EMT Tutorial
ESIG Spring Workshop

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ENERGY SYSTEMS INTEGRATION GROUP

TELOS ENERGY

ELECTRANIX
SPECIALISTS IN POWER SYSTEM STUDIES

Agenda

- Introduction (15 minutes)
- Identification of Need (40 minutes)
- Data Intake & Organization (30 minutes)
- System Model Construction & Quality Assurance (30 minutes)
- Q&A (15 minutes)

Coffee Break (10:15am – 10:45am)

- Simulations (20 min)
- Analysis and Actions/Mitigations (35 min)
- Software Tool Vendors (50 min)

Introduction & Industry Need

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Why Electromagnetic Transient (EMT) Studies?

- Previously, EMT modeling and analysis was used for specific local phenomena (lightning evaluation, insulation coordination, transformer and line energization, harmonic analysis)
- With proliferation on inverter-based resources (IBRs), FACTs devices, HVDC and power electronic interphased loads, the dynamic behavior of power systems is becoming impacted by fast-response power electronic devices.
- New stability concerns are being observed such as e.g. sub-synchronous control interactions, particularly in weak parts of the grid with multiple IBRs. .
- Need for studies in simulation environment capable of capturing fast (sub-cycle) dynamic phenomena.
- Additionally, large disturbance events resulting in tripping of multiple IBRs have revealed another challenge, where more detailed (but also more accurate) models can help with timely detection and mitigation.

NERC Disturbance Events – Importance of Fault Ride-Through Evolution and Model Accuracy

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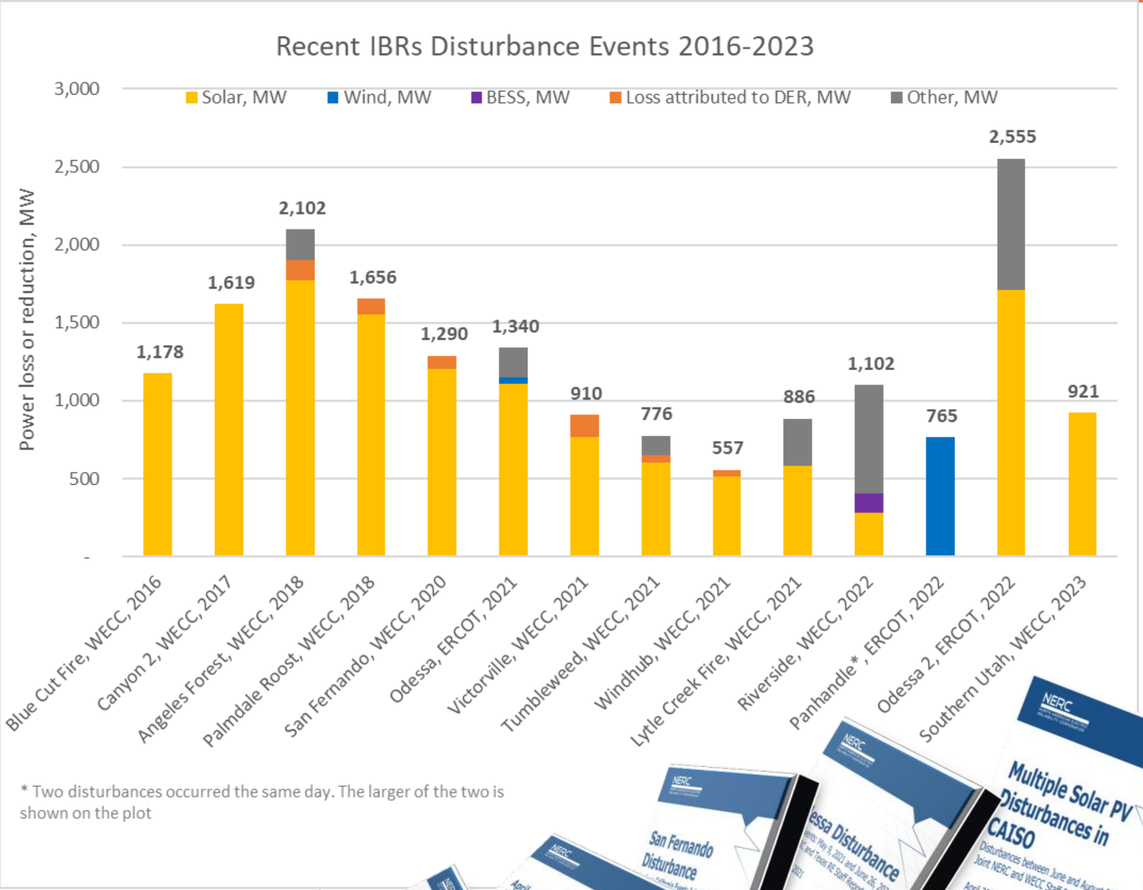
Table 1.1: Causes of Solar PV Active Power Reductions		
Cause of Reduction	**Odessa 2021 Reduction [MW]**	**Odessa 2022 Reduction [MW]**
Inverter Instantaneous AC Overcurrent	–	459
Passive Anti-Islanding (Phase Jump)	–	385
Inverter Instantaneous AC Overvoltage	269	295
Inverter DC Bus Voltage Unbalance	–	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

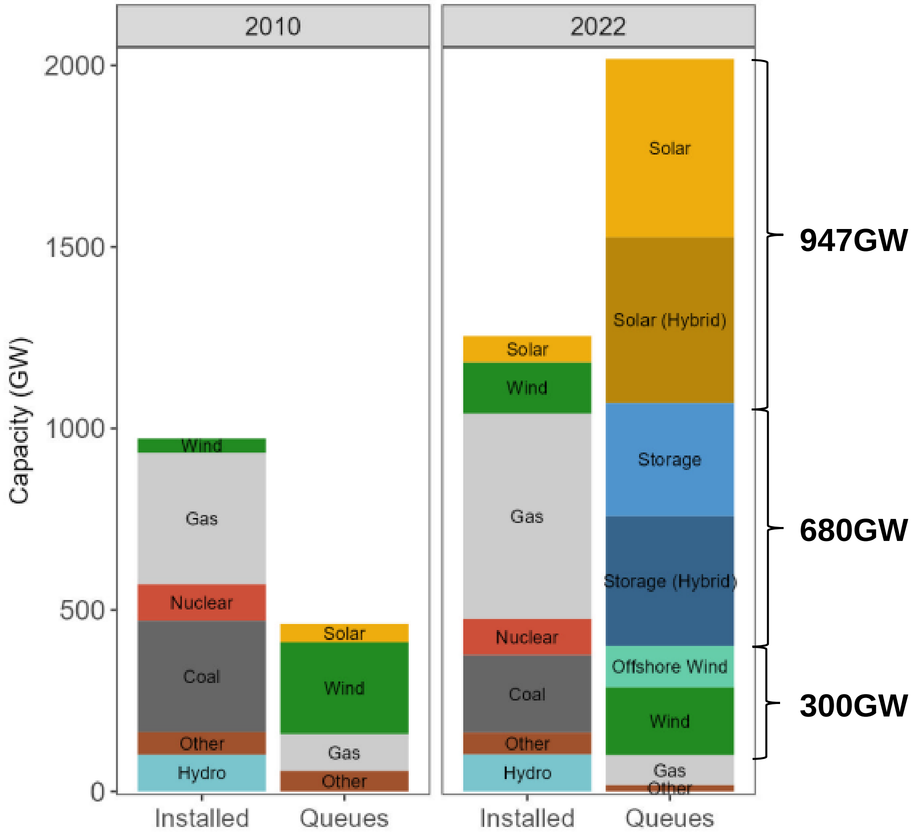


Source: NERC Event Reports

Importance of EMT Models Going Forward

- Over 2000 GW of total generation and storage capacity in the U.S. interconnection queues, as of the end of 2022, of which over 96% are inverter-based resources (IBRs)
- EMT models are important not just for EMT studies but for IBR conformity assessment with applicable interconnection requirements and benchmarking with phasor domain models
- Only a few areas in the U.S. currently are collecting EMT models during interconnection process
- Manufacturers are discontinuing products or going out of business – EMT models are hard to obtain at that stage
- Missed opportunity of conformity assessment post-commissioning model validation
- **By the time EMT study is needed, collecting models is too late!!!!**

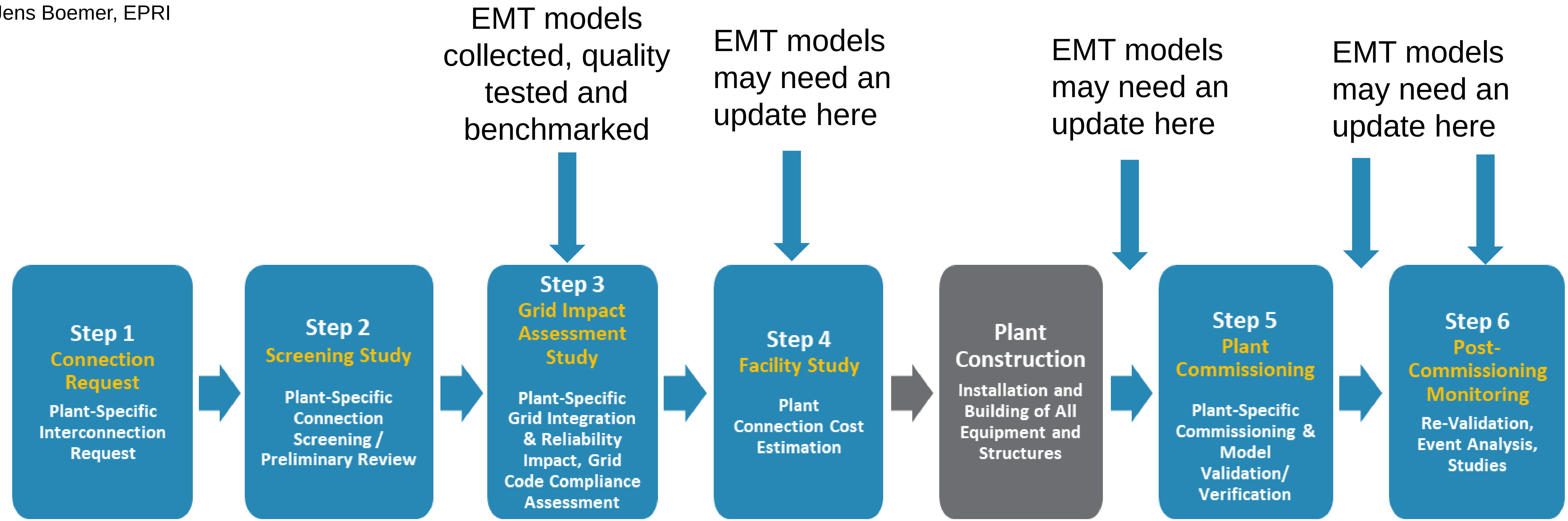
Entire U.S. Installed Capacity vs. Active Queues



Source: LBNL, [Queued Up: Characteristics of Power Plants Seeking Transmission Interconnection]

Collect and Quality Test EMT Models at the Interconnection!

