

Academic perspective

Introduced and chaired by
Keith Bell

ScottishPower Professor of Smart Grids at the University of Strathclyde
and a co-Director of the UK Energy Research Centre

Featuring contributions by

Prof Dragan Jovcic

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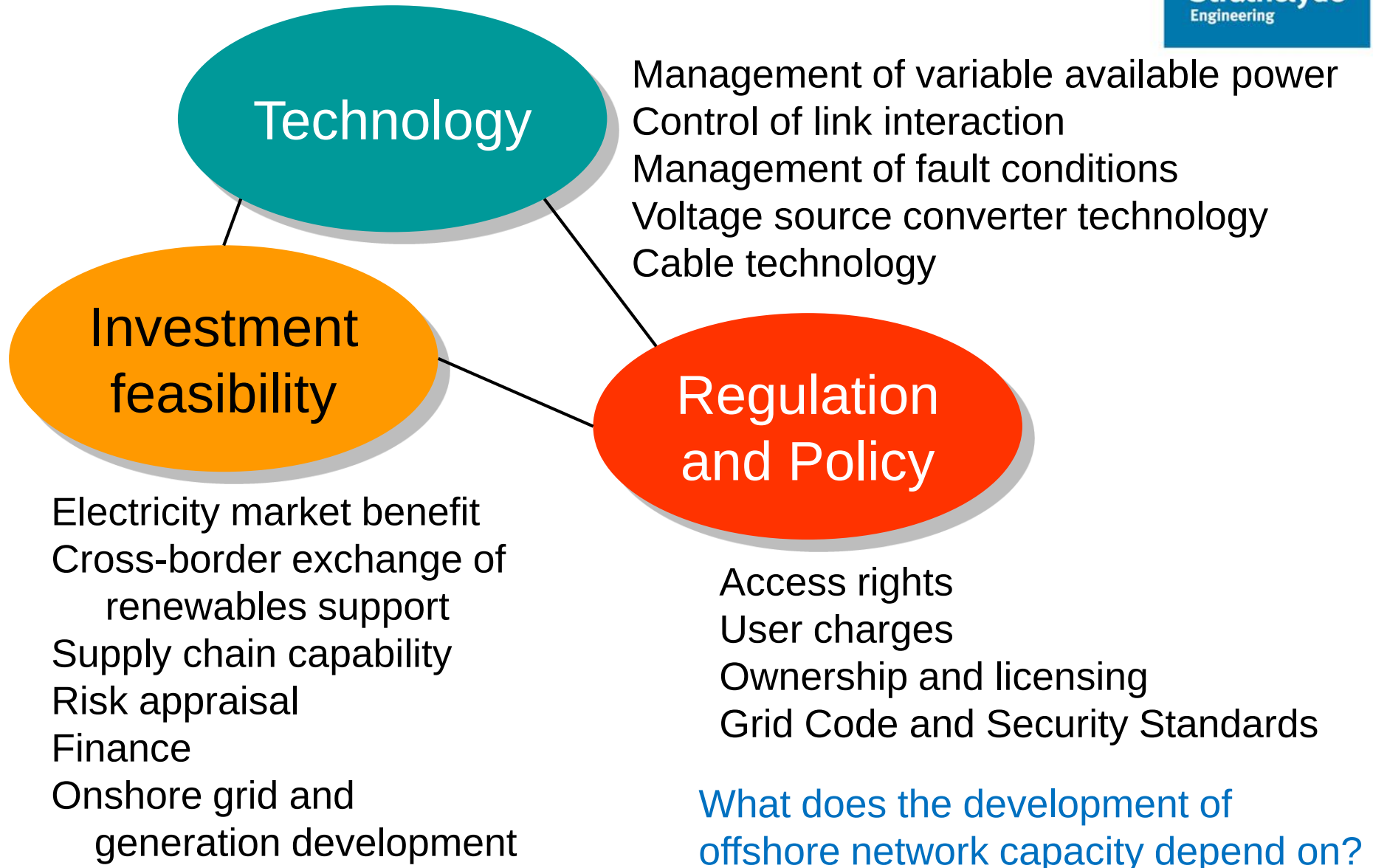
Prof Lie Xu

University of
Strathclyde

Dr Callum MacIver

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Offshore grid dependencies



Current EPSRC-related grants

Title	PI	End	Value	Subject
EPSRC Centre for Doctoral Training in Future Power Networks and Smart Grids	S McArthur	30/09/2022	4404164	[Not solely HVDC]
EPSRC Centre for Doctoral Training in Power Networks at The University of Manchester	P Crossley	30/09/2022	3947522	[Not solely HVDC]
EPSRC Centre for Doctoral Training in Wind and Marine Energy Systems	W Leithead	30/09/2022	3893966	[Only a small part on networks and HVDC]
Underpinning Power Electronics 2012: Hub	M Johnson	18/08/2019	4108787	Research, community and pathways to impact [of power electronics]. Themes: Devices, Components, Converters and Drives
Supergen Wind Hub	W Leithead	18/06/2019	2967189	[Only a small part on networks and HVDC]
High Current Module and Technologies Optimised for HVDC	P Palmer	15/12/2018	1016809	Role that advanced power semiconductor module design can play in improving the efficiency and increasing the capacity of Voltage Source, HVDC converters
Towards Enhanced HVDC Cable Systems	G Chen	14/10/2018	1113804	Performance of the insulation and the development of novel operating methodologies for HVDC cables
Mitigating the effect of low inertia and low short-circuit level in HVDC-rich AC grids	J Liang	14/12/2017	295632	Investigations will be undertaken of the inertia support from HVDC converters
Underpinning Power Electronics 2012: Converters Theme	A Forsyth	31/10/2017	2018422	Increasing the efficiency and extending the voltage / power / overload capability of high voltage converters. [Also compact converters for vehicles, aircraft, ships]
MTVN: Multi-Terminal VSC-HVDC Networks - Grid Control	M Barnes	29/10/2017	534863	Best way to control and manage [DC grids]
FCL/B: An Integrated VSC-HVDC Fault Current Limiter/Breaker	M Barnes	30/07/2017	640219	Faster, smaller, cheaper solution [than ABB's hybrid] to enable offshore location of circuit breakers
Underpinning Power Electronics 2012: Components Theme	P Mellor	30/06/2017	1976371	Power module & assembly, passive components, device drivers & sensing, design tools/methods, structural & functional integration; operational management & control
System Architecture Challenges: Supergen+ for HubNet	T Green	31/12/2016	763980	[Not solely HVDC]
DC Networks with DC/DC Converters for Integration of Large Renewable Sources	D Jovicic	16/12/2016	734786	Integration of large renewable power parks with DC networks which include DC/DC converters

