12 Feb 2025, 3rd In-Person Foundation Models for the Electric Grid Workshop

Building smarter grids with AI: Insights from EU projects

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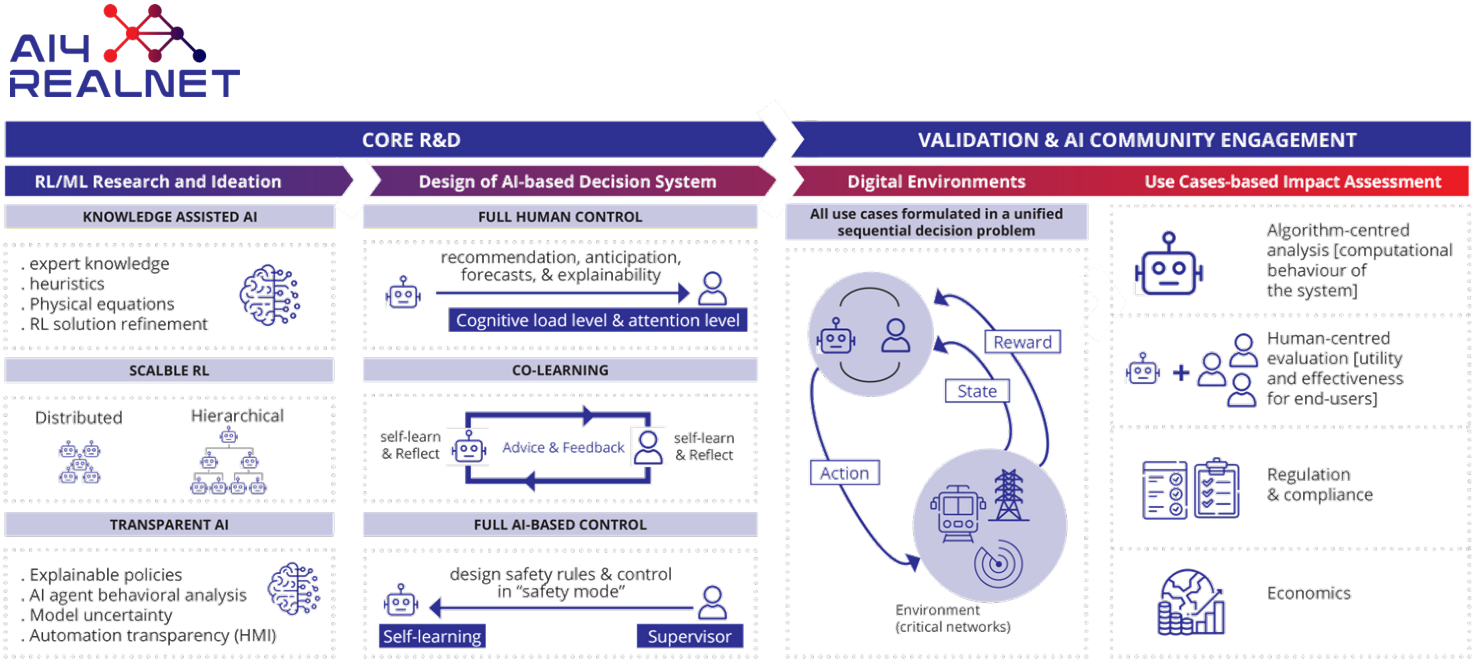
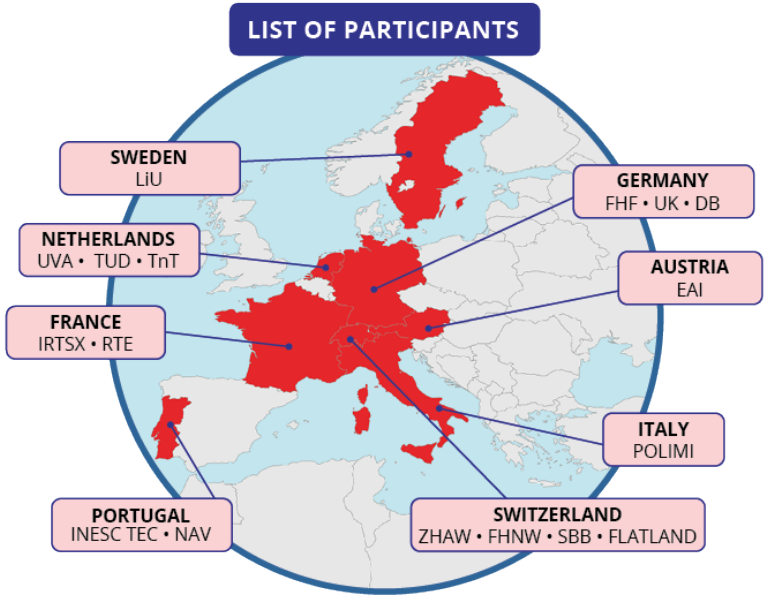
INESC TEC AI ecosystem for energy

