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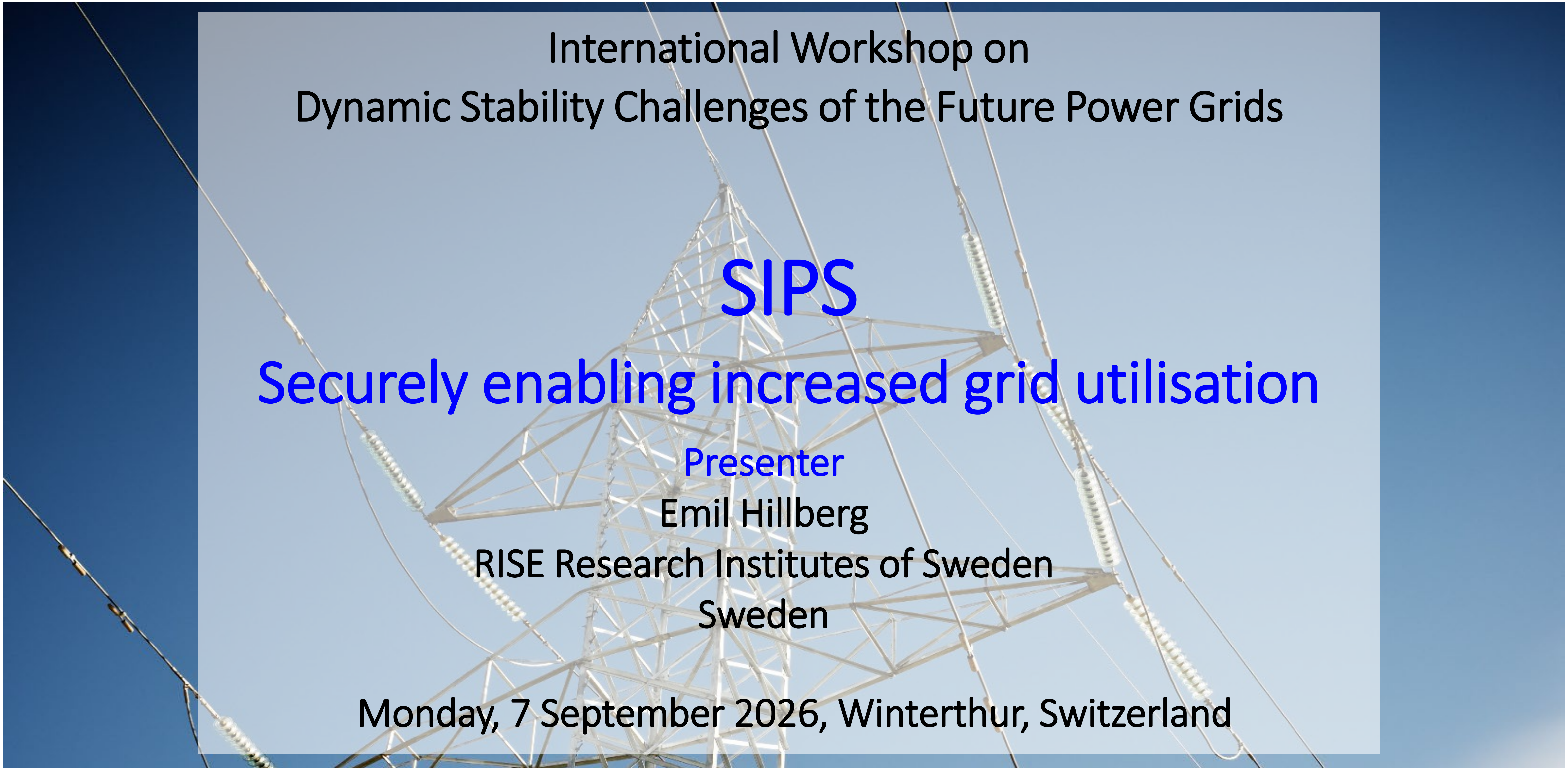


International Workshop on
Dynamic Stability Challenges of the Future Power Grids

SIPS

Securely enabling increased grid utilisation

Presenter
Emil Hillberg
RISE Research Institutes of Sweden
Sweden

Monday, 7 September 2026, Winterthur, Switzerland

Agenda

- Introduction
- SIPS overview
- Examples of SIPS implementations
- Advances in research on SIPS
- Conclusions and outlook

Introduction

Introduction: RISE Reseach Institutes of Sweden

RI. SE | Research Institutes of Sweden

- We are a state-owned company with nearly 3,300 employees who contribute to transforming knowledge from research into new products and services.
- Our mission is to work with our customers and partners to develop competitive solutions that drive sustainable development forward.
- With our unique breadth and collective expertise, we can take a systemic perspective on complex sustainability issues.
- In our more than 130 test beds, products and processes of the future can be tested and scaled up.

ri.se/en/
power-system-analysis


4th

Largest institute in Europe after Fraunhofer, CEA, and TNO


We are represented at

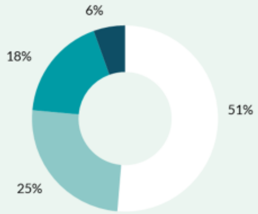
35

locations around Sweden

4,329

SEK million, net sales

Adjusted operating profit: 145 SEK million
Adjusted operating margin: 3,3 %

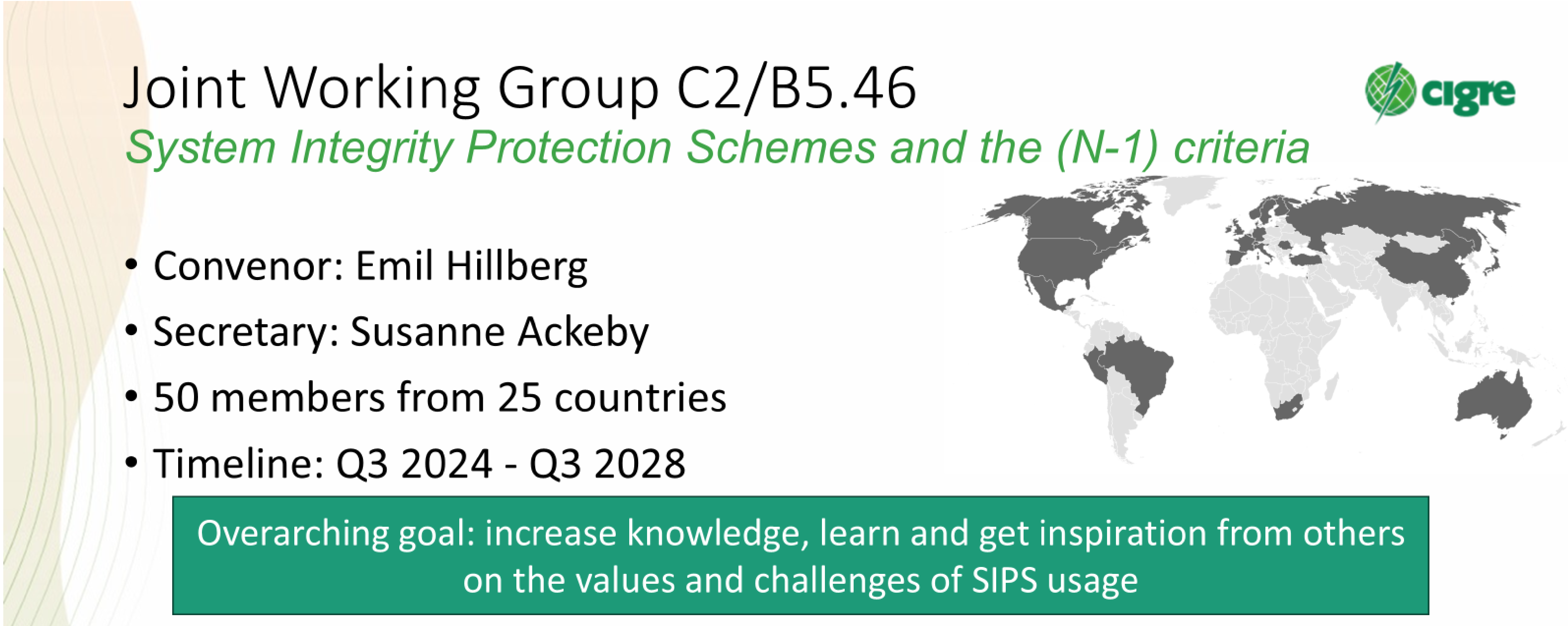


Revenue distribution

□	Business sector	2,222 MSEK
▨	Public funds	1,087 MSEK
▨	State funds	783 MSEK
■	EU funds	237 MSEK

All figures refer to 2024.

Introduction: Sources and further reading



Joint Working Group C2/B5.46

System Integrity Protection Schemes and the (N-1) criteria

- Convenor: Emil Hillberg
- Secretary: Susanne Ackeby
- 50 members from 25 countries
- Timeline: Q3 2024 - Q3 2028

Overarching goal: increase knowledge, learn and get inspiration from others on the values and challenges of SIPS usage

Introduction: Sources and further reading

System Integrity Protection Schemes for added transfer capacity
SPS4SE

”Increasing the knowledge of SIPS as part of the smart transmission grid
For reliable and secure capacity increase of exsisting grids”

Timeline: Jan. 2023 – Dec. 2025
Coordinator: RISE Research Institutes of Sweden

Introduction: Sources and further reading

Research work by PhD candidates

Gabriel Malmer, Lund University

Arvid Rolander, KTH Royal Institute of Technology

SIPS overview

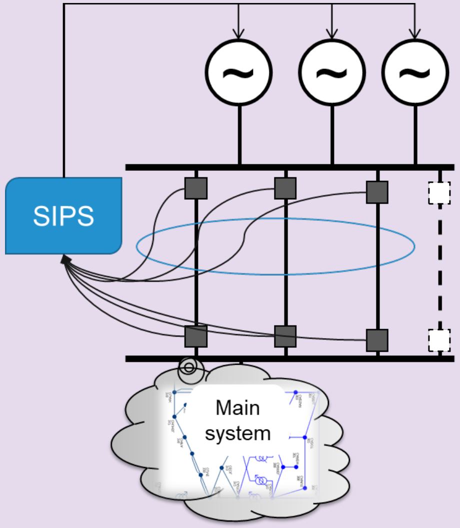
SIPS background

- Significant need for increased power transfer capacity in transmission & sub-transmission grids
    - Increased demand, long lead-times, increased utilisation and decreased margins

      ↓

    - Need for solutions to maintain secure operation under given circumstances
- Various alternative solutions are being developed and deployed worldwide, where **SIPS** represent some of such.

- *System Integrity Protection Schemes* can support a resilient & sustainable future energy system
- *SIPS* enable:
    - **Increased transfer** in normal operation, during maintenance, pending grid expansion
    - **More secure operation** with automated control to mitigate large disturbances



- Awareness of *SIPS* increase internationally, with varying degrees of implementation and use in power systems around the world