Estimated total effective value: ~£7.25 million

European grants involving UK academics

- PROMOTioN
- TWENTIES Work Package 5, 2009 - 2013
- BestPaths, October 2014 – September 2018



DEMO 1 HVDC Links in offshore wind farms and offshore Interconnections

The aim of this demonstration is to reduce the risks of HVDC links connecting offshore wind farms and to foster new suppliers and sub-suppliers of HVDC technology.



DEMO 2 HVDC-VSC Multivendor Interoperability

The goal of the demonstration is to outline the conditions to ensure maximum interoperability for HVDC-VSC converters connected to a DC system.



DEMO 3 Upgrading multi-terminal HVDC Links using Innovative components

The demonstration aims to design, develop and test new technological solutions allowing to upgrade multi-terminal HVDC links.



DEMO 4 Innovative Repowering of AC Corridors

Demo 4 objectives are addressed in three parallel sub-projects.



DEMO 5 Superconductor cables power up for DC grids

Prototype scale validation of the technical feasibility of integrating DC superconducting cable links within an AC meshed network.



See <http://www.bestpaths-project.eu/>

TWENTIES project

Technology

Management of variable available power
Control of link interaction
Management of fault conditions
Voltage source converter technology
Cable technology

Investment feasibility

Electricity market benefit
Cross-border exchange of power

WP5



WP11



Demo 3

What does the development of offshore **grids** depend on?

Top & Tail Transformation

Multiple UK universities funded by EPSRC, October 2011 – September 2015

‘Top’ of the network

- Architectures and technical implications of an intercontinental electrical transmission system
- Integration of super-scale multi-terminal HVDC systems UK/European power system



Enabling technologies

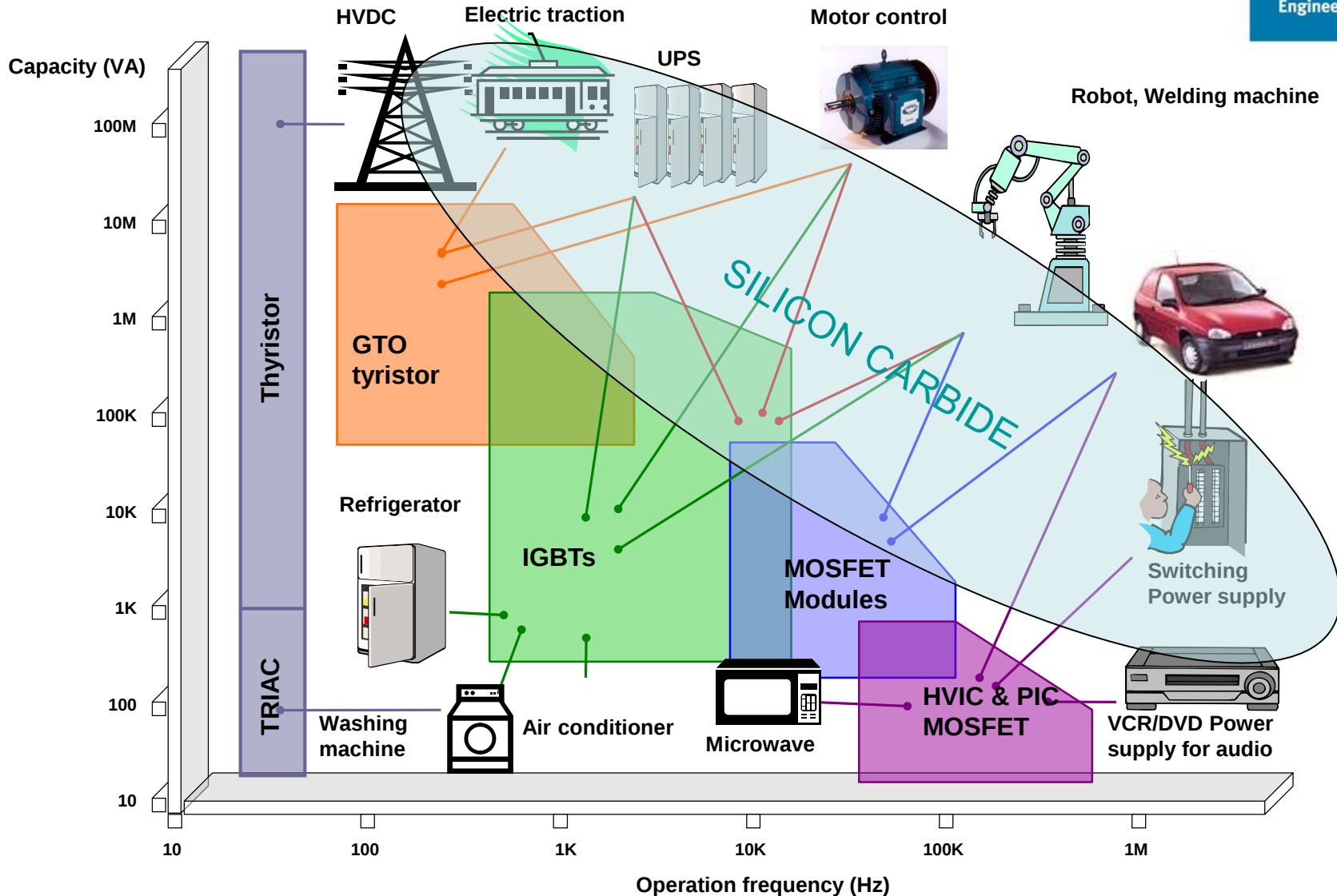
materials science, power electronics and new analysis tools



