accommodates future changes to the grid

Cons:

- Possibility to over-constrain loads, which costs money and may make theoretically good projects unfeasible.
- Possibility to miss issues if requirements are set incorrectly

Framework alternatives – Active Power Variation

1. Limit harmonic/sub-harmonic content in load active power.

Pros:

- Can target frequency ranges and limit magnitudes according to equipment limits
- Allows varied load profiles provided key frequencies aren't introduced

Cons:

- Requires very careful specification of frequency content measurement
- Requires understanding of how frequencies interplay with each other
- Requires understanding of how duration of perturbations interacts with magnitude of perturbations.
- May be more difficult to monitor and enforce, and more difficult to conceptualize.
- Data center loads may not be able to avoid certain frequencies.

Framework alternatives – Active Power Variation

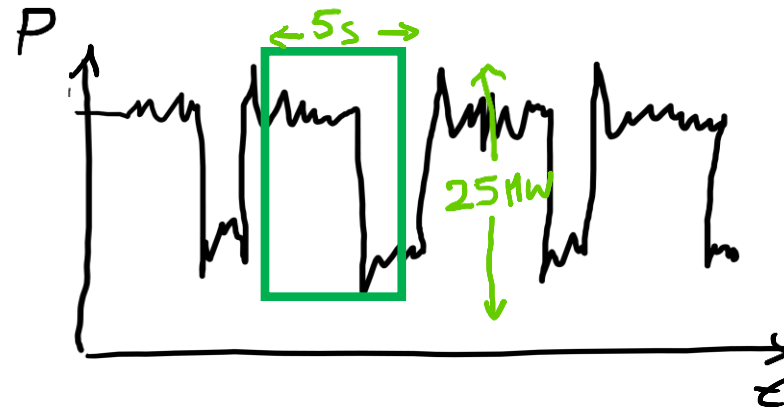
2. Limit absolute variation magnitude.

Pros:

- Conceptually simple to understand
- Addresses multiple concerns
- Allows any type of load variation within the magnitude limit.

Cons:

- Hard to choose a single value that protects equipment adequately and doesn't over-constrain load shapes.



Framework considerations – Ride through


- You can use a ride-through profile (similar to IBR FRT curves) but...
 - Does that mean no-trip or no-temporary-reduction (eg. UPS pickup)?
 - If temporary reduction is allowed, how fast should they return? 1s?
 - Note: Consider frequency, load-rejection overvoltage, dynamic voltage control, and how many loads may trip together for a common event.
 - Load rejection of multiple collocated loads could cause significant temporary overvoltage. **How can we fix this?**
- Consider that many or maybe most loads will not be able to initially meet this criteria, particularly if you don't allow temporary reduction.

Example requirement: ATC

- [Load Interconnection Guide, rev 15](#) – published August 22, 2025 (pages 32-35)
- [ATC Planning Criteria, V25](#) – published August 28, 2025 (pages 34-37)
- Uses a blanket requirement, but allows studies to prove exceptions.

#2: Blanket Requirement to avoid studies, Individual requirement based on studies

- Uses absolute variation magnitude limit: <25 MW over any 5 second period

	Criteria	Department:	System Planning
		Document No:	PLG-CR-0001-V25
Title: Transmission System Planning Criteria		Issue Date:	August 28, 2025
		Previous Date:	February 4, 2025

ATC
Load Interconnection Guide

Revision 15.0
August 22, 2025

Example Criteria: ATC (Loads > 200 MW)

