DC Transmission Grids: Components, Modelling, Control and Protection Challenges

IEEE Distinguished Lecturer seminar
September 2025

Dragan Jovcic,
Aberdeen HVDC research Centre
University of Aberdeen,
Aberdeen, UK
d.jovcic@abdn.ac.uk

Outline

1. DC network challenges

2. DC grid components:
   1. DC Circuit Breakers,
   2. New MMC converters,
   3. DC/DC converters,
   4. DC hubs,
   5. DC grid hardware demonstration,

3. DC grid modelling,

4. DC grid control,

5. DC grid protection,

6. Conclusions,

Presentation slides will be made available to the host.

1. DC network challenges

Motivation for DC grid

•EU has ambitious plans for renewable energy in North Sea (over 400GW of wind energy is available),
•Scotland has awarded seabed rights for 27GW of offshore wind under Scotwind (£730 million),
•200 individual 2 GW HVDC links in North Sea is not cost-effective,
•Also medium voltage collection/distribution DC grids, DC microgrids, Marine systems,

Why DC?

•DC has lower losses, no reactive power, simpler power control, smaller lines/cables, lower insulation...
•Submarine cables over 50-100km, over 200MW are not feasible as AC transmission,
•"War of the currents" in early 20th century (Edison versus Westinghouse and Tesla),
•DC has challenges with voltage stepping (transformer) and current interruption (DC Circuit Breaker),

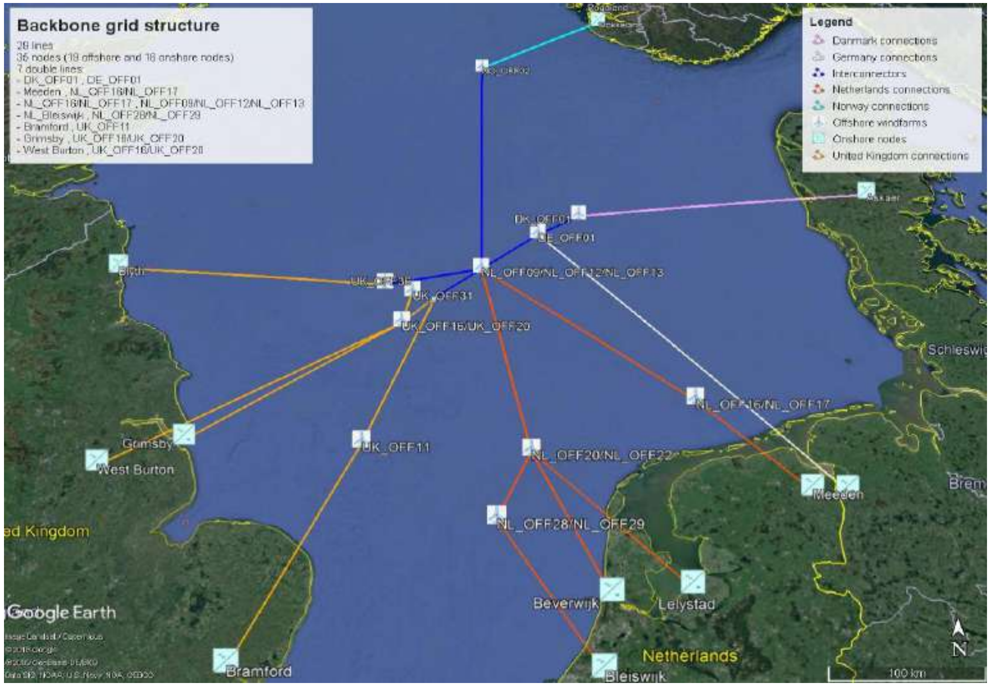


Figure 1. European North Sea DC grid (in planning)

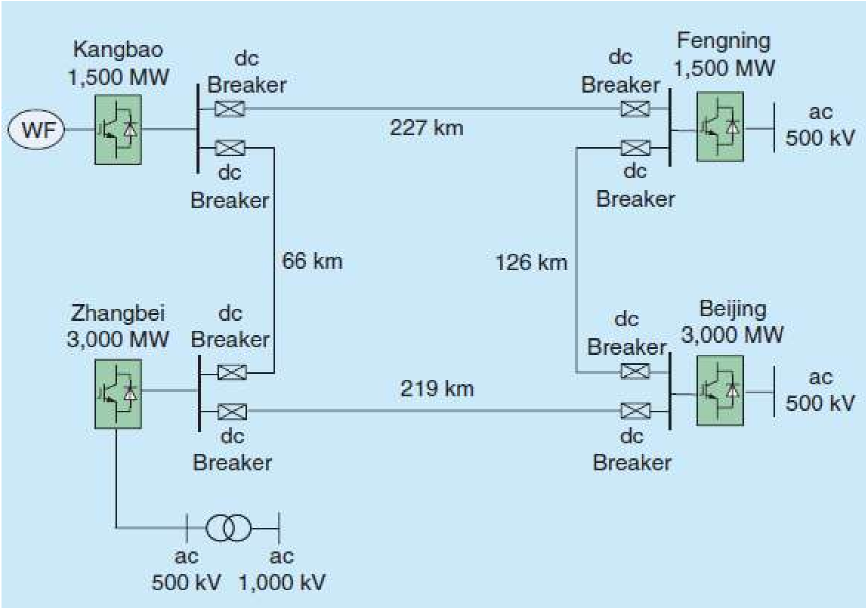


Figure 2. Zhangbei DC grid (operational since 2020)

1. DC network challenges

There are over 200 HVDC (High Voltage Direct Current) systems worldwide

- Used for submarine links, power control, connecting non-synchronised systems, long-distance, high power,
- LCC (Line commutated converters) use thyristors since 1956. Power reversal by voltage reversal,
- VSC (Voltage source converters) use IGBTs since 2000. Power reversal by current reversal,
- MMC (Modular Multilevel Converter) topology since 2010. Improved efficiency, rating and power quality,
- Hybrid converters (LCC and MMC), Few installed recently.

