International Workshop on
Dynamic Stability Challenges of the Future Power Grids

Coordinated voltage control and the value of reactive power

Presenters
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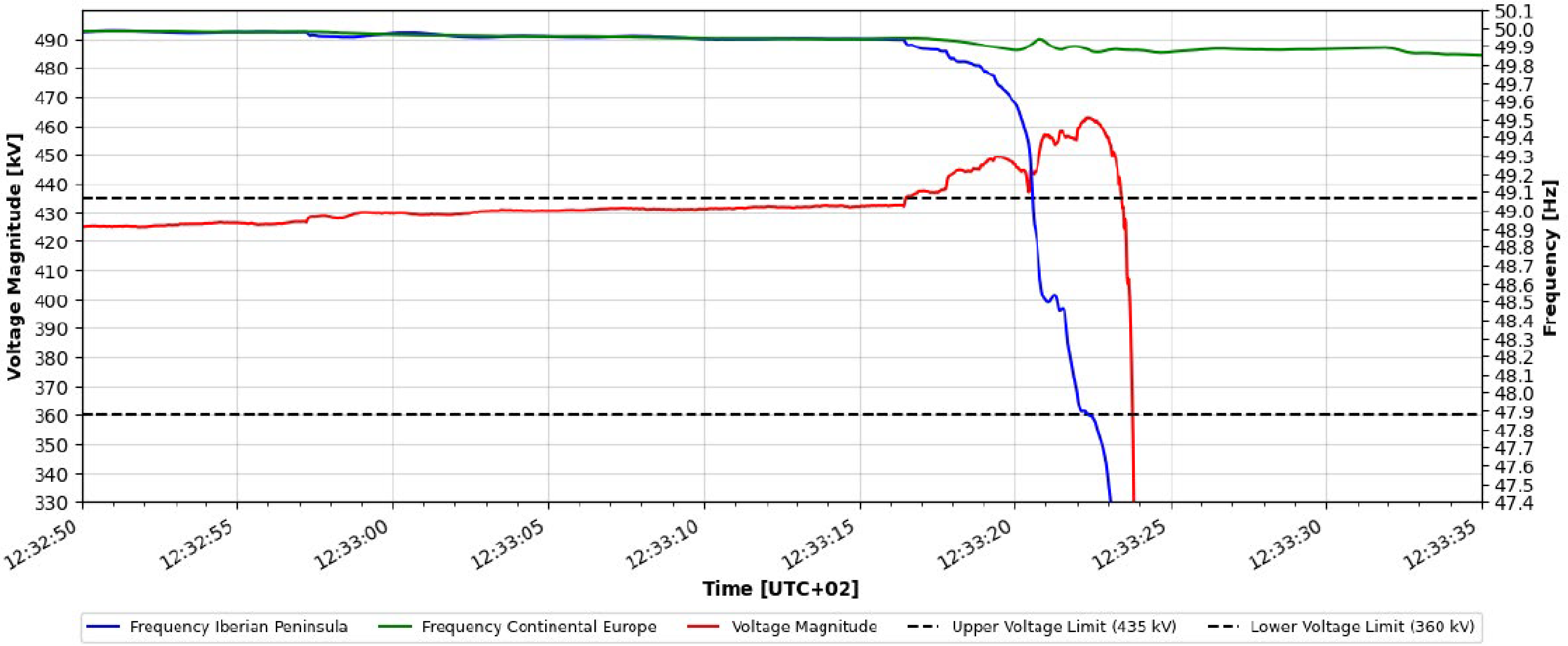
- Introduction – Challenges with voltage control and management of reactive reserves
- SysOpt and CoordQ projects – Motivation and objectives
- Example of Applications
  - Hierarchical and Coordinated voltage control schemes (Kjetil)
  - Value of reactive power (Daniel)
- Conclusions

What happened in Spain and Portugal 28 April?

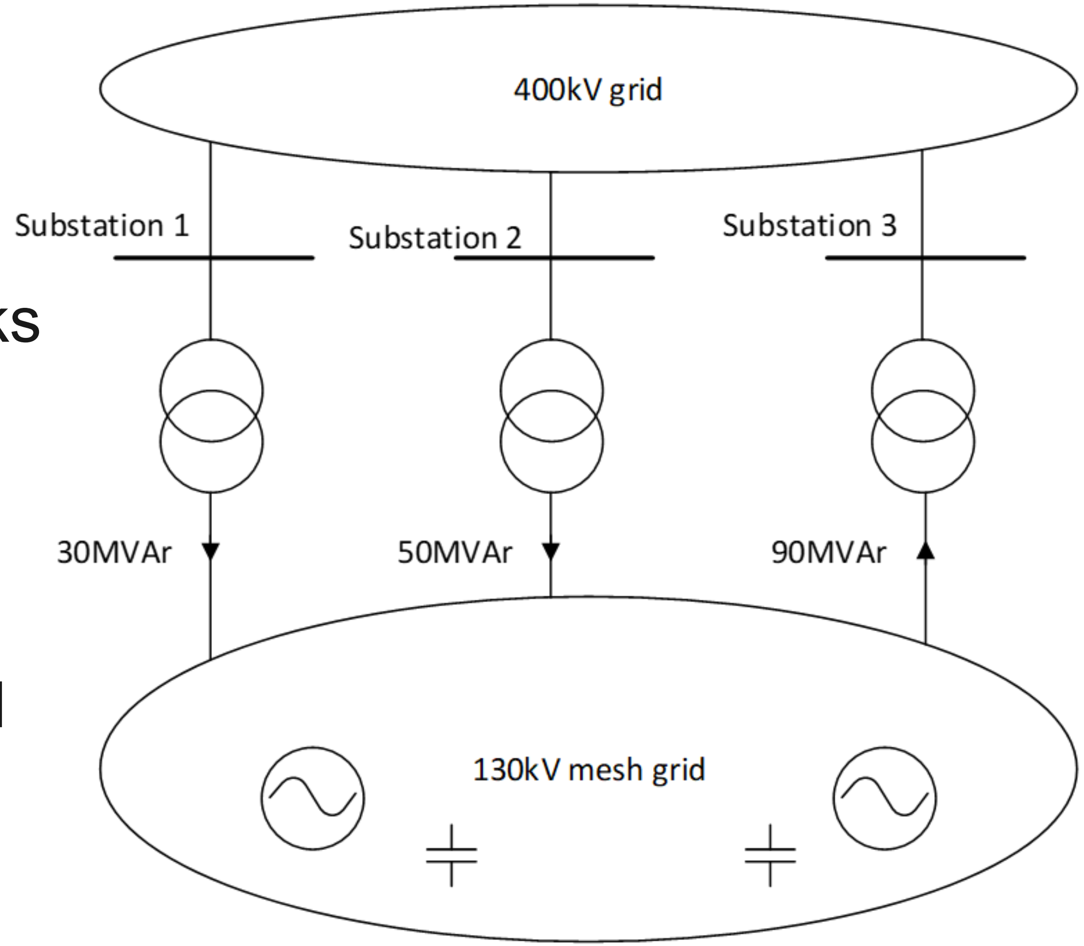


igure 1-4: Evolution of the frequency and the voltage in the substation of Carmona (Spain) and of the frequency in the rest of Continental Europe (substation of 3assencourt, Switzerland) during the incident

From https://www.entsoe.eu/publications/blackout/28-april-2025-iberian-blackout/

Case example TSO-DSO coordination

- Problem: Circulating *Mvars* between grid levels (here transmission and regional grid)
- Approach: Explore coordination between power plants and reactors/capacitor banks at 132 kV level and OLTCs to minimize *Mvar* loop flows
  - and consequently, reduce losses
- Challenge: How to maintain "decoupled" voltage control in the local grid areas and at the same time coordinate setpoints? (need simple solutions!)

