Computing Cyber-Physical Power Systems

Peter Palensky

TU Delft



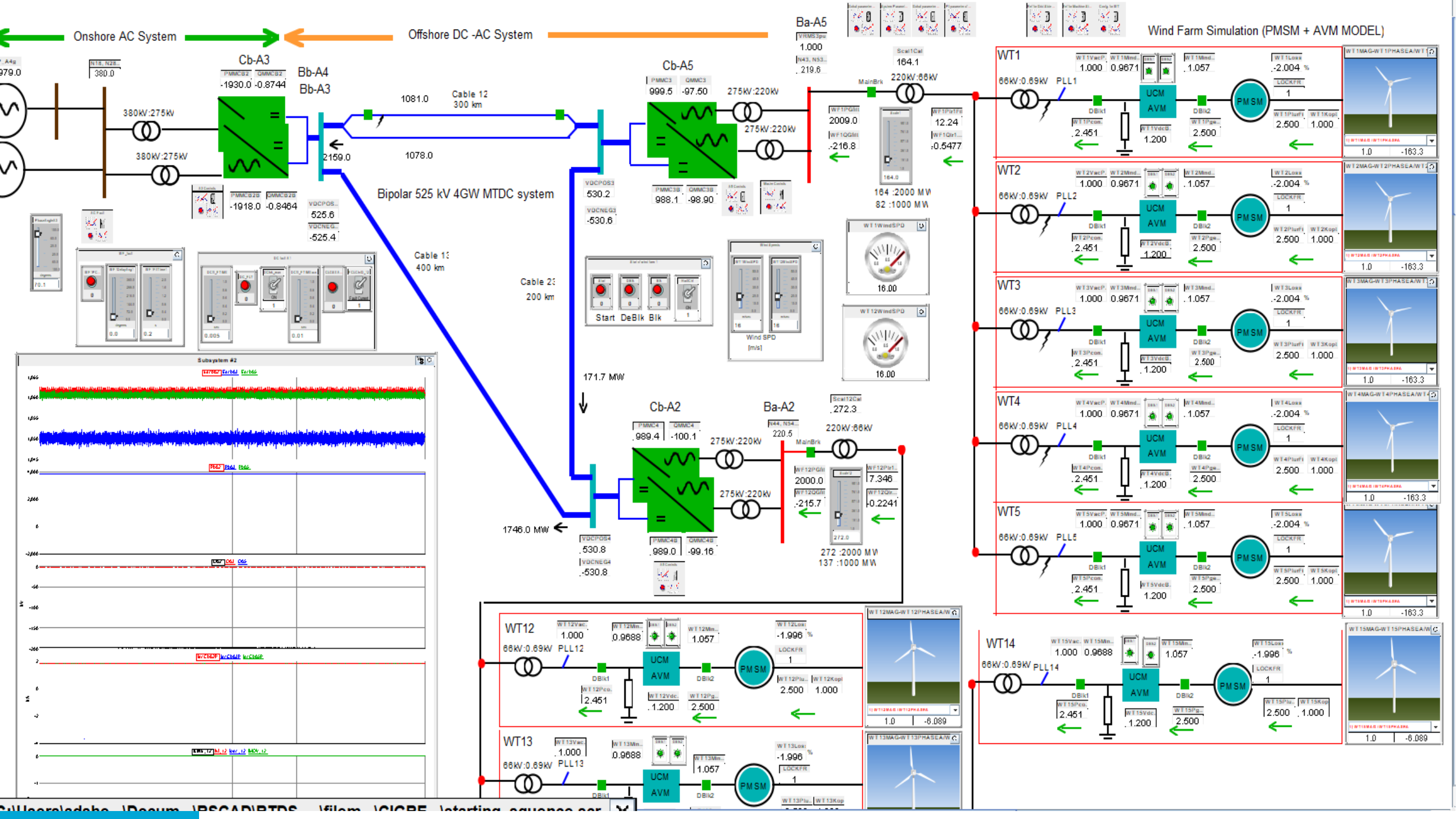
Peter Palensky

TU Delft

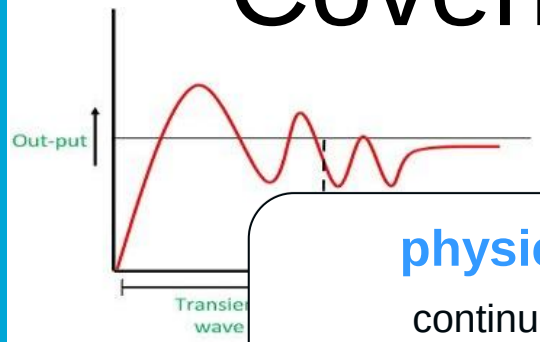
Chair Intelligent Electrical Power Grids
Director Delft Energy
PI Amsterdam Metropolitan Solutions Institute
Head Dept. Electric Sustainable Energy

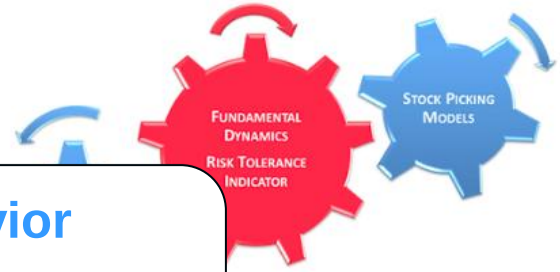
Before

TU Vienna, Austrian Institute of Technology
South Africa, California, Korea, Germany,...


Onshore AC System
Offshore DC -AC System
Wind Farm Simulation (PMSM + AVM MODEL)
Cb-A3
Bb-A4
Bb-A3
Cb-A5
Ba-A5
Cb-A2
Ba-A2
380kV:275kV
275kV:220kV
220kV:66kV
Cable 12
300 km
Cable 13
400 km
Cable 23
200 km
Bipolar 525 kV 4GW MTDC system
1081.0
1078.0
2159.0
171.7 MW
1746.0 MW
164 :2000 MW
82 :1000 MW
272 :2000 MW
137 :1000 MW
Start DeBlk Blk
Wind SPD
WT1
WT2
WT3
WT4
WT5
WT12
WT13
WT14
66kV:0.69kV
PLL1
PLL2
PLL3
PLL4
PLL5
PLL12
PLL13
PLL14
UCM
AVM
PMSM
MainBrk

Covering modern Power Systems





physical world

continuous models

energy generation, transport, distribution, consumption, etc.

roles/behavior

game theory models

Humans, agents acting on behalf of a customer, market players, etc.