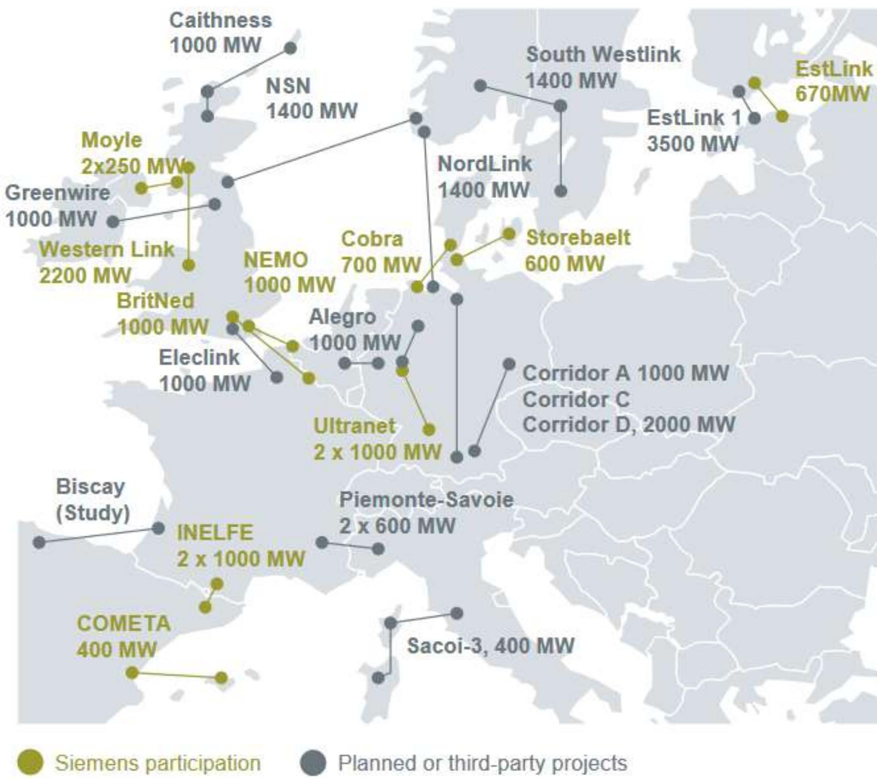


Figure 3. INELFE 2GW HVDC station and new HVDC links in Europe (source SIEMENS 2018).

1. DC network challenges

Almost all the existing HVDC links operate as two terminal systems:

- There is no major equipment on DC side (only DC cable),
- Fault isolation only on AC side, (Traditional mechanical AC Circuit Breakers),
- Only one DC voltage level is possible, (voltage stepping on AC side),
- Any fault on DC side implies that whole link is disconnected (AC CB tripping),

Several multitreminal HVDC operating,

- Zhushan 5-terminal HVDC has one hybrid DC CB installed,
- Nanao 3-terminal HVDC has one mechanical DC CB installed,
- Shetland-Caithness-Moray, multiterminal HVDC (no DC CBs)

4-terminal Zhangbei DC grid has been in operation in China since 2020,

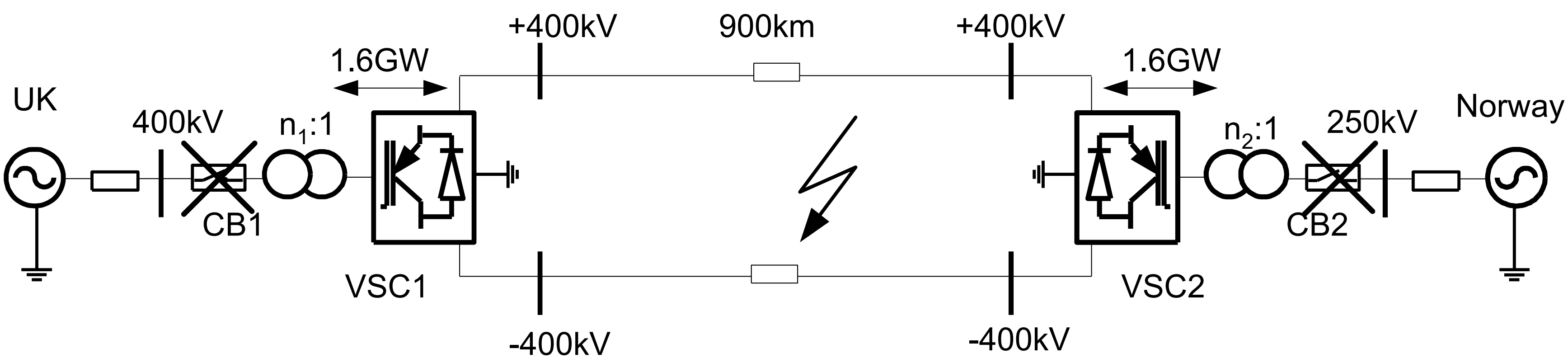


Figure 4. A VSC HVDC link.

