PSCC 2026 Tutorial: Modeling, Control, Stability Analysis and Simulation of Low-Inertia Power Systems

Insights from Practice: How to conduct large-scale dynamic simulations of low-inertia power systems?

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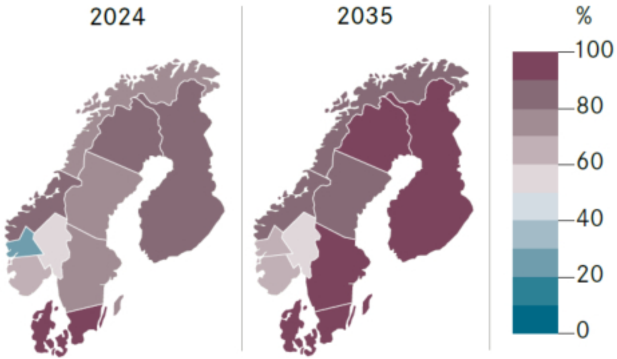
June 8, 2026

The Complexity Cliff: Modeling Complexity rises with CIDER Penetration!

Maximum Converter-Interfaced Generation Shares
per Zone in the Nordic Synchronous Area



Source: Svenska Kraftnät, Energinet, Finrgid, Statnett: Nordic Grid Development Perspective 2025, June 2025

With high CIDER-penetrations:

- **Predominantly converter-interfaced generation in Transmission Networks** (TNs)
- **Significant converter-interfaced generation in Distribution Networks** (DNs)

» We may need to model a **large number of converter-interfaced resources** at transmission level and **include the distribution layer**!

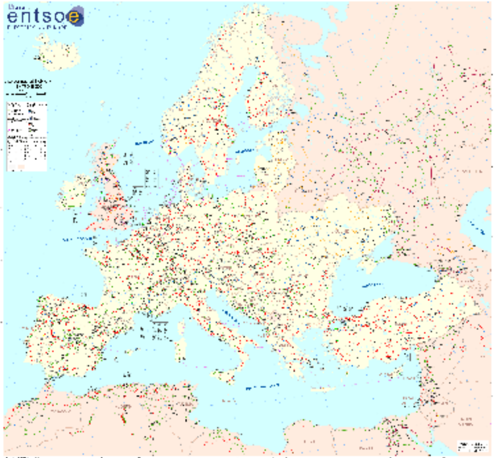
Traditionally, **DSOs lack dynamic models** of their systems:

- Potentially power flow models available
- Confidentiality, GDPR, and data quantity make **data collection and management an enormous challenge**

CIDER: Converter-Interfaced Distributed Energy Resources, DN: Distribution Network, TN: Transmission Network

Building System Level Dynamic Studies: Modeling an Entire Continent

Goal: Develop a dynamic model to study **global phenomena (system inertia, frequency containment reserve, inter-area oscillations)** in the **interconnected power system of continental Europe** [1]



Source: entsoe.eu

verified load-flow model

standard dynamic models

frequency measurement of a system event

Assign standard models by technology type

- P > 250 MW: assign SM model, governor (TGOV1), AVR (SEXS) and PSS (PSS2A) models to generator
- otherwise: model generator as negative constant impedance

Parameter Tuning and verification across simulation tools

Final model:
Out of 10 829 generators, 1 013 SMs with all controls

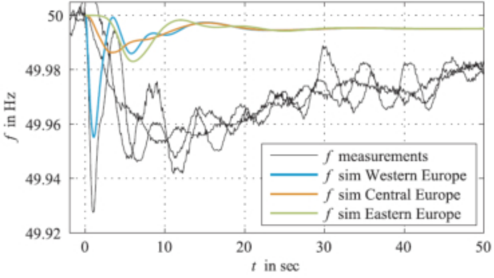
Inspired and informed by A.Semerov et al., 2015

[1] presented in: A. Semerow, "Dynamic Study Model for the Interconnected Power System of Continental Europe in Different Simulation Tools“, 2015 IEEE PowerTech, doi.org/10.1109/PTC.2015.7232578

Building System Level Dynamic Studies: Tuning an Entire Continent

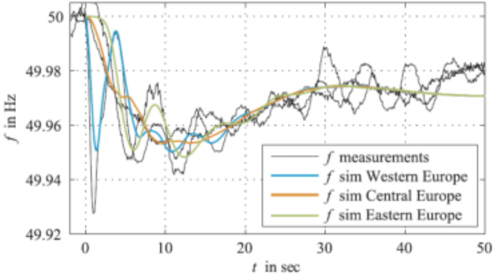
Element	Model	Variable Parameters	Observable Impact
Synchronous Machine	SM	Acceleration time constant T_A	System inertia, observable RoCoF
Governor	TGOV 1	Droop R Time constants T_{G2}, T_{G3}	Frequency reserve, steady-state frequency deviation
Automatic voltage regulator	SEXS	Gain K	Voltage regulation stiffness, reactive power response
Power system stabilizer	PSS2A	Gain K_{S1}	Oscillation damping

Standard Parameters vs. Event Recording



Source: A. Semerov et al., 2015

Tuned Parameters vs. Event Recording



Source: A. Semerov et al., 2015

RoCoF: Rate-of-Change-of-Frequency, SM: Synchronous Machine

Let's go Step by Step!

Phase 1:

Scoping the Test Case and Research Question

- Which phenomena do we observe or are concerned with?
- What are our desired study outcomes?

One-Way Dependency

The choice of phenomena to consider is the **most consequential decision** in the entire workflow.

