EnergyVille

HVDC grid developments

Need for new modeling tools and approaches

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KU Leuven / EnergyVille

KU Leuven as university

- Founded **1425**
- Consistent recognized academic leadership
- Top ranked institute
- University World Rankings 2018: 48th
- Reuters: **TOP 10 OF MOST INNOVATIVE UNIVERSITIES IN THE WORLD**

Nr 1 in Europe

1. Stanford University (US)
2. Massachusetts Institute of Technology - MIT (US)
3. Harvard University (US)
4. University of Pennsylvania (US)
5. KU Leuven (Belgium)
6. KAIST (South Korea)
7. University of Washington (US)
8. University of Michigan System (US)
9. University of Texas System (US)
10. Vanderbilt University (US)

KU LEUVEN

Some KPI of KU Leuven

A COMPREHENSIVE UNIVERSITY

78 bachelor's programmes

(74 taught in Dutch,
4 in English)

205 master's programmes

(141 taught in Dutch,
62 in English, 2 in French)

44 advanced master's programmes

(19 taught in Dutch, 24 in English and 1 in Spanish)

KU LEUVEN IN NUMBERS

Founded in 1425

14 campuses in 10 cities across Flanders

16 faculties

57,286 students

20,524 staff members

+250,000 alumni

OUR RESEARCH

7,296 researchers

475 million euros research expenses

5,098 PhD students

124 spin-offs

Last updated: February 2018

EnergyVille Flemish energy research partnership by:

VITO | **KU Leuven** | **imec** | **UHasselt**

Flemish energy research collaboration by

EnergyVille

The energy transition: EnergyVille's vision

Distributed renewable energy

Information- & communication-technology

Technological innovation

+

Cost reduction

Sustainable Energy System

- Multi-scale but mainly decentralized energy system
- Electricity dominant vector
- Coupling with heat, gas, …
- Key role of cities (highly complex urban context)

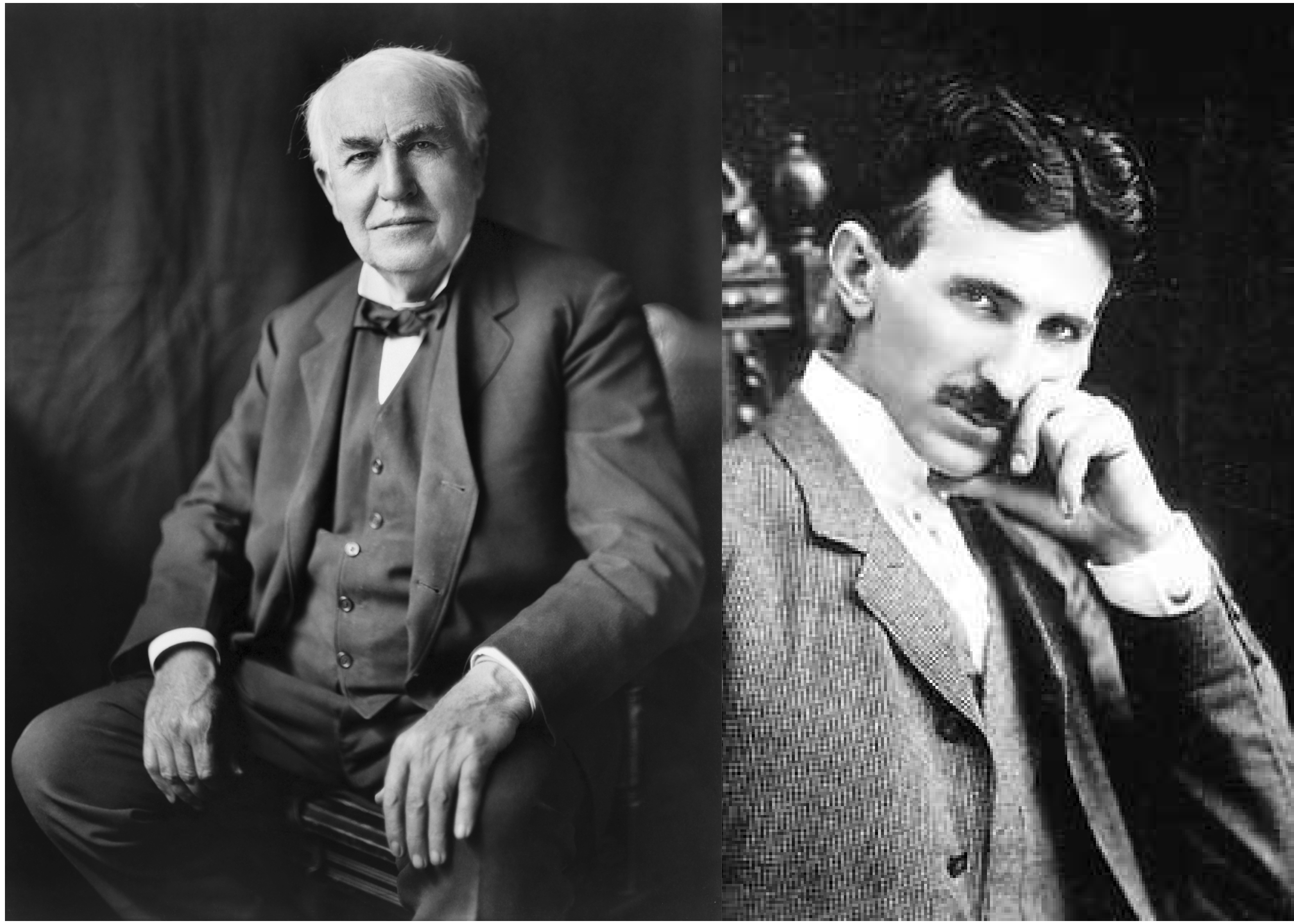
Energy Ville

Agenda

- KU Leuven & EnergyVille
- HVDC: an historic perspective and new applications
- HVDC, the key enabling technology for the supergrid
- New models are needed!
- Real-time simulation applications for HVDC & HVDC grid research

History: Struggle of the (scientific) titans

- At the dawn of electricity (1885 – 1890s): two struggling parties
  - Thomas Edison
  - Nicola Tesla (and Westinghouse)
- War of the currents: http://www.youtube.com/watch?v=kn-nhXMhXQ4
- Edison was heavily opposed to AC (Electrocution of condemned people was shortly called “Westinghousing”)
- AC won because of:
  - Easy to transfer up to higher voltages
  - Rotating field
  - Breaking DC currents



Edison & Tesla (Source Wikipedia)

HVDC in the power system

- Revival of DC from the ’50s: High Voltage DC
  - Used for the transport of bulk power over long distances
  - Used for undersea (cable) connections
  - Used for the interconnection of non-synchronous networks
    - 50-60 Hz back-to-back: Japan, South-America
    - Asynchrounous networks: Fr–UK, Scandinavia – Continental Europe, Europe – Russia,. . .
- Second revival from the second half of the ’90s
  - New markets (e.g. China and India)
  - Switching/acting component at first were mercury valves and later thyristors . .
  - Transistor based components (IGBT) for HVDC started in the 90’s
  - Cable connections become more important
  - ⇒ New applications such as offshore
- +/- 100 schemes

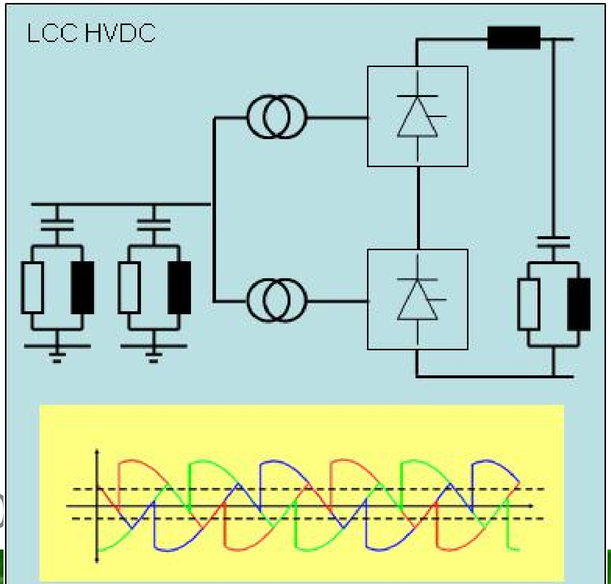
Main properties of HVDC installations vs AC

- Fewer cables are needed for equal power transmission
- No reactive losses
  - No stability distance limitation
  - No limit to cable length
  - Lower electrical line losses
- No need for maintaining synchronism
  - Connecting different frequencies
  - Asynchronous grids (UCTE – UK)
  - *Black start* capability?
- Power flow (injection) can be fully controlled
- Can be cheaper…
  - Transmission line/cable is cheap(er), converter is expensive
- Often turnkey projects
- “Special component” in the eye of the system operator

HVDC: two available converter technologies

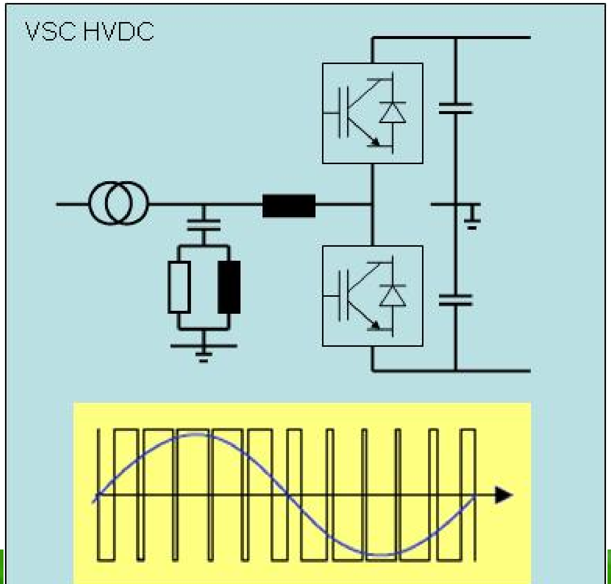
CSC or LCC technology

- Uses thyristors
- Largest power ratings
- Cheapest & lowest losses
- Harmonics & large filter installation
- Mass impregnated cables
- Active power control
- Not for offshore