1. DC network challenges

- Demand to connect a new load or generator to DC lines
- Multiple HVDC in close proximity,
- Meshing on dc side to increase security, flexibility and asset utilization,
- In case of a DC fault, we do not want whole system to collapse (3.7 GW loss in capacity)
- We need capability to isolate DC grid segments,

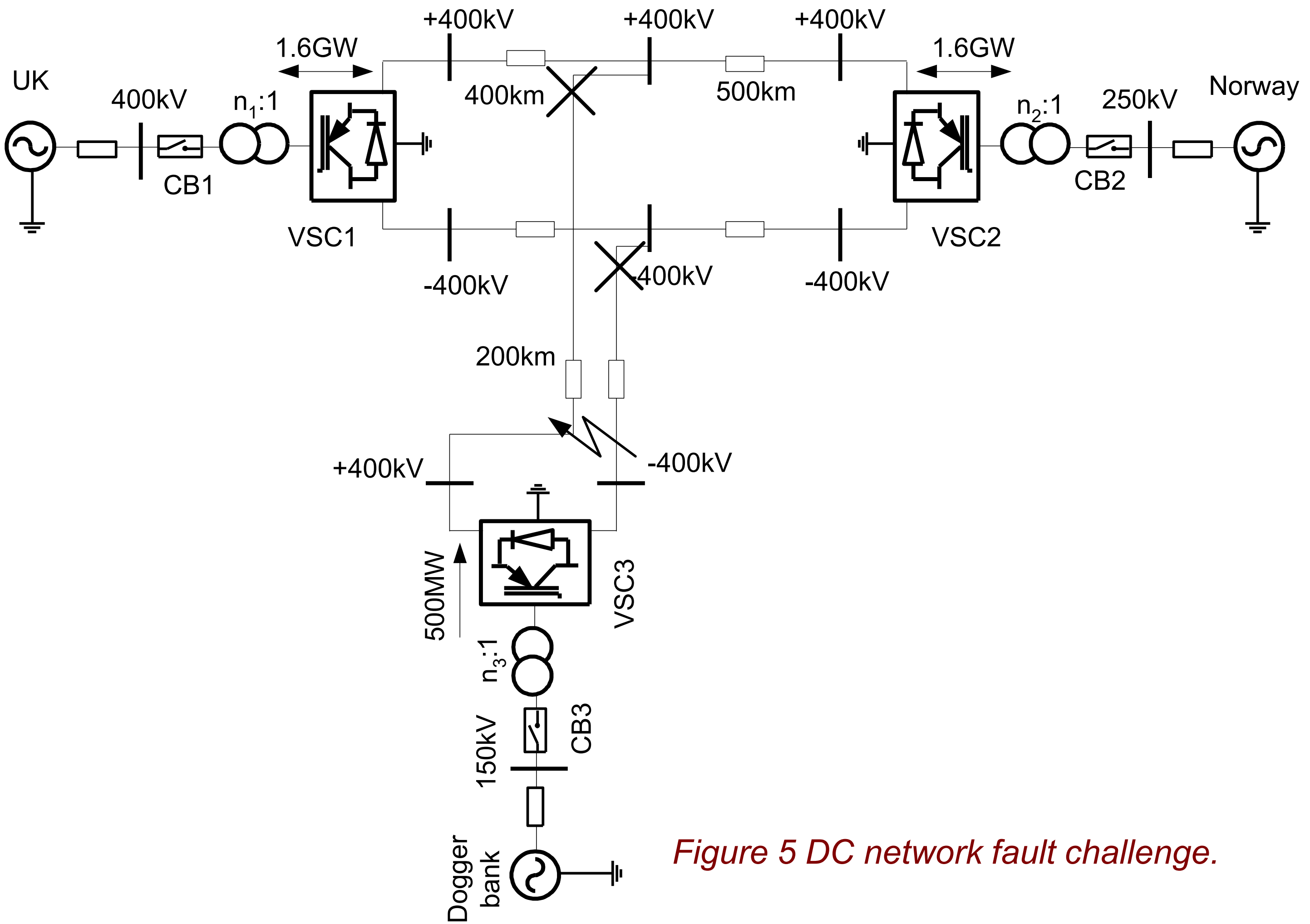


Figure 5 DC network fault challenge.

1. DC network challenges

- It is highly desirable to have capability to change DC voltage level,
- We also may want to integrate LCC DC systems (voltage polarity reversal),