Study Phenomenon
e.g. concerns on converter-driven interactions

→

Required Time-Scales
e.g. sub-cycle $\mu s - ms$

→

Model Detail
e.g. full EMT switching dynamics converter controls

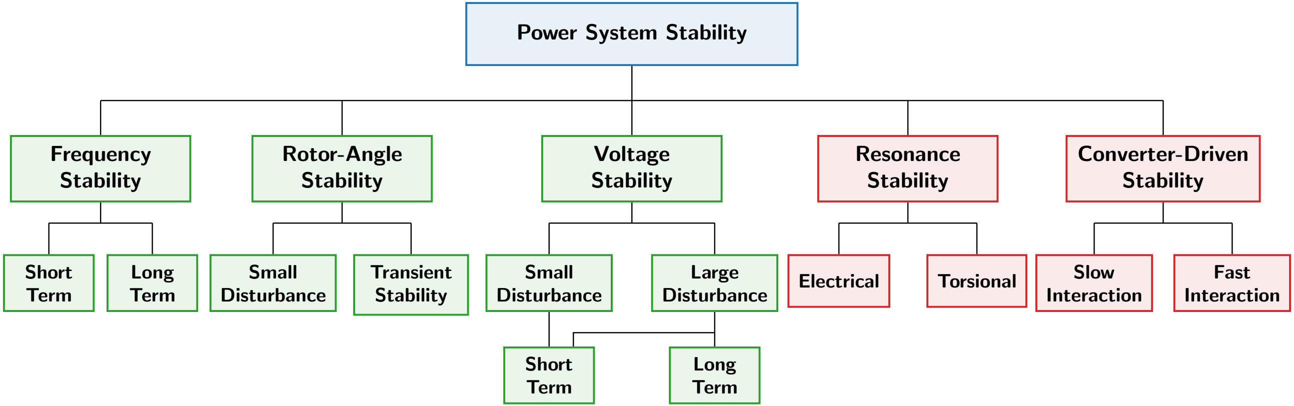
→

Simulator Type
e.g. EMT (RMS not suitable)

Considerations for reaching a decision:

- System characteristics, observed stability issues, or stability concerns
- Which insights should results provide?
- Ideally, define **a research hypothesis or question** that relates to specific stability classes and time-scales.

Stability Classes Revisited for CIDER-Dominated Systems



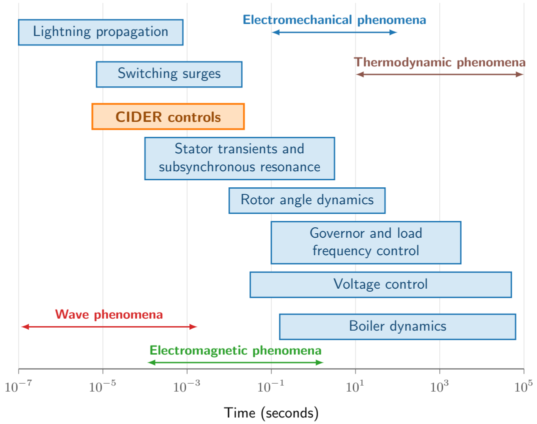
Traditional Stability Classes
phenomena impacted by converter-interfaced resources

Added Stability Classes
phenomena caused by converter-interfaced resources

Based on Hatziargyriou et al., *IEEE Trans. Power Syst.*, 2021, 10.1109/TPWRS.2020.3041774

CIDER: Converter-Interfaced Distributed Energy Resources

Relation of Time-Scales to Stability Phenomena



Based on J.D. Lara, et.al. , *IEEE Trans. Power Syst.,2024,* *10.1109/TPWRS.2023.3303291*

In CIDER-dominated systems, we need to identify:

- **relevant controllers and corresponding time-scales**
- power system phenomena related to the control time-scales of interest

Example: Voltage Control

- **Traditionally consider**: synchronous machines, over-excitation limiters, tap changers, SVCs, Statcoms, capacitor and reactor banks, (simple) load dynamics
- Typical time-scales: ranges from **sub-second to minutes**
- If **CIDER support voltage control need to consider their voltage control dynamics**

» We need to **model faster time-scales**.

CIDER: Converter-Interfaced Distributed Energy Resources, SVC: Static VAR Compensator

Phase 1:

Scoping the Test Case

Phase 2:

Choosing a Time-Domain Simulator

- Which time-scales to consider?
- How to choose a simulator?

Time-Domain Simulation Methods for Power Systems

Slower phenomena · Less detail · Larger scale ⟷ **Faster phenomena · More detail · Smaller scale**

	Phasor Domain (RMS)	Dynamic Phasors	Hybrid (RMS + EMT)	EMT (average-value)	EMT (switching-level)
Typical time step	**∼5–20 ms**	**∼0.1–5 ms**	**Mixed modeling**	**∼10–100 μs**	**∼ 1 μs**
What it captures	Electromechanical dynamics (frequency, rotor angle, voltage)	Subsynchronous phenomena, harmonic interactions, converter-driven slow dynamics	Fast phenomena in EMT zone, slow elsewhere	Converter-driven fast dynamics, resonances, control interactions	Switching, harmonics, electromagnetic interactions
Limitations Challenges	Blind to resonance phenomena	Bandwidth selection non-trivial	Interface approximations, EMT zone definition	Scale limitations few hundred buses	Scale limitations few converters
Example simulators	PowerFactory, PSSE, STEPSS, Dynawo, Sienna/Dyn	DPsim, Modelica	PowerFactory, PSCAD, Simulink, Sienna/Dyn	PSCAD, PowerFactory, EMTP	PSCAD, Simulink, EMTP

How to choose a simulation tool?