VSC technology

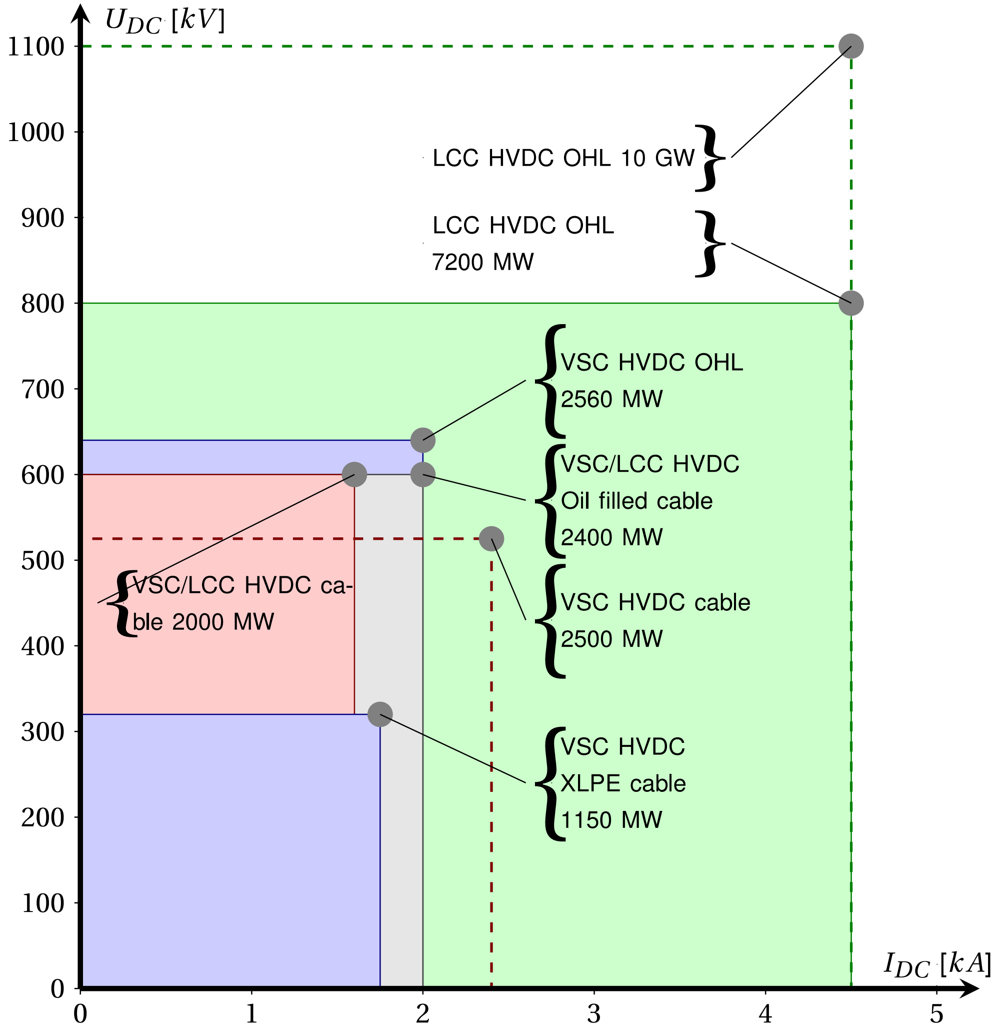
- Uses IGBT
- Power still limited
- More expensive + 1% / converter losses
- Clean sinus & small footprint
- XLPE cables
- Active and reactive power control
- Offshore possible



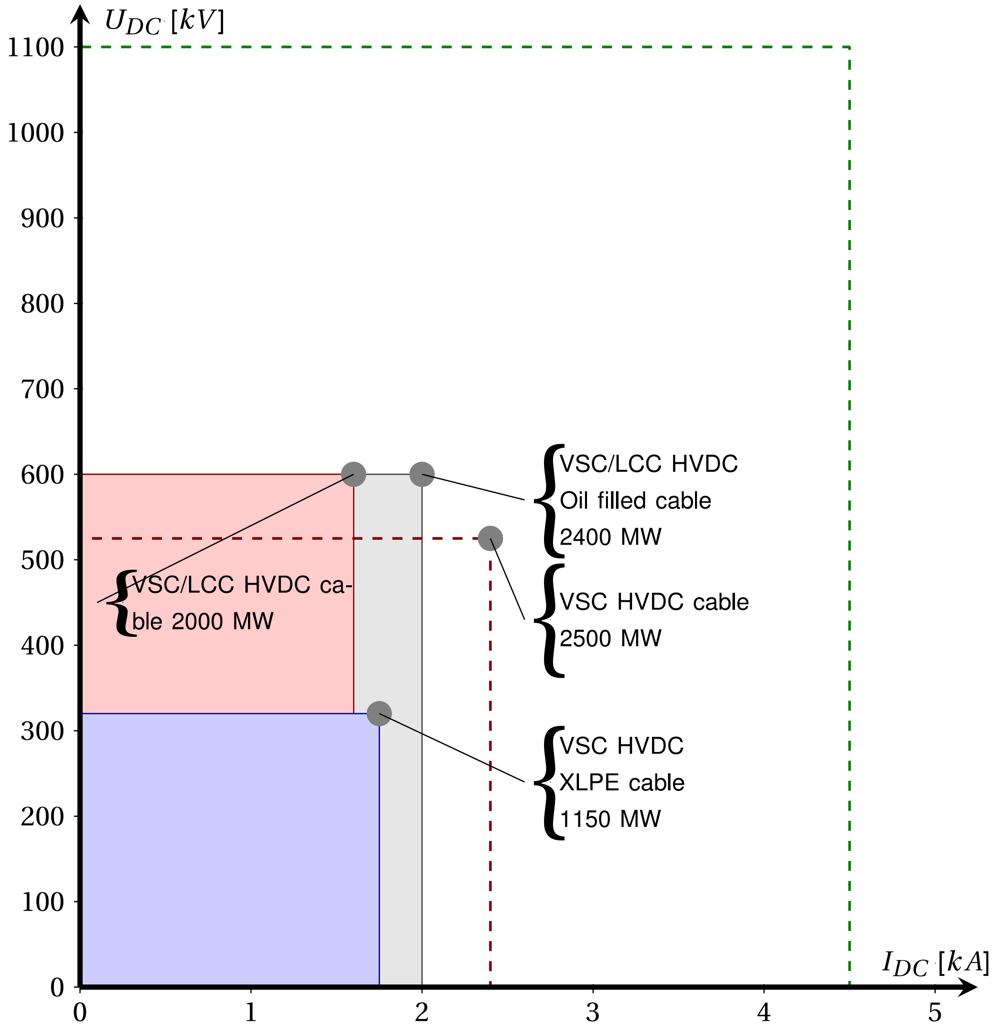
➔Now MMC topology

System sizes

HVDC system capabilities



HVDC cable system capabilities



New technologies provide more flexibility to operate the grid

- HVDC technology has become essential
  - to connect remote offshore wind
  - to interconnect non -synchronized systems
  - to reinforce the transmission system
  - Underground, also for short distances

- Key technology for large-scale integration of renewable energy sources

ENTSO-E TYNDP 2014: >20 000 km DC by 2030
40 % of total investments

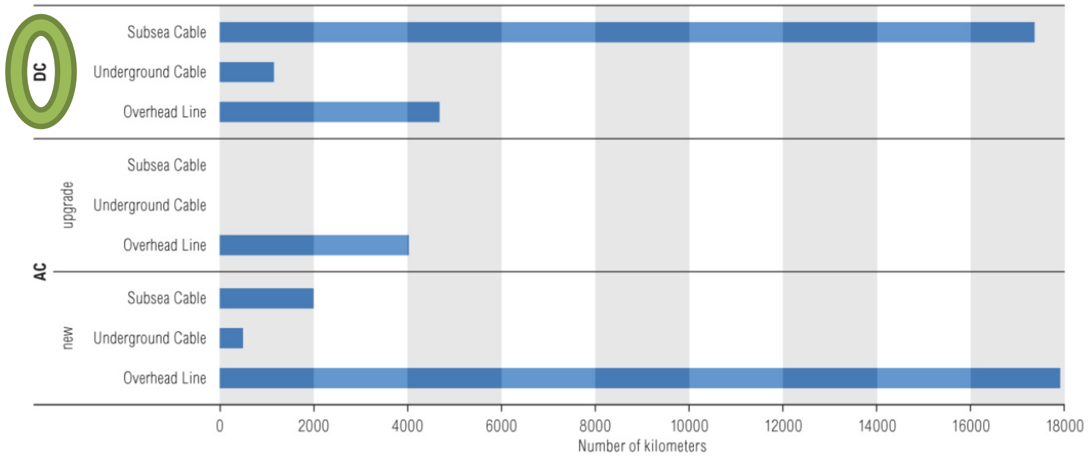
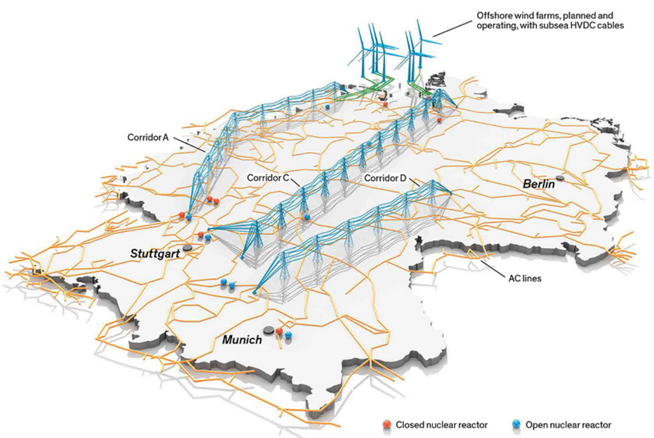