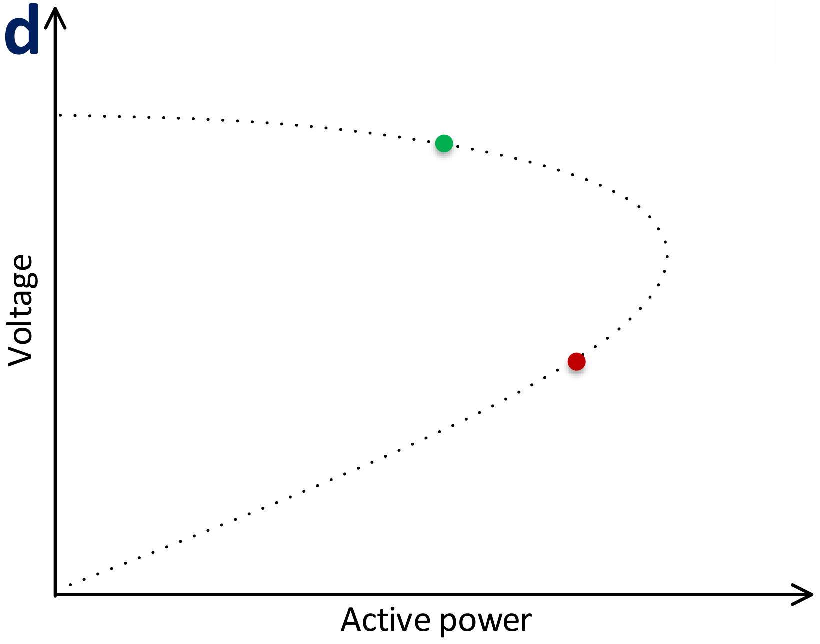


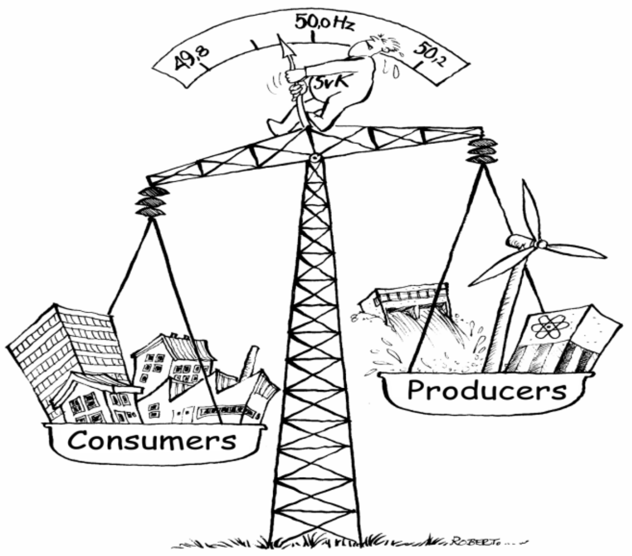
Ref: Thuc Duong

Balancing and stability

- Not only about frequency and active power

- **Voltages must be maintained at acceptable levels**
- **..and be stable!**





Source: Statnett

University of
South-Eastern Norway

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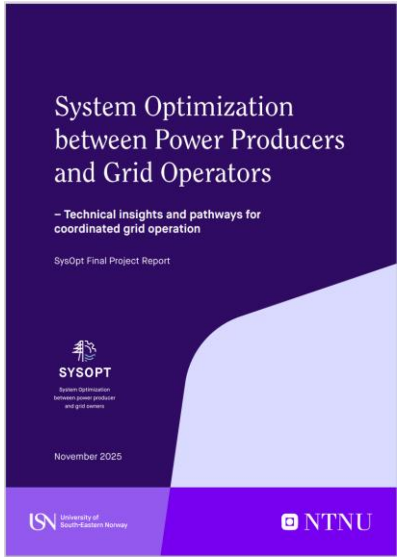
Promo video on Vimeo:
🎥 https://vimeo.com/usn/sysopt



Technical Roadmap
SysOpt_Rapport_V4_digital.pdf

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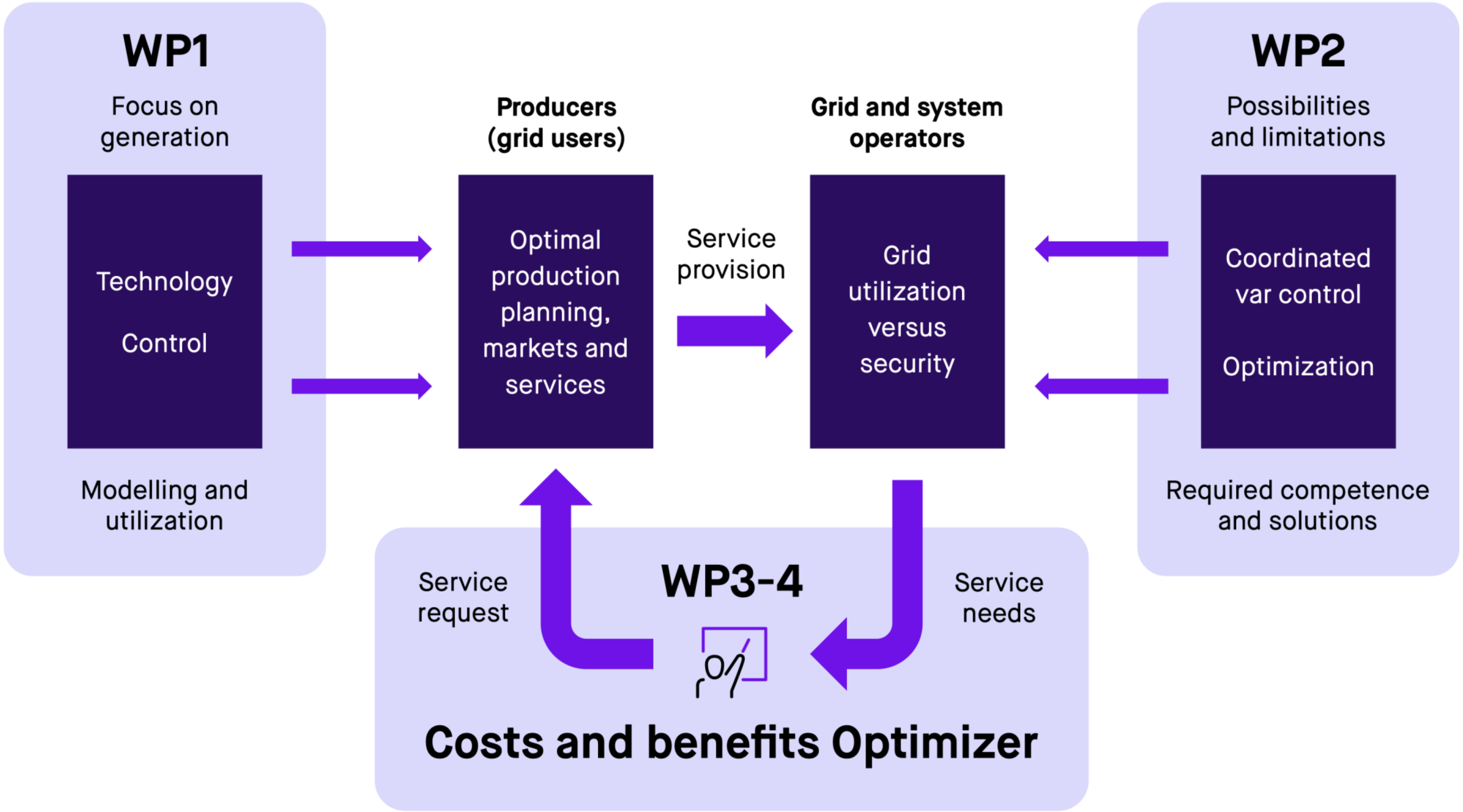
Objectives

To optimize the interface between power producers and grid owner…

- by utilizing available capacity (of <u>generators</u> and grid components)
- and developing efficient control systems, focusing on <u>voltage control</u>, <u>coordination</u> and use of <u>reactive reserves</u>.
- Thus, ensuring <u>operational security</u> of the future energy system.
- that can lead to <u>fair</u> and <u>cost-effective system services</u>

Organization of SysOpt



Project SysOpt: System Optimization between power producers and grid owners

WP1
Service providers

WP2
Coordinated voltage control

WP3
System Optimization

WP4
Guidelines and framework

Partners

USN University of South-Eastern Norway

NTNU

Statnett

Statkraft

Skagerak Energi

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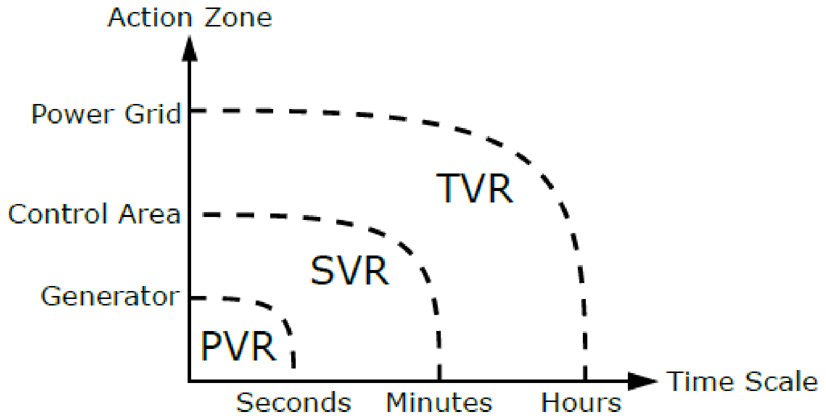
Secondary Voltage Regulation (SVR) + Optimal Power Flow (OPF)