With your defined research question, consider the following:

- **Phenomena Coverage** (non-negotiable!)
  Does the tool capture the **time-scales** and **physical phenomena** you need?
- **Automation and Scripting**
  Can you run large studies **programmatically**?
  Are APIs or command line interfaces available?
- **Extensibility**
  Can you **add or customize models** and implement new control strategies?
- **Computational Scalability**
  How does **runtime** scale with system size?
  Does the tool support **parallelization**?
- **Practicality and Familiarity**
  Consider cost, support, learning curve **and** team experience.
  Who can support you in case of questions?

Trade-Offs are likely inevitable!
Scalability ↔ Phenomena Coverage ↔ Desired System Detail ↔ System Size
I highly recommend spending some time to test and choose!

Introduction to STEPSS (RMS-Domain Simulations)

STEPSS: Static and Transient Electric Power Systems Simulation

- **PFC**: Power flow computation
- **RAMSES**: RApid Multiprocessor Simulation of Electric power Systems
  Fortran-based, **with a Python interface**
- **Codegen**: Coge generator that translates user-defined models from block-diagrams to Fortran

Want to use STEPSS?

- Documentation, test cases, models, tutorials available here: https://stepss.sps-lab.org/
- Free to use up to 1000 buses, 2 cores
- **Full version available for research**, reach out to stepps@sps-lab.org
- In doubt? Just reach out.

Example Code for Generator Outage:

```python
import pyramses
# --- Conduct Simulation ---
case = pyramses.cfg("cmd.txt")
# --- Store results ---
case.addTrj("out.trj")
case.addOut("output.trace")
# --- Execute initial step ---
ram.execSim(case, 0)
# Trip generator (500 MW)
ram.addDisturb(0.5, "BREAKER SYNC_MACH SM35G1 0")
# --- Run simulation ---
try:
    ret = ram.contSim(20)
    ram.endSim()
except:
    print(ram.getLastErr())
```

Why do I like it?

- **I managed to run >18 000 converters for 20 s in a ~ 5 minutes runtime!**
- It is a completely **code- and file-based** simulator that allows control of many variables.

Phase 1:

Scoping the Test Case

Phase 2:

Choosing a Simulator

Introduction to Two System-Level Modeling Attempts

Applying the Workflow to Real Test Cases

Example 1: Danish Island

Source: DTU

Key Concerns

- Will the **island survive islanding**?
- How can the system be **restarted** in case of a **blackout**?
- 100% Renewable generation target, vicinity to offshore wind parks

Phase 1: Scoping the Test Case

- Focus on 60 kV system stability
- Identified **phenomena** of interest: **small-signal** stability, **converter-driven** and **resonance** stability during **islanding and black-start** under 100% renewable generation
- Requires **EMT simulations**

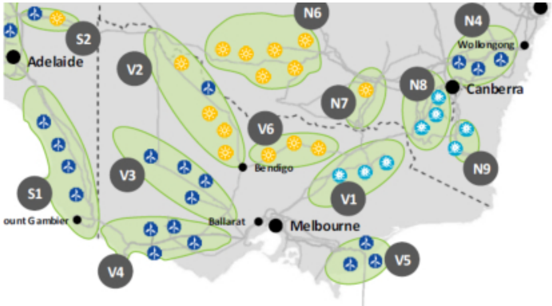
Phase 2: Selection of the Simulator

- ✔ Power-Flow model available in PowerFactory
- ⟳ RMS model in PowerFactory
- ⟳ EMT model in PSCAD (familiarity of our team)

The system is a **candidate** for the ongoing **IEEE Task Force on Benchmark Networks for Low Inertia Systems** - Stay tuned.

Example 2: Victoria (Australia)

VIC



Source: AEMO

Key Concerns for Study

- How much can **distributed resources** in Victoria support the system-level **frequency response**?
- Can they be **as effective as large batteries**?

Phase 1: Scoping of the Test Case

- Focus on short-term **frequency stability**
- Consider **location of distributed resources in the distribution system**
- » Develop dynamic model capturing transmission and distribution networks

Phase 2: Selection of the Simulator

- Use average-models for converter-interfaced resources
- Distribution layer resources prevent EMT-level studies
- **RMS studies with STEPSS:** experience with simulator, contact to Petros Aristidou

Modeling completed, details in:

- J. Vorwerk et al., EPSR 2024, 10.3929/ethz-b-000682585
- J. Vorwerk, PhD Thesis, 2023, DOI:10.3929/ethz-b-000643071
- github.com/vorjo/VICSystem

Phase 1:

Scoping the Test Case

→

Phase 2:

Choosing a Simulator

→

Phase 3:

Initializing your Dynamic Model: Steady-State Model

- Which operating points to study?
- How to build a power flow model if it does not exist?

Potential Data Sources and their Limitations

TSO Data

- ✓ Transmission topology, branch data, large generators
- ✓ Expansion planning results enable scenario development
- ✗ No distribution network data

» **Best starting point**

DSO Data

- ✓ MV/LV structure and load profiles
- ✓ Models can contain errors and discrepancies
- ✗ Data-sharing and GDPR limitations

» **Use model structure as a template**

Market/ SCADA

- ✓ Real dispatch and historical profiles
- ✓ Historical snapshots
- ✗ Selection of scenarios can be challenging

» **Good for dispatch validation and realistic scenario selection**

PMU Measurements

- ✓ Voltage and current phasor measurements
- ✗ Sparse coverage, limited access

» **Good for validation**

Manufacturer Data

- ✓ Component parameters, control and protection info
- ✗ Often incomplete or confidential

» **Ask for specific parameters**

Satellite Info

- ✓ Installed capacity estimates e.g. per post-code
- ✗ No electrical behavior info

» **Distribution of capacity estimates**

No single data source is sufficient → modeling requires combining incomplete and inconsistent information

Phase 1: Scoping the Test Case → Phase 2: Choosing a Simulator → **Phase 3: Steady-State Model**

Phase 3: VIC Test Case

VIC Test Case: Data Sources and Assumptions

Available Data

AEMO 2020 ISP - Step Change Scenario
Generation mix targets for 2025, renewable energy zones, interconnector augmentation, load forecasts

VIC Transmission Network
Bus and line parameters, generation capacities, expanded for 2025, Link to ISP 2020 Database

AEMO Single-Line Diagram
Location of voltage-controllable devices, tap changers, shunt compensation, used for voltage control placement

Optimal Energy Dispatch, 5 Representative Days
DC-OPF solution, TN level only Provided by collaborators.

