Using Julia for Research on Electric Power Systems

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National Technical University of Athens
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CV overview

Education

2005 Diploma in Mechanical Engineering, NTUA.

2007 M.Sc. with Distinction in Power System Engineering & Economics, University of Manchester.

2012 Ph.D. in Electrical Engineering, University of Manchester.

Positions

2012 . . . Senior Researcher @ Université de Liège, School of Electrical Engineering & Computer Science

– with Prof. L. Wehenkel.

2022 . . . Research Associate (part-time) @ National Technical University of Athens, School of Electrical Engineering

– with Prof. A. Papavasiliou.

Research Agenda

Development of novel techno-economic concepts, methods and tools for cyber-physical electric power system planning and operation.

Areas of interest & expertise

- Reliability, resilience and risk management.
- Power system economics & electricity markets.
- Stochastic optimization under uncertainty.
- Machine learning applications.

Why am I here?

- Using Julia & JuMP since 2015 for all my research/teaching activities:
  - proof-of-concept implementation for research projects.
  - real-life implementations.
- Experimental contribution in Power Systems specific Julia packages.
- Not a coder/software developer.

Presentation Outline

1. A brief introduction to Electric Power Systems

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2. PowerModels.jl and other notable packages

3. Example applications

The modern Electric Power System

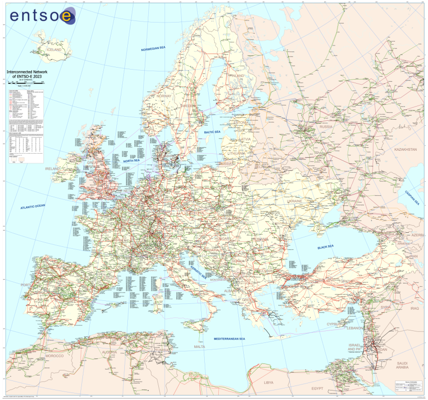
A fascinating technical challenge

- The largest, most complex man-made machine.

At the center of today's societal needs

- Access to clean, secure and affordable electricity as a human right.

The European Interconnected High-Voltage Grid

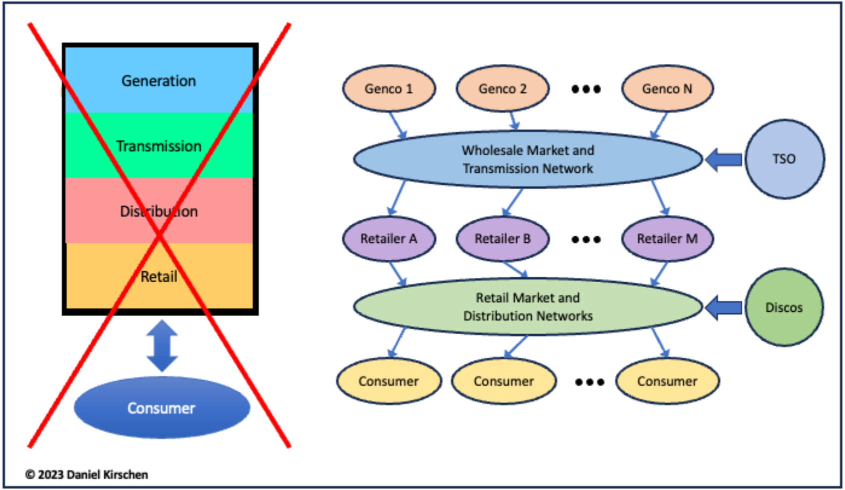


- ∼ 3k – 5k large power plants ($\geq$ 100 MW).
- ∼ 20k nodes.
- ∼ 30k branches (*i.e.* lines and transformers).
- ∼ 30 Transmission System Operators (TSOs).
- ∼ 20-30% of your Electricity Bill.

- ▶ Interactive map available from ENTSO-e.

Who is who?

D. S. Kirschen [1]



Operational requirements

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Technical feasibility (μs – s)

- Must ensure that power generated $\approx$ power consumed.

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- Must also keep currents & voltages within secure/acceptable ranges.

