ETH
Eidgenössische Technische Hochschule Zürich
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SEPOPE 2012

eeh power systems laboratory

Security-Constrained Optimal Power Flow including Post-Contingency Control of VSC-HVDC lines

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IRENE-40 European Project

- **I**nfrastructure **R**oadmap for the **E**nergy **N**etworks in **E**urope for the next **40** years

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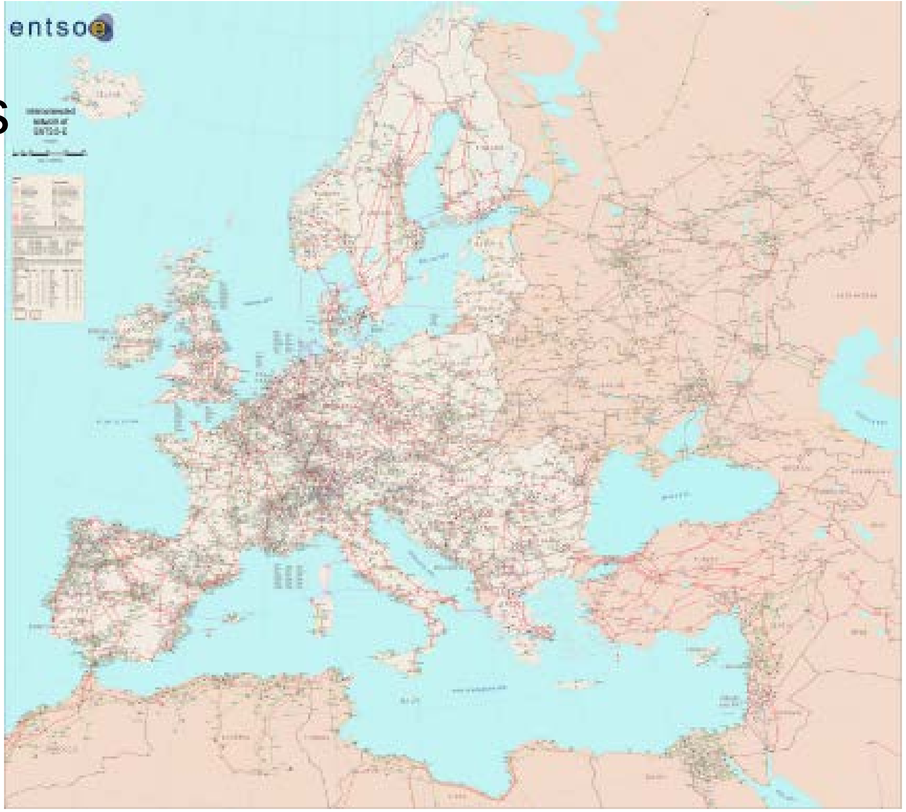
- Partners:
  - 5 European Universities:
    RWTH Aachen, Imperial College, Delft, NTUA, ETH Zurich
  - ABB, Siemens, Alstom, Energy Center of the Netherlands

IRENE-40

- Identify expansion measures with respect to:
  - Sustainability → more RES
  - Security
  - Competitiveness → efficient market operation



- Possible Options:
  - AC Lines, FACTS devices, HVDC lines, regulatory measures, etc.

"Cost of Security" Index

- The "Cost of Security" represents the additional generation dispatch costs, in order to satisfy the N-1 criterion.
- Compare the total generation costs resulting from a Security-Constrained Optimal Power Flow (SC-OPF) and from a standard AC Optimal Power Flow (AC-OPF)
- Cost of Security =

  Gen.Costs (SC-OPF) – Gen.Costs (AC-OPF)
- Goal: find the *least* "Cost of Security"

Motivation

VSC-HVDC lines can act fast and actively relieve line overloadings after a contingency

Therefore:

We need a Security-Constrained OPF,

which takes into account the increased control capabilities of

the VSC-HVDC lines after a contingency.