Saedi et al., *Applied Energy, 2021* 10.1016/j.apenergy.2021.117598

Real 22 kV Australian DN (one feeder)
Provided by DSO, 93 nodes, 12 MVA hosting capacity

Missing Data - Assumptions Required

Reactive Power Consumption
Assumed $\varphi = 0.98$ for all buses

Voltage Control Setpoints
Assumed all generators and voltage controllable devices control bus voltages to 1 p.u.

Transformer Tap Changer Parameters
Location known from AEMO single-line diagram, parameterization not available, fall back to standard parameters

Small-scale PV in DN
Only net load per TN node available, individual DN connection data is absent

Dynamic Model Parameters
Only nameplate data for large generators, fall back to standard models and parameters

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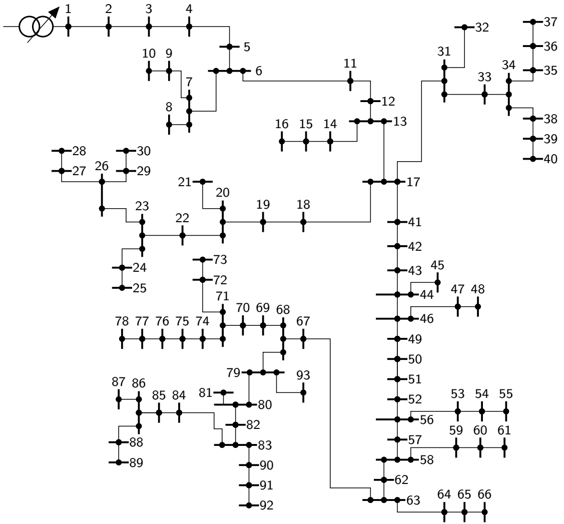
AEMO: Australian Energy Market Operator, DN: Distribution Network, DSO: Distribution System Operator, ISP: Integrated System Plan, VIC: Victoria

Starting Point: Victoria TN and DN Models

VIC Transmission Network

- 125 buses, 139 lines, 5 interconnectors, 51 transformers
- 66 kV-500 kV transmission
- DC links to Tasmania and South Australia
- AC links to South Australia and New-South Wales
- 40 generators, thereof **6 large-scale PV and 17 wind farms**

Sample DN Feeder



DN: Distribution Network, TN: Transmission Network, VIC: Victoria

From One Distribution Network (DN) to a System-Level Model

Key Idea: Represent the distribution layer by replicating **one realistic DN** across transmission buses.

Available Information

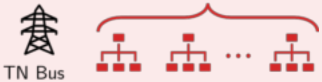
System Peak Load 10 GW

One Real DN: 22 kV, 93 nodes, max. 12 MW

Constant load shares per TN bus

Attempt 1: Full Population

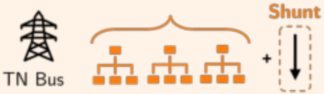
- Assign DNs proportional to load
- Many parallel DNs per TN bus



599 DNs > 50000 buses
Extensive simulation time expected

Attempt 2: Cap per TN Bus

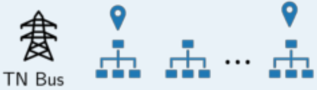
- Limit to max. 3 DNs per TN bus



Simulation feasible
but significant **voltage violations** observed

Attempt 3: Voltage-Driven Population

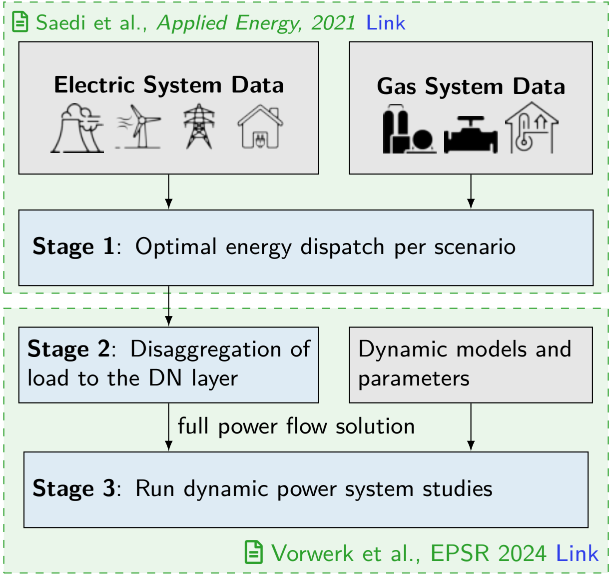
- Add DNs only where voltage limits are violated



Final Model
203 DNs, > 18 000 buses
feasible and consistent

Diversification (applies to power flow simulations)
DN parameters randomised: $r, x, b \pm 10\%$, load distribution within DN randomised, $\cos\varphi = 0.98$ assumed

Which operating points to study?



Key Research Question: How much can **electrification of residential heating** support the frequency?