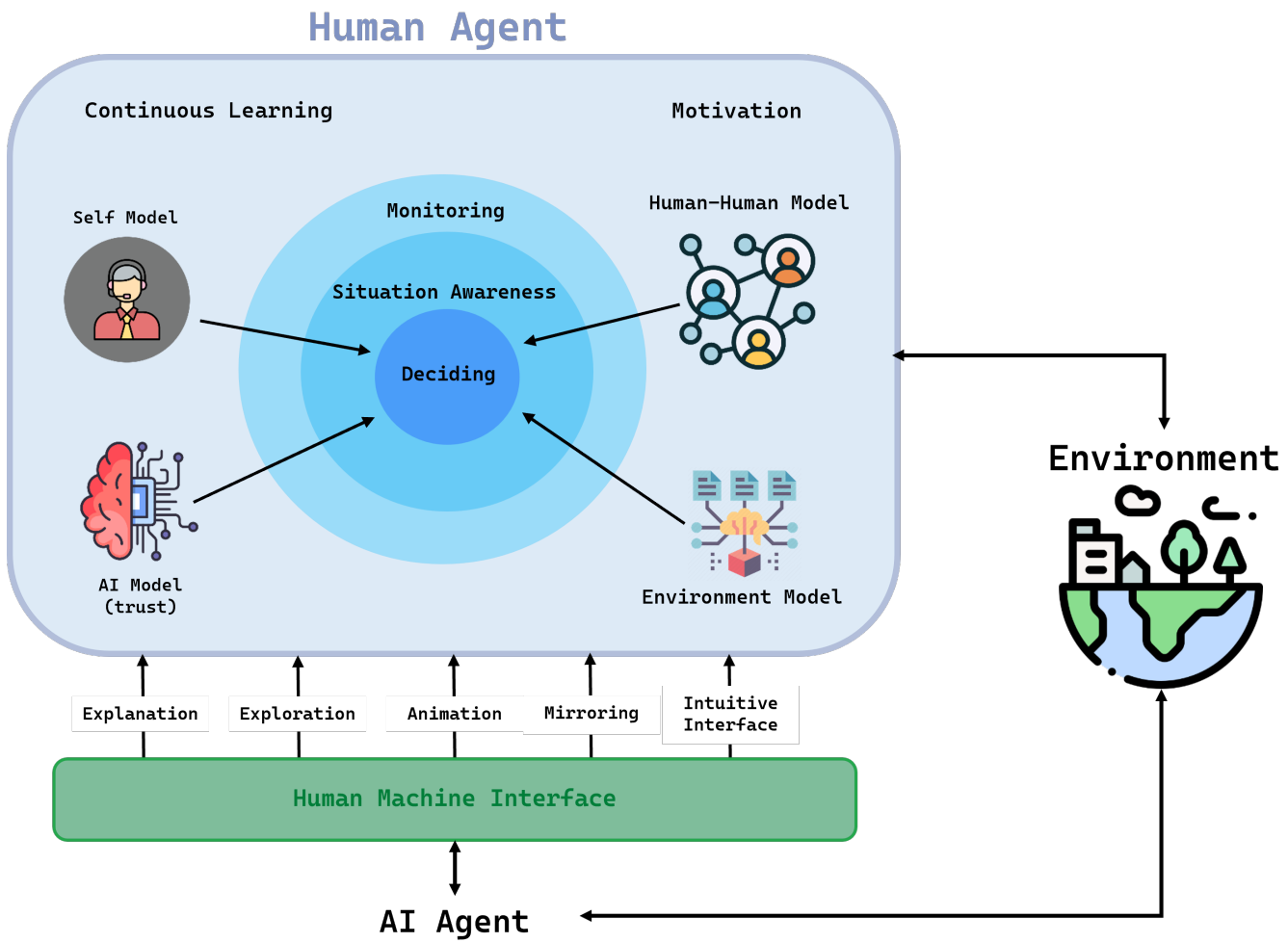
AI4REALNET in a nutshell





Use Cases

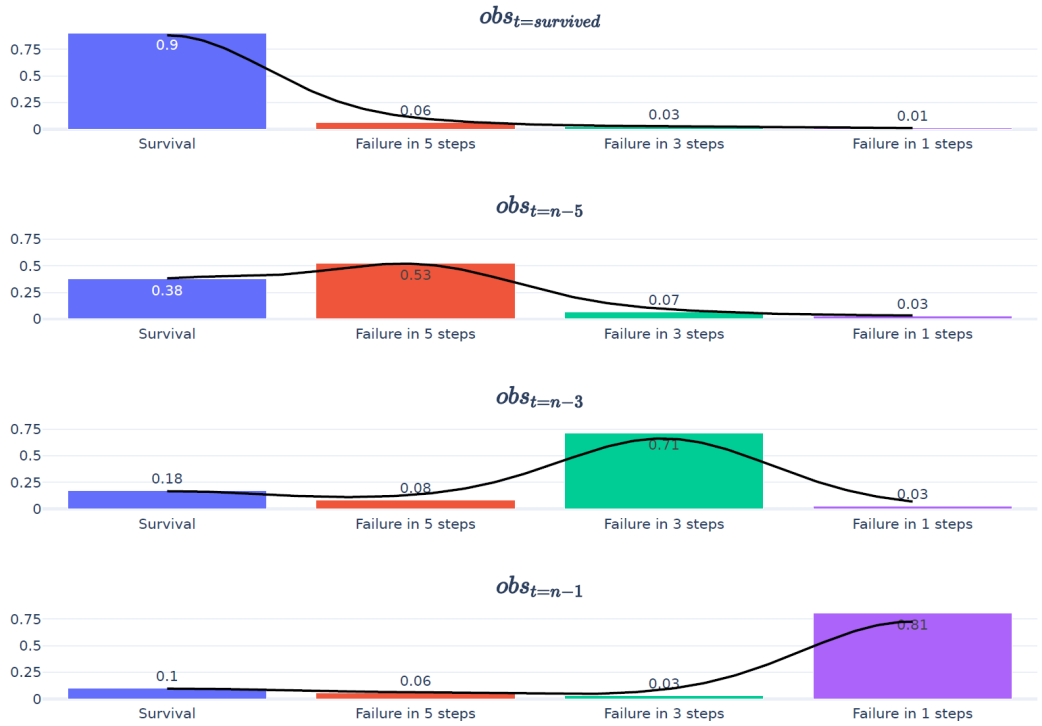
Conceptual framework

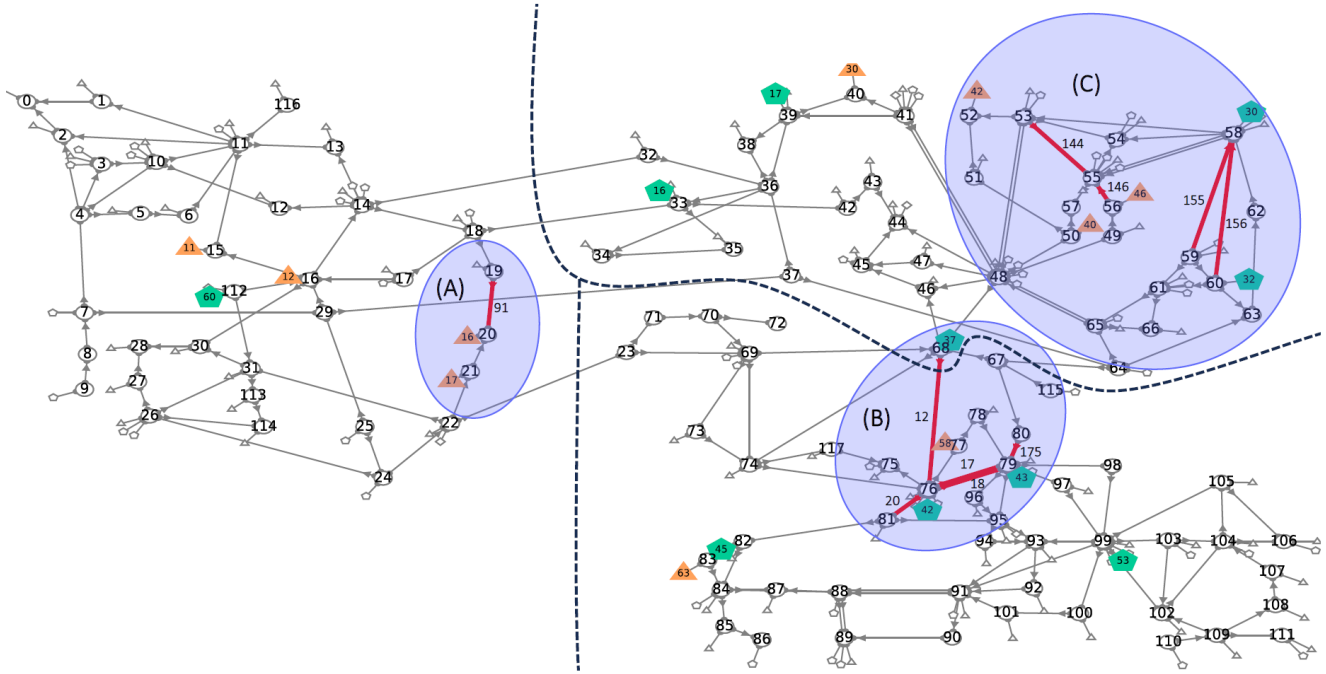


Framework

Highlight 1: Explainability of AI agent behaviour

GOAL: prediction approach to detect AI agent failures beforehand

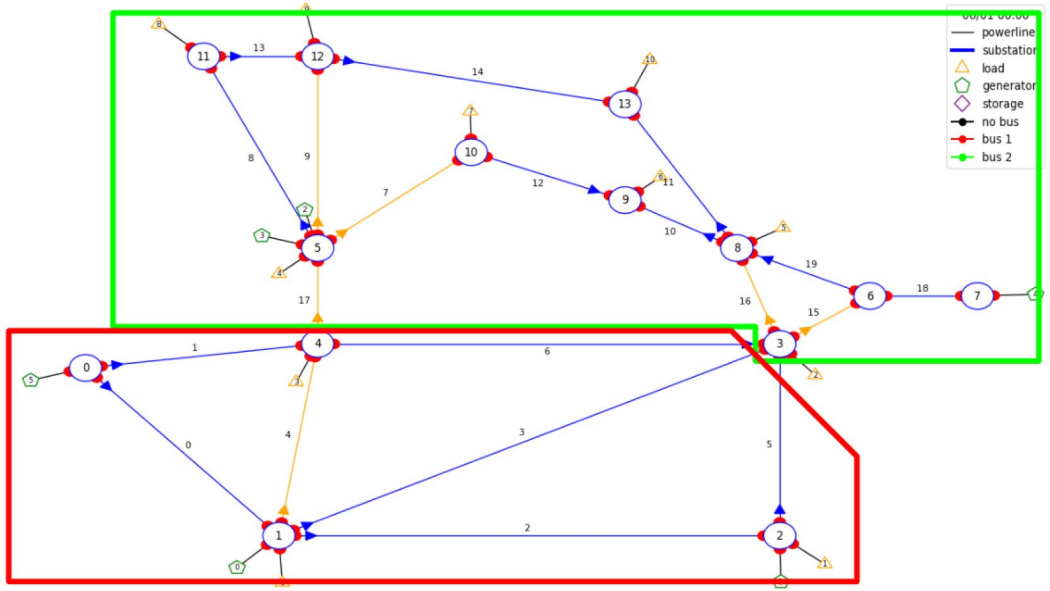


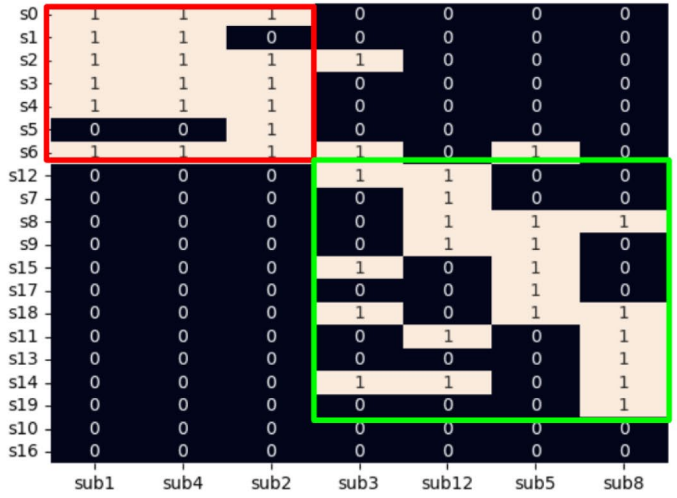


Lehna et al., 2024

Highlight 2: Distributed reinforcement learning

GOAL: Divide into subproblems that can lead to distinct learning processes with less computational and data requirements