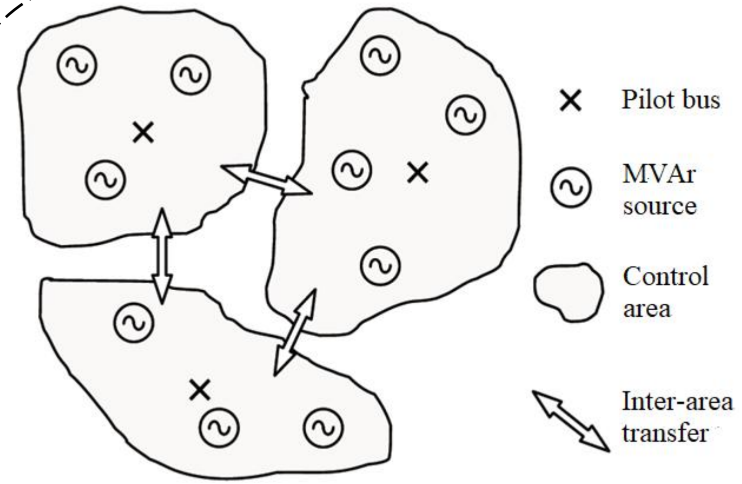
It is fundamental to **decouple** control layers, so as to avoid conflicting regulation actions.



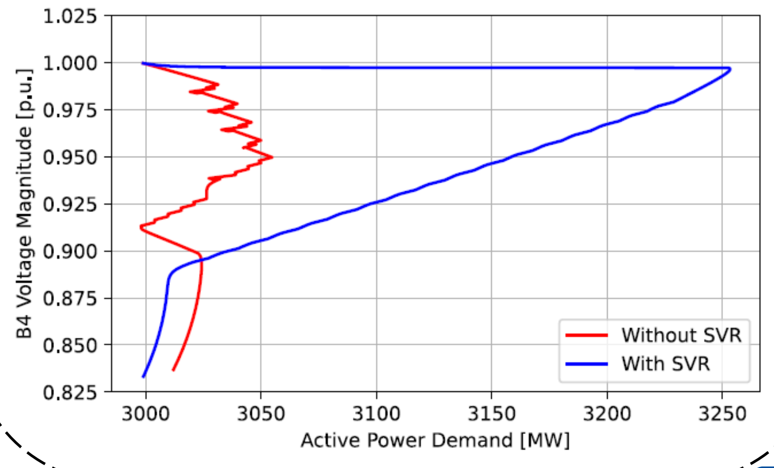
PVR: individual generator AVRs.

SVR: control areas, through pilot buses.

TVR: centralized optimizer and OPF.

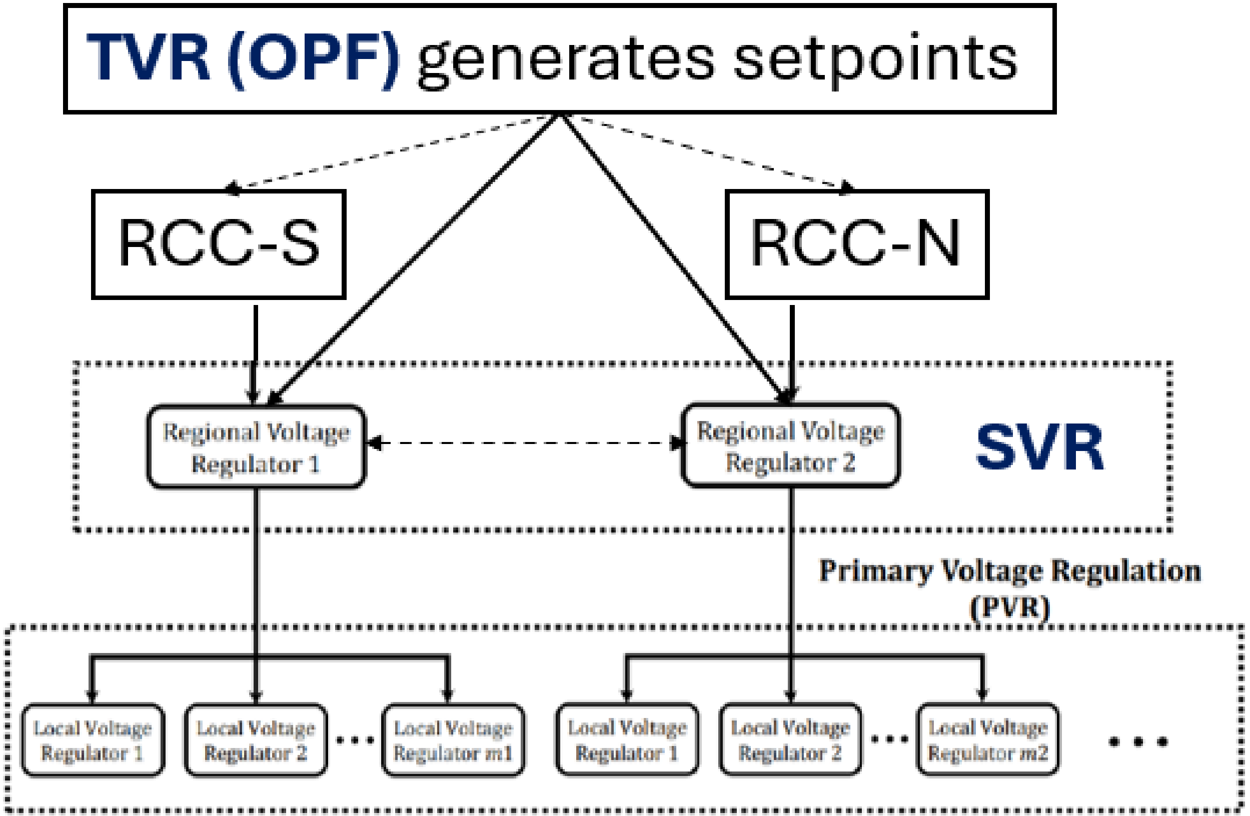


What to expect from SVR?



Secondary Voltage Regulation (SVR) + Optimal Power Flow (OPF)

SVR + TVR (OPF)



OPF Objectives

- Minimization of active power losses
- Voltage level max./min. limits

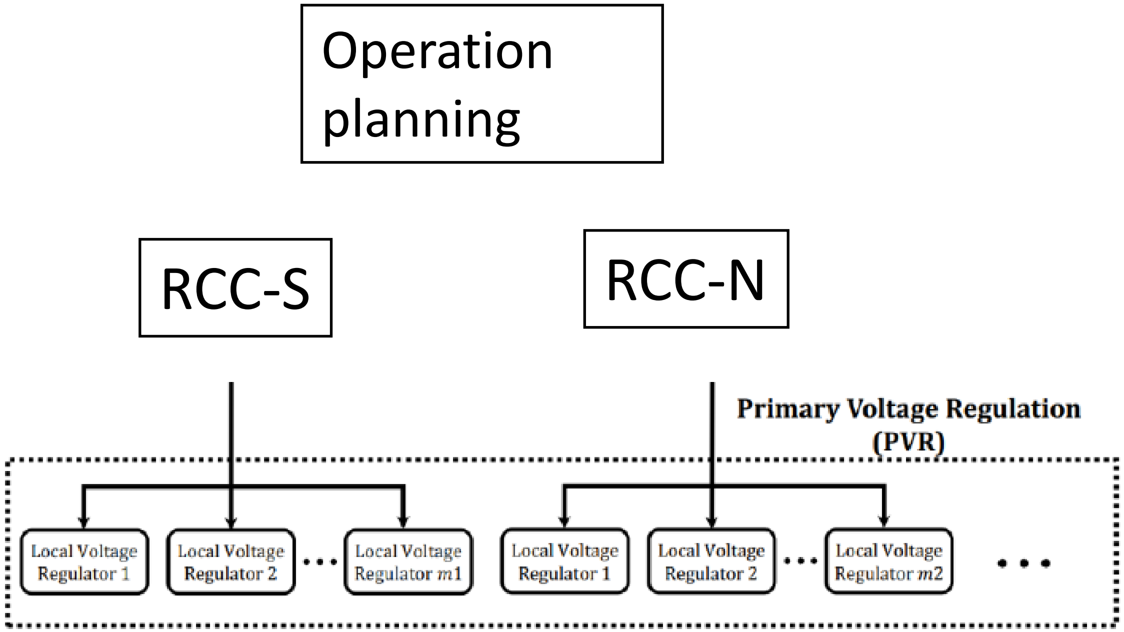
SVR Objectives

- Flat voltage behavior within area
- Improvement of loading margins
- Fair utilization of MVAr resources