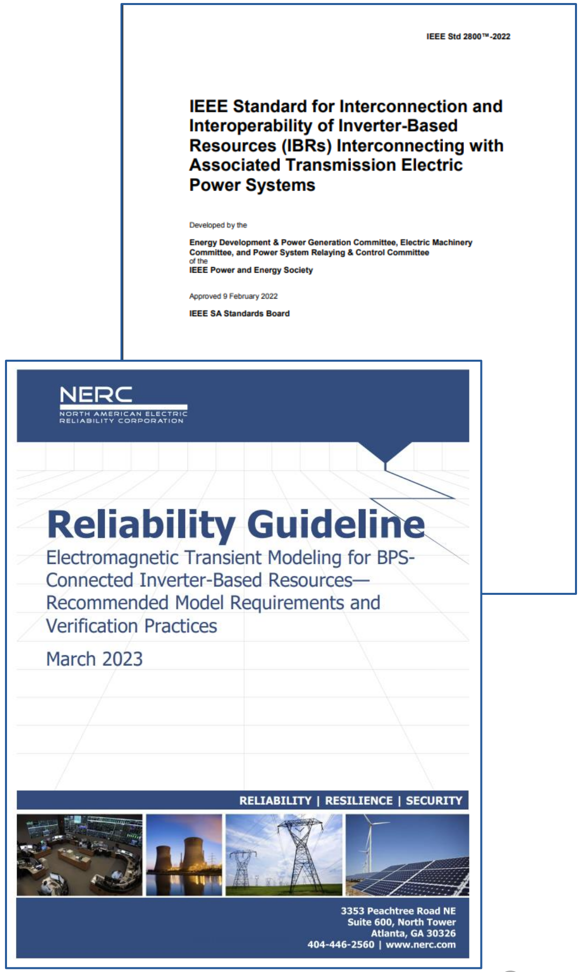
Figure adopted from
Jens Boemer, EPRI



* Every time EMT model is updated, quality testing, validation/benchmarking steps are repeated, and some relevant studies may need to be repeated depending on the model change

Emerging Requirements & Standards for EMT modelling and Studies

- **ERCOT, ISO-NE, CAISO** and some other areas already require EMT models during interconnection process and have **detailed model quality testing and validation requirements.**
- **IEEE 2800-2022** Standard for Interconnection and Interoperability of IBRs Interconnecting with Associated Transmission Electric Power Systems – establishes EMT modeling data requirements (among other things)
- **NERC MOD-026-2** Verification of Dynamic Models and Data for BES Connected Facilities – to verify that the dynamic models and associated parameters represent the in-service equipment of BES Facilities – current revision draft includes requirements for EMT models
- **NERC Reliability Guideline** on EMT Modeling of IBRs
- **FERC Order 2023** requires submission of accurate/representative EMT models at the interconnection request stage (in areas that are conducting EMT studies)
- **NERC Project 2022-04** EMT Modeling – to address lack of accurate modeling data and the need to perform EMT studies during the interconnection process and long-term planning. Affected NERC Standards: FAC-002, MOD-032, and TPL-001



IEEE Std 2800™-2022

IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems

Developed by the

Energy Development & Power Generation Committee, Electric Machinery Committee, and Power System Relaying & Control Committee
of the
IEEE Power and Energy Society

Approved 9 February 2022

IEEE SA Standards Board

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NORTH AMERICAN ELECTRIC RELIABILITY CORPORATION

Reliability Guideline

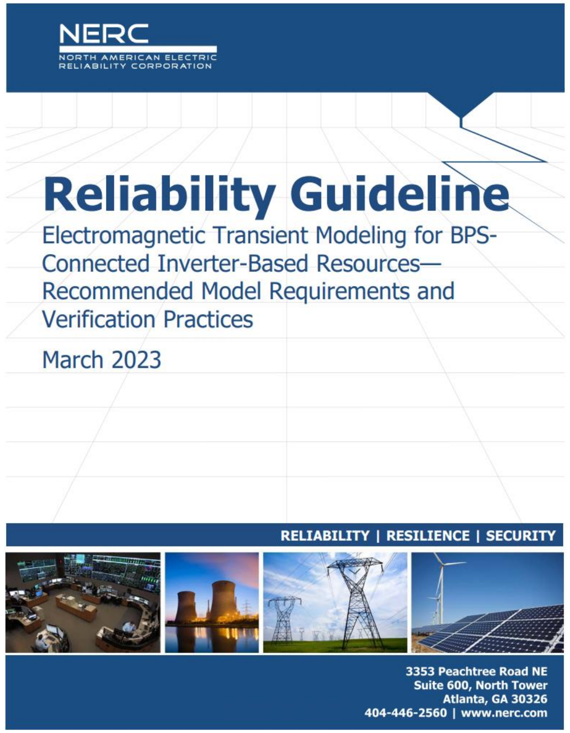
Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources—Recommended Model Requirements and Verification Practices

March 2023

RELIABILITY | RESILIENCE | SECURITY

3353 Peachtree Road NE
Suite 600, North Tower
Atlanta, GA 30326
404-446-2560 | www.nerc.com

NERC EMT Task Force



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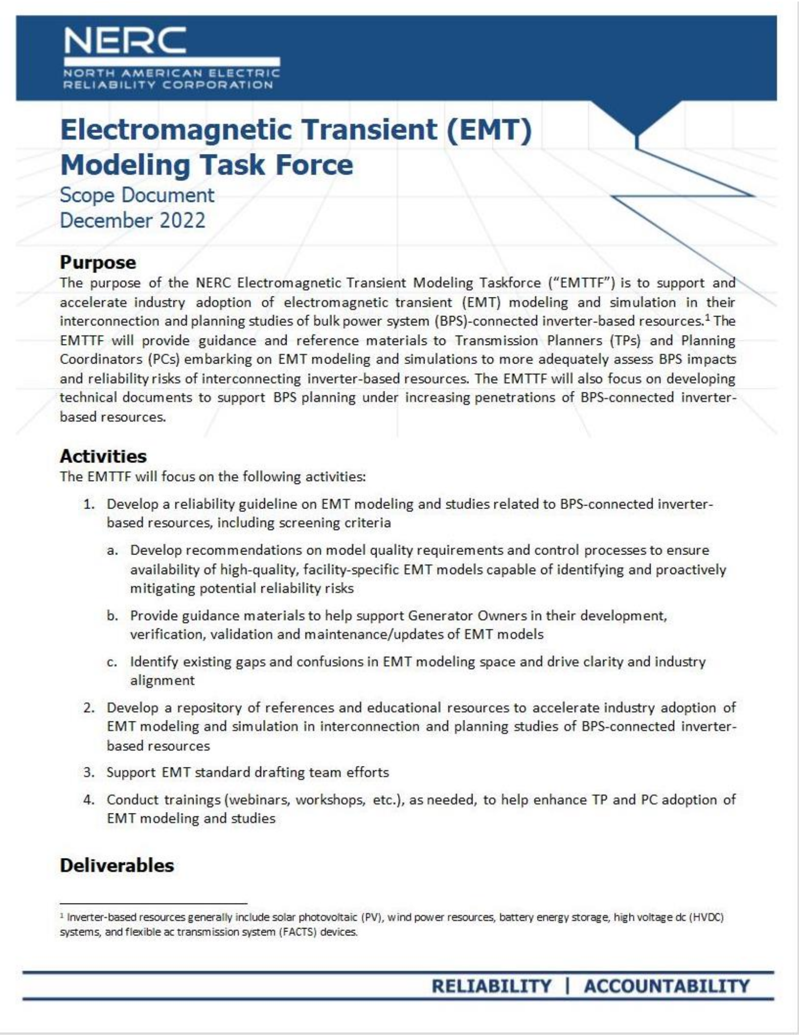
- Modeling requirements
- Model quality assessment
- Screening for EMT study need
- Assess VRT capability and performance
- Resourcing for EMT studies
- Different flavors of EMT models



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Electromagnetic Transient (EMT) Modeling Task Force

Scope Document
December 2022

Purpose

The purpose of the NERC Electromagnetic Transient Modeling Taskforce ("EMTTF") is to support and accelerate industry adoption of electromagnetic transient (EMT) modeling and simulation in their interconnection and planning studies of bulk power system (BPS)-connected inverter-based resources.[1] The EMTTF will provide guidance and reference materials to Transmission Planners (TPs) and Planning Coordinators (PCs) embarking on EMT modeling and simulations to more adequately assess BPS impacts and reliability risks of interconnecting inverter-based resources. The EMTTF will also focus on developing technical documents to support BPS planning under increasing penetrations of BPS-connected inverter-based resources.

Activities

The EMTTF will focus on the following activities:

1. Develop a reliability guideline on EMT modeling and studies related to BPS-connected inverter-based resources, including screening criteria
   a. Develop recommendations on model quality requirements and control processes to ensure availability of high-quality, facility-specific EMT models capable of identifying and proactively mitigating potential reliability risks
   b. Provide guidance materials to help support Generator Owners in their development, verification, validation and maintenance/updates of EMT models
   c. Identify existing gaps and confusions in EMT modeling space and drive clarity and industry alignment
2. Develop a repository of references and educational resources to accelerate industry adoption of EMT modeling and simulation in interconnection and planning studies of BPS-connected inverter-based resources
3. Support EMT standard drafting team efforts
4. Conduct trainings (webinars, workshops, etc.), as needed, to help enhance TP and PC adoption of EMT modeling and studies

Deliverables

[1] Inverter-based resources generally include solar photovoltaic (PV), wind power resources, battery energy storage, high voltage dc (HVDC) systems, and flexible ac transmission system (FACTS) devices.

RELIABILITY | ACCOUNTABILITY

Wrapping up: Vol. 2,EMT Studies

- Scoping detailed EMT studies
- Building EMT study models
- Interconnection studies
- Transmission planning studies
- Material modification and model updates during interconnection study process and post COD

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Identification of Need for EMT Studies

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Why do we need EMT?

Simply… to obtain the accuracy needed in our studies to design our power grid reliably.

- Some phenomena are difficult or impossible to predict using traditional Phasor Domain (PD) tools.
- The transition to inverter-based generation is challenging our ability to predict outcomes.

- Events are reinforcing the need for advanced studies and tools! (NERC reports)
- Using EMT, we are catching issues before projects go in service every day!

NERC Major Event Reports

Major Event Reports

- December 2022 Winter Storm Elliott Report
- March/April 2022 California Battery Energy Storage System Disturbances
- April 2023 Southwest Utah Disturbance Report
- June 2022 Odessa Disturbance Report
- March 2022 Panhandle Wind Disturbance Report
- June-August 2021 CAISO Solar PV Disturbance Report
- May/June 2021 Odessa Disturbance Report
- February 2021 Cold Weather Outages in Texas and the South Central United States
- July 2020 San Fernando Solar PV Reduction Disturbance Report
- January 2019 Eastern Interconnection Forced Oscillation Event Report
- January 2018 South Central Cold Weather Event Report
- April and May 2018 Fault Induced Solar Photovoltaic Resource Interruption Disturbances Report
- September 2017 Hurricane Irma Event Analysis Report
- August 2017 Hurricane Harvey Event Analysis Report
- October 2017 Canyon 2 Fire Disturbance Report
- August 2016 1200 MW Fault Induced Solar Photovoltaic Resources Interruption Disturbance Report
- April 2015 Washington D.C. Area Low-Voltage Disturbance Event
- Cold Weather Training Materials
- January 2014 Polar Vortex Review
- October 2012 Hurricane Sandy Event Analysis Report
- October 2011 Northeast Snowstorm Event
- September 2011 Southwest Blackout Event
- February 2011 Southwest Cold Weather Event
- August 2003 Northeast Blackout Event

Since 2017!

← 2003 Blackout

Dynamic Models Overview

“All models are wrong, some are useful.”

-- George Box, British Statistician

Less accurate

Easier to use

Highly accurate

Difficult to use

Completely accurate

Important to understand how the models are wrong and how it impacts the conclusions drawn from the analysis (conservative v. optimistic)

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Types of Power Plant Models

Generic Positive Sequence Models

- Model structure is fixed, only parameters are provided
- White-box structure
- Suitable for large system, transmission planning studies
- Software tools like PSSE, PSLF, TSAT

OEM-Specific Positive Sequence Models

- Model structure is determined by the OEM
- Black-box structure
- Suitable for studies requiring more detail, some interconnection studies
- Software tools like PSSE, TSAT

OEM-Specific EMT Models

- Proprietary models are created by the OEM
- Black-box structure
- Required for special applications (weak grid, series-compensation, etc.)
- Software tools like PSCAD, EMTP, ATP

Reduced detail and complexity — Increasing detail and complexity

Large studies, many assets modeled — Focused studies, critical assets modeled

The “right” (most appropriate) model to use depends on the application, risk, and data available

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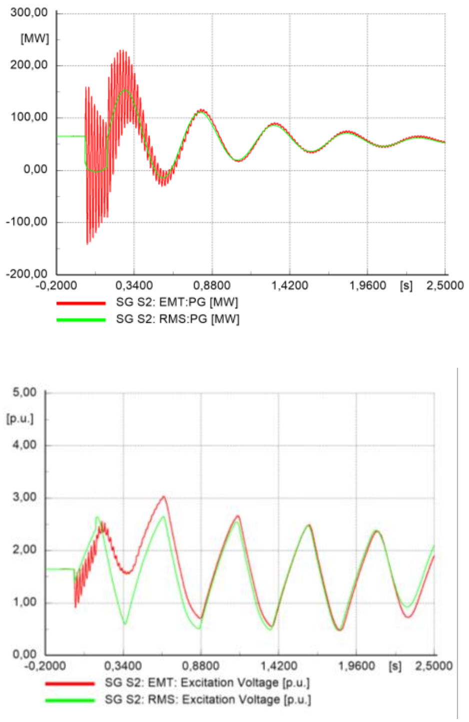
Tools Applicability

Positive Sequence Tools

- Looser model-product relationship
- Millisecond time-steps
- Positive-sequence only
- Fundamental frequency (or near to it)
- Many equipment details are omitted or simplified
- Transport delays are generally not able to be represented
- Fewer software dependencies

EMT Tools

- Close model-product relationship
- Microsecond time-steps
- Three-phase representation
- Full spectrum, utilizing diff. equations
- Highly detailed – small differences matter… (i.e., breaker contact opening)
- Transport delays can be accurately represented
- More complex software & compiler dependencies