Highly correlated state-action pairs are grouped together to create simpler

Losapio et al, 2024

Highlight 3: Interactive AI

GOAL: Experimentation of bi-directional virtual assistants for joint decision-making

notifications about risks and events

Alerts

Overload on line 5_10_7

Warning: the line 7 connecting nodes 5 and 10 is overloaded by 112%

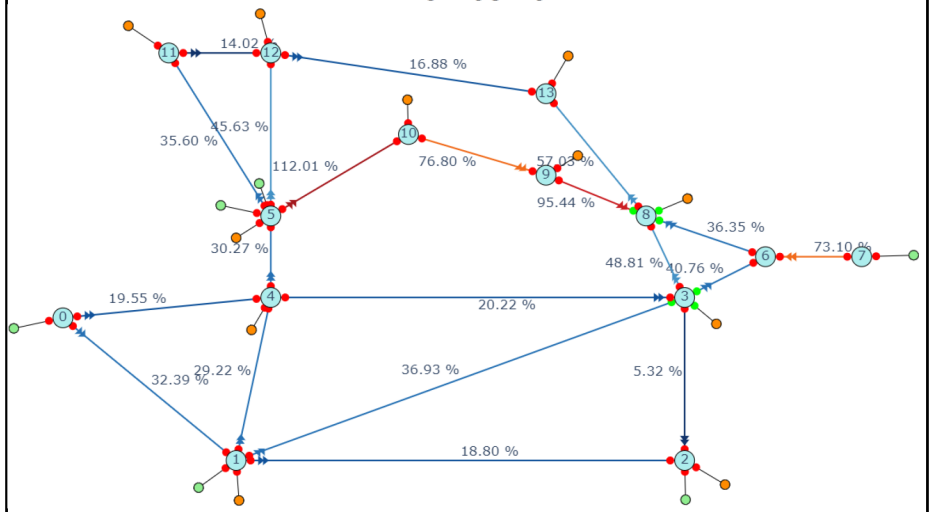
Security

Risk of N-1 contingency on line 9_10_12

Security

real-time view of the environment with tools like zooming

Context



AI-based suggestions that operators can adopt

Recommendations

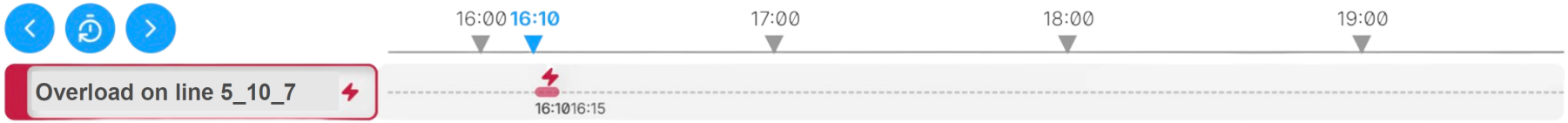
Topological change

Switching to the scheme at substation 5

Redispatch

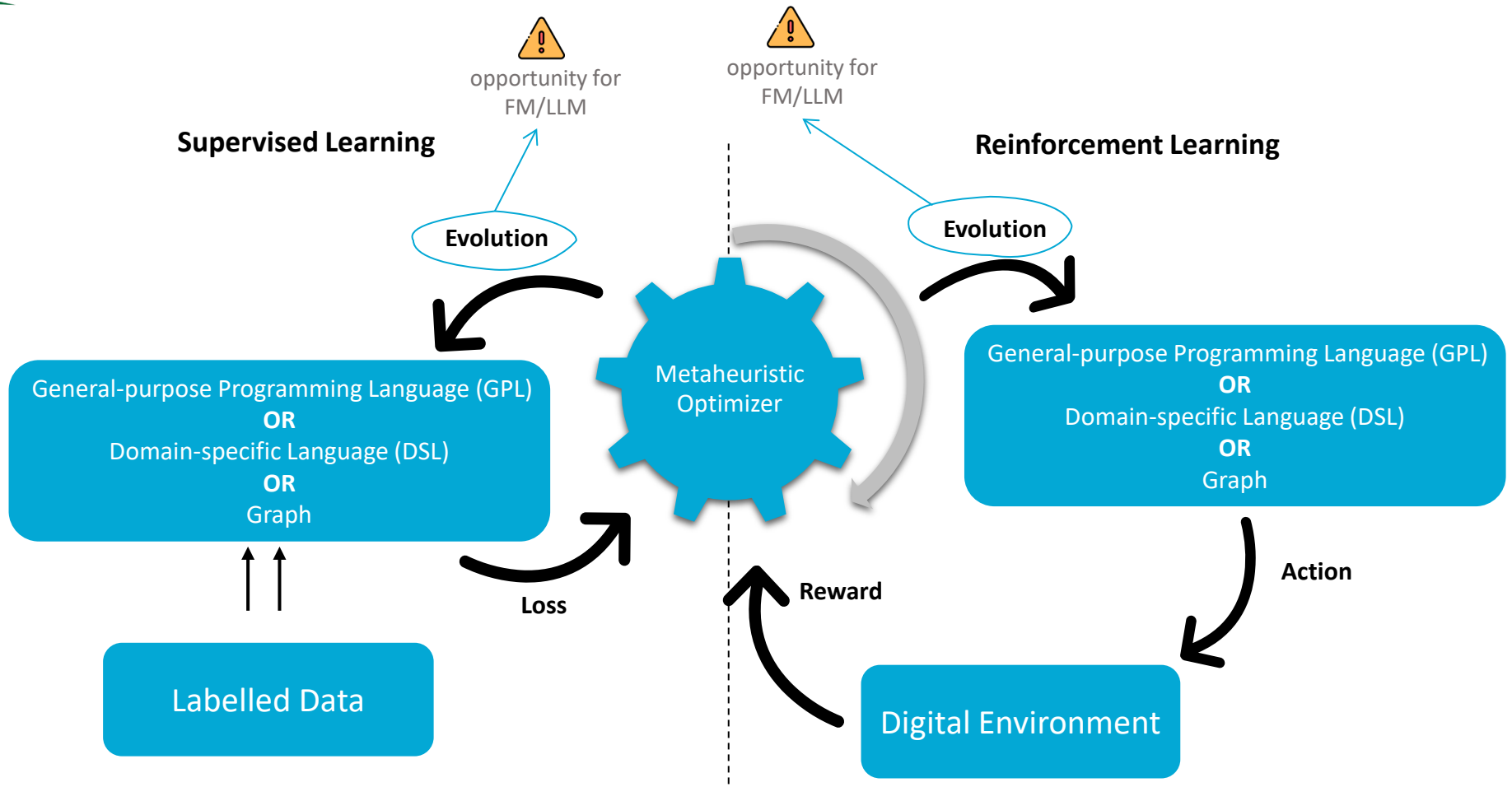
Reduce the generator 2 by 3 MW

Timeline



tracking time steps and event history for analysis

Evolving symbolic model (ESM) concept



Fernandes et al.

ESM for dynamic security assessement

template evolution process

```
if { Conditional Statements } :
      { Sequence of Action }
elif { Conditional Statements }:
      { Sequence of Action }
else:  { Sequence of Action }
```

Example of a simplistic template for ESM

Algorithm 1 Evolution process of the ESM

Require: Kb, T_0, T_f

1: Generate a symbolic model, SM_i (II-B).
2: Tune numerical constants of SM_i (DE).
3: **while** $T > T_f$ **do**
4: Generate neighbor symbolic model, SM_n (III-B).
5: Tune numerical constants of SM_n (DE).
6: **if** $\mathcal{F}_i > \mathcal{F}_n$ **or** $\mathcal{R}(0,1) < e^{\frac{\mathcal{F}_i - \mathcal{F}_n}{T \cdot Kb}}$ **then**
7: SM_i=SM_n
8: Adjust T according to cooling scheme
9: Perform simplification on SM_i (III-C).