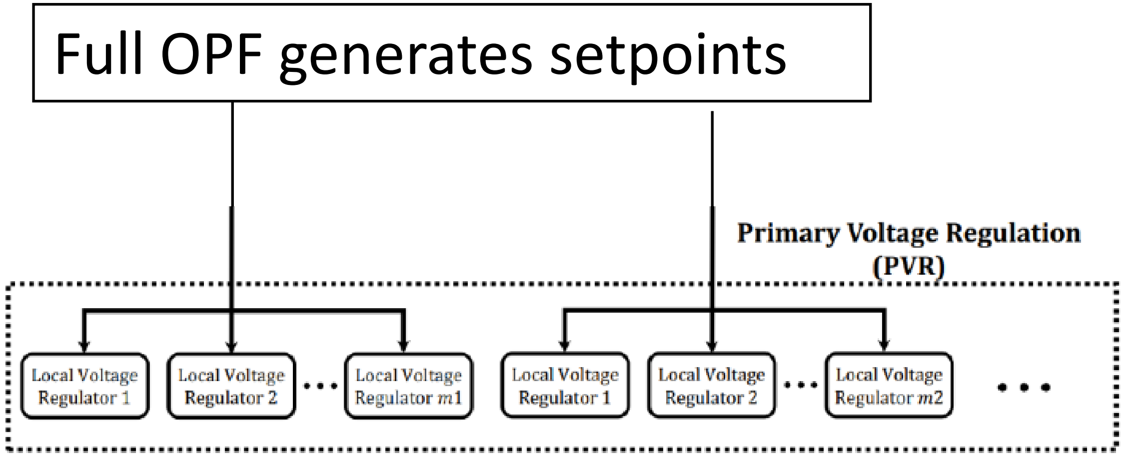
Coordinated voltage control - basic ideas

Different coordination approaches:

Today…

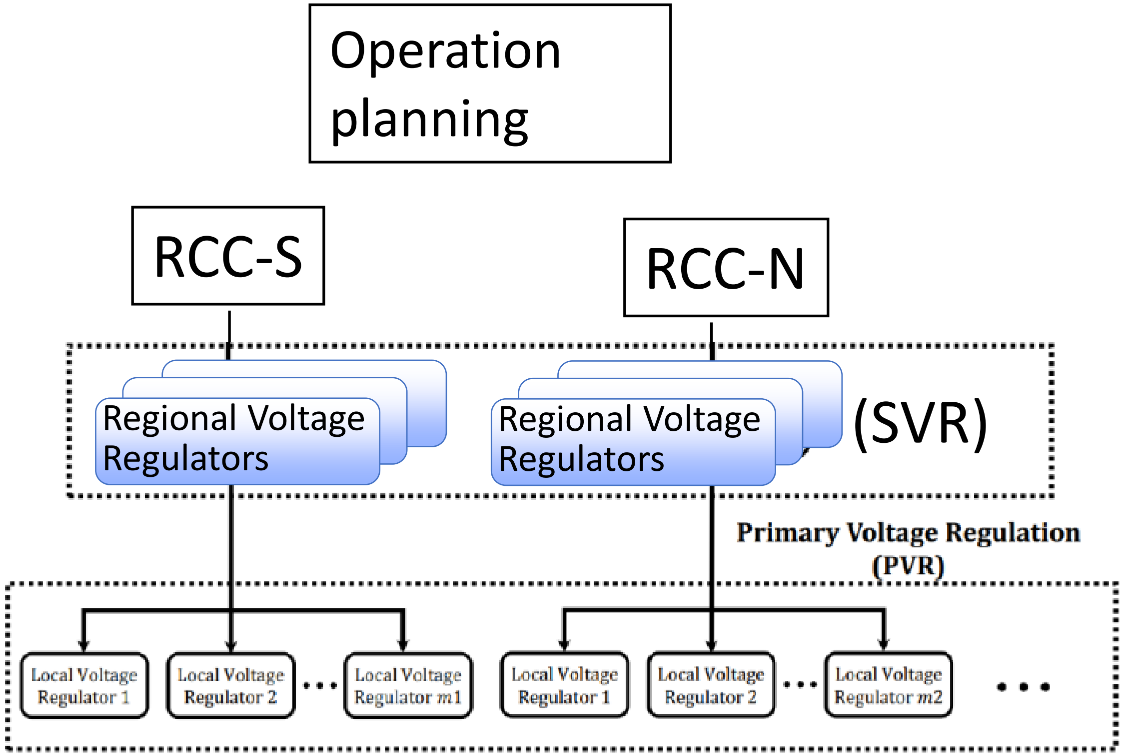


Fully automated and centralized (probably not practical)