cyber-physical energy system

information technology

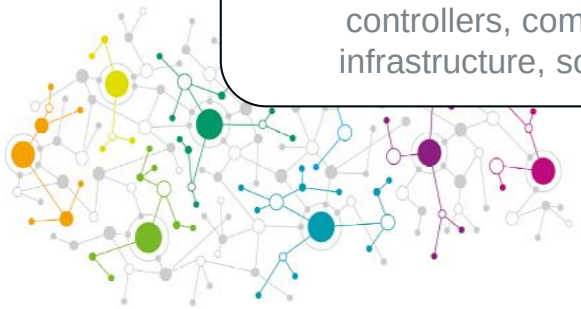
discrete models

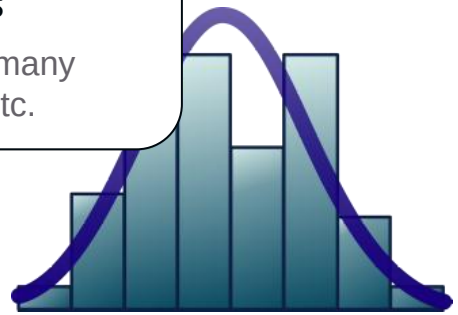
controllers, communication infrastructure, software, etc.

aggregate/stochastic

statistical models

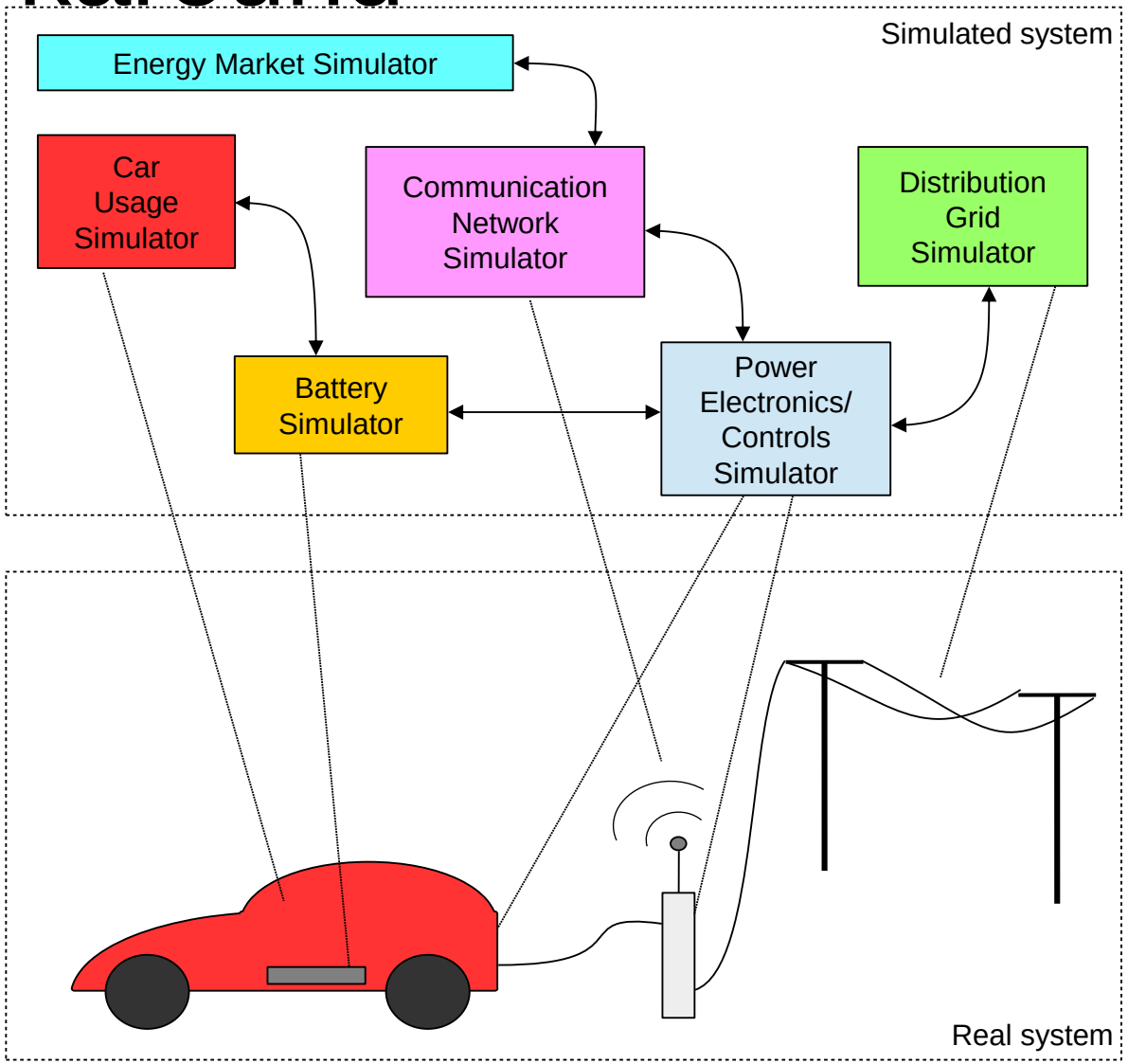
weather, macro-view of many individual elements, etc.





Workaround

- Co-Simulation
- Combine the best of x worlds
- Problems
  - Performance
  - Interfacing
  - Scenarios



AI/ML Research

1000+ scientists in climate and energy
700 scientists in AI domain

AI, Data & Digitalisation
By Convergence

TU Delft · Erasmus MC · Erasmus University Rotterdam

Centre for Energy Systems Intelligence
Leads: Mathijs de Weerdt (TUD), Yashar Ghiassi-Farrokhfal (EUR)



Delft AI Energy Lab
"With AI": Jochen Cremer, Faculty EEMCS
"In AI": Peyman Mohajerin Esfahani, Faculty 3ME

