HVDC-WISE

CIGRE SESSION 2024

C1-C4 WORKSHOP “RESILIENCE BY DESIGN”

HVDC-WISE is supported by the European Unions’ Horizon Europe program under agreement 101075424.

UK Research and Innovation (UKRI) funding for **HVDC-**WISE is provided under the UK government’s Horizon Europe funding guarantee [grant numbers 10041877 and 10051113].

The HVDC-WISE Project

Speakers:

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SUPERGRID INSTITUTE

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THE NATIONAL HVDC CENTRE

HVDC-WISE

AGENDA

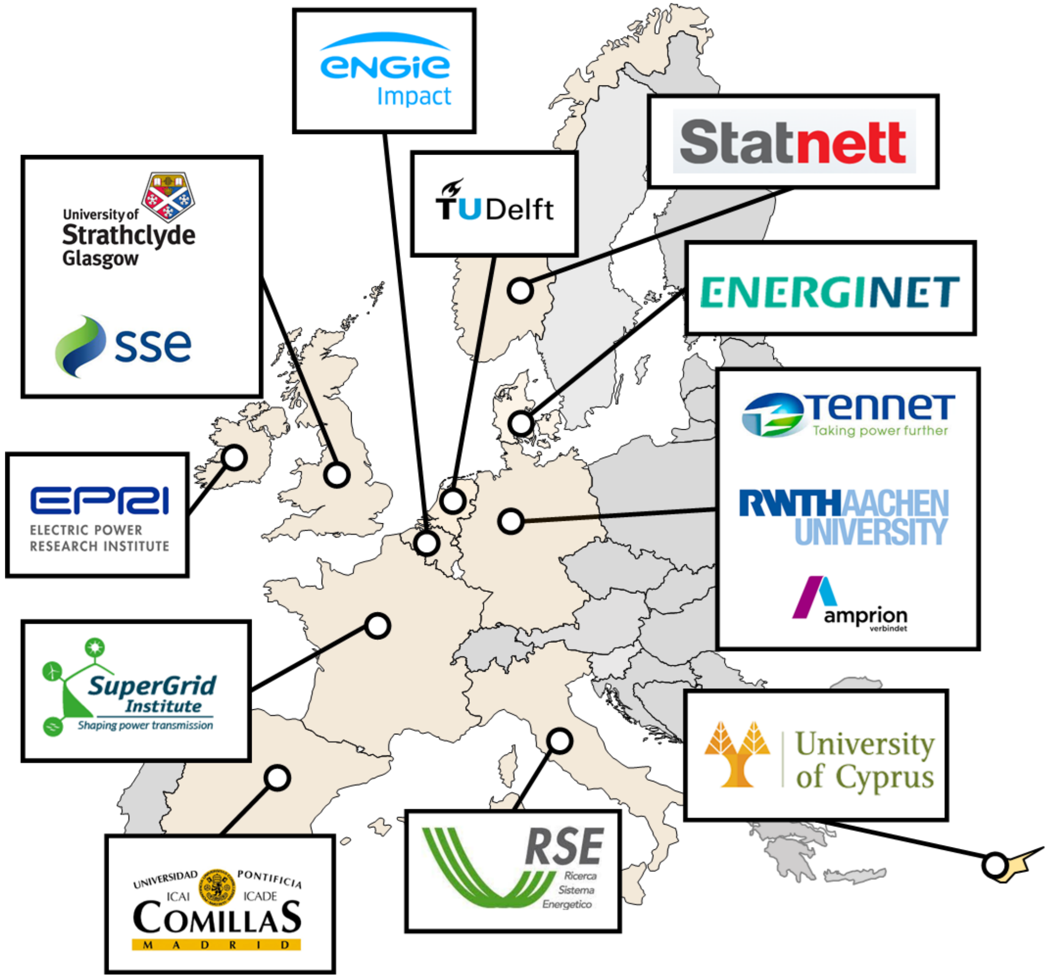
- Project introduction
- Views on resilience related to HVDC systems
- Example results

PROJECT INTRODUCTION

HVDC-WISE

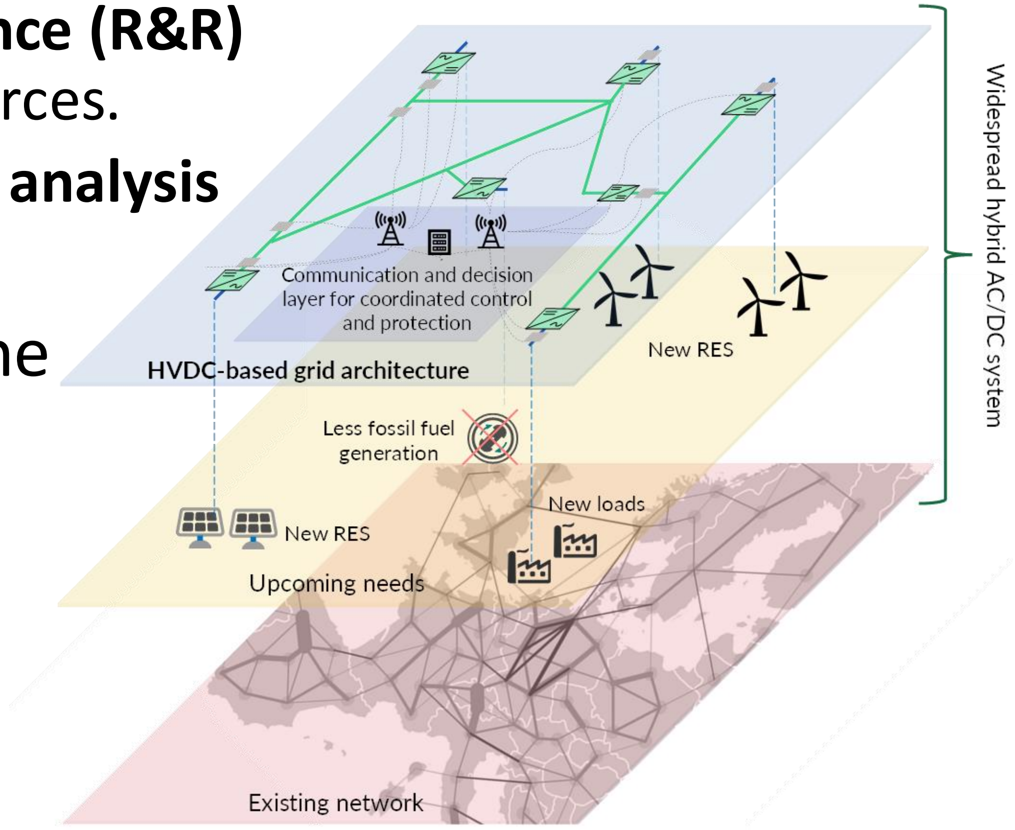
HVDC-based grid architectures for reliable and resilient **WI**de**S**pr**E**ad hybrid AC/DC transmission systems

- Duration: 42 months (October 2022 to March 2026)
- 14 partners from 10 different countries



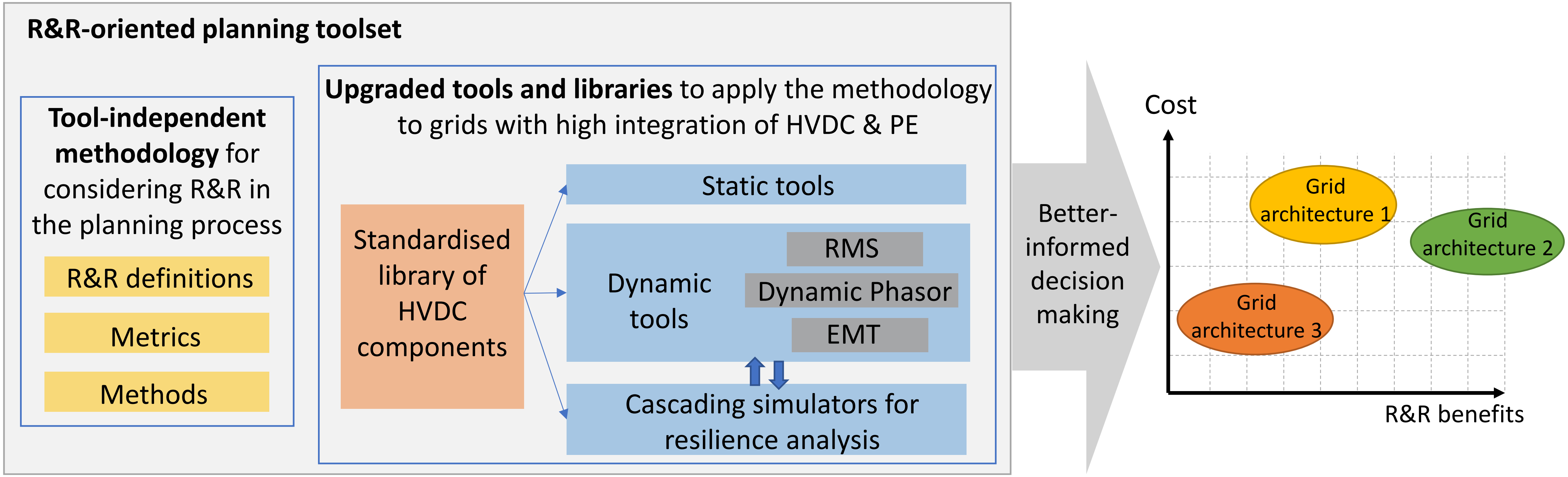
GENERAL OBJECTIVE

- The goal of HVDC-WISE is to contribute to the development of **hybrid AC/DC transmission grids** by :
  - Identifying **HVDC-based grid architectures** that can be deployed to **enhance system reliability and resilience (R&R)** and facilitate the integration of new renewable sources.
  - Creating new **R&R-oriented network planning and analysis tools**.
- HVDC-based grid architecture concepts are the combination of:
  - HVDC configurations
  - Technological components
  - Operation algorithms (C&P)
  - Deployment plan



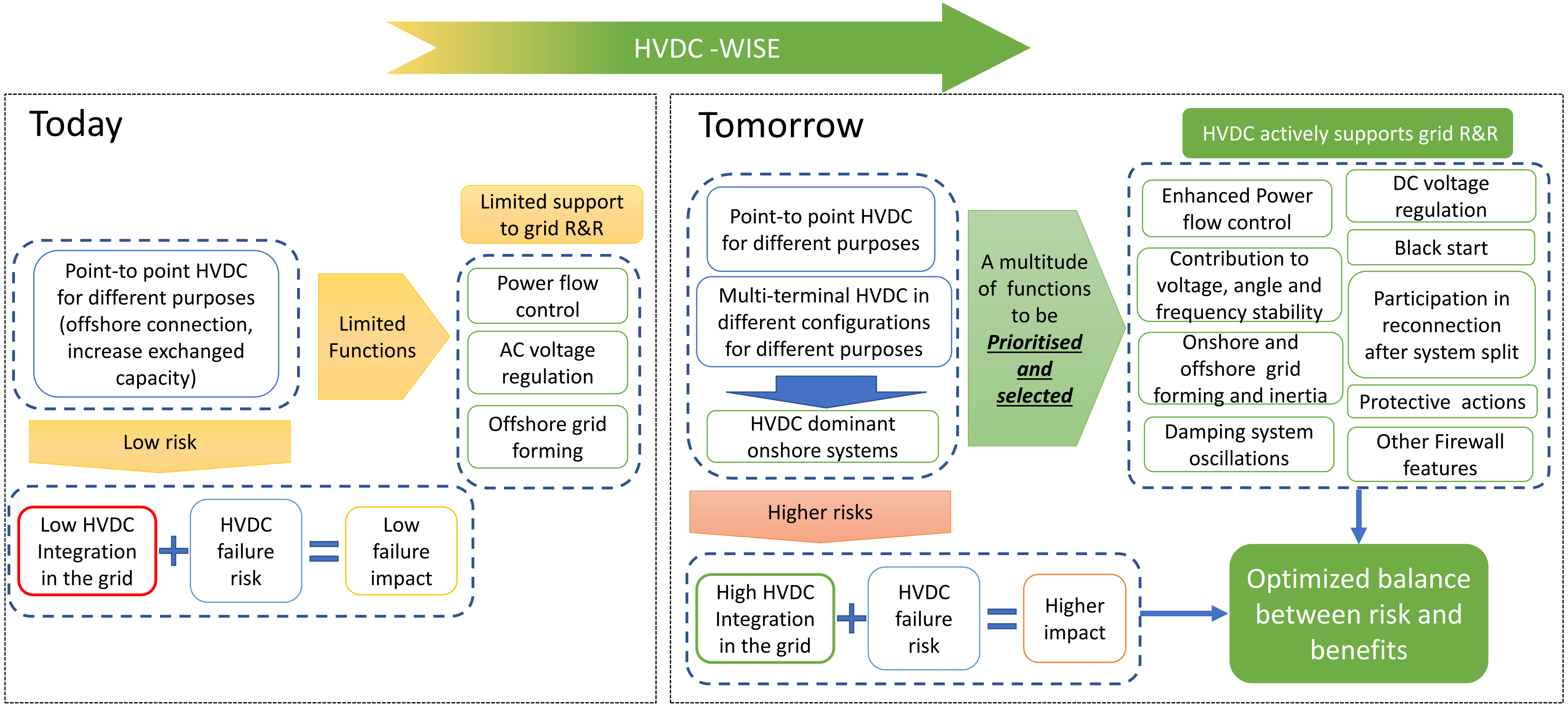
OBJECTIVE 1

- To develop complete reliability-&-resilience-oriented **planning toolsets** (metrics, methodology, and tools) with appropriate representation of different HVDC-based grid architecture concepts aiming to fulfil transmission system operators needs.



