Towards a Real-Life Artificial Intelligence Application for Electricity Transmission System Tertiary Voltage Control

Dr. Efthymios Karangelos

Asst. Prof. in Electrical Power Systems

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School of Electrical & Electronic Engineering
Scoil na hInnealtóireachta Leictrí agus Leictreonací
UCD

How to pronounce my name?

How to pronounce my name?

Ef

Ch**eff**

How to pronounce my name?

Ef-thy

Ch**eff**

Think

How to pronounce my name?

Ef-thy-mi

Cheff

Think

Mini

How to pronounce my name?

Ef-thy-mi-os

Cheff

Think

Mini

Boss

My journey before UCD

Education

2005 🇬🇷 Diploma in Mechanical Engineering, National Technical University of Athens.

2007 🏴󠁧󠁢󠁥󠁮󠁧󠁿 M.Sc. with Distinction in Power System Engineering & Economics, University of Manchester.

2012 🏴󠁧󠁢󠁥󠁮󠁧󠁿 Ph.D. in Electrical Engineering, University of Manchester.

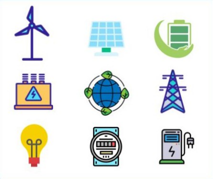
Positions

2005 – 06 🇮🇹 Power Supply Assistant Supervisor, Turin Winter Olympic Games, GE Energy Rentals.

2012 – 24 🇧🇪 Senior Researcher, Institute Montefiore, Université de Liège.

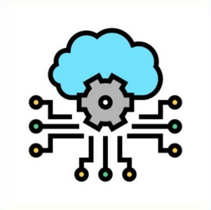
2022 – 24 🇬🇷 Research Associate (part-time), National Technical University of Athens, School of Electrical Engineering.

Research Agenda

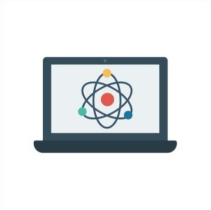


Electric Power Systems

Stochastic Optimisation



Artificial Intelligence



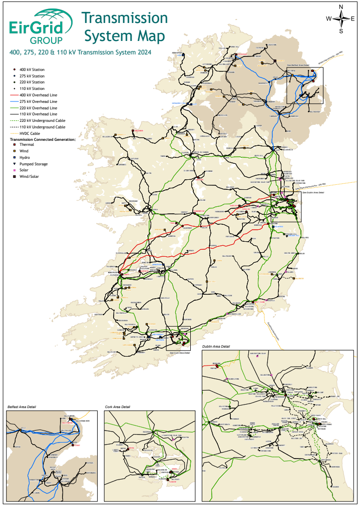
Quantum Computing

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

- Risk, reliability & resilience management.
- Power system economics & electricity markets.

Presentation Outline

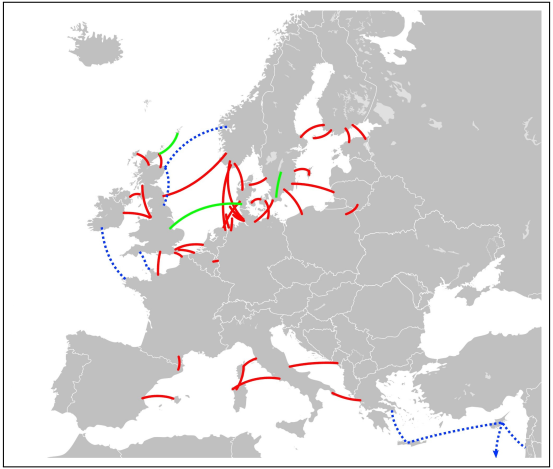
The Electrical Power Grid



"*The largest, most complex machine ever made*" [1].

- All-Ireland Transmission Grid:
  - ∼ 1.5k Buses.
  - ∼ 1.8k Lines.
  - – 2 System Operators (TSOs).
- ENTSO-e Transmission Grid:
  - ∼ 20k Buses.
  - ∼ 30k Lines.
  - ∼ 30 System Operators (TSOs).

Towards a More Deeply Interconnected Future



- ✓ Sharing more economy and security across national borders.
- ⋆ Scale and complexity are only set to increase.

Power System Security is Vital

https://earthobservatory.nasa.gov/images/154238/blackout-in-andalusia

What are the Modern Day Challenges?

- RES uncertainty & variability.
- Decentralisation, markets & proliferation of distributed generation.
- Extreme weather events *vs* an aging system infrastructure.
- Grid digitalisation introducing cyber-physical threats.