9.2 Voltage Ride Through

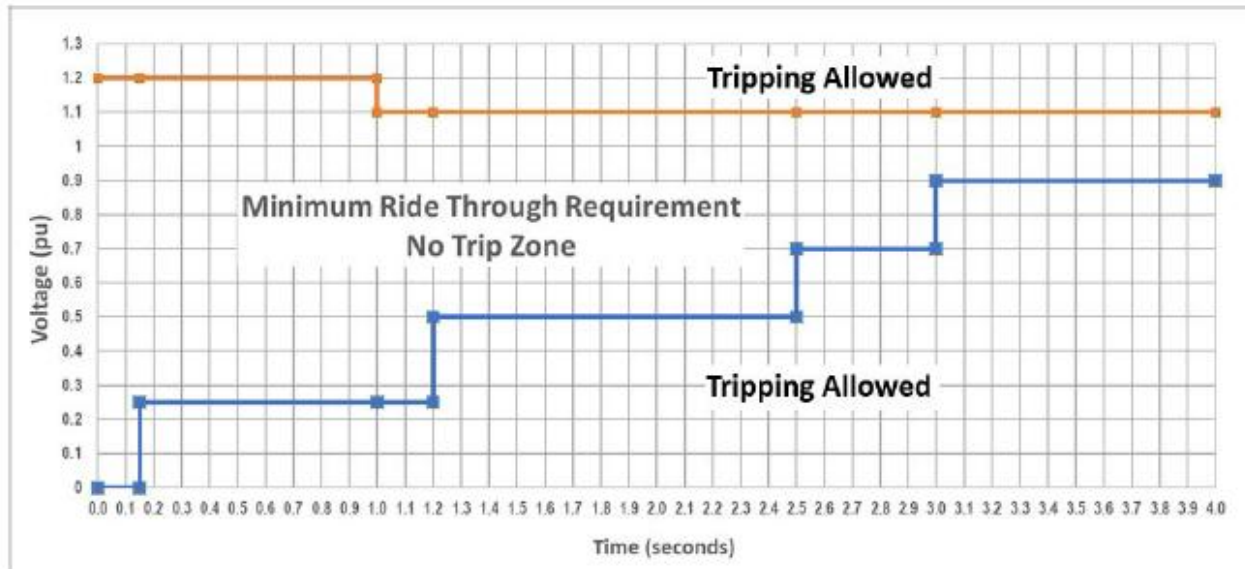



Figure 9.2-1: Voltage Ride Through Curve for Large Loads

	Criteria	Department:	System Planning
		Document No:	PLG-CR-0001-V25
Title: Transmission System Planning Criteria		Issue Date:	August 28, 2025
		Previous Date:	February 4, 2025

ATC
Load Interconnection Guide

Revision 15.0
August 22, 2025

POI Voltage (pu)	Minimum ride-through time (s)
$V > 1.20$	May ride-through or trip
$V > 1.10$	1
$V > 1.05$	Continuous
$V < 0.90$	3
$V < 0.70$	2.5
$V < 0.5$	1.2
$V < 0.25$	0.15

Note 1: Load must ride through 3 voltage deviation events within 10 seconds

Note 2: POI Voltage is at the connection point to the ATC transmission system. For ride-through, the relevant voltage is the lowest (in the case of undervoltage) or highest (in the case of overvoltage) magnitude fundamental frequency phasor component of the applicable voltages at the POI relative to the nominal voltage. Instantaneous phase voltages may exceed these levels.

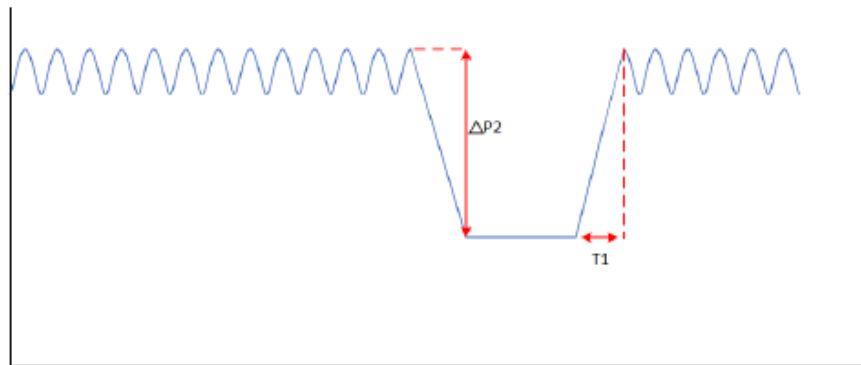
Note 3: Load should not trip for instantaneous transients due to normal system events such as faults, energization or switching.

Example Criteria: ATC (Loads > 200 MW)

Table 9.1-1: Active Power Oscillation Criteria Limits

Constant	Limit	Unit
$\Delta P2$	25	MW
T1	5	seconds
P3	50	MW
R2	0.5	MW/second (MW/s)

Criterion 1: Repetitive changes in load active power must be $< \Delta P2$ for any period of time $< T1$ seconds calculated using a sliding time window.