‘Tail’ of the network

- Impact of customer service needs on energy network design.
- New approaches to voltage regulation & to power quality provision
- Social acceptance of changes in service and energy provision and influence on adoption of new technology
- Use of legacy infrastructure

Future technology: high power, high frequency devices



Future technology: higher voltage cables

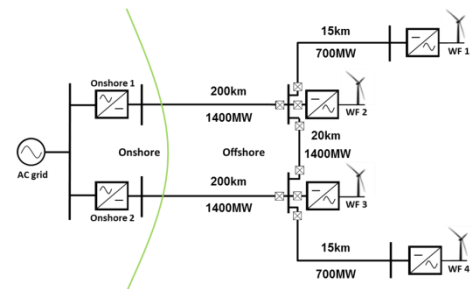
- Existing or planned HVDC links
 - Interconnexion France-Angleterre (IFA), commissioned 1986
 - 2 bipoles (8 cables), $\pm 270\text{kV}$, 926 A
 - MIP, $\sim 3\text{cm}$
 - Total power: 2GW
 - Western HVDC Link (the ‘bootstrap’), due to be commissioned 2016
 - 1 bipole (2 cables), $\pm 600\text{kV}$, 1875 A
 - Mass impregnated paper polypropylene laminate
 - Total power: 2.2 GW continuous
- The challenge: develop insulation materials for a 1GV, 5kA cable
 - Total power: 40GW
 - Conductor diameter
 - mass impregnated paper (MIP): $\sim 15\text{cm}$
 - XPLE: $\sim 10\text{cm}$
 - Need to manage mechanical characteristics to be installable

Future technology: multi-terminal HVDC

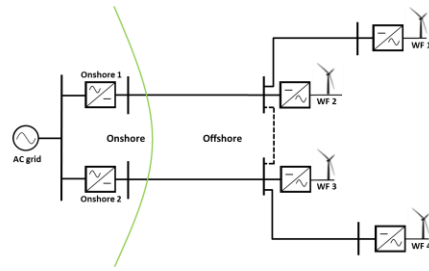
- Connecting DC branches together allows the number of (large, expensive, lossy) converters to be minimised → multi-terminal HVDC
 - New DC branches can be teed into existing point-to-point branches
- Provided there is headroom on a route at a given time, DC grids and the flexibility of power electronics promise
 - a great deal of flexibility in direction of power
 - shared use of assets between connection of generation and inter-area power exchanges → better utilisation of assets, improved cost-benefit
- How is control of different terminals to be coordinated?
- Can responses to faults be adequately managed?
- Does protection and control depend on reliable, fast communications?
 - Droop controls are feasible for coordinating terminals including after loss of a branch or a converter
 - DC faults propagate through the DC cables with sub-millisecond, difficult to rely on communication for protection.

Scope and design of offshore networks

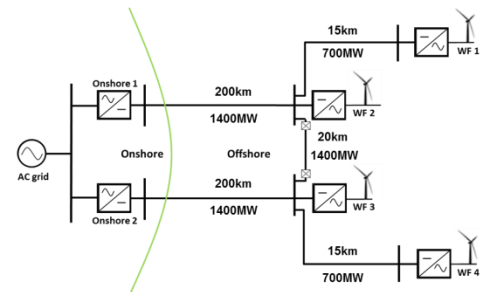
- Costs and benefits of DC breakers?
- Value of multiple paths?
- Loss of infeed risk?
- *See MacIver & Bell, IEEE Trans on Power Delivery, April 2016*