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An Unprecedented Computational Workload

- Need to perform a massive number of complex simulations in a short time frame so as to accurately assess the system security risks.
- Taking decisions to optimally manage said risks is an even more complex task.

AI for Power System Security Management

IEEE Transactions on Power Systems, Vol. 4, No. 2, May 1989

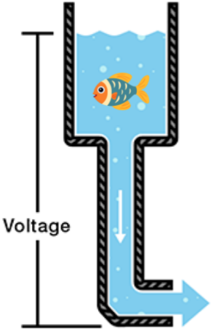
An Artificial Intelligence Framework for on-line Transient Stability Assessment of Power Systems

L. Wehenkel, Th. Van Cutsem* and M. Ribbens-Pavella
Dept. of Electrical Engineering
University of Liège, Inst. Montefiore - B28
B 4000 - Liège, Belgium

- Not really a new idea (cf [2]), rather an existing idea gaining traction [3].
- Complexity explosion is the main accelerator.
- Most breakthroughs are at the academic/proof-of-concept stage.

Presentation Outline

Transmission System Voltage Control



Goal: Maintain Voltage $V_n \in [V_{min}, V_{max}]$ for all nodes N.

$V_n < V_{\mathrm{min}}$: load shutdown, risk of voltage instability/collapse.

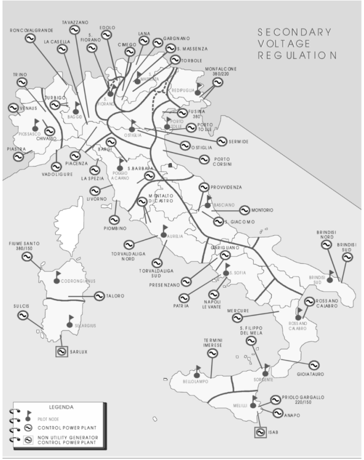
$V_n > V_{\mathrm{max}}$: safety & equipment damage risks.

while minimising active power (resistive) losses.

Main Resource: Generator Reactive Power Output

- Shunt capacitors/inductors, static VAR compensators.
- Transmission switching.

Hierarchical Control Approach – *circa* 1985 [4,5,6,7,8]



Source: Corsi *et. al* [4]

Primary Layer: Maintains **a generator** voltage setpoint, by adjusting reactive power output.

- ∼ a few seconds.

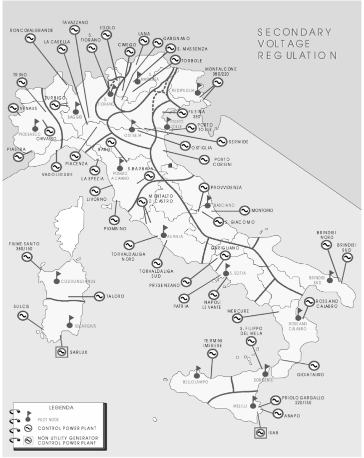
Hierarchical Control Approach – *circa* 1985 [4, 5, 6, 7, 8]

Secondary Layer: Maintains **a pilot bus** voltage setpoint, by coordinating the reactive power output of participating generators.

$\sim$ a few seconds/minutes.

Primary Layer: Maintains **a generator** voltage setpoint, by adjusting reactive power output.

$\sim$ a few seconds.



Source: Corsi *et. al* [4]

Hierarchical Control Approach – *circa* 1985 [4, 5, 6, 7, 8]

Tertiary Layer: Maintains **control area** voltages within bounds, by choosing the setpoints.

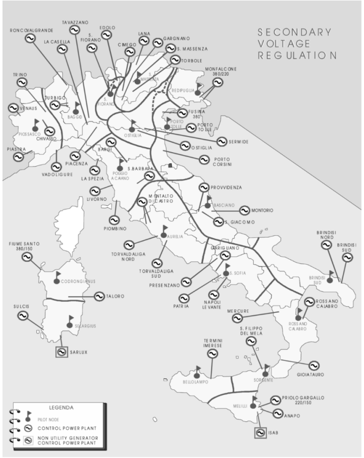
- ∼ a few tens of minutes.

Secondary Layer: Maintains **a pilot bus** voltage setpoint, by coordinating the reactive power output of participating generators.

- ∼ a few seconds/minutes.