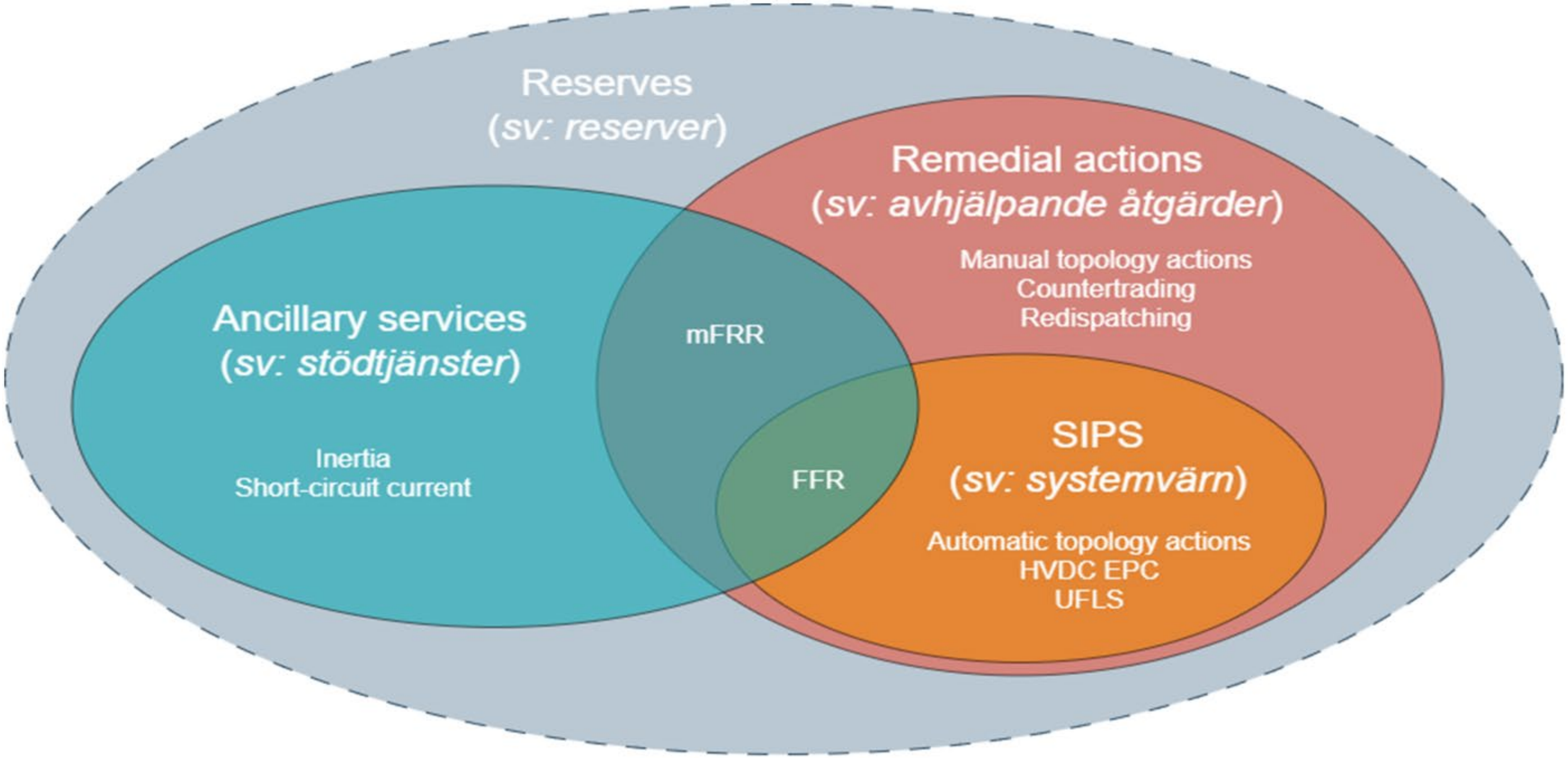
SIPS non-standardised naming and definitions…

- International expressions used including
  - System (Integrity) Protection Schemes (SIPS / SPS)
  - Special Protection Systems (SPS)
  - Remedial Action Schemes (RAS)
  - Wide Area Monitoring, Protection and Control/ Systems (WACS / WAMPAC)
  - Defence Plan
  - …

SIPS is seen as an umbrella term and can be defined as:

automatic systems which apply
curative control actions
as the response to a **critical condition,**
in order to increase the power system **reliability**
and/or **available capacity**.

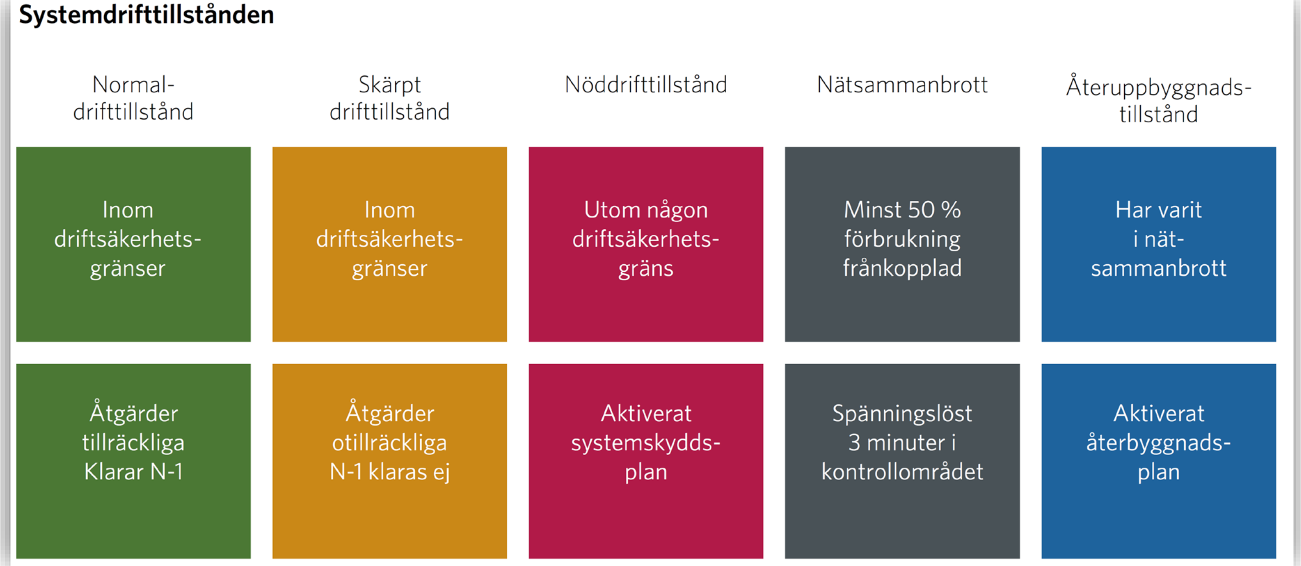
SIPS in relation to of ancillary services and remedial actions



SIPS and the System States

- SIPS can support the system to
  - return to normal from alert state
  - increasing normal operation
  - return to alert from emergency state
  - prevent blackout in emergency operation

- SIPS control actions include e.g.
  - regulating load and generation
  - regulating HVDC and other controllable equipment
  - grid reconfiguration
  - more innovative solutions…



Systemdrifttillstånden

Normal-drifttillstånd	Skärpt drifttillstånd	Nöddrifttillstånd	Nätsammanbrott	Återuppbyggnads-tillstånd
Inom driftsäkerhets-gränser	Inom driftsäkerhets-gränser	Utom någon driftsäkerhets-gräns	Minst 50 % förbrukning frånkopplad	Har varit i nät-sammanbrott
Åtgärder tillräckliga Klarar N-1	Åtgärder otillräckliga N-1 klaras ej	Aktiverat systemskydds-plan	Spänningslöst 3 minuter i kontrollområdet	Aktiverat återbyggnads-plan

SIPS to increase capacity
- actions to mitigate degradation in system state

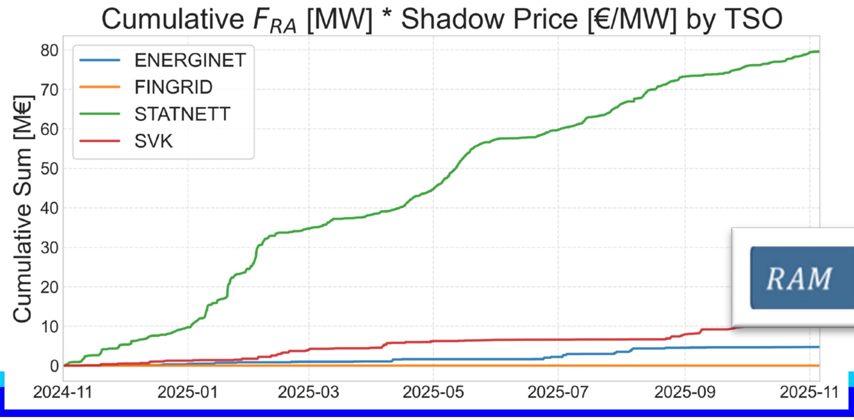
SIPS to prevent large disturbances
- actions to mitigate instability and cascaded tripping

SIPS triggering types

Event based:	**Response based:**
Triggered by event (e.g. breaker status)	Threshold trigger (frequency, voltage, current, etc.)
Static, complex enabling criteria (operating status of large no of breakers etc.)	Dynamic/adaptive, effective for multitude of scenarios and unforeseen contingencies
Fast (direct trip signals), foreseeable result	Slower, effectiveness subject to operating scenario

SIPS values

- Values connected to risk of large disturbances
  - Extreme societal impact from rare events
  - Quantification example from the Iberian peninsula event:
    Impact whole of Spain & Portugal for 12h
    8 deaths and ~1.6 billion €
- Increased available power transfer capacities
  - Strengthens market coupling during normal operations and during limitations in the grid
  - Quantification example from flow-based capacity allocation:
    1st year operation with flow-based in the Nordics
    ~100 million € based on transfer capacity increase by ”remedial actions”



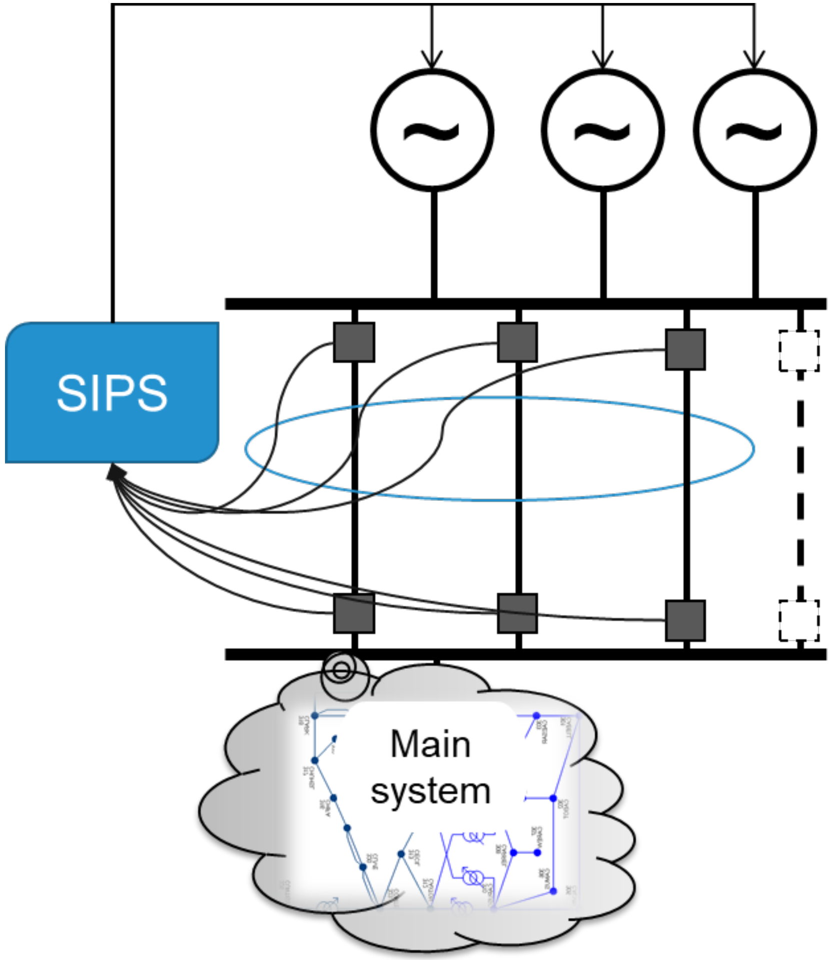
SIPS contribution

$$RAM = F_{MAX} - F_{RM} - F_0 - AAC + RA + AMR - IVA$$

SIPS functional view

Simplified example: Locked-in generation

- N-1 capacity < installed generation capacity
- Without system protection: max production = N-1 capacity
- Solution: prevent over-load in case of critical contingency
- SIPS logic:
  - IF line disconnection in corridor
  - Disconnect generation to prevent over-load on remaining lines

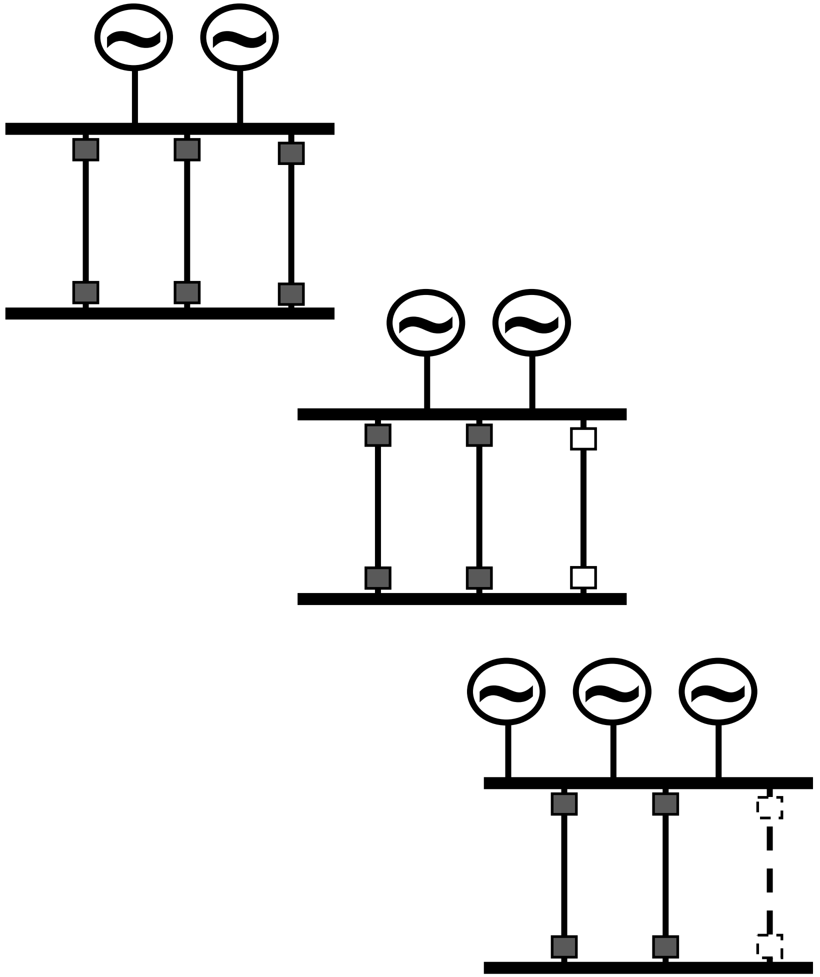


Notes:

- Similar logic for areas with large load centres as well as in meshed grids
- SIPS functionality independent of capacity limitation type (being stability or thermal capability)

SIPS enabling power transfer above conventional N-1 capacity …

3 situations



Case 1: Increased capacity in **normal operation**

- E.g. spring flood, peak load …

Case 2: Maintaining capacity in **non-intact grid**

- E.g. planned maintenance

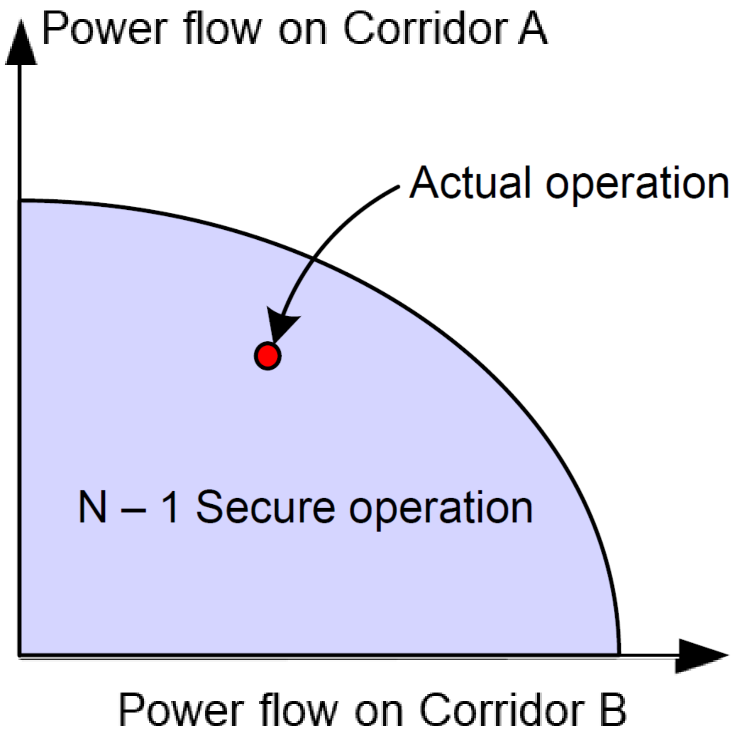
Case 3: Increased capacity pending **grid development**

- E.g. new production/load

SIPS increasing reliability and security against extreme events…

SIPS, N-1, & N-k

I: Secure operating area
and actual operating point

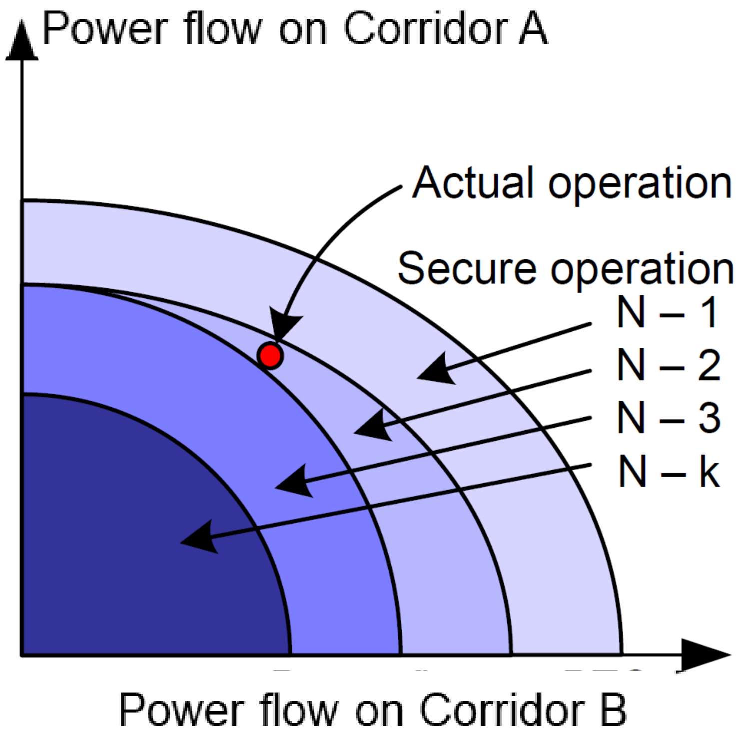


SIPS increasing reliability and security against extreme events…

SIPS, N-1, & N-k

I: Secure operating area
and actual operating point

II: *N-k* security



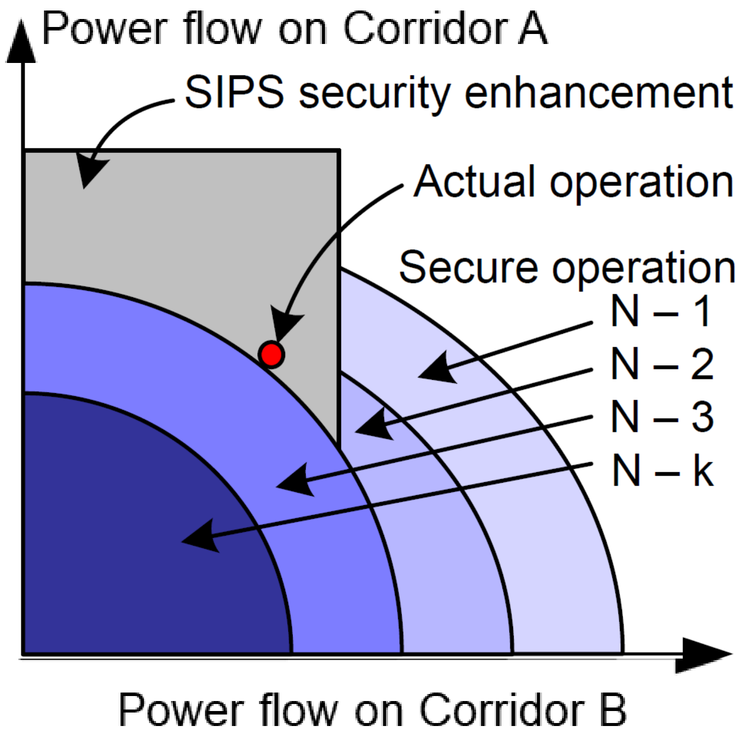
SIPS increasing reliability and security against extreme events…

SIPS, N-1, & N-k

I: Secure operating area
and actual operating point

II: *N-k* security

III: Security enhancement
by automatic actions



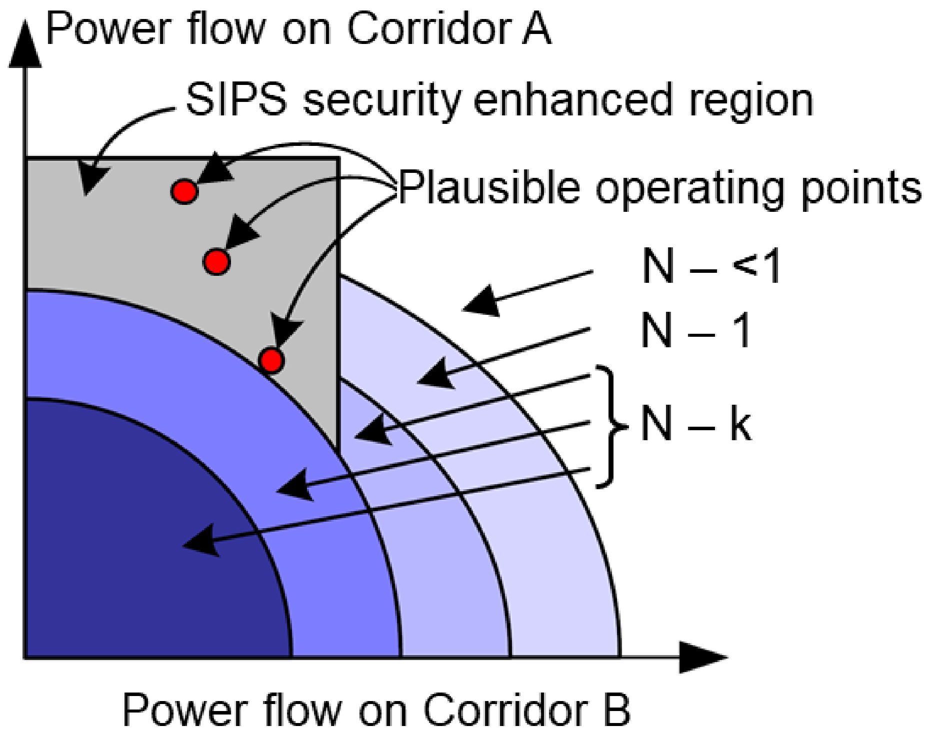
SIPS increasing reliability and security against extreme events…