*VSC: Voltage-Source Converter technology

OUTLINE

1. Method
2. Case Studies
   - Operation: 10-bus network
   - Planning: European Network
3. Conclusions

Proposed Security-Constrained OPF (SC-OPF)

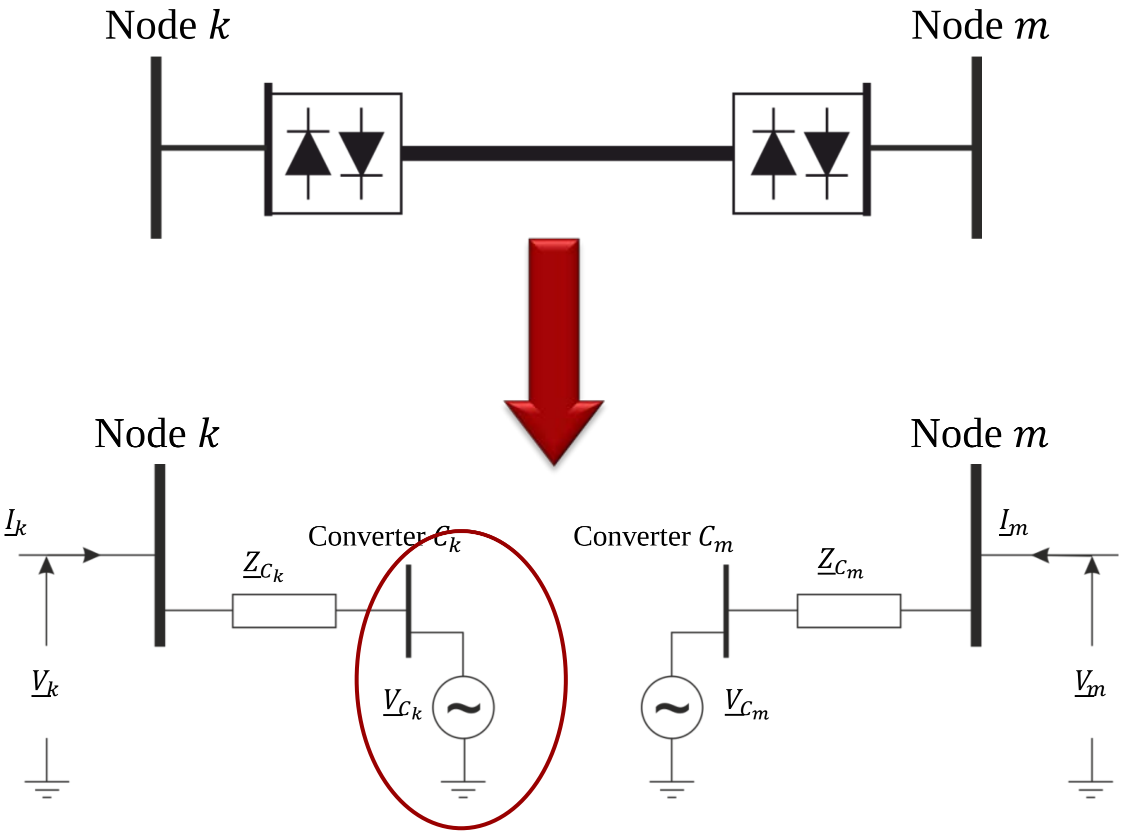
- The proposed SC-OPF is based on the current injection method for the calculation of the line currents in case of a line outage.

1. Standard AC-OPF
2. Model for VSC-HVDC lines
3. Current Injection Method
4. Extension for VSC-HVDC Post-Contingency Control
5. Extension for increased accuracy

VSC-HVDC Model

- Two virtual nodes for each HVDC line
- Each converter represented by a voltage source
- Constraint for the exchanged active power