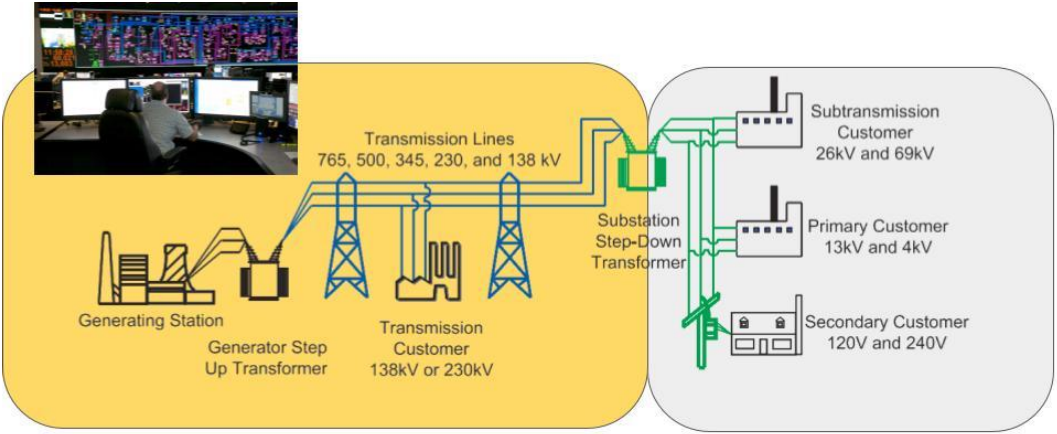
Primary Layer: Maintains **a generator** voltage setpoint, by adjusting reactive power output.

- ∼ a few seconds.



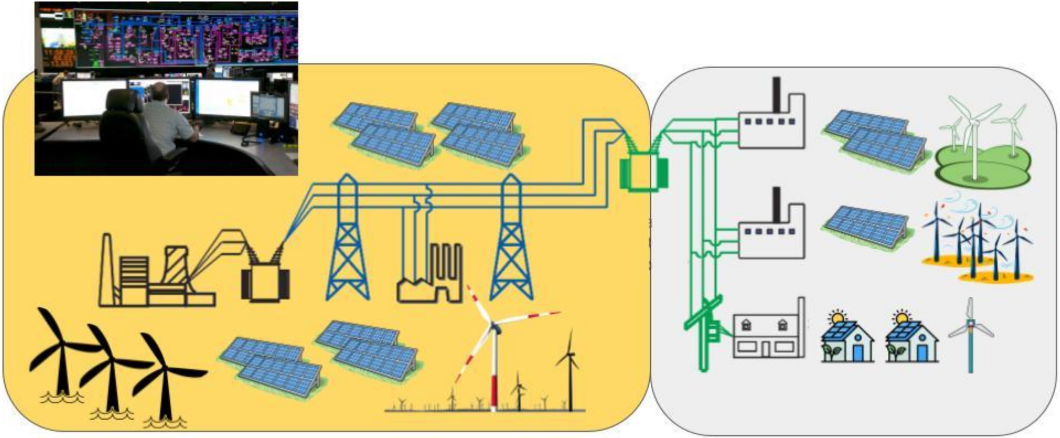
Source: Corsi *et. al* [4]

Why revisit Tertiary Voltage Control (TVC)?



✓ In the past: TSOs could rely on experience *vs* familiar issues.

Why revisit Tertiary Voltage Control (TVC)?



X Today: facing uncertainty, unobservability & unfamiliar issues (overvoltage).

Tertiary Voltage Control under Uncertainty

- ✗ Optimisation techniques only suit a (crude) static approximation.
- ✗ This still requires solving an XXL Mixed-Integer Non-Linear Problem.
- ✗ Over several alternative forecast scenarios for every half-hour of the next day.

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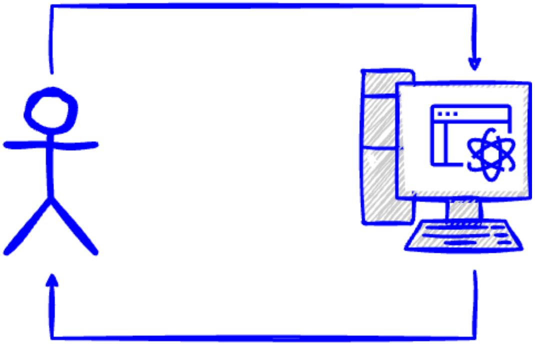
A practical alternative