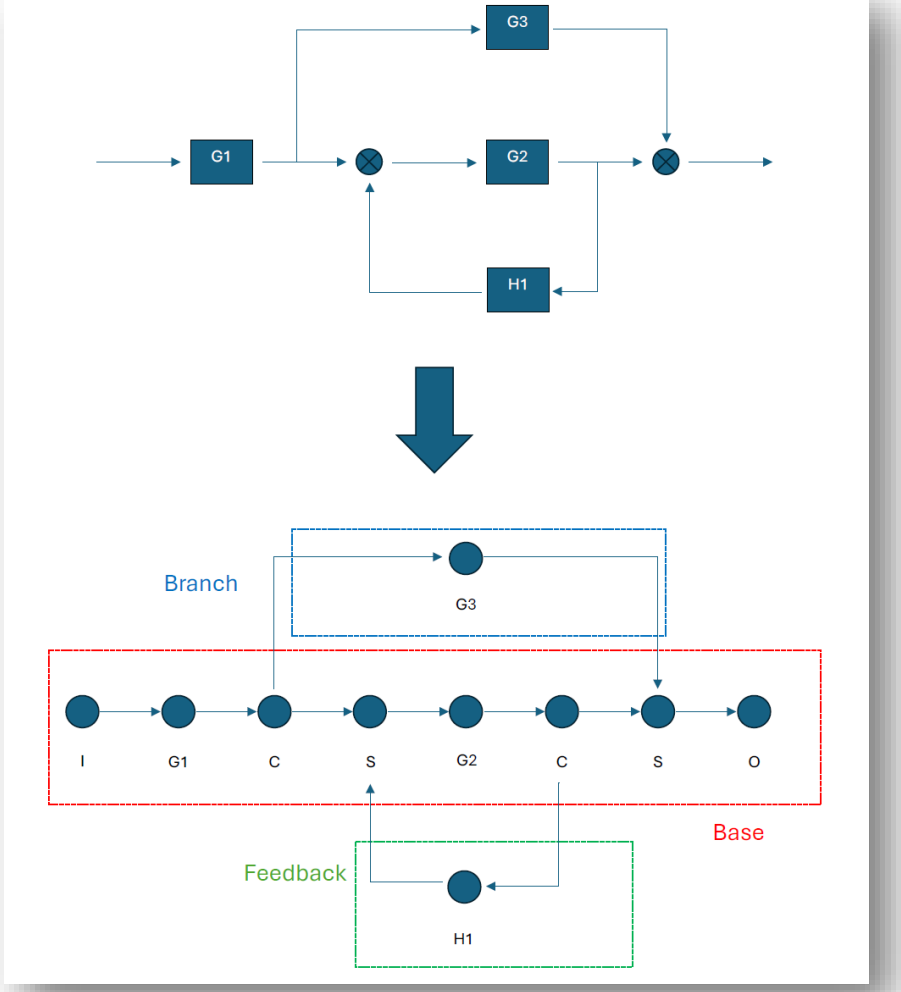
```
#--------------ESM Classifier--------------#
if {0.7 × H_GFM/Wind_ZPM + 4.03 × H_Sym/Load < 6.40  AND
    3.56 × Res_noFRT × H_Sym − 5.87 × Res_IP < −2}:
                    return {1}
elif {  −7.87 × Load + 3 × Load × H_Sym < −8.18  }:
                    return {1}
else :              return {0}
```

```
if (S>0):
    if (1.6 × (S × H_Sym) + 0.33 × (H_Sym/Res_IP)) < 1.42) :
        H_sa  =  1.32 × (PV_ZPM/H_Sym)
        H_va  =  2.02 × (Load/Res_IP)
    else:
        H_va  =  13.11  × S
```