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Economic Optimality (min – hrs)

- Must also be using the cheapest generation resources.

Technical security (s – min)

- Must also keep currents & voltages within secure/acceptable ranges.

Technical feasibility (μs – s)

- Must ensure that power generated $\approx$ power consumed.

Operational requirements

Socio-Economic optimality (hrs – yrs)

- Must also decarbonize, renew/expand infrastructure *etc.*.

Economic Optimality (min – hrs)

- Must also be using the cheapest generation resources.

Technical security (s – min)

- Must also keep currents & voltages within secure/acceptable ranges.

Technical feasibility (μs – s)

- Must ensure that power generated $\approx$ power consumed.

What types of computational applications do we need?

Modeling

Assessment

Control & optimization

E.g.: Power Flow Modeling

What?

- Given power generations, loads and the grid properties compute the nodal voltages and branch flows.

How?

- Solve a set of non-linear equations (Kirchoff Current and Voltage Laws)
  - Newton-Raphson or Gauss-Seidel algorithms typically used.
  - Commercial software can handle grids of thousand nodes in seconds.

E.g.: N-1 Security Assessment

What?

- Given power generations, loads and the grid properties check if any single component failure leads to unacceptable flows/voltages.

How?

- Create alternative grid snapshots corresponding to each component failure scenario.
- Solve the corresponding power flow problems and.
- Compare results against applicable limits.

E.g.: N-1 Security-Constrained Optimal Power Flow

What?

- Given ~~power generations~~, loads and the grid properties ensure that no single component failure leads to unacceptable flows/voltages.

How?

- Integrate the power flow equalities and the applicable limits as the constraints of a (non-linear) optimization problem.
- Choosing power generation dispatch and voltage settings so as to minimize the system operating cost.

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1. A brief introduction to Electric Power Systems
2. PowerModels.jl and other notable packages

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PowerModels.jl

A Julia package for Steady-State Network Optimization

- Development lead by C. Cofrin *et al.* [2] @ LANL.
- Early versions appeared around 2016/17.
- Today it is the reference EPS package (v.0.21.2).
- Find out more on YouTube.

PowerModels.jl

Data Formats

- MATPOWER
- PSS/E
- json

Power Flow Models

- Full AC (Non-linear)
- DC Approximation (Linear)
- 2^{nd} Order Conic Relaxation (SOCP)

Solvers

- GUROBI
- CPLEX
- IPOPT

- And many others not listed here.
- Main idea is to decouple the data, from the power flow model and these two from the solver.
- Or rather, combine & conquer.

How do I use PowerModels.jl?

- Parser functionality is always my choice to bring any power grid data in the Julia environment.
- I write my own Power Flow/Optimal Power Flow formulation with similar/additional functionalities as needed.
  - It is always important to understand the model you are using.
  - Using built-in models for validation/verification.
  - Also relying on JuMP to state my optimization problems.
- Stay-tuned for some examples in the 3rd part of the slides.

The PowerModels.jl solar system

PowerModelsDistribution.jl	3-phase Unbalanced Distribution grids
PowerModelsStability.jl	Distribution grids with Stability constraints
PowerModelsProtection.jl	Fault studies
PowerModelsITD.jl	Integrated Transmission & Distribution grids
HydroPowerModels.jl	SDDP for HydroThermal MultiStage Optimization
PowerModelsACDC.jl	Hybrid AC/DC systems
PowerModelsRestoration.jl	Power System Restoration tasks
PowerModelsGMD.jl	Geomagnetic disturbances
PowerModelsAnalytics.jl	Visualisation of grids and results
PowerModelsAnnex.jl	Exploratory works in progress (anything goes!)

Other notable Packages

PowerSystems.jl	Alternative Power Grid data parsing framework
PowerSimulations.jl	Integrated Resource Planning & Market simulator
PowerSimulationsDynamics.jl	Time-domain simulations
POMATO	Power Market simulator (python/Julia)
PandaModels	Parser from the PandaPower format

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⋆ I have not used/tested every single Package mentioned here...