Stage 1: Strengthened DC-OPF

- Scenarios: **Three different electrification levels** for **five exemplary days** with hourly resolution →**600 operating points**
- **Outputs:**
  - Optimal **active power setpoints** of generators
  - TN nodal load: background + additional load from electrification

Stage 2: Disaggregation of TN Nodal Load

- Use constant load factors to disaggregate background and added electric load to the DNs
- Run complete power flow to obtain **full load flow solution**

AEMO: Australian Energy Market Operator, TN: Transmission Network, DN: Distribution Network, OPF: Optimal Power Flow

Phase 1: Scoping the Test Case → Phase 2: Choosing a Simulator → Phase 3: Steady-State Model →

Phase 4:

Building the Dynamic System Model

- How to choose and parameterize **component models**?
- How to **validate** and **evaluate** the system model?

Which model to choose for individual components?

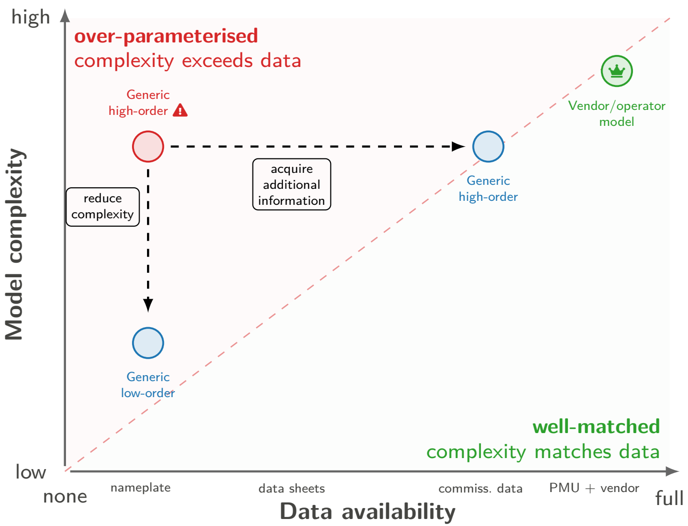
Model Complexity must match available data!
Vendor models incl. their structures and parameters are often unavailable, hence we fall back to generic models.

- Model parameterization is typically an **underdetermined problem**
- Multiple parameter sets can reproduce the same measured response

» Start with simplest appropriate model!

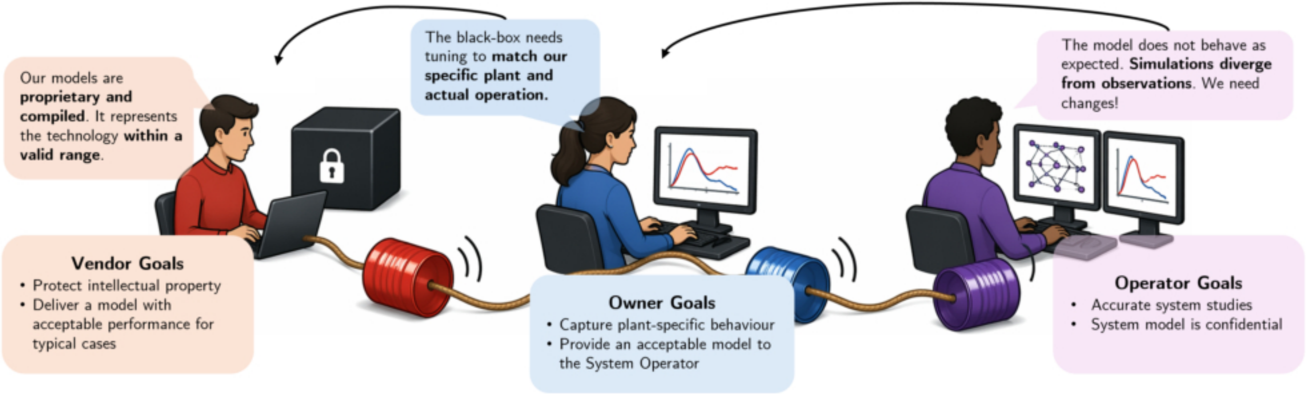
Available Libraries (that I found useful in the past)

- NEPLAN Exciter and Turbine and Governor, Wind Turbine Models, PSS Models
  All including typical parameter ranges
- WECC Renewable Energy Models, WT4 model, Battery Storage Guideline
- Argonne National Laboratory Hydro-governor models



More parameters ≠ better model! Reduce the complexity to match your available data.

The Problem with Vendor Models



- There is a **continuous feedback loop**: vendor ⇄ owner ⇄ TSO
- Submitted models can be **outdated, unvalidated** or **not in the required format** (black boxes)
- Compiled vendor models are **not accessible**, which limits reproducibility and peer review

» **Vendor models are very detailed. That does not make them safe and sound for system-level stability studies!**

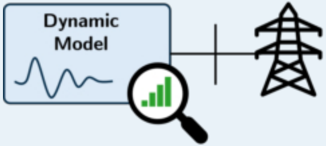
Selecting and Parameterizing Generic Dynamic Models

	Wind Turbine	Hydro Turbine
1. **Identify Resource and Phenomena** Stability class, required dynamics, required sub-models	**Converter-Driven Stability** **Converter** + Controller + Protection	**Short-term Frequency** Machine + AVR + PSS + Governor
2. **Choose Simplest Model** IEEE Std., WECC, IEC, NEPLAN	**WT4 Turbine Type** generic WECC parameters, grid code for protection and control parameters	**5th order SM + SEXS + PSS2A + HYGOV** NEPLAN standard parameters, control parameters from grid code
3. **Implement and Initialize** Sanity checks, test initialization for different operating points	**Connect WT to small test system** Check operating points, power dispatch and initialization	**Connect all models to small test system** Check operating points, power dispatch and initialization
4. **Disturbance and Credibility Check** Run dynamic simulations, check behavior for potential contingencies	**Check dynamic behavior** Current injections, LVRT thresholds, mode switching, reactive power response	**Load steps and short circuits** Check transient behavior of sub-modules, controls and expected deviations

Not all Missing Data is Equal: How to select which parameters to tune?

