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400 KV UNDERGROUND CABLING

Challenges of implementing 400 kV underground cabling in the Danish transmission network

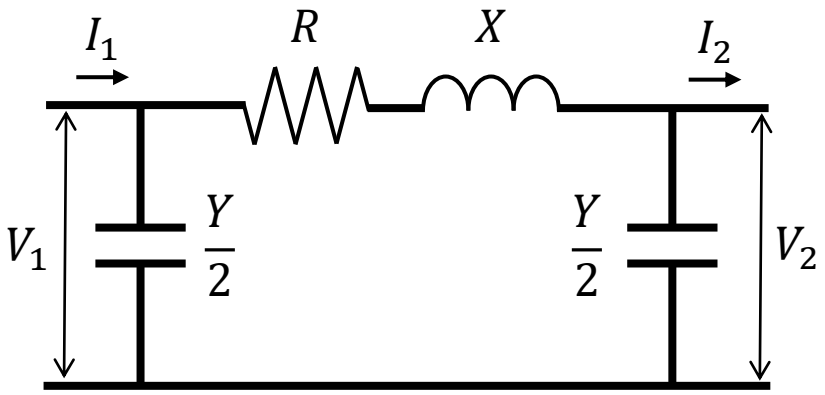
David Dyrvig
Operational Design - Energinet

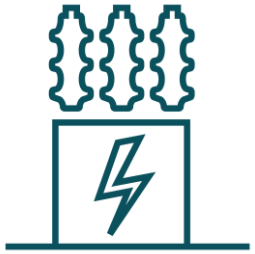
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400 KV CABLES

Many technical differences between Overhead Lines and Underground Cables

- Capacitive reactive power:
- Changes the resonance frequency
- Requires more auxiliary equipment
  - Harmonic filters
  - Reactive compensation
  - Local controls for equipment





Auxiliary equipment



Repair time



Thermal loading



Fault statistics



Service life

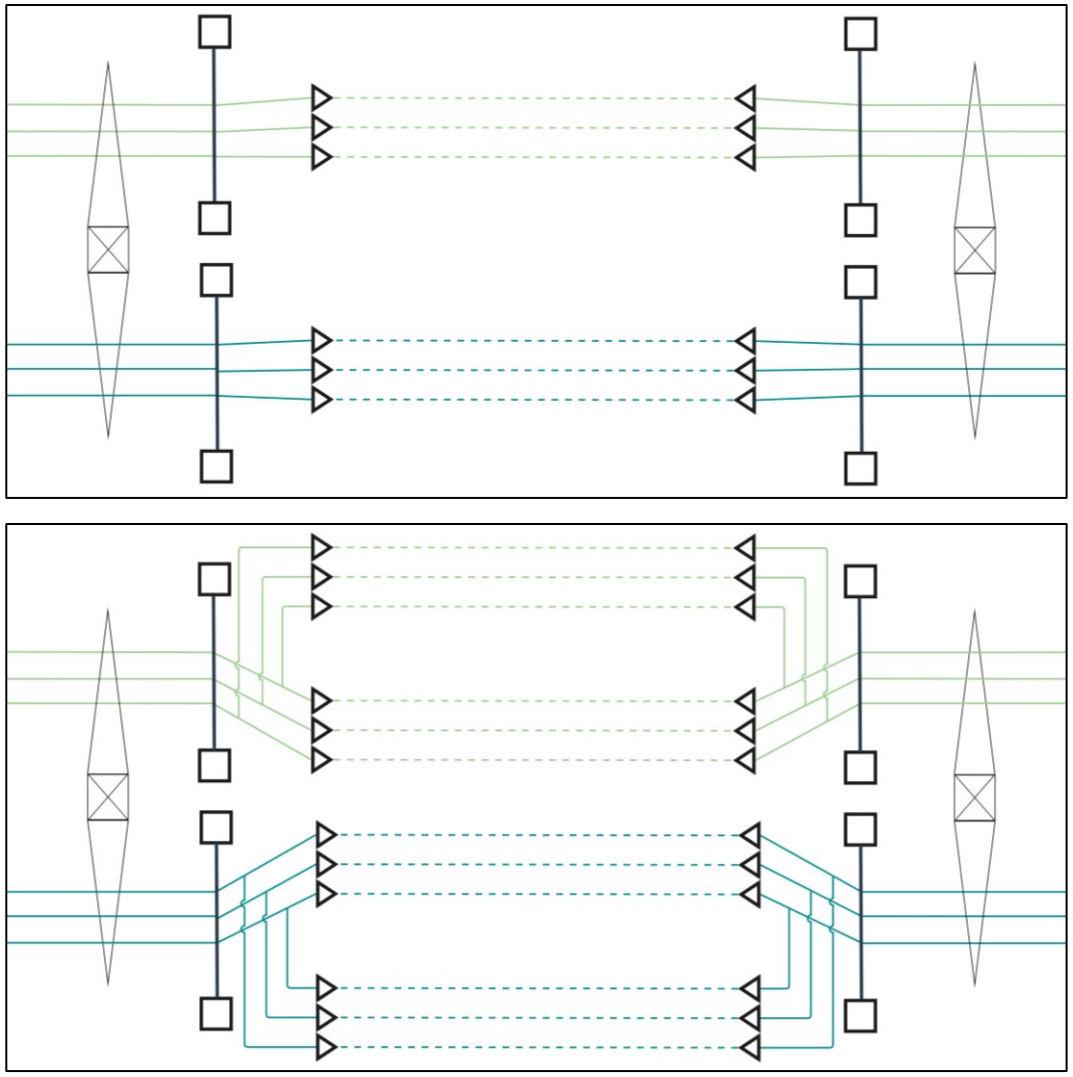
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400 KV CABLES