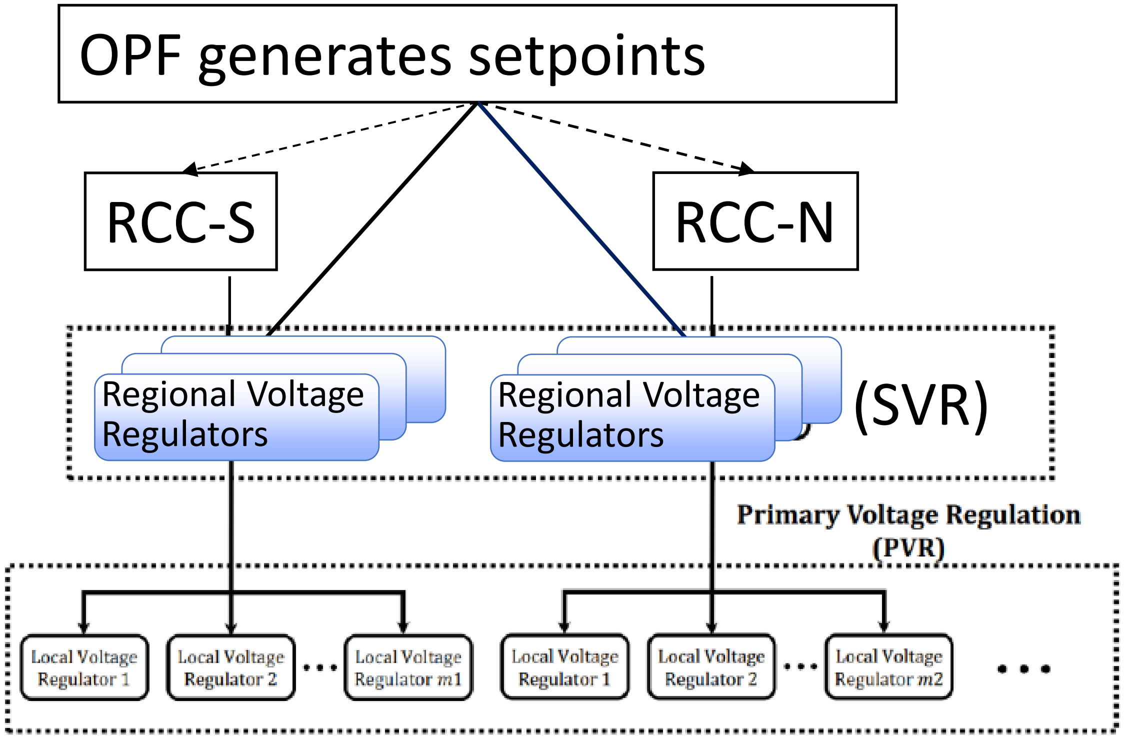


Coordinated voltage control - basic ideas

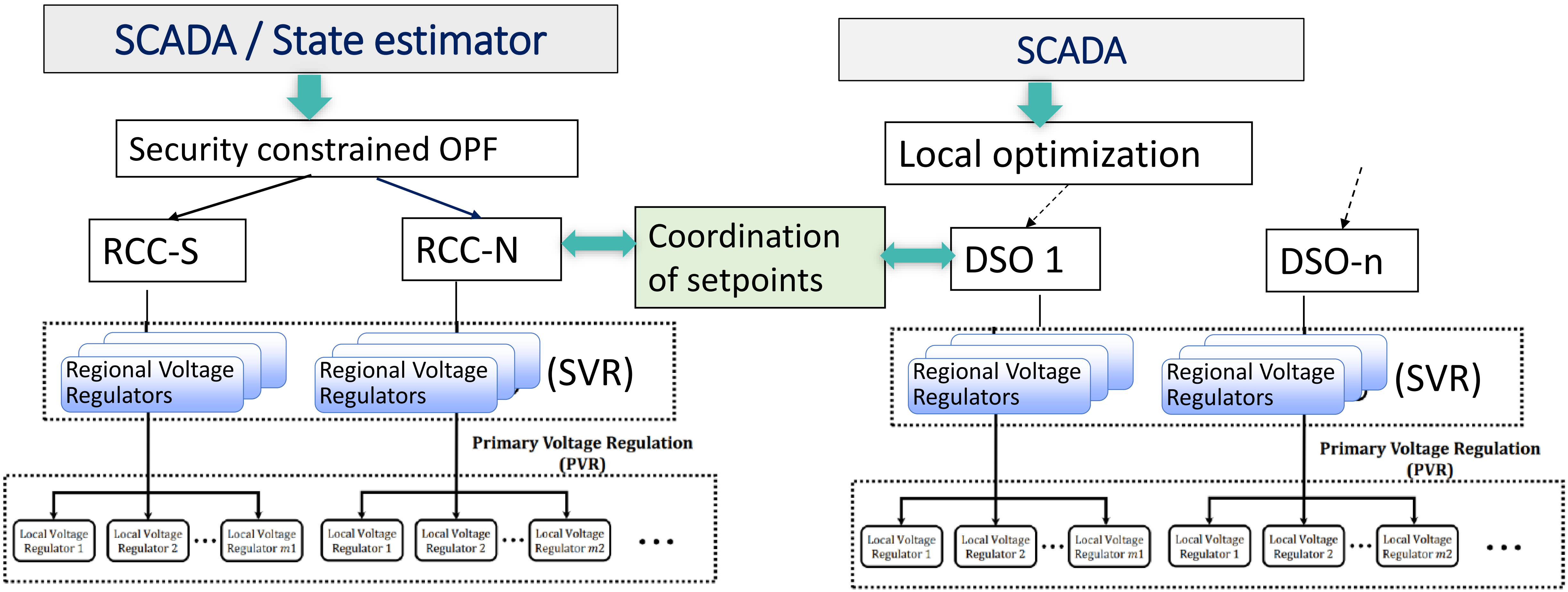
Practical solution…



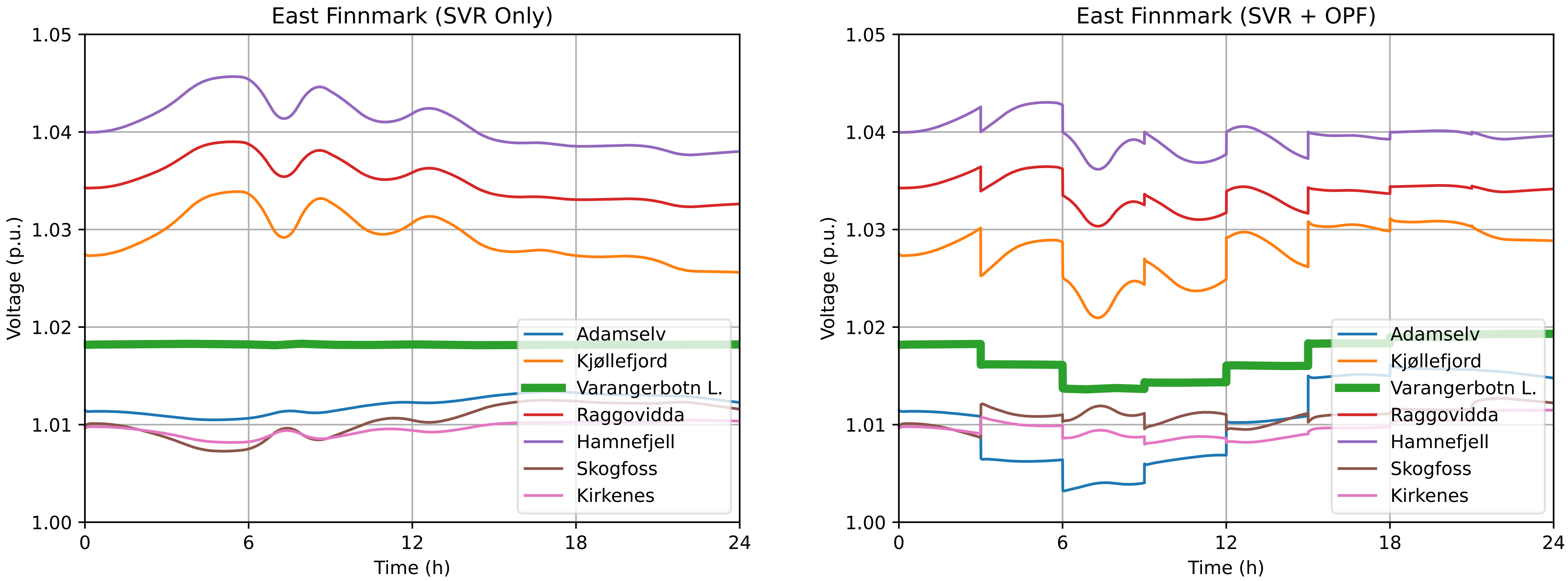
Near-optimal solution



Coordinated control – TSO-DSO

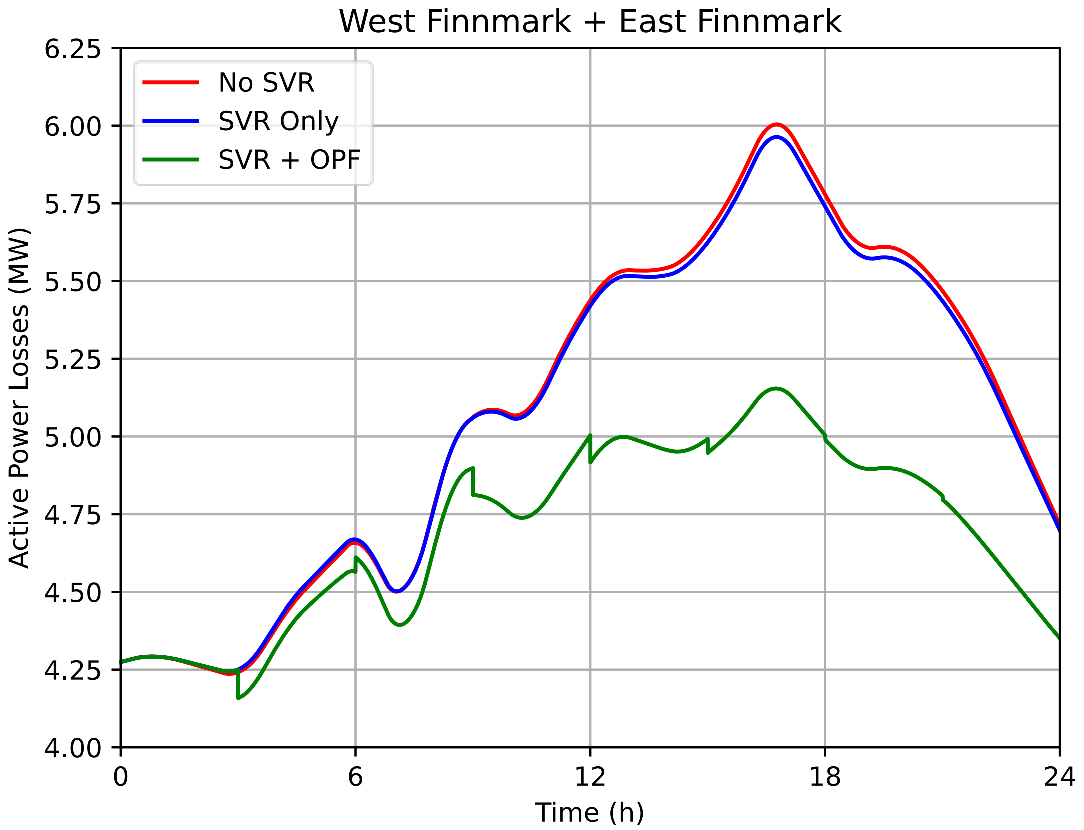


Dynamic Simulation Results: SVR Only × SVR + OPF



Main remark: OPF also mitigates the influence of wind pattern on voltage profiles, again through pilot bus variations.

Dynamic Simulation Results: No SVR × SVR Only × SVR + OPF



Main remark: OPF setpoint updates throughout the day build a consistent trend of loss reduction, esp. during peak hours.

Loss Metrics: SVR + OPF

Peak reduction: **13.3%** or **800 kW**

Avg. reduction: **6.8%** or **410 kW**

Avg. NO4 day-ahead price: **10 €/MWh**

Avg. cost savings: **4.1 €/h**
100 €/day
3000 €/month
36000 €/year

Conclusions & Next Steps

- SVR + OPF is a solid enough control strategy for Finnmarksnettet. All individual objectives are attained (to a certain degree) in a complementary manner.

- It is always possible to expand the case studies: contigency analyses, even more realistic scenarios, other SVR/OPF approaches… All of these are still under investigation.

- One interesting untapped potential: performing grid voltage control through the wind power plants, by making them operate in power factors other than unity. Future work?