DIgSILENT RMS-EMT Model Benchmarking

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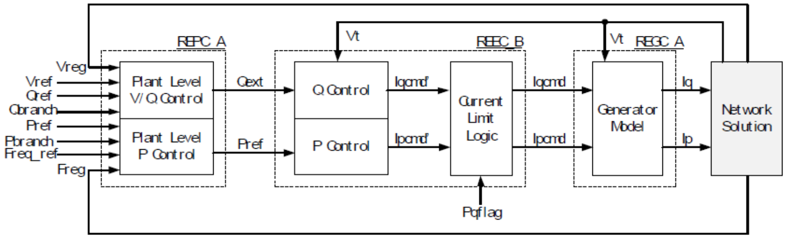
Model Applicability

Positive Sequence Models

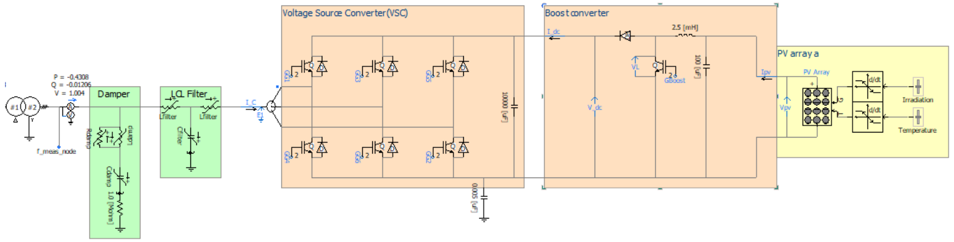
- Many equipment details are omitted or simplified
- Faster control loops are omitted or highly simplified
- Complex controllers, state machines, limiters, etc. are simplified
- Power electronic bridge and switching are omitted
- DC-side representation is omitted
- Transport delays are generally not able to be represented

EMT Models (OEM-Specific)

- Highly detailed equipment models based on product firmware
- Faster control loops should be included in detail
- Complexity of controls can (should) be captured
- Power electronic bridge is represented; switching can be represented
- DC-side representation should be included
- Transport delays can be accurately represented



https://www.esig.energy/wiki-main-page/generic-models-pv-plants/



https://www.pscad.com/knowledge-base/article/521

Model Development Basis

Positive Sequence Models

- Controller is redeveloped manually for suitable representation
- Parameters typically require manual translation
- Engineering judgment is required for simplification

EMT Models (OEM-Specific)

“Real-Code” Approach

- Machine-translation from firmware code to model code
- Not all of product firmware is suitable for model code;
- Parameters have 1:1 correspondence; timesteps and task rates must be coordinated

Manual Translation Approach

- Manual redevelopment of controller functionality
- Engineering judgment and time is required
- Parameter translation can vary; timestep and task rates may vary

“Real-Code” Industry Groups
IEEE Task Force "Use of Real-Code in EMT Models for Power System Analysis”

CIGRE B4.82 (Guidelines for Use of Real-Code in EMT Models for HVDC, FACTS and Inverter based generators in Power Systems Analysis)

Engineering judgment is still required

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OEM v. Generic EMT Models

OEM-Specific Models

- Represents specific product firmware revisions
- Note: must be tied not only to a make, or model, but also to the firmware release
- Revision control cannot be overstated
- Revision control cannot be overstated
- Parameter set must be aligned with the as-running product
- If all of these are met; very high confidence is achieved

Non-Engineering Aspects

- Proprietary code; black-boxed
- Almost always released under NDA only

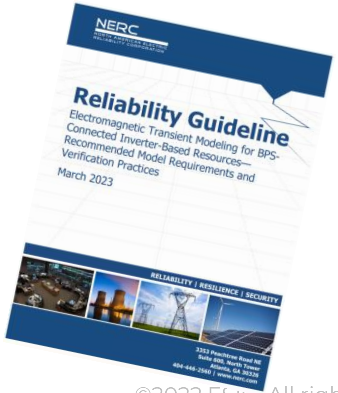
Generic Models

- Not tied to any particular make, model or firmware
- Much greater uncertainty in fidelity
- Suitable for research / academic studies

Sometimes there are no better options

- Representation of very old legacy products
- Aggregate representation of DER in system-level studies
- Protection relays…

[NERC's Reliability Guideline on EMT for BPS IBR]



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EMT Models- What are they used for?

Classical Fast Transient Studies

- Lightning
- TOV, TRV, IRRV
- Switching Studies
- Fault transients
- Insulation coordination

Special Studies

- Protection
- Control design
- Harmonic analysis
- Real-time simulation

Dynamic Performance Studies

- Control interactions
- Sub-synchronous oscillations
- Weak grid
- Fault ride-through
- Performance verification
- Event replication

Research and Academia

- Education
- New technology development
- Scenario sensitivity analysis

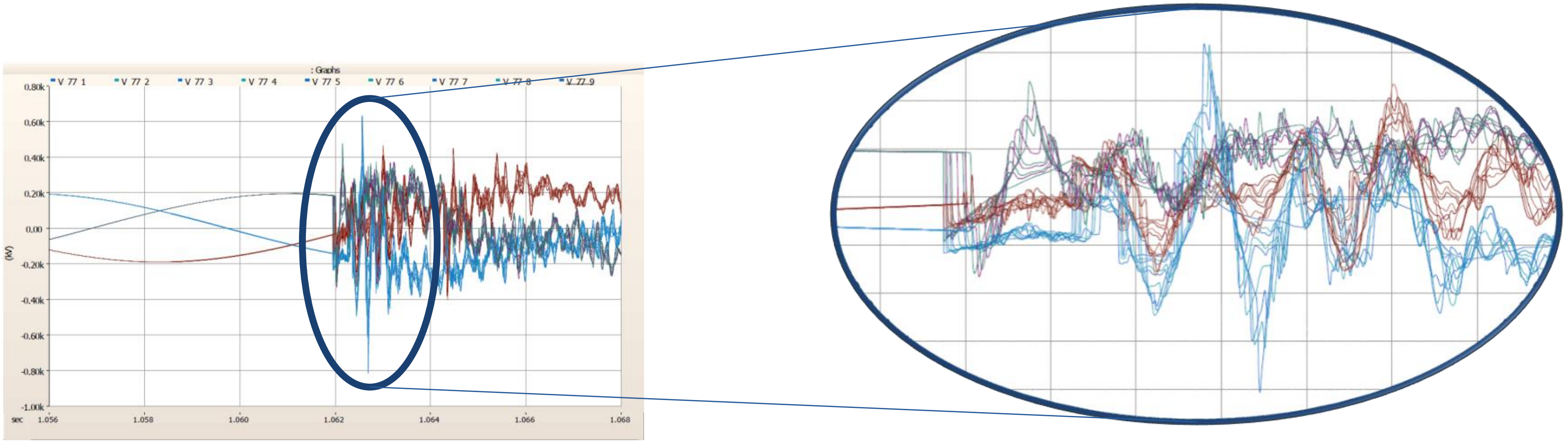
Classical Transient Studies – Last 50 years!

Categories

- Lightning
- TOV, TRV, IRRV
- Line/Transformer/device switching, fault transients
- Insulation coordination or design

What kind of model is used?

- Generally high bandwidth (in some cases *very* high bandwidth)
- IBR models often simplified or neglected
- Extent of system model is generally limited. Can be run using “ordinary” computers



Capacitor breaker re-strike example

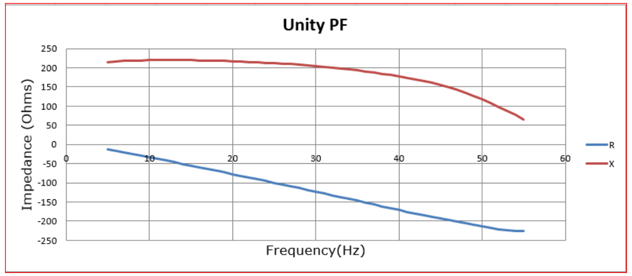
Special Studies

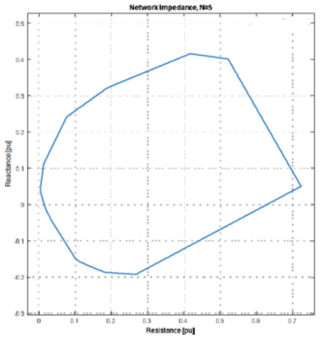
Categories

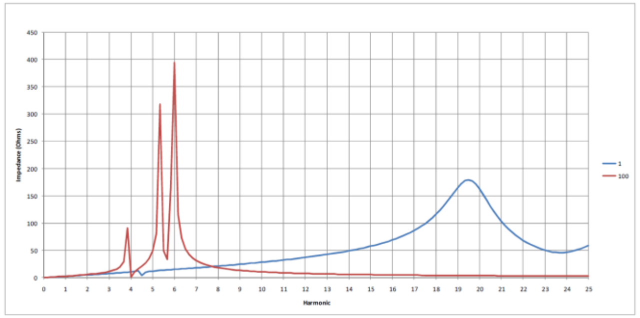
- Protection (validating or checking detailed fault current behaviour)
- Control design (tuning or designing complex control algorithms)
- Harmonic analysis (evaluating harmonic performance or system characteristics)
- Real-time simulation (testing hardware against simulated networks)

What kind of model is used?

- These study model assumptions are centered around the specific need.







Dynamic Performance Studies – not new but…

New focus driven by energy transition

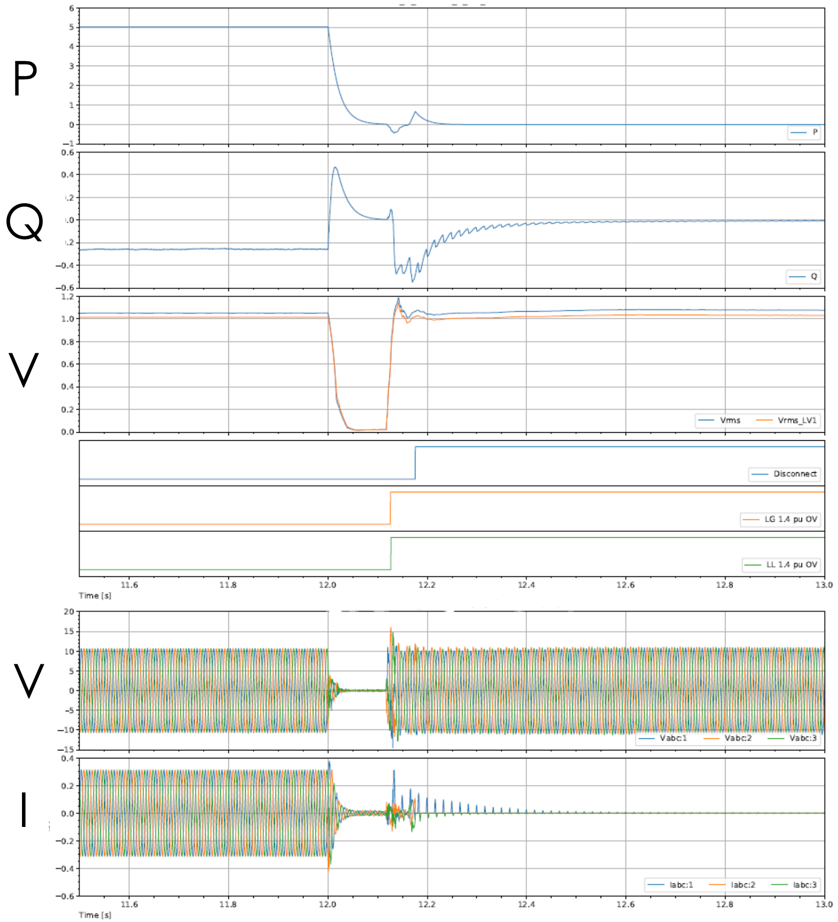
Categories

- Control interactions
- Sub-synchronous oscillations
- Weak grid performance evaluation
- Fault ride-through evaluation
- Performance capability verification according to standards
- Event replication or analysis

What kind of model is used?

- Varying, but may be extensive, requiring large sections of power system to be modelled.
- May require unusually powerful computers.
- Overlaps or supplements with conventional planning Phasor Domain studies

IBR Ride-Through Failure Example



To do, or not to do... an EMT study?

This deserves careful consideration. The answer depends on:

- HR and study resources → *Who* will perform the analysis?
- Complexity of system and technical difficulty in analysis
- Availability of models (if you don't have them, don't do a study)
- Impact of consequences: What is the worst that could happen?

Consider:

- IBR ride-through impact (how many can you lose before you are *really* worried?)
- Historical observed oscillations or events
- Dramatic future changes to network
- Series capacitors or very large interconnections
- Very high IBR penetration

When not to do an EMT study?

Consider if:

- The risks can be evaluated in using a simpler method or in a simpler tool
- Inadequate resources (people, tools)
- Improperly scoped study – will consume valuable resources and not provide useful, actionable results
- Availability of models (if you don’t have them, don’t do a study)
- Results of the analysis would not impact decision-making

The answer may be “no” or “not this time”… because we don’t always need EMT!!