AI for Energy Grids Lab

ICAI lab (with Alliander)
Lab manager: Jochen Cremer



CaSET ELSA AI Lab
Lab manager: Neil Yorke-Smith

NL AI Coalitie

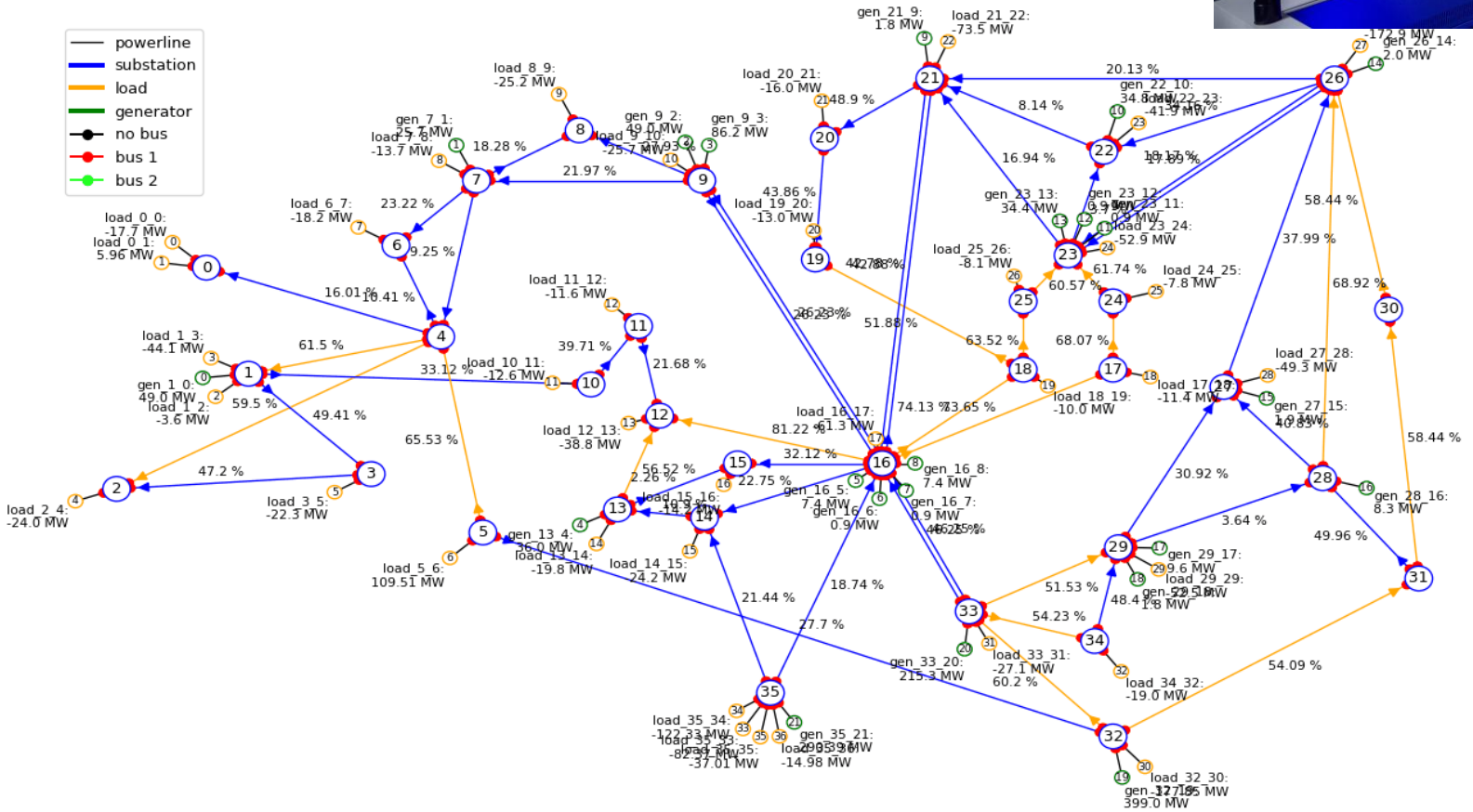
Werkgroep Energie & Duurzaamheid
Chair: Mathijs de Weerdt