Double-circuit cable systems are often a technical necessity – especially on 400 kV

Double cable causes:

- Higher capacitance
- Increased compensation
- Greater impact on harmonics
- Higher fault frequency



Top: Single-circuit cable systems
Bottom: Double-circuit cable systems

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WHY USE 400 KV UNDERGROUND CABLES?

- Reduced environmental impact
- Infrastructure near urban areas
- Water or other physical constraints
- Political decision

"Future 400 kV transmission lines will be underground cabled to the extent that this is technically feasible."

Translation from:
The Danish PSO Agreement on Underground Cabling (2020)





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FRAMEWORK

What is technically feasible?

Risk based evaluation and assessment, with a Precautionary Approach

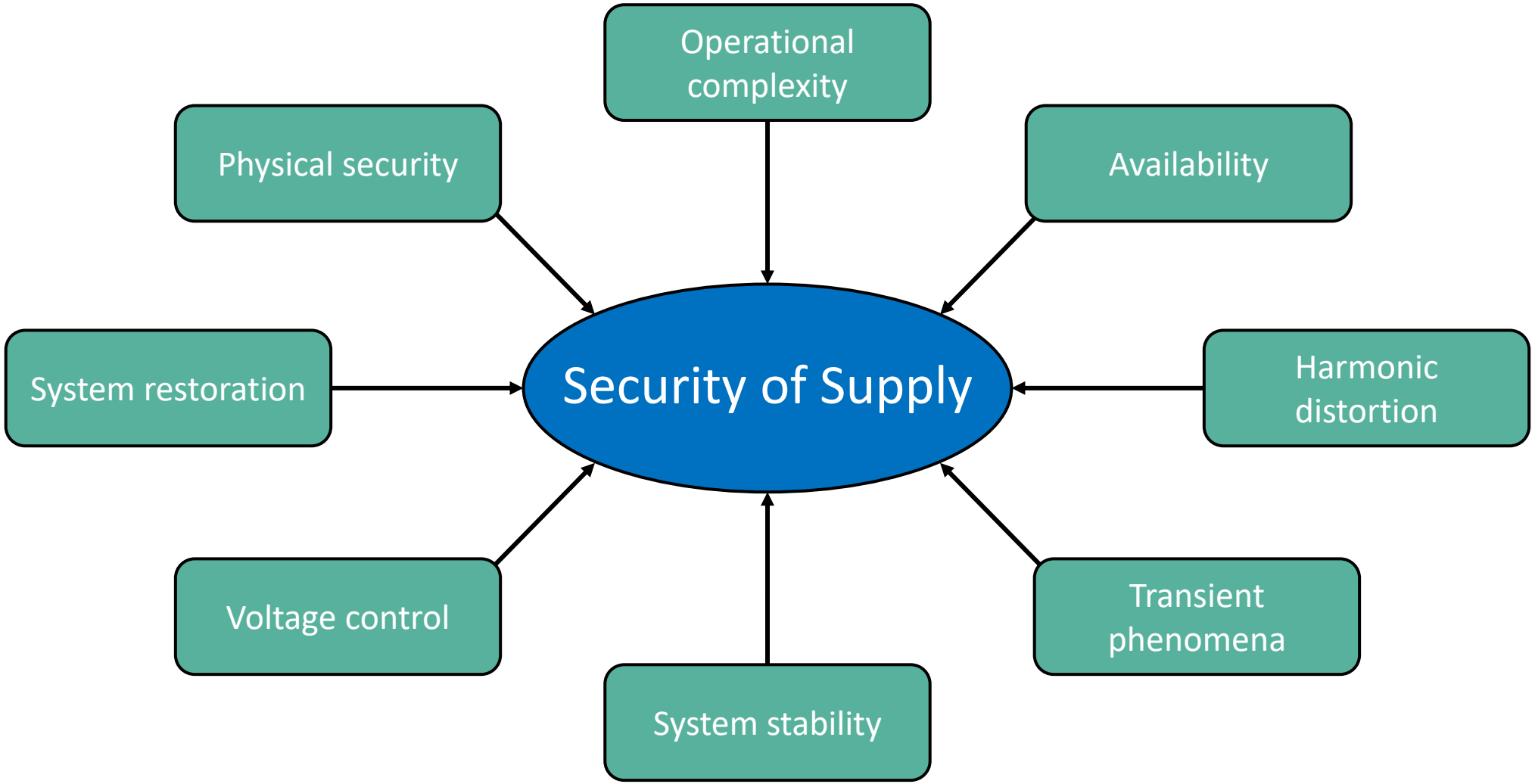
Security of Supply as the Governing Objective