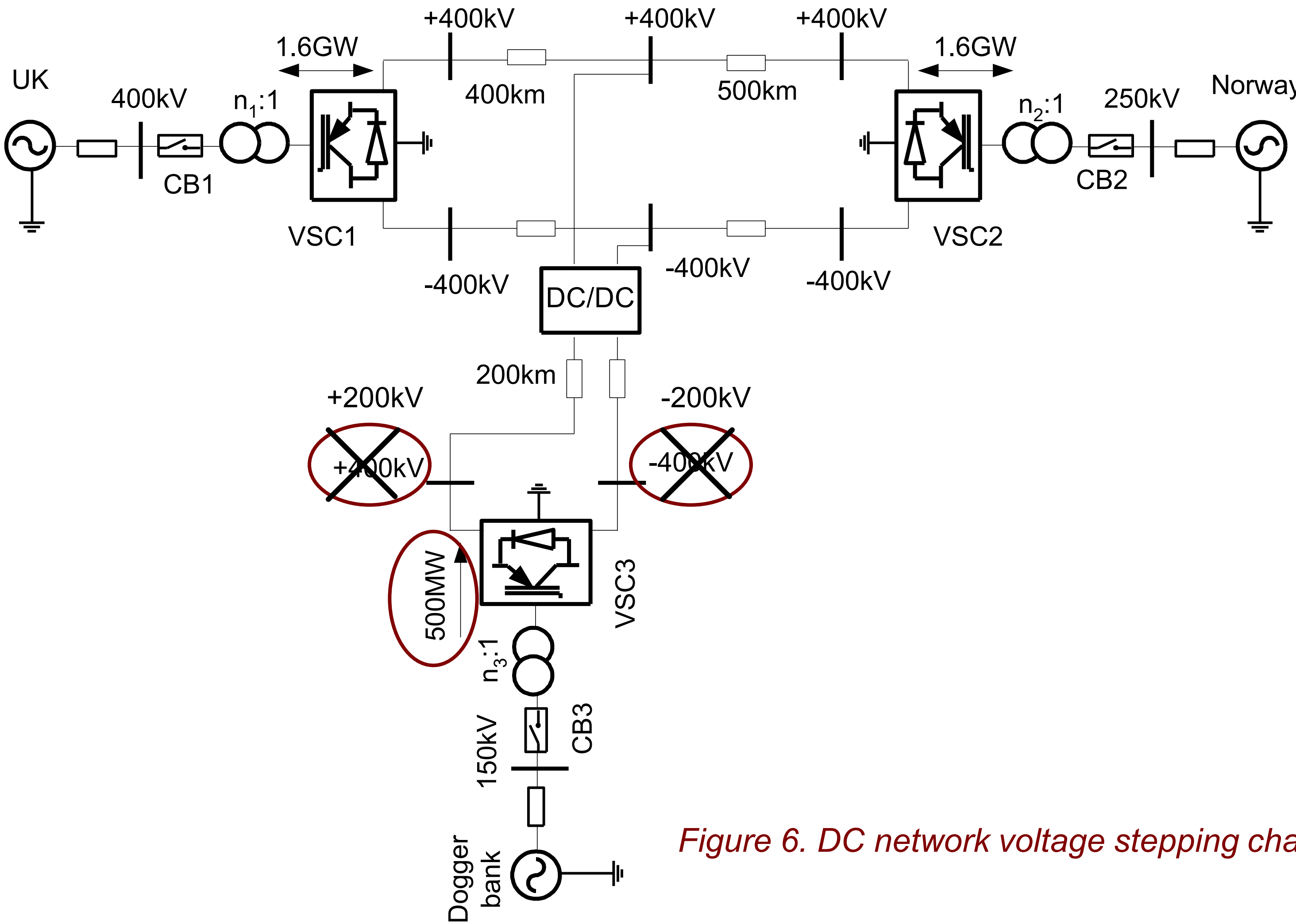


Figure 6. DC network voltage stepping challenge.

1. DC network challenges

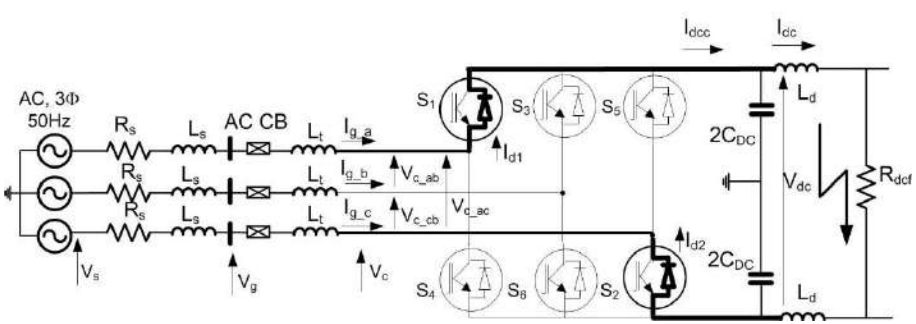
We want DC grids of same reliability and performance as AC grids but there are significant differences:

•protection challenges

- Converters have no over-current (blocking at 2pu current),
- Converters have no under-voltage capability (blocking at 0.8pu voltage),
- Diode rectifiers give large fault currents,
- DC Circuit Breakers are costly,
- DC lines have low impedance (R+jωL) (ω=0),
- Series reactors and energy absorbers,
- Fast protection operation is required (2-5ms),
- Interoperability,

•control challenges

- No inertia (no stored energy),
- Very fast control is required (within 10-20ms)
- Low tripping margin,
- Interaction between many control loops,



