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Dynamic Simulation and Stability Limits of Large-Scale Transmission Systems with Renewables

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FEN

Summary

- Dynamic stability future Continental ENTSO-E system with high share of converter-based renewable energy sources (RES)
- Assessment of large disturbances, in particular islanding scenarios
- New dynamic simulation framework: modular, flexible, robust initialization, fast
- Comparison of different converter models and impact on stability
- Simulation for a wide range of generation distribution and and RES-shares
- Results:
  - Computation of stability contours for assessment of expected disturbance impact
  - Simple converter models systematically underestimate impact on dynamic stability
  - Insights in complex dynamic couplings and cascaded outages

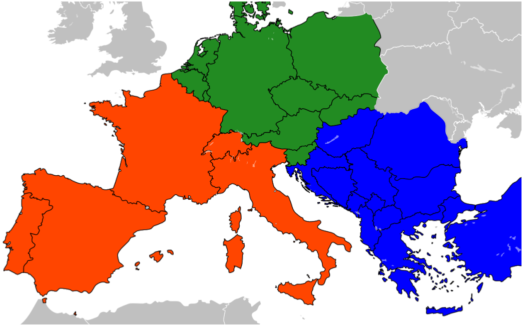
Agenda

Dynamic simulation of large transmission grids

RES modeling

Results for secure power system operation

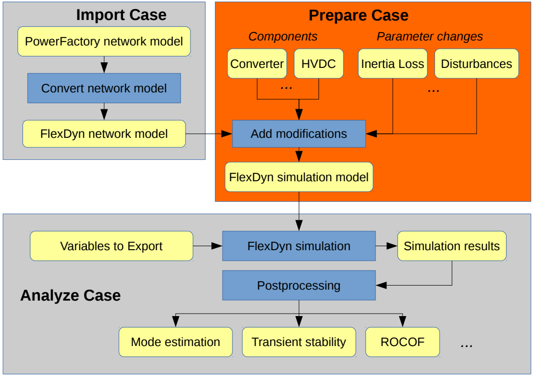
Background: Risk from transients in the transmission grid



- Scenario: System split into multiple synchronous areas (similar to 2006 event)
- Challenge: Loss of multiple GW of import or export in each area

- Background:
  - Dynamic power system stability of large disturbances in the future Continental ENTSO-E system
  - Challenges and potential support from converter-based generation
- System parameters:
  - Continental ENTSO-E dynamic model
  - Share of converter-based renewables
  - Initial load flow distribution
  - Converter control approaches

Simulator Framework

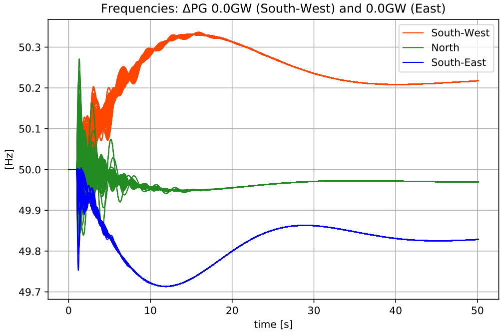


- Modular framework combining symbolic and numerical methods.
- Runs approximately realtime for large Continental ENTSO-E dynamic model ($\approx$ 10'000 buses and 1'000 generators).

Simulation Workflow

- Definition and symbolic differentiation of component equations (only structure)
- Parameterization of components and assembly of network model
- Two-step initialization approach (important for feasible Voltage/reactive power setpoints)
  1. Solve OPF problem (with bounds on PG,QG,VG)
  2. Solve dynamic initialization problem (with bounds on AVR,Turbine,Generator)
- Post-processing, computation of performance metrics, visualization

System split of Continental ENTSO-E Base case



- Performance metric of interest: Rate-of-change of frequency (ROCOF) approximated with swing-equation
  $$R = \dot{\omega} = \frac{P_{gen} - P_{load} - P_{losses}}{2H} = \frac{\Delta P}{2H}$$
- ROCOF estimated in simulation over 2000ms time window

- Loads are fixed, shift of generation power between regions (up to $\pm$15GW)
- New RES is included by reducing synchronous machines an adding converters

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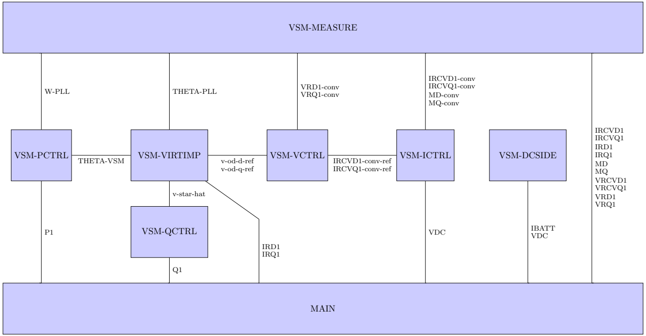
Modeling of converter based generation