Figure 0-3 TYNDP 2014 investment portfolio - breakdown per technology



E-merge Alliance, IEEE Spectrum, Friends of the supergrid, ENTSOE

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- HVDC: an historic perspective and new applications
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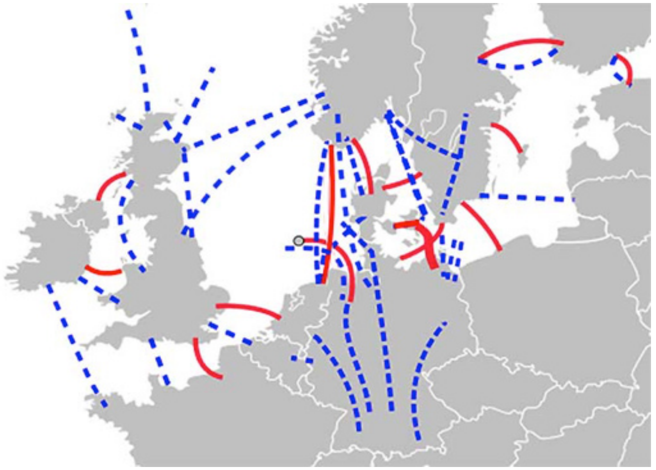
- Real-time simulation applications for HVDC & HVDC grid research

Research vision

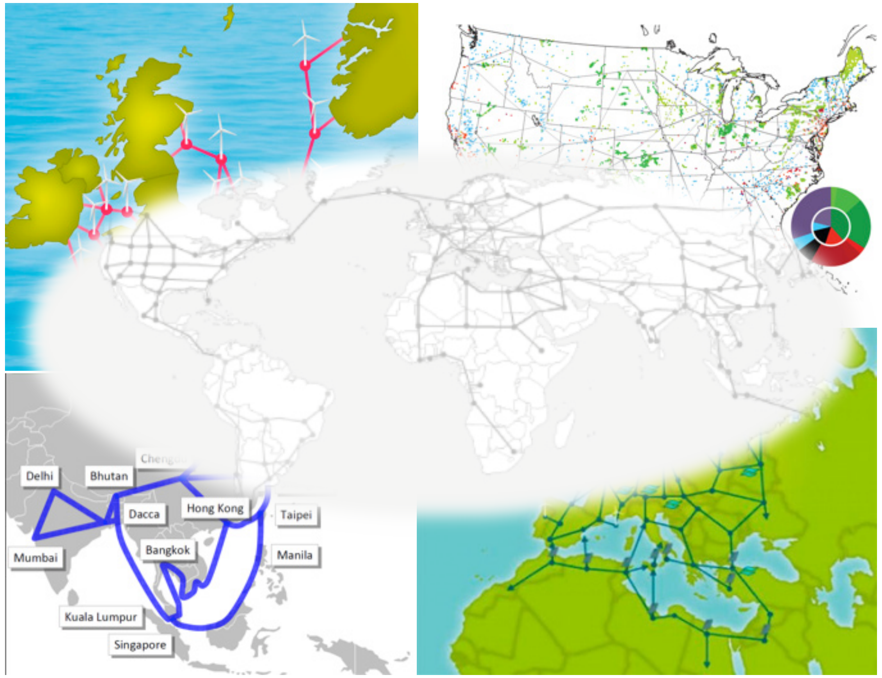
From present and proposed point-to-point connections…



HVDC is key technology for large-scale integration of renewable energy sources

Worldwide HVDC market is in excess of $4 billion annually and rising

towards meshed HVDC grids



Research challenges

TODAY	IN FUTURE
From **point-to-point** connections …	… to multi-terminal and meshed **grids**
Protection From protecting the AC system …	… to fast-acting DC system protection
Control From one manufacturer (turnkey) per link …	… to multi-vendor interoperability
Operation From HVDC as “assistance” for AC grid …	… to AC & HVDC grid as parts of same grid
Grid code From complying with AC system requirements …	… to complying with both AC and DC grid requirements

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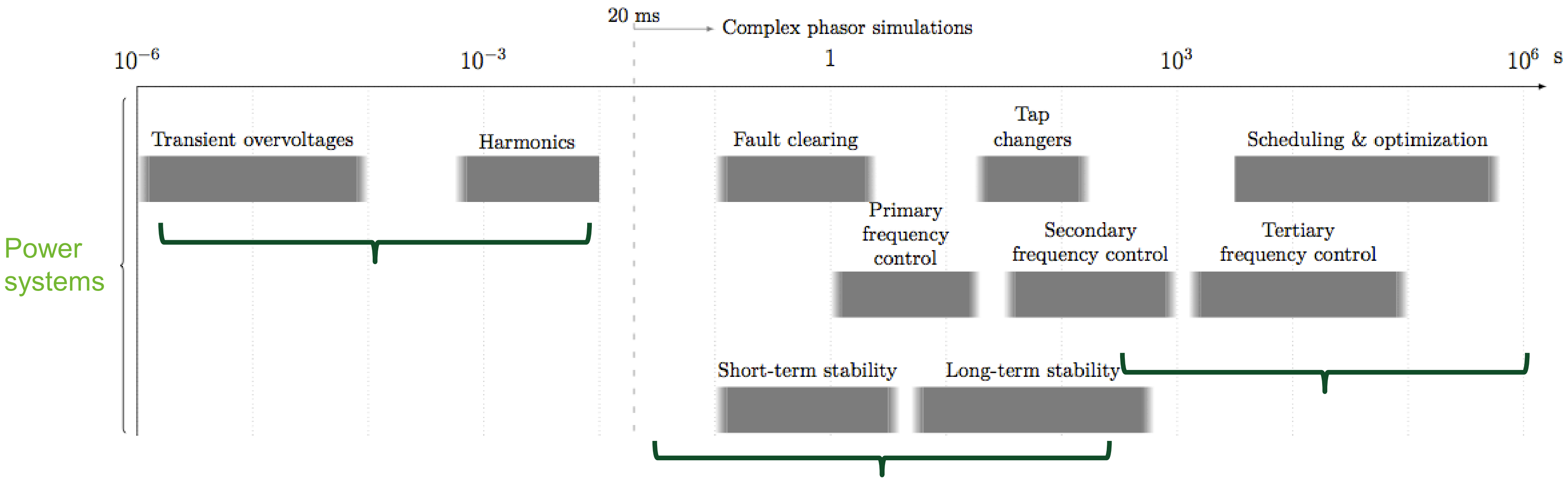
Where are we heading?

- Paradigms shifts for power system planning, operation, control & protection
  - Renewables becoming standard (168 GW wind (2017) + 100 GW solar (2016))
  - Liberalized energy market
  - Continued electrification
  - Aging power system

- Planning
  - Flexibility (control action) accounting for uncertain investments while maintaining reliability
- Operation
  - Reliable operations while considering uncertainty of renewable generation and flexible controls
- Control
  - Power electronics-dominated systems with low inertia
- Protection
  - New technology and new behavior!