SIPS, N-1, & N-k

I: Secure operating area and actual operating point

II: *N-k* security

III: Security enhancement by automatic actions

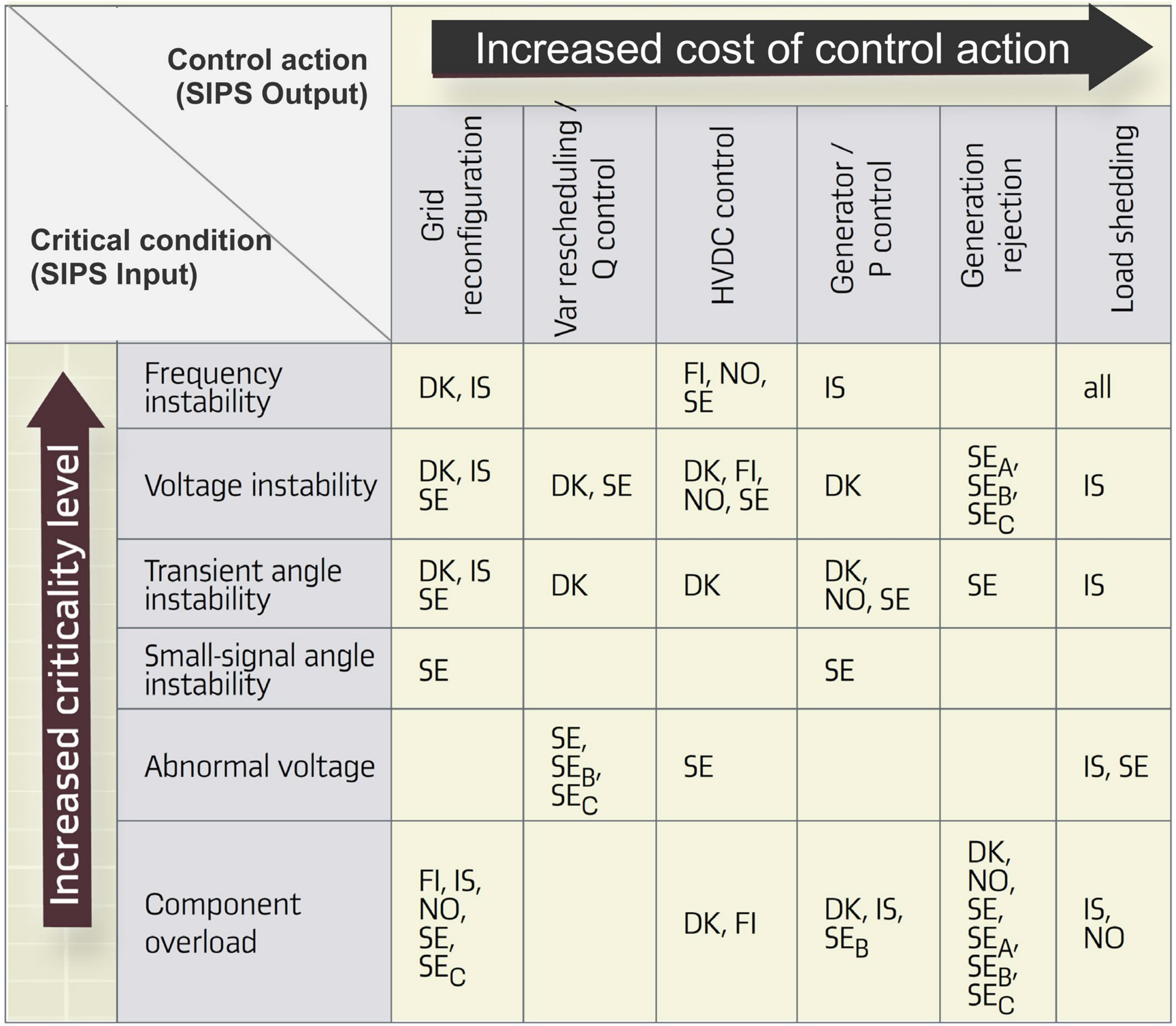


Examples of SIPS implementations

Examples of SIPS implementations: Nordic overview

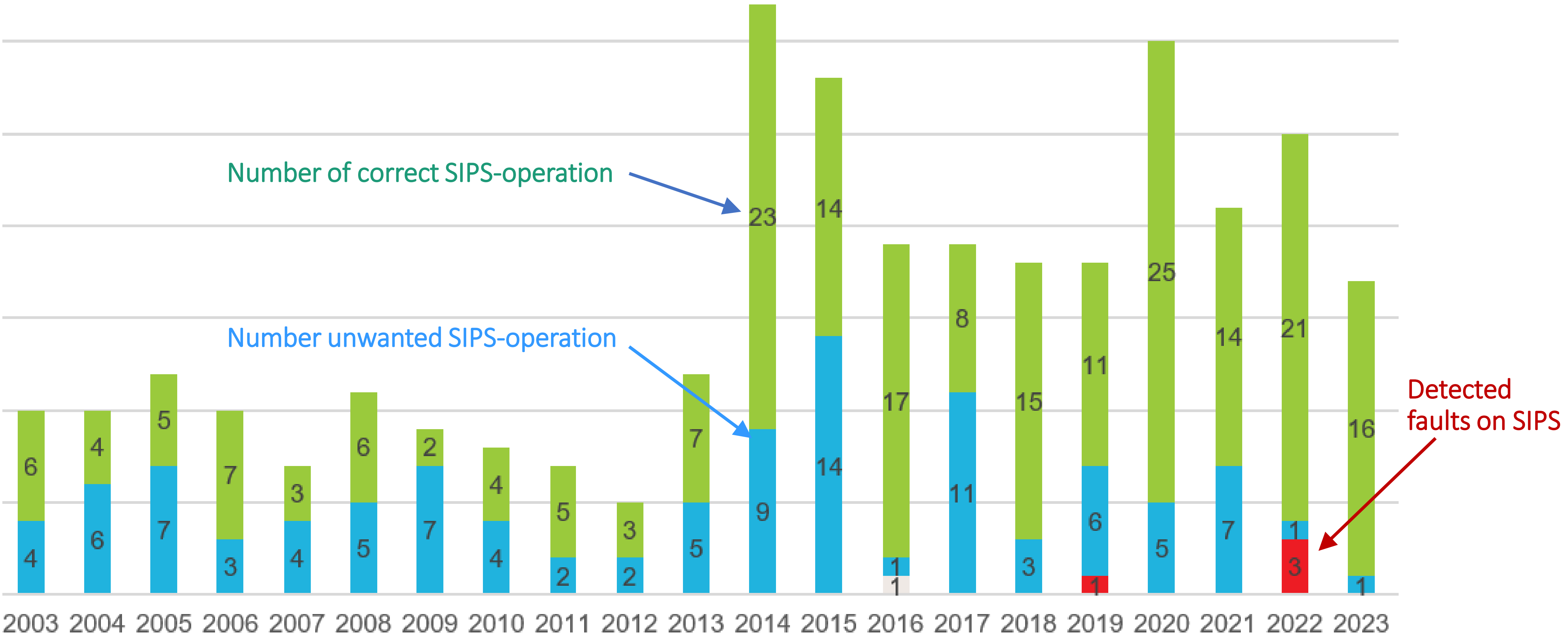
SIPS functionalities in operation in the Nordic power system

- **TSOs:**
    - **DK - Energinet (Denmark)**
    - **FI – Fingrid (Finland)**
    - **IS - Landsnet (Iceland)**
    - **NO - Statnett (Norway)**
    - **SE - Svenska kraftnät (Sweden)**
- **DSOs (in Sweden, operating grids up to 130 kV):**
    - **SE_A – Ellevio**
    - **SE_B - E.ON**
    - **SE_C – Vattenfall**



Control action (SIPS Output) / **Critical condition (SIPS Input)**	Grid reconfiguration	Var rescheduling / Q control	HVDC control	Generator / P control	Generation rejection	Load shedding
Frequency instability	DK, IS		FI, NO, SE	IS		all
Voltage instability	DK, IS SE	DK, SE	DK, FI, NO, SE	DK	SE_A, SE_B, SE_C	IS
Transient angle instability	DK, IS SE	DK	DK	DK, NO, SE	SE	IS
Small-signal angle instability	SE			SE		
Abnormal voltage		SE, SE_B, SE_C	SE			IS, SE
Component overload	FI, IS, NO, SE, SE_C		DK, FI	DK, IS, SE_B	DK, NO, SE, SE_A, SE_B, SE_C	IS, NO

Examples of SIPS implementations: operations Statnett (Norway)

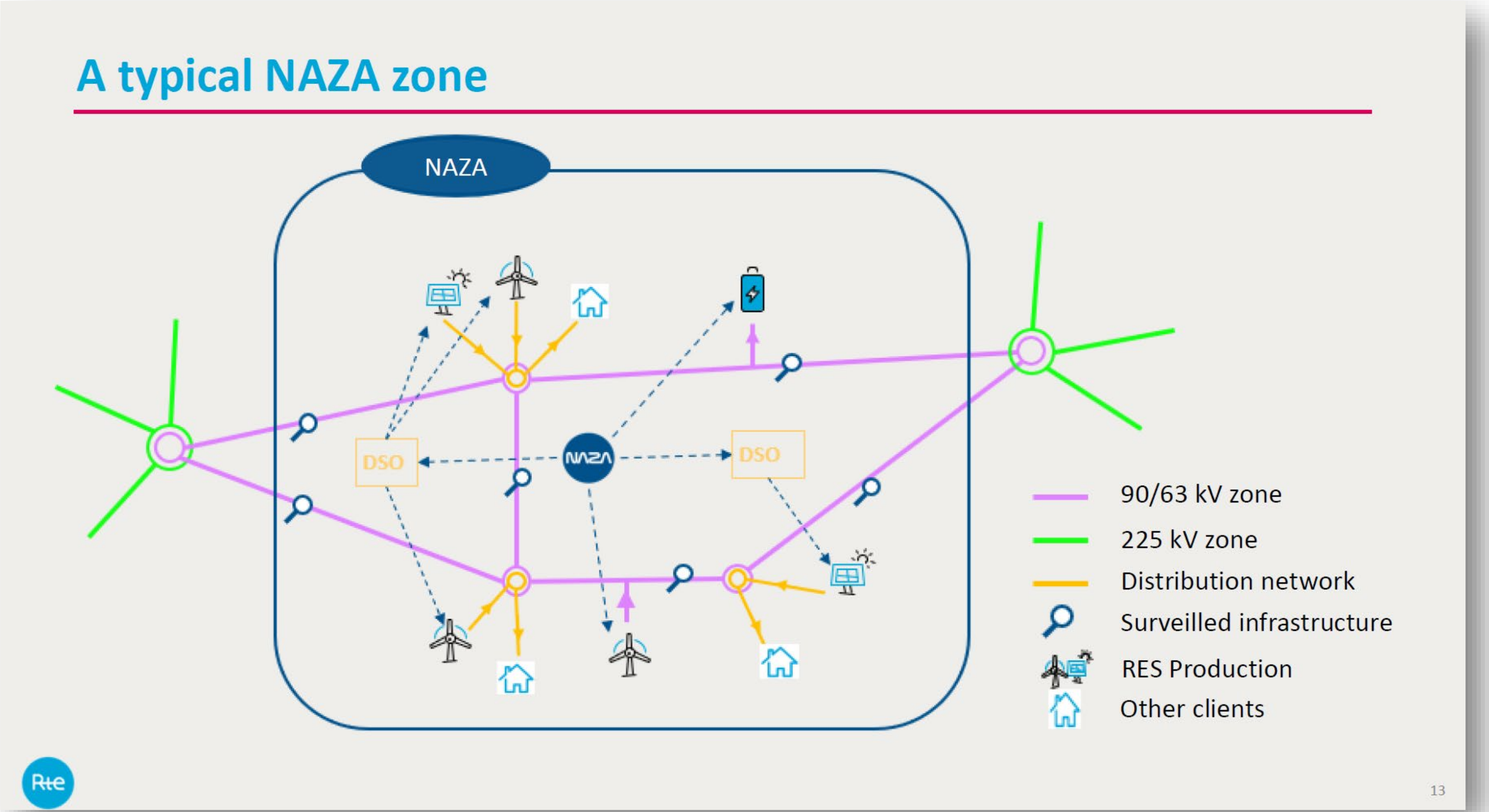


Number of correct SIPS-operation

Number unwanted SIPS-operation

Detected faults on SIPS

Examples of SIPS implementations: RTE (France)



A typical NAZA zone

- 90/63 kV zone
- 225 kV zone
- Distribution network
- Surveilled infrastructure
- RES Production
- Other clients

Examples of SIPS implementations: REE (Spain)

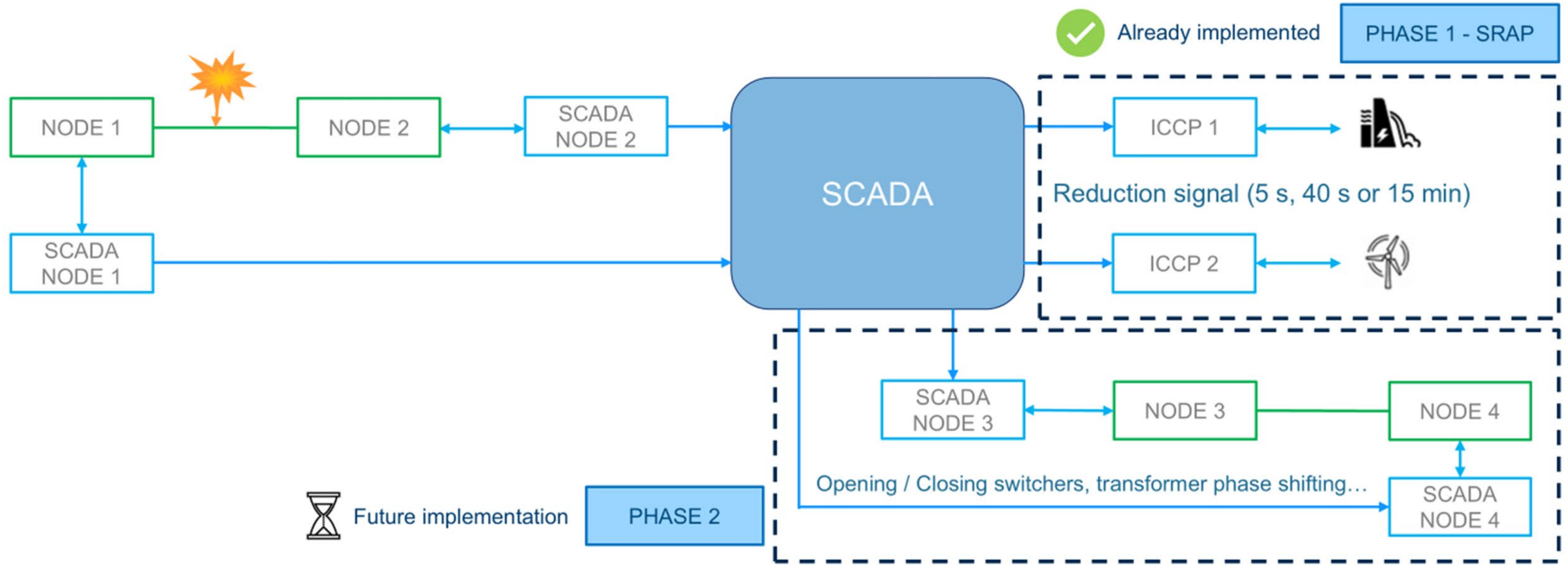
Quijote project

red eléctrica

General description of the project

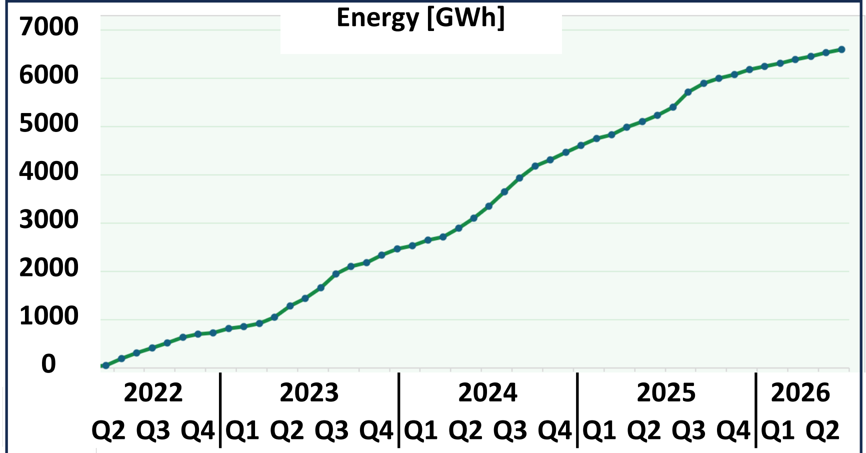
Quijote is an operational tool, integrated in the Scada System of the Control Center, that automatically sends set points to prequalified units upon the detection of predefined events in the transmission grid.