Based on Pizano-Martinez et al., IEEE TPS, 2007



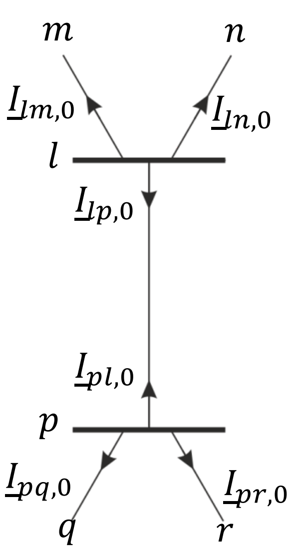
$$P_k + P_m + P_{DC,loss} = 0$$

Current Injection

- Virtual injection currents eliminate the flow on the outaged line

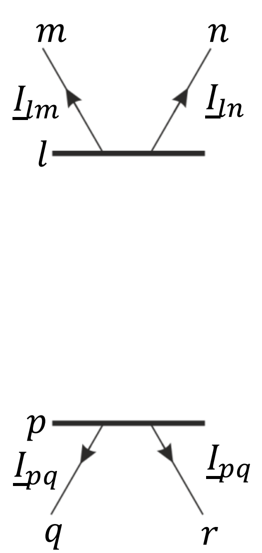
pre-fault

$$\underline{V}_0 = \underline{Z}_0 \cdot \underline{I}_0$$



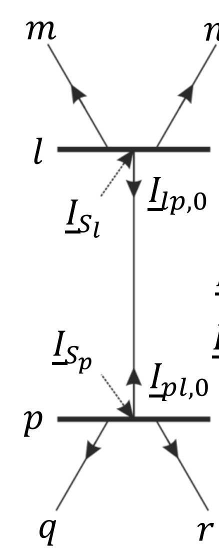
post-fault

$$\underline{V}_F = \underline{Z}_F \cdot \underline{I}_F$$



$\approx$

$$\underline{V}_F = \underline{Z}_0 \cdot (\underline{I}_F + \underline{I}_S)$$

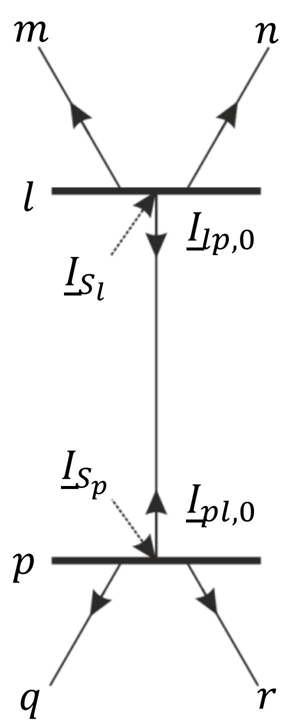


$$\underline{I}_{S_l} = \underline{I}_{lp}$$

$$\underline{I}_{S_p} = \underline{I}_{pl}$$

post-fault

$$\underline{V}_F = \underline{Z}_0 \cdot (\underline{I}_F + \underline{I}_S)$$



Change in line flows

$$\Delta \underline{I}_{line} = \underline{Y}_L \cdot \Delta \underline{V} = D \cdot \underline{I}_S$$

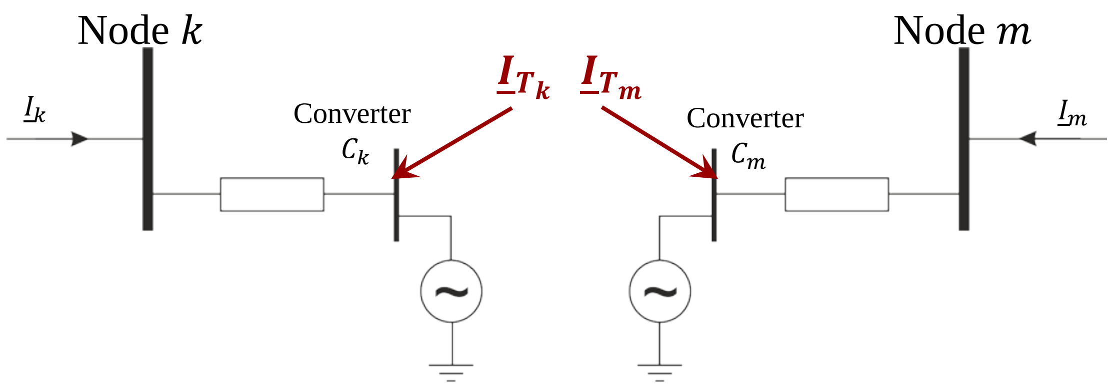
- Main Assumption:

Bus injections *before* the outage e.g. gens, loads

$$\underline{I}_0 = \underline{I}_F$$

Bus injections *after* the outage e.g. gens, loads

HVDC for post-contingency control

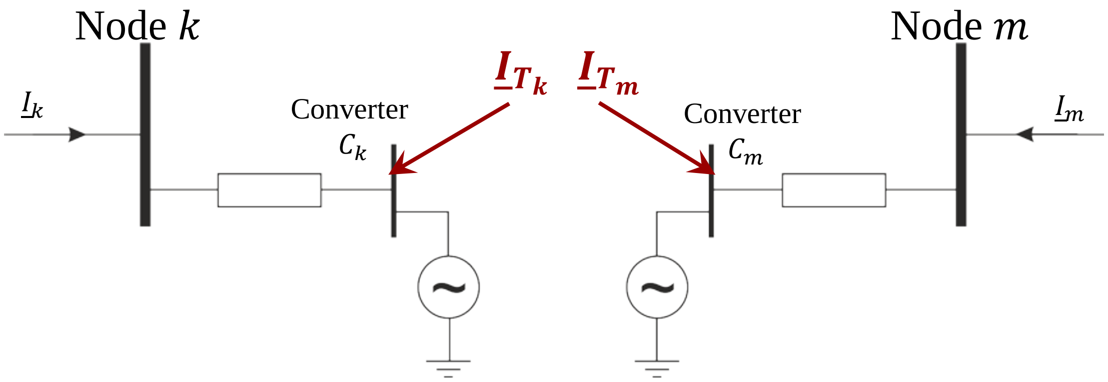


- If an HVDC “participates” during the outages:

$$\underline{I}_{0,\mathrm{HVDC}} \neq \underline{I}_{F,\mathrm{HVDC}}$$

Bus Current Injections at HVDC nodes are no longer zero

HVDC for post-contingency control



- With VSC-HVDC, we can control:
  - The active power flow, in order to relieve overloadings on other lines (one additional optimization variable)
  - The reactive power flow, in order to keep the voltage at the HVDC buses to a pre-determined setpoint

Extension for increased accuracy

- In reality:

pre-fault $\underline{I}_0 \neq \underline{I}_F$ post-fault

for all buses.

$$\underline{I}_T = \begin{bmatrix} \underline{I}_{T_1} \\ \underline{I}_{T_2} \\ \vdots \\ \underline{I}_{T_i} \\ \vdots \\ \underline{I}_{T_n} \end{bmatrix}$$

- We assume an additional current $\underline{I}_{T_i}$ for each bus, so that:
  - P and Q remain constant at PQ buses
  - P and V remain constant at PV buses
  - V and δ remain constant at slack buses

(extension proposed by Hug, Andersson, PSCC 2008)

SC-OPF Wrap-up

- Determine the injection currents $\underline{I}_S$, $\underline{I}_T$
- Calculate the line flows after the fault

$$\underline{I}_{line,post-fault} = \underline{I}_{line,0} + D \cdot \left(\underline{I}_S + \underline{I}_T\right)$$

- Include them in the constraints
- Additional constraints of the AC-OPF
- Additional constraints for the HVDC model