- Existing models and tools are inadequate to tackle problems

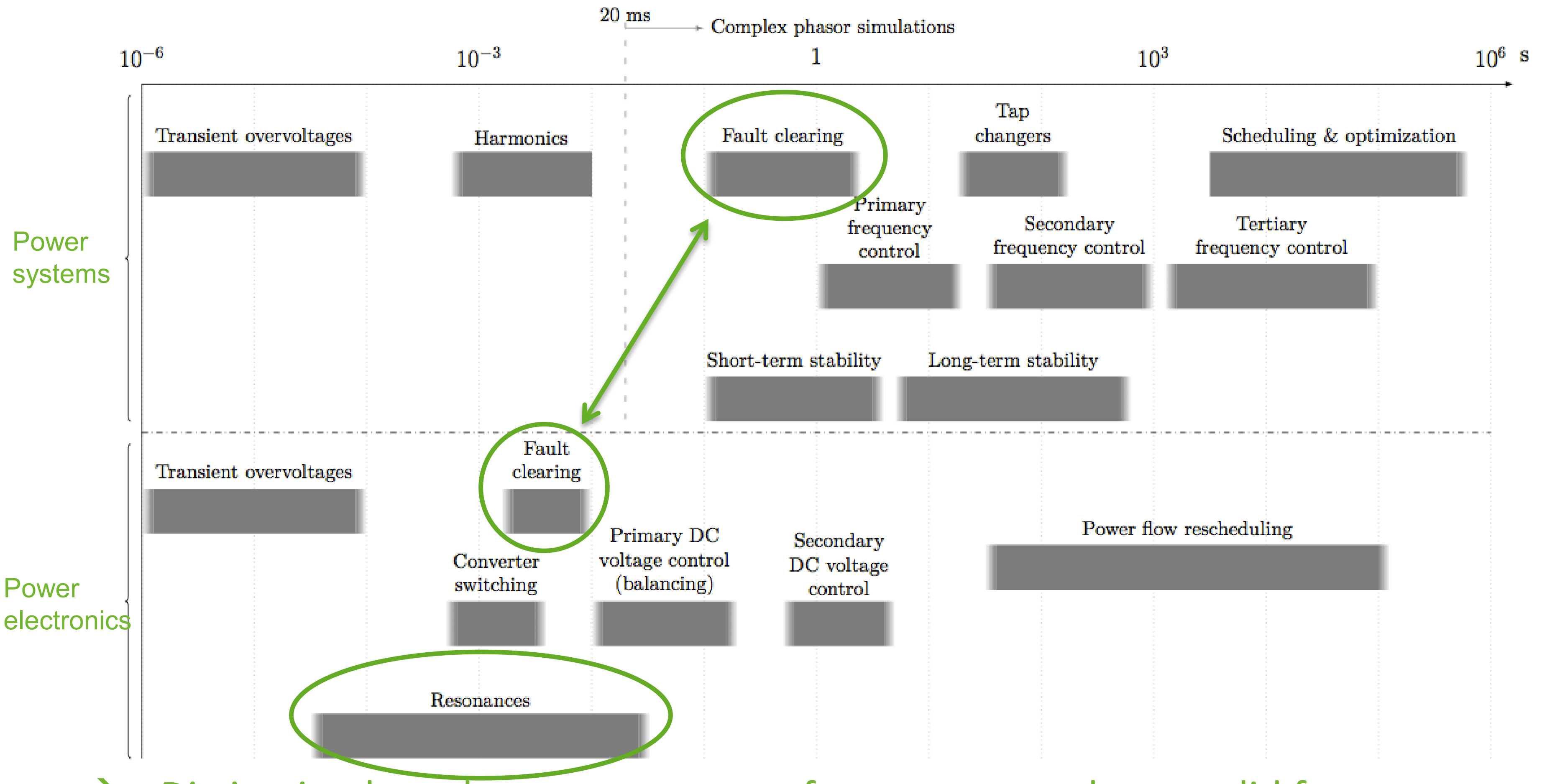
Power system modeling approaches



- Power system phenomena with different time constants
  → different classes of simulation programs
  - Electromagnetic transient (EMT)-type programs
  - Electromechanical stability (phasor-based) programs
  - Steady-state power flow programs

Image source:
J. Beerten, Modeling and Control of DC grids

New technology → new models needed



→ Distinction based on power system frequency not always valid for systems based on power electronics

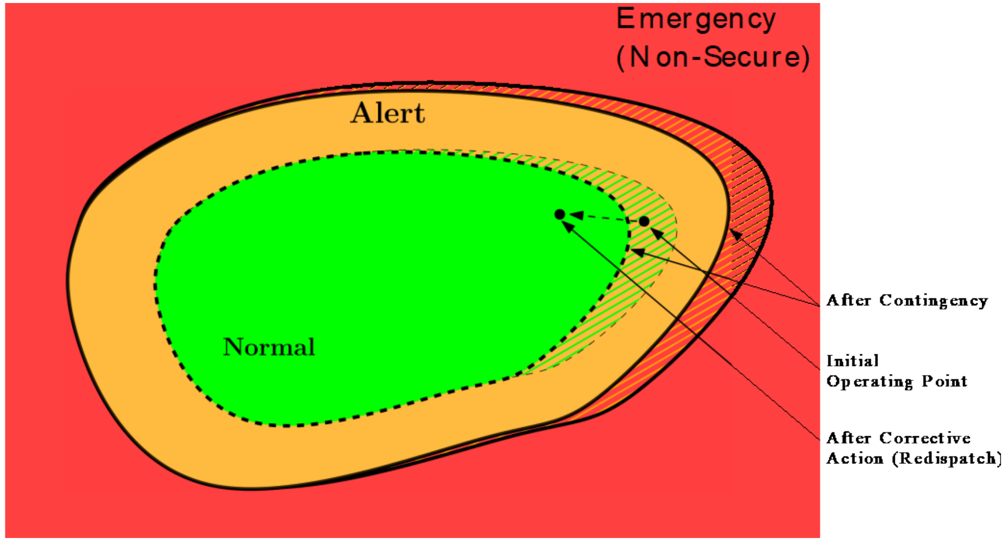
→ Much faster systems

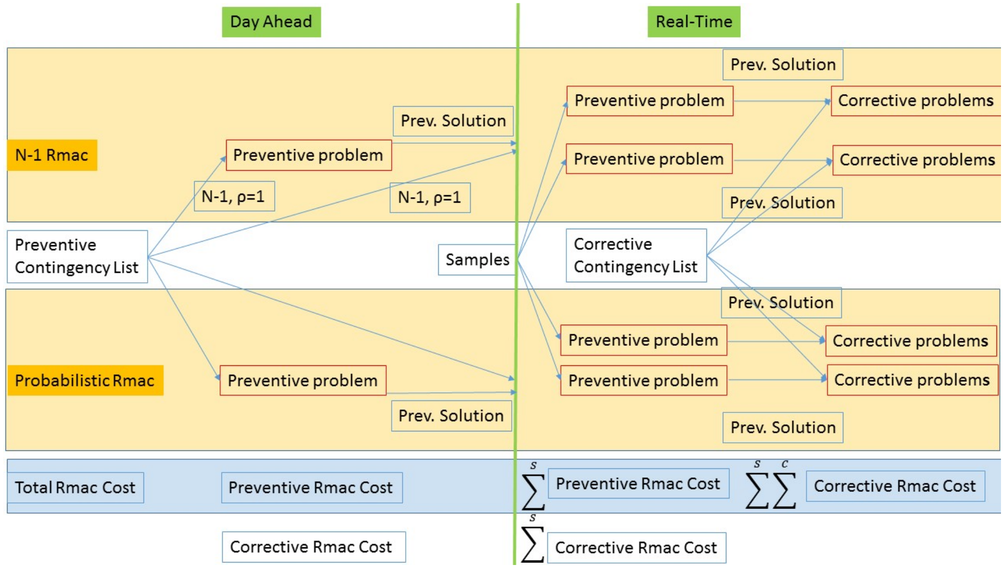
→ New interactions

Image source:
J. Beerten, Modeling and Control of DC grids

New problems ==> new methods and tools needed for operation

- Towards risk-based assessment
  - Deterministic ==> Probabilistic
  - Reliability criterion (N-1, N-k, Probabilistic)
- Including forecasts and energy storage
  - Multi-timestep
- Different control actions
  - HVDC active and reactive power control
  - Redispatch: Active and reactive power
  - Ancillary services
  - Line switching
  - Preventive and corrective actions
  - Operational rules
- Level of detail
  - Spatial and time granularity
  - Balanced or unbalanced flow
- Multiple stakeholders
- Simplifications in modeling (DC formulation, lossless,…)
- Visualization of outputs





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- Different control actions
  - Redispatch: Active and reactive power
  - Ancillary services
  - HVDC and PST controls
  - Line switching
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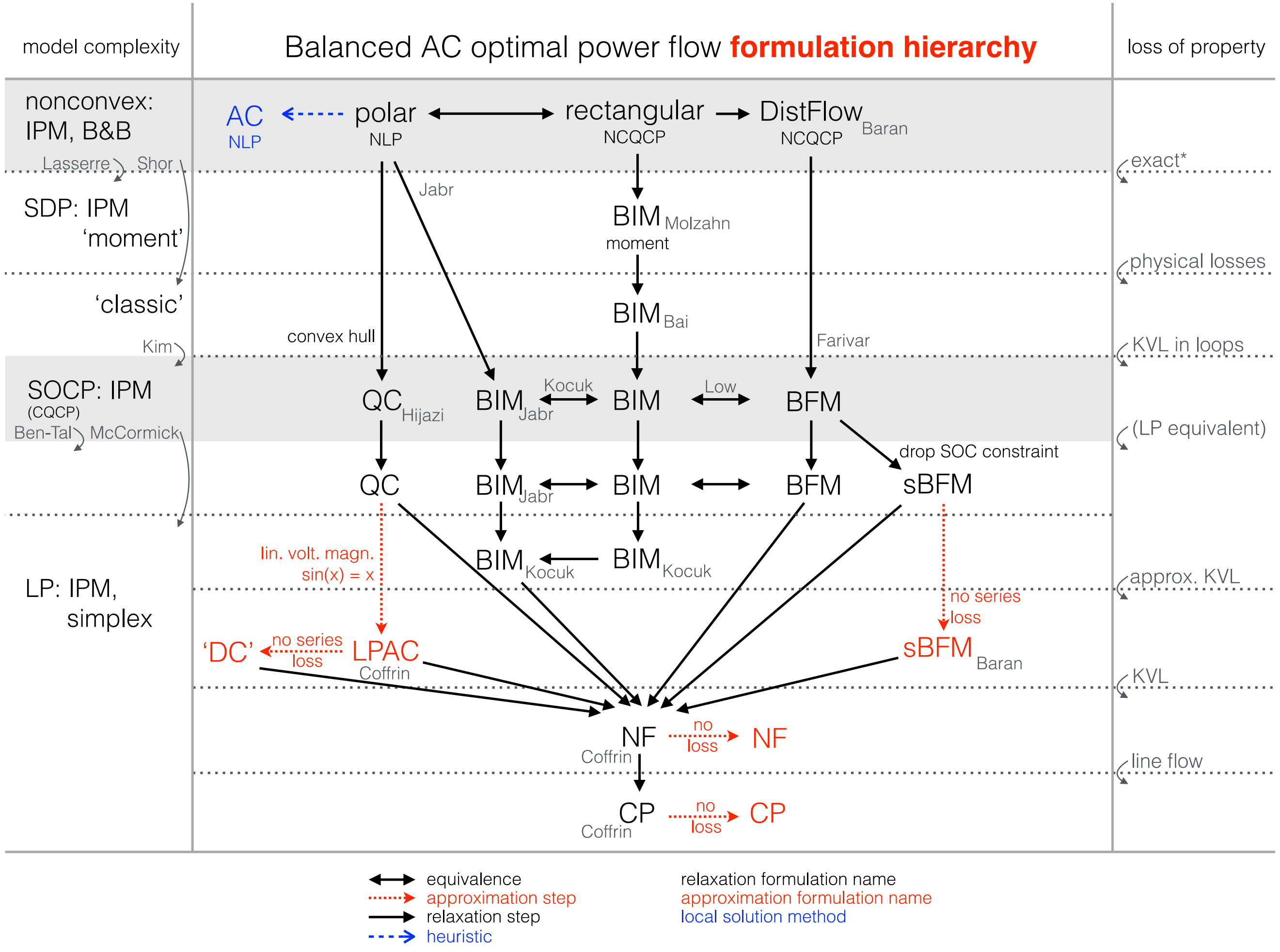
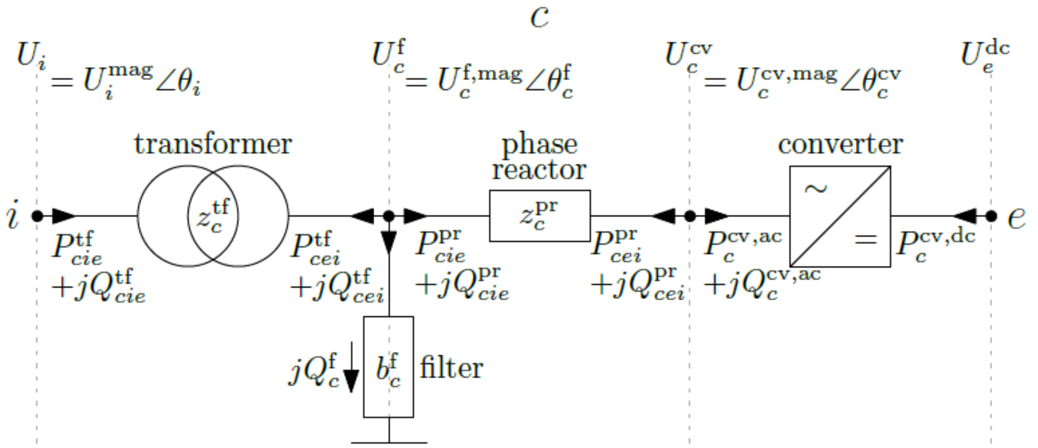