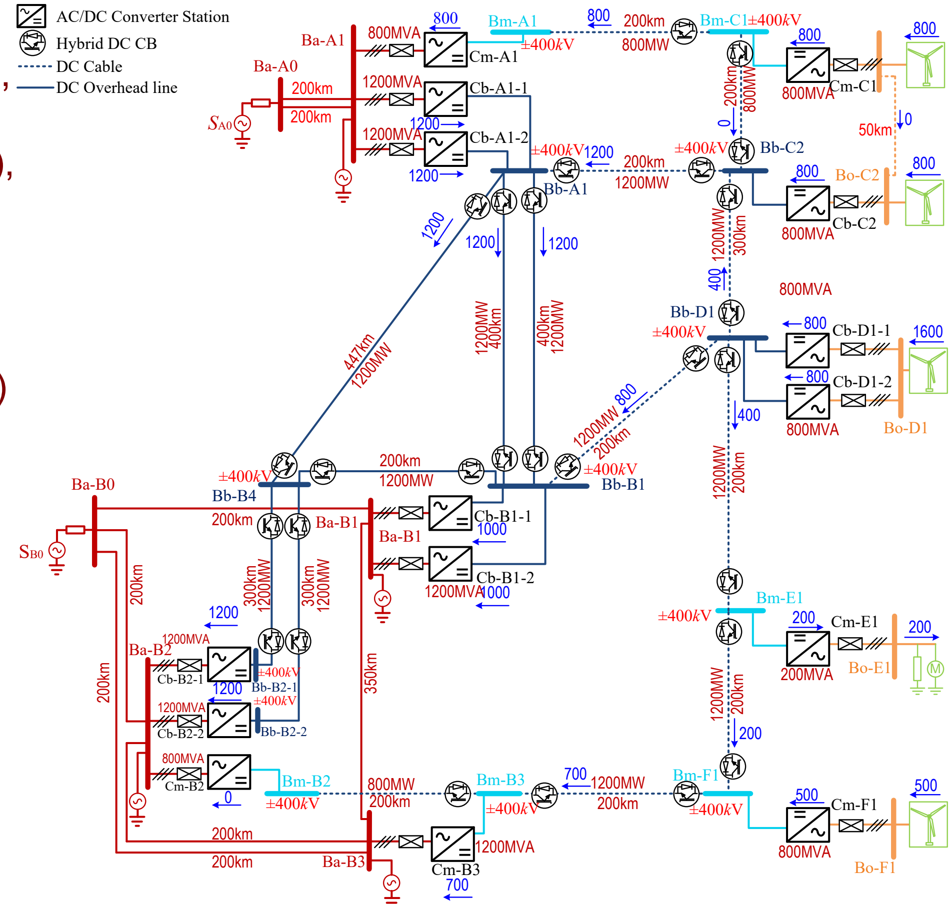


Figure 7. VSC converter under DC fault, and 10 Terminal DC grid (CIGRE B4 Benchmark).

2. DC grid components: DC Circuit Breakers

Why is DC Current interruption difficult?
AC Circuit Breakers exploit natural current zero crossing,
•zero crossing every 10ms on 50Hz system,
•energy dissipation is minimal since average current is zero,

DC Circuits have no zero current crossing,
•If we open contacts, arc is created and current continues to flow. High temperature results.

Interrupting DC current:
•Using solid state devices (high costs),
•Using additional resonant circuits to create zero crossing in mechanical switches (slow and complex)

DC current needs to be commutated into another branch,
•Energy dissipation,
•Large energy absorbers are required

Fault current will rise very fast,
•Peak current can be very large, beyond breaking capability of DC CB
•Series inductors are needed, but they:
  – increase energy that should be dissipated,
  – deteriorate stability,
  – deteriorate voltage deviations,

Continuous arc (3mm) even at very low current of 1.5A

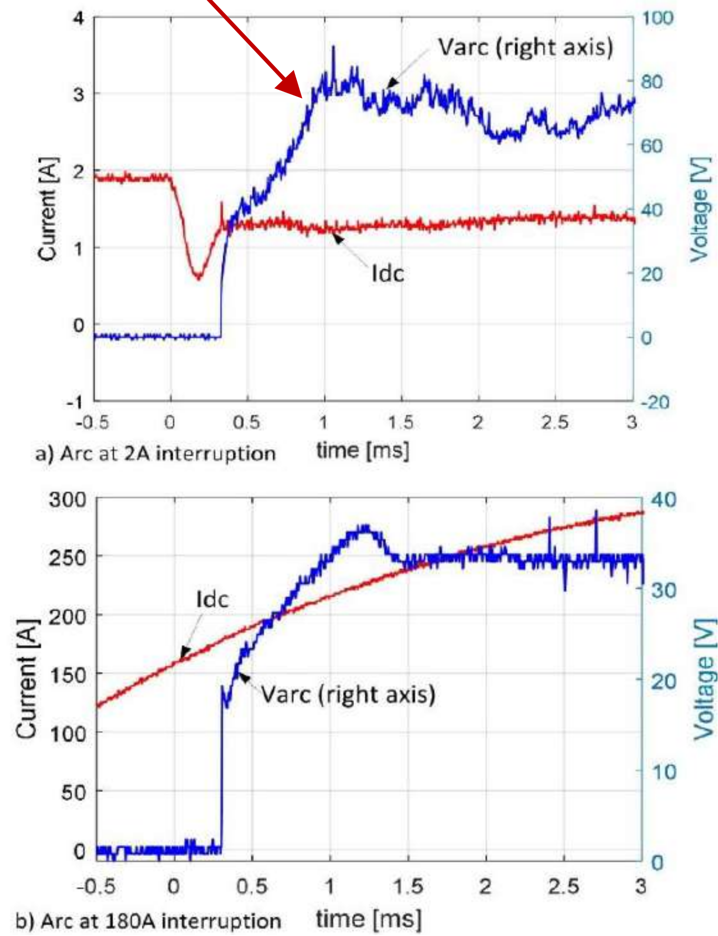
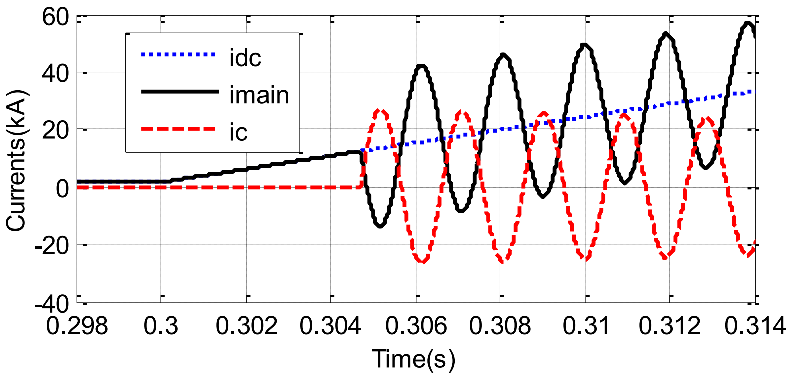