OUTLINE

1. Method
2. **Case Studies**
   - **Operation: 10-bus network**
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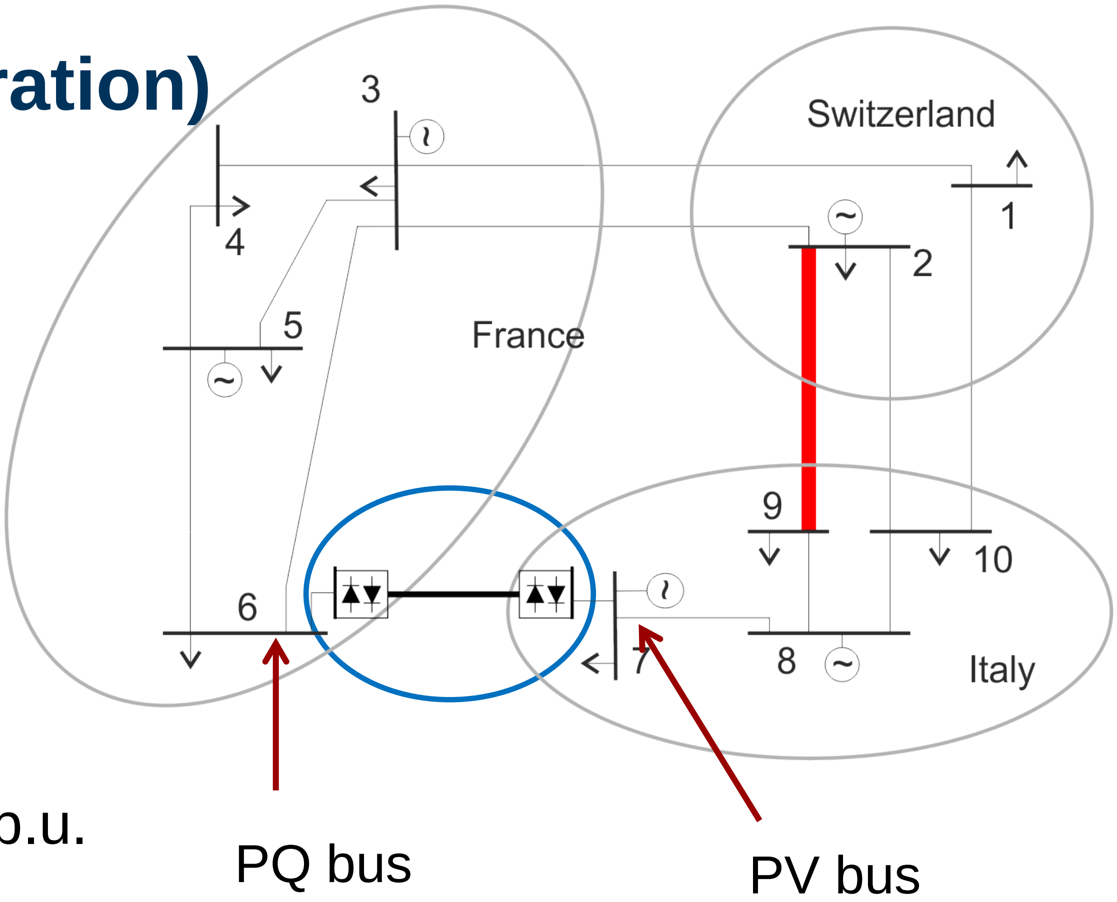
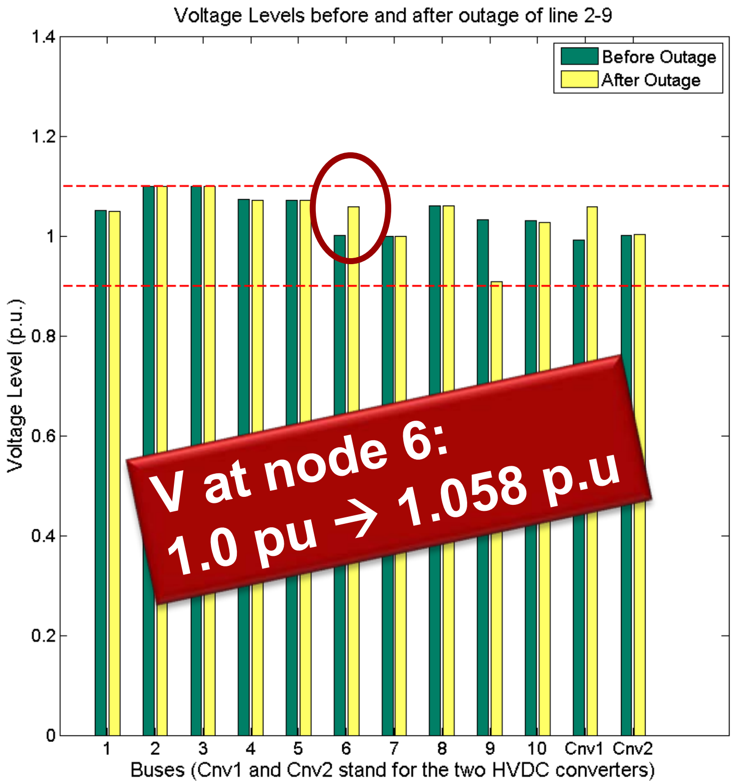
Case Study #1 (operation)