New problems ==> new methods and tools needed for operation

- Open source tool for solving hybrid AC/DC power systems
- Optimal Power Flow with both point-to-point and meshed and dc grid support
- Power Flow with both **point-to-point and meshed** AC and DC grid support
- Different formulations (detail/approximations)
- Julia/JUMP implementation: PowermodelsACDC.jl
- https://github.com/hakanergun/PowerModelsACDC.jl



PARAMETRIZATION OF HVDC CONVERTER MODELS

	transformer	filter	phase reactor	$Q_c^{\mathrm{cv,ac,min}}$
MMC	$\{0,1\}$	0	$\{0,1\}$	$\pm$
VSC	$\{0,1\}$	1	$\{0,1\}$	$\pm$
LCC	1	1	1	≥ 0

- Next steps:
  - Including reliability constraints
  - Stochastic formulation
  - Planning applications

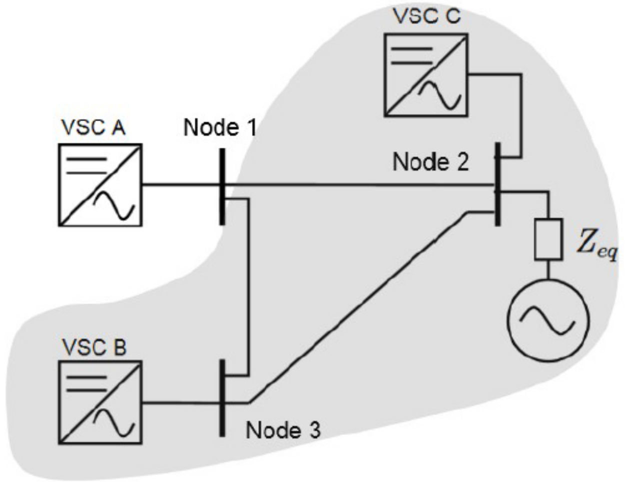
AC/DC OPF OBJECTIVE VALUES AND GAP. (NUMERICAL ISSUE INDICATED *)

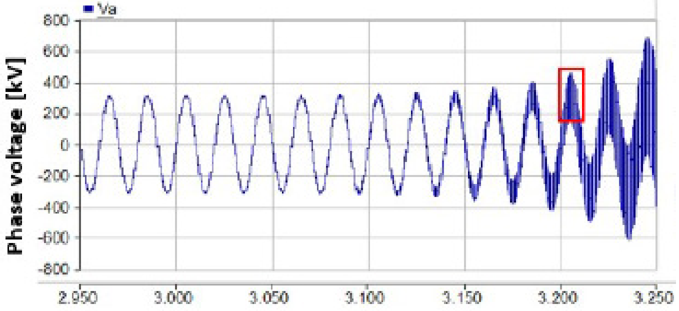
case	AC	SDP		QC		BIM SOC		BFM SOC		'DC'	
	obj ($/h)	obj ($/h)	gap (%)	obj ($/h)	gap (%)	obj ($/h)	gap (%)	obj ($/h)	gap (%)	obj ($/h)	'gap' (%)
case5_2grids	397.367	397.364	0.001	363.502	8.522	363.502	8.522	363.503	8.522	379.842	4.410
case5_acdc	194.139	194.119	0.010	183.763	5.345	183.763	5.345	183.763	5.344	178.314	8.151
case5_dc.m	17762.4	*	*	15037.8	15.339	15037.8	15.339	15037.8	15.339	17690.9	0.403
case24_3zones_acdc	150228	*	*	150156	0.048	150156	0.048	150156	0.048	144791	3.619
case5_dcgrid	55.052	55.050	0.004	55.050	0.004	55.050	0.004	55.050	0.004	51.179	7.036
case5_b2bdc	193.019	193.007	0.006	182.833	5.277	182.833	5.277	182.834	5.277	177.209	8.191
case39_acdc	41968.9	41965.7	0.008	41961.8	0.017	41961.8	0.017	41961.8	0.017	41413.5	1.323
case3120sp_acdc	2142635	*	*	2131097	0.539	2130988	0.544	2131097	0.539	2082166	2.822

New dynamic models needed for HVDC systems

- Traditional tools include models for HVDC (recent versions)
  - Available models in tools lack detail
  - HVDC grid models mostly missing
  - Single operating mode
- Industry (system operators) still focused on averaged models for most dynamic analysis studies
- Available models for studies are either:
  - Generic model (application range is limited)
  - Vendor supplied models (under NDA), application range is limited!
- Correct representation of all elements, not just the converter (e.g. cable)

Network electromagnetic interaction studies with multiple converters (PhD Alejandro Bayo Salas)

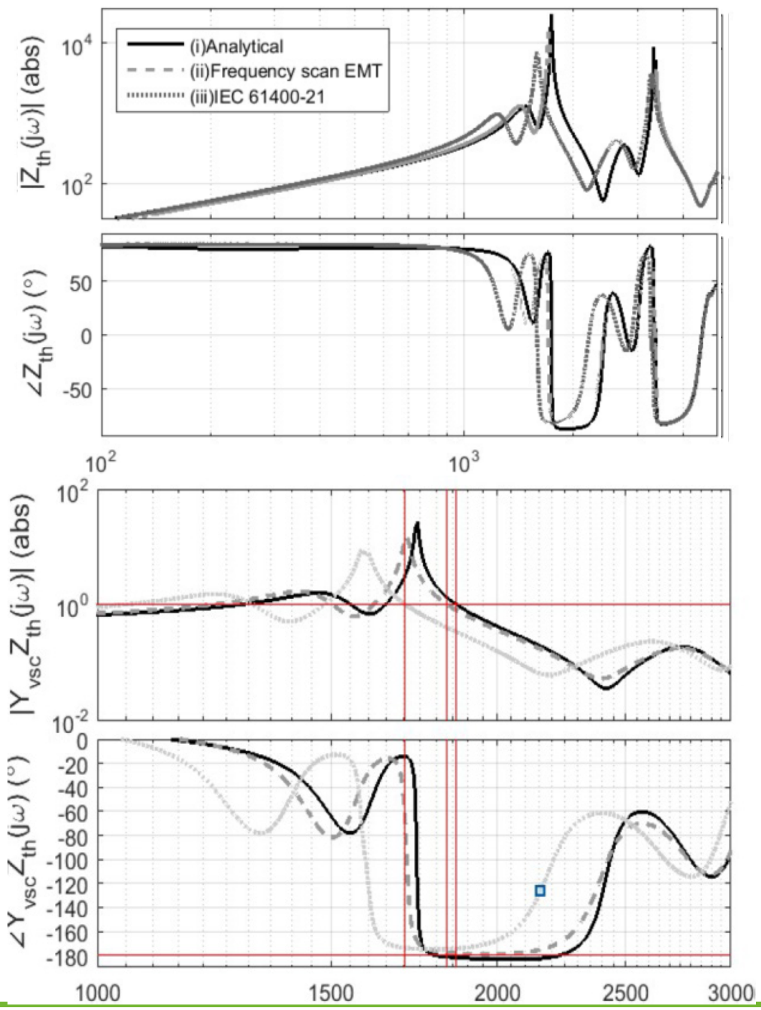




Instability~1875Hz

[A. Bayo-Salas, J. Beerten and D. Van Hertem, "Analytical methodology to develop frequency-dependent equivalents in networks with multiple converters," *2017 IEEE Manchester PowerTech*, Manchester, 2017, 6 pages.]