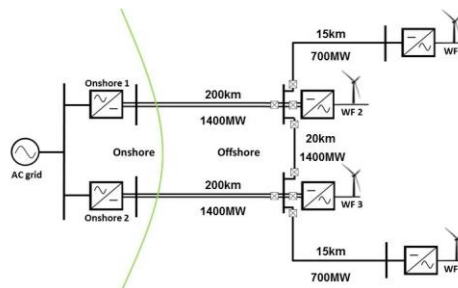
Multi-terminal



AC protected

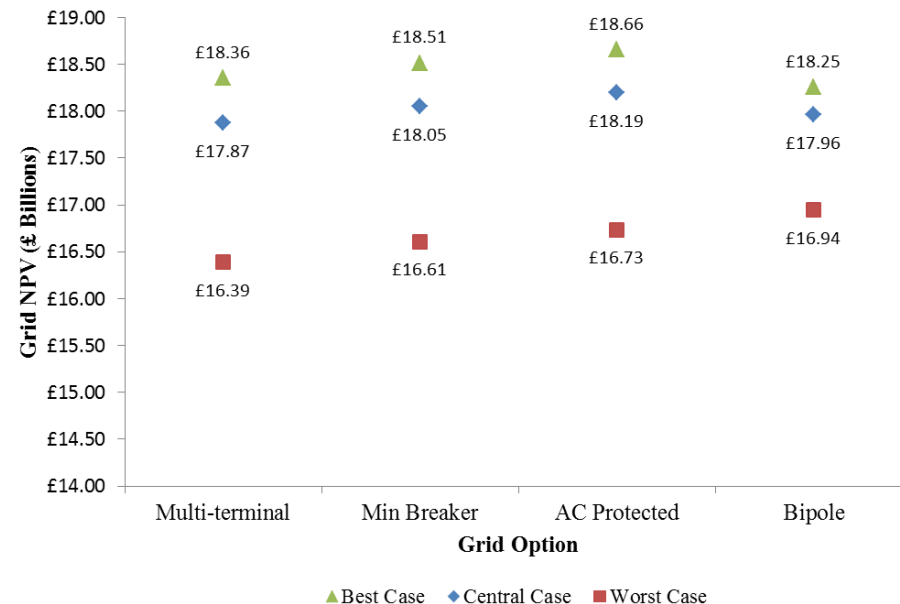


Minimum DC breaker



Bipole

25 year NPV of grid options

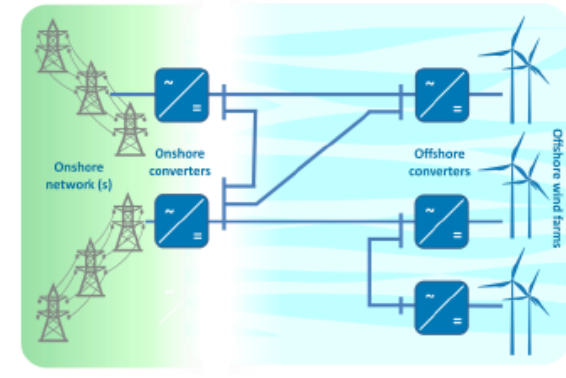
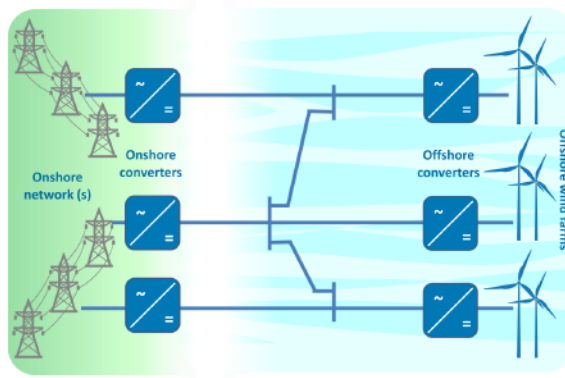
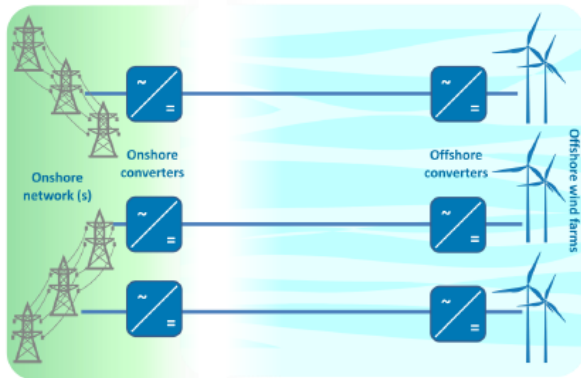


Questions: operation of supergrids

- How to determine the ideal set-points of different terminals of a DC grid?
- How to ensure that ubiquitous, fast acting converters
 - can ride-through short-circuit faults on either the AC or DC system?
 - do not interact adversely?
- How to exploit a very high capacity network branch such that its loss does not cause problems?
 - Loss of infeed on an interconnector or generation connection
 - Displacement of power onto other branches

Questions: interconnecting DC grids

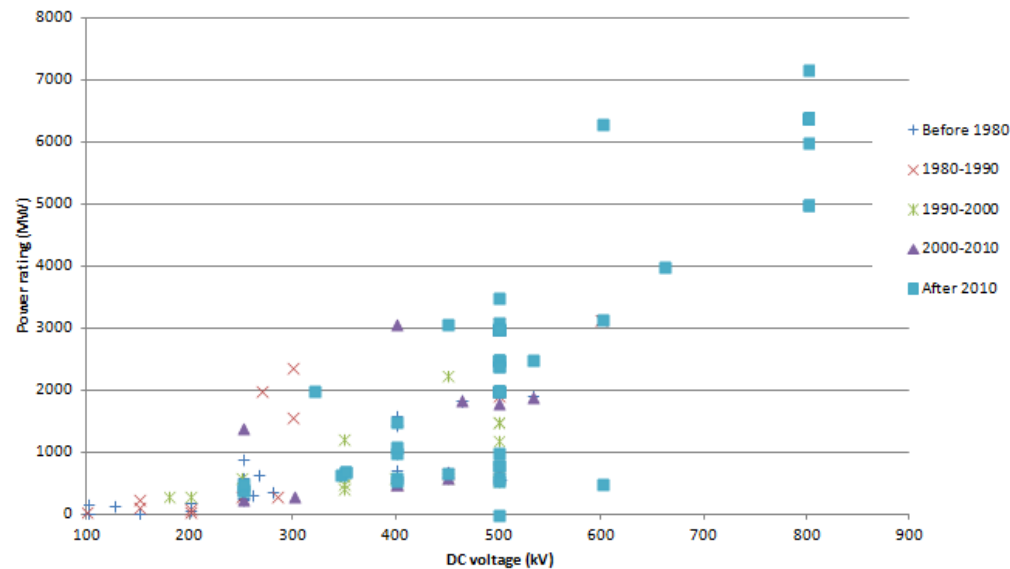
- Extensibility of pre-existing DC connections
 - Need for standard DC grid voltages?
 - Design and operation of DC/DC converters?
- Design and operation of low cost/high efficiency DC power flow controller in meshed grids?
- How to ensure the inter-operability of converters from different vendors with different converter configurations during both steady-state and fault conditions?