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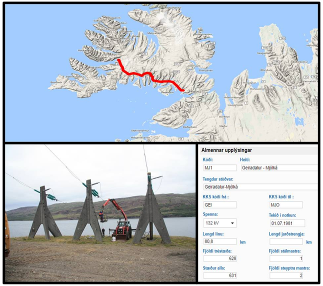
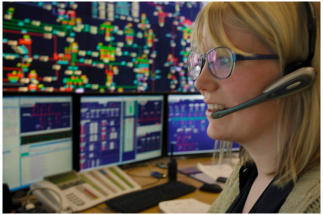
Reliability management

- Making decisions under uncertainty, from long-term system development to real-time system operation.





- A reliability criterion sets the basis to determine whether or not the system reliability is acceptable.

Real-time operation reliability management

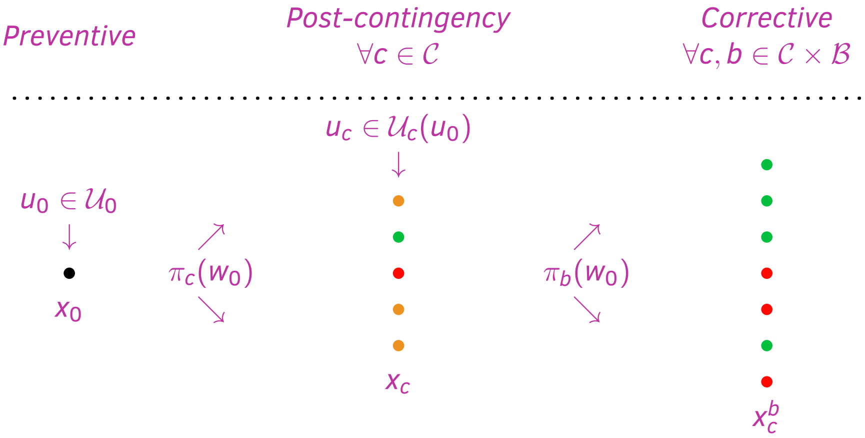
Karangelos & Wehenkel [3]

Horizon: (5' $\sim$ 15')

- Power injections assumed relatively predictable.
- Uncertainty on:
  - $\rightarrow$ occurrence of contingencies $c \in \mathcal{C}$;
  - $\rightarrow$ behavior of post-contingency corrective controls $b \in \mathcal{B}$.
- Decisions on Active Power Generation:
  - $\rightarrow$ apply preventive (pre-contingency) control $u_0 \in \mathcal{U}_0(x_0)$?
  - $\rightarrow$ prepare post-contingency corrective controls $u_c \in \mathcal{U}_c\,(u_0)\,\forall c \in \mathcal{C}$?

Transitions of the system state

Karangelos & Wehenkel [3]



w_0: spatial/temporal correlation in transition probabilites.

Steady-state operational limits

Karangelos & Wehenkel [3]

- AC power flow (rectangular coordinates);
- voltage magnitude bounds per node;
- voltage angle difference & apparent power flow bounds per branch;
  - → less restrictive for the intermediate problem stage;
- active & reactive power generation bounds per unit;
  - → ramping restrictions between preventive & corrective active power dispatch;
- voltage set-points per unit;
- no loss of load.

Chance-constrained SCOPF

Karangelos & Wehenkel [3]

$$\min_{\mathbf{u}\in\mathbf{U}} CP(x_0,u_0) + \sum_{c\in\mathcal{C}} \pi_c \cdot CC(x_0,u_0,c,u_c); \tag{1}$$

$$h_0(x_0,u_0) \leq 0; \tag{2}$$

$$\mathbb{P}\left\{ \; h_c(x_c^b,u_c) \leq 0 \;\middle|\; (c,b) \in \mathcal{C}\times\mathcal{B}\right\} \geq 1-\varepsilon; \tag{3}$$

$$\mathbf{u} \in \mathbf{U} \equiv \{u_0 \in \mathcal{U}_0(x_0); u_c \in \mathcal{U}_c(x_0,u_0,c) \forall c \in \mathcal{C}\}. \tag{4}$$

- Reformulated as a Mixed-Integer Non-Linear Programming Problem.
- Algorithmic solution approach implemented in Julia.