Reproducing the instability with dynamic models



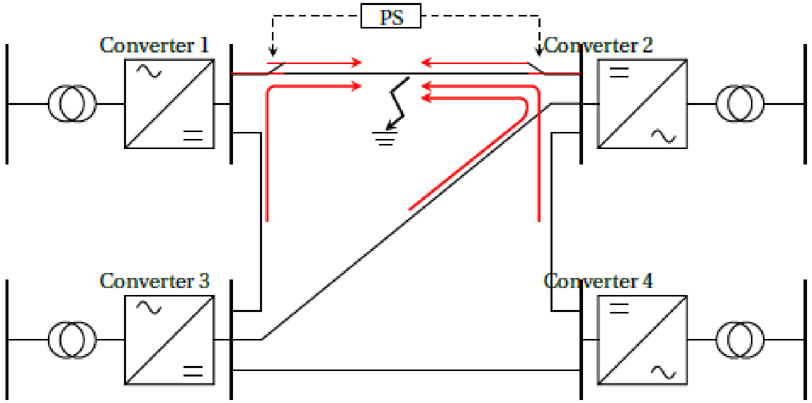
1. According to standards
2. EMT software: reproducing accurately EM dynamics
3. Proposed methodology including control dynamics

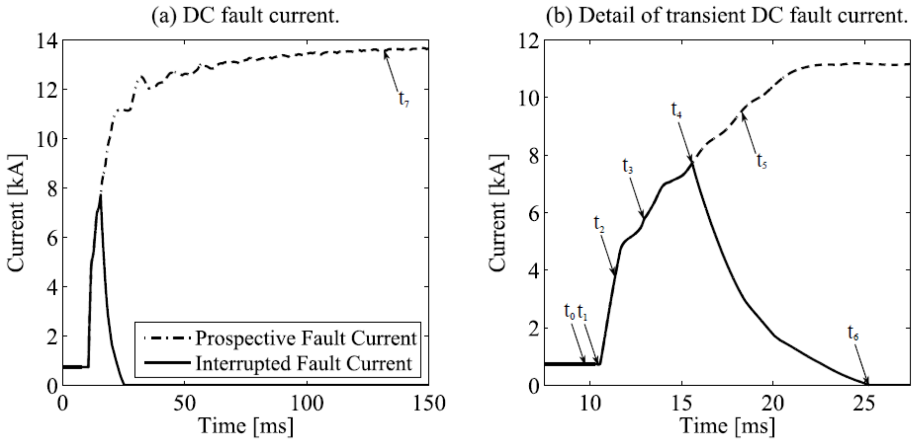
Control dynamics influence on network resonances: necessary for harmonic studies

1. System stable, resonance at 1705Hz
2. System stable, resonance at 1834Hz
3. System unstable, resonance at 1864Hz

System stability is here a trade-off of representing with the same accuracy electromagnetic and control dynamics

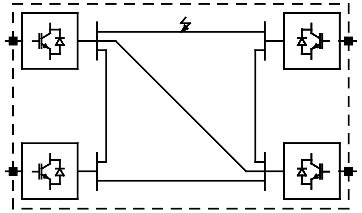
Protection of DC grids
Fault currents within a DC grid



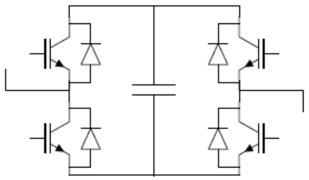


- Fault current:
  - No zero crossings
  - High rate-of-rise
  - High steady-state value
- DC phenomena much faster than AC phenomena
- VSC behaves totally different from LCC

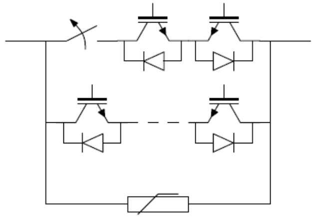
Different technologies exist to interrupt a DC fault current



- Converter ac breakers
  - As used in existing projects
  - Slow (40-60 ms opening time)
  - Not selective



- Fault-current blocking converters
  - Higher losses compared with half-bridge
  - Fast (response within few ms)
  - Not selective

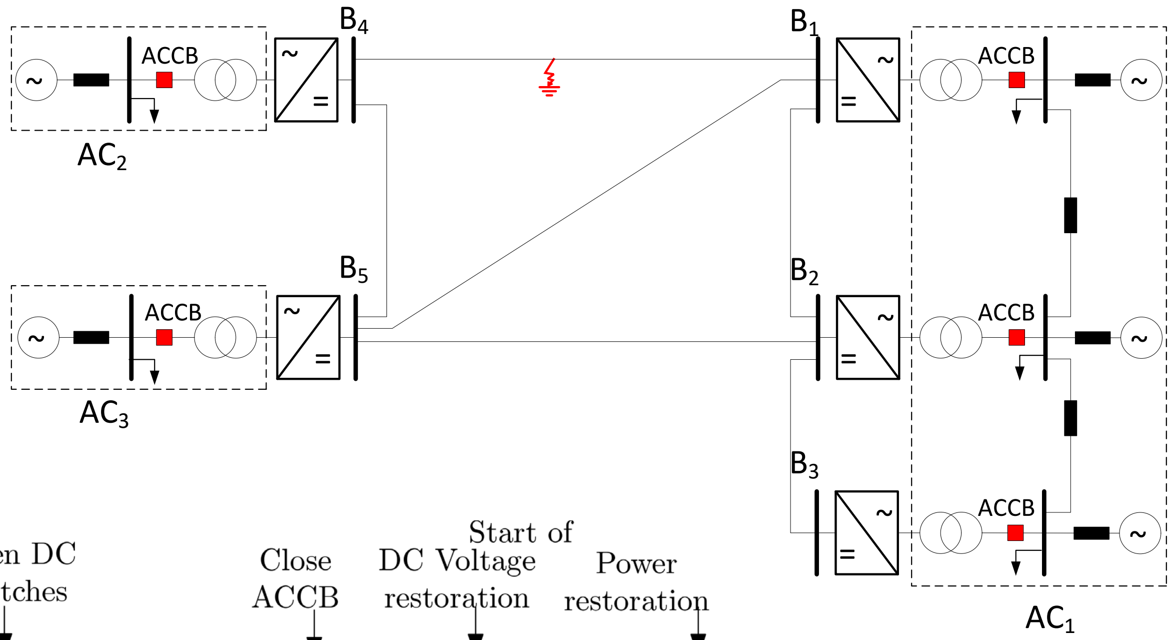


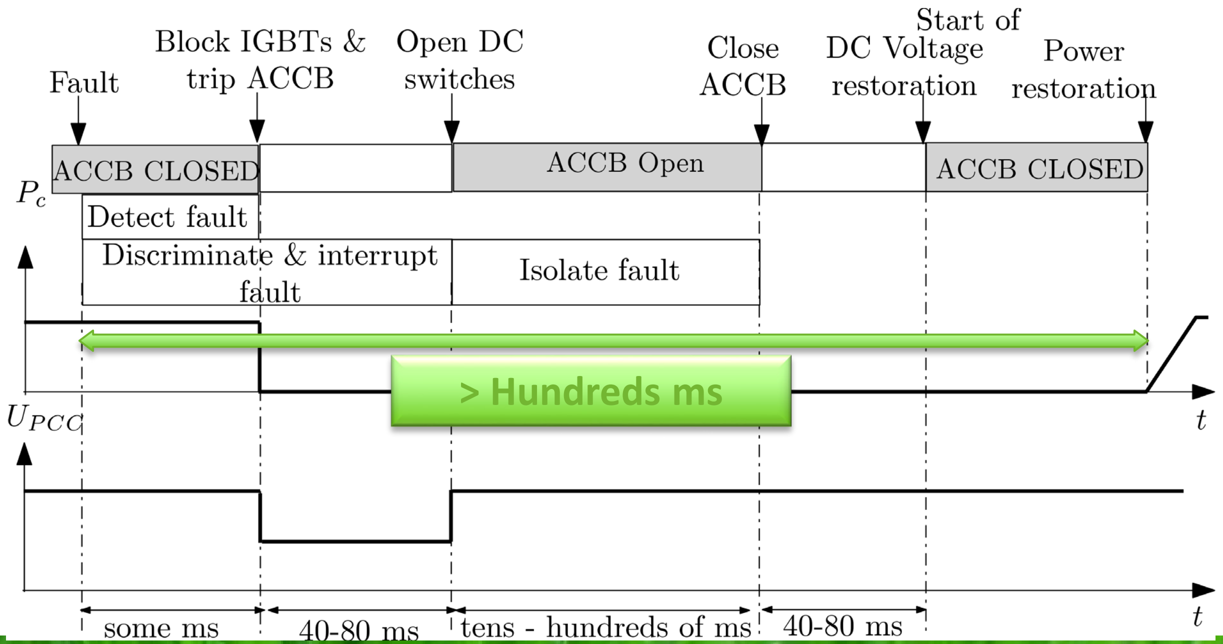
- DC Circuit Breakers
  - Operation times of 2-10 ms
  - Trade-off in losses vs. speed
  - Allows selective fault clearing

PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

DC contingencies – DC fault using non-selective fault clearing (AC circuit breakers)

- Impact on DC grid
  - Loss of whole DC grid
- Impact on AC grids
  - Loss of generation/load