AI: Artificial Intelligence, ML: Machine Learning

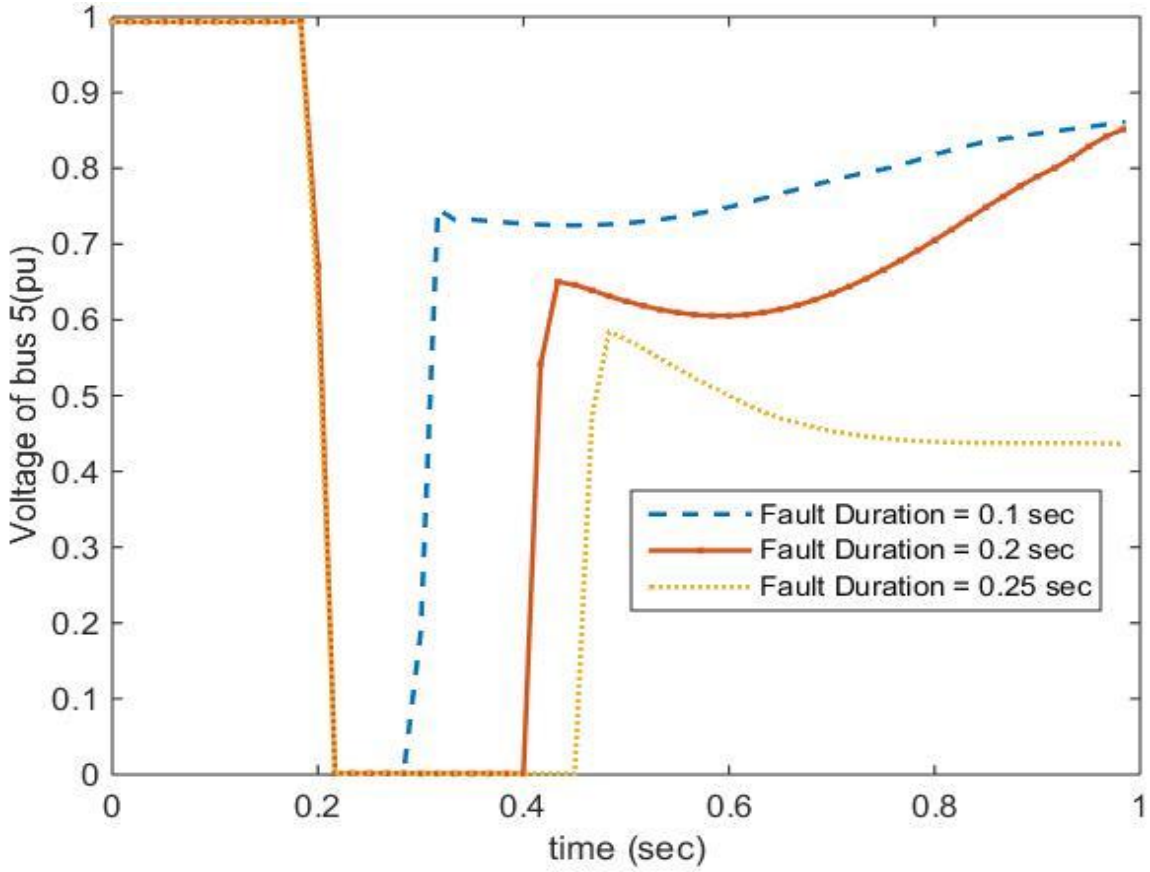
Human-in-the-loop

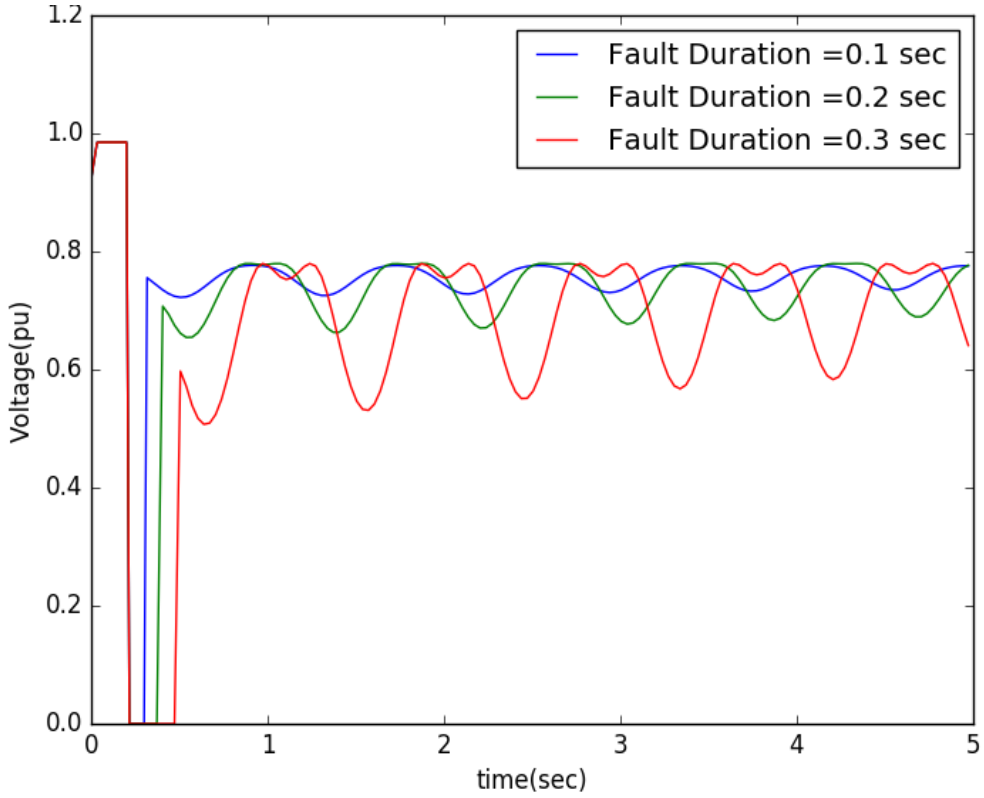
TU Delft Control Room of the Future





Example: Voltage Stability





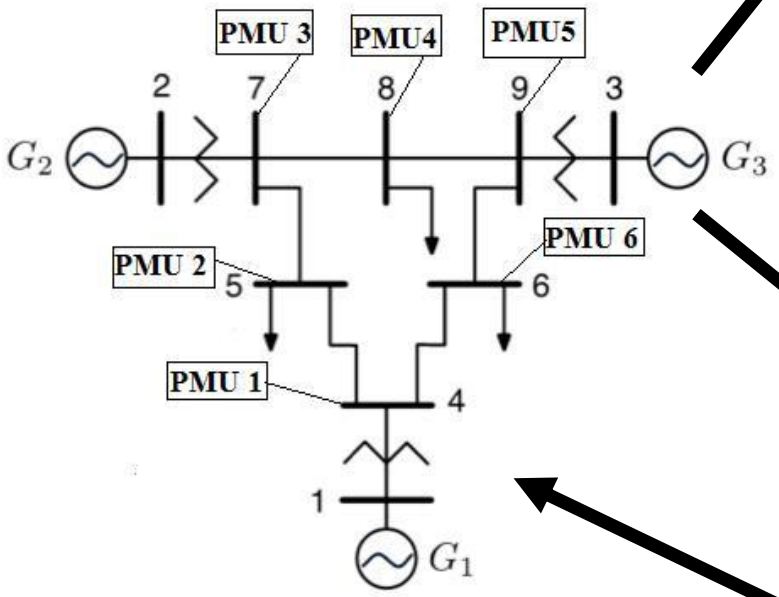
FIDVR: fault-induced delayed voltage recovery

Faster-than real time twins?

validation?
coverage?

explainability?

Real System



Identification

Model

Signatures

Surrogate

Offline Learning

Non-RT

Detection

(smart) Forecast

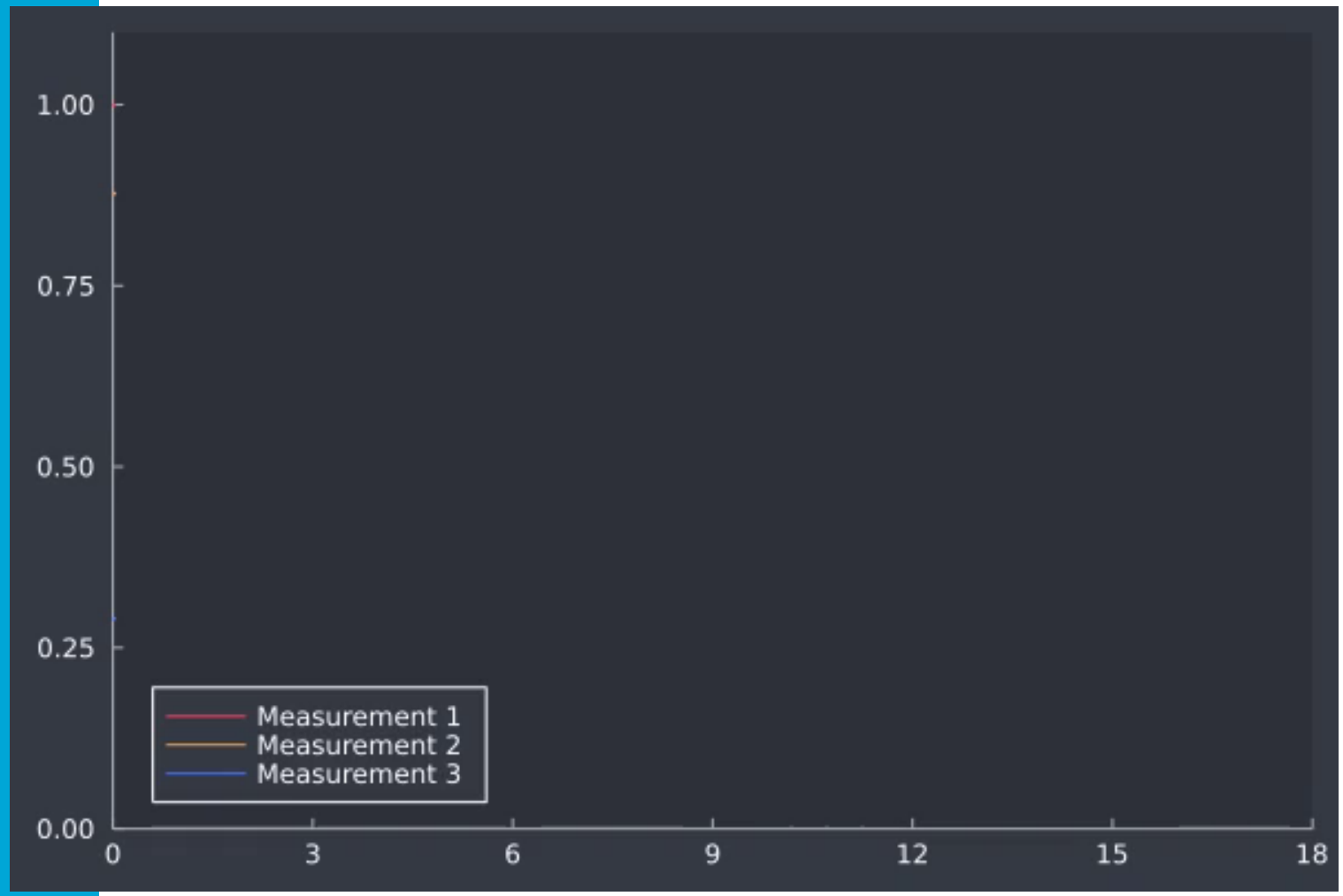
incl. remedial actions?