8x technical assessment parameters

- 400 kV cables in project
- 400 kV cables in portfolio

Final assessment is based on the combined risk profile of the 8x parameters.

RISK ASSESSMENT PARAMETERS



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AVAILABILITY

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Fault statistics for 400 kV AC onshore cables and

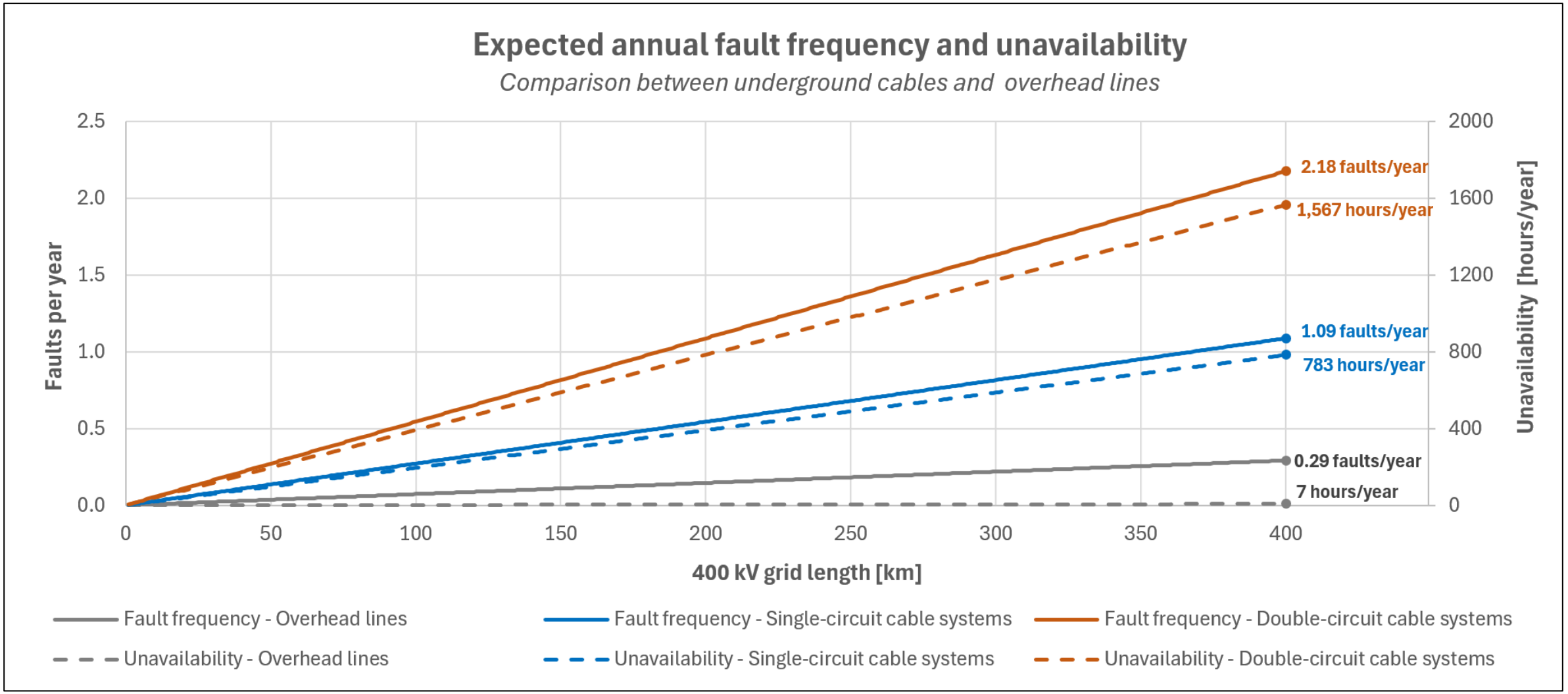
Type of technology	Faults pr. 100 km pr. year	Average repair time
400 kV cables	0.272	88 days globally 30 days in Denmark
400 kV overhead lines	0.35 *(All faults)*	24 hours
	0.073 *(Permanent faults)*	