- But when we do need it, we need to have the tools, models, and expertise ready.
- EMT supplements and adds to our existing tools and processes. It generally doesn’t replace them.

Buckle up!!

Data Intake & Organization

EMT Model Intake

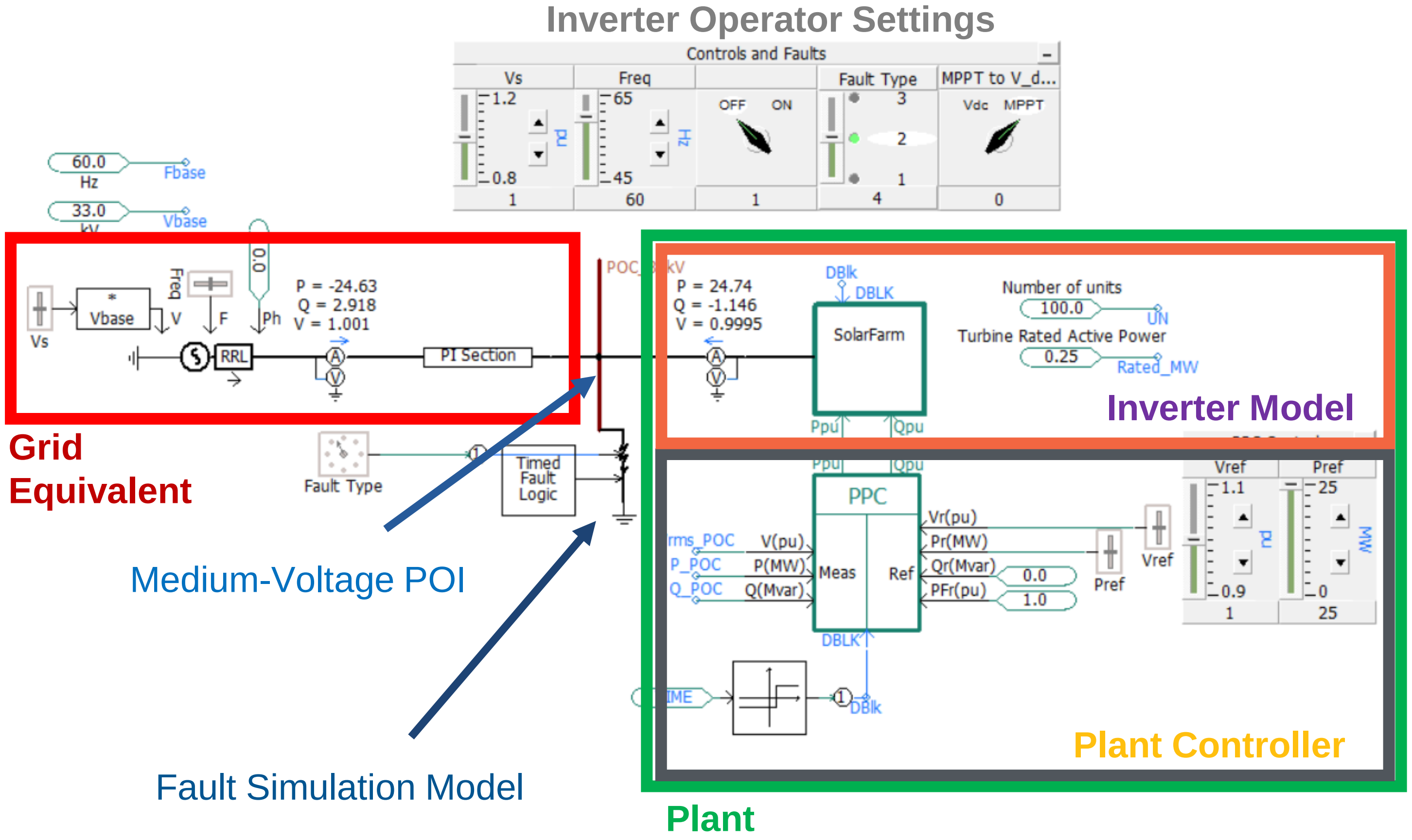
- Why collect and check EMT models?
  - Need models to do EMT studies!
  - Inaccurate models -> inaccurate studies (limited value)
  - Should be done before model used in studies
    - Discovering that a model is unusable during a study leads to delays
- Should you collect models for all plants, even if not under study?
  - Yes! Like buying insurance for when you need to include that plant in a future study
  - **Very** difficult to get accurate models for legacy plants

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

Typical EMT Plant Model Structure

- Different requirements seek to verify / exercise different parts plant response
- PSCAD's simple solar farm example
  - DC-AC inverter
  - Power plant controller (PPC)
  - PV Array
  - Boost converter
  - Scaling Component

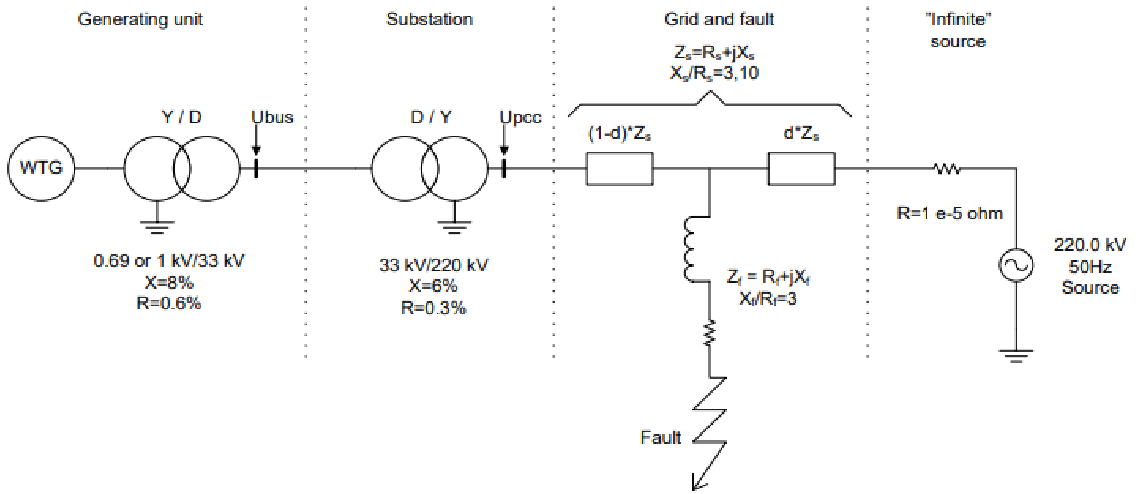


EMT Model Intake – Performance Testing

- Performance testing during model intake can be:
  - Variable voltage source behind Thevenin impedance (SMIB)
  - Voltage / frequency play-in tests
  - Plant with a few nearby buses modelled based on system data
- Publicly posting automated test-system and requiring test reports with model submissions is very efficient!
  - Less burden on testing for planners, just need to verify results
  - Projects under study can iterate plant design based on testing before submission

Figure 1 An example test circuit for model acceptance testing[20]

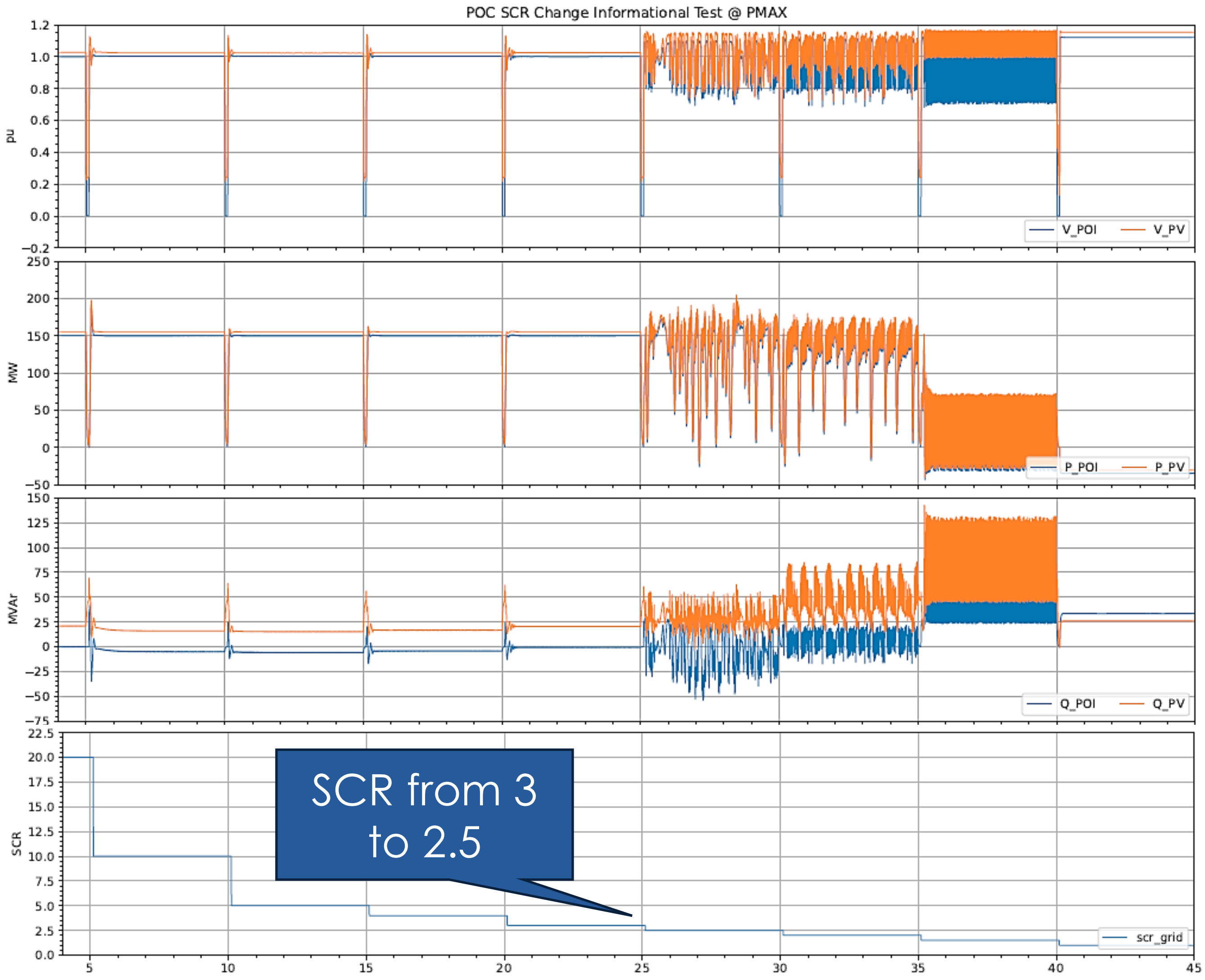
1. *Wind farm model acceptance set-up*



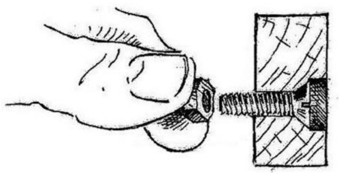
https://aemo.com.au/en/energy-systems/electricity/national-electricity-market-nem/participate-in-the-market/network-connections/modelling-requirements

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)



What do we need and when?



Interconnection Application → **Final Design Determined** → **Commissioning of IBR Plant** → **Lifetime of IBR Plant**

- Full plant model
- Reasonable plant design and equipment parameters (some aspects may be generic)
- Reasonable response to a generic equivalent grid
- Good model quality and initialization
- Model useful for preliminary interconnection study / design

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- Exact plant design and equipment parameters (nothing generic)
- Plant controller tuned gains for the specific interconnection
- Model useful for final interconnection study / design evaluation and operations studies

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- Post-commissioning model update (should be minor)
- Model updates as a result of post-event validation or settings change due to performance concerns
- Model maintenance as modelling state of the art changes

Resources / Examples

- Electranix Model Requirements
  - https://www.electranix.com/publication/technical-memo-pscad-requirements-v12/
- NERC Electromagnetic Transient Modeling for BPS-Connected Inverter-Based Resources— Recommended Model Requirements and Verification Practices
  - https://www.nerc.com/comm/RSTC_Reliability_Guidelines/Reliability_Guideline-EMT_Modeling_and_Simulations.pdf
- ERCOT Model Quality Requirements / Testing*
  - https://www.ercot.com/services/rq/re
- AEMO Dynamic Model Acceptance Test (DMAT)
  - https://aemo.com.au/-/media/files/electricity/nem/network_connections/model-acceptance-test-guideline-nov-2021.pdf?la=en&hash=3287CA490B21CE0634D954440940232E
- ATC Inverter-Based Resource PSCAD Model Verification*
  - https://www.atcllc.com/customer-engagement/
- Many other examples!