OBJECTIVE 2

- To identify, propose and compare different **HVDC-based grid architecture concepts** aiming to address TSOs' reliability and resilience needs for widespread AC/DC systems.



OBJECTIVE 3

- To identify, assess, and model emerging technologies for HVDC-based grid architecture concepts needed for the deployment of widespread AC/DC transmission grids.

Technical solutions

Selection

- Features, potential and limitations
- Technical readiness and technological challenges

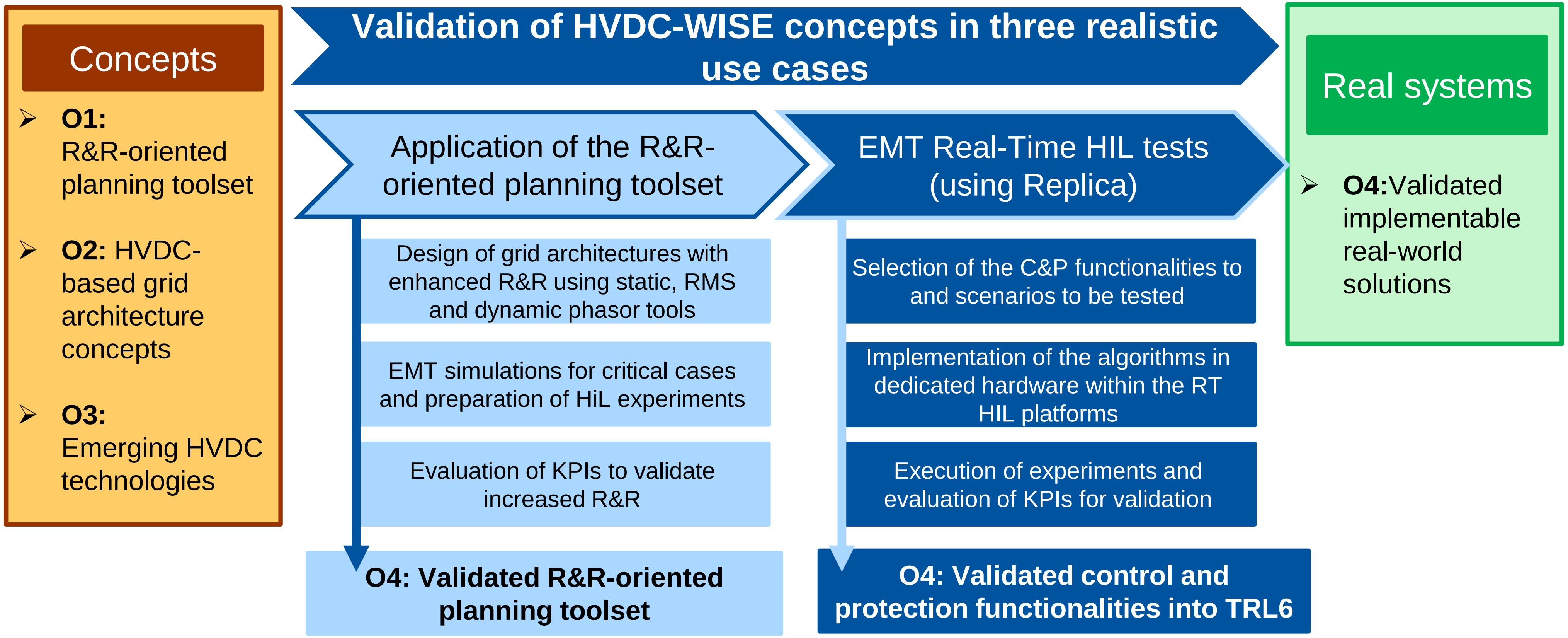
Modelling

- Models in a standardized library
- Evaluation of key parameters allowing architecture selection

Models allowing resilience-oriented planning

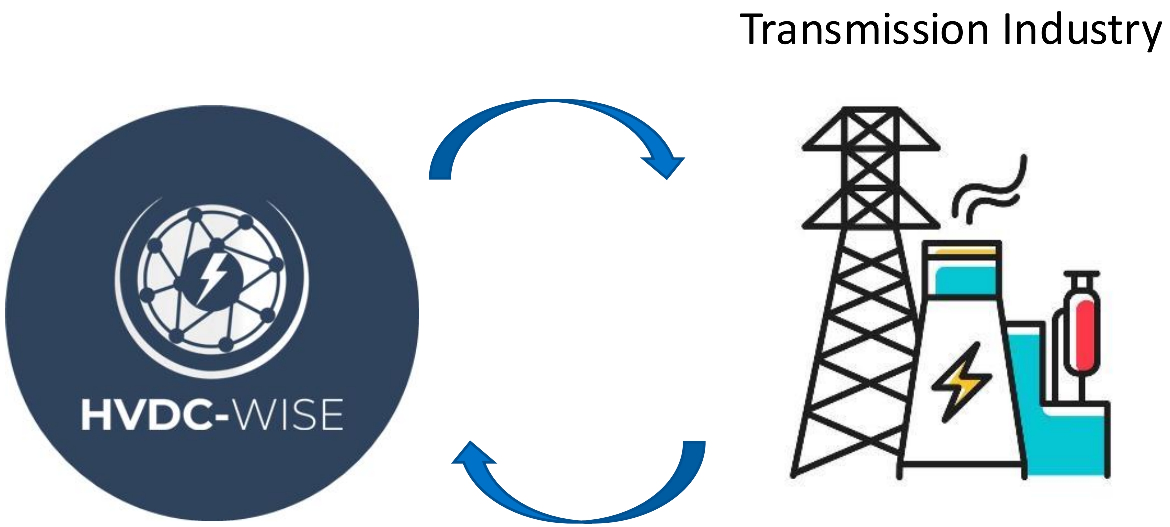
OBJECTIVE 4

- To validate in an industrially relevant environment the resilience-oriented planning toolset and the HVDC-based grid architecture concepts on three realistic use cases.



OBJECTIVE 5

- To prepare for the adoption and deployment of the proposed solutions by the industry.



WORK BREAKDOWN STRUCTURE

Phase 1: Definitions, expectations and solutions
(grid architectures and R&R-oriented planning toolset)

WP2 : Requirements, opportunities, frameworks, and demonstration needs for R&R of future AC/DC systems

WP3 : Concept architectures for reliable and resilient AC/DC systems

WP4 : Enabling technologies for future AC/DC hybrid systems

WP5 : Simulation tools for R&R-oriented planning and operation of hybrid AC/DC power systems

Phase 2: Value demonstration

WP6 : R&R-oriented network expansion planning methodology: application to use cases

WP7 : Validation of control and protection concepts on EU representative use cases

Two transversal WPs

WP1 : Project management

WP8 : Pathways towards hybrid AC/DC grids: dissemination and exploitation

Thank you!

Follow

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HVDC-WISE is supported by the European Unions' Horizon Europe program under agreement 101075424.

Innovate UK supports **HVDC-**WISE project partners through the UK Research and Innovation Horizon Europe Guarantee scheme.

RESILIENCE RELATED TO HVDC SYSTEMS

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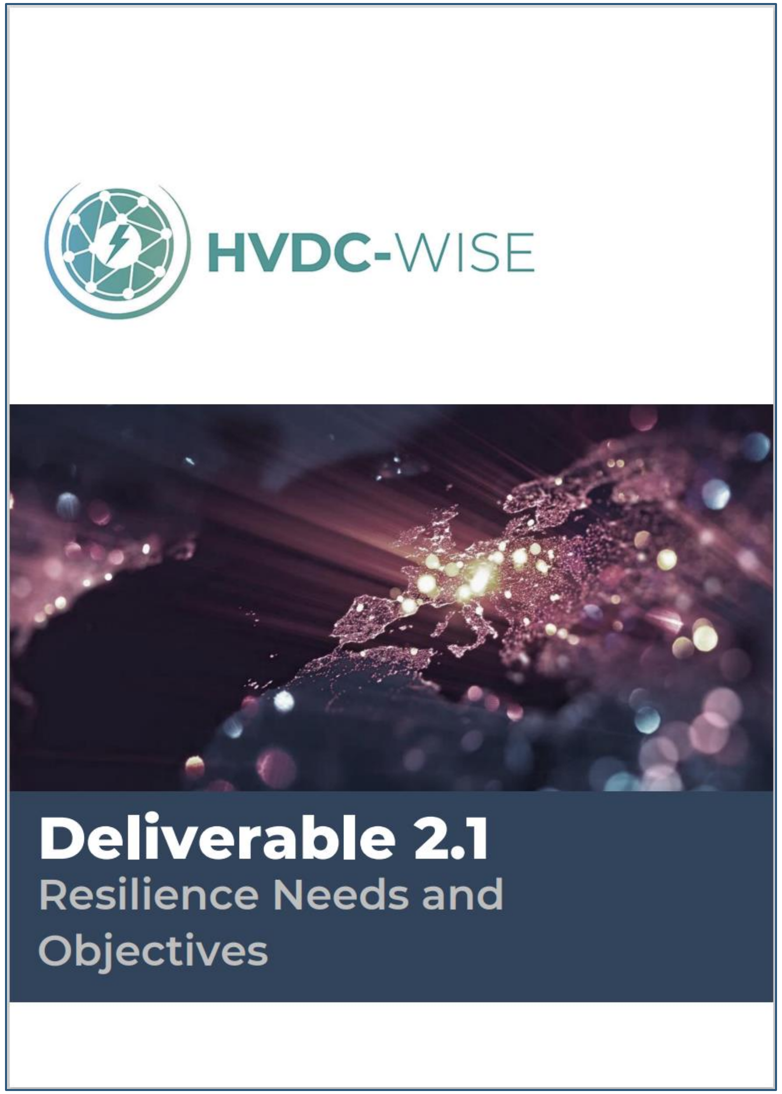
D2.1: RESILIENCE NEEDS AND OBJECTIVES

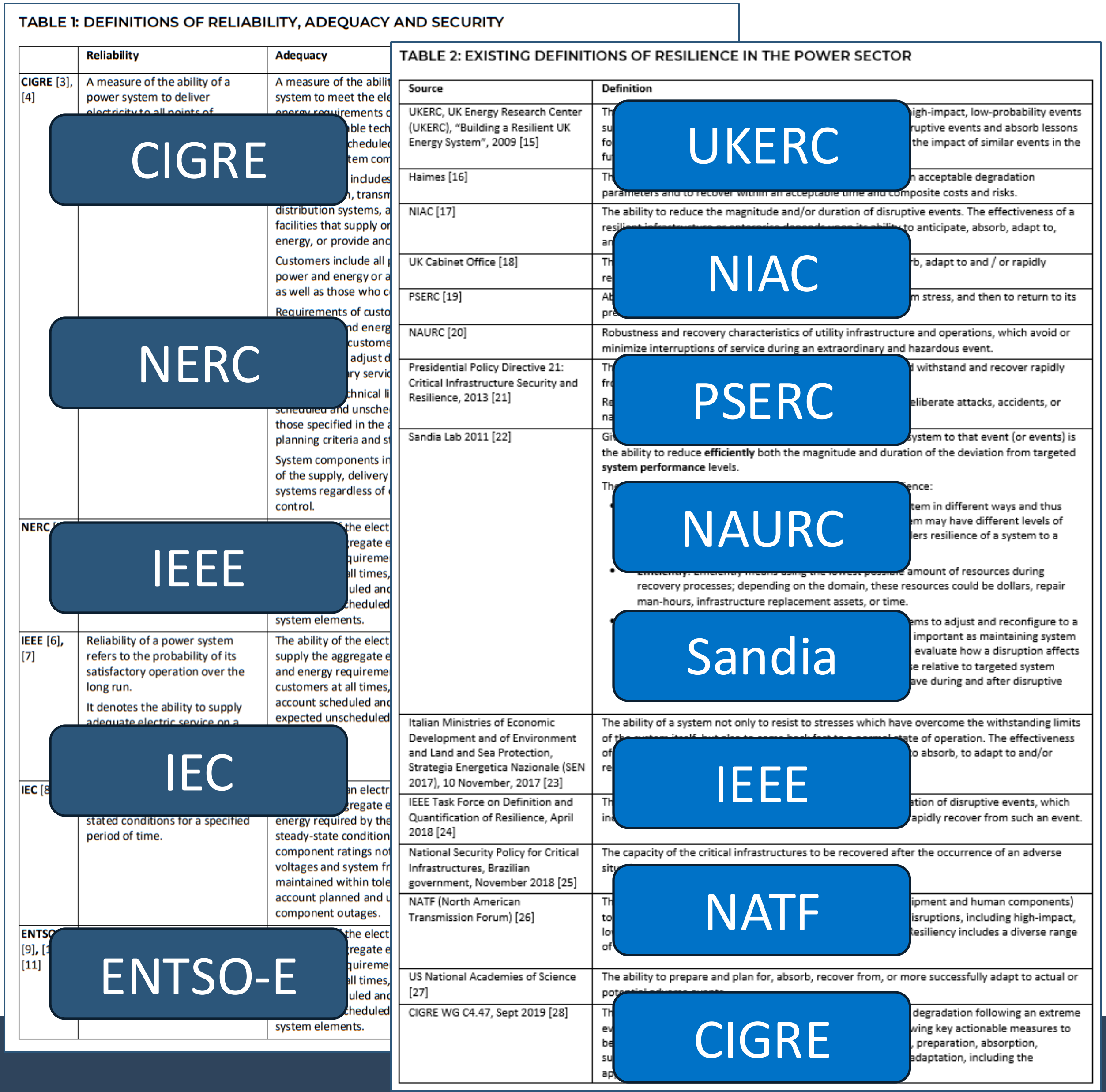
- Review of industry definitions of reliability and resilience in power systems
- TSO expectations for R&R with the deployment of HVDC solutions within their networks
- Survey of existing and planned HVDC links (useful spreadsheet resource available to download)
- Identifying opportunities, risks and barriers for HVDC in delivering R&R benefits
- Outline of research objectives for remainder of the project
- Initial views on codes, standards and regulatory framework issues
- Examples of hybrid AC/DC architectures