In a second phase, Quijote will be able to programme and execute automatic actions on the grid.



SIPS - Spanish power system, November 2024

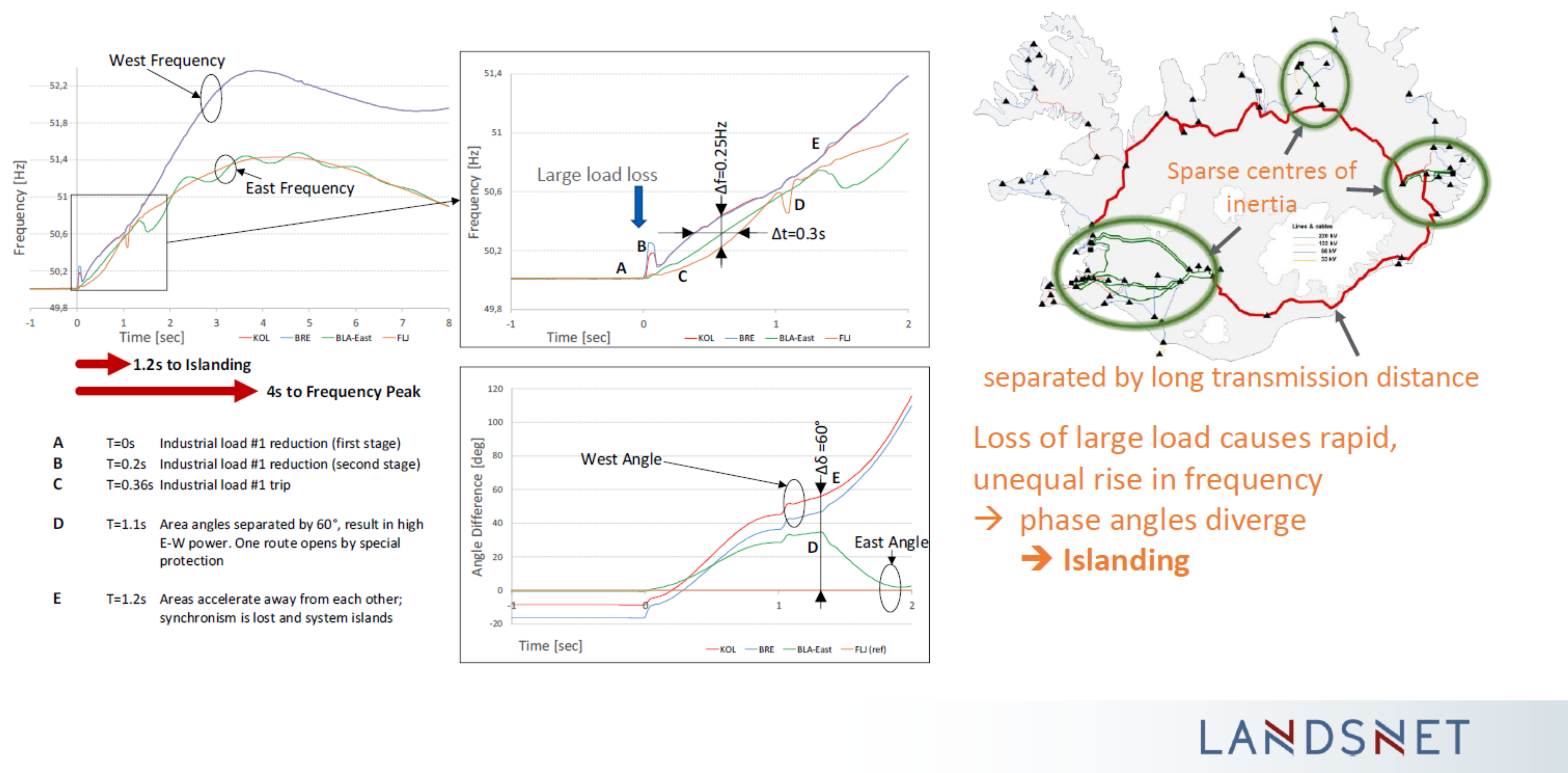
4



Energy that would have been curtailed without SRAP = 6600 GWh

Note: Data as of 31 May 2026.

Examples of SIPS implementations: Landsnet (Iceland)



1.2s to Islanding

4s to Frequency Peak

A	T=0s	Industrial load #1 reduction (first stage)
B	T=0.2s	Industrial load #1 reduction (second stage)
C	T=0.36s	Industrial load #1 trip
D	T=1.1s	Area angles separated by 60°, result in high E-W power. One route opens by special protection
E	T=1.2s	Areas accelerate away from each other; synchronism is lost and system islands

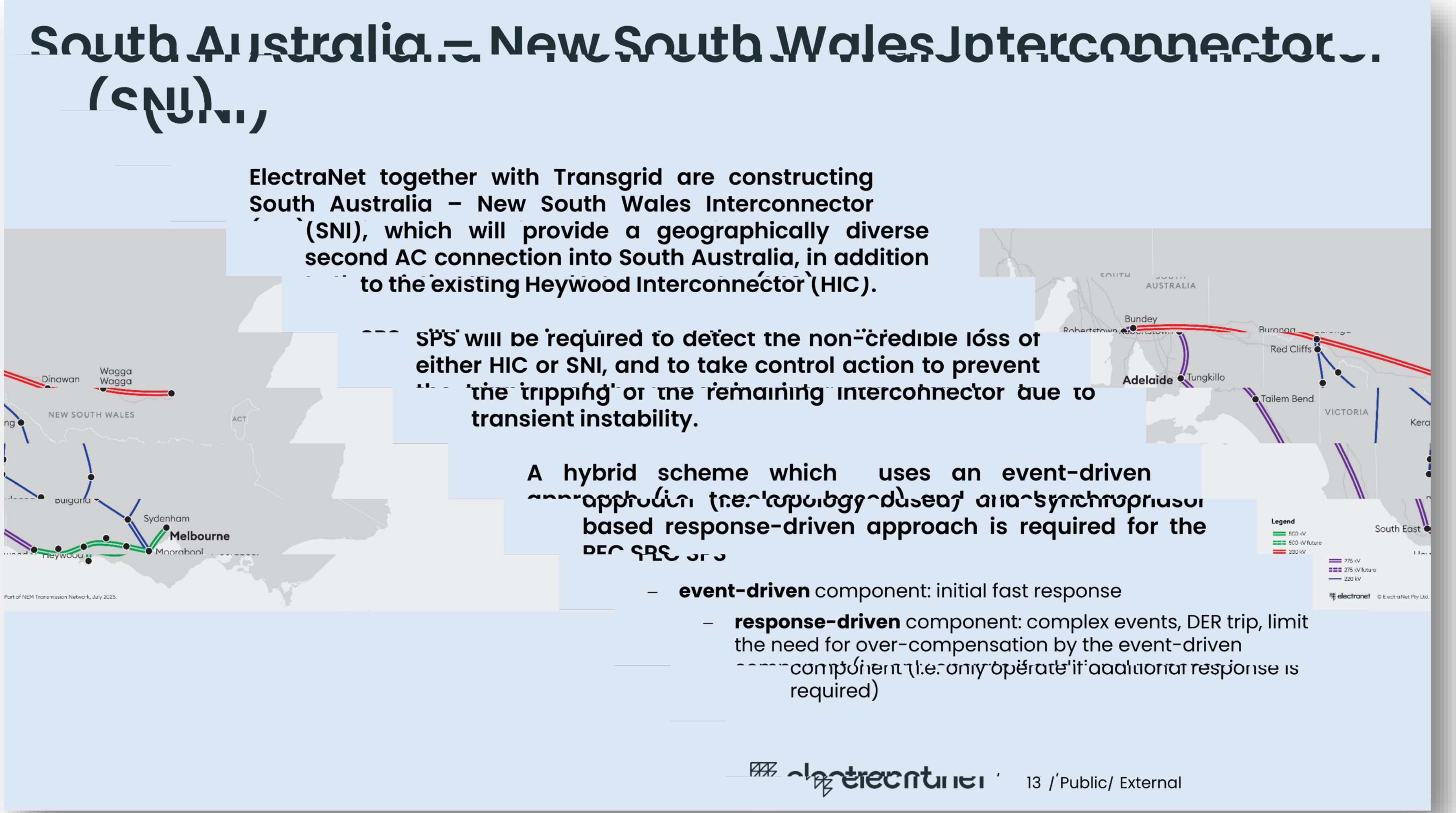
separated by long transmission distance

Loss of large load causes rapid, unequal rise in frequency

→ phase angles diverge

→ Islanding

Examples of SIPS implementations: Electranet (South Australia)



South Australia – New South Wales Interconnector (SNI)

ElectraNet together with Transgrid are constructing South Australia – New South Wales Interconnector (SNI), which will provide a geographically diverse second AC connection into South Australia, in addition to the existing Heywood Interconnector (HIC).

SPS will be required to detect the non-credible loss of either HIC or SNI, and to take control action to prevent the tripping of the remaining interconnector due to transient instability.