9.1 Load Active Power Oscillations & Ramp Rate Limits

Customer's equipment/facility shall be designed and operated within the maximum allowable variation limit of steady state (continuous load operation) active power oscillations as follows and as measured at the point of connection to the ATC transmission system. Note that these values are the total aggregate values for all sites at a given point of interconnection, or at multiple sites if oscillations are driven by common processes across multiple sites.

Criterion 2: Any change (increase or decrease) in active power $> P3$ MW should be limited to $< R2$ MW/s.

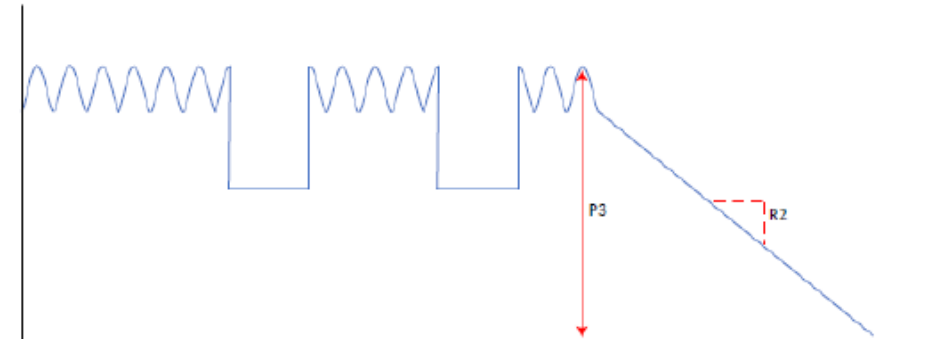


Figure 9.1-4: Active Power Criterion for P3 and R2 Example

Variability Mitigation

- “Load floor”
- HV/MV energy storage
 - E-STATCOM with or without GFM BESS
- DC level (power supply) storage (eg Nvidia GB300 or DC storage)
- Low voltage GFM BESS or GFM BESS behind series reactor (+ load-tracking?)
- Full conversion UPS with large energy storage or supercapacitors
- Thyristor switched resistor
- Software mitigation?