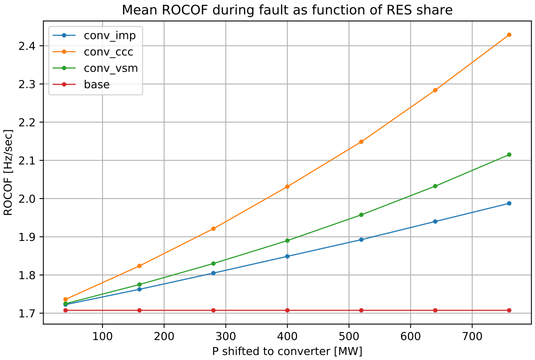
- Three types of common converter models
  - **IMP:** Impedance models of converter (simplified static model, often used)
  - **CCC:** Current-controlled capacitor model (PV-converters without storage)
  - **VSM:** Virtual synchronous machine model (converters with battery storage)
- IMP is simple to simulate and often used for simulation in large systems
- *How accurate are simulation results with IMP compared to realistic CCC models?*
- *What are the benefits of using VSM with dynamic grid support?*

VSM converter model



- Several controllers for grid support, similar to synchronous machine.
- Model and tuning based on:
  Salvatore D'Arco, Jon Are Suul and Olav B. Fosso: A Virtual Synchronous Machine implementation for distributed control of power converters in SmartGrids. Electric Power Systems Research 122 (2015) pp.180-197.

Kundur system: ROCOF and RES



- Shift of generation to RES reduces inertia: $R = \frac{\Delta P}{2H}$
- Simulation with varying shares of IMP, CCC and VSM
- Increase rate depends on converter type

- ROCOF increases with RES

Computation of a ROCOF premium for different RES models

- Roughly linear dependence on RES generation share: $R = R_0 + K \cdot P_{\text{RES}}$
- For IMP, $K_{\text{IMP}} = .37 mHz/sec$ per MW renewables
- Estimate of ROCOF premium:
  $K_{\text{CCC}} = 2.6 \cdot K_{\text{IMP}}$
  $K_{\text{VSM}} = 1.5 \cdot K_{\text{IMP}}$
- IMP systematically underestimates the ROCOF, confirmed for a wide range of load flow distributions
- Can use ROCOF premium to update existing results (also from other projects) obtained with with IMP models

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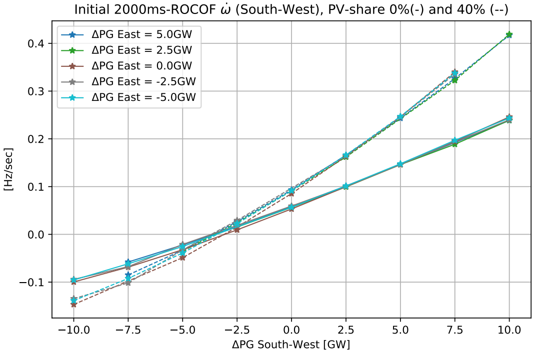
Continental ENTSO-E: varying power balance and RES-share (IMP-type)

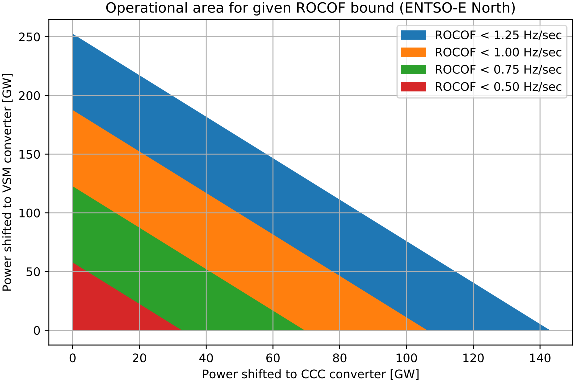


- **Mean ROCOF values** in South-West as a function of generation power added to the region. Case with 0% and 40% RES.
- Shift of generation to RES reduces inertia, generation shift changes power balance:
  $R = \frac{\Delta P}{2H}$
- Similar pattern in other regions (but different slopes, depending on power balance and generation settings)

Estimation of impact of converter types

- Plot confirms the roughly linear dependence of ROCOF on RES share and power balance (also seen in smaller systems) as predicted from Swing-equation
- Linear interpolation allows update coefficients for ROCOF computation
- ROCOF can be estimated for different shares and types of RES-models (CCC, VSM) without further simulation

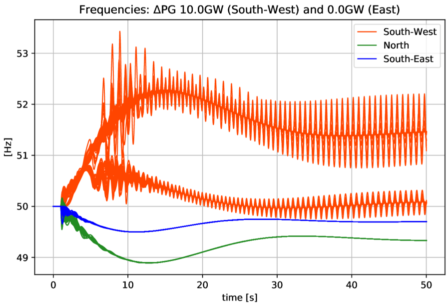
Application: Stability contour for the grid operator

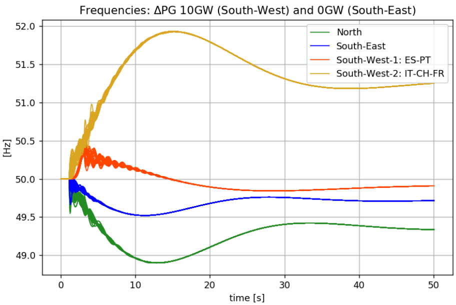


- Results allow fast mapping of current and future operating points

- Informs the grid operator when the system approaches a risky state (e.g. $R > 1$Hz/s)
- Can be used for monitoring of the dynamic security through the grid operator
- Can be created for a wide range of load flows and events, and intersected accordingly

More insights: emerging synchronous clusters





- Cascaded split: For higher generation, after the initial split, South-West separates into multiple synchronous zones.
- Simulation-based identification of regional frequency clusters (robust, system constraints accounted for)

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Thank you for your attention!

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