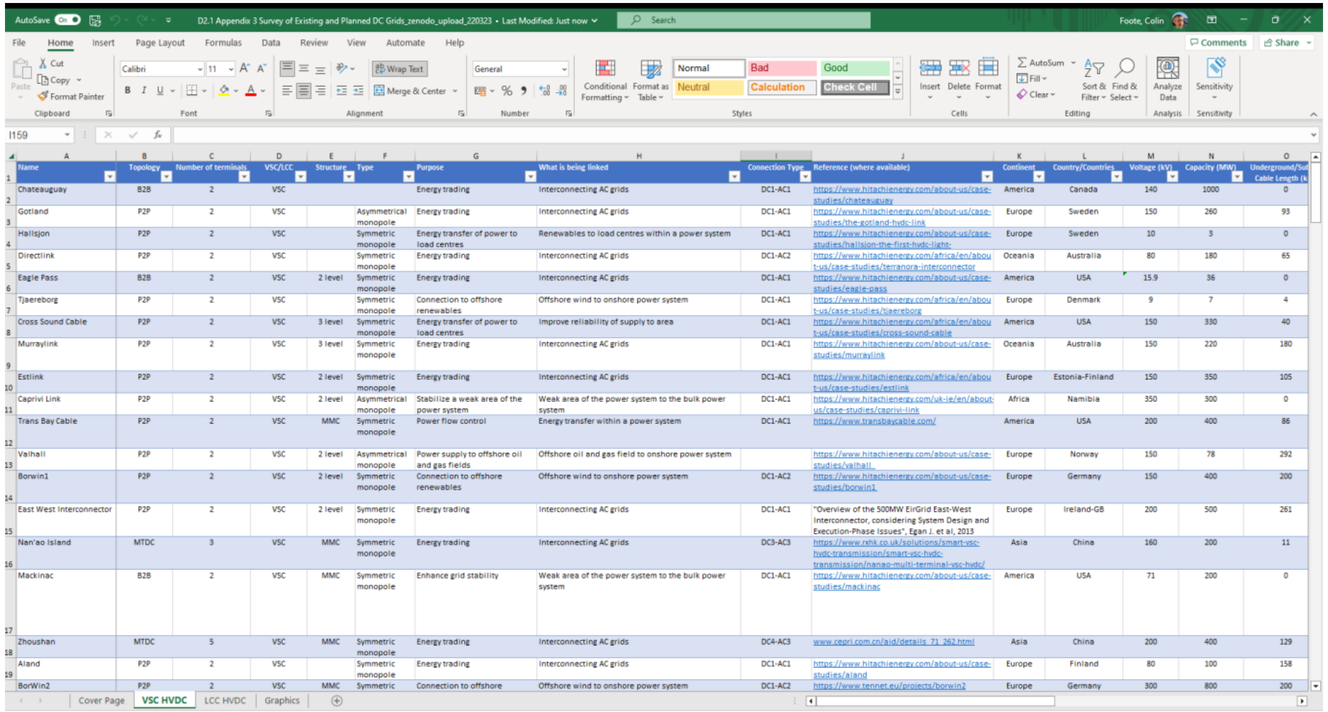
DEFINING RELIABILITY AND RESILIENCE

- Detailed review of literature on R&R concepts
- Reliability is widely understood
  - →Adequacy
  - →Security
- Resilience has different interpretations
- HVDC-WISE using definition from CIGRE WG C4.47:

ability to limit the extent, severity, and duration of system degradation following an extreme event

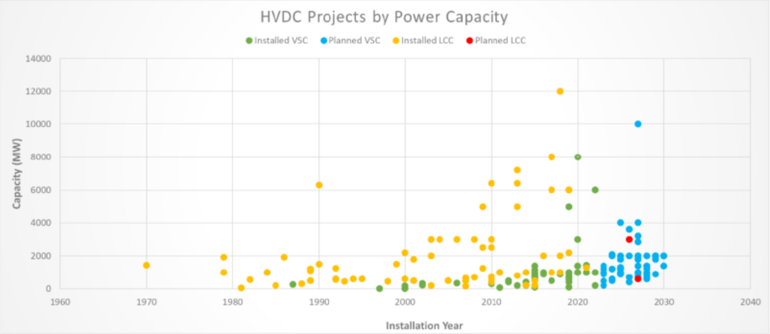


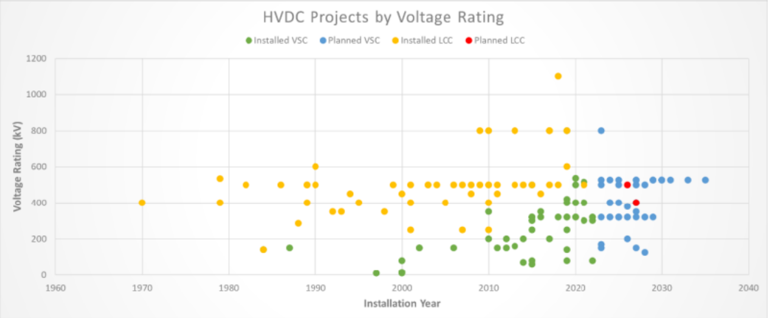
SURVEY OF EXISTING AND PLANNED HVDC LINKS

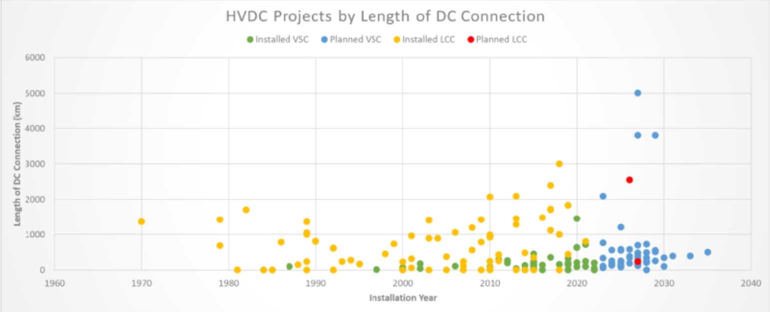


Name	Topology	Number of terminals	VSC/LCC	Structure	Type	Purpose	What is being linked	Connection Type	Reference (where available)	Continent	Country/Countries	Voltage (kV)	Capacity (MW)	Underground/Sub Cable Length (k
Chateauguay	B2B	2	VSC			Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/chateauguay	America	Canada	140	1000	0
Gotland	P2P	2	VSC		Asymmetrical monopole	Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/the-gotland-hvdc-link	Europe	Sweden	150	260	93
Hallsjon	P2P	2	VSC		Symmetric monopole	Energy transfer of power to load centres	Renewables to load centres within a power system	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/hallsjon-the-first-hvdc-light-	Europe	Sweden	10	3	0
Directlink	P2P	2	VSC		Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC2	https://www.hitachienergy.com/africa/en/about-us/case-studies/terranora-interconnector	Oceania	Australia	80	180	65
Eagle Pass	B2B	2	VSC	2 level	Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/eagle-pass	America	USA	15.9	36	0
Tjaereborg	P2P	2	VSC		Symmetric monopole	Connection to offshore renewables	Offshore wind to onshore power system	DC1-AC1	https://www.hitachienergy.com/africa/en/about-us/case-studies/tjaereborg	Europe	Denmark	9	7	4
Cross Sound Cable	P2P	2	VSC	3 level	Symmetric monopole	Energy transfer of power to load centres	Improve reliability of supply to area	DC1-AC1	https://www.hitachienergy.com/africa/en/about-us/case-studies/cross-sound-cable	America	USA	150	330	40
Murraylink	P2P	2	VSC	3 level	Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/murraylink	Oceania	Australia	150	220	180
Estlink	P2P	2	VSC	2 level	Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/africa/en/about-us/case-studies/estlink	Europe	Estonia-Finland	150	350	105
Caprivi Link	P2P	2	VSC	2 level	Asymmetrical monopole	Stabilize a weak area of the power system	Weak area of the power system to the bulk power system	DC1-AC1	https://www.hitachienergy.com/uk-ie/en/about-us/case-studies/caprivi-link	Africa	Namibia	350	300	0
Trans Bay Cable	P2P	2	VSC	MMC	Symmetric monopole	Power flow control	Energy transfer within a power system	DC1-AC1	https://www.transbaycable.com/	America	USA	200	400	86
Valhall	P2P	2	VSC	2 level	Asymmetrical monopole	Power supply to offshore oil and gas fields	Offshore oil and gas field to onshore power system		https://www.hitachienergy.com/about-us/case-studies/valhall	Europe	Norway	150	78	292
Borwin1	P2P	2	VSC	2 level	Symmetric monopole	Connection to offshore renewables	Offshore wind to onshore power system	DC1-AC2	https://www.hitachienergy.com/about-us/case-studies/borwin1	Europe	Germany	150	400	200
East West Interconnector	P2P	2	VSC	2 level	Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC1	"Overview of the 500MW EirGrid East-West Interconnector, considering System Design and Execution-Phase Issues", Egan J. et al, 2013	Europe	Ireland-GB	200	500	261
Nan'ao Island	MTDC	3	VSC	MMC	Symmetric monopole	Energy trading	Interconnecting AC grids	DC3-AC3	https://www.rxhk.co.uk/solutions/smart-vsc-hvdc-transmission/smart-vsc-hvdc-transmission/nanao-multi-terminal-vsc-hvdc/	Asia	China	160	200	11
Mackinac	B2B	2	VSC	MMC	Symmetric monopole	Enhance grid stability	Weak area of the power system to the bulk power system	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/mackinac	America	USA	71	200	0
Zhoushan	MTDC	5	VSC	MMC	Symmetric monopole	Energy trading	Interconnecting AC grids	DC4-AC3	www.cepri.com.cn/aid/details_71_262.html	Asia	China	200	400	129
Aland	P2P	2	VSC		Symmetric monopole	Energy trading	Interconnecting AC grids	DC1-AC1	https://www.hitachienergy.com/about-us/case-studies/aland	Europe	Finland	80	100	158
BorWin2	P2P	2	VSC	MMC	Symmetric	Connection to offshore	Offshore wind to onshore power system	DC1-AC2	https://www.tennet.eu/projects/borwin2	Europe	Germany	300	800	200

- Published as spreadsheet to support data filtering and analysis
- Comprehensive list of projects
  - →157 VSC
  - →75 LCC
- Assessed in terms of Type, Purpose, Topology, kV, MW
- Trends reviewed with R&R opportunities and vulnerabilities
  - →More VSC, bipoles, multi-terminal
  - →Increasing power rating and voltage
- Emerging common designs







TSO COMMON ISSUES OF CONCERN

- HVDC converters offer the potential to act as **the foundation of stability** in the future hybrid AC/DC system, but it is recognised that new solutions will be required.
- HVDC converters depend on programmable control software and do not have an inherent overload capability, leading to a **risk of very fast changes** in condition from acceptable operation to failure.
- **Multiple issues relating to system stability** and power quality in hybrid AC/DC systems must be addressed.
- Future hybrid AC/DC systems need to be designed with similar levels of **redundancy and dependability** to AC systems. There must be fall-back cover for failure of any higher-level grid controller or communications
- Dependence on digital information for the functioning of the entire system raises concerns around **cyber resiliency**.