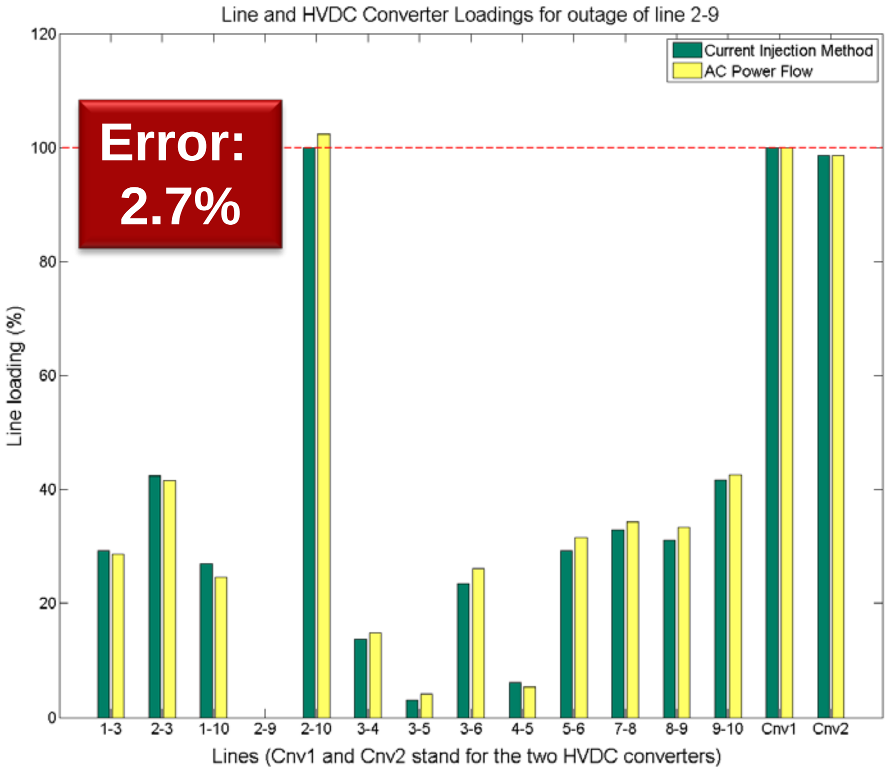
- Outage of Line 2-9
- HVDC at nodes 6-7
  - Node 6: PQ bus
  - Node 7: PV bus
- Post-contingency
  - Node 6 Voltage: 1.05 p.u.