Solution principle

Karangelos & Wehenkel [3]

- Any chosen decision partitions the contingency set ...

Preventive Only $\mathcal{C}_{\mathcal{P}}$	**Preventive & Corrective** $\mathcal{C}_{\mathcal{C}}$	**Not Secured** $\mathcal{C}_{\mathcal{X}} = \mathcal{C} \setminus (\mathcal{C}_{\mathcal{C}} \cup \mathcal{C}_{\mathcal{P}})$

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Preventive Only	Preventive & Corrective	Not Secured
$\mathcal{C}_{\mathcal{P}}$	$\mathcal{C}_{\mathcal{C}}$	$\mathcal{C}_{\mathcal{X}} = \mathcal{C} \setminus (\mathcal{C}_{\mathcal{C}} \cup \mathcal{C}_{\mathcal{P}})$

+ we get a lower-bound for the probability of interest;

$$\mathbb{P}\Big\{\dots\Big\} \geq 1 - \left(\sum_{c \in \mathcal{C}_{\mathcal{X}}} \pi_c + \sum_{c \in \mathcal{C}_{\mathcal{C}}} \pi_c \cdot \pi_c^f \right),$$

e.g., $\mathbb{P}\Big\{\dots\Big\} \geq 1$ when all cntgcies are in preventive only.

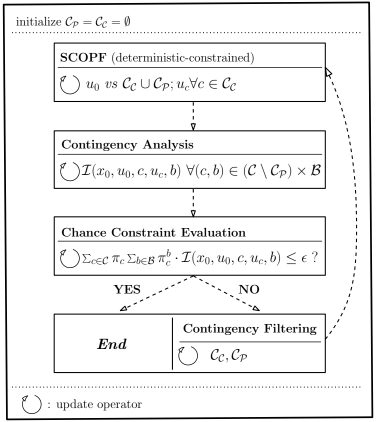
Algorithmic decomposition overview

Karangelos & Wehenkel [3]

In a nutshell

1. update decisions *vs* deterministic constraints;
2. evaluate post-contingency violation probability;
3. update contingency subsets;
   - preventive only;
   - preventive & corrective;

✓ stop when reliability target is OK.



Algorithm components

Karangelos & Wehenkel [3]

Deterministic SCOPF

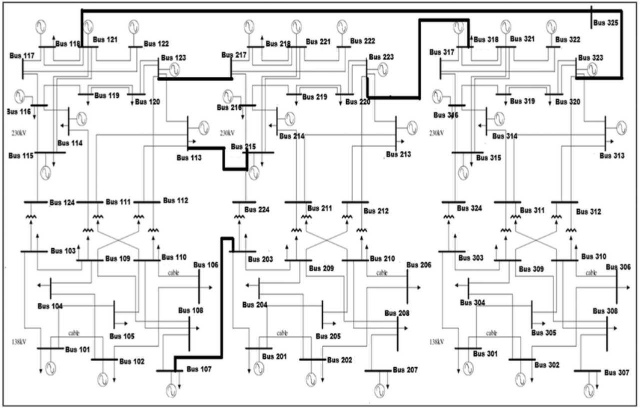
- JuMP/IPOPT implementation *vs* given contingency subsets;

Contingency analysis OPFs

- examining both the working & failing behavior of corrective controls;
- per contingency & cc behavior, minimization of fictitious active/reactive power injections;
- returns a zero optimal value for feasible OPF instances;
- non-zero objective indicative of the magnitude of constraint violations implied by the contingency & cc behavior.

The test-case

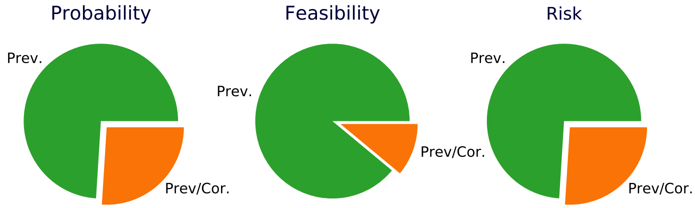
Karangelos & Wehenkel [3]



- 111 single component outages;
- Corrective control failure probability assumed 0.01.