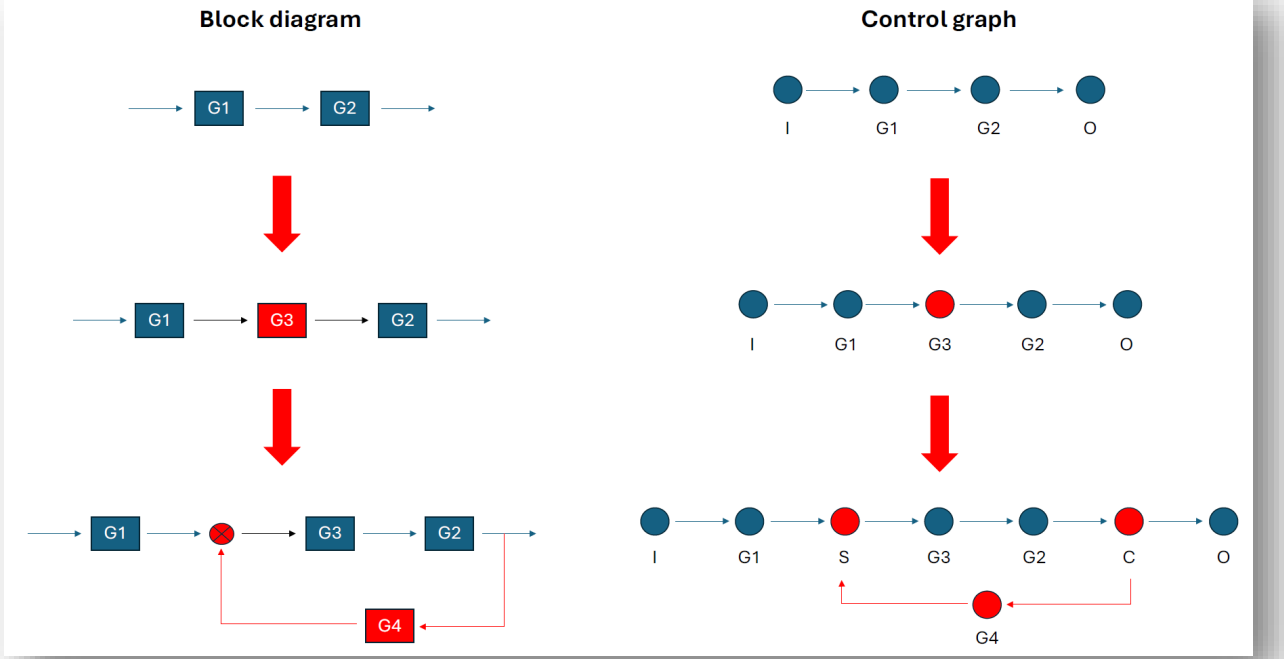
Decision system

ESM for learning control systems with grid-forming

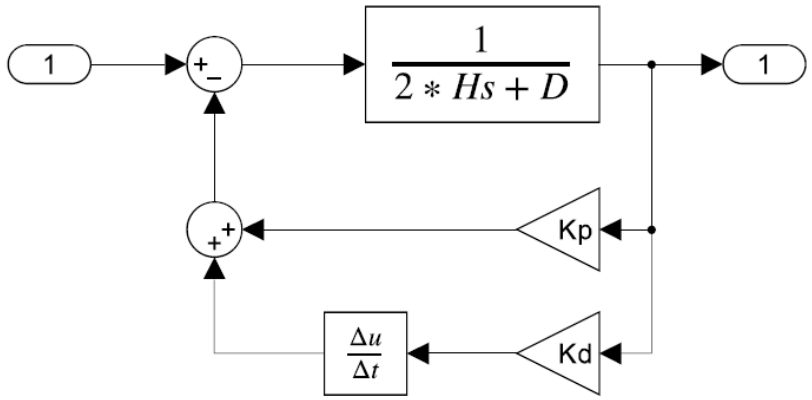
Knowledge representation



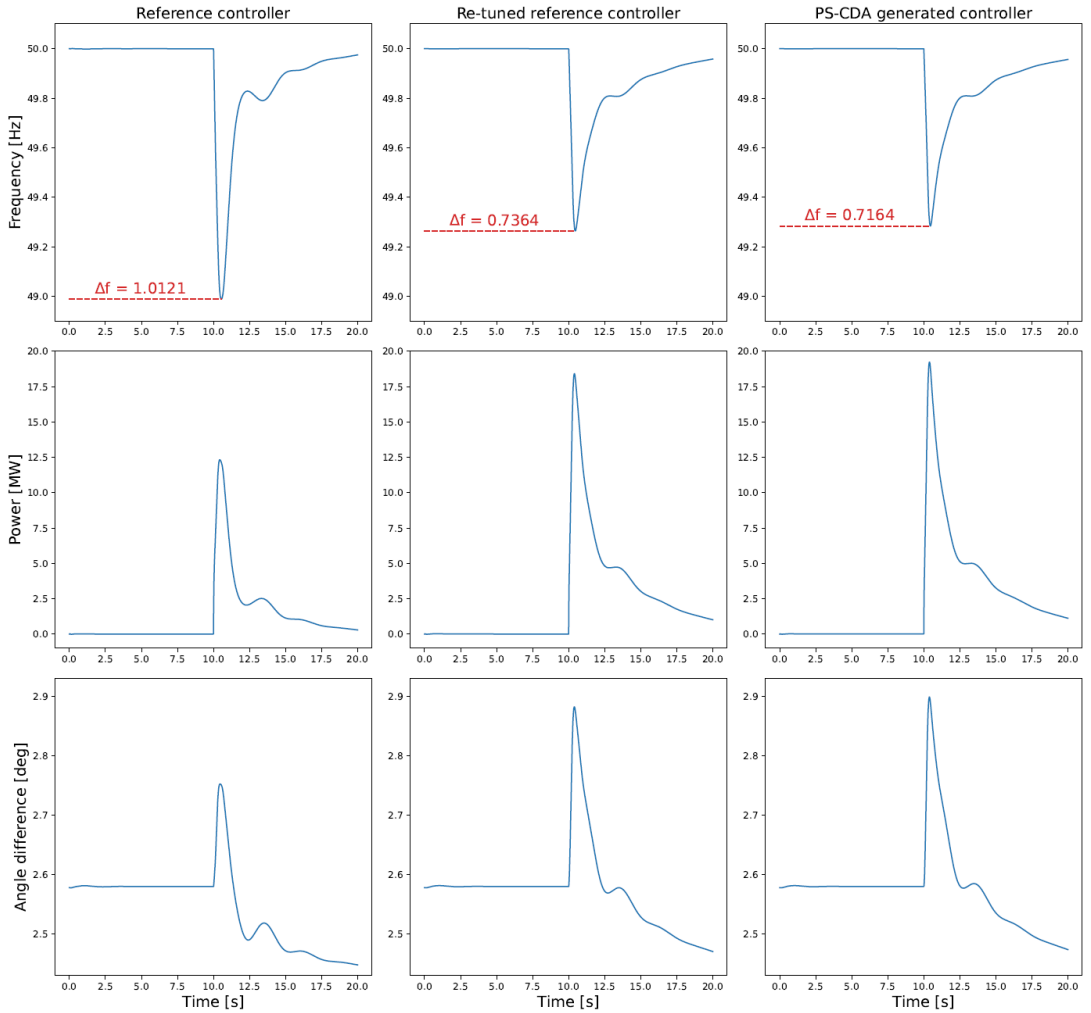
Evolution of control graphs



ESM for learning control systems with grid-forming



Control system learned with ESM for the GFM converter



Testing and experimentation facility (TEF)

AI·EFFECT

Defined by the EC as a ***"combination of physical and virtual facilities, in which technology providers can get primarily technical support to test their latest AI-based software and hardware technologies in real-world environments"***

Danish Node

District Heating and Sector Coupling

Dutch Node

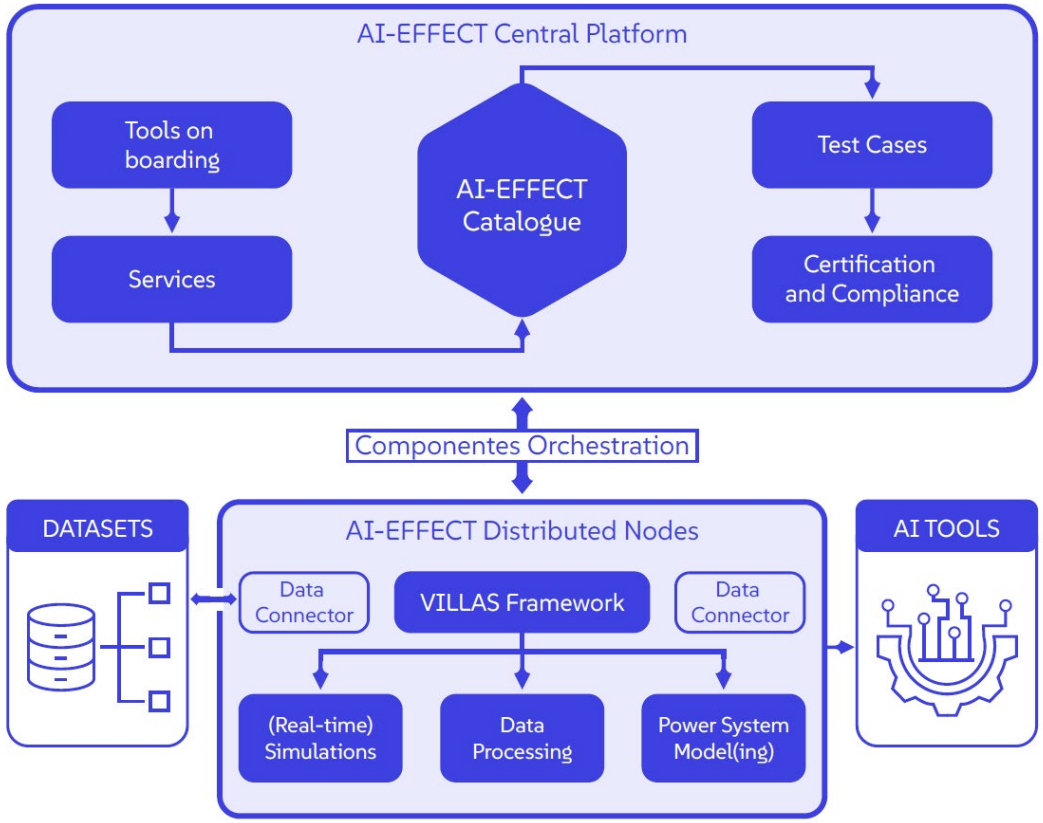
Transmission System Congestion Management

German Node

DER Integration in Distribution System

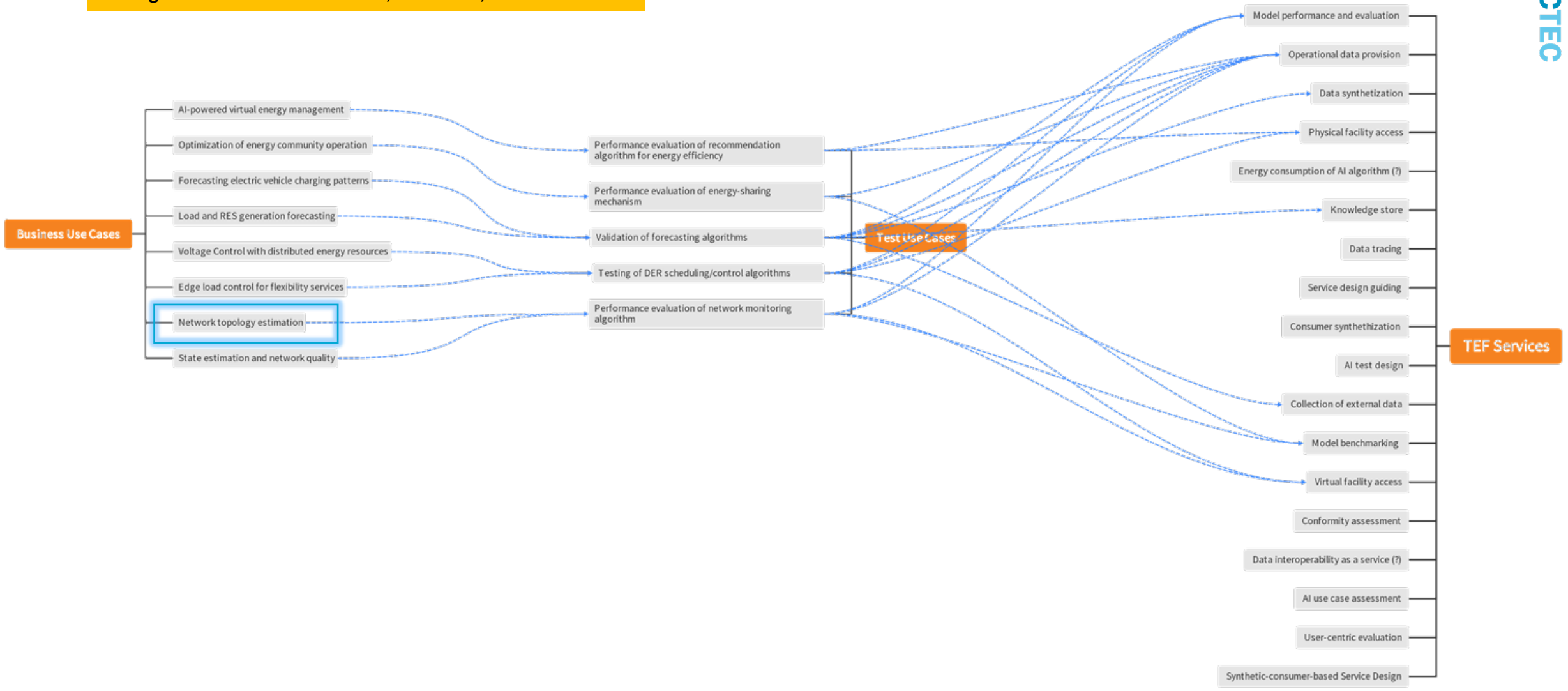
Portuguese Node

Energy Community Data Space



Testing and experimentation facility (TEF)

Portuguese node: business cases, test cases, and TEF services



TEF: Low voltage network reconstruction

Discover Low Voltage grid **topologies** given **smart meter data**

WHY?