Figure 8. Opening mechanical contacts (2m/s) under DC current (measurements)

2. DC grid components: DC Circuit Breakers

Mechanical DC CB

- Parallel LC circuit,
- Opening time around 8-10ms (slow),
- Long arcing,
- Interruption is not certain,
- Mechanical (cost/losses are moderate),



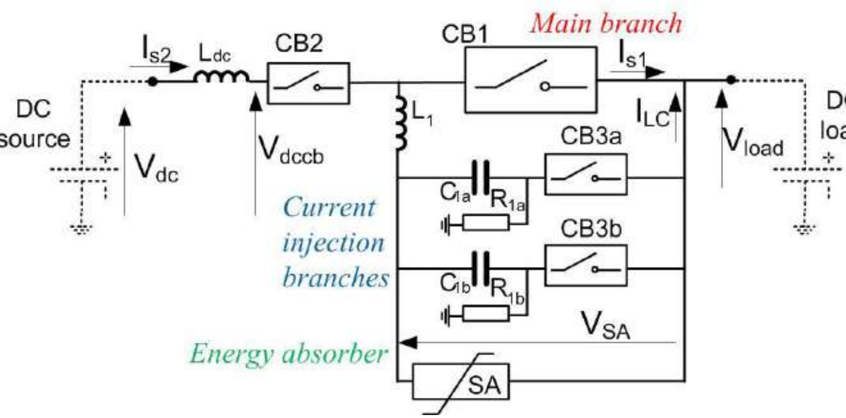
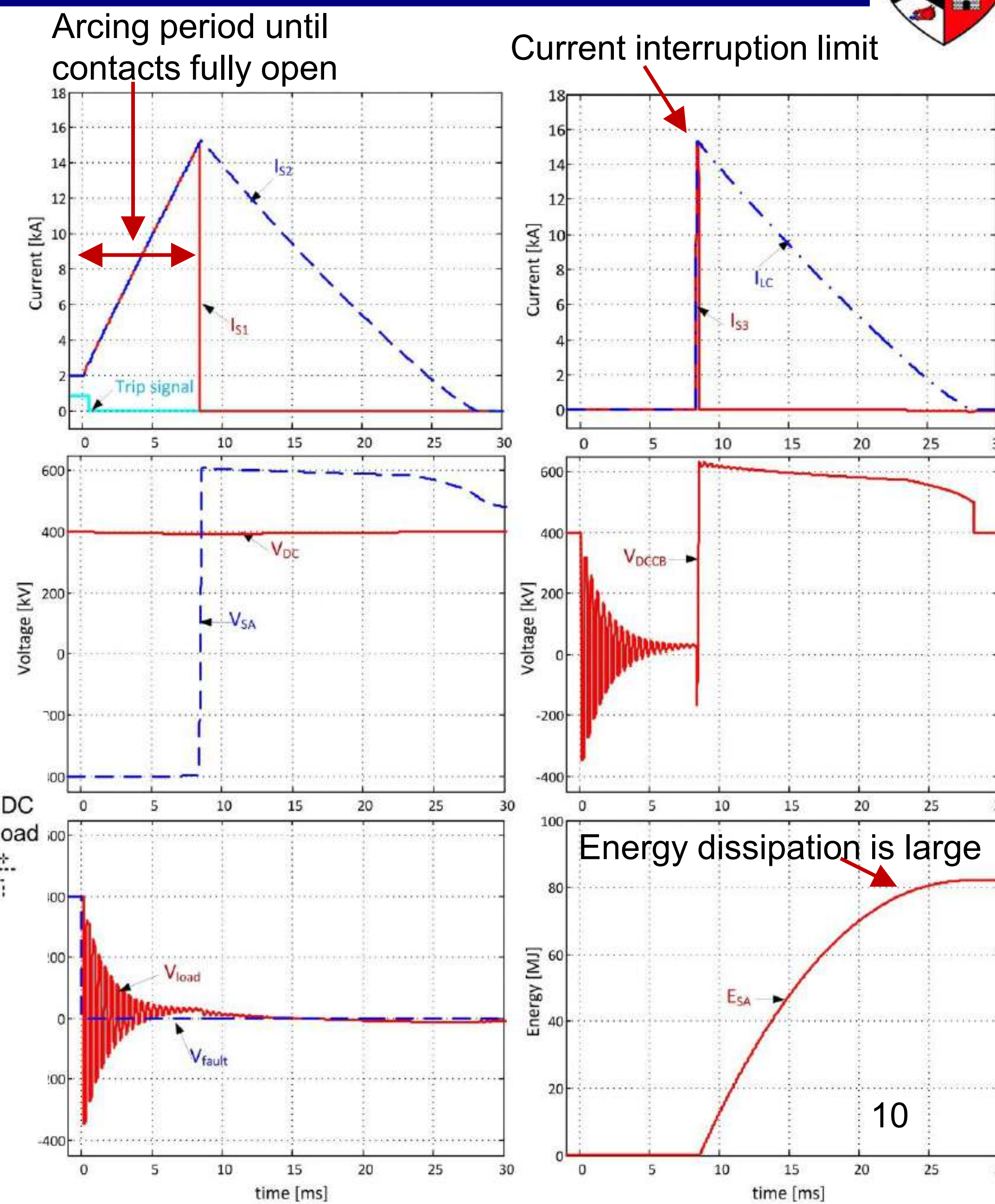
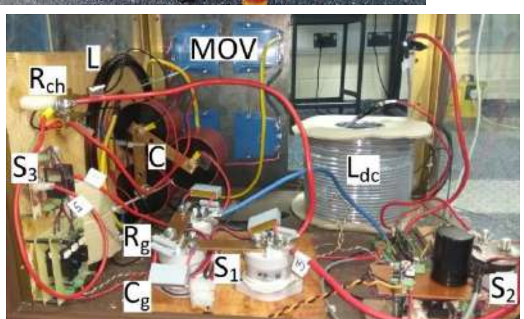