Scenario

Classification

Robust Decision

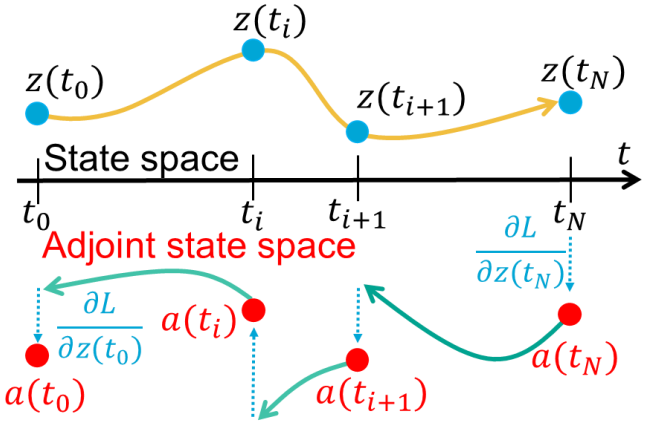
Probabilistic real-time security assessment

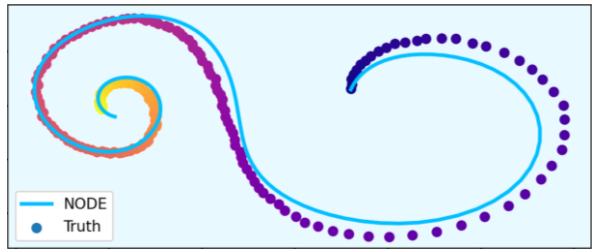




Mert Karacelebi

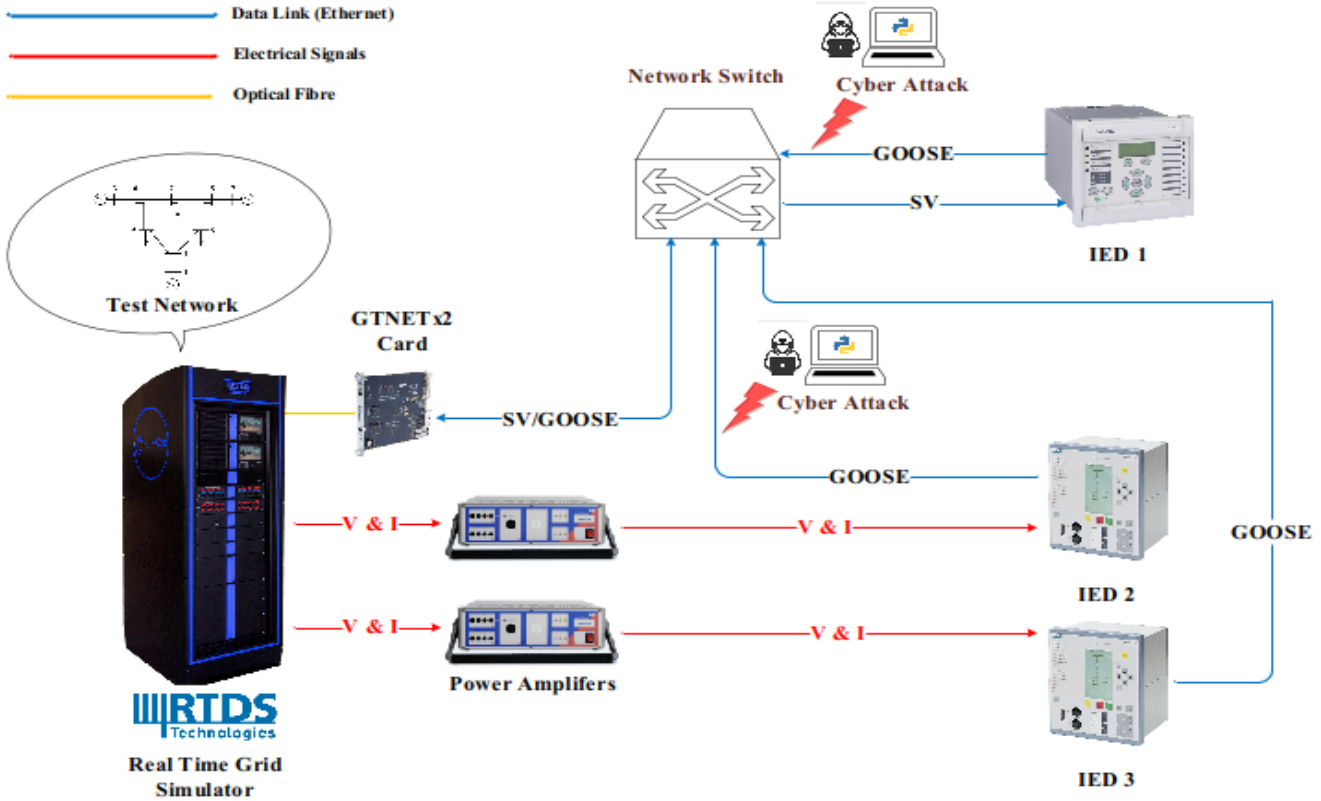
Neural ordinary differential equations





1 notch tougher: cyber-physical

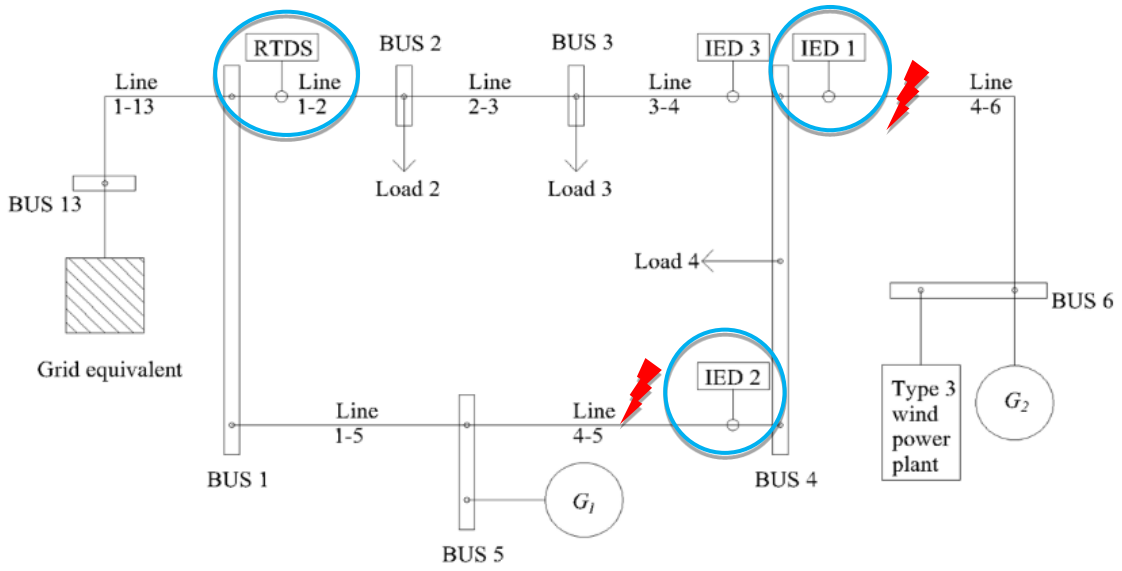
- Reconnaissance
- Preparation
- Execution