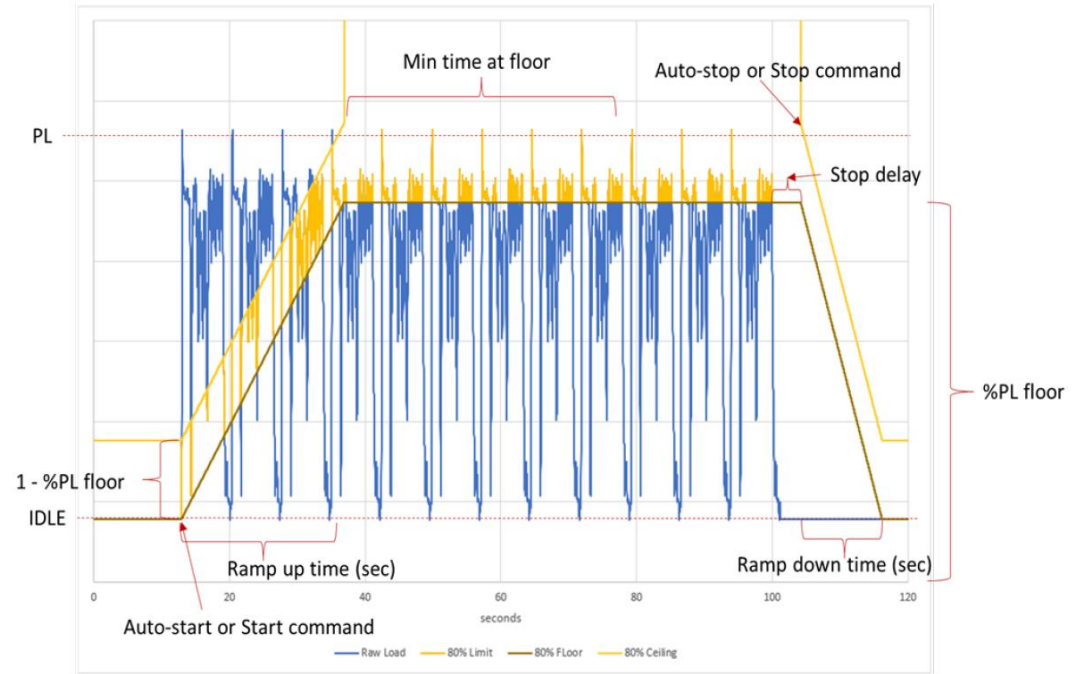


Fig. 7. Energy-storage solution simulated on the power waveform from Figure 1

Solution	Reliability	Performance	Energy	Cost	Ability to meet tightest spec	Dependency on the developer	Lifetime
Software-only mitigation	Medium	Medium	High	Medium	High	High	High
GPU power smoothing	High	Medium	High	Low	Medium	Medium	Medium
Rack-level energy storage	High	High	Low	High	High	Low	High

TABLE I

SUMMARY OF VARIOUS PROPOSED SOLUTIONS. FOR ENERGY, COST, AND DEPENDENCY ON THE DEVELOPER, LOWER IS BETTER.

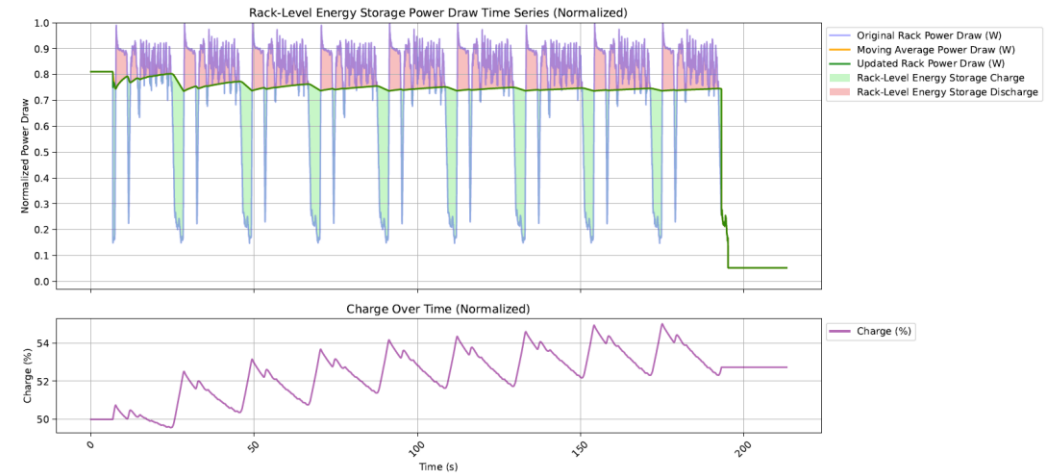


Fig. 7. Energy-storage solution simulated on the power waveform from Figure 1

Power Stabilization for AI Training Datacenters

Special Studies - Classical Studies

Classical Studies

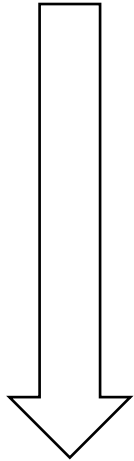
- “Traditional” EMT Studies:
 - TOVs, Line Design and Insulation Coordination
 - Energize lines, cables, transformers, shunt capacitors
 - Faults and recovery TOVs
 - Rating and Performance studies
 - Lightning
 - TRV
 - & more..

Good resource (one of many):

https://www.pscad.com/uploads/knowledge_base/application_20guide_202008_1.pdf

Study Techniques

Time Step



- Steady State
- Long Duration Time Domain Analysis
- Transient Stability Dynamic Performance
- EMT Dynamic Performance
- TOV and Switching Transients
- TRV and Lightning

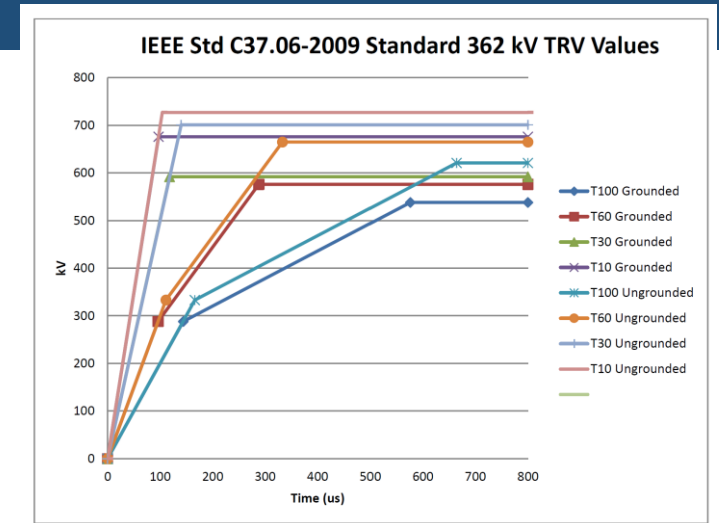
Lightning Studies – fast front transients