Bus Voltages
pre-fault vs. post-fault

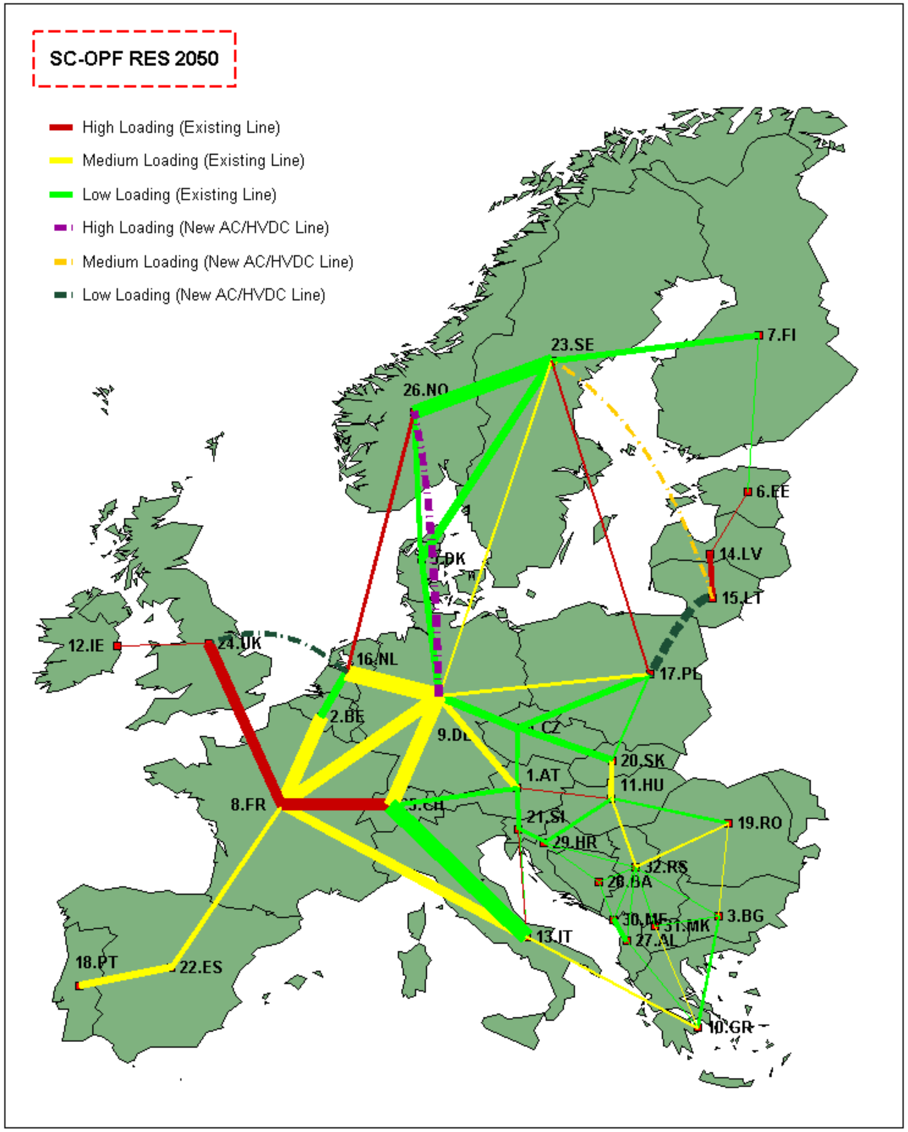


Post-Fault Line Flows:
Current Injection vs. AC power flow



Case Study #2 (planning): European Network

- 32 nodes, 104 branches, ~100 generators
- Generation Scenario: 80% RES in 2050
- SC-OPF: 12 most critical outages
- Addition of: 3 HVDC+1 AC



Case #2: Cost of Security with post-contingency control [PCC]

	No Expansion	Addition of 1 AC + 3 HVDC lines
Standard AC-OPF	9.52 million €/h	9.50 million €/h
SC-OPF with PCC	10.61 million €/h	10.52 million €/h
Cost of Security	1.09 million €/h	1.02 million €/h
Reduction in Cost of Security	6.4%	

~300-600 million Euros per year can be saved

Cost of Security: Additional generator re-dispatch costs, so that the N-1 criterion can be satisfied

Case #2: Cost of Security with and without PCC

	Cost of Security	Reduction in Cost of Security
No expansion	1.09 million €/h	---
Expansion *without* PCC	1.08 million €/h	1 %
Expansion with PCC	1.02 million €/h	6.4 %

*PCC = Post-contingency control

Conclusions

- Algorithm which integrates in a *single* optimization problem:
  - a Security-Constrained OPF including VSC-HVDC lines, and
  - calculates the control actions of multiple VSC-HVDC lines after line outages (post-contingency control)

- The algorithm can be used in both operation and planning studies → the "Cost of Security" index has been introduced for the planning studies

- The control capabilities of the VSC-HVDC lines have the potential to significantly decrease the "Cost of Security".

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Obrigado!

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