Chance-constrained SCOPF ($\varepsilon = 10^{-5}$)

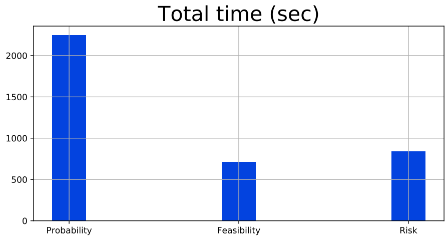
Karangelos & Wehenkel [3]

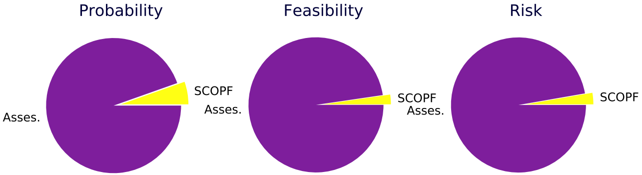


Filter	Probability	Feasibility	Risk
Total Cost ($)	892.37	896.78	892.37
Explicit Contingencies	13	5	7
Chance level	$9.85 \cdot 10^{-6}$	$5.28 \cdot 10^{-6}$	$9.85 \cdot 10^{-6}$

Chance-constrained SCOPF ($\varepsilon = 10^{-5}$)

Karangelos & Wehenkel [3]



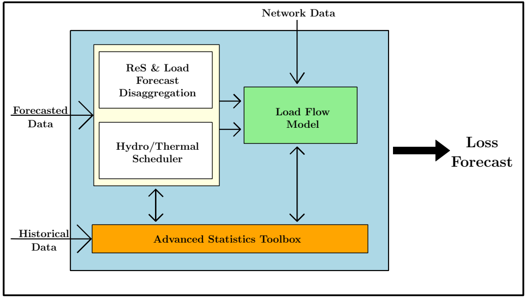


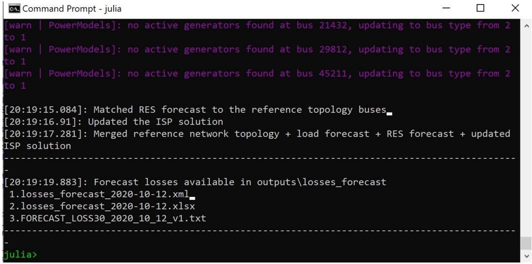
Tertiary Voltage Control Optimization

Donnon, Cuvelier, Karangelos *et al.* [4]

- Goal is to keep Nodal Voltages acceptable.
- By choosing Voltage Setpoints for a subset of Generators.
- ACOPF benchmark implementation as per the specification of the French System Operator.
- Available on GitHub.

Real-life Forecasting Application at IPTO (Greek TSO)





- Day-ahead forecasting of the losses on the Greek Transmission system.
- Combining power flow & ridge-regression for statistical post-processing.
- Delivered Julia implementation still in daily service (since 2020).

Thank you for your attention!

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References I

[1] D. Kirschen, Power Systems: Fundamental Concepts and the Transition to Sustainability. Wiley, 2024. [Online]. Available: https://github.com/Power-Systems-Textbook

[2] C. Coffrin, R. Bent, K. Sundar, Y. Ng, and M. Lubin, "Powermodels.jl: An open-source framework for exploring power flow formulations," in 2018 Power Systems Computation Conference (PSCC), June 2018, pp. 1–8.

[3] E. Karangelos and L. Wehenkel, "An iterative AC-SCOPF approach managing the contingency and corrective control failure uncertainties with a probabilistic guarantee," IEEE Transactions on Power Systems, vol. 34, no. 5, pp. 3780–3790, 2019.

[4] B. Donon, F. Cubelier, E. Karangelos, L. Wehenkel, L. Crochepierre, C. Pache, L. Saludjian, and P. Panciatici, "Topology-aware reinforcement learning for tertiary voltage control," Electric Power Systems Research, vol. 234, p. 110658, 2024.