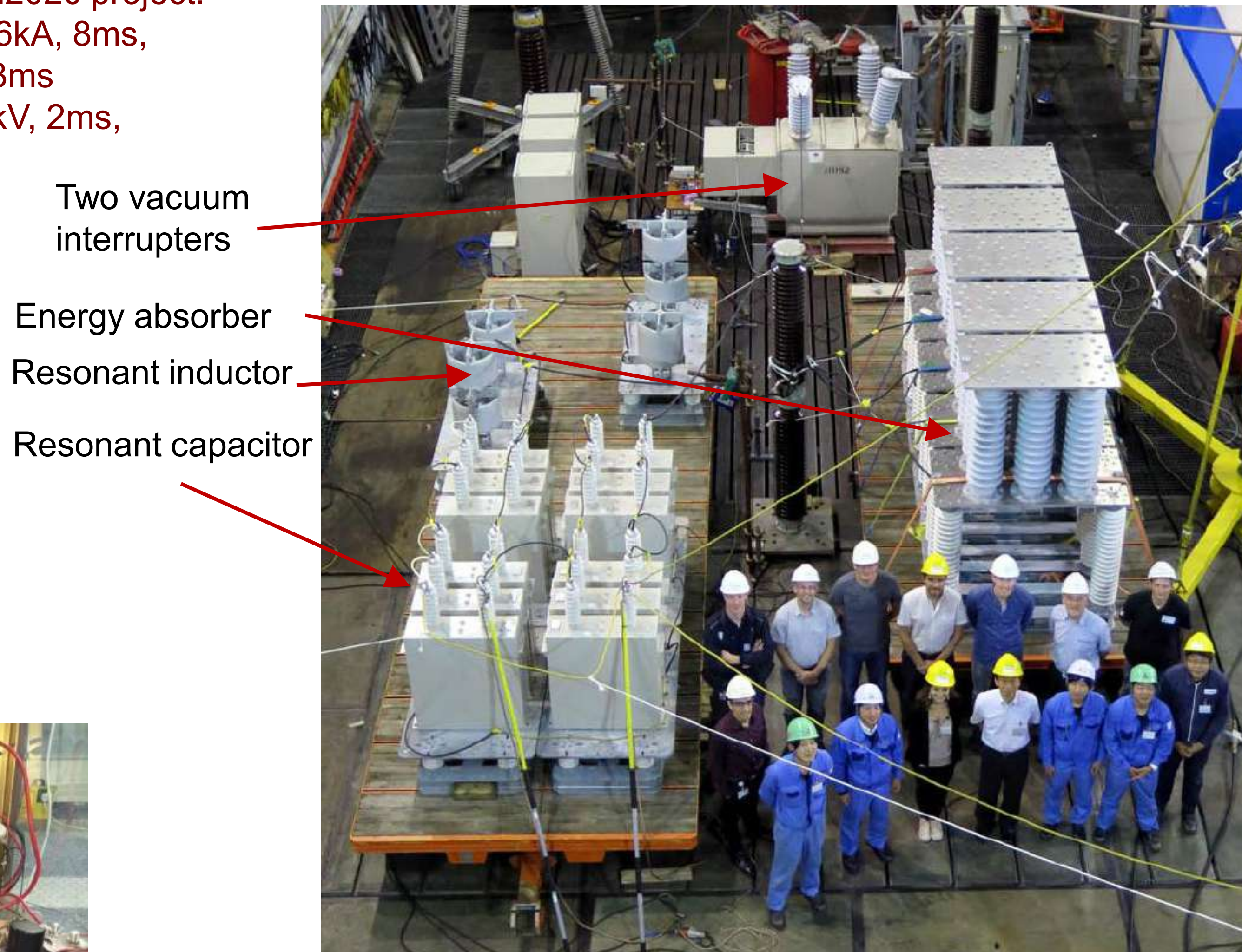
Figure 9. Mechanical DC Circuit Breaker.



2. DC grid components: DC Circuit Breakers

- DC CBs tested in EU Horizon2020 project:
    - Mitsubishi 160kV, 16kA, 8ms,
    - ABB 350kV, 20kA, 3ms
    - SCiBreak 10kA, 81kV, 2ms,





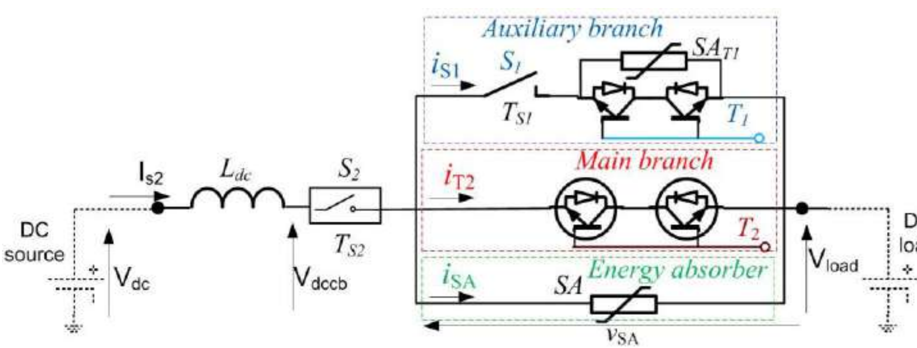
https://www.promotion-offshore.net/

Figure 10. Left: 500A, 1.5kV mechanical DC CB developed at Aberdeen laboratory. Right: Mitsubishi 72kV, 16kA, DC CB, tested at DNV-GL in Horizon2020 Promotion project.