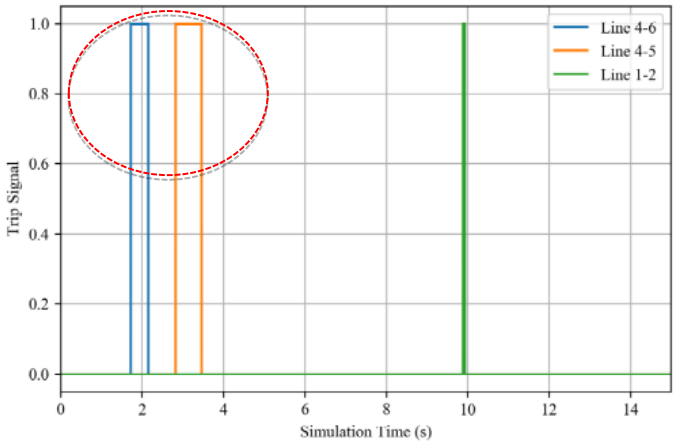

```
    Type: IEC 61850/GOOSE (0x88b8)
▾ GOOSE
    APPID: 0x8000 (32768)
    Length: 156
    Reserved 1: 0x0000 (0)
    Reserved 2: 0x0000 (0)
  ▾ goosePdu
      gocbRef: P446_SVSystem/LLN0$GO$gcb01
      timeAllowedtoLive: 2001
      datSet: P446_SVSystem/LLN0$OPGOOSEDataset
      goID: P446_GOOSE
      t: Mar 17, 1994 22:13:49.941999971 UTC
      stNum: 1
      sqNum: 23628
      test: False
      confRev: 3
      ndsCom: False
```

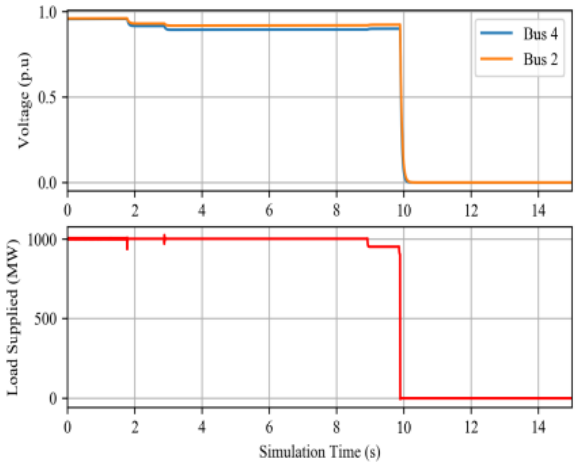
Wireshark snippets GOOSE data frame

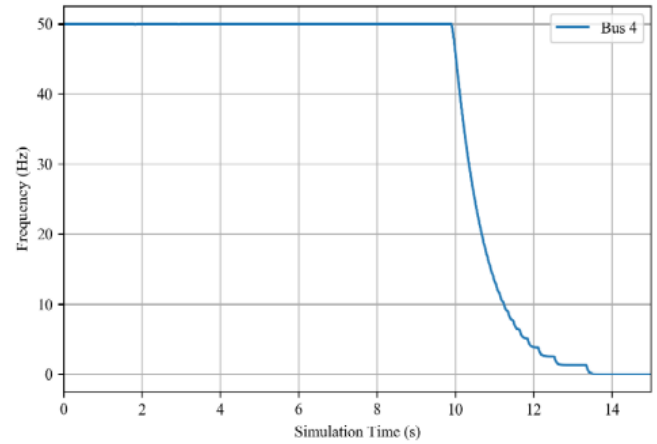
Full Blackout (N-1 anyone?)



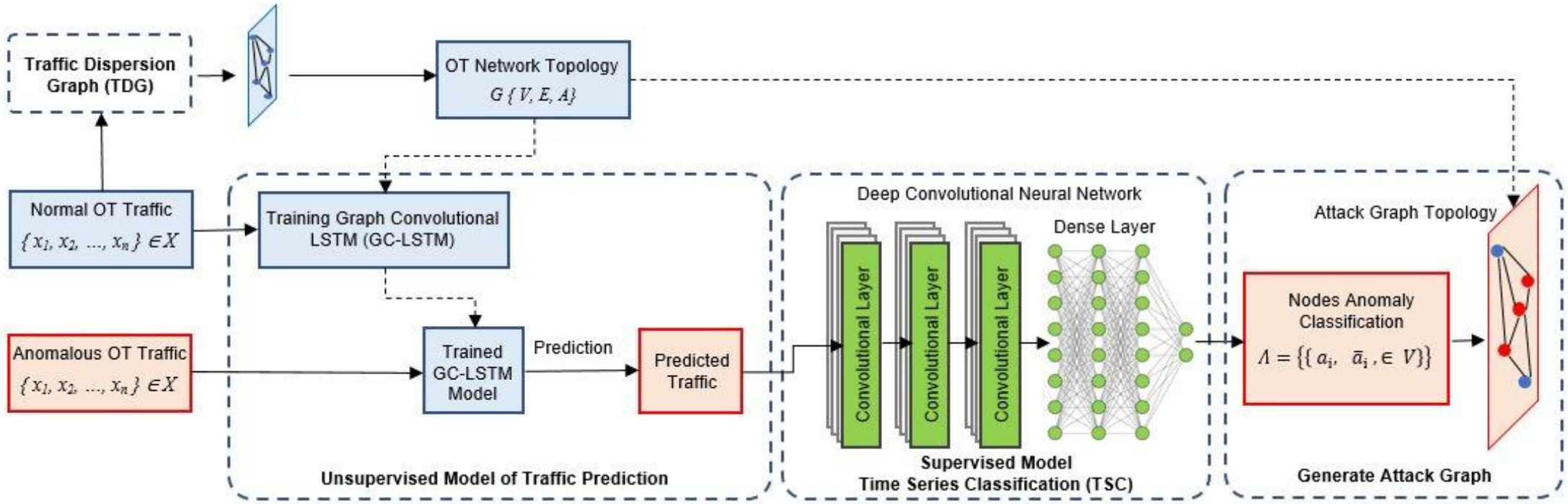
- Coordinated GOOSE cyber attack on IEDs 1 and 2
- Lines 4-6, 4-5 disconnected. G1 lost
- Voltage drops below limit of 0.92 p.u
- Overload protection trips line 1-2 (1.1 p.u, delay 7s) after cyber attack
- Leads to cascading failure and blackout