The Problem: Parameter identification is not unique → multiple parameter sets reproduce the same results.

Sensitivity Setup

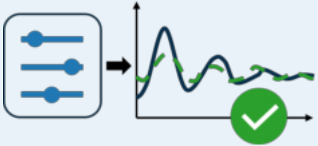


- Identify **phenomena related metrics**
- » Short-term frequency: Frequency nadir, RoCoF, steady-state frequency deviation
- Identify **parameters of potential high impact**

Sensitivity Analysis

- Identify parameters with **highest sensitivities** per metric
- Search for parameter values in available data
- Which recorded data would help? (time-scales, locations, responses)

Tune Parameters

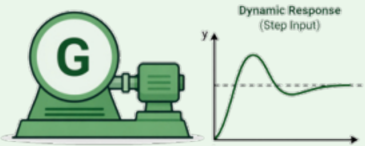


- Tune sensitive parameters, accept literature defaults for the rest
- Tune **the same parameters for all units**
- **Tune parameters of similar time-scales together**, e.g. steady-state to fast dynamics

! Sensitivity is study-specific: parameters **critical for frequency studies may be irrelevant for voltage studies**.

Validation Hierarchy of Dynamic Models

Unit-Level Validation



- Model structure, parameters, and basic dynamic behavior
- **Grid** typically considered through **equivalent**
- **Examples:** Step response, time constants, model structure correctness

Plant-Level Validation

- **Plant controller performance**, coordination and internal dynamics
- **Grid** typically **represented** through **equivalent**
- **Examples**: LVRT, FRT performance, reactive power response, active power recovery, controller actions

System-Level Validation

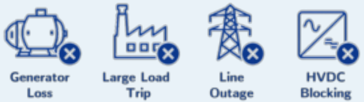
- Validate entire system against recorded events
- Interactions between plants, controls and the grid
- **Examples**: Wide-area frequency response, voltage events, inter-area oscillations

System level models, require system-level validation evidence!

FRT: Fault-Ride-Through, LVRT: Low-Voltage-Ride-Through

Options for System-Level Dynamic Model Validation

Recorded System Events

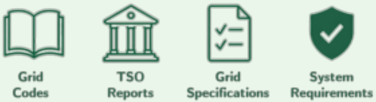


How to obtain

- **TSO disturbance databases** (might require research agreements)
- ENTSO-E transparency platform
- **Post-event reports**
- WAMS / synchrophasor networks: Some TSOs publish aggregate statistics

! The event must excite the phenomena that you are interested in!

Grid Codes & Reports



How to obtain

- National grid codes (RoCoF limits, nadir, V recovery)
- TSO annual reports (inertia, nadir, FCR availability)
- Power system requirements and standards
- Academic literature

✔ **Always available**

! Targets can only provide bounds

Modal Analysis

How to obtain

- Some TSOs publish **dominant mode frequency and damping ratios**
- WAMS-based modal identification published by TSOs: real-time or historical mode tracking
- Eigenvalue analysis of reference models

! Large systems have many eigenmodes. Matching might be difficult.

FCR: Frequency Containment Reserve, RoCoF: Rate-of-Change-of-Frequency, TSO: Transmission System Operator, V: Voltage, WAMS: Wide Area Monitoring System

Phase 1: Scoping the Test Case → Phase 2: Choosing a Simulator → Phase 3: Steady-State Model → Phase 4: Dynamic Model

Phase 4:

Phase 4: VIC Test Case

VIC Dynamic Model: Components and Parameterization

	Component	Model	Details
Steam Gen	$\geq$ 300 MVA	6th order SM + TGOV1 + **SEXS** + **PSS2A**	Uniform parameters
	$<$ 300 MVA	6th order SM + TGOV1 + **ST1A**	Uniform parameters
Hydro Gen	$\geq$ 300 MVA	5th order SM + **HYGOV** + **SEXS** + PSS2A	Uniform parameters
	$<$ 300 MVA	5th order SM + **HYGOV** + **ST1A**	Uniform parameters
TN-Conv. Interfaced	Wind & large PV	WECC WT4	Uniform parameters, no frequency support, adjusted **voltage control parameters locally** to prevent oscillations
	Batteries	WECC battery model	Uniform parameters, **only** frequency control
DN Loads	Heat Pumps	Universal thermal load model[2], **inverter-interfaced units**	Physical parameters from uniform distribution, **active power droop depending on operation point**
	Other	Exp. load + 3rd order induction machine	Random parameters from uniform distribution
Inter-connectors	AC	6th order SM + const. excitation + TGOV1	Uniform, standard machine parameters, inertia + droop constants changed to reflect kinetic energy contribution
	DC	constant power injectors	no contribution to any local control

VIC Dynamic Model: The Tuning Process

VIC

Uniform Tuning of the Following Parameters:

- PSS gains,
- TGOV Steam governor droop and time constants,
- Hydro governor reset time.