*Test networks are publicly posted

Data Organization

- 4+ iterations of a single plant model not uncommon from application to post-commissioning
- Documentation model updates (changes made, test reports, etc.) is important
- Code management and versioning tools (Github, SVN) can be leveraged
- Possible to store models in data repositories, models automatically "fetched" for studies

Model test Summary	
Model Test date:	
Reviewer	
Project Name:	
Interconnection Location:	
Rated Capacity at POC:	
Manufacturer:	
Equipment type: (eg. PV, Wind, BESS or Hybrid)	
Equipment version:	
Documentation files (OEM):	
Documentation files (site specific):	
Model Files supplied:	

Model Submission → Intake Process → Accepted Model → Prepare for Database → Database of tested, ready to use models → "Fetch" specific models for system studies

System Model Construction and Quality Assurance

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System Model Construction and Quality Assurance

Consider:

1. How big?
2. What detailed models to include?
3. How to construct the model?
4. Is it correct?

Keep in mind:

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

https://www.iso-ne.com/static-assets/documents/2020/04/new-england-geographic-diagram-transmission-planning.pdf

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…

Too Small

“Grey Zone”

Too Big

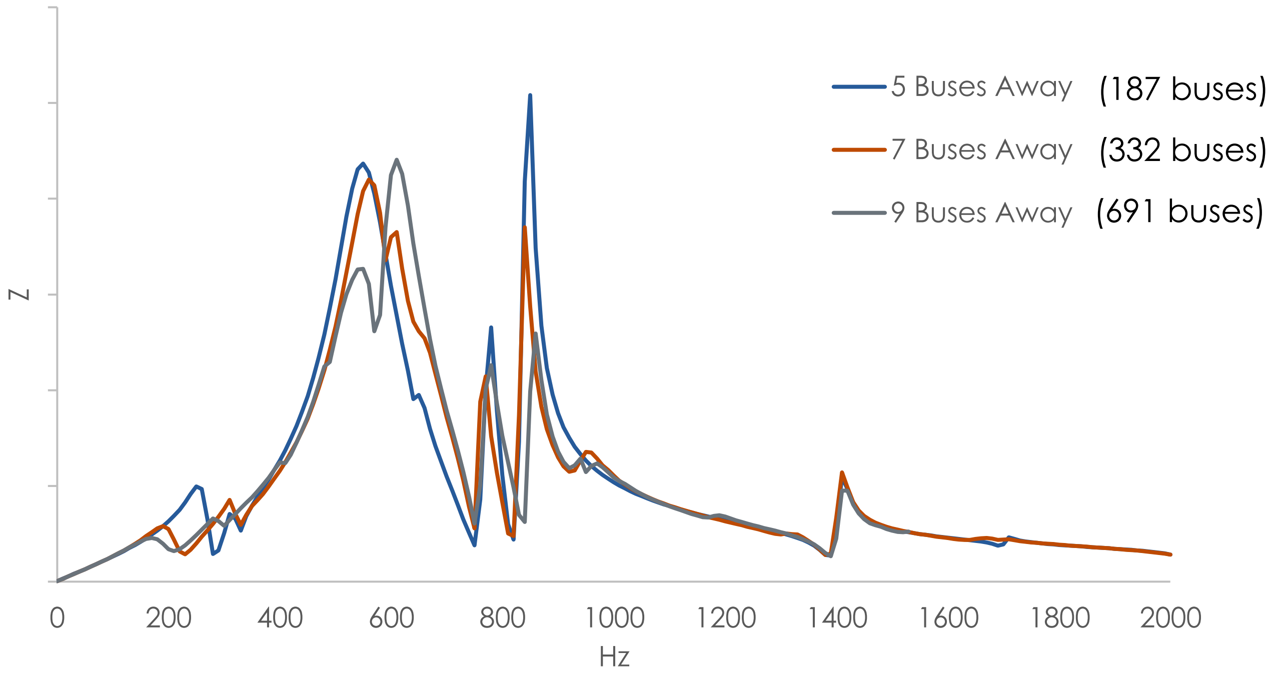
-Missing key device dynamics (machines, HVDC, etc.)
-Network Equivalents having outsized impact on dynamics
-Frequency response inadequate for phenomena of interest

-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

- The time domain response is related to the frequency response of the network
- When enough of the circuit is represented, the Network Equivalent is far enough away and will not affect the transient response
- Generally, shunt capacitors and long transmission lines dominate the electrical frequency response

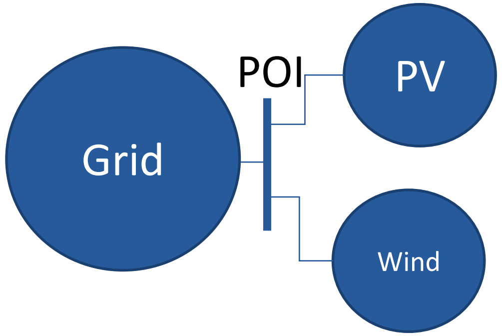


Detailed Models to Include: Nearby IBRs

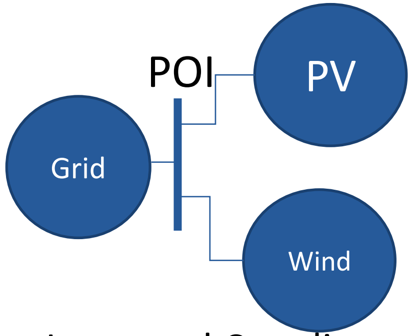
Synchronous Plants
Inverter-Based Plants

Impact of Nearby Inverter-Based Resources

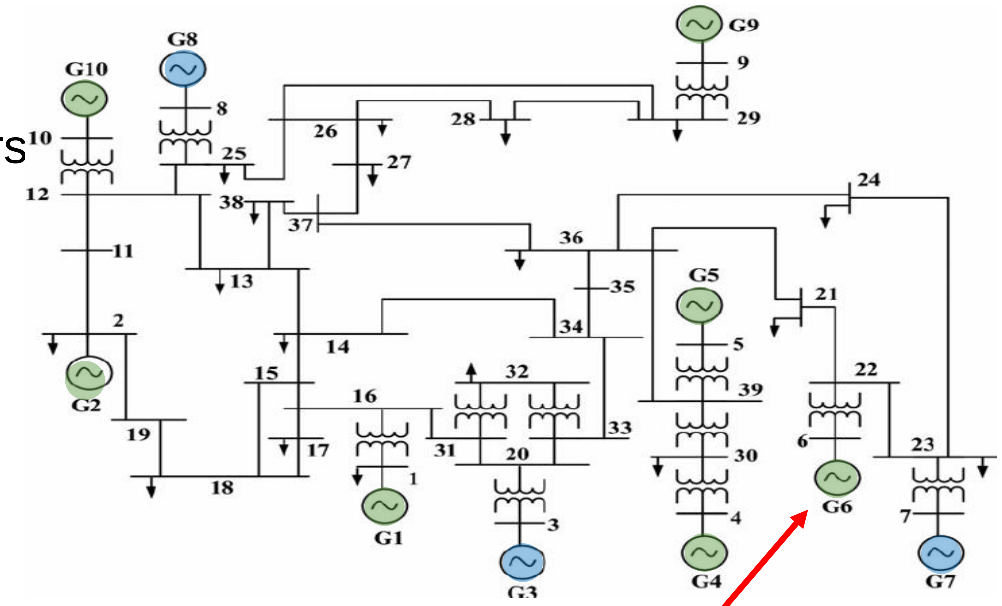
- Wind plants, solar plants, STATCOMs, SVCs, HVDC
- Interaction risk is strongly dependent on controls & tuning
- Screening methods are limited, but coupling between inverters (and risk of interaction) is stronger on weak grids
- Unable to assess interactions without EMT models



Reduced Coupling



Increased Coupling



If G6 is being evaluated, how many other inverter plants should be captured?

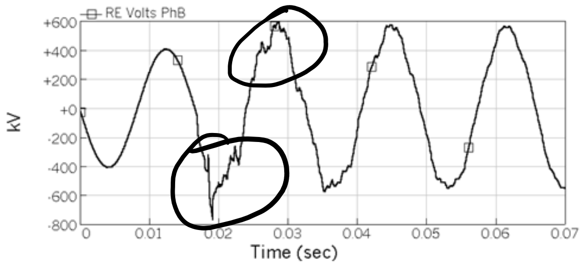
Technical References

- CIGRE "Connection of Wind Farms to Weak AC Networks" B4.62, Technical Brochure 671
- ERCOT Panhandle Renewable Energy Zone Study Report

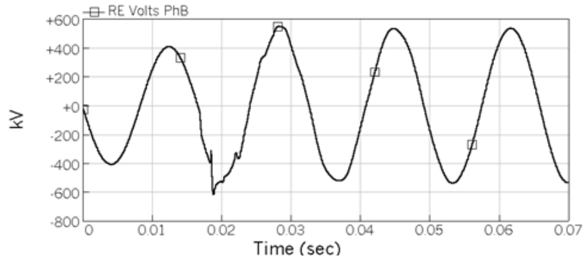
Detailed Models to Include

- “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
- Loads: ZIP vs CLOD / CMLD style vs non-generic
- non-IBR generation: standard library models

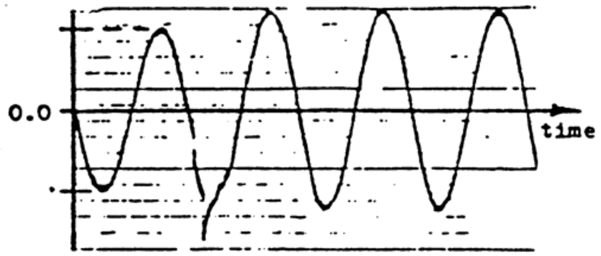
Bergeron model



Frequency dependent (phase) model



Field test measurement



Full System Model Construction

- Manually creating large EMT system models is challenging:
  - Data entry is time consuming and source of errors
  - Difficult to change extents of system
- Generally done with commercially available tools, either 3rd party or built into EMT software
- Two main approaches:

Method 1:

Combine pre-solved loadflow data with database of detailed models into an EMT model based on a subsystem of kept buses

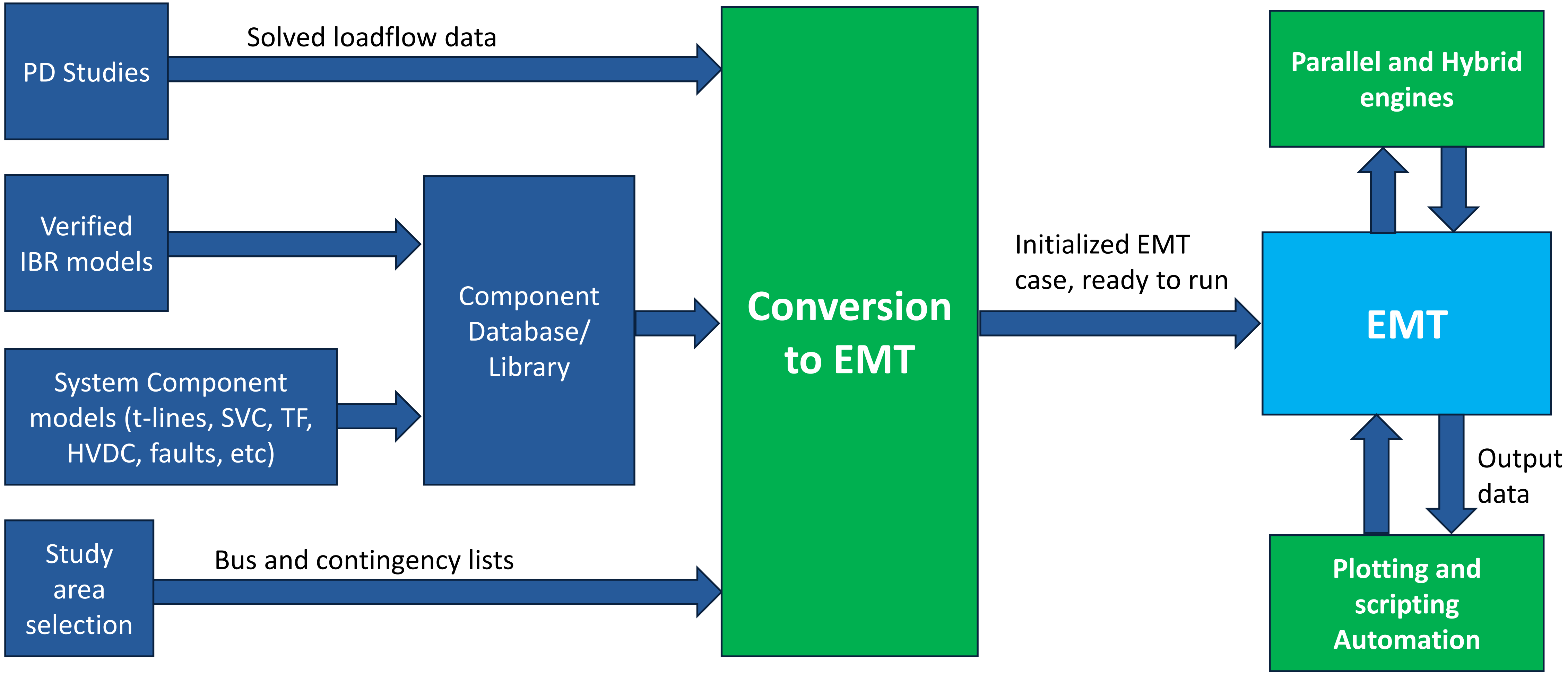
- Synchronize initial conditions with existing loadflow / transient stability study data
- Allows for flexible kept system selection / network equivalent creation