Act early: IDS and attack graphs

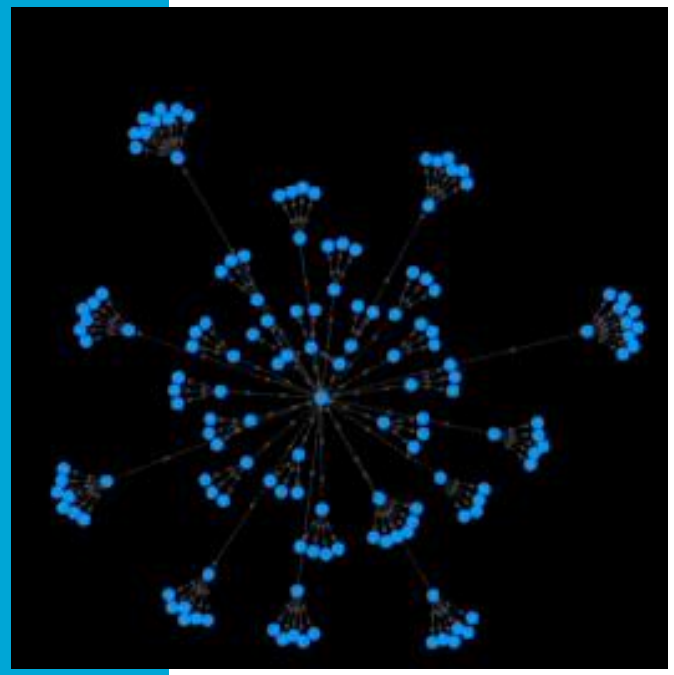


Steps:

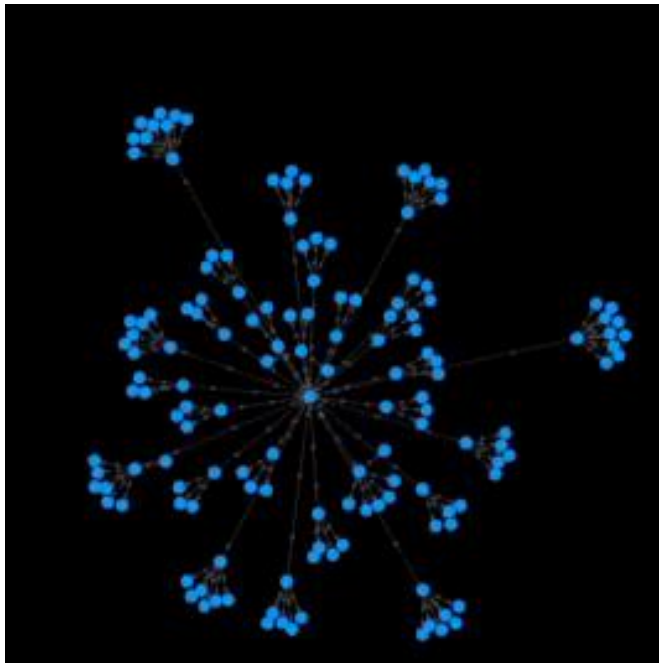
1. Graph-Convolutional-LSTM training and Traffic Dispersion Graph (Traffic model)
2. Deep Convolutional Neural Network (Classifier) training
3. Online node classification
4. Attack Graph Generation

IDS: Intrusion Detection System

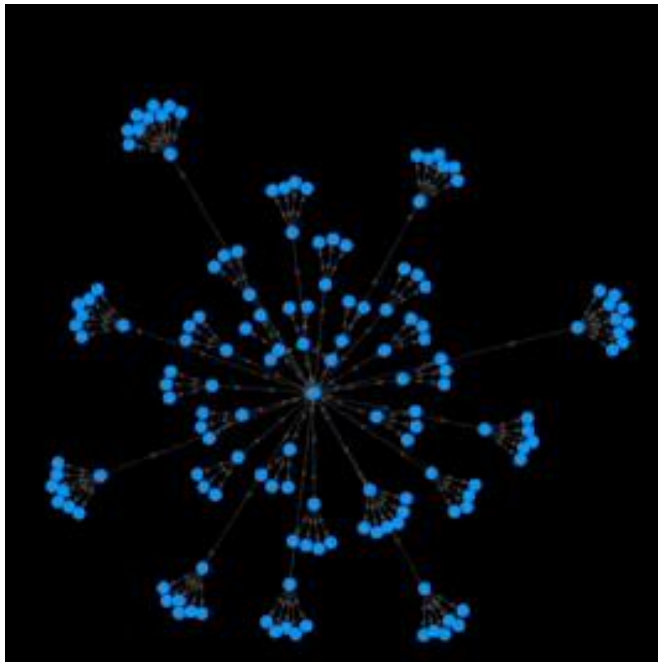
Attack graph visualization



Single Substations Attack



Multiple Substations Attack



Wide Area Attack

Quantum Computing for power problems

We convert the **continuous minimization problem** into **combinatorial optimization problem**:

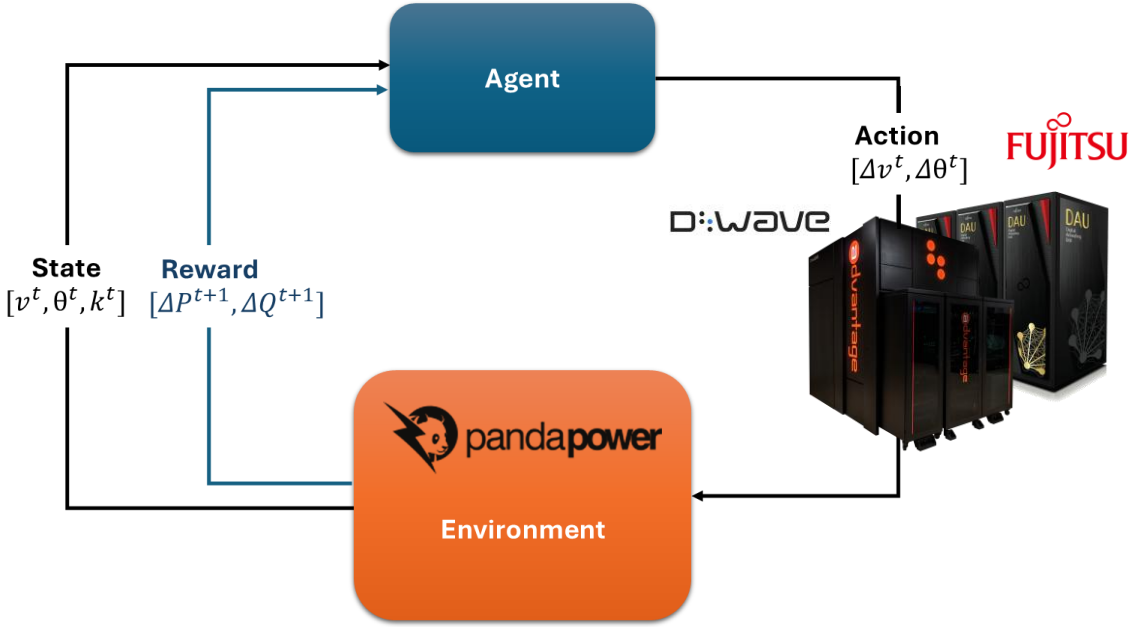
$$\min_{\boldsymbol{\mu},\boldsymbol{\omega}\in\mathbb{R}^n} H(\boldsymbol{\mu},\boldsymbol{\omega}) = \sum_{i=1}^{N} \left(P_i - P_i^G + P_i^D\right)^2 + \left(Q_i - Q_i^G + Q_i^D\right)^2,$$