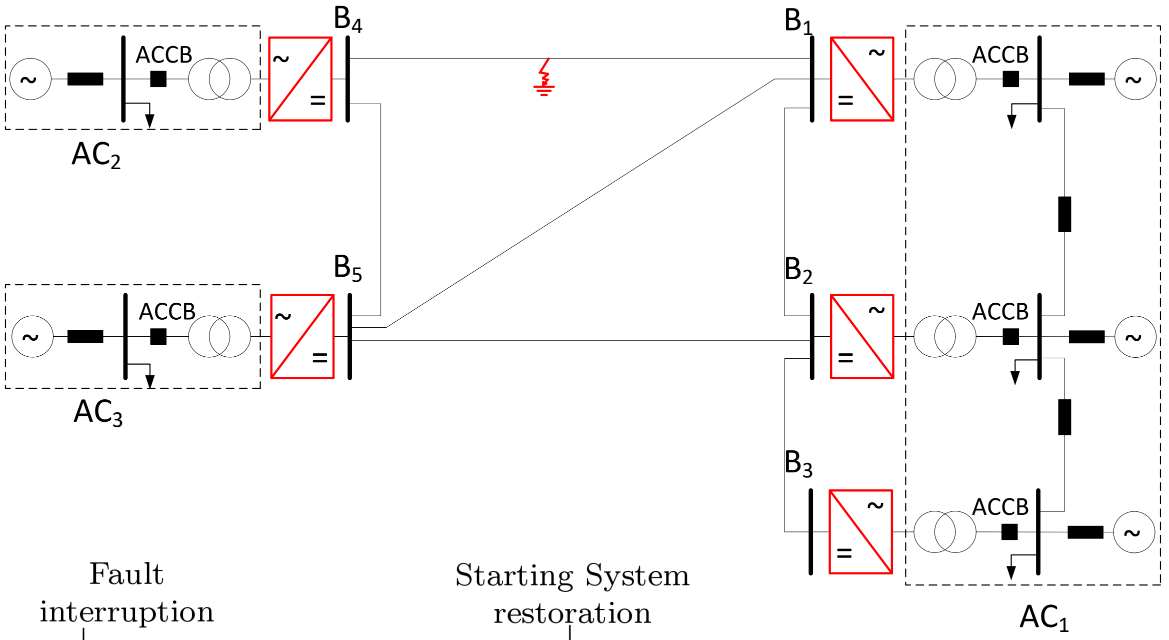


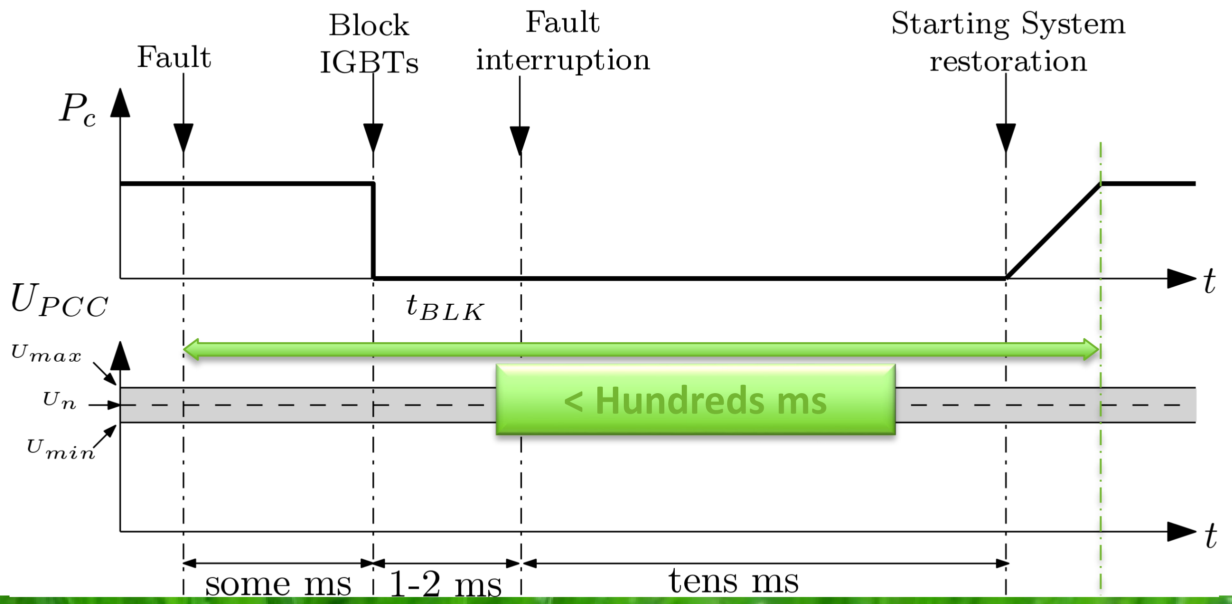


PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

DC contingencies – DC fault using non-selective fault clearing (converter with fault blocking capability)

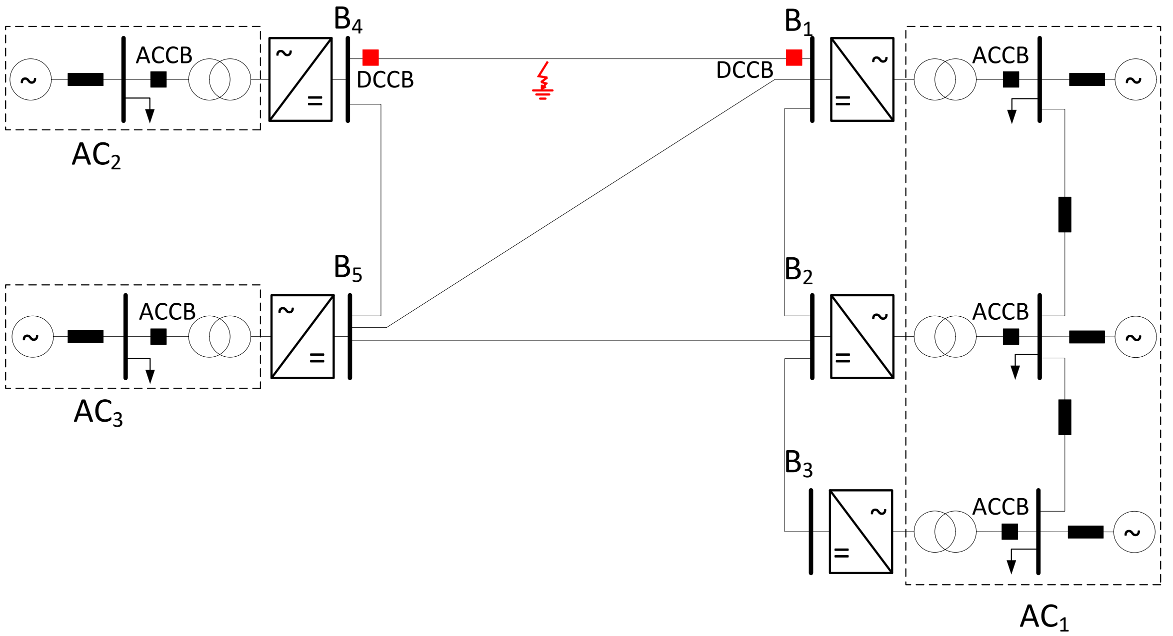
- Impact on DC grid
  - Temporary loss of whole DC grid
- Impact on AC grids
  - Loss of generation/load

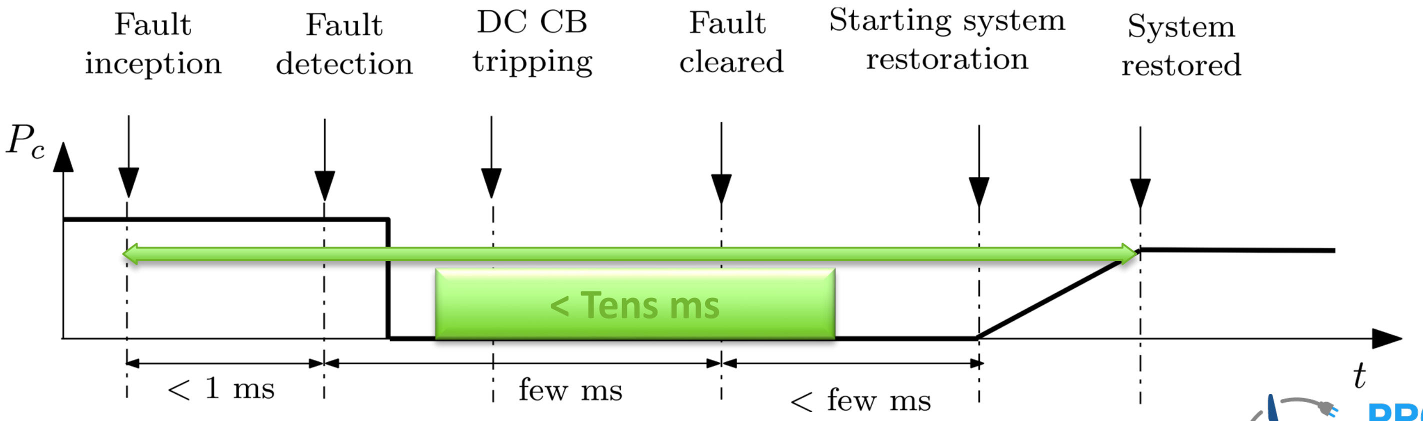




DC contingencies – DC fault using fully selective fault clearing

- Impact on DC grid
  - Temporary power & voltage transient
- Impact on AC grids
  - Very short transient