EVENTS AND DISTURBANCES

- Root causes
  - Routine faults and operational conditions
  - Natural events like extreme weather
  - Physical or cyber attacks
- Responses
  - Very complex combined AC and DC systems may react inappropriately to contingencies
  - Expansion of HVDC and its growing influence on the power system means the risks associated with unforeseen or adverse behaviour is a significant threat
  - Even relatively minor, routine faults or changes of system state may trigger undesired responses
- System consequences, TSOs highlighted:
  - Energy dissipation in offshore hubs
  - Wide-area system splits
  - Role for HVDC schemes in system restoration in future hybrid AC/DC systems

ARCHITECTURES FOR AC/DC SYSTEMS

Within the project, the term **HVDC-based grid architecture** is defined as a combination of:

a) **Purpose** of the HVDC link/network (e.g., interconnection, offshore wind)

b) **Embedment level** of the HVDC network within the AC system (e.g., fully embedded within one synchronous area)

c) **Topology and configuration** of the reinforcing infrastructure (point-to-point vs. MTDC, bipolar vs. monopolar, etc.),

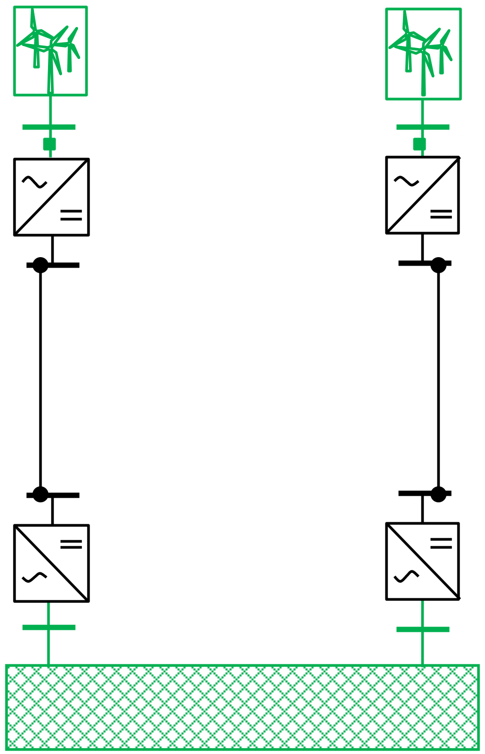
d) **Technological components** (converters, breakers, storage devices, etc.)

e) **operation algorithms** (or operational functions) for **control and protection**

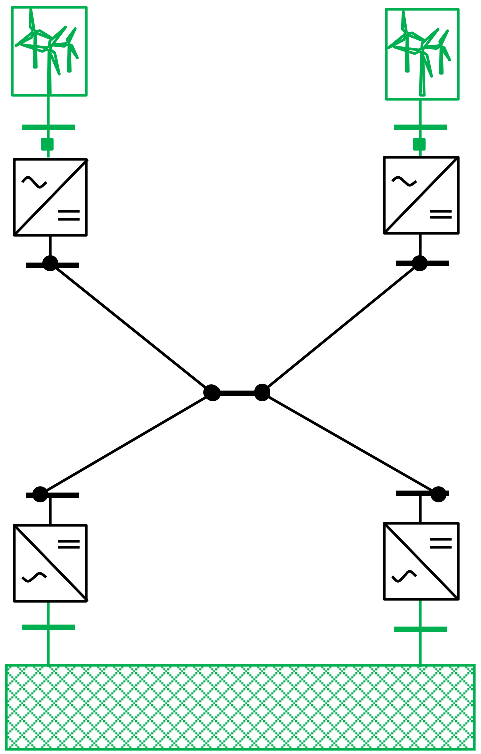
f) **Deployment plan** specifying how to build such grid in a stepwise manner.

DC-SIDE TOPOLOGY

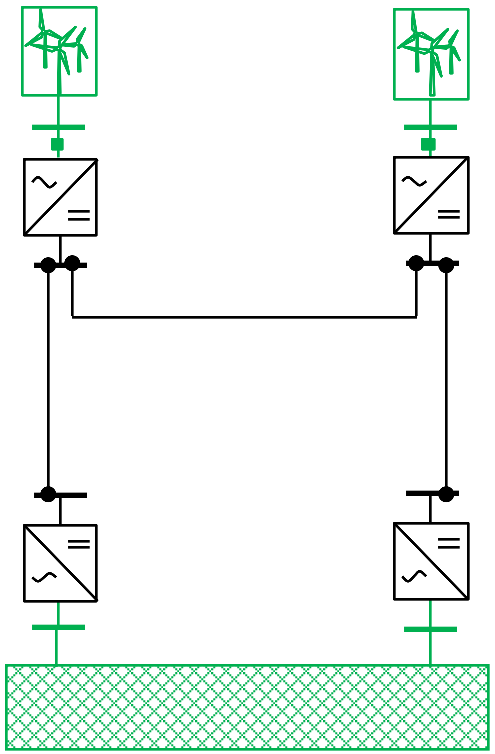
DC1 (P2P)



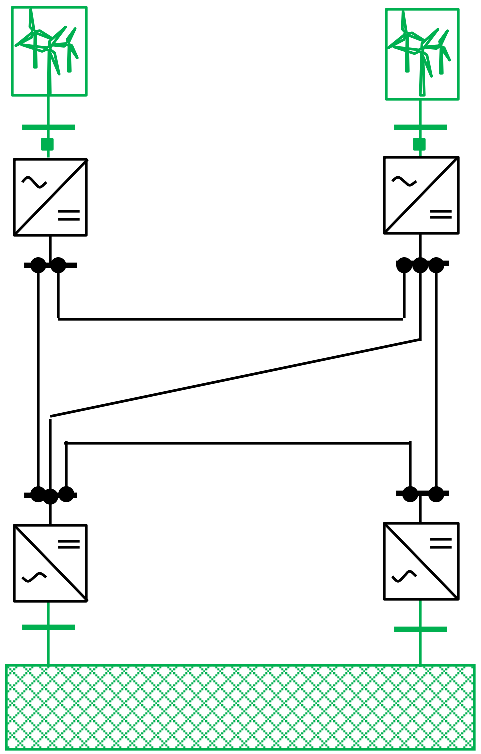
DC2 (radial)



DC3 (linear)



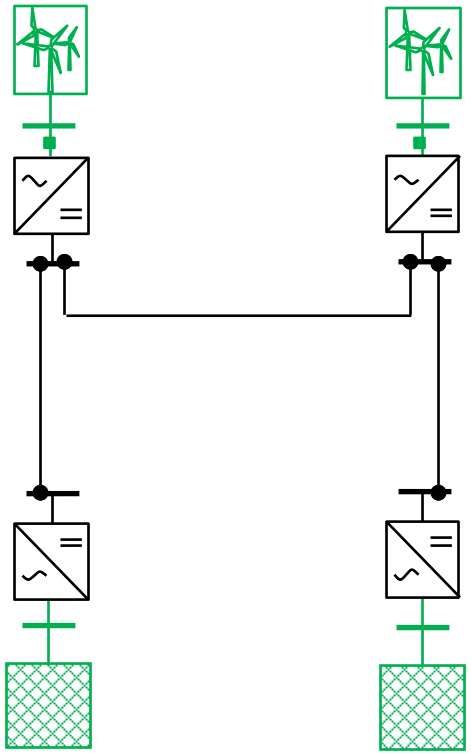
DC4 (meshed)



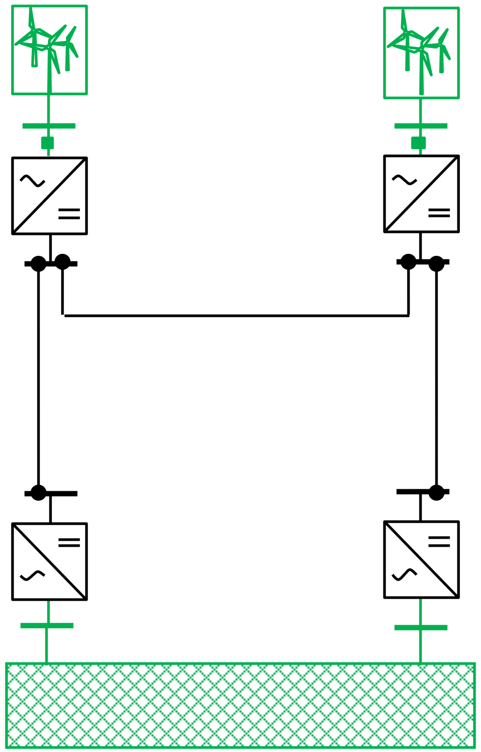
Note: Single line diagrams; Project use cases focus on 525kV Bipole Systems

AC EMBEDMENT LEVEL

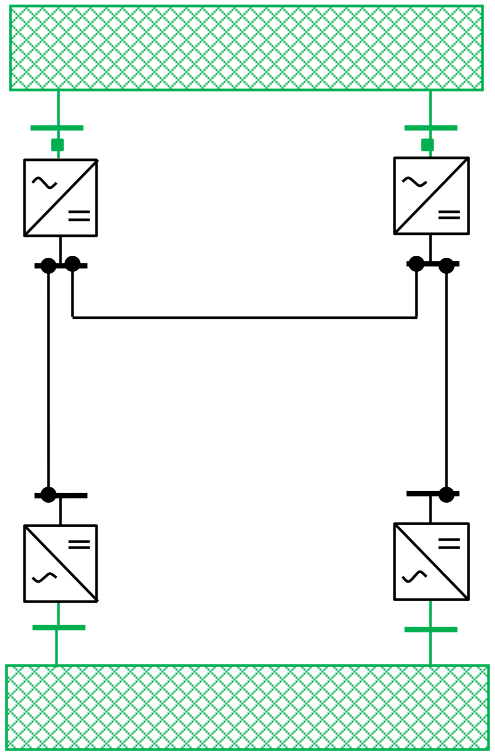
AC1 (all separate)



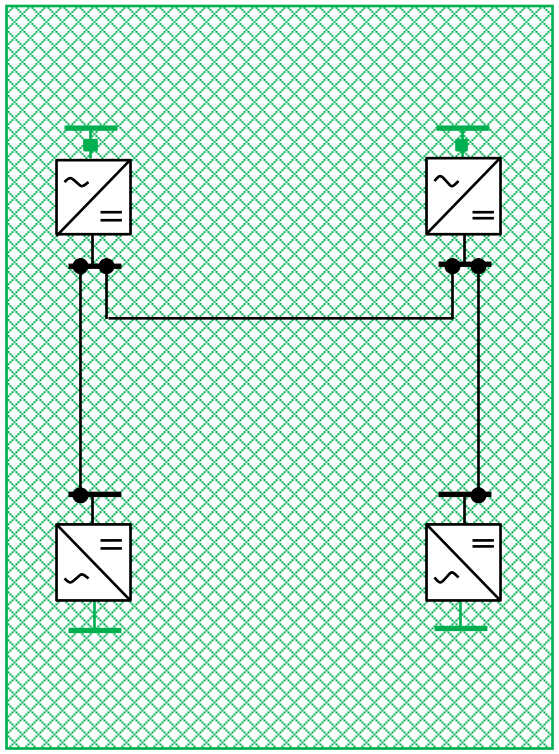
AC2a (embed. + OWP)



AC2b (two embed.)



AC3 (fully embedded)