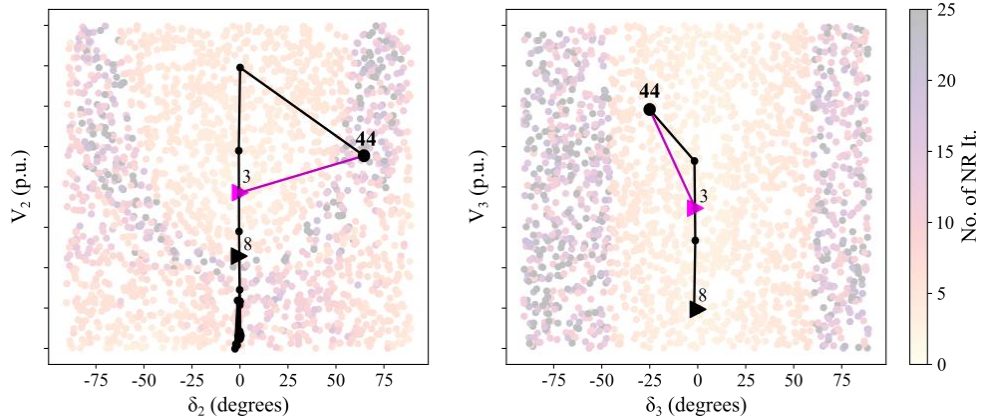
where

$$\mu_i = \mu_i^0 + x_{i,0}^{\mu}\Delta\mu_i - x_{i,1}^{\mu}\Delta\mu_i$$
$$\omega_i = \omega_i^0 + x_{i,0}^{\omega}\Delta\omega_i - x_{i,1}^{\omega}\Delta\omega_i$$

We **Iteratively update** $\boldsymbol{\mu},\boldsymbol{\omega}$ and $\boldsymbol{\mu^0},\boldsymbol{\omega^0}$ until $H(\boldsymbol{\mu},\boldsymbol{\omega}) < \varepsilon_{\text{tol}}$

$\boldsymbol{\mu}$ and $\boldsymbol{\omega}$ are *node* properties in rectangular coordinates, $x_{i,0/1}^{\mu}$ and $x_{i,0/1}^{\omega}$ are binary decision variables.





--> Quantum-Enhanced RL for PowerFlow!

(Q)RL agent shifts initial voltages from a region where 44 NR iterations are needed to 3

NS: Newton-Raphson
RL: Reinforcement Learning

25 years into the Future?



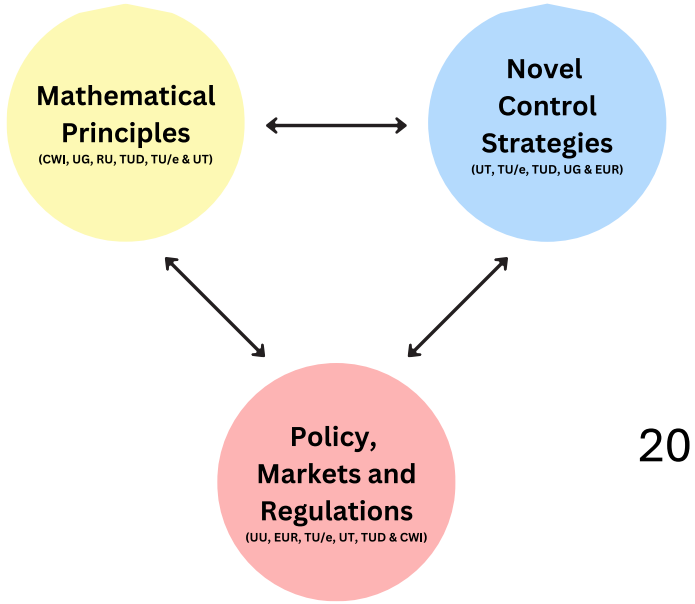
- Autonomous operation, self-organization
- Digital twins for everything
- Electrification (of the rest of the world)
- New math for cyber-physical dynamics



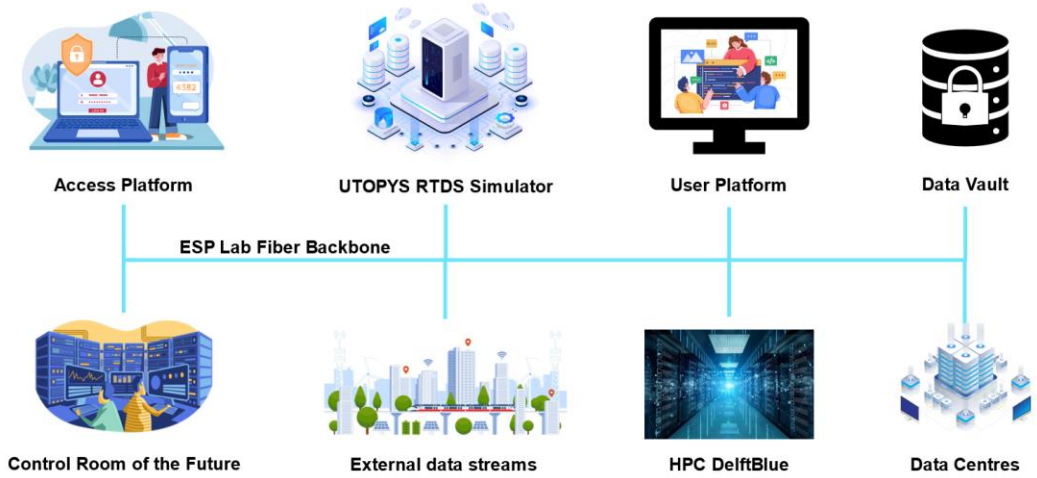
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UTOPYS ecosystem





20 years program…







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