- Incorrect or inexistent topological and electrical characterization
- Traditional approaches lack robustness to voltage errors

Initial Conditions

- Power measurements
- Voltage measurements

No additional information

Electric Characteristics Prediction
(for a candidate Topology)

$$\left(V_i(t), P_i(t)\right)$$

$$Z_{ij} = \left\langle \frac{V_i(V_i - V_j)}{\sum_{k\in\mathcal{J}} P_k} \right\rangle_t$$

$$\tilde{V}_i(t)$$

$$V_i - V_j \approx Z_{ij} \sum_{k\in\mathcal{J}} \frac{P_k}{\tilde{V}_i}$$

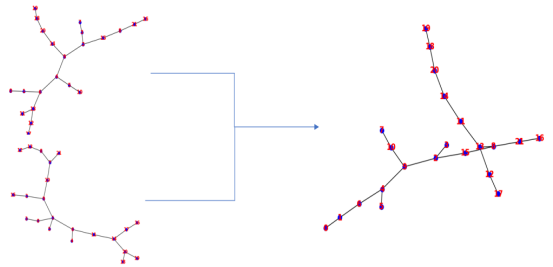
$$\tilde{\tilde{V}}_i(t)$$

Compute the fitness score

Genetic Algorithm evolution

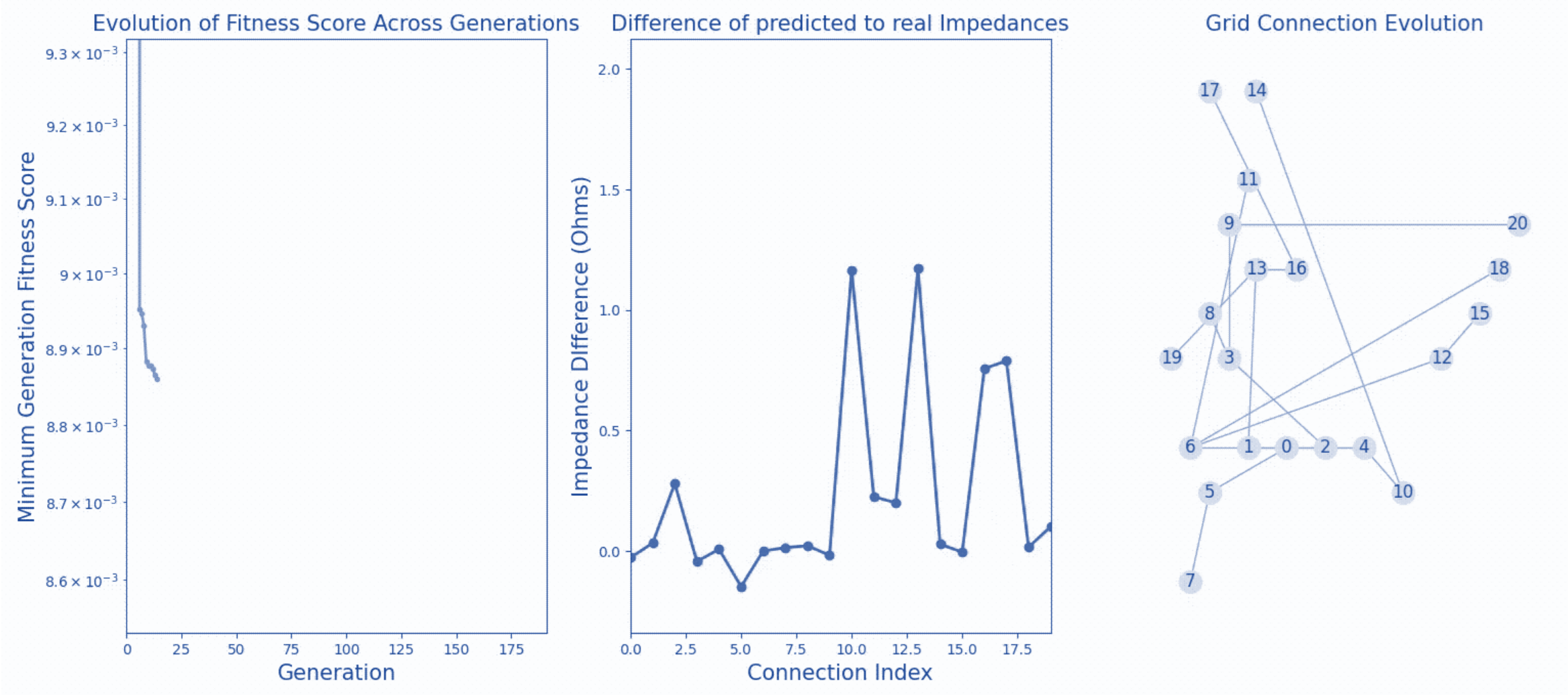
Generate a new offspring using the traditional GA operators

- Grid mutation
- Grid recombination weighted with fitness scores
- Elite selection



Convergence to the correct topology

TEF: Low voltage network reconstruction



Smart alarm management

evdate	evdesc				
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I> INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P330	TR		
2014-01-02 06:33:14.000	SE SAO JORGE	30	TR		
2014-01-02 06:33:14.000	SE SAO JORGE		TR		
2014-01-02 06:33:14.000	SE SAO JORGE		TR		
2014-01-02 06:33:13.000	SE SAO JORGE	P502	TRANSFORMADOR2	MAX I> INST UP2 - DIF	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I>>> INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I>>> TEMP	DISPARO
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	PROT DEFEITO FASE-FASE	DISPARO
2014-01-02 06:33:24.000	SE SAO JORGE	P332	SAO MAMEDE	SUPERVISAO CIRCUIT DESL	ALARME
2014-01-02 06:33:14.000	SE SAO JORGE	P330	TRANSFORMADOR2	NORMALIZACAO TENSAO+FREQ	INACTIVO
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	DISJUNTOR	DESLIGADO
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	PROT TERRAS RESIST INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	MAX I>> INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	PROT TERRAS RESIST INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P329	TSA+REACTANCIA2	MAX Io> DTR INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P329	TSA+REACTANCIA2	MAX Io>>DTR INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I>>> INST	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	MAX I>>> INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	MAX I> INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P328	PATAIAS	PROT TERRAS RESIST INST	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P329	TSA+REACTANCIA2	MAX Io>>>INST PHB	ARRANQUE
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I> INST	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I>> INST	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	PROT DEFEITO FASE-FASE	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	PROT TERRAS RESIST INST	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P332	SAO MAMEDE	MAX I>>> TEMP	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P328	PATAIAS	PROT TERRAS RESIST INST	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	MAX I>>> TEMP	DISPARO
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	PROT DEFEITO FASE-FASE	DISPARO
2014-01-02 06:33:14.000	SE SAO JORGE	P509	BARRAMENTO2	TENSAO BARR	56.386 KV Baixo
2014-01-02 06:33:14.000	SE SAO JORGE	P329	TSA+REACTANCIA2	MAX Io>>>INST PHB	NORMAL
2014-01-02 06:33:14.000	SE SAO JORGE	P326	MIRA D'AIRE	DISJUNTOR	DESLIGADO

only ~10% of 8,631,091 historical records are relevant

Source: E-REDES SCADA Alarm event log data
(a snapshot for less than a second)

Power system more complex to operate

Operation complexity rising at a fast pace
(e.g., DER, prosumers, grid maintenance)

Grid monitoring & protection equipment

Large volume of real-time and historical alarms data

Decision-making under pressure

High-volume of the information generated during outages

up to 200 alarm messages per minute

High Cognitive Load!

Alarms!