A hybrid scheme which uses an event-driven approach (i.e. topology-based) and a synchrophasor based response-driven approach is required for the PEC SPS

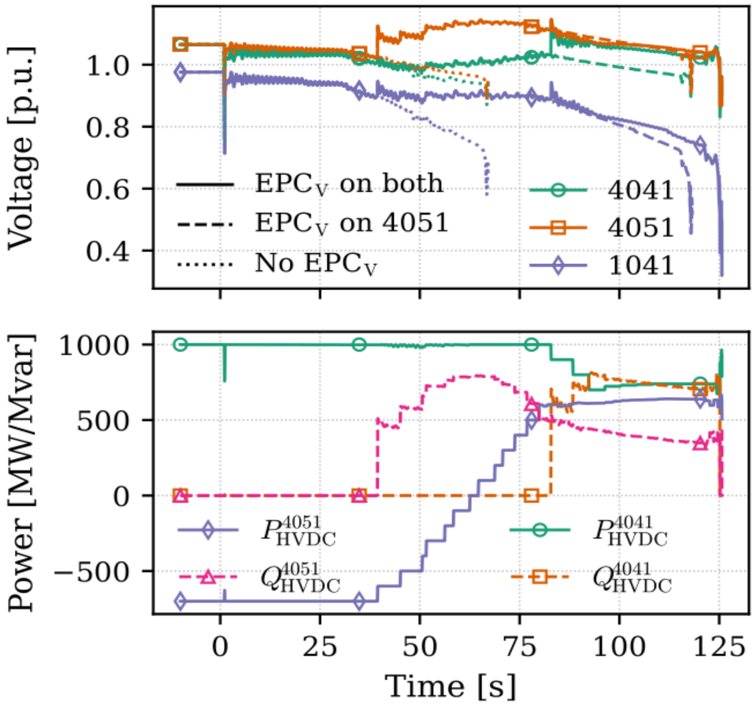
- **event-driven** component: initial fast response
  - **response-driven** component: complex events, DER trip, limit the need for over-compensation by the event-driven component (i.e. only operate if additional response is required)

electranet 13 / Public/ External

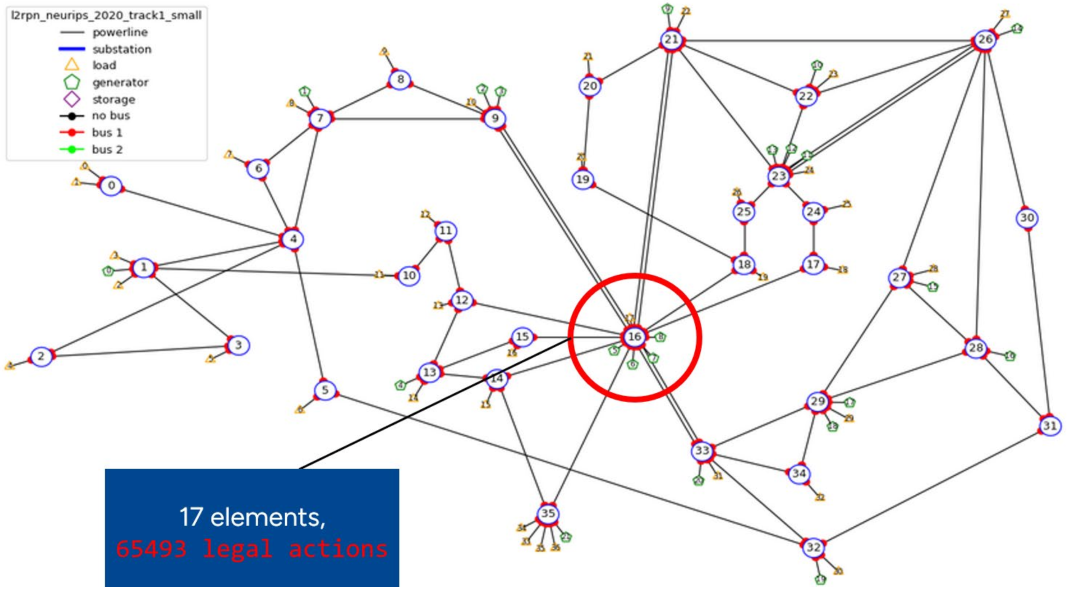
Advances in research on SIPS

Advances in research on SIPS

1. HVDC emergency power control to prevent voltage instability



2. Ai supported grid reconfiguration



17 elements,
65493 legal actions

1. HVDC emergency power control to prevent voltage instability

- Research work by **Gabriel Malmer, PhD candidate Lund University**, published in:
    - G. Malmer, E. Hillberg, O. Samuelsson,
      VSC-HVDC setpoint adjustment for maximum grid utilisation under voltage constraints,
      SEST 2026
    - G. Malmer, E. Hillberg, O. Samuelsson
      Increased capacity using VSC-HVDC emergency control in voltage stability-constrained systems
      IET Generation, Transmission & Distribution, 2026

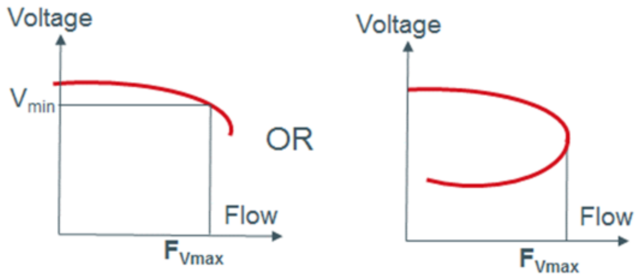
1. HVDC emergency power control to prevent voltage instability

Motivation: HVDC one of the largest controllable assets in the transmission system

- Climate action requires electrification + decarbonisation
- Energy efficiency + environmental regulations also drivers
  - Demand for grid capacity rapidly increasing
- Power system already changing with more PEIDs
  - HVDC one of the largest controllable assets in the transmission system
  - VSC-HVDC: Fast and independent controllability of P and Q

Research question:

How should VSC-HVDC emergency power control (EPC) be designed to increase capacity and/or security in voltage stability-constrained systems?



1. HVDC emergency power control to prevent voltage instability

Hypothesis: an optimal HVDC setpoint can be identified to provide highest loadability

Optimal setpoint

- Active-reactive trade-off P_g/Q_g function of angle difference δ:

$$\frac{Q_g - Q_0}{P_g - P_0} = \frac{1}{\tan\delta}$$

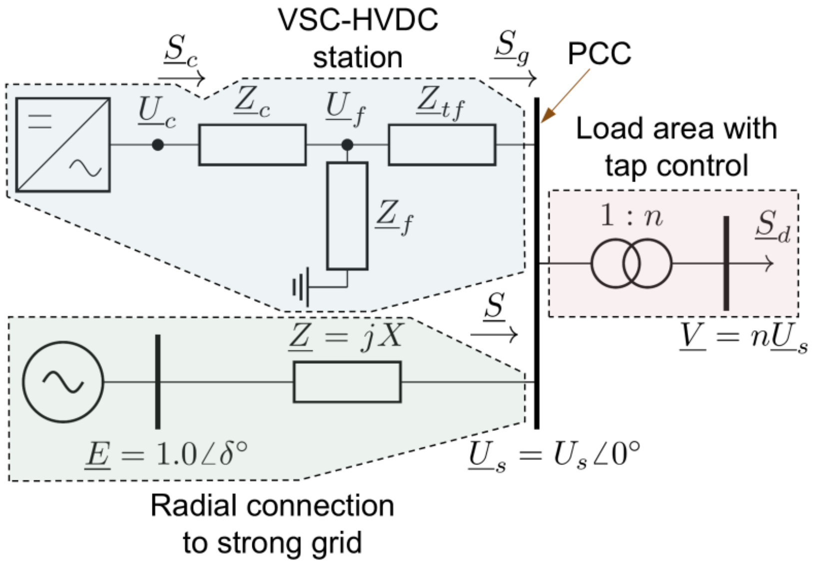
- Intersection (P_x, Q_x) between limits gives transition angles δ_i and δ_v:

$$\delta_i = \arctan\left(\frac{P_x - P_0^{(i)}}{Q_x - Q_0^{(i)}}\right)$$

$$\delta_v = \arctan\left(\frac{P_x - P_0^{(v)}}{Q_x - Q_0^{(v)}}\right)$$

- Optimal active power setpoint P_g^* = piecewise function of δ:

$$P_g^*(\delta) = \begin{cases} r_v \sin\delta + P_0^{(v)}, & \delta < \delta_v \\ r_i \sin\delta_i + P_0^{(i)} = r_v \sin\delta_v + P_0^{(v)}, & \delta_v \le \delta < \delta_i \\ r_i \sin\delta + P_0^{(i)}, & \delta \ge \delta_i \end{cases}$$

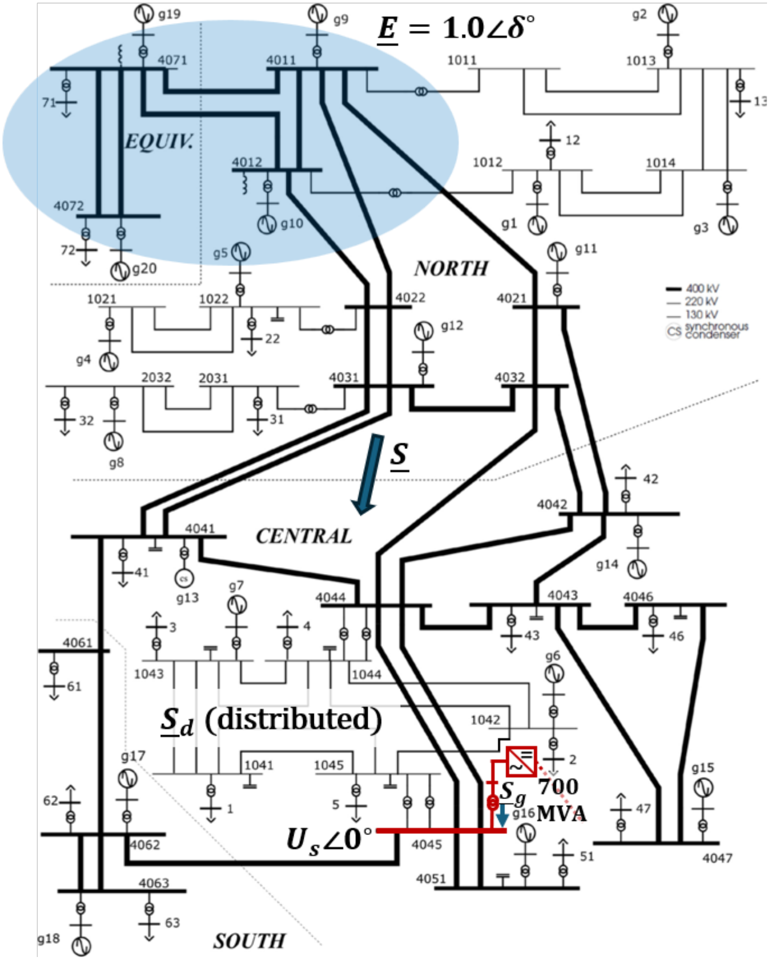


1. HVDC emergency power control to prevent voltage instability

Experimental set-up

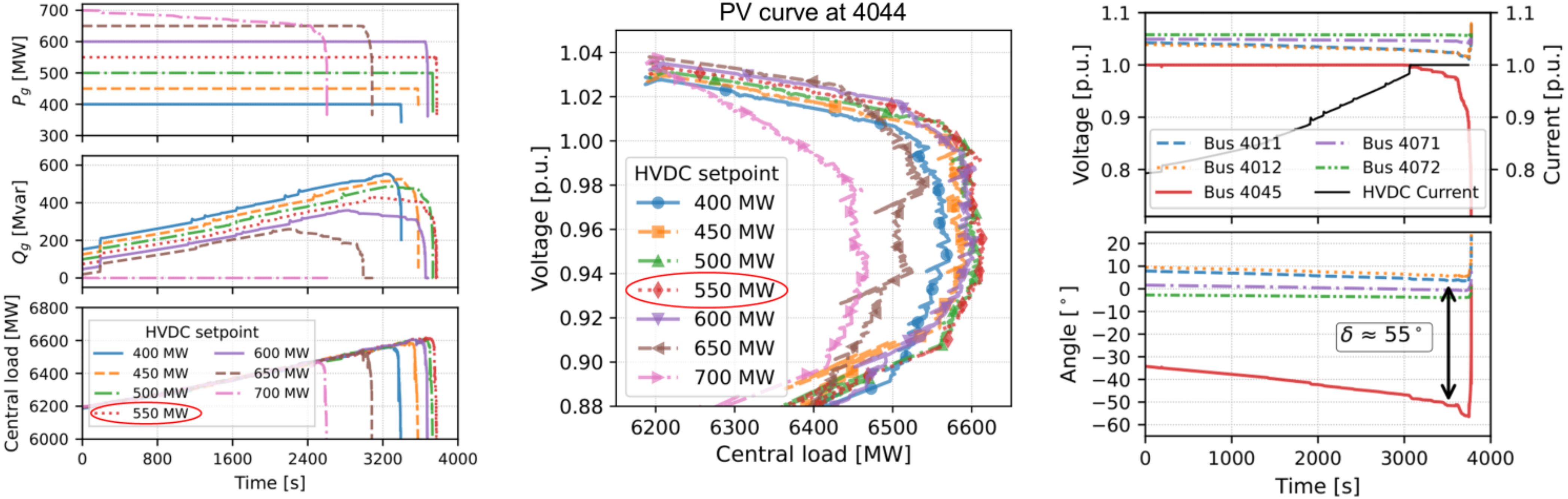
- IEEE Nordic Test system
  - Benchmark for long-term voltage stability
  - *North* + *Equiv*. = net gen, *Central* = net load

- Simulation setup:
  - 700 MVA VSC-HVDC connected to 4045 ($\underline{U}_s$)
  - Slow load ramp in *Central* $(0.15\ \mathrm{MW/s})$
  - OLTCs keep load voltages close to $1.0\ \mathrm{p.u.}$
  - VSC in $(P_{4045}^{\mathrm{ref}}, U_{4045}^{\mathrm{ref}} = 1.0\ \mathrm{p.u.})$ control mode
  - Seven cases: $P_{4045}^{\mathrm{ref}} \in \{400, 450, \ldots, 700\}\ \mathrm{MW}$