Note: Single line diagrams; Project use cases focus on 525kV Bipole Systems

RESULT: AC/DC MATRIX

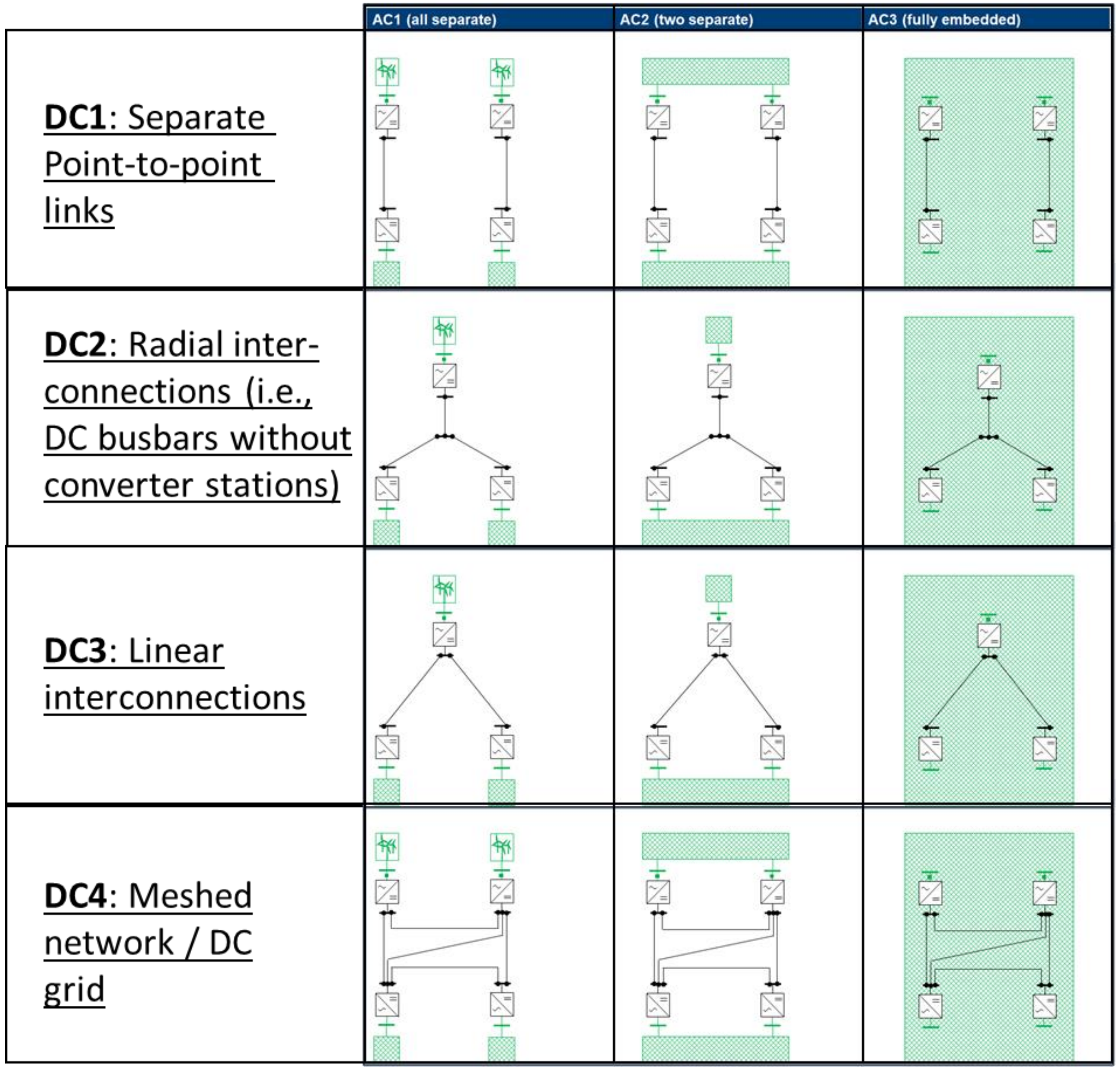
Outcome: Classification method with four HVDC topologies and four AC embedment scenarios **(matrix)**

Horizontal axis:

- **AC embedment** level
- Each AC system can have different attributes ("grid strength", etc.)

Vertical axis:

- Cross-variation of **HVDC topology** (regardless of configuration, technology)
- Planned: Extension to also include DC/DC converters



RELIABILITY KPIS

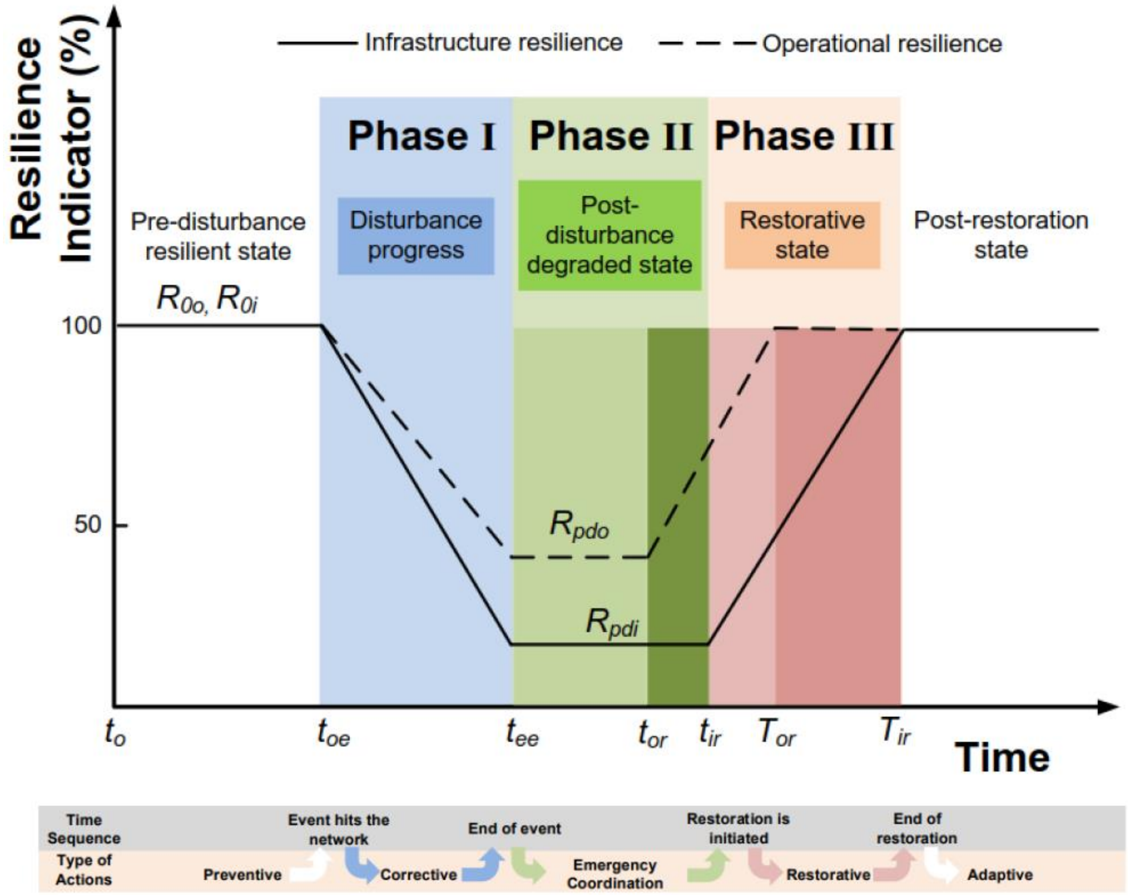
- The proposed KPIs are based on the ENTSO-E CBA guidelines
- But additional KPIs are introduced to capture more complex stability aspects of future power systems (reflecting TSO concerns)
  - B6 Adequacy
  - B7 Flexibility
  - B8 Stability, which includes the following sub-KPIs
    - B8.0 Angle stability (instead of ENTSO-E "Qualitative stability indicator")
    - B8.1 Frequency Stability
    - B8.3 Voltage Stability
    - B8.4 Converter-Driven Stability (as defined by IEEE)
    - B8.5 HVDC grid stability (new term for HVDC-WISE)

} Example Test Methods presented for each

(ENTSO-E "B8.2 Black start services" considered as part of resilience)

RESILIENCE KPIS

Multi-phase resilience trapezoid



CIGRE C4.47 key actionable measures

- Anticipation
- Preparation
- Absorption
- Sustainment of critical system operations
- Rapid recovery
- Adaptation, including the application of lessons learnt

RESILIENCE KPIS

Assessment of specific events

- Phase 1: Disturbance progress
  - →D1.1: Speed of degradation
  - →D1.2: Maximum system degradation
  - →D1.3: Firewall effect
- Phase 2: Post-disturbance degraded state
  - →D2.1: Duration of degraded state
- Phase 3: Restorative state
  - →D3.1: Type and completion of restoration
- Overall KPI
  - →DO.1: Incapability to serve the load
  - →DO.2: Total infrastructure unavailability

Long-term system assessment

Provides an overall assessment of the power system to various threats/events, by combining their consequences with their probability of occurrence.

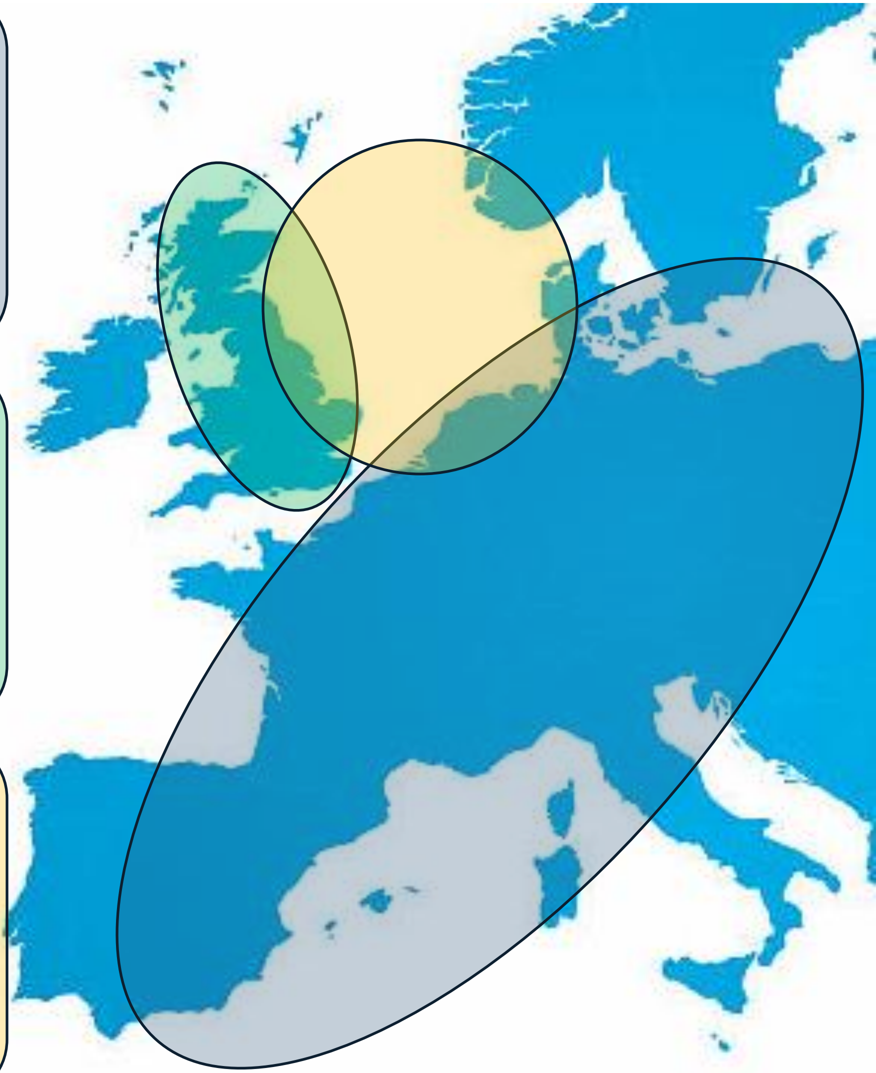
- PO.1: Return Period (RP) of events
- PO.2: Expected Energy Not Served (EENS)
- PO.3: Expected duration of outage or outage duration index

USE CASES

1. Large, highly-meshed network
HVDC embedded in single synchronous zone, operating in parallel with AC corridors. System remains AC-dominated.
Investigate HVDC overlay grids, interaction risks, impact of failure.
Large model enables testing of analysis tools.

2. Small or medium synchronous area
HVDC to transfer power from wind-rich zones onshore and offshore. Connection of large offshore wind plus embedded links forming multi-terminal networks.
Investigate hybrid AC/DC grid dominated by HVDC and converters.
Smaller model enables analysis of whole system.

3. Multi-purpose offshore HVDC grid
Offshore wind integration and inter-area energy trading.
Interconnection of use cases 1 and 2. Need to respect requirements of different areas. Opportunity for new inter-area services while maintaining firewall.
Model will interface to UC1 and UC2 models, or reduced equivalents.