CIGRE Joint WG C1.B4.65

Recommended voltages for HVDC grids

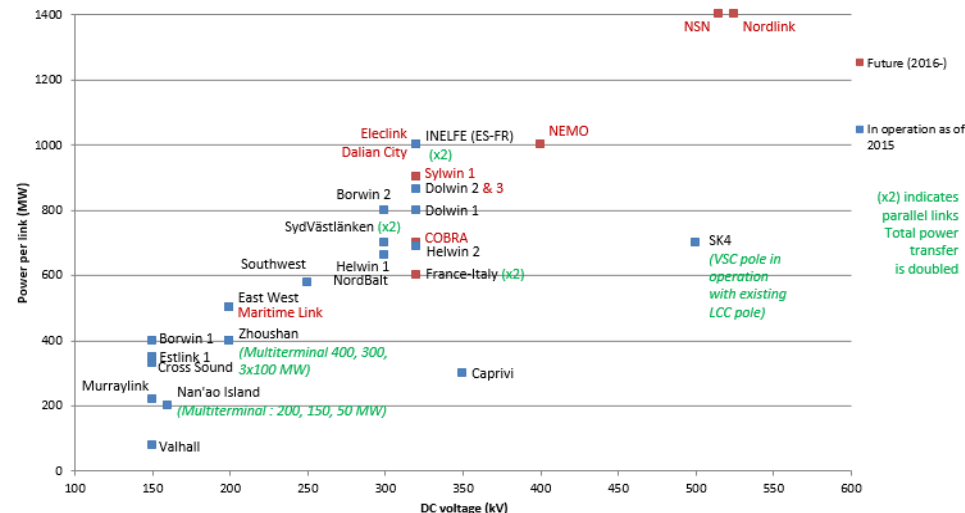
DC voltages vs Power rating, LCC systems (excluding back-to-back)



- Report of CIGRE Joint WG C1.B4.65 forthcoming
 - A proposed list of recommended values
 - Proposed definitions for steady state DC voltages
 - Drivers and guidance for system planners for choosing recommended voltages (or when not to) → flowchart

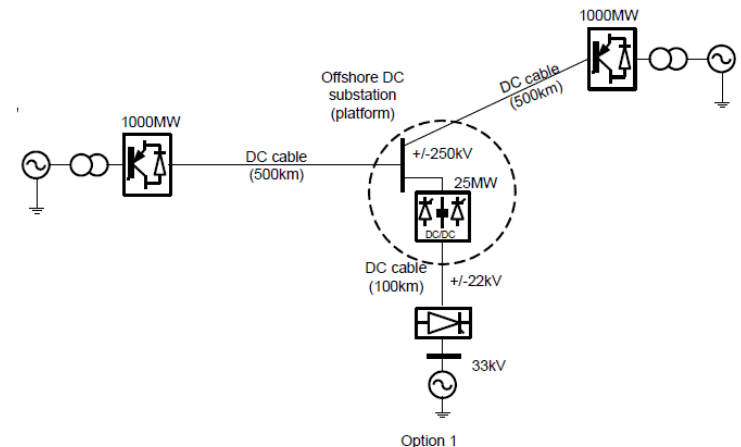
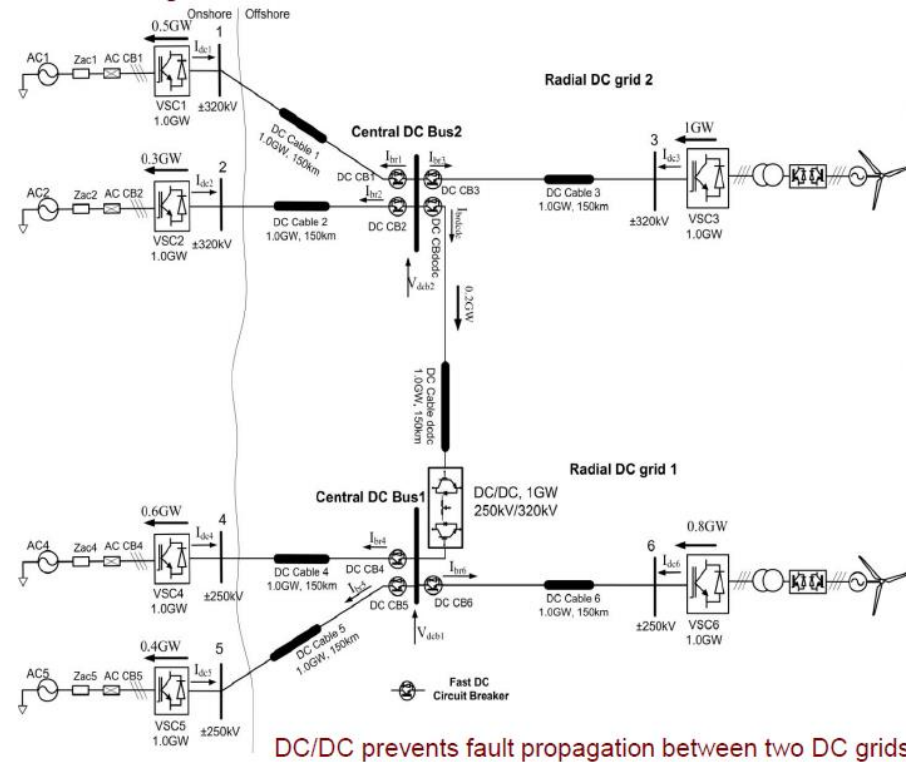
- HVDC project voltages to date generally bespoke
 - Utilise available technology at minimum cost
 - Optimise for power and continuous and maximum converter, OHL and cable voltages, AC voltage, harmonics