1. HVDC emergency power control to prevent voltage instability

Results



- Current-limited regime ($\delta > \delta_i$), $\delta = 50–60^\circ$ and $U_s = 0.95–1.0\ \mathrm{p.u} \Longrightarrow \boldsymbol{P_g^*} = \mathbf{510–610\ MW}$
  - Supports the setpoint rule

1. HVDC emergency power control to prevent voltage instability

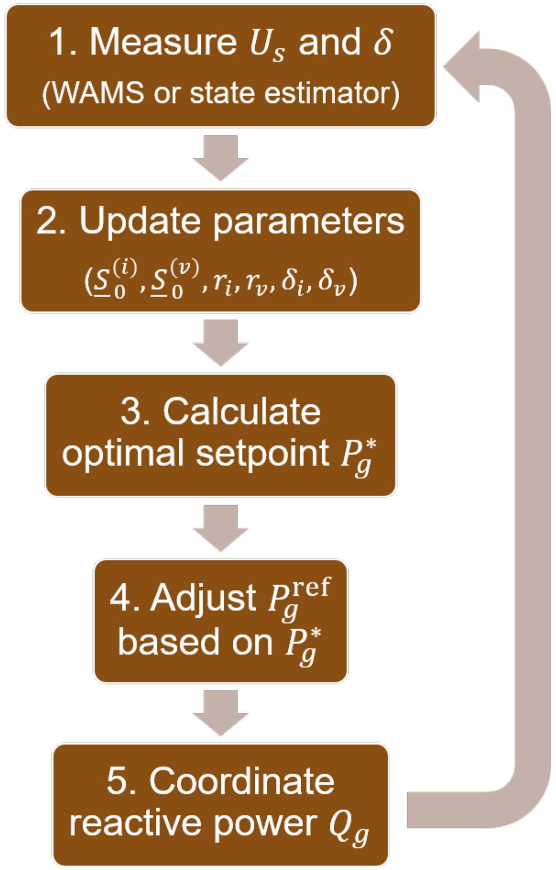
Conclusions

- Optimal set-point for HVDC emergency support in voltage stability situations can provide significant impact on transfer capacity

- The proposed schemes has been:
  - analytically derived,
  - tested on a benchmark system, and
  - can be implemented following a proposed implementation framework

- Limitations and assumptions need further attention, as does coordination with other remedial actions or reserves

Proposed implementation framework



1. Measure U_s and δ (WAMS or state estimator)

2. Update parameters $(\underline{S}_0^{(i)}, \underline{S}_0^{(v)}, r_i, r_v, \delta_i, \delta_v)$

3. Calculate optimal setpoint P_g^*

4. Adjust P_g^{ref} based on P_g^*

5. Coordinate reactive power Q_g

2. Ai supported grid reconfiguration

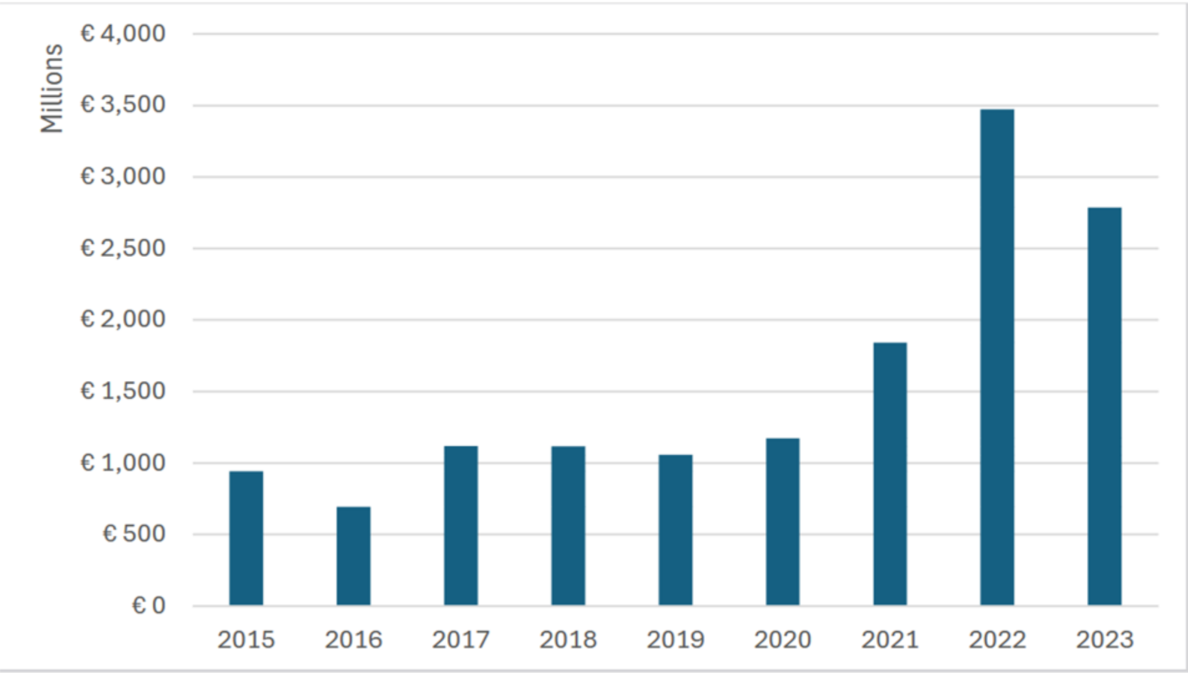
- Research work by **Arvid Rolander, PhD candidate KTH**, published in:
    - A. Rolander, X. Weiss, E. Hillberg, L. Nordström,
      Benchmarking deep reinforcement learning algorithms for learning topological remedial actions,
      SEST 2026
    - A. Rolander, X. Weiss, M. R. Hesamzadeh, E. Hillberg, L. Nordström,
      Combined use of grid reconfiguration and redispatch in congested power systems,
      IEEE PES GM 2026

2. Ai supported grid reconfiguration

Motivation: redispatch & countertrading are costly remedial actions

Congestion Management

- Redispatch/Countertrading
- Billions spent in Germany alone
- Lead times for lines: 10 years



Congestion management costs DE, data from ENTSO-e

2. Ai supported grid reconfiguration

Hypothesis: grid reconfiguration is an alternative

Topology control: Cheap, but difficult

- Redirect power flow by splitting nodes
- ~2^{N-1} options per substation

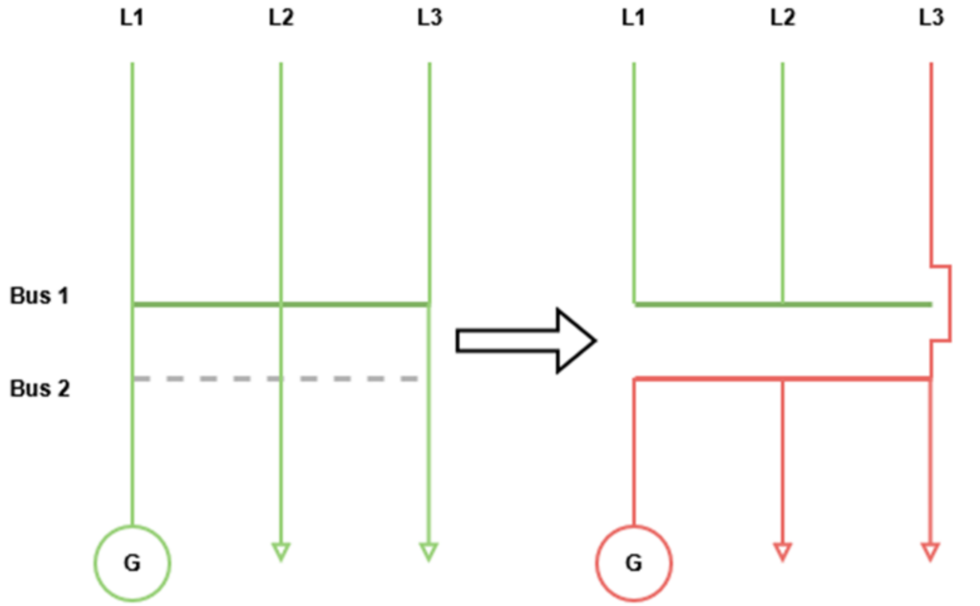
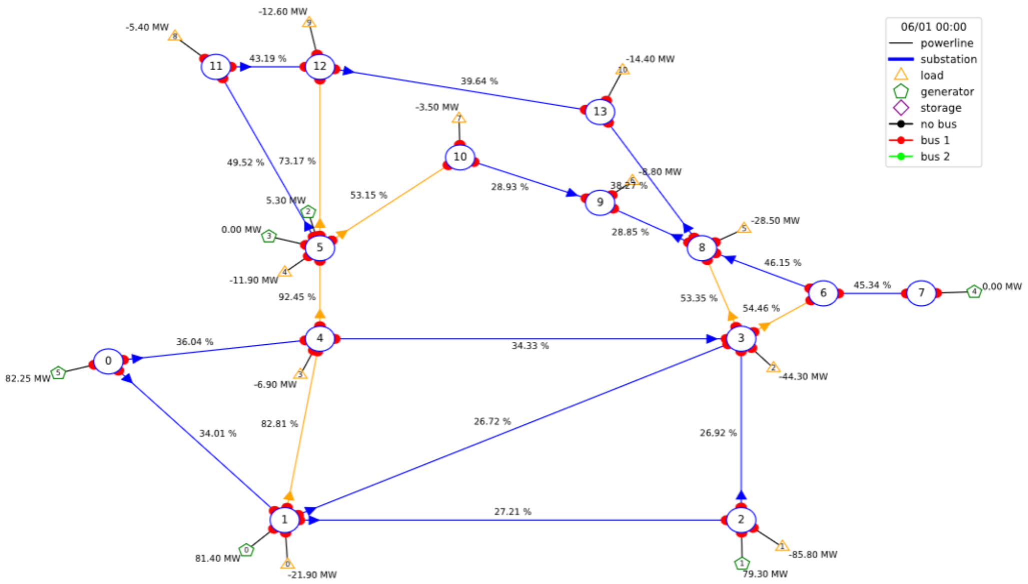


Illustration of substation split. 6 elements, ~32 configurations

16 elements → 33k configurations…

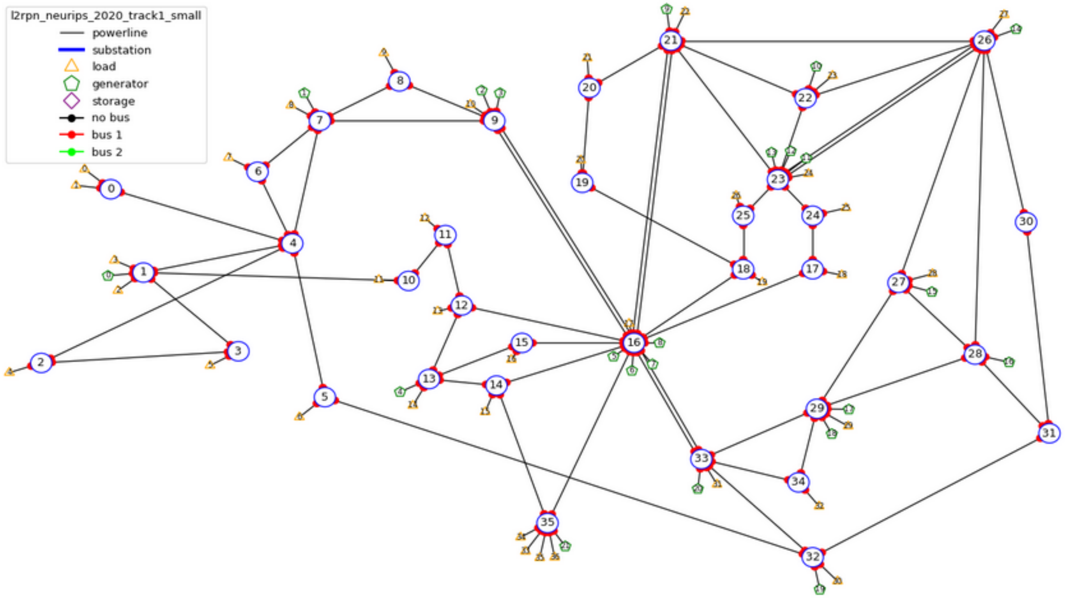
2. Ai supported grid reconfiguration

Experimental set-up



IEEE 14-bus system:

134 actions 1004 scenarios



36-bus subset of IEEE 118-bus system:

66,679 actions → 2,291 after factorization, 576 scenarios

- Grid2Op simulation environment,
- One month per scenario in 5-minute timesteps

2. Ai supported grid reconfiguration

Case studies:

A. Benchmarking Ai agent's functionality

On-policy and off-policy

PPO

- Learns from *current data*, discard past data
- Stable
- Standard in RL for topology control

IQN/Rainbow

- Learns from any data
- Distributional – model return distribution
- Reuses experience

B. Combining redispatch & grid reconfiguration

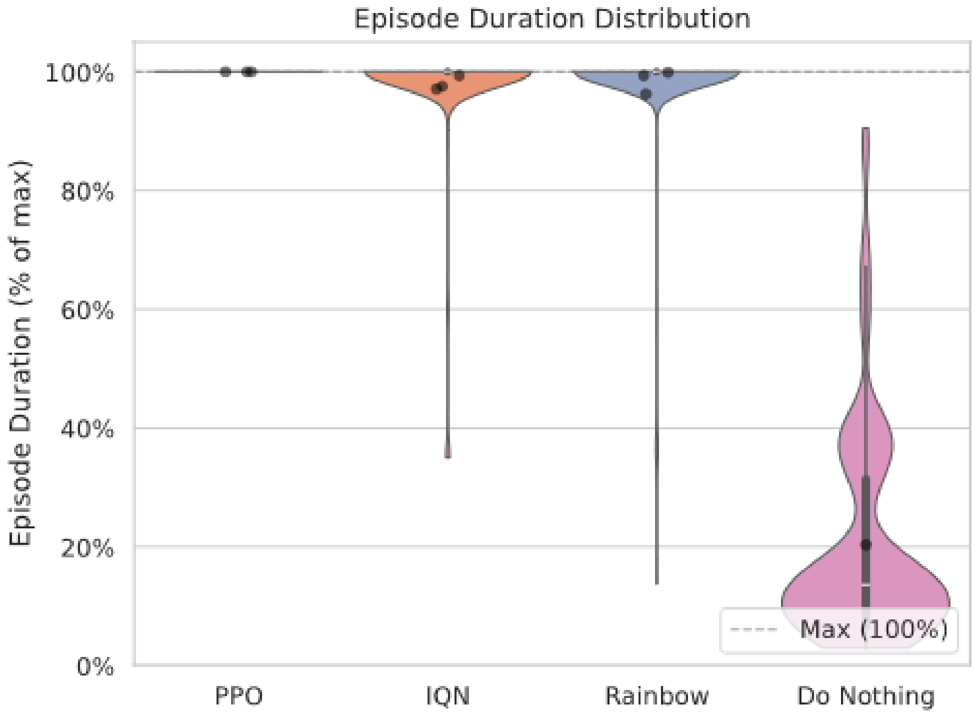
1. Optimal power flow based redispatch
2. Reinforcement learning agent
3. RL + OPF static combination
4. RL + OPF dynamic combination

2. Ai supported grid reconfiguration

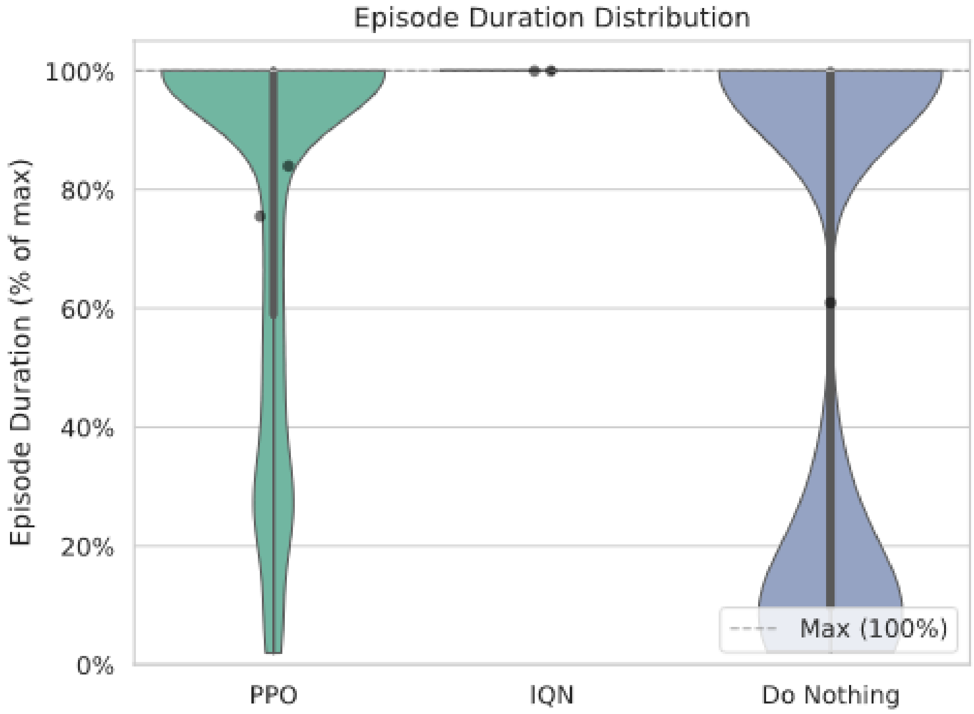
Results

A. Benchmarking Ai agent's functionality

IEEE 14-bus system



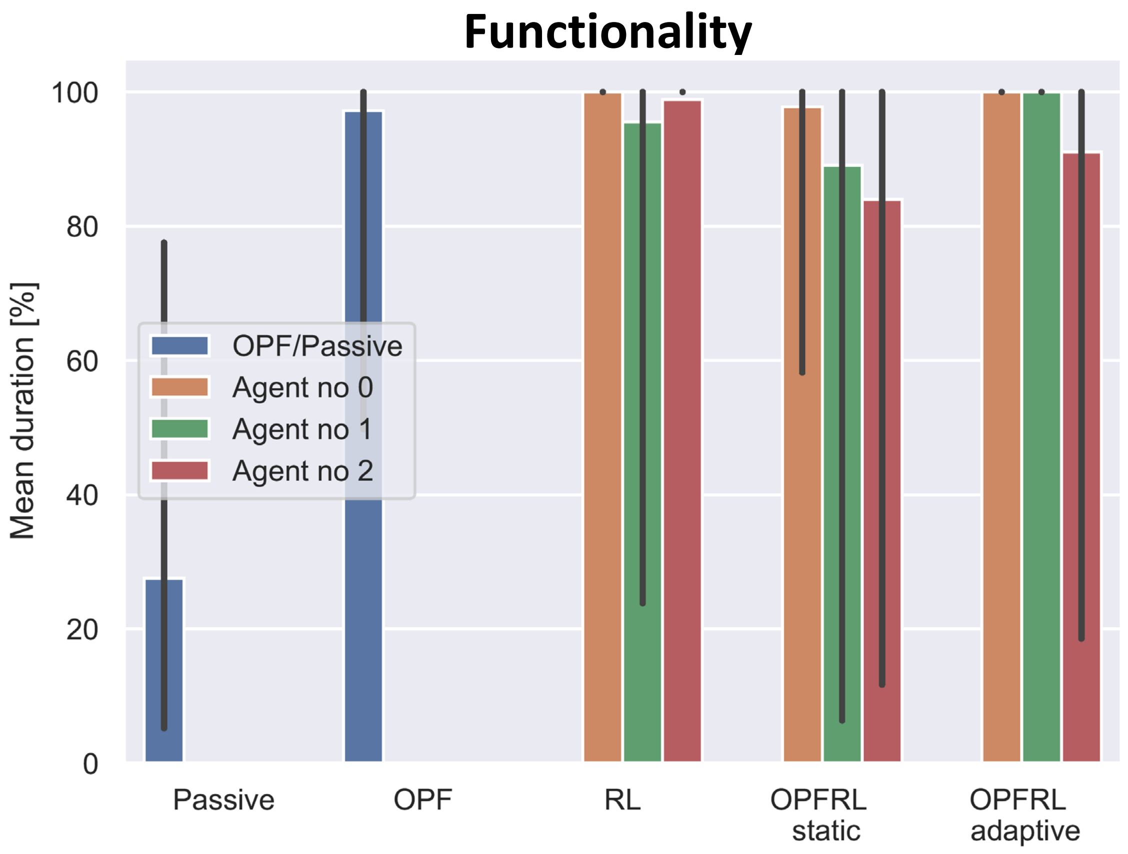
36-bus subset of IEEE 118-bus system

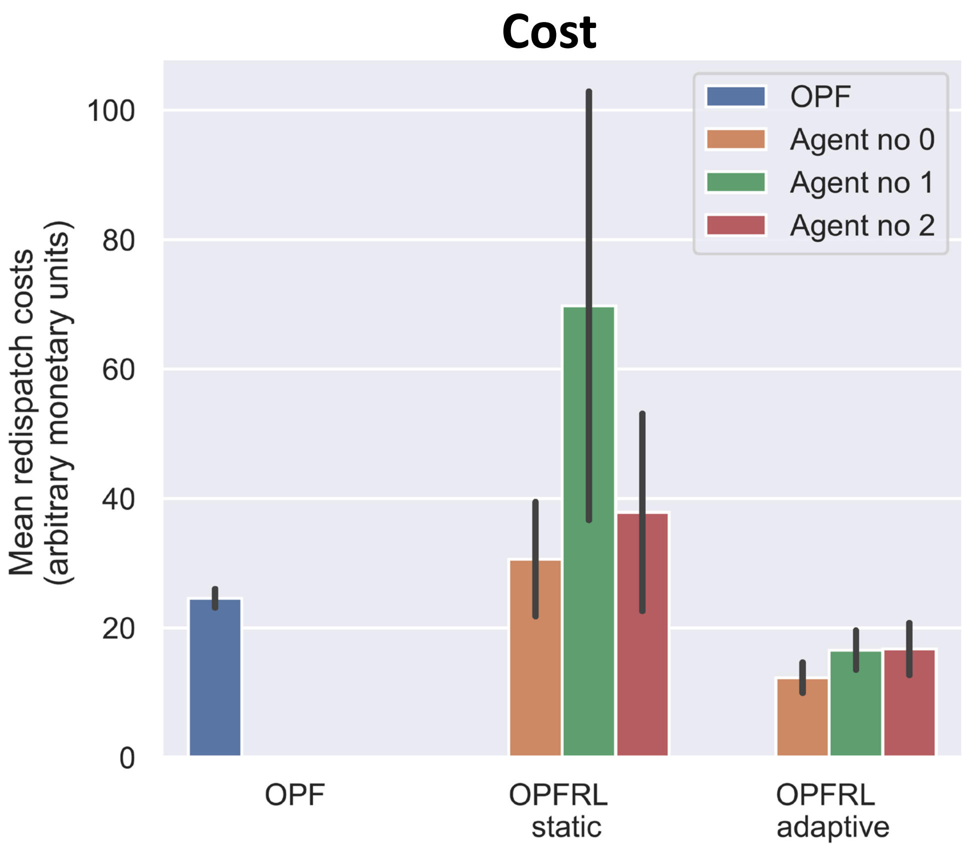


2. Ai supported grid reconfiguration

Results

B. Combining redispatch & grid reconfiguration





2. Ai supported grid reconfiguration

Conclusions

- Ai supported grid reconfiguration is a viable solution to
  - provide preventive decision support or
  - provide curative actions in a future SIPS implementations
- Cost of redispatch can be significantly decreased using Ai supported grid reconfiguration
- Still much work to be done until realisation:
  - Reduction of effective action space needed in order to cope with large systems
  - Significant functional impact between agent types and availability of data
  - Robustness and stochastic outages require further studies

Conclusions and outlook

Conclusions and outlook

System Integrity Protection Schemes:

- A measure to decrease the risk of large disturbances
  - Limiting extent of High-Impact Low-Probability events may have huge societal value
- Can be used to increase available transfer capacity
  - More efficient use of existing grids
  - Faster connection of customers – generation, demand, & storage
- Increase the complexity and potentially new risks
  - Deep understanding needed in design, implementation, control and evaluation
  - Important with suitable tools and processes

Conclusions and outlook

Increased interest and implementations worldwide, but
More research is needed!

- NEW R&D project: **SecureGrids**
  - Collaboration between Sweden, Austria, Latvia & Spain
  - Bridging the gap between flexibility markets, flexible connection agreements, and system security requirements.
  - Main objectives:

1. Develop and validate SIPS and other remedial actions as solutions to **meet grid operator challenges**

2. Develop methodologies for **systematic and coordinated utilisation** of different remedial actions and ancillary services

3. Provide **recommendations for regulatory frameworks** to enable planning and operation of future electricity grids with increased utilisation

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Emil Hillberg

Senior Researcher Electric Power Systems
RISE Research Institutes of Sweden
Adjunct Associate Professor **Lund University**
Emil.Hillberg@ri.se