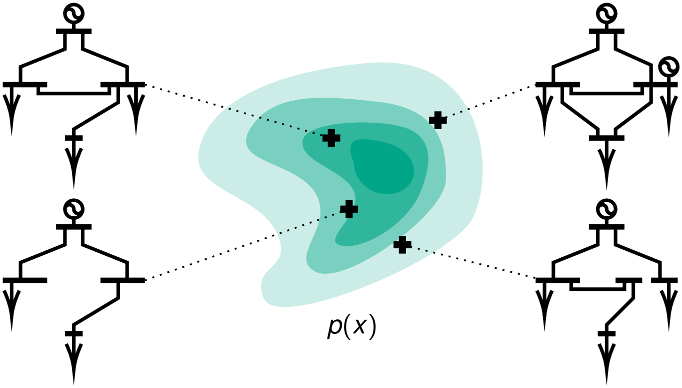
1. Use an AI-based decision-support tool (AI-DST) to quickly suggest suitable control actions for any forecasted scenario.
2. Check whether the suggested actions indeed render operation feasible.
3. Let operators focus only on those scenarios where the AI-DST fails.

Design Requirement #1: Rely on (any) Simulator



- Historical data could only be used to learn how to operate the past system.
- We are facing new behaviours of an evolving system.

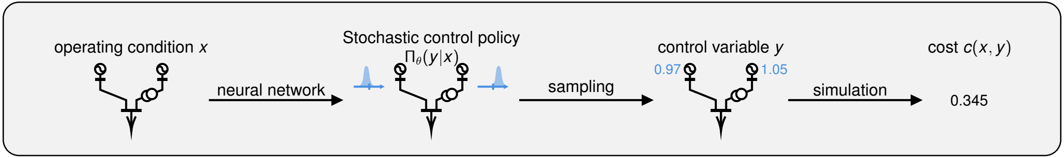
Design Requirement #2: Manage Topological Variability



- Real-life power grids have changing topologies.
- Components may also change IDs between different system snapshots.

Presentation Outline

Stochastic Control Policy Framework



- A power grid **operating condition** (*i.e.*, topology, active power generation, load, voltage control architectures, *etc.*) is passed as an input x.
- A Graph Neural Network outputs a **probability distribution** $\Pi_\theta(y|x)$ for the vector y of control variables.
- Values for y can thus be **sampled**, and passed to the cost function $c(x, y)$ evaluated by a **physical simulation**.

Machine Learning Approach

- We define $\Pi_\theta(y|x)$ as a **multivariate Gaussian distribution** whose mean value is the output of a trainable **Graph Neural Network** $f_\theta(x)$.

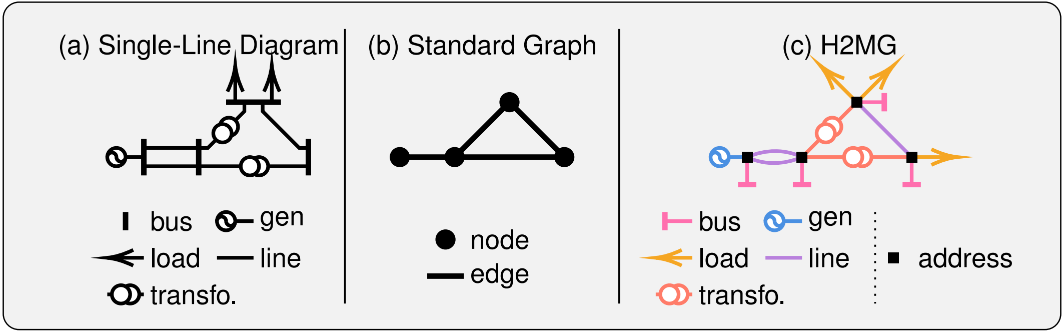
$$\Pi_\theta(y|x) = \mathcal{N}\left(f_\theta(x), \sigma^2 1\right)$$

REINFORCE algorithm

- At each iteration, several physical **simulations with different** (x, y) combinations allow to estimate a **gradient descent** direction w.r.t. the **parameters** θ of **probability distribution** $\Pi_\theta(y|x)$.