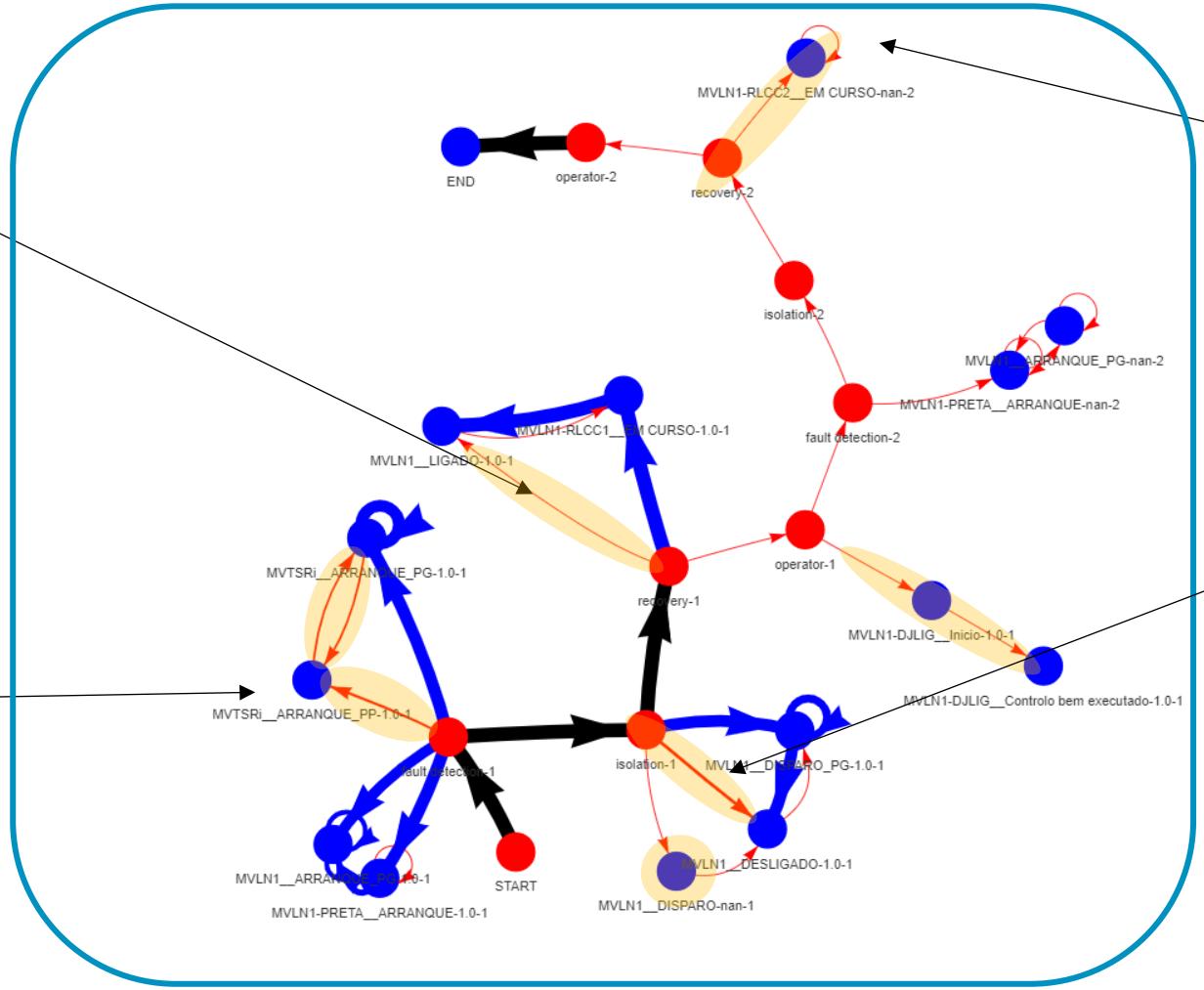
Decisions!

Data!

Smart alarm management

Time synchronization problem
(reclosure cycle event after circuit breaker closed)

Abnormal pickup during phase-to-ground fault

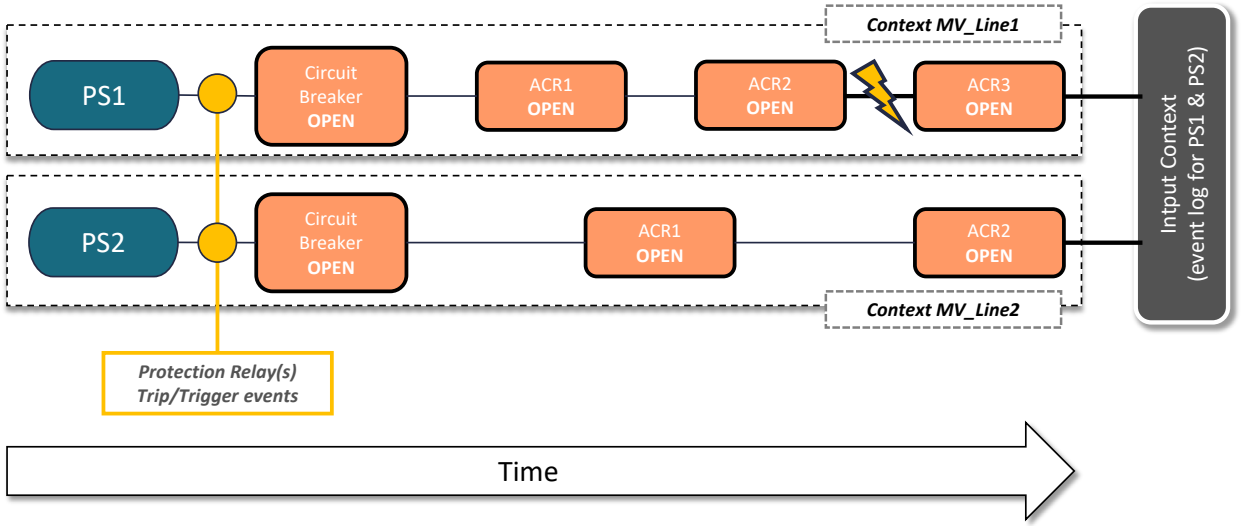


Operator sent command to close a circuit breaker after it was closed already

Missing event
(circuit breaker opens without a protection TRIP)

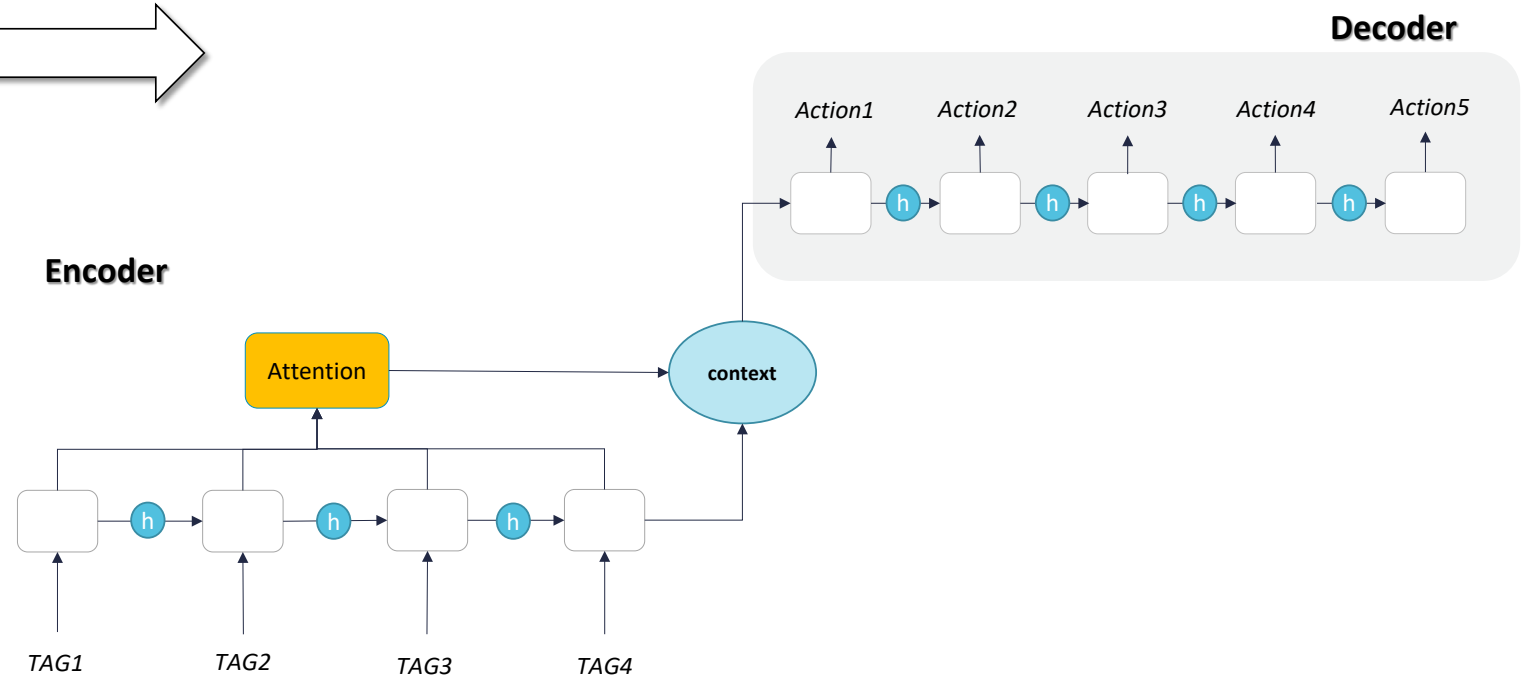
Graph for a collection of short phase-to-ground cases