Project SysOpt: System Optimization between power producers and grid owners

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Current Market Setup

Market Structure

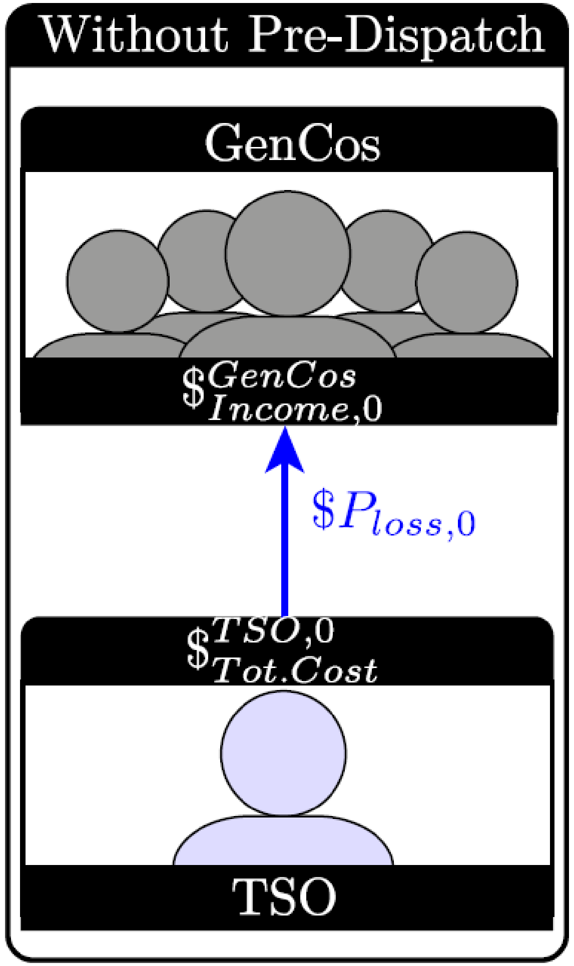
Multiple Generator Companies (GenCos) participate in the active-power market, while Statnett operates the transmission grid as the Norwegian TSO. We do not have a reactive power market.

Cost of Transmission Losses

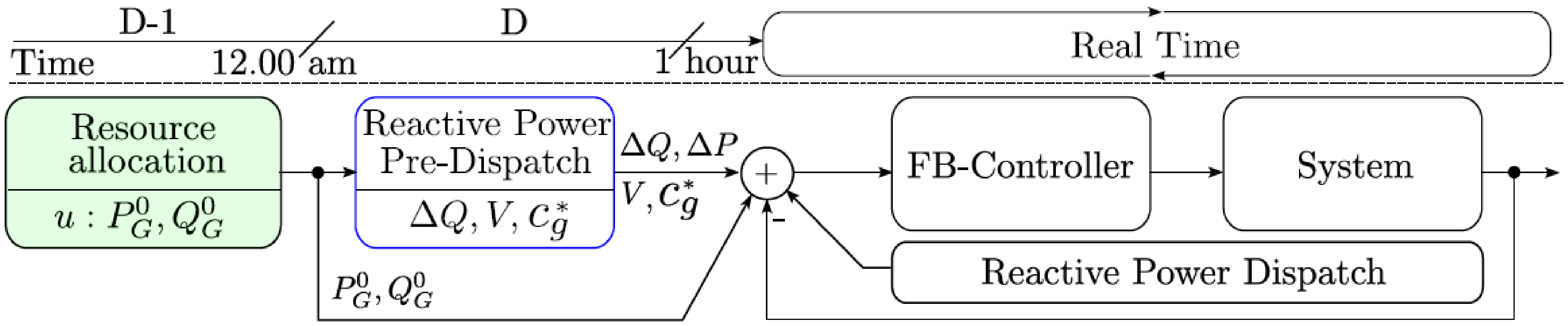
Transmission losses require additional active power generation, purchased at the market price. **The TSO initially bears the associated costs, which are ultimately borne by society.**

Reactive Power Provision

GenCos are required to provide reactive power within specified power-factor limits. **Reactive power provision is not separately remunerated.**

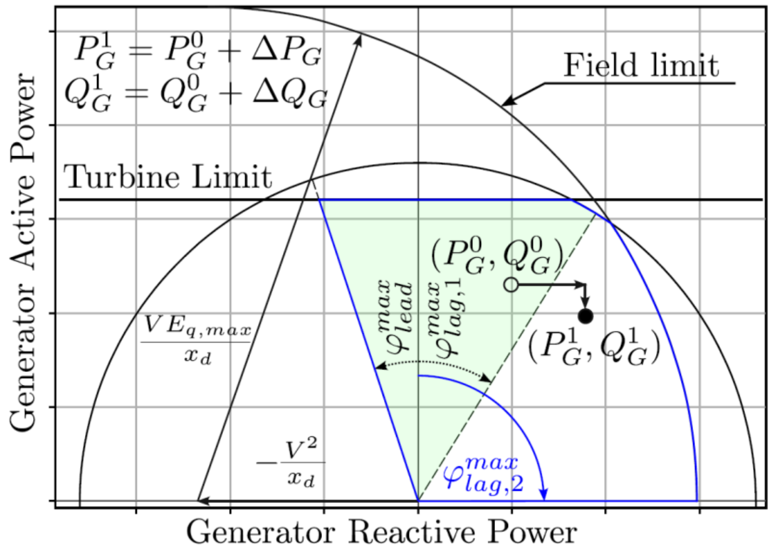


Pre-Dispatch Step



Current Procedure
Active power setpoint determined by the market.
Reactive power follows from the rule-based terminal-voltage setpoint.

Pre-dispatch step
Additional reactive-power flexibility ΔQ is used to **minimize active-power losses**. Additional reactive power provision is **remunerated**
Similar as proposed in (Hao, S. (2003)).

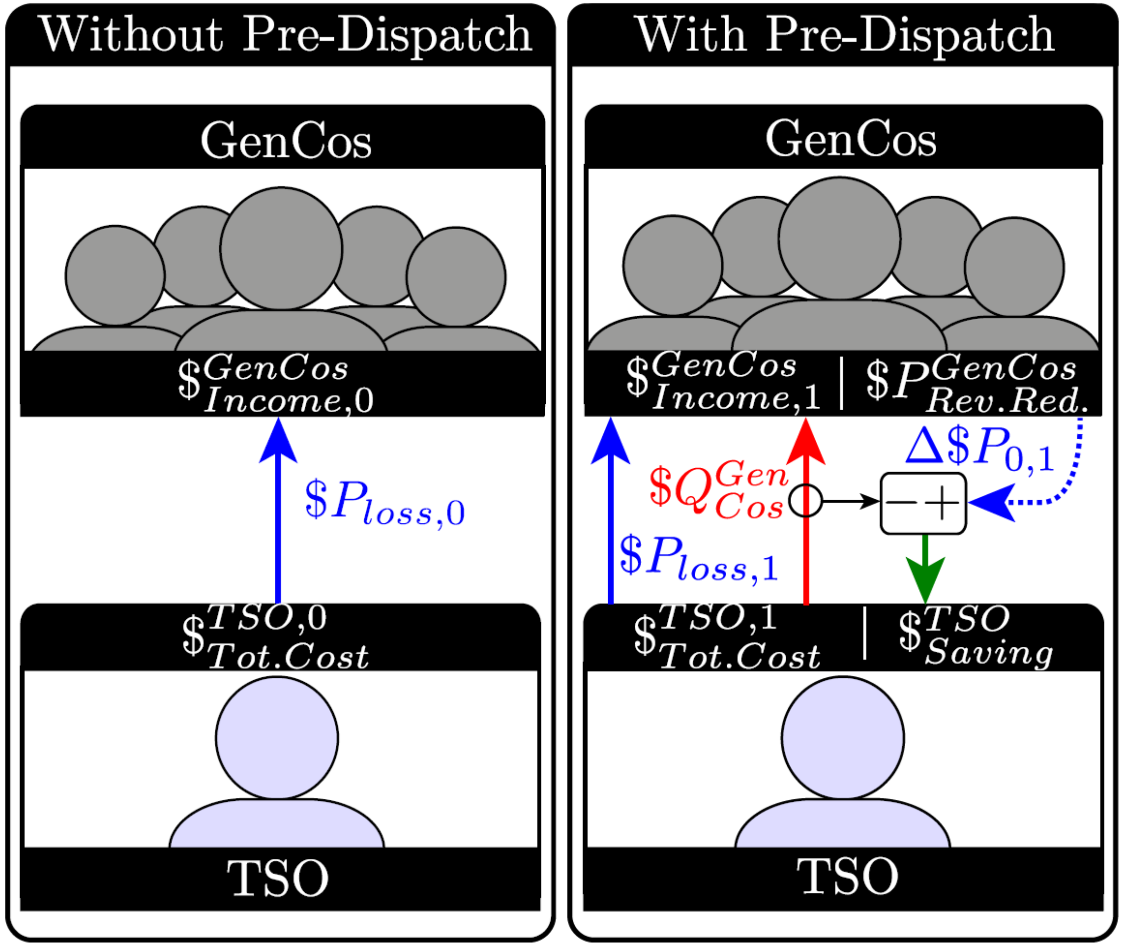


Economic Trade-Off Between TSO and GenCos

With pre-dispatch:
- The TSO **pays for additional reactive power**
- Reduced losses lead to **lower active-power procurement costs**

Economic interaction:
- The monetary benefits of the TSO and GenCos are a **zero-sum game under the considered remuneration model.**
- A higher TSO saving corresponds to a lower GenCos income, and vice versa.