Method 2:

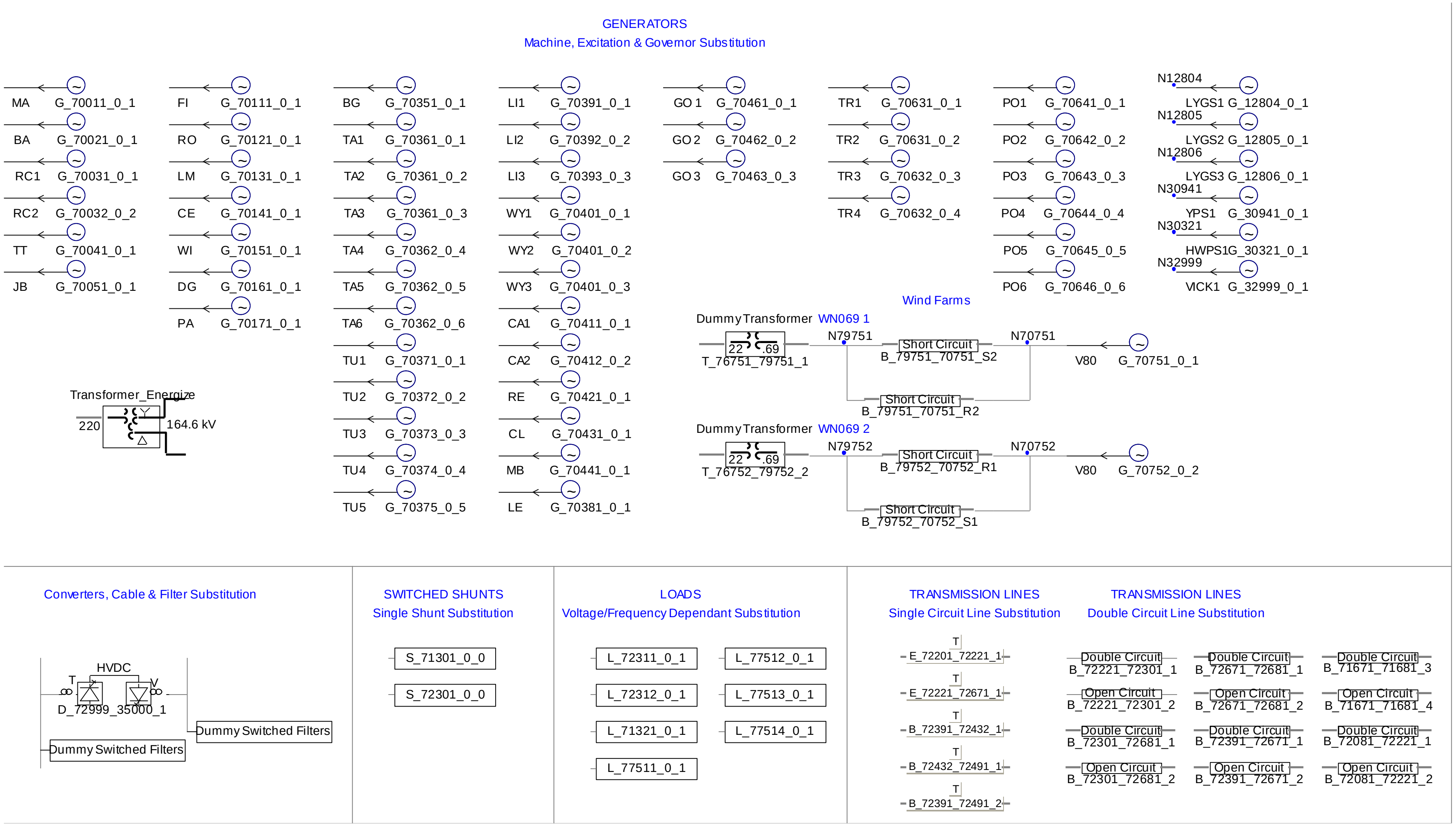
Utilize load-flow solvers within the EMT program to solve for initial conditions for detailed models

- May have limited flexibility in changing kept system limits
- May have discrepancies in initial conditions compared to existing loadflow / transient stability study data
- Allows for re-solving for new initial conditions within EMT without re-translating

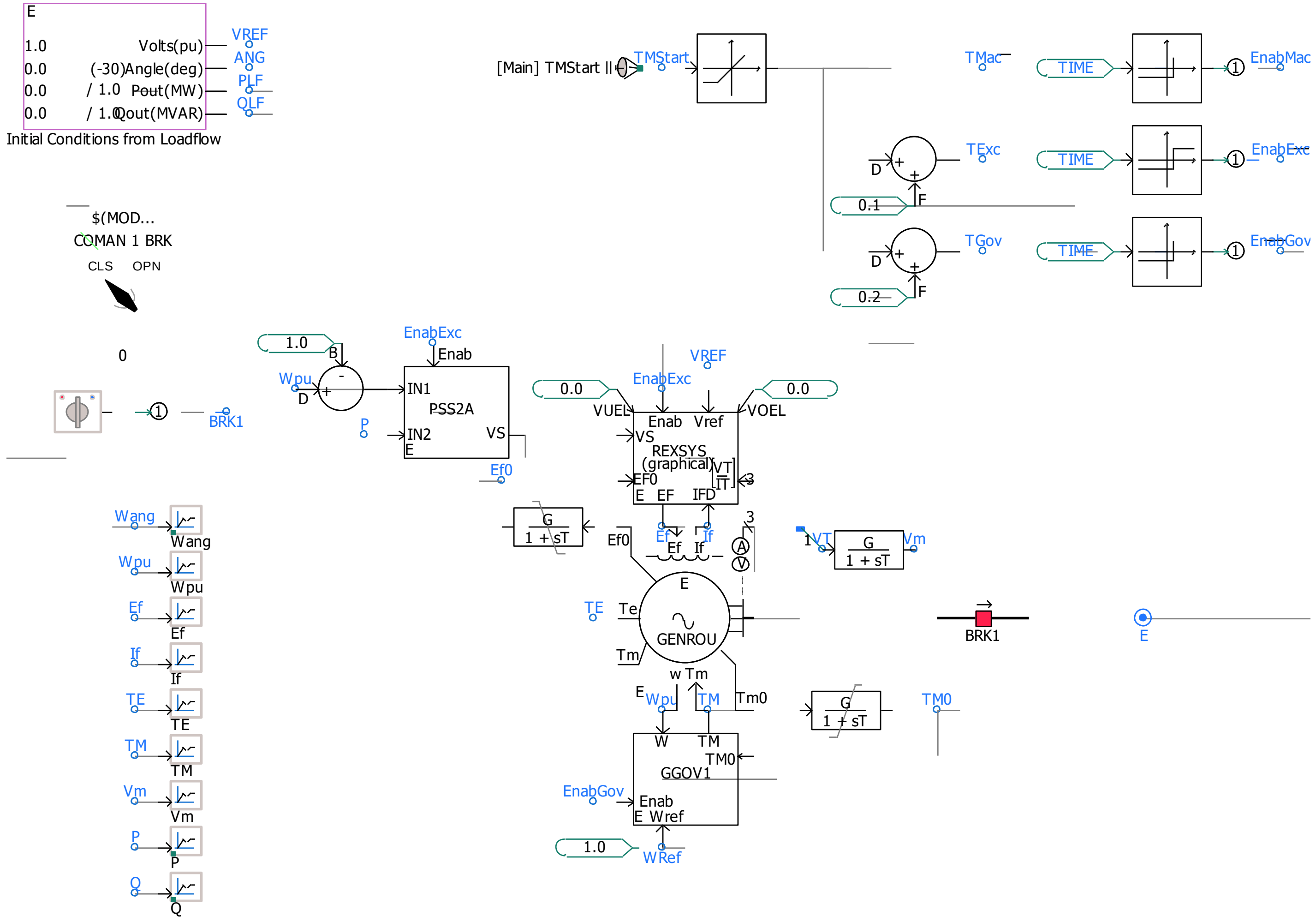
Full System Model Construction Example Process

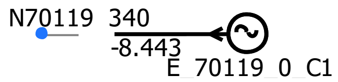


Full System Model Construction Database Example



Full System Model Construction
Generator Model Example



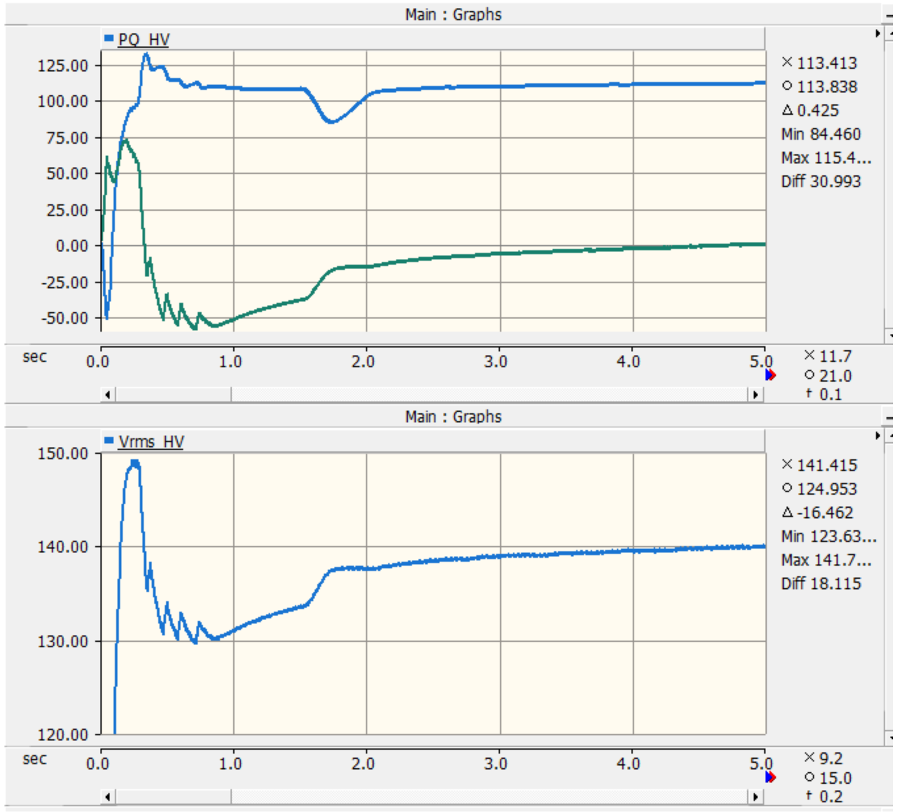


Note: all machines become swing buses during initialization!

Full System Model Construction
EMT Initialization Considerations

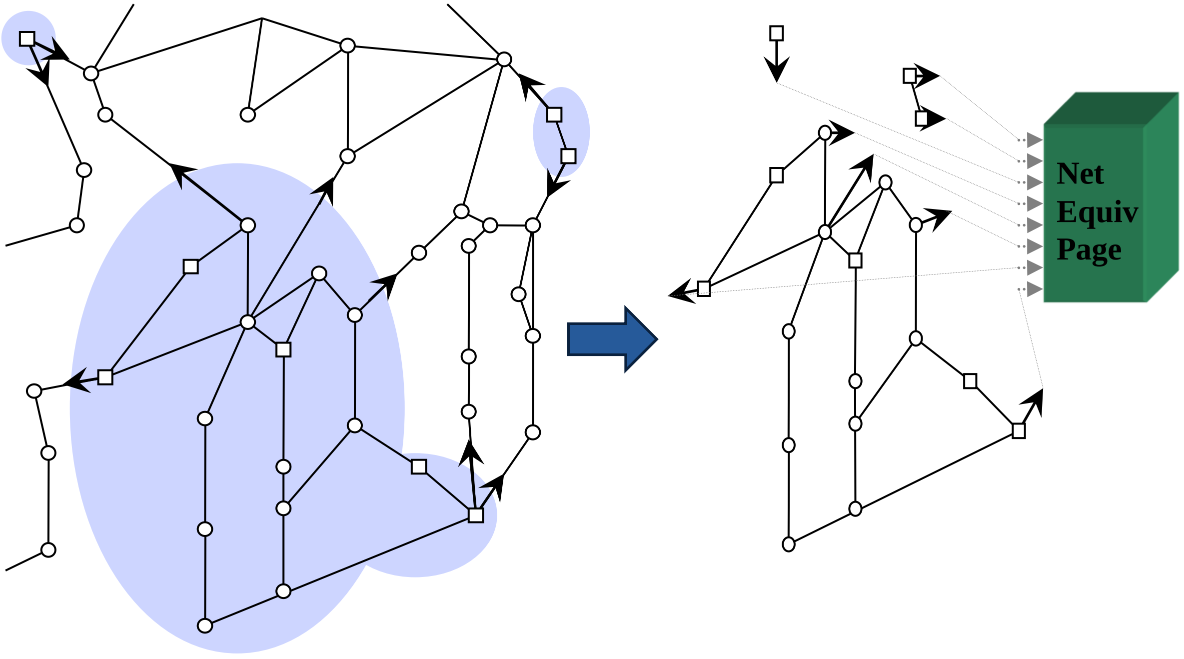
- Unlike RMS models, EMT models typically initialize from 0 voltage, 0 current
- It is important that models initialize quickly because they run slowly
- All models are expected to initialize within 5 – 10s of simulation time, even when regulators are intentionally slow
- Models are slowed most by switching (inverter) models
- Snapshots are possible but require all models to be compatible
- Careful back-calculating of state variables can help!