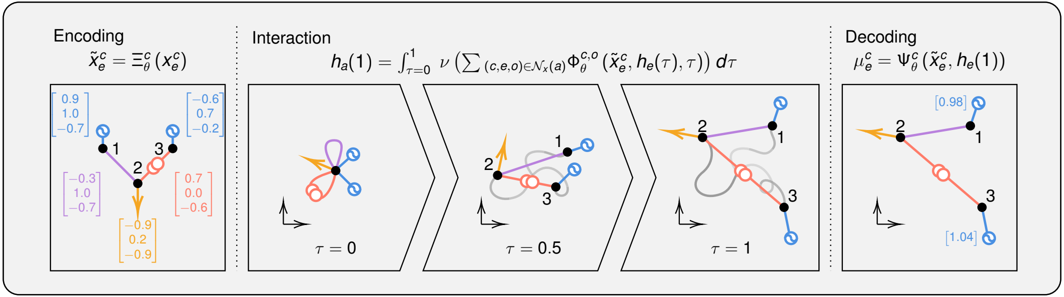
$$\theta^* \in \arg\min_{\theta \in \Theta} \mathbb{E}_{\substack{x \sim p(\cdot) \\ y \sim \Pi_\theta(\cdot|x)}} \left[c(x, y)\right].$$

Hyper-Heterogenous Multi-Graphs (H2MG) Representation



- Preserves all **physical & cyber couplings** (*e.g.*, voltage control architecture) between the power grid components.

Graph Neural Network with NODE coupling



- Local **information exchange** between addresses connected via a hyper-edge modelled as a **continuous dynamical system**.
- Once the dynamic system reaches its **final state**, class-specific decoders translate the H2MGNODE embeddings into **meaningful quantities**.

A Public Dataset for Tertiary Voltage Control?

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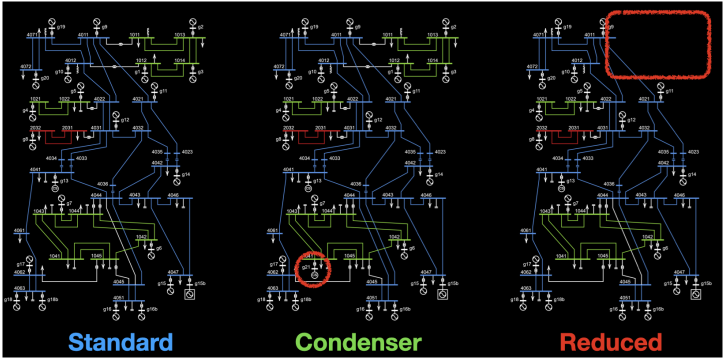
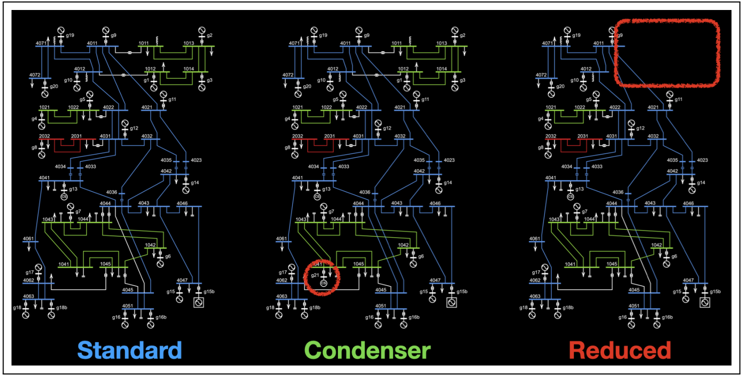
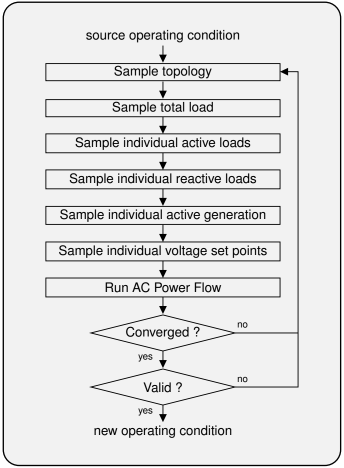


Nordic-32 test case variants

A Public Dataset for Tertiary Voltage Control?



Nordic-32 test case variants



Benchmarking *vs* an AC-OPF

Table: Operating conditions w/ violation.

	Standard test set	Condenser test set	Reduced test set
Start	58%	58%	59%
ACOPF baseline	0.98%	0.82%	1.0%
GNN trained on Standard	**5.2%**	5.8%	18%
GNN trained on Condenser	5.4%	**5.1%**	46%
GNN trained on Reduced	35%	34%	**4.6%**
GNN trained on All	4.5%	4.5%	4.7%

Benchmarking *vs* an AC-OPF

Table: Operating conditions w/ violation – **5% tolerance**.