OBJECTIVES, EXPECTATIONS AND SUCCESS CRITERIA

- Planning and operation with 100% carbon neutral sources and local dominance of power electronics
- Investigation of technology limitations of power electronics in hybrid AC/DC systems
- Apply the R&R analysis framework for expansion planning in hybrid AC/DC grids
- Propose expansion plans that minimize costs while satisfying technical constraints
- Improve R&R and dynamic behaviour
- Improve operational flexibility of transmission networks
- Prevent negative impact of HVDC solutions
- Grid codes and standards development

- Develop and test
  - → New control and protection functions
  - → Cyber resiliency analysis
  - → Models of new technologies
  - → R&R-oriented planning framework and analysis tools
- Test and demonstrate solutions in industrially relevant context
- Effective dissemination
  - → Roadmap for changes to codes, etc.
  - → Data, models, tools
  - → Training materials, workshops, publications, webinars

CIM/ CGMES library

Static

RMS

DyPh

EMT

Real-time

EXAMPLE RESULTS

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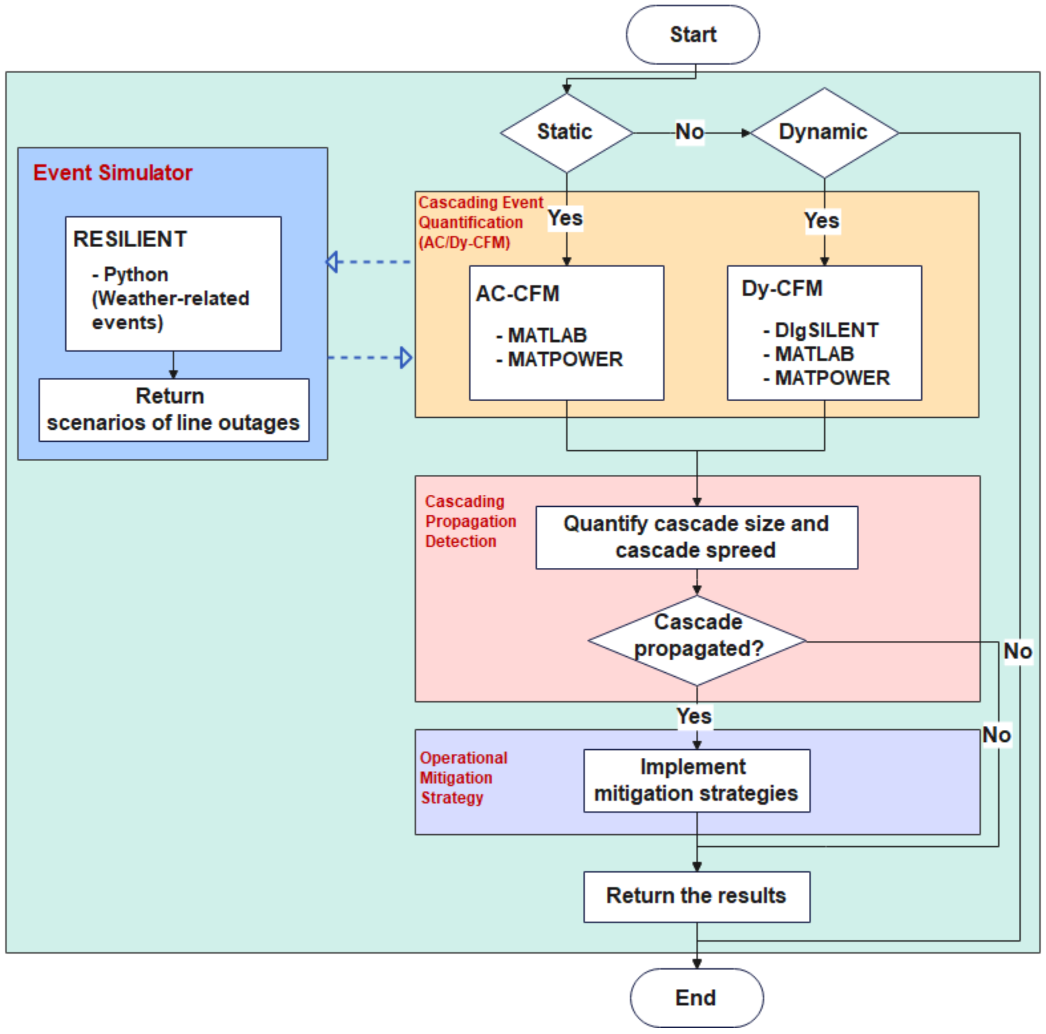
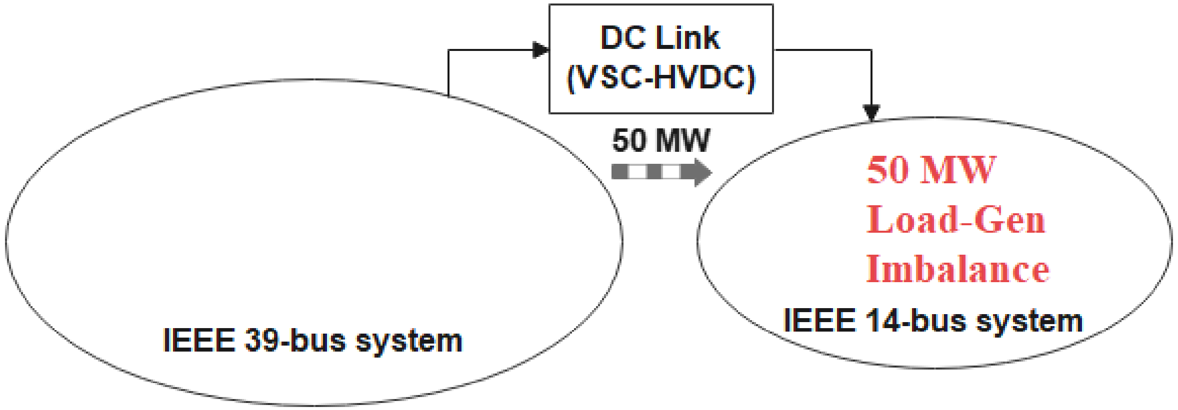
DYNAMIC CASCADE FAILURE MODELLING TOOL

- **Aim of the Tool:**
  - To quantify cascading event that benefits from both static and dynamic simulations
  - To develop operational mitigation strategies against cascading propagation
- **Overall Framework**
  - **<u>Quantification</u>** of cascading failures using specific resilience metrics and KPIs
  - **<u>Detection</u>** of cascading propagation
  - Operational **<u>Mitigation</u>** Strategies against Cascading Propagation



EXAMPLE OF TESTING DY-CFM TOOL

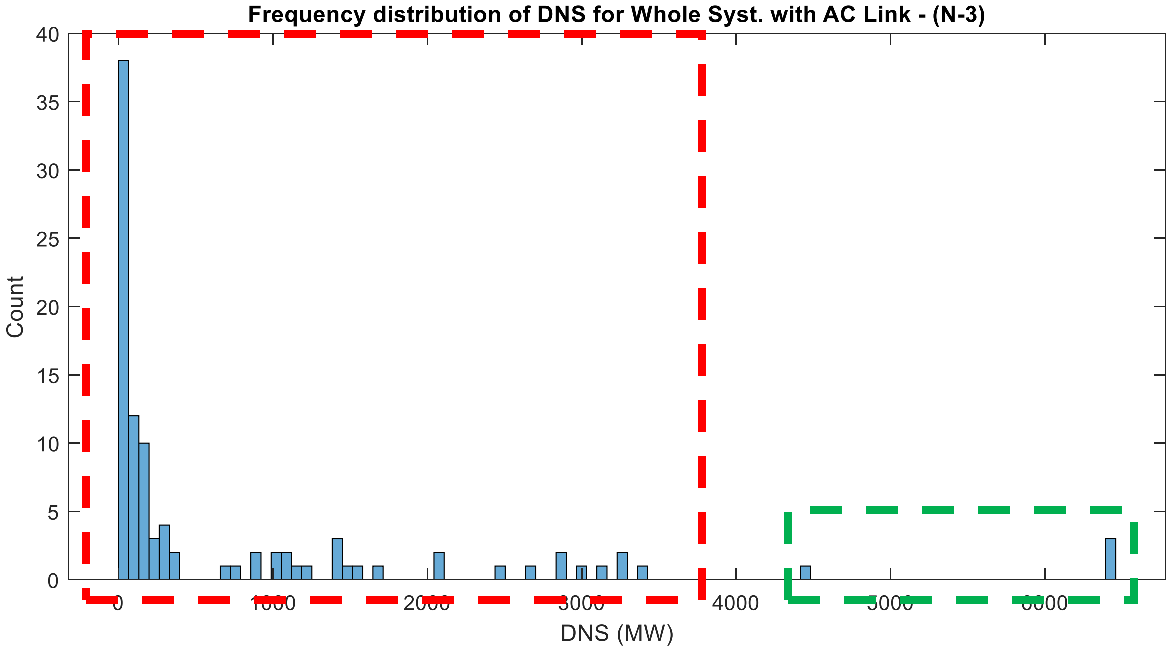
- Test system:
  - IEEE 39-bus and 14-bus systems interconnected with an AC link and point-to-point HVDC link
- System Controllers:
  - AVR and Governors
- Protective Relays:
  - Overcurrent Relays, Under-frequency load shedding, Over/Under frequency generator tripping

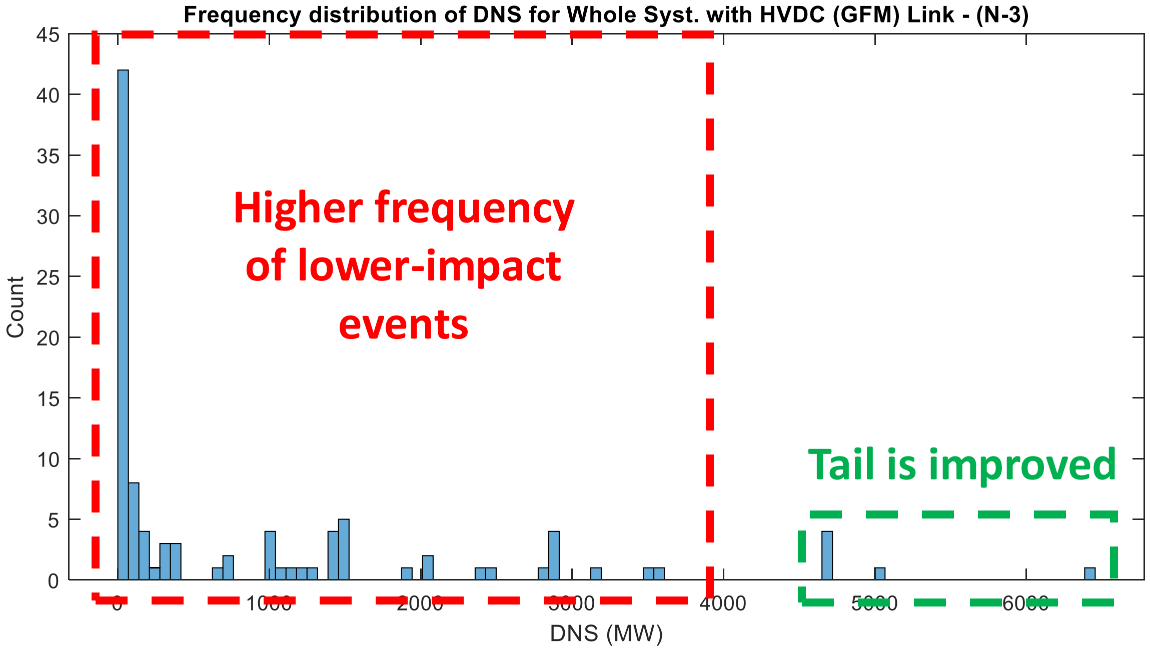


System	39 Bus	14 Bus	Whole System
Load (MW)	6194.7	259	6453.7
HVDC Connections	Bus 16	Bus 13	

EXAMPLE RESULTS WITH DY-CFM

- Cascading analysis was performed using Dy-CFM with and without HVDC link for N-1, N-2, N-3 and randomly generated contingencies
  - Tradeoffs between tail risk mitigation and higher frequency, lower-impact events.
- The simulations are able to quantify the role of HVDC in the cascading propagation in the interconnected system.





CONTROL FUNCTIONALITY

Core Functions

- Swap grid following - grid forming and interplay with DC side
- DC-side multi-converter oscillations – supplementary damping control