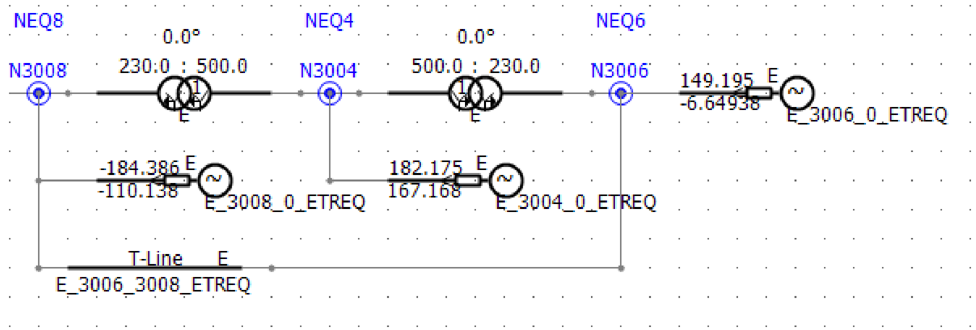
Model achieves a steady-state within 5 seconds

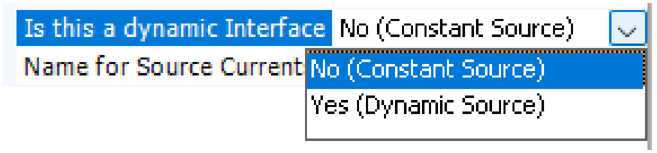


Full System Model Construction
External System Modelling

- External network typically modelled as NxN 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

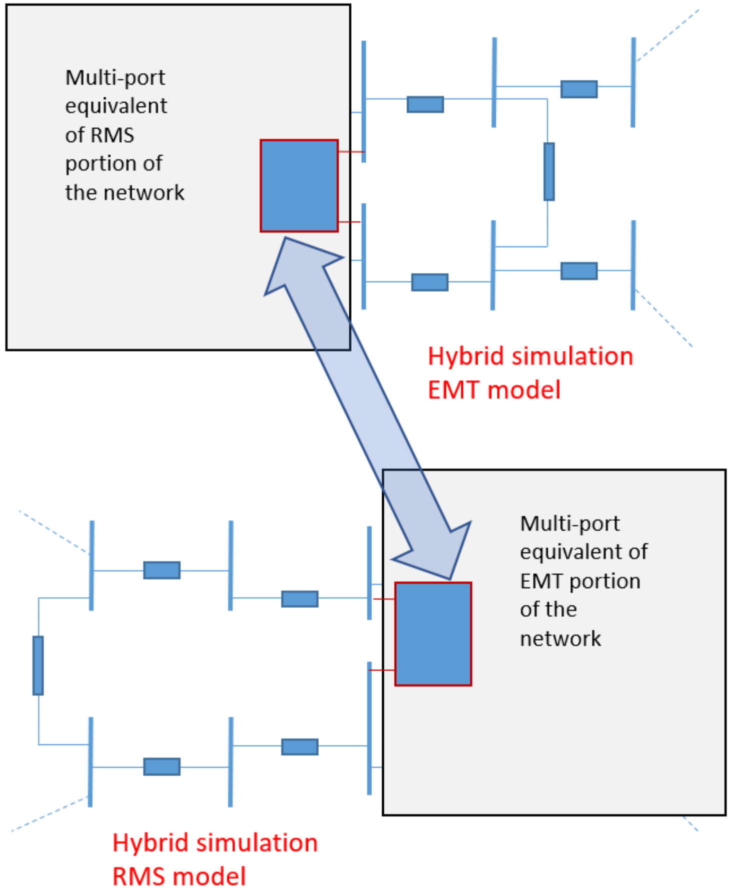






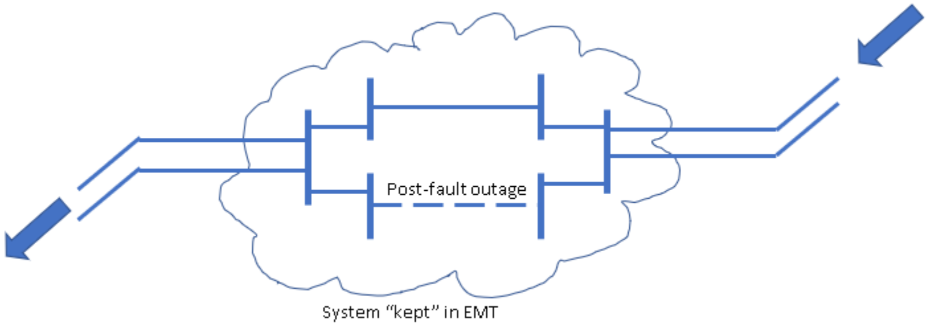
Hybrid / Co-simulation

- Simultaneous runs using both RMS and EMT simulation
  - Interface models on both sides, exchange of terminal information.
  - EMT models (to represent detailed wind/solar models, HVDC/facts devices, etc…).
  - RMS models (to represent the full AC system, including all modes of oscillation from nearby machines).



Hybrid / Co-simulation

- Typical use cases:
  1. High path flows through study area. Post contingency angles (and therefore powerflow) will be wrong at the boundaries with fixed source equivalents
  2. Inter-area machine dynamics. Areas swinging against each other will not be represented with fixed source boundary equivalents
  3. Uncertainty. What don’t I know? How do I get the very best warm fuzzy feeling about my study accuracy?

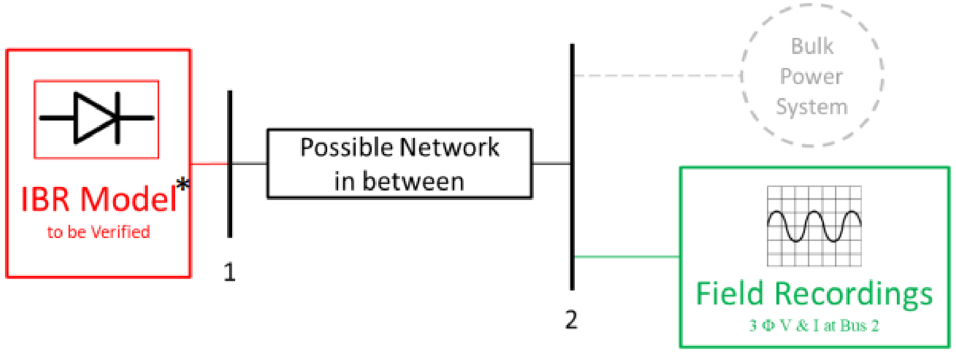


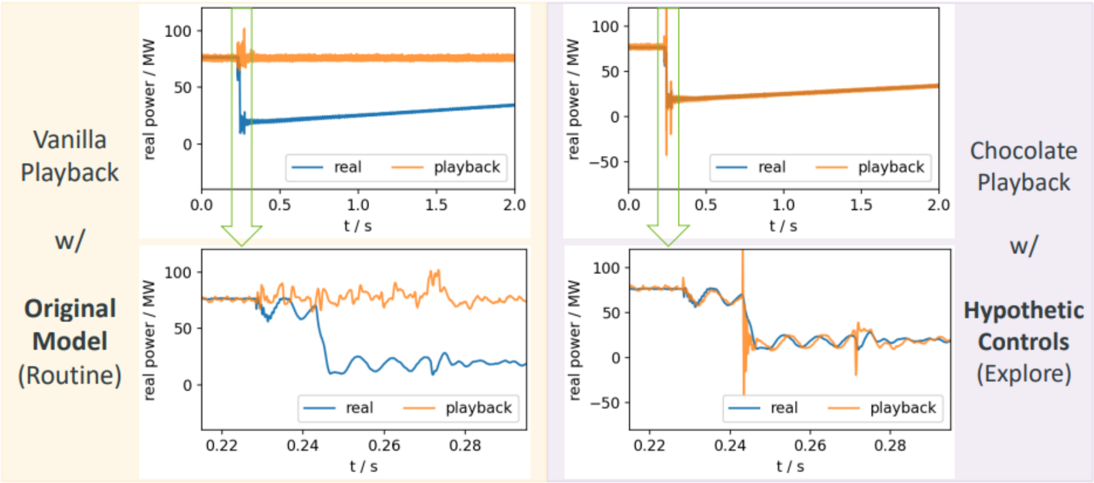
Full System Model Construction Checking Accuracy

- 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

Post-Commissioning Model Validation is in Early Stage

- High resolution data recording on site is normally not required or may not be set appropriately to capture the events of interest
- Even if recorded, event data is at the site and may be overwritten
- IEEE 2800 data recording and retention requirements and IEEE P2800.2 proposes a procedure for capturing data and performing phasor domain and EMT model validation
- ERCOT developed a proposal (NOGRR255) for data recording and retention aligned with IEEE 2800, Table 19.
- At NERC IRPS and IEEE PES GM, ISO-NE has presented an example of an EMT model validation of a PV plant.





Source: [Qiang "Frankie" Zhang, "IBR Model Verification at ISO-NE Using Playback Method", NERC IRPS Meeting, June 2023]

Simulations

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Contingency Scoping

- Key question for any engineering task… "What question are you trying to answer?"
- Almost as important, "What are you *not* looking for?"
- A *minimal* set of scenarios and contingencies must be chosen to answer your question, leveraging other knowledge and studies as much as possible (Transient Stability isn't dead!). This is an uncomfortable process and requires experience and collaboration!
- Screening studies can be useful to reduce case lists

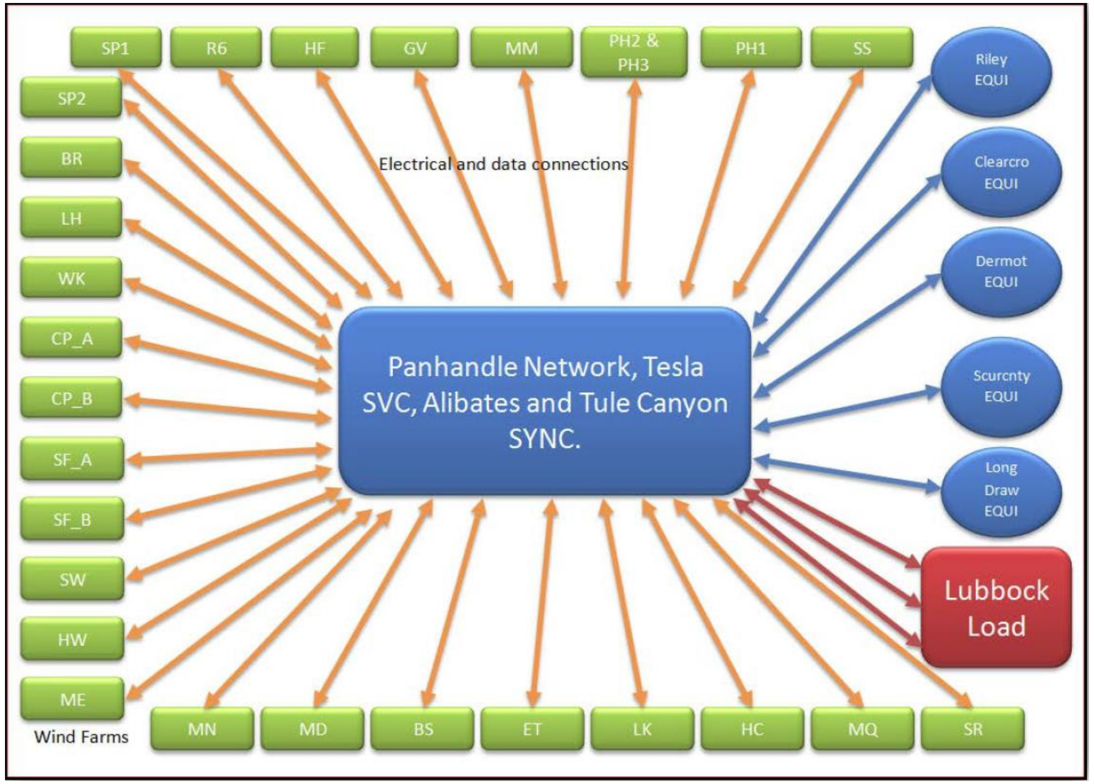
Contingency Scoping

- Use PD studies to help select
  - Marginal results, criteria violations, unsolved cases
- Consider that light load vs. heavy load is not easy to generalize which is worse. Light load may produce high voltages and low thermal conditions, but heavy load may exacerbate flows (or reduce local flows!)
- N-x to cause IBR heavy regions or interconnections to be disconnected from sources of strength, or cause high flows.
- Radial to series caps is very bad
- Contingencies which cause regional high voltage can cause FRT failure if transients are added in.