Individual Tuning of the Following Parameters:

- **WECC WT4 voltage control** parameters to achieve stable voltages at connection nodes, individual parameters per WT4 model
- Interconnectors: Change inertia constants and installed power to match w

Tuning Target

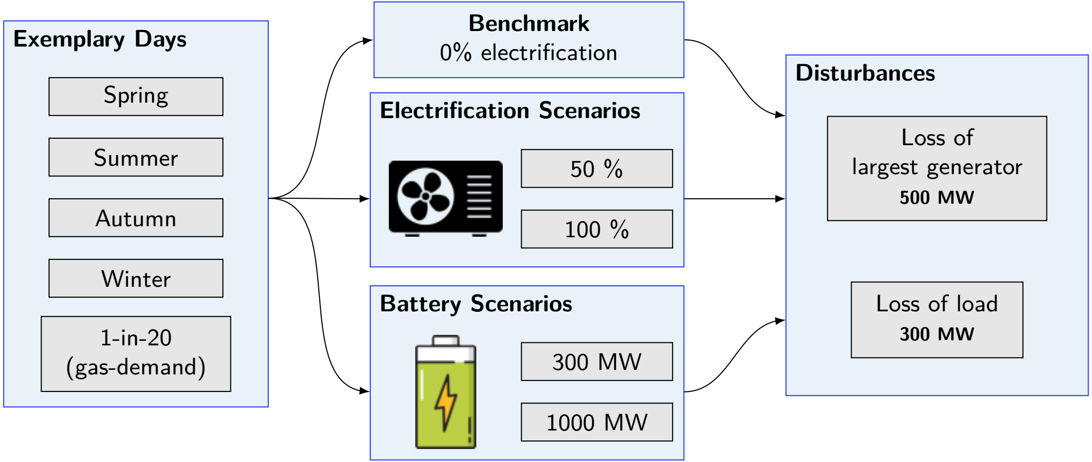
- Published AEMO report on trip of **multiple generators in Queensland** [3]
- ! **No PMU or SCADA** access, estimated pre-fault dispatch from a similar day
- ! Only frequency traces for Queensland and New South Wales available
- ! We neither modeled under-frequency load-shedding, nor the rest of the Australian system with detail, hence the goal was a **qualitative match of key frequency metrics**

Use of the Final Model

- We cannot claim that this is an exact model
- It is good for comparing the impact of operating points on frequency reserve and frequency stability
- Results should be understood relatively rather than absolute values

[1] AEMO: Trip of multiple generators and lines in Central Queensland and associated under-frequency load shedding on 25 May 202, Oct 2021,Link

VIC Dynamic Model: Overview of the Studied Operating Conditions

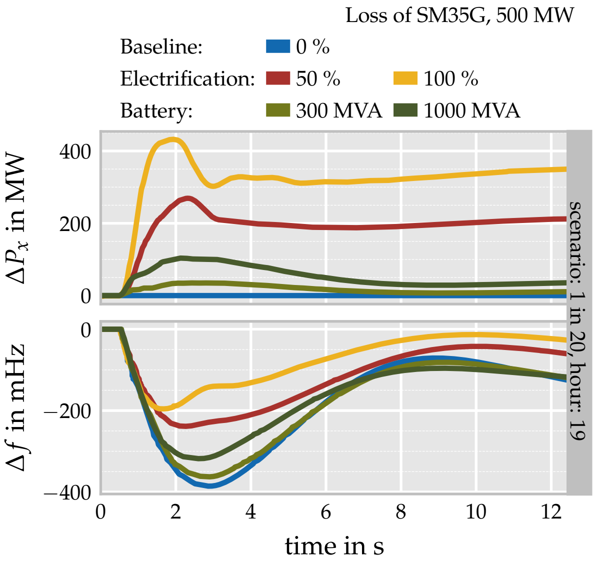


The steady-state scenarios are built on the **ISP 2020 Step Change** scenario and represent the **projections for 2025**.

With hourly resultion, we executed 600 dynamic simulations.

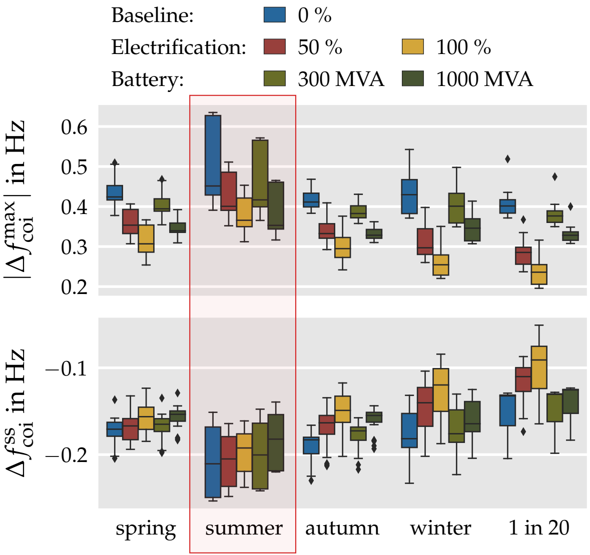
AEMO: "2020 Integrated System Plan", available at Link