Key question:
- How much can the TSO offer for reactive power while still achieving savings?
- Consequently, what is the value of reactive power



Methodology

We formulate a parametric OPF in which the reactive power price, cg, is treated as a parameter. For each cg, the OPF determines the optimal control variables u(cg) and system states x(cg).

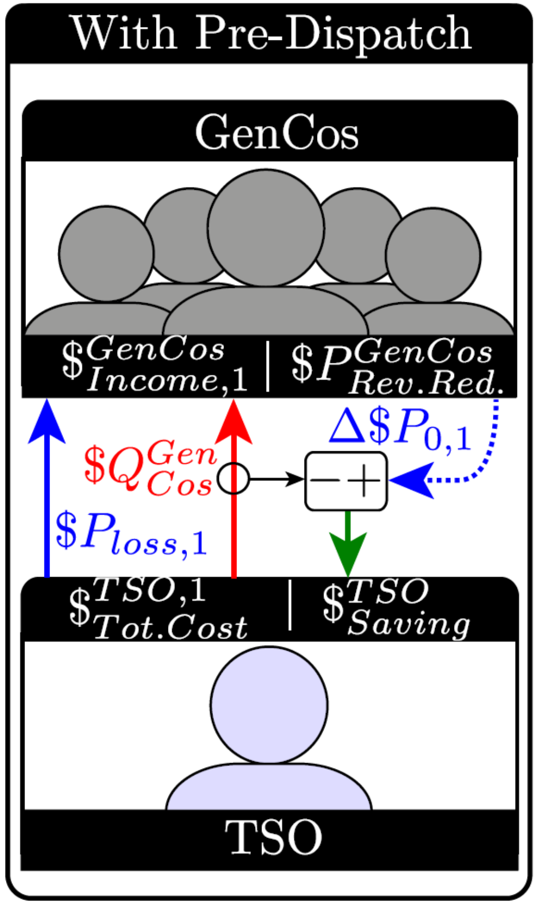
Objective: minimize loss costs + reactive power remuneration

$$(u(c_g), x(c_g)) = \operatorname*{argmin}_{u,x} \overbrace{C^{Day}_{Ahead} P_{loss,1}}^{\$P_{loss,1}(u,x,c_g)} + \overbrace{\boxed{c_g} \left(\underbrace{\sum_{k \in \mathcal{G}} |\Delta Q_{G,k}| + \sum_{k \in \mathcal{W}} |\Delta Q_{W,k}|}_{|\Delta Q^{Gen}_{Cos}|} \right)}^{\$Q^{Gen}_{Cos}(u,x,c_g)}$$

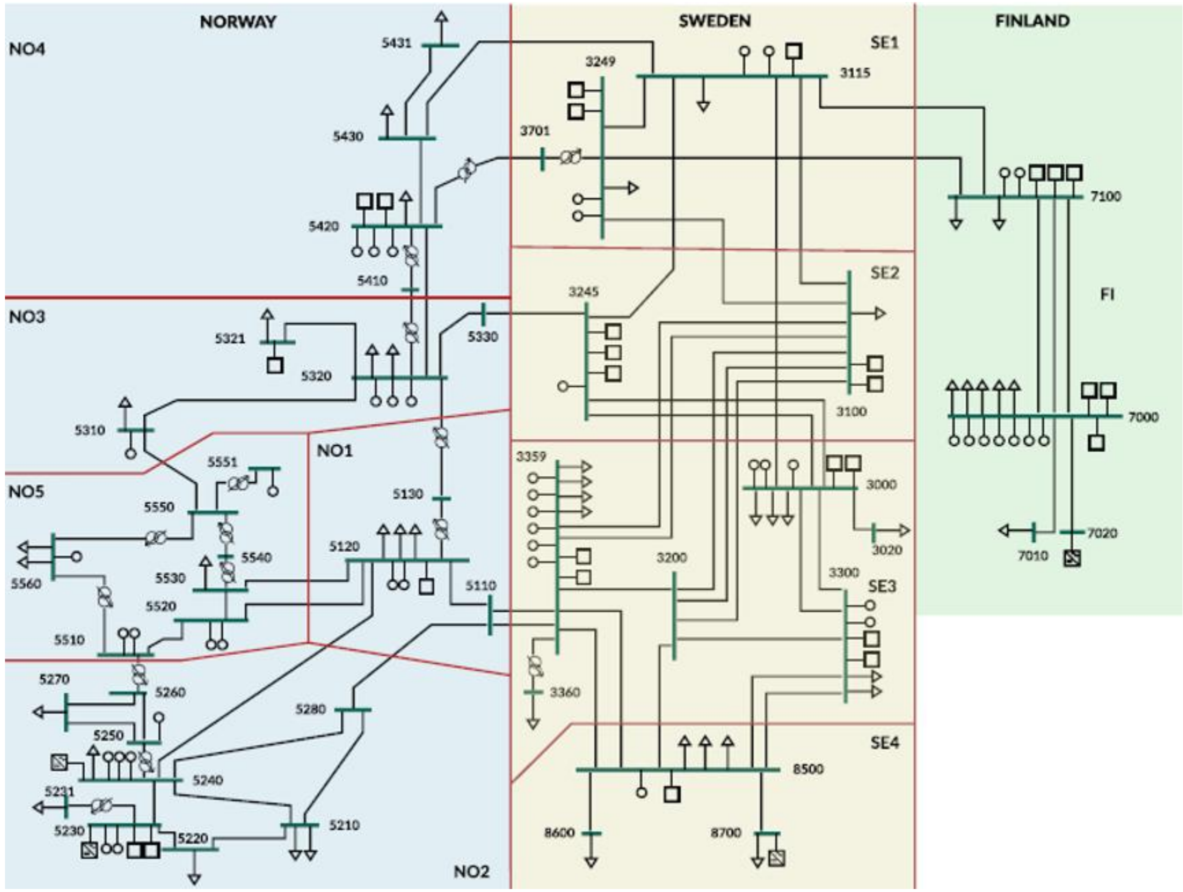
$$\text{s.t.} \quad g(u,x) \leq 0, \quad h(u,x) = 0$$

h(u,x): Basic AC power-flow equations
g(u,x): Operation limits.

cg: reactive power price parameter



Nordic 45 Test Model

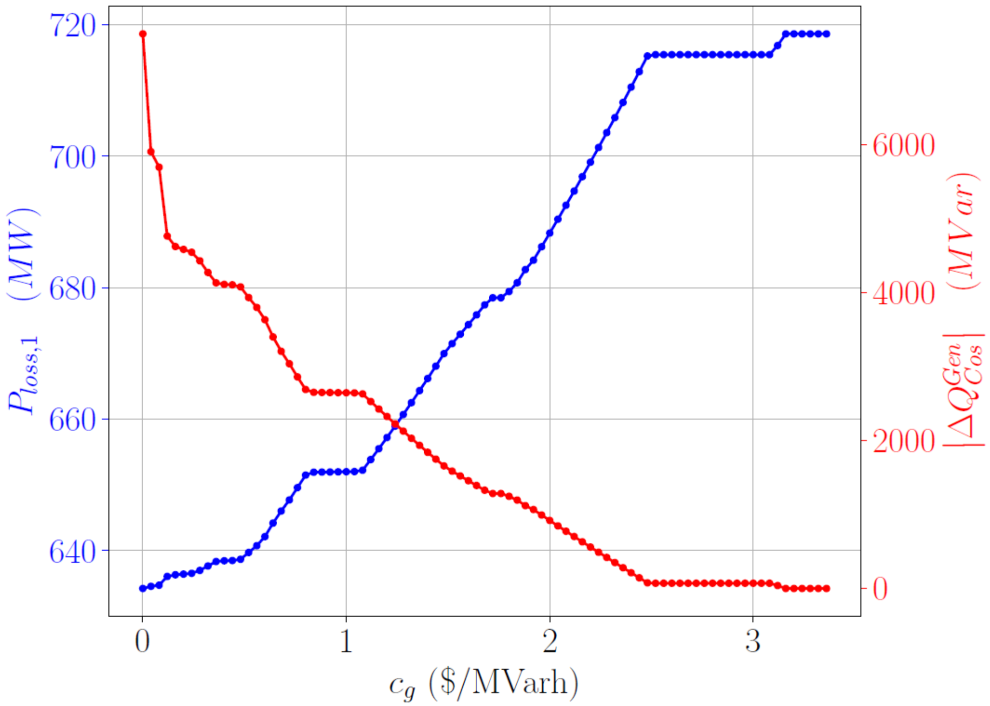


A benchmark transmission system model for the Nordic region, including Norway, Sweden, and Finland.