Supplementary Functions

- AC side stability support by MTDC
- Determination of MTDC set points

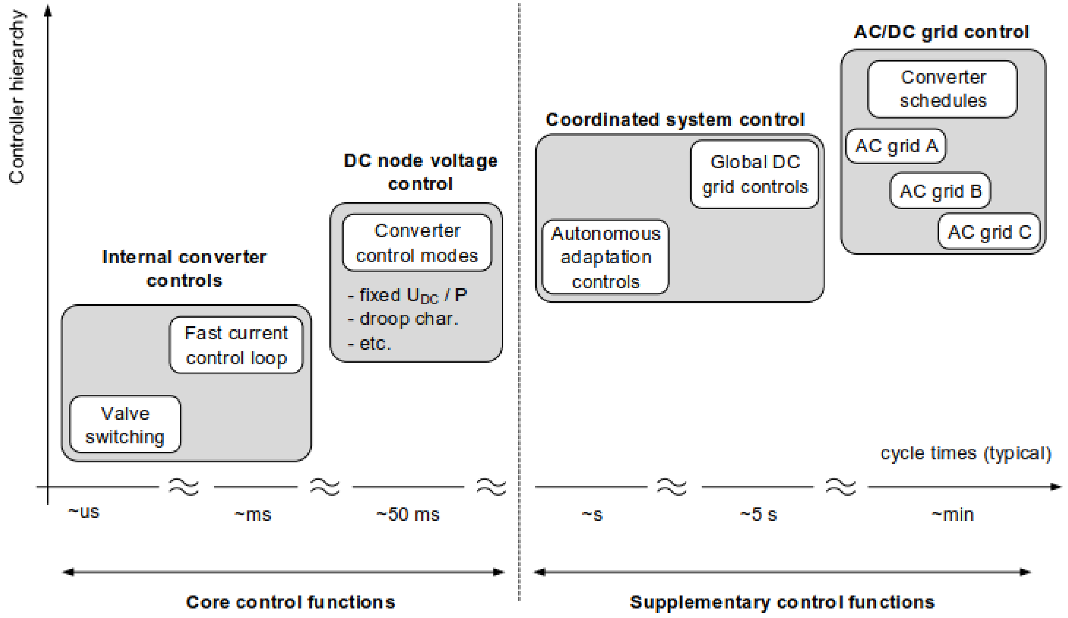
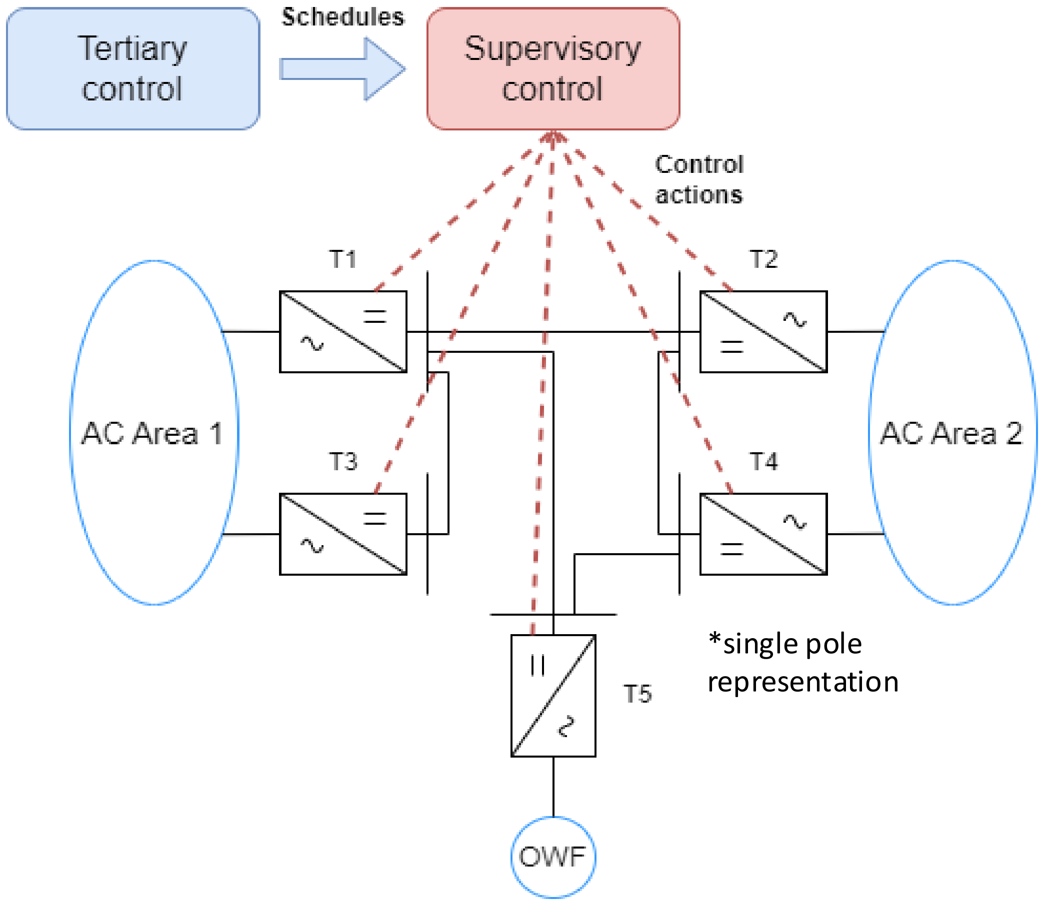
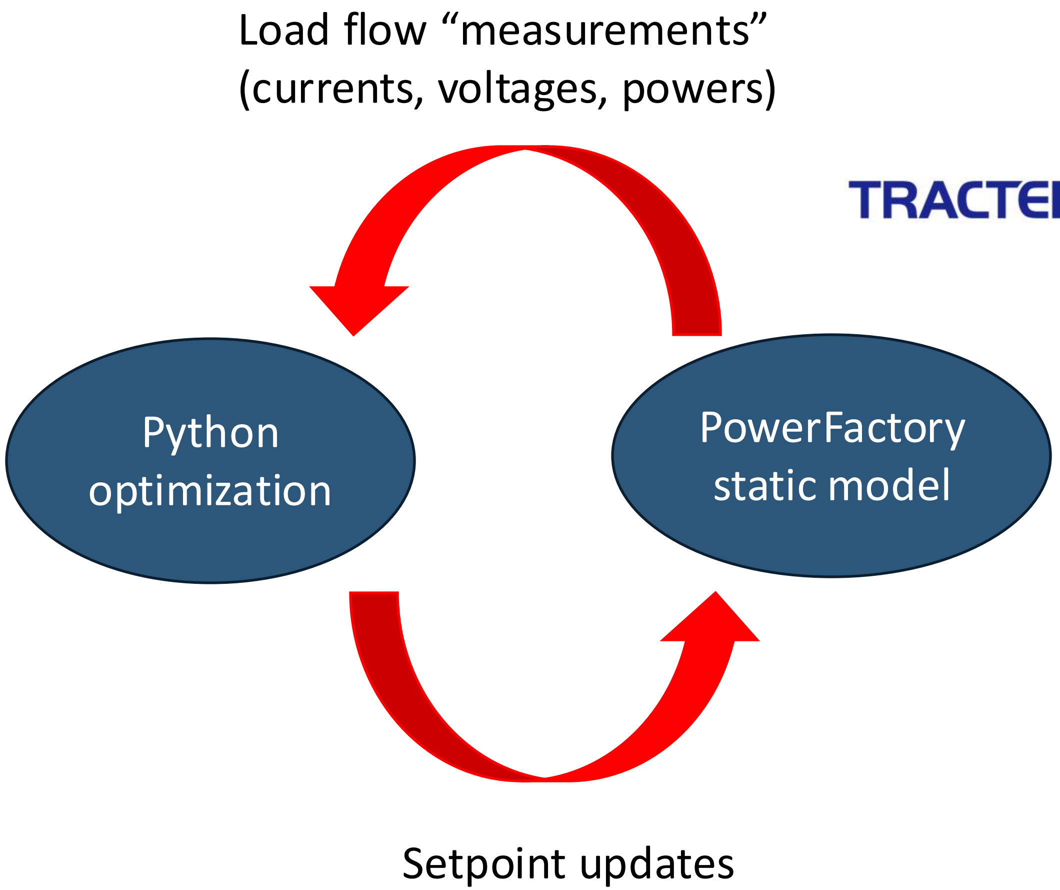


Figure 1: IEC standard guidelines (figure from IEC TS 63291-1:2023) [1]

[1] International Electrotechnical Commission. IEC TS 63291-1:2023. 2023. DOI:IEC TS 63291-1:2023 | IEC Webstore

DETERMINATION OF MULTI-TERMINAL SETPOINTS



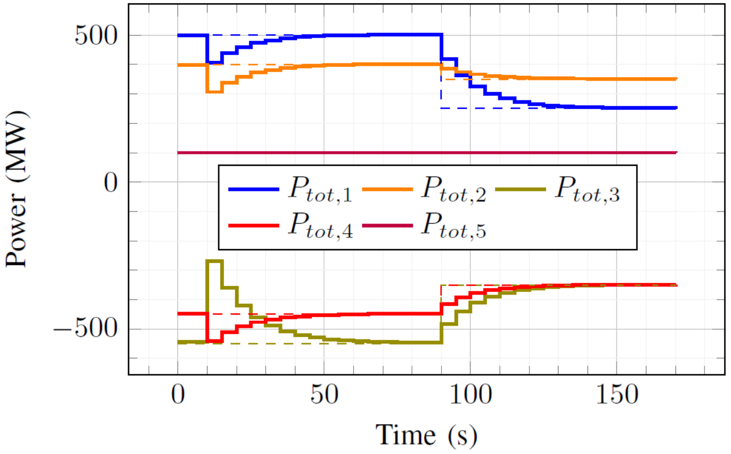


- Bipole configuration with DMR
- All terminals dispatchable except T5

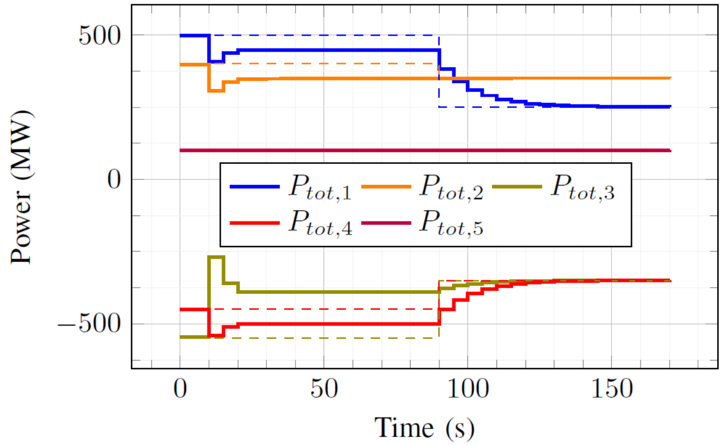
- Python optimization using SciPy
- PowerFactory load flow function

RESULTS

VSC powers if there is no constraint on the neutral voltages



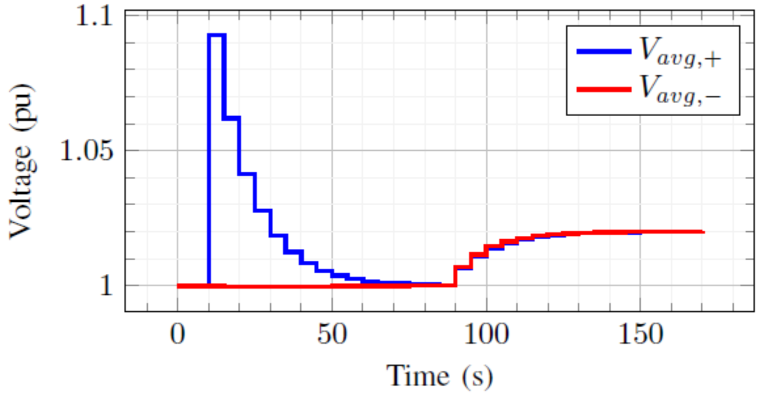
VSC powers with constraint on the neutral voltages



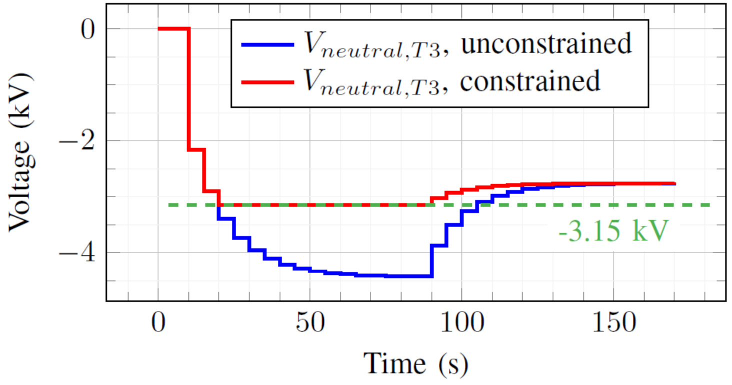
T3 was exporting power:

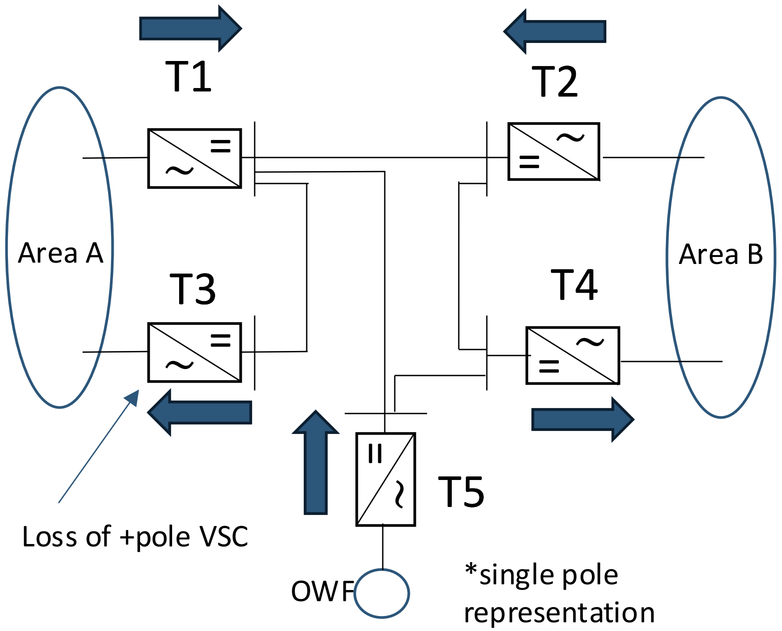
- DC voltage increase in the positive pole
- negligible impact on negative pole voltages