Sources:

Cable faults: CIGRE (August 2024). Paris Session, Paper ID 11258. Insulated Cable Statistics 2012 to 2021.
OHL faults: ENTSO-E Regional Group Nordic (November 2025). 2024 Nordic and Baltic Grid Disturbance Statistics.
Average repair time: Energinet estimations from operational experiences

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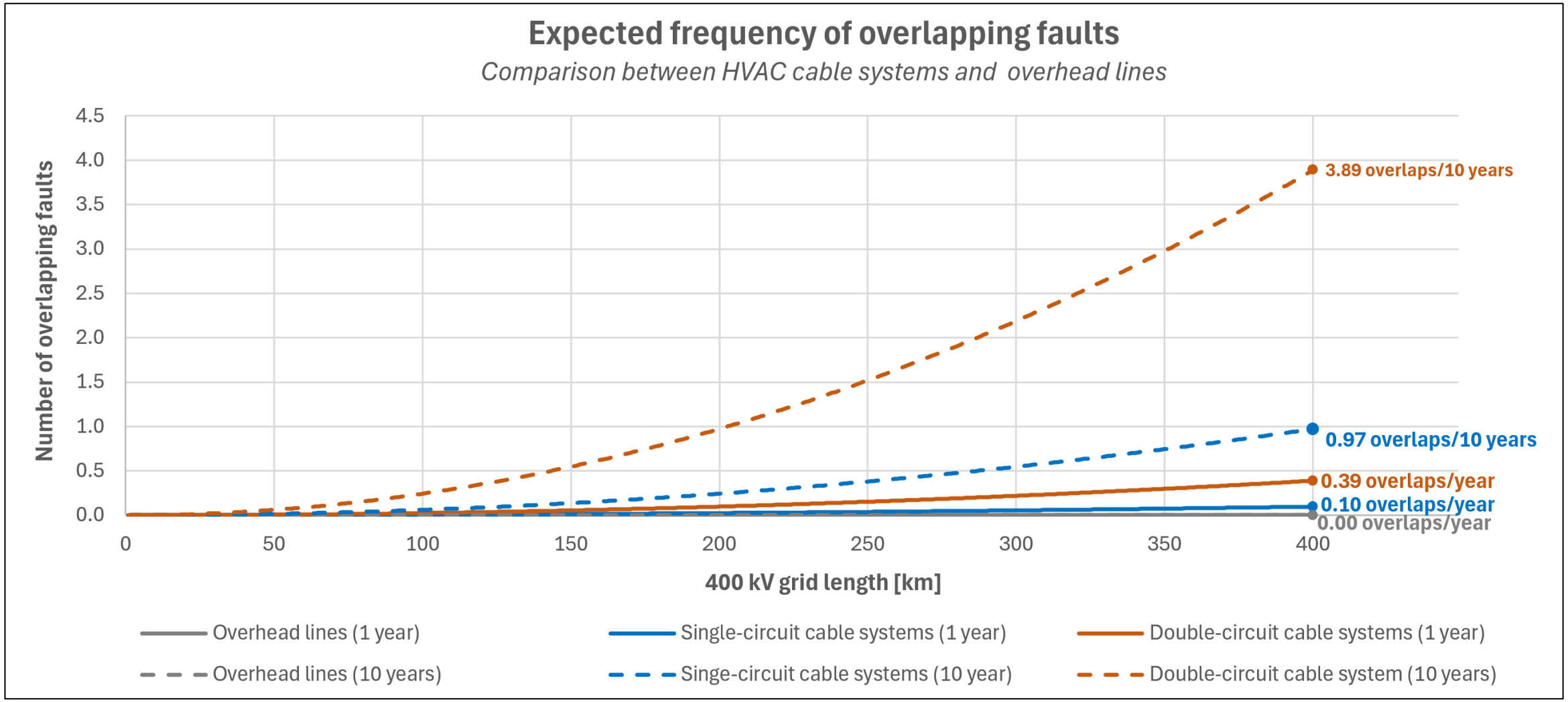
AVAILABILITY