DC voltages vs Power rating, VSC systems (excluding back-to-back)



DC/DC converters

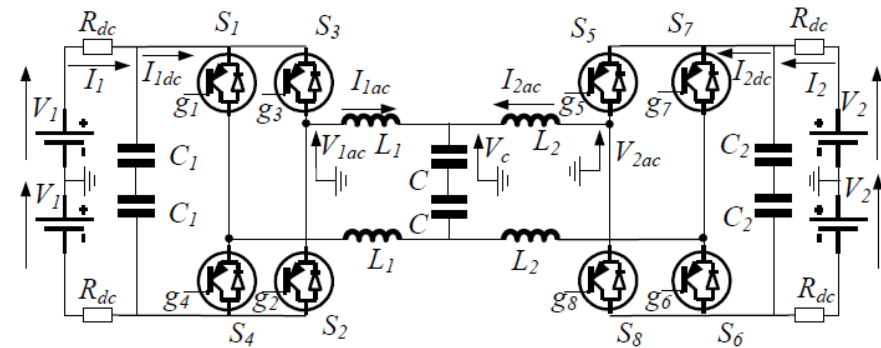
- Allow interconnection of existing HVDC grids operating at different voltages
- Allow low power connections to be teed off a high power link



Figures courtesy of Prof Dragan Jovcic, University of Aberdeen
 For further information, see, for example Jovcic, D., and J. Zhang.
 "High power IGBT-based DC/DC converter with DC fault tolerance"
Power Electronics and Motion Control Conference (EPE/PEMC), 2012
15th International. IEEE, 2012.

DC/DC converter

- DC/DC converter provides
 - DC voltage stepping
 - DC fault isolation
 - DC power flow control
- Aberdeen MMC-based design:
 - No transformers, implies low weight and core losses
 - Capacitors and air core reactors allow high frequency operation
 - Total loss for DC/DC is 1.24%-2.1% (200-500Hz)
 - Offshore, use higher frequency (500Hz) to reduce weight and size
 - Onshore, reduce frequency (300Hz) to reduce losses



UK academic research themes



- High voltage, high current power electronic devices
 - Includes MMC converter switched at low frequency
- High voltage DC cables
- Converter topology and control
 - Physical size, losses, behaviour under fault conditions, controllability
- Fault management
 - Detection and location of faults
 - Fault clearance / DC breakers / system recovery
- Operation and control of multi-terminal HVDC grids
 - Includes inter-operability (vendors and converters)
 - Coordination of converter control and protection devices
 - Real-time simulation of large scale DC networks
- Design of HVDC grids
 - Operability and impact of faults on AC grids
 - Extensibility
- DC/DC conversion

Extra slides: PROMOTioN WP1 outputs to date

Dr Callum MacIver

System planning & grid topologies

Main Findings

- A range of studies have identified different roadmaps - often different assumptions and methodologies so hard to compare directly but:
 - multiple regional grids more likely than a single European super grid
 - Case for complex grids dependant on level of offshore wind deployment
 - Case for complex grids depends on detailed optimisation

Main Gaps

- Need to identify how where when and why complex offshore topologies might develop
- Need to understand chronological evolutions towards multi-terminal or meshed grids

Operation of Converters in DC Grids

Main Findings

- A range of studies have investigated steady state operation & control as well as dynamic stability in DC grids:
 - Solutions identified and tested to various degrees that suggest DC grids can be operated effectively
 - Various droop control schemes proposed (V-I, P-V etc.)

Main Gaps

- Need to develop more extensive modelling (steady state, RMS, EMT) and testing of control strategies based on MMC and DRU converter technology
- Need to test interoperability of different converter technology/vendors (especially MMC and DRU)

Interaction of WTGs and Converters

Main Findings

- Studies mainly been focused on VSC to date
- Methods for f/P control, V/Q control, black start and power oscillation damping proposed and tested at simulation level
- DRU newer but initial studies prove concept

Main Gaps

- Interoperability between WT, converter and cable vendors
- Lack of real large scale testing
- Lack of generally accepted offshore grid codes
- DRU concept early stage, operation within complex DC grids yet to be analysed

DC Grid Protection Systems

Main Findings

- Numerous protection schemes proposed by academia/industry
- Non-Unit (local measurements): fast
- Unit (data communication between 2 ends): greater selectivity
- Protection philosophy dependent on grid size, cost of protection, size of acceptable loss

Main Gaps

- No single solution fulfils all requirements so no final consensus
- Combination of basic principles required
- Need to identify and develop solutions to be deployment ready
- Multi-vendor compatibility required

DC Circuit Breakers

Main Findings

- 3 main design options:
 - Resonant/mechanical breakers (low loss, low cost, 5-10ms)
 - Solid state breakers (high loss, high cost, <1ms)
 - Hybrid breakers (low loss, high cost, <5ms)
- Several large scale test on hybrid and resonant designs