- Study objective: Determine impact of lightning strikes, i.e. is shield wire / surge arrester / insulation design sufficient to avoid damage to equipment
- Very fast lightning current surges (50-100 μ s duration) striking either conductors or ground wires / tower
 - Direct strike on conductor: risk of exceeding arrester / insulation levels, flashover risk
 - Strike on tower: risk of voltage build-up on tower exceeding insulation level (back flash-over)
- Important modelling details and assumptions:
 - Ultra small time-step (nsec)
 - Surge shape
 - Stray capacitance
 - Lead inductance
 - Grounding/shielding
 - Tower modelling
 - Steep front arrester models
- Mitigation:
 - More surge arrestors, more grounding, more shield wires

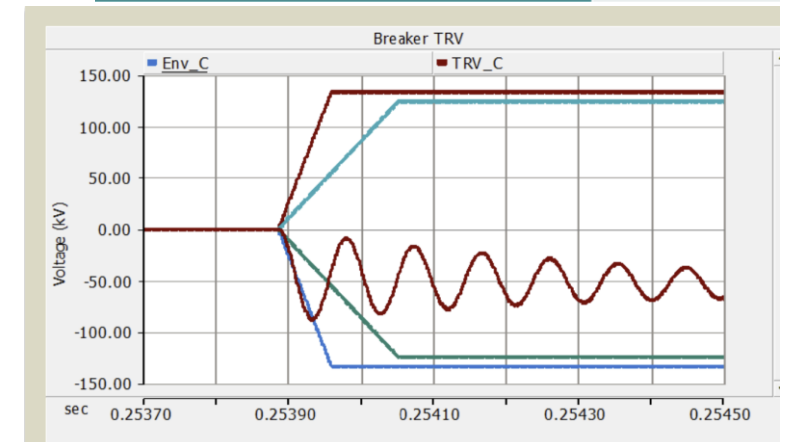
Example Resource: <https://www.pscad.com/knowledge-base/article/286>

Transient Recovery Voltage (TRV) Studies

- Study objective: Simulate how quickly the voltage across a breaker builds up when clearing a fault
- If voltage builds up too quickly, re-strike is possible
- IEEE/IEC standards define withstand voltages
- Modelling considerations:
 - Small time steps, relatively small models required (1 station in-detail + FD T-lines out of station)
 - Stray capacitance
 - Detailed buswork modelling
- Mitigation:
 - Check with breaker manufacturer on actual TRV withstand capability! May be higher than what is in standards
 - If still failing, higher-rated breaker may be needed, or additional devices (e.g. surge/grading capacitor)
- Example Resource: <https://www.pscad.com/knowledge-base/article/683>



Description	Capacitance (pF)
• Earthing Switch	50
• Current Transformer	200
• Capacitive Voltage transformer – outdoor	5500
• Surge Arrester	80
• SF6 to Air Bushing	100
• Voltage Transformer	200



Switching Studies

- Line / transformer energization, faults, capacitor / reactor switching, open-line resonance, and more..
- Study objectives: determine peak overvoltages, peak arrester energies, verify equipment overvoltage ratings not exceeded, check for problematic resonances
- Modelling considerations:
 - Medium-sized model (2-3 buses away may be sufficient) required for the correct frequency response
 - Timestep of few μs to 50 μs (depending on phenomena)
 - Point-on-wave effect for faults/energization
 - Statistical switching
 - Non-linear models important (saturation, remanence, frequency dependant lines etc..)
- Mitigation:
 - Will vary based on specific issue.. Harmonic filters, pre-insertion resistors, point-on-wave breakers,
- Reference: <https://www.pscad.com/knowledge-base/article/684>