Note: Only permanent faults of Overhead lines are considered

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AVAILABILITY



Note: Only permanent faults of Overhead lines are considered

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VOLTAGE CONTROL

- 400 kV cables introduces additional reactive power
- Voltage control is a prerequisite
- More reactors are needed
  - No loading compensation
  - Redundancy
- Reactors needs to be controlled
  - Additional local controllers
  - Increased risk of controller interactions



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OPERATIONAL COMPLEXITY

400 kV underground cabling increases operational complexity:

- Reduced availability
- Frequent disturbances
- Additional assets
- Complex and non-intuitive voltage control
- Complex energization of cable systems
- Cable hotspots



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FUTURE SYSTEM BEHAVIOUR

- Harmonic distortion
  - Cables changes network resonance frequency
  - Effects may occur far from the cable area
  - Interactions in a future converter-based system
- System stability
  - Increased risk of unexpected control interactions
  - Reduced damping of oscillations
- Transients
  - Increased risk of transient overvoltages
  - Challenges with zero-missing





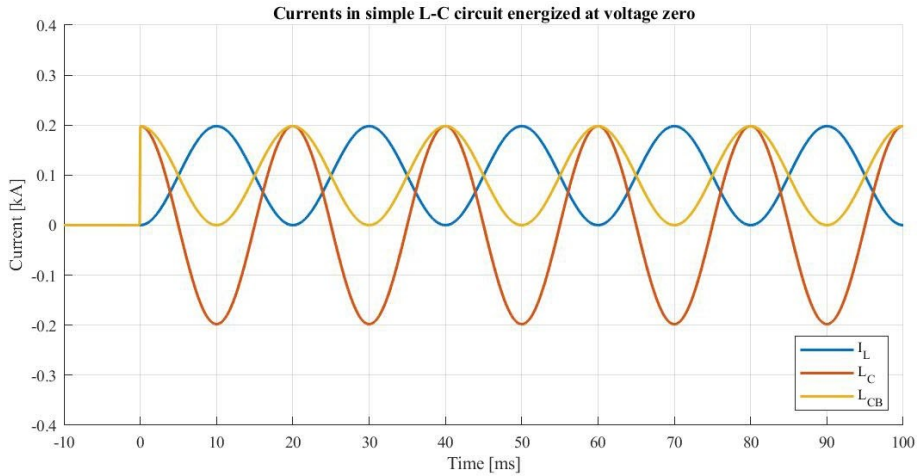
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SYSTEM RESTORATION

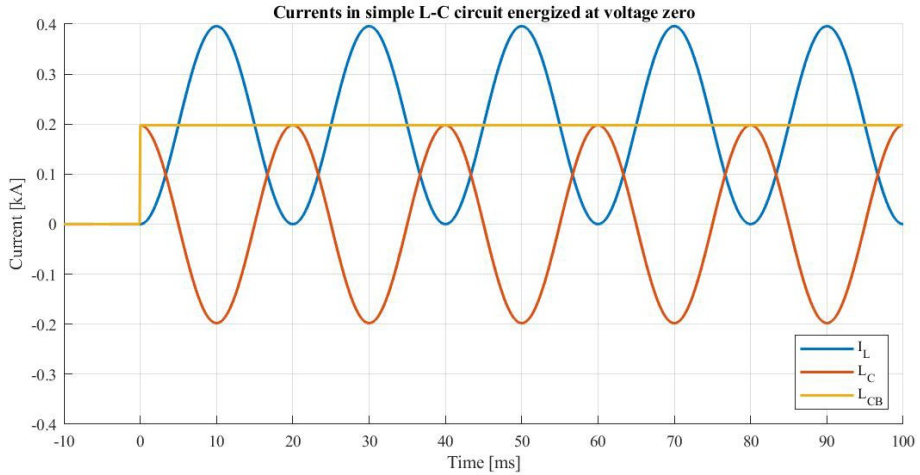
- High flexibility and several options are required:
  - All 400 kV lines must be able to be used as first line in a corridor
  - Ability to black start with a limited black start unit

- Direct compensation
  - Zero-miss phenomenon ($\leq 50\%$)
  - Pre-Insertion Resistors ($\leq 80\%$)

- Cables could increase restoration time



50% direct compensation



100% direct compensation

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PHYSICAL SECURITY

- Overhead lines:
  - Simple components
  - Easy to replace and repair
  - Temporary restoration method
  - High exposure
  - Difficult to protect comprehensively

- Underground cables:
  - Complex components
  - Difficult to replace and repair
  - Additional auxiliary assets to protect
  - Low exposure
  - Centralised points of exposure



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QUESTIONS?

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