	Standard test set	Condenser test set	Reduced test set
Start	44%	44%	46%
ACOPF baseline	0.52%	0.49%	0.45%
GNN trained on Standard	**1.6%**	1.5%	6.0%
GNN trained on Condenser	1.9%	**1.4%**	20%
GNN trained on Reduced	21%	20%	**1.5%**
GNN trained on All	1.5%	1.3%	1.5%

Ongoing tests on the French system (Rte)

- South-West part of France
- About 1200 buses, 1600 branches
- Dataset of 15000 day-ahead planning snapshots collected over 2 years
- Topology dependent continuous and discrete control variables:
  - up to 70 Shunts (on/off)
  - up to 70 Transfo set-points (discrete)
  - up to 7 Secondary Voltage Control set-points (continuous)
- Use of cloud computing and RTE in-house physics simulator
- **First results are very promising**

Publications & Coding Resources

Topology-Aware Reinforcement Learning for Tertiary Voltage Control, Donon, B.; Cubélier, F.; Karangelos, E. et al., *Electric Power Systems Research 234*, 2024.

Towards a Real-life Application of AI for the French Transmission System, Donon, B.; Karangelos, E. and Wehenkel L, *Pylons CIGRE Greece 6*, 2024.

GNN Implementation | **Data Generator** | **Nordic32 Variants** | **ACOPF Benchmark**

Presentation Outline

1. Background & Motivation
2. Tertiary Voltage Control Use Case
3. Overview of Methods & Results
4. **Lessons Learnt & Next Steps**

What Were the Main Challenges?

Ill-defined real problems still require solutions

- No universally acceptable formulation of the TVC Problem.
- TSOs are much better at practically solving than rigorously describing the TVC problem.
- No academic benchmark featuring realistic topological variability and a defined hierarchical voltage control structure.

Real problems with messy data still require solutions

- Historical operation snapshots contain load-flow solutions (i.e., the effect of TVC) rather than TVC decisions.
- Transmission system components are frequently reordered/renamed.

Why Could this Approach Work?

Rich Data Model

- ✓ The H2MG framework allows to encode all all the physically relevant features for the problem under consideration.

Sampling-based Simulation Backbone

- ✓ Learning based on a sample of physically meaningful operating conditions, representative of the life of the system in terms of exogenous and endogenous sources of variability.
- ✓ Learning and validation based on the use of already existing simulators faithfully modelling the physical phenomena for the problem of concern.
- ✓ Free of any ‘smoothness’ assumptions (not explained in this talk) and therefore applicable to discrete and continuous controls and non-differentiable physics simulators.

What Happens Next?

Acknowledgements

This work was carried out through a research collaboration between ULiège and RTE-France, by a team composed of

B. Donon, F. Cubélier, E. Karangelos, and L. Wehenkel, from ULiège
and
L. Crochepierre, C. Pache, L. Saludjian, and P. Panciatici, from RTE-France

The team would like to thank Vincent Barbesant and Florian Benoit for insightful discussions about the tertiary voltage control problem, Rémy Clément and Marc Schoenauer for their help in formalising the H2MG approach, and the operators of the Alan GPU cluster at the University of Liège.

Thank you for your attention!

Dr. Efthymios Karangelos

efthymios.karangelos@ucd.ie

School of Electrical & Electronic Engineering
Scoil na hInnealtóireachta Leictrí agus Leictreonací
UCD

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[3] L. Duchesne, E. Karangelos, and L. Wehenkel, “Recent developments in machine learning for energy systems reliability management,” *Proceedings of the IEEE*, vol. 108, no. 9, pp. 1656–1676, 2020.

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[5] J. Paul, J. Leost, and J. Tesseron, “Survey of the secondary voltage control in France: Present realization and investigations,” *IEEE Transactions on Power Systems*, vol. 2, no. 2, pp. 505–511, 1987.

[6] J. Sancha, J. Fernandez, A. Cortes, and J. Abarca, “Secondary voltage control: analysis, solutions and simulation results for the Spanish transmission system,” *IEEE transactions on power systems*, vol. 11, no. 2, pp. 630–638, 1996.

[7] N. Janssens, “Tertiary and secondary voltage control for the Belgian hv system,” in *IEE Colloquium on International Practices in Reactive Power Control*, pp. 8/1–8/4, 1993.

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[8] P. Panciatici, F. Bena, P. Pruvot, N. Janssens, J. Deuse, and M. Stubbe, “Centralized voltage control: a key point for optimal operation of power systems,” *Cigre Paper*, vol. 39116, 1998.