VIC Dynamic Model: System-Level Time-Domain Results



VIC Dynamic Model: Frequency Indicators

Generator Loss



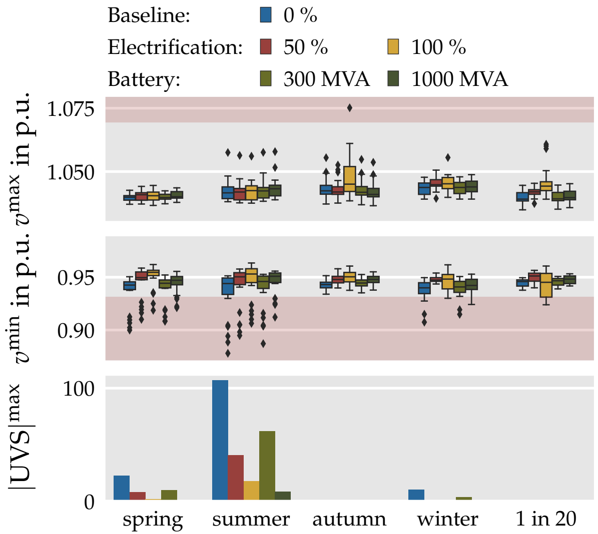
low potential for thermal loads

Key Findings

- Significant **daily variations** occur
  - 200 mHz in summer
  - Correlates with online **rotational inertia**
- Thermal loads are **extremely effective during winter months**, when their consumption is high
  - Droop gain **favorable** for a generator loss
- Thermal loads **still outperform** batteries when their potential is the lowest
  - Droop gain **disadvantageous** for a generator loss
  - Large battery similar to 100 % electrification

VIC Dynamic Model: Voltage Indicators

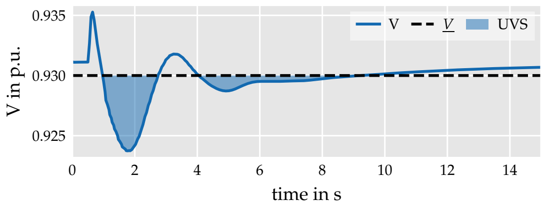
Generator Loss



Undervoltage Score (UVS)

Systematic score to assess the severity of a voltage violation:

$$\text{UVS} = \sum_{i \in \mathcal{B}} \int_{t_{v,i \leq \underline{v}}}^{t_{v,i \geq \underline{v}}} (\underline{v} - \underline{v}_i(t))dt$$



Key Findings

- generally observe **undervoltages** rather than overvoltages
- results indicate **interdependence** between **frequency and voltage**, voltage improves with frequency

Phase 1:

Scoping the Test Case

Phase 2:

Choosing a Simulator

Phase 3:

Steady-State Model

Phase 4:

Dynamic Model

Open Research Questions and Final Remarks

Additional Hints and Tips

- **Start data collection as early as possible! It is tedious and takes the most time.**
  - Be mindful and cautious with shared data. It might be wrong and conflicting.
  - Test and validate any model, no matter where you obtained it from.
- **While collecting data, build a dynamic model using generic unit models.**
  - Choose generic models that reflect your desired phenomena, if uncertain run tests.
  - Build one resource, one step at a time to avoid errors.
  - Uniform parameterization simplifies implementations and is easier to simulate at first.
  - Perform sensitivity studies to identify parameters for tuning.
- **Tune the entire system model from slow to fast dynamics.**
  - Tune parameters that impact on the same time-scales in your models at the same time
  - Tuning using formal methods (least-squares, optimization-based) is challenging due to non-linearity and over-parameterization of the problem
  - Be aware of risk of overfitting your model to one event recording. Ideally, validate with multiple recordings.
- **Automate as much as possible.**
  - Reduction of human errors.
  - Automated simulations can run for different scenarios in parallel and on external devices over a longer period.
  - Evaluation of large dynamic studies is tedious, build system-level indices for your metrics of interest.
- **Focus on the big picture - Do not get lost in details that do not matter for your study scale!**

Simulation Speed-Up: How can we reduce the simulation cost?

Simulation Paradigm

What dynamics do we need to resolve?

- RMS vs EMT vs hybrid
- Dynamic phasors
- Multi-rate simulation
- Adaptive time stepping

? Under which conditions is **EMT truly necessary** at system-scale?

? What are other **intermediate domains** for modeling?

Bottleneck Identification

Where does the runtime actually come from?

- Detect **slow or stiff dynamics**
- **Selectively simplify** (e.g. by dynamic equivalents) only what dominates runtime

? How to detect and replace critical dynamics**detect and replace critical dynamics** automatically?

Computational Acceleration

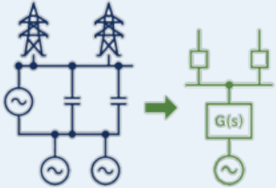
How do we solve the same equations faster?

- Parallel simulation
- Domain decomposition
- Co-simulation
- **GPU / HPC**

? Which **advancements** can we **exploit**?

Simulation Speed-Up: How can we reduce the model?

Physics-Based Approaches

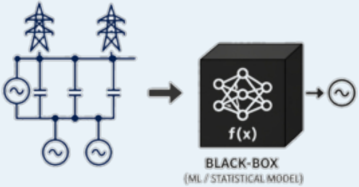


Goal: Interpretable structure

- Aggregate dynamics into **physics-based model**
- Use **established system equivalents**, e.g. SM
- Apply **model-order reduction** methods

? Tuning of controllers to represent response of multiple units

Black-Box Approaches



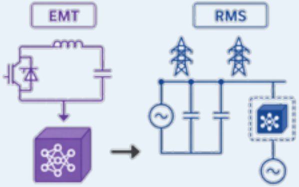
Goal: Map input-output behavior

- Learn **statistical, classic or ML-based surrogates**
- Based on **trajectories** and, or **measurements**
- Option: **physics-informed ML**

? Integrate neural surrogates into time-domain solvers

? Robust validation, error estimation and **stability boundaries**

Hybrid-Domain Approaches



Goal: **Inform large-scale RMS** with **EMT-informed dynamics**

- Identify **critical subsystem**
- Learn in **EMT domain**, integrate back into **RMS models**

? **Identification** of **critical dynamics**

? **Robustness** of equivalent for **operating ranges**

? **Quantification of errors**

Thank you for joining us!

Collaborators supporting development of the presented methods and test cases:

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You are more than welcome reach out for discussions and follow-up!

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