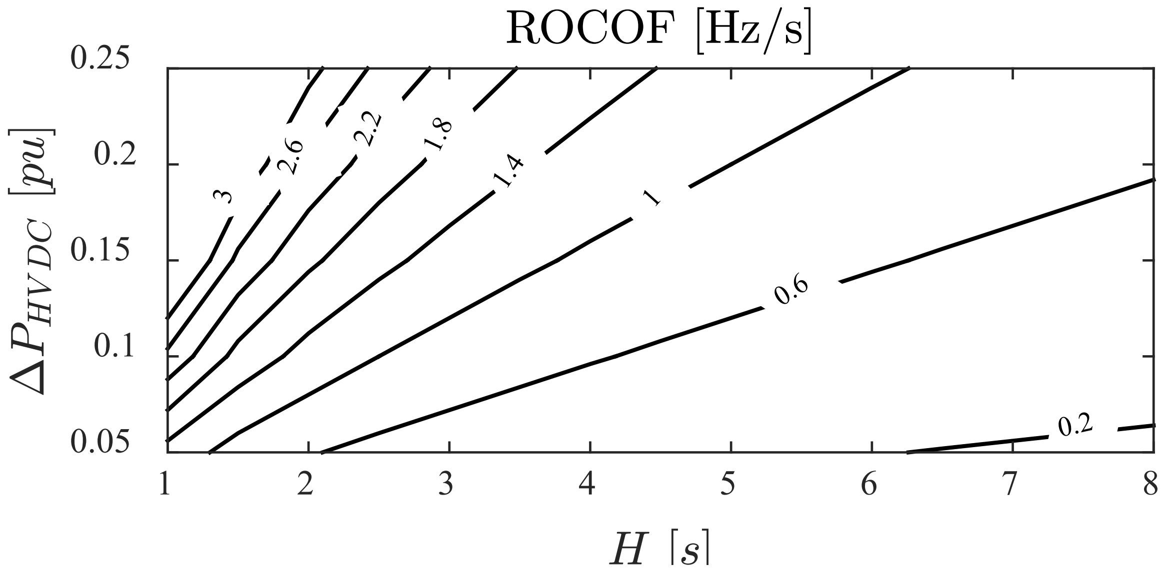




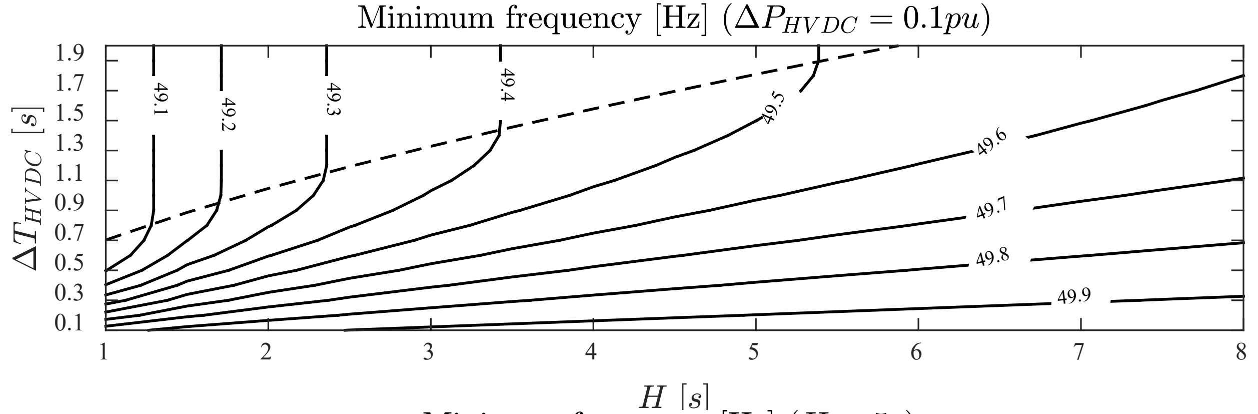
PROMOTioN
PROGRESS ON MESHED HVDC OFFSHORE TRANSMISSION NETWORKS

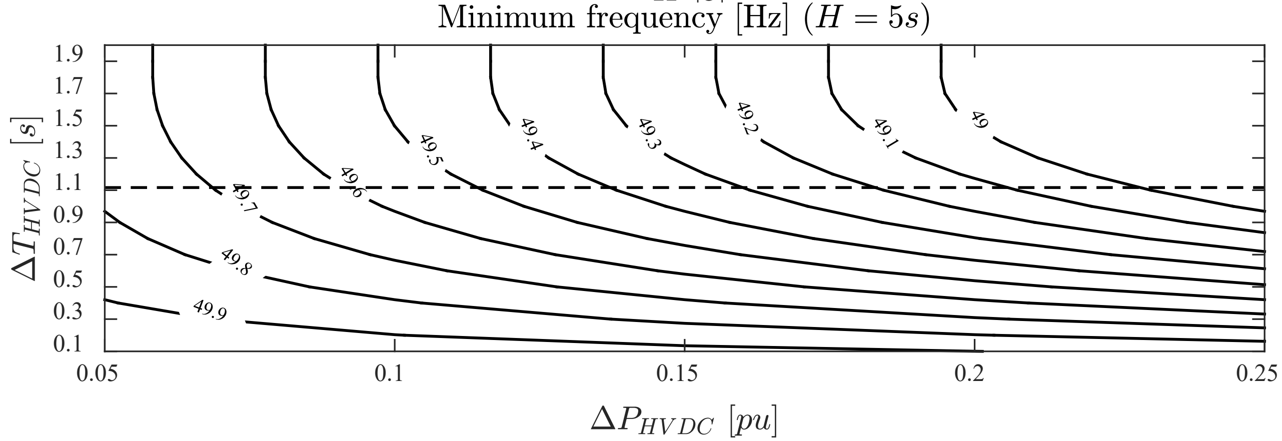
Impact on AC stability (frequency stability)

- Parameters
  - Inertia constant H: 1-8
  - $\Delta P_{HVDC} = 0.05 \;- 0.25\, pu$
  - $\Delta \mathrm{T}_{\mathrm{HVDC}} = 0.1 \;- 2s$
- ROCOF mainly depends on system Inertia & $\Delta \mathrm{P}_{\mathrm{HVDC}}$



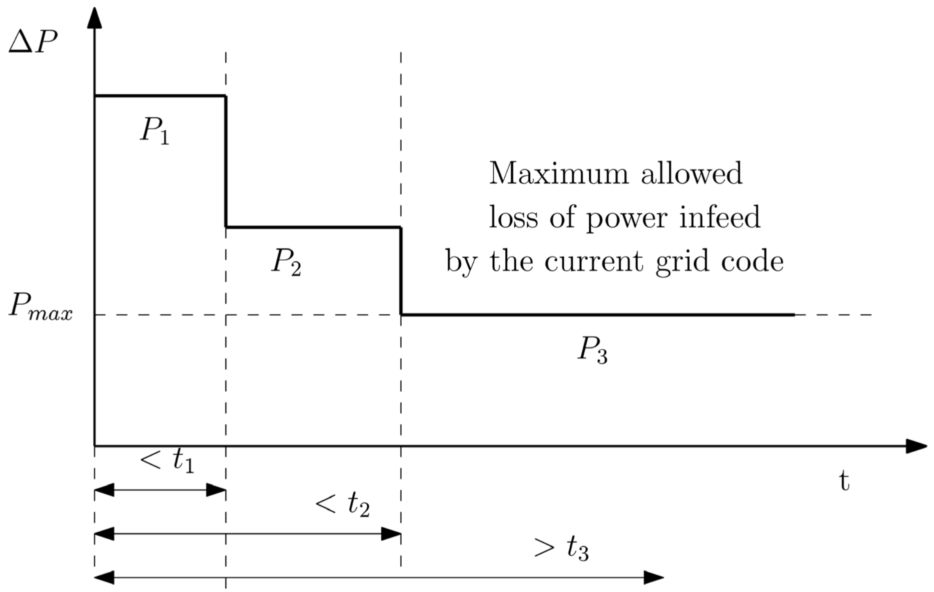
- Minimum instantaneous frequency (f_{min}) increases if power is quickly restored
  - Maximum allowed power restoration time





Possible future AC grid code

- Current AC grid code only defines maximum allowed permanent loss
  - E.g. UK grid code: That level of loss of power infeed risk which is covered over long periods operationally by frequency response to avoid a deviation of system frequency outside the range 49.5Hz to 50.5Hz for more than 60 seconds. Until 31st March 2014, this is 1320MW. From April 1st 2014, this is 1800MW.
- Possible future AC grid code:
  - Transient loss P_1: restoration within t_1 (e.g. one cycle)
  - Temporary loss P_2: restoration within t_2 (e.g. hundreds ms)
  - Permanent loss P_3: equal to maximum allowed permanent loss



Abedrabbo, M; Wang, M; Tielens, P; Dejene, FZ; Leterme, W; Beerten, J; Van Hertem, D; 2017. Impact of DC grid contingencies on AC system stability. IET Conference Publications; 2017; Vol. 2017

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Need for real-time simulations

- Given the increased complexity of , we can **no longer depend on individual testing** of components
  - Testing real device behavior where models are not available
  - Model validation
  - Multiple devices connected to a single system
  - Testing more than only power systems (communication, interfacing,…)
  - Multi-vendor interoperability
  - Training operators
  - Compliance testing (e.g. FAT)
- Real-time is not necessarily better
  - Model accuracy vs speed
  - Detail of the remaining system?

Examples Hardware-In-The-Loop for HVDC applications

- HVDC replica models
  - Existing EMT models of HVDC converters are not sufficient
  - Strongly advocated by some (incl. TSO, HVDC experts & vendors) as standard
  - Entire control cubicles of the HVDC link (possibly with backup etc.)
  - Evaluating interaction with AC system
  - Important consequence!
- IEDs
  - AC and DC relays near HVDC stations
  - IEC 61850 application of HVDC (future)
- Other secondary equipment?
  - Measurement equipment
  - Independent DC grid master controller
  - New components
  - …

HVDC IED developed and tested

- Zedboard
  - Sufficient computing power to have several algorithms in parallel
  - Multiple I/O capabilities
- Device has been developed
- Configurable
- Central or decentral configuration
- Communication protocol
  - Ethercad or HSR
- Developing test circuits and tests:
  - Using similar types of tests as for AC relays
  - Fault detection
  - Selectivity
  - Noise sensitivity
  - …
- Promotion KTH IED
- Mitsubishi IED
- Next step: MTTE testing

More at 1h45!

Conclusions

- HVDC is not a new technology
- But new developments result in strong growth
  - New converter types
  - New transmission needs (growth and RES)
  - More dynamic/flexible use of the grid
- HVDC grids are feasible future option!
- However, new models are necessary, for all time domains
- Several specific HVDC related application exist for real-time testing

Thank you for your attention!

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