Average DC voltages



Neutral voltage at T3



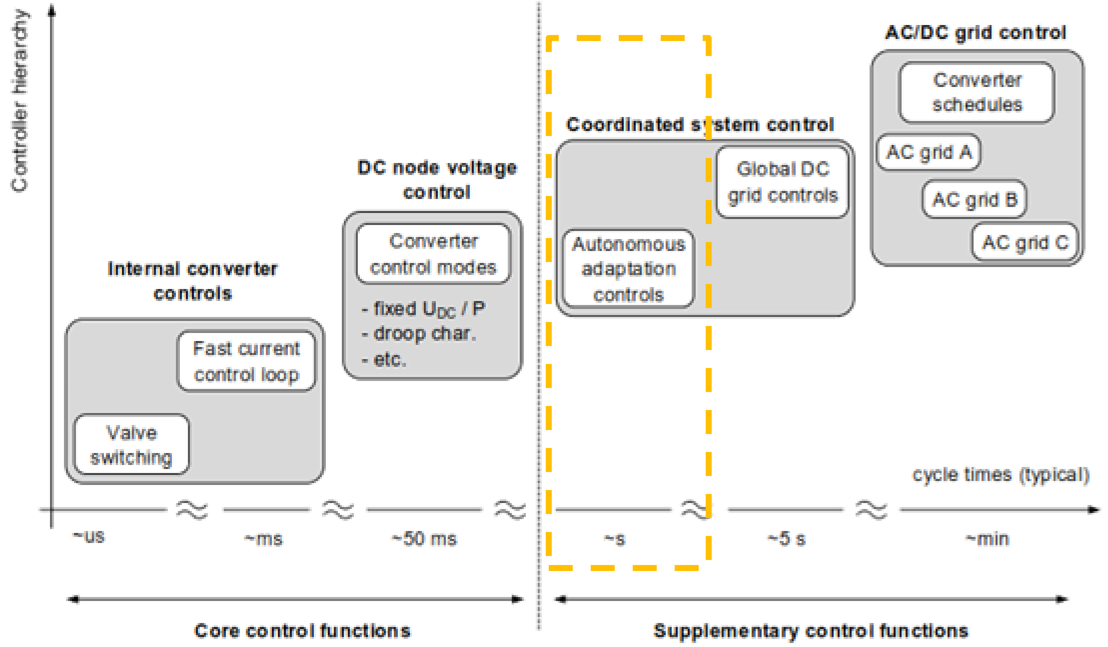


- MPC dispatch change
  - Trip of positive pole VSC at T3
  - MPC rebalances the power to best meet schedule
  - At t=90 s, new power and voltage setpoints are received
    - In the case of constrained neutral voltage on the DMR, the MPC reduces power flow to prevent cable damage

AC SIDE SUPPORT TARGETED SERVICES

Expected services in HVDC systems

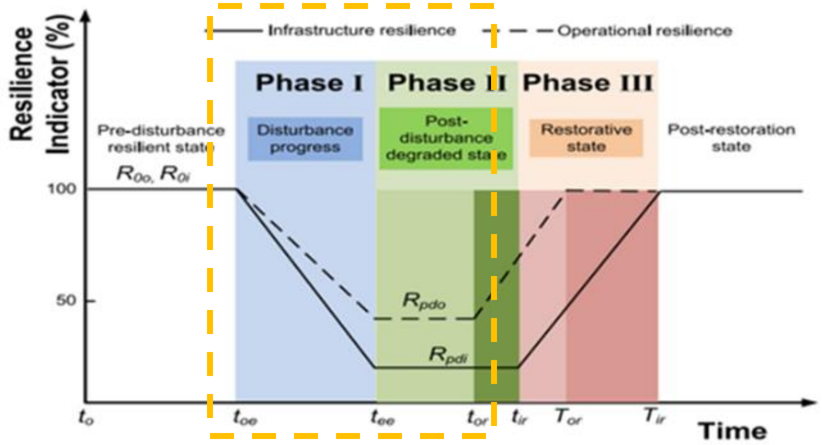
	Functionality	Embedded	Non-embedded
1	Voltage control	x	x
2	Static and dynamic reactive power control	x	x
3	Active power control[4]	x	x
4	Frequency control – FCR delivery	–	x
5	Frequency control – FRR delivery	–	x
6	Frequency control – RR delivery	–	x
7	Power oscillation damping (POD)	x	x
8	Sub-synchronous damping (SSD)	x	x
9	Emergency Power Control (EPC)	x	x
10	AC line emulation	x	–
11	Special protection schemes (SPS)	x	x
12	DC Loop Flow	–	x
13	Operating an island	–	x
14	System restoration	–	x
15	System Inertia (SI)	x**	x



Which functionalities can be provided/enhanced via **a coordinated control system** in the range of **hundreds of ms to seconds**?

- Low-frequency power oscillation damping (electromechanical oscillations from 0.1 to 1 Hz)
- AC line emulation
- Frequency control

Possibility to use current technologies (e.g., WAMS)



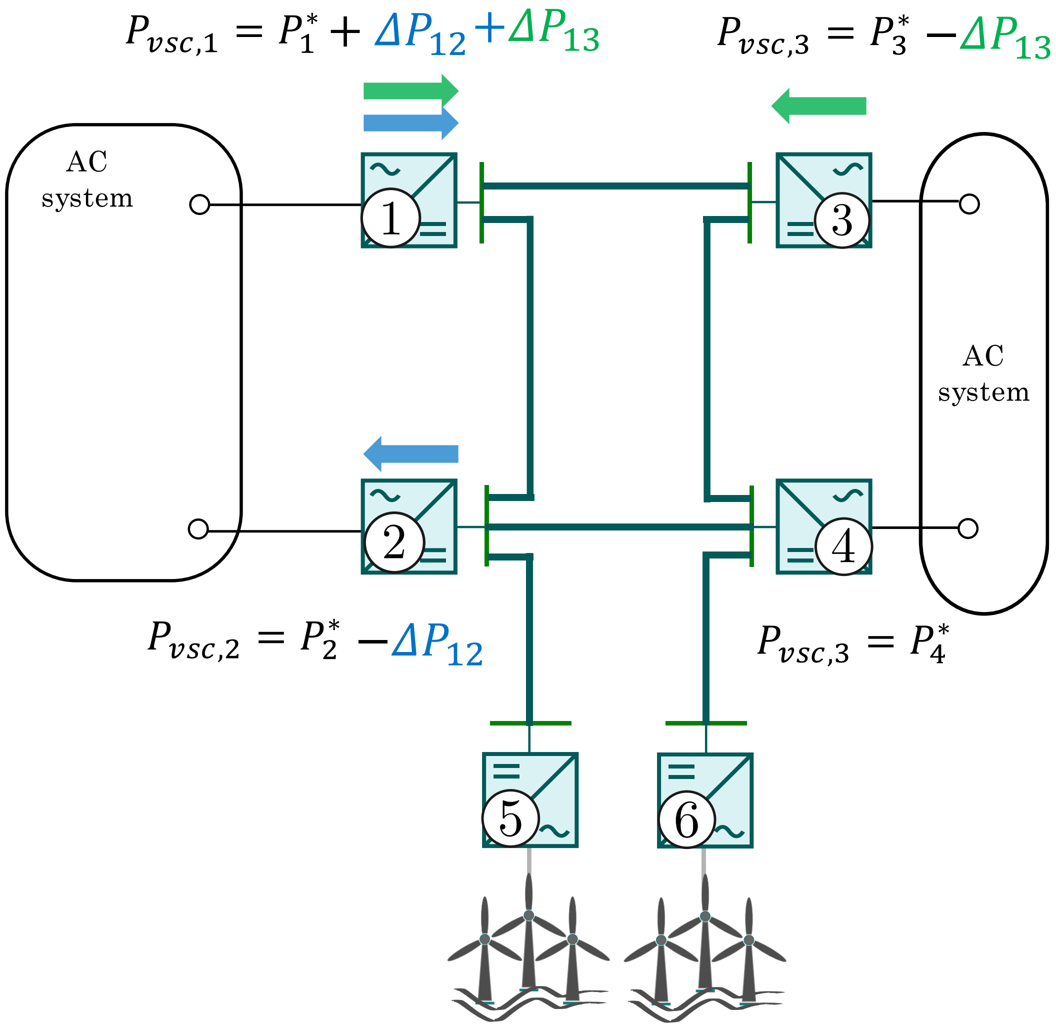
PROPOSED FRAMEWORK

To avoid interfering with the DC voltage control, the **sum of supplementary active power modulations should be zero**.

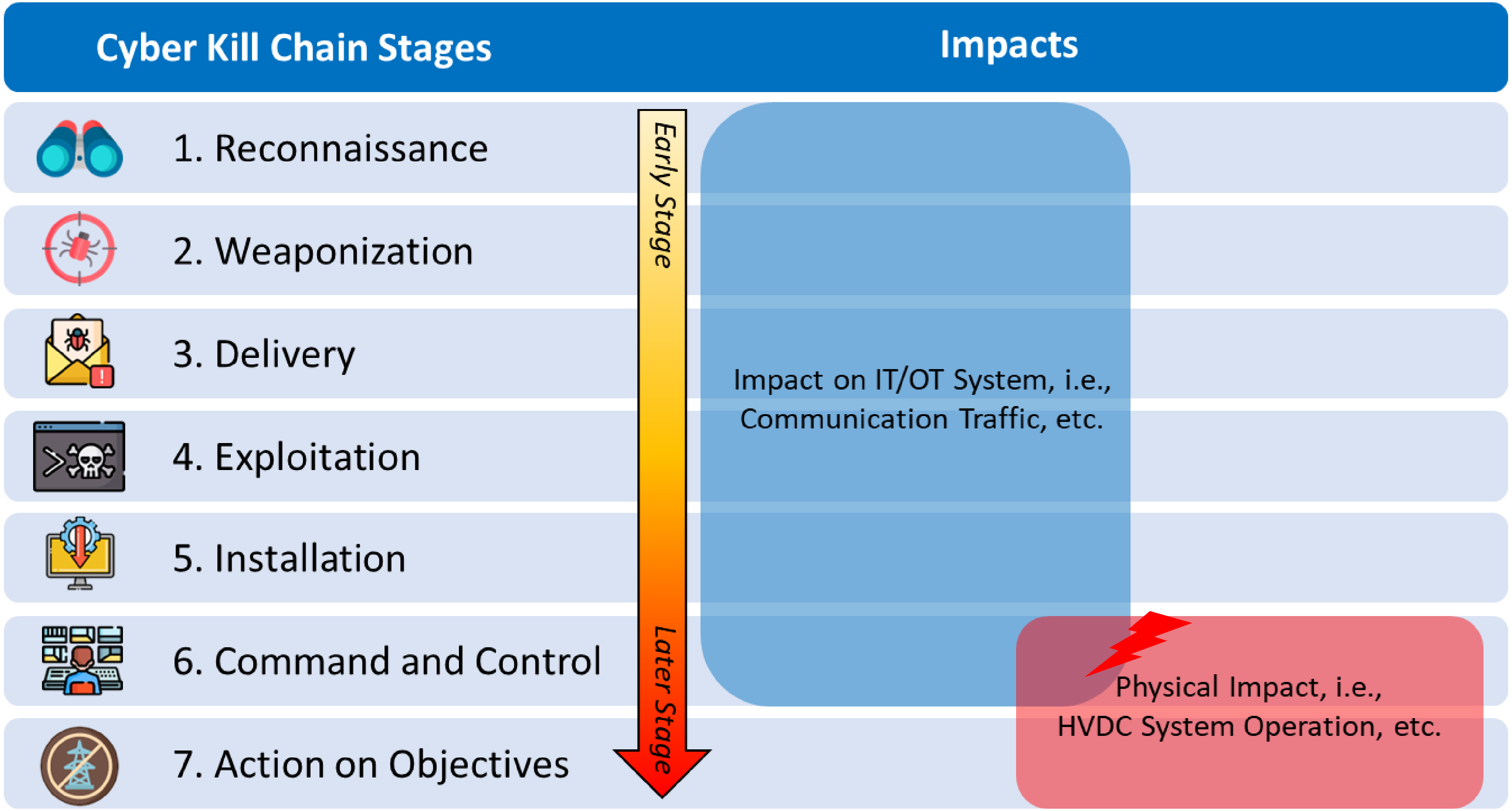
The **"channeling"** concept can be used: If converter i modulates its power by ΔP_{ij}, converter j modulates the same amount of power in the opposite direction, thus $-\Delta P_{ij}$.

Proposed controllers will now have as control input the modulated power of the channel ΔP_{ij} (and no ΔP_1 and ΔP_2 separately).

There can be $\frac{n(n-1)}{2}$ channels, where n is the number of dispatchable stations.



CYBER ATTACK SCENARIOS



CYBER RECOMMENDATIONS

1. The importance of the early stages of detection.

- Early-stage cyber-attack detection is crucial for minimizing the potential adverse impacts of cyber-attacks in HVDC grids.

2. The mitigation strategies must take into account both physical and cyber anomalies.

3. Implementation of secure protocols.

- The IEC 61850 standard is inadequate in dealing with advanced cyber-attack scenarios.
- Security mechanisms such as the RSA algorithm, which typically functions well in IT systems, may not be effective due to processing time constraints of 4 milliseconds.

4. Communication time latency constraints.

- The best possible delay fiber optic communication is 0.5 ms per 100 km.
- The delay limit from inherent communication channels and security applications must be considered for implementing the HVDC control and protection mechanism.

5. Proposed a throughput-based anomaly detection in the HVDC operational technology network

- The OT traffic originates from automated processes with deterministic and homogeneous characteristics.
- Use Graph Convolutional Long Short-Term Memory to identify OT traffic anomalies and pinpoint anomaly locations.

Thank you!

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