In our studies we used the Nordic 44 model which is now updated and from now on the Nordic 45 model.

Price Sweep Results

Considering the active power losses and the reactive power compensation plotted over the reactive power price, we see the following (we assume an active power market price of 70 €/MWh):



1) At low reactive-power prices, procuring additional Q is economically attractive, allowing the OPF to substantially reduce transmission losses.

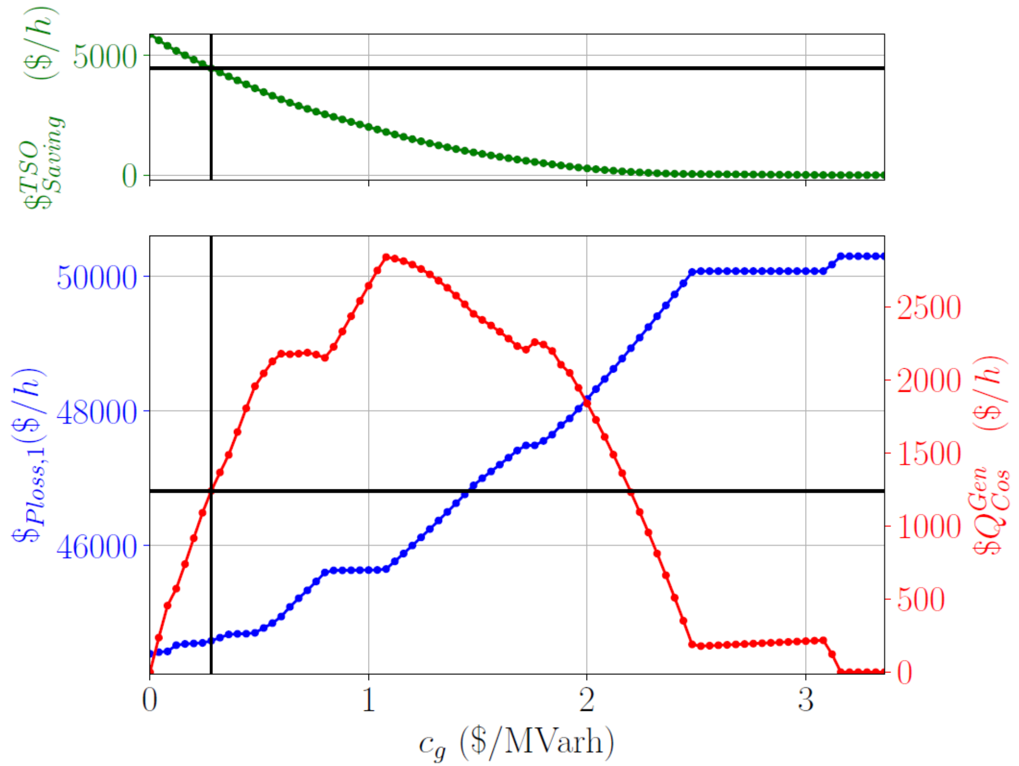
2) As the reactive power price increases, less additional reactive power is procured and transmission losses increase.

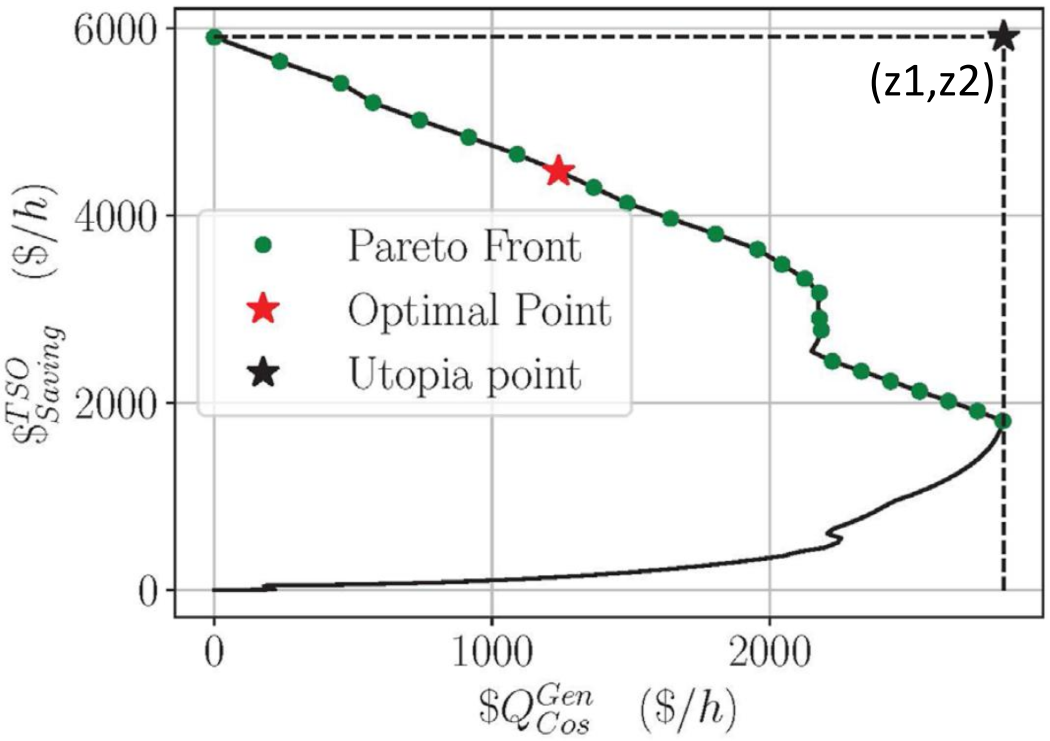
3) Above approximately 3.16 €/MVArh, additional reactive-power procurement is no longer economically attractive for this operating point.

Pareto / Selected Solution

The TSO's and the GenCos' objectives are in conflict. We therefore seek a solution on the Pareto front that guarantees TSO savings while providing fair remuneration for reactive-power flexibility.

$$\min_{c_g \in C_g} \max \left\{ \left(z_1 - \$Q^{Gen}_{\text{Cos}}(c_g) \right),\ \left(z_2 - \$S^{TSO}_{\text{Saving}}(c_g) \right) \right\}$$





Conclusion

Reactive power has a case-dependent economic value
Reactive-power pre-dispatch can **reduce active-power losses** while providing additional income to GenCos.
For the investigated operating point, procurement is economically attractive up to approximately **3.16 $/MVArh**.

A trade-off exists between TSO savings and GenCo remuneration
- Pareto-optimal solutions occur for remuneration levels of approximately **0–1.08 $/MVArh**.
- Using our trade-off criterion, a remuneration of approximately **0.25 $/MVArh** is selected.

The numerical values are case-specific and depend on the network model, operating point, available reactive-power flexibility, and active-power market price

Limitations
1) Reactive-power reserves not considered
2) Computationally inefficient price sweep
3) Model and operating-point uncertainties not considered

To be continued in the new project

CoordQ

Coordinating Reactive Power Resources

–

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Førsteamanuensis,
Universitetet i Sørøst-Norge (USN)

Kilde: Skagerak Kraft/Lede

References

Hao, S. (2003). A reactive power management proposal for transmission operators. IEEE Transactions on Power Systems 18, 1374–1381. doi:10.1109/TPWRS.2003.818605

H. R. de Brito, V. M. de Souza and K. O. Uhlen, “Hierarchical Voltage Control for Improved Dynamic Performance of a Norwegian Grid Subsystem,” IEEE PES Innovative Smart Grid Technologies Conference Europe (ISGT Europe), Valletta, Malta, 2025. DOI: 10.1109/ISGTEurope64741.2025.11305514

H. R. de Brito, V. M. de Souza and K. O. Uhlen, “Multi-objective Voltage Control Optimization Applied to the Norwegian Transmission Network,” submitted to International Journal of Electrical Power & Energy Systems (IJEPES), 2026.