Main Gaps

- Development of sufficient models for detailed and system level studies
- Development of sufficient test/demonstration procedures to mimic full stresses experienced in DC grid application
- Continued development of design concepts to enhance speed, losses and cost performance

Regulatory and Financial Barriers

- Main Findings

- Multitude of studies looked at a vast number of issues
- Some issues well covered (consenting/planning) while others less so (finance mechanisms for meshed grids)
- Some alignment between reports, e.g. need for clarity on which party is liable for delays in which aspects of projects

- Main Gaps

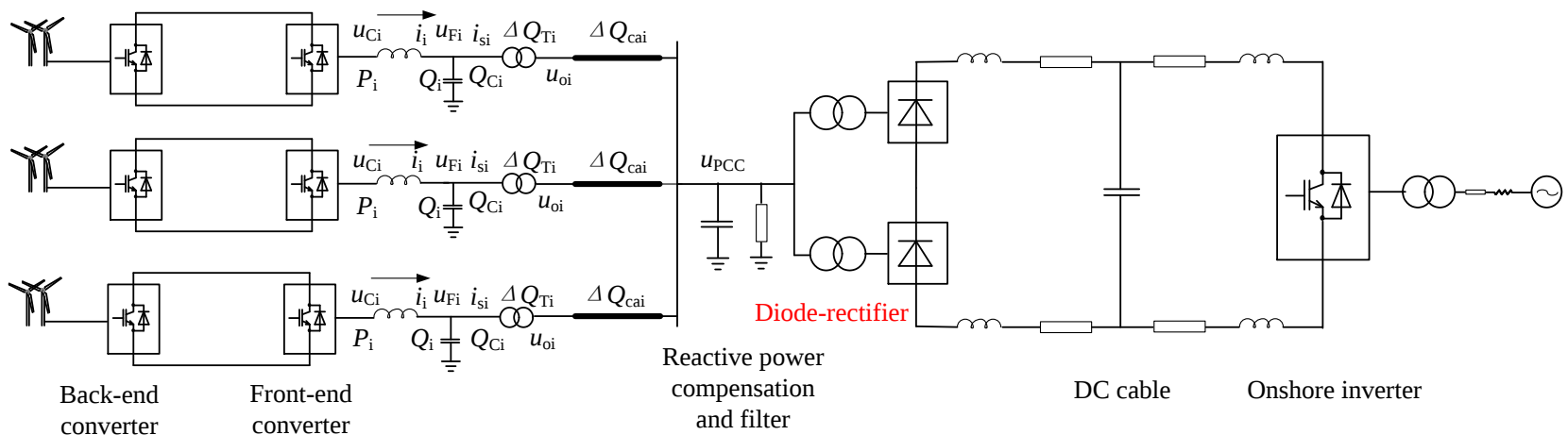
- Some conflicts between proposals
 - e.g. appoint single TSO for offshore area or revise national support schemes to make them mutually compatible
- Need to develop a definitive EU wide legal, economic and financial framework within which offshore grids can develop

Extra slides: PROMOTioN WP3 technical issues

Prof Lie Xu

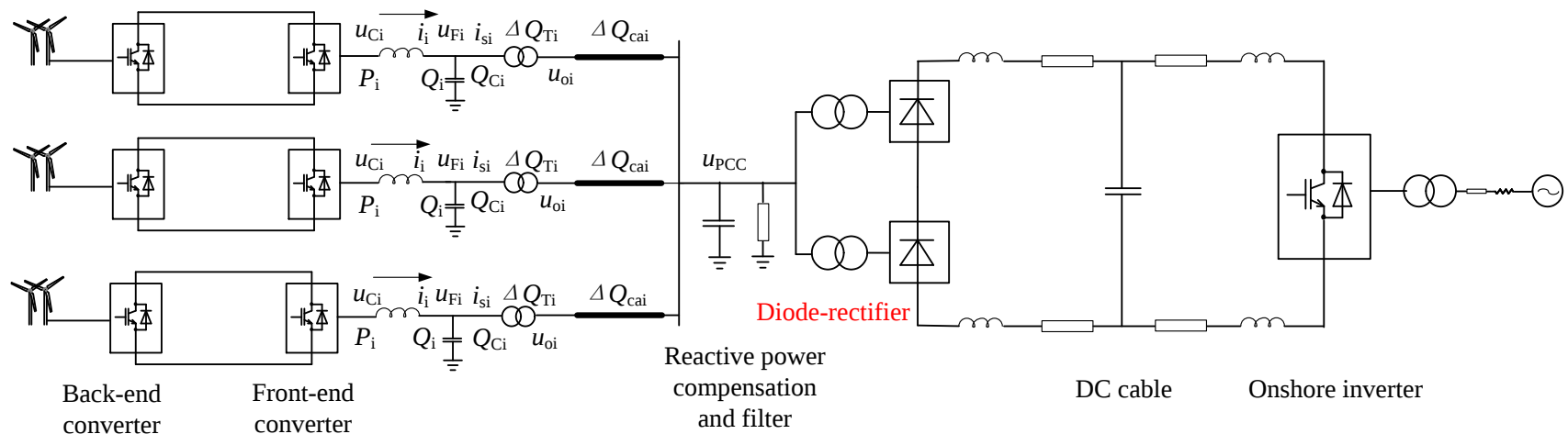
Technical challenges with Diode Rectifier Unit (DRU) connected OWF

- Offshore Wind farm (OWF) AC network has to be controlled by the wind turbines
- Active power from the DRU is controlled by rectified DC voltage which indeed is determined by the offshore AC voltage magnitude (so frequency plays no part)
- What communications are required between individual WT and station controller, cluster controller etc?