Simulation Speed

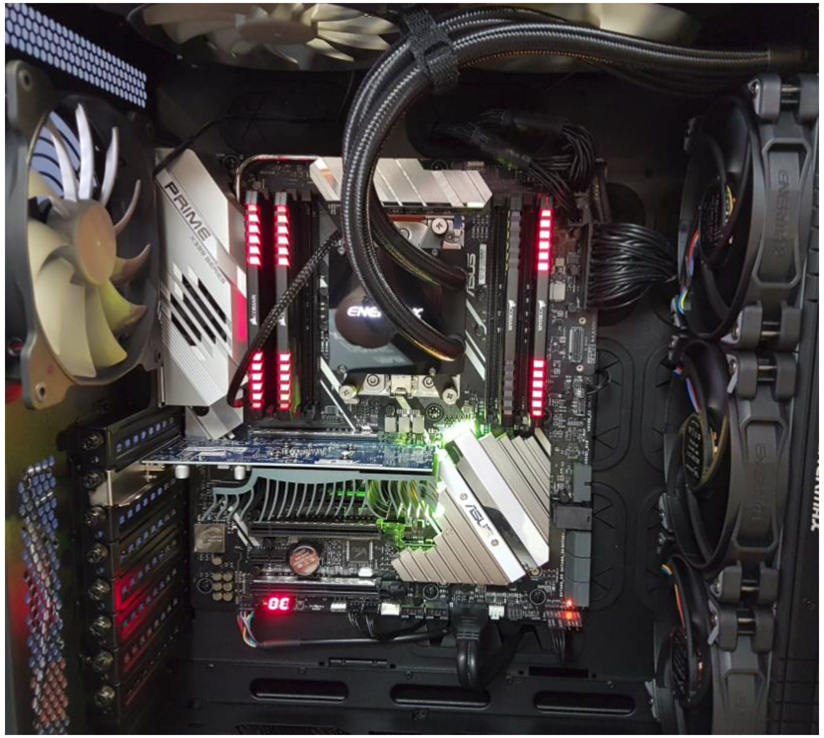
- EMT simulations run much slower than transient stability simulations (e.g. >1 hour per 10s of simulation for medium sized system)
  - Small timestep
  - Switching models (interpolation)
  - Complex models
- Speed can be increased by:
  - Segmenting big case into multiple smaller cases using parallel-computing
    - Port communication “overhead”
    - Hardware-limited
  - Average sources vs switching models
  - Snapshots
  - Larger timestep
  - Reduce system size (last resort)

Parallel Simulation Example



Hardware

- If using parallel computing, increasing # of cases beyond number of physical cores may result in overall speed reduction
- High core-count machines such as AMD Threadrippers better suited for highly parallelized cases than lower core-count machines even if they have faster single core performance
- Electranix Approach: multiple Threadrippers with highest commercially available core-count shared between all study engineers. Latest machine (TR9!) is 96 cores, up to 5.3 GHz
- Liquid cooling
- Lots of high-quality RAM



Analysis and Actions/Mitigations

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Time-Series Data Output

(Free image from Pexels, courtesy of Mike Bird)
https://www.pexels.com/photo/a-tractor-carrying-a-stack-of-hay-12973212/

Results Processing Considerations

Output is Massive

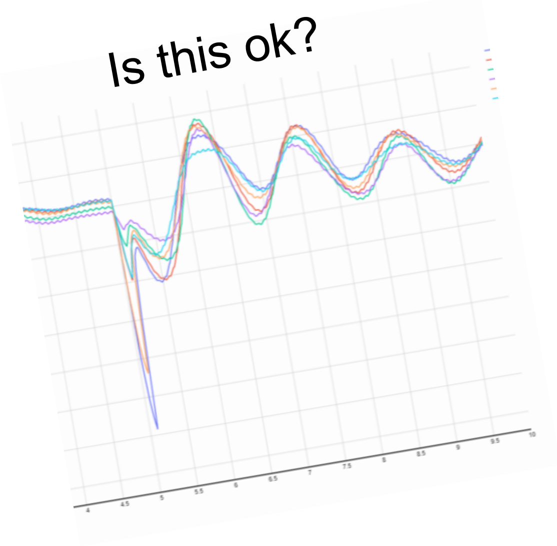
- Data output rises exponentially with the number of plants
  - More contingencies
  - More operating conditions
  - More channels / signals
- Thousands of files, 10s – 100s+ of GB

What do you look for?

- Lots of dynamics will be captured in EMT simulations
- Not all of them are problems, which ones are?
- What was the original concern driving the study?
- Is your “aperture” wide enough to pick up problems that you didn’t anticipate?

Where do you look?

- Which signals do you look at? RMS or phase quantities?
- What additional signal processing is warranted? Phase domain, dq0 domain, sequence domain, frequency domain?
- Is the time-resolution of your output sufficient?



https://www.pexels.com/photo/cat-lying-beside-a-puppy-8570243/

What do you look for? And how?

Possible issues:

- Ride-through failure, momentary cessation
- Voltage recovery and stability
- Very high or extended transient voltages
- High or low steady state voltages
- Undamped oscillations in P, Q, V
- Harmonic content
- Loss of synchronism or slipped poles

Where do you look?

- Which signals do you look at?
- Are you capturing the signals at sufficient resolution? Do you have enough storage?
- What additional signal processing is warranted? Phase domain, dq0 domain, sequence domain, frequency domain, etc.?

A High-Level View

Results screening tools (like the one below) help to quickly home in on the problematic cases

	WF1	WF2	WF3	WF4	WF5	WF6	WF7	WF8	WF9	WF10	WF11	WF12	WF13	WF14	WF15	WF16	WF17	WF18	WF19	WF20	WF21	WF22	WF24	WF27	WF28
Fault 1																									
Fault 2																									
Fault 3																									
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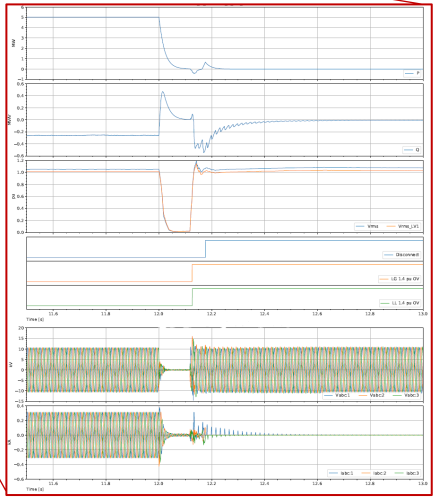


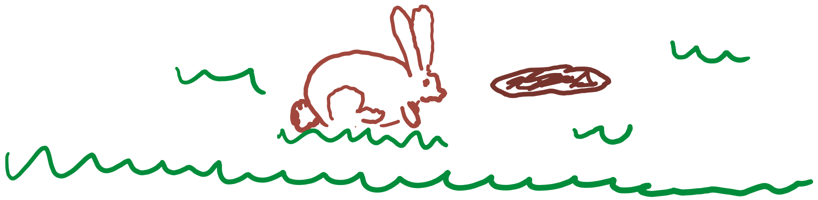
Cast a side net, sensitive, automated → Focused, engineering judgment

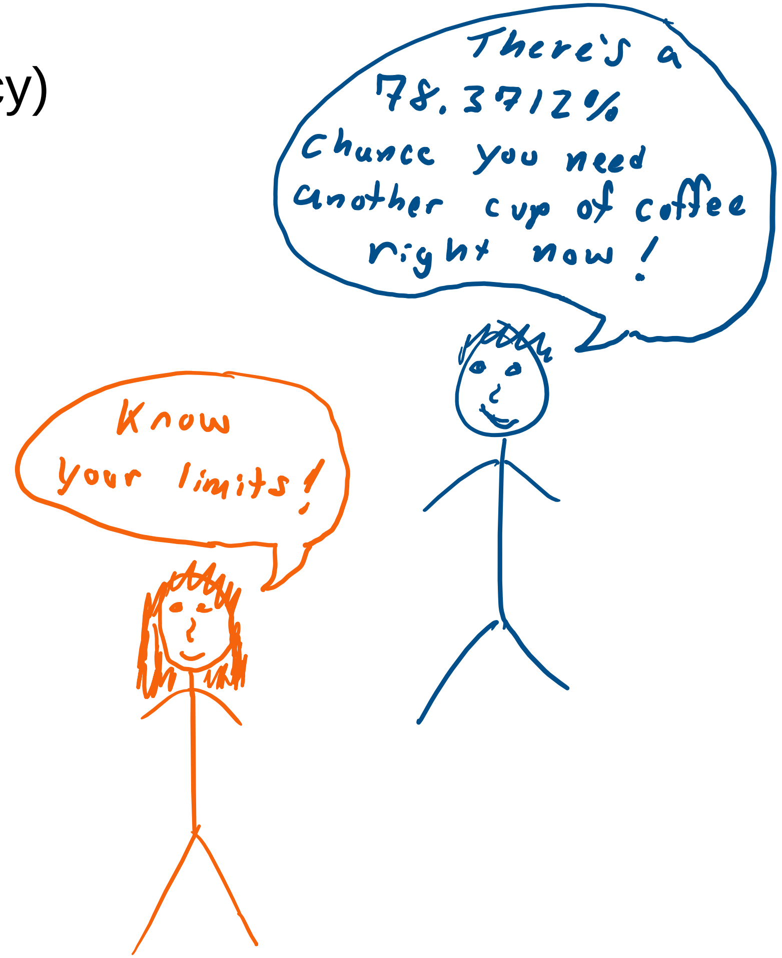
Model Fidelity & Robustness

Remember: Detail does not mean accuracy (False Precision Fallacy)

- What phenomena are occurring?
- What is the cause?
- What assumptions may be at play?
- Are those assumptions still valid?

Answering these with confidence can become a rabbit hole of sensitivity analysis :/





Need for EMT Model Validation

An Example from ERCOT:

Generation Interconnection	QSA**	Commissioning	Operations
• Provide PSS/e model • PSS/e model quality tests • PSCAD model and tests request may be triggered at this stage*	• PSCAD model and quality tests • PSCAD model validation • Benchmark PSS/e↔PSCAD using model quality tests onwards	• Verification of key settings of PSCAD models • Model quality tests (PSS/e and PSCAD) are required for any model or setting changes during Commissioning	• Keep dynamic models up to date • Verification of key settings within 2 years and every 10 years • For changes to settings, model quality tests and verification are required

Is the model:

- **Accurate**
- **Usable**
- **Site-Specific**
- **Performance** conforms with interconnection requirements?

→ Resource Owners are Responsible

* If SSR or others EMT studies are deemed necessary in the interconnection process
** QSA: Quarterly Stability Assessment

Source: Xiaoyu (Shawn) Wang, "EMT Modeling and Studies in ERCOT", ESIG Fall Technical Workshop, 2021

Mitigation Hierarchy

Highly Application-Dependent

- Some mitigations may not be effective or create additional challenges
- Combinations of mitigations may be effective or necessary

Inverter Controls: Custom engineering

Operations: Remedial action schemes (RAS)

Transformer Design: Impedance reduction

STATCOM or SVC: Improved power transfer

Synchronous Condenser: Grid “stiffening”

Transmission Line Design:
Line length
Phase layout
Parallel circuits
Operating voltage

Lower Costs — Higher Costs

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Achieving a Balance

- Very important to keep focused on answering “The Question”, and not to let details derail the entire study.
- Reporting must have layers of detail, with very clear summary and recommendations.
- Lots of engineering judgement is required, and a clear understanding of the limitations of the state of the art… engineers want to be perfectionists, but we have to keep our balance.

Next: EMT Software Tools

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