Smart alarm management



Occurrence

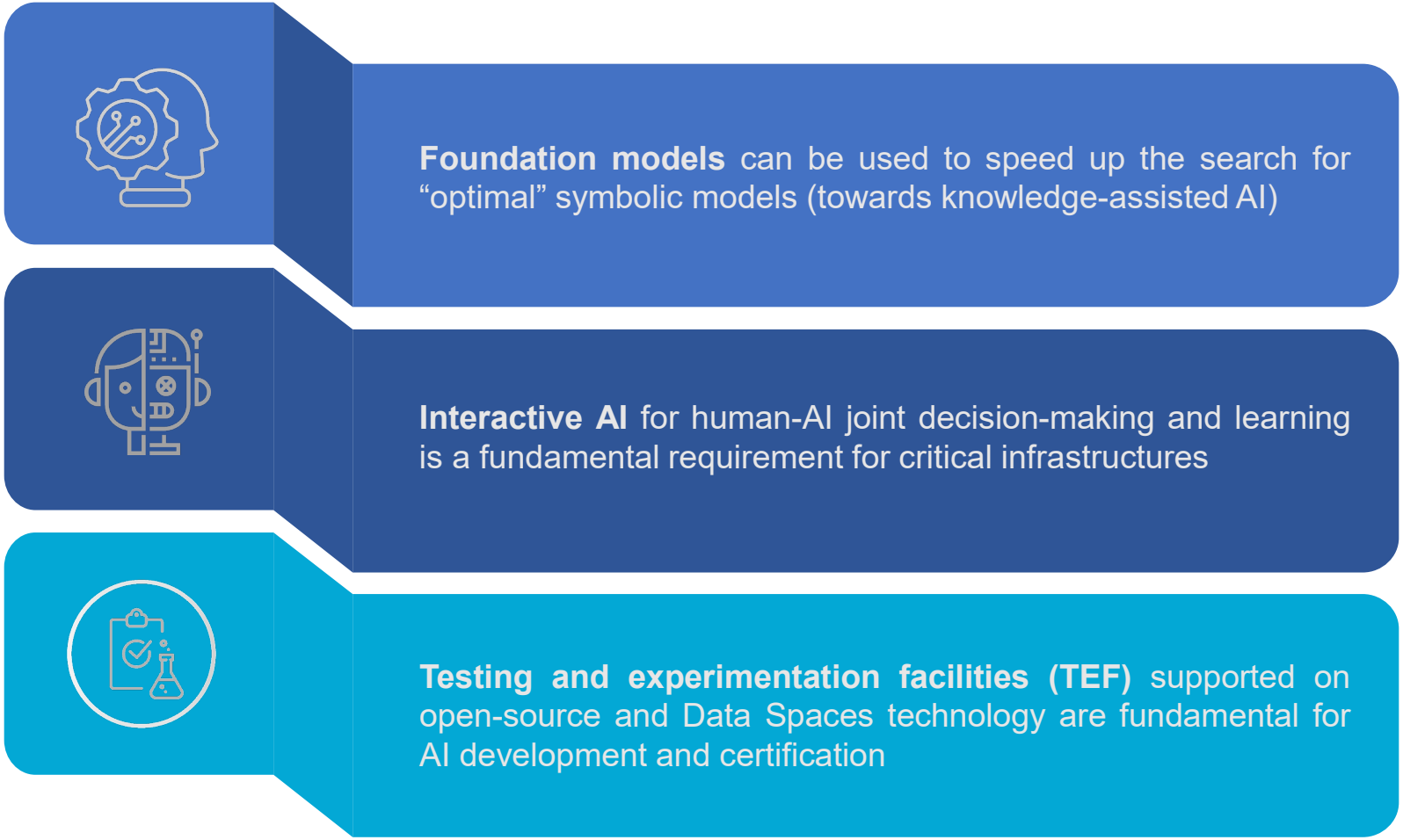
- Fault in line segment between Automatic Circuit Reclosers (ACR) 2 and 3 protection equipment's
- Circuit breaker opening for Primary Substations (PS) 1 and 2



Campos et al.

Andrade et al.

Concluding remarks



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TEF: Low voltage network reconstruction

for a candidate Topology

Power Conservation Procedure (PCP)

Power conservation approximation

$$V_i - V_j = Z_{ij} I_{ij} \approx \frac{Z_{ij}}{V_i} \sum_{k \in \mathcal{J}} P_k$$

Estimate Impedances

Averaging over historical timeseries

$$Z_{ij} = \left\langle \frac{V_i (V_i - V_j) - \sigma_i^2}{\sum_{k \in \mathcal{J}} P_k} \right\rangle_t$$

Estimate Real Voltage

Using predicted impedances

$$\left(\text{Topology}, P_i(t), Z_{ij}\right) \overset{\text{Power Flow}}{\Longrightarrow} \tilde{V}_i(t)$$

Correct Impedances (CI)

$$V_i - V_j \approx Z_{ij}^C \sum_{k \in \mathcal{J}} \frac{P_k}{\tilde{V}_k} \qquad Z_{ij}^C = \left\langle \frac{V_i - V_j}{\sum_{k \in \mathcal{J}} \frac{P_k}{\tilde{V}_k}} \right\rangle_t$$

Correct Estimated Voltages

$$\left(\text{Topology}, P_i(t), Z_{ij}^C\right) \overset{\text{Power Flow}}{\Longrightarrow} \tilde{V}_i^C(t)$$

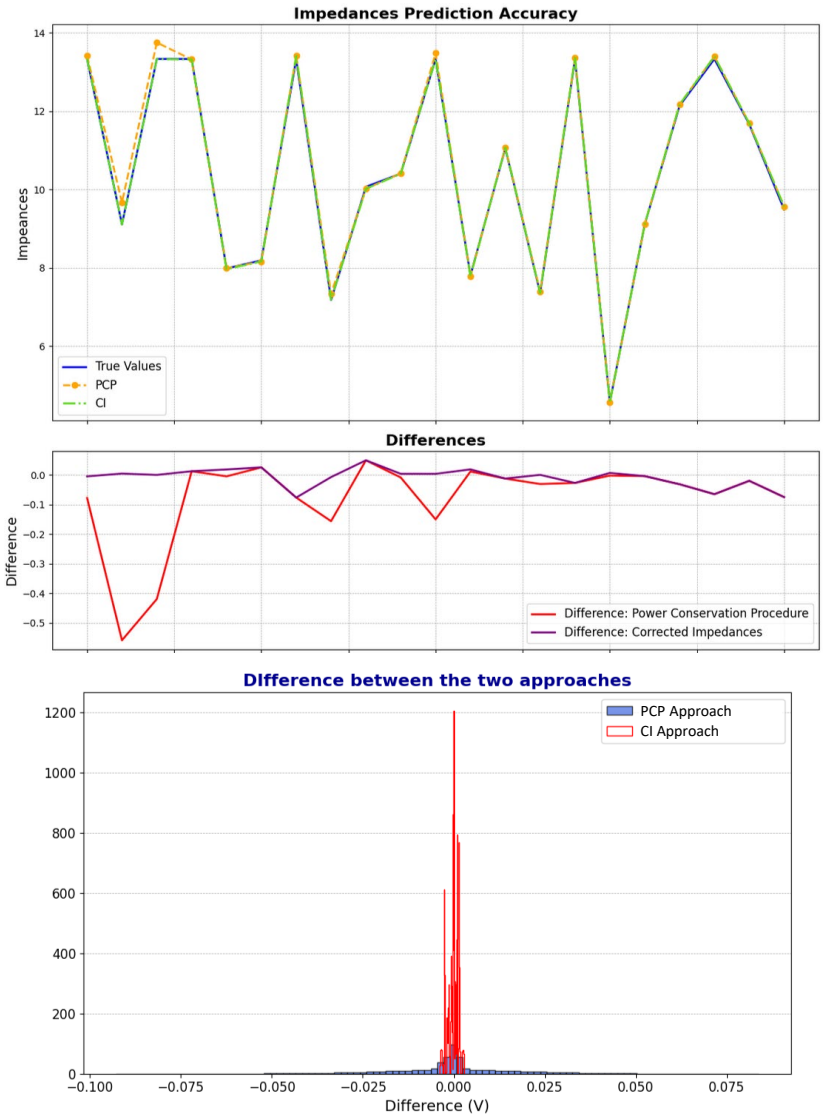
Compute Fitness Score

$$F(\text{Topology}) = \left\langle V_i(t) - \tilde{V}_i^C(t) \right\rangle_{t,i}$$

Grid mutation

Grid recombination

Elite selection



Predicted voltage converge to the real value for the correct connections