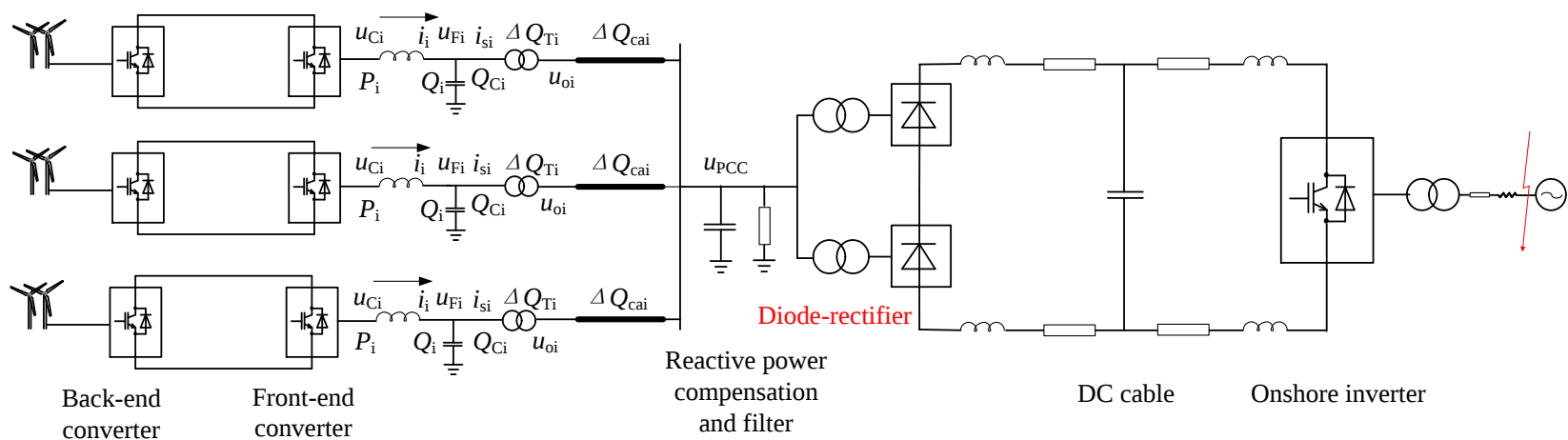
Technical challenges with Diode Rectifier Unit (DRU) connected OWF

- System protection and ride through during various fault conditions, e.g. offshore AC fault, onshore AC fault, DC fault remain challenging and yet to be examined properly.
- Interoperability of DRU and MMC based HVDC converters in a large multi-terminal network is unexamined.



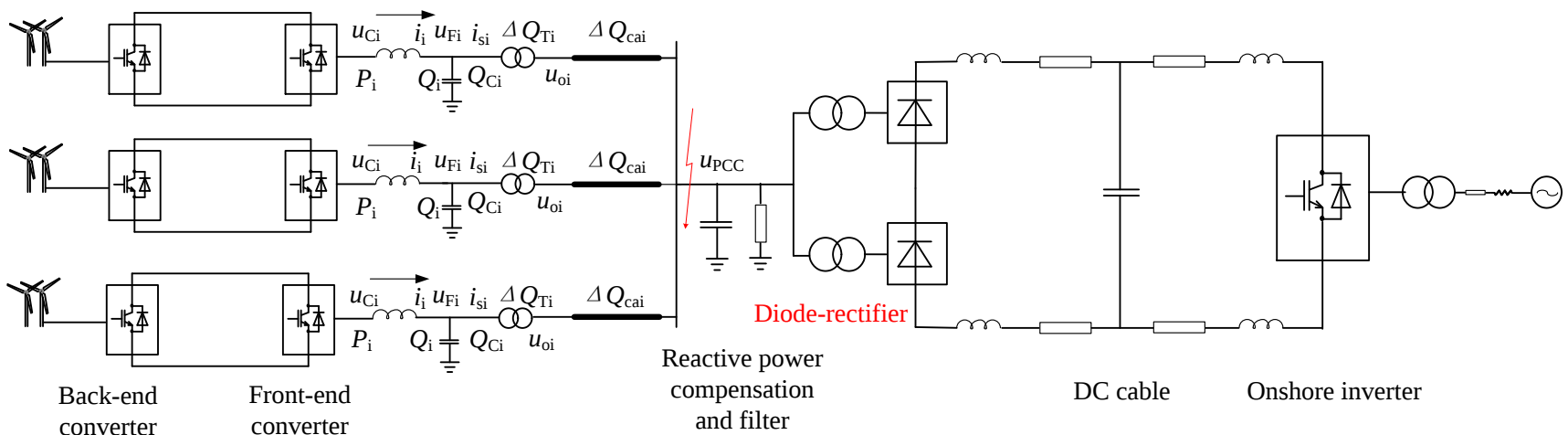
Ride through onshore AC fault for DRU connected OWF

- Active power transmission significantly reduced
- Potential DC over voltage
- DC chopper?
- Or consider that WT AC voltage limit naturally prevents the WTs from exporting power – power reduction at WT level.



Characteristics during an offshore AC fault for DRU connected OWF

- Collapse of offshore AC voltage
- WT limits fault current – what fault current profile required for protection purpose
- Can the WTs provide the required fault current in order to correctly activate the protection device
- Consider post-fault recovery – how fast the system can recover



Characteristics during an DC fault for DRU connected OWF

- Collapse of offshore AC voltage due to DRU
- WT limits fault current – fault current profile (?)
- Onshore MMC also sees DC fault – protection/control depending on MMC configuration
- Do we consider this as permanent fault – trip WF (?)