2. DC grid components: DC Circuit Breakers

Hybrid DC Circuit Breaker:

- 2-5ms opening time,
- requires 2 high voltage valves (converter has 6 valves),
- self protection (16kA is peak interrupting current),
- opening time of disconnector is the main limitation,
- multiple operations require large energy absorbers,



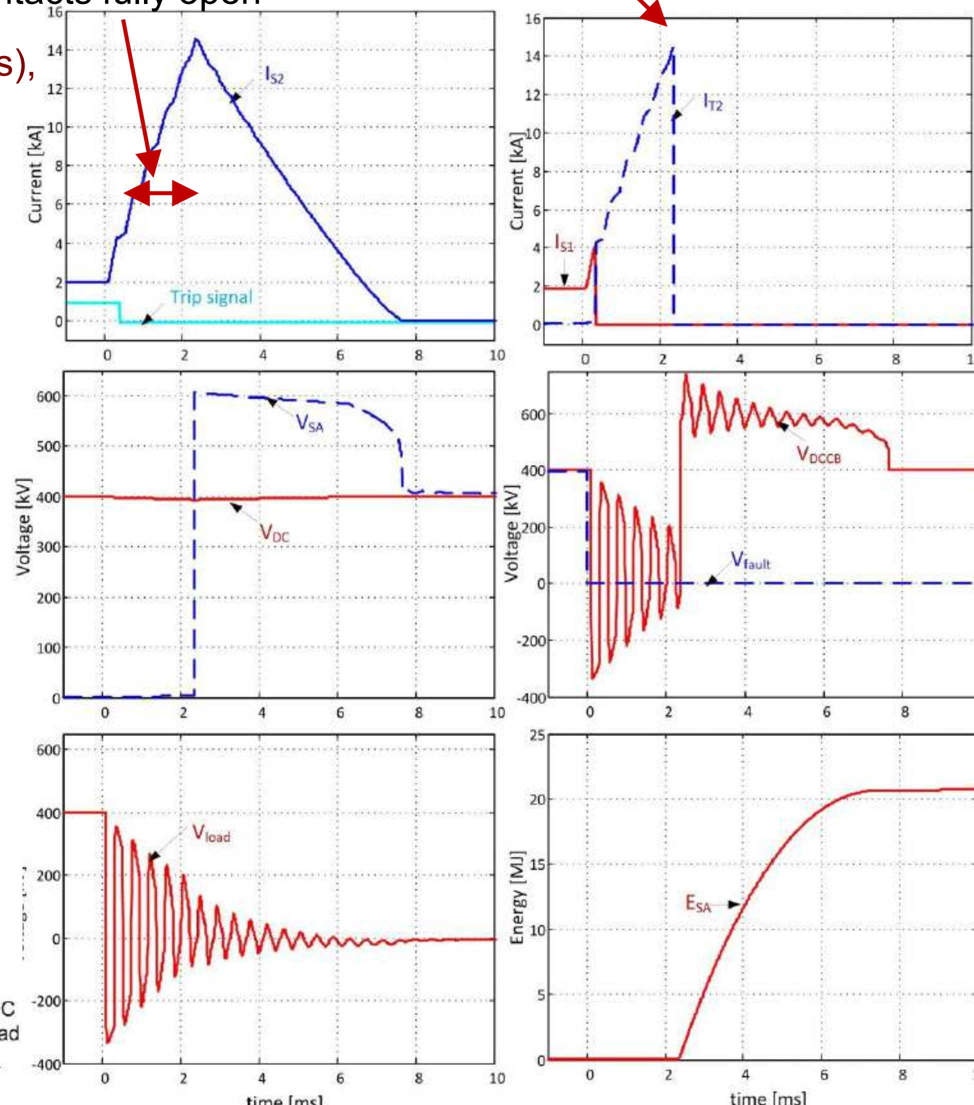


Figure 11. Hybrid DC Circuit Breaker topology, and photo of DC CB installed at Zhoushan project.

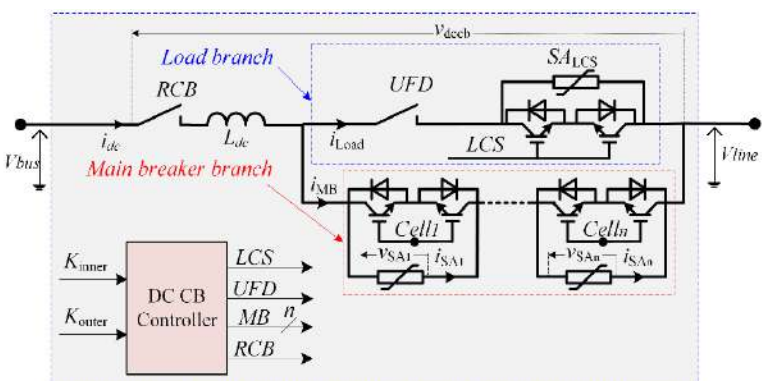
2. DC grid components: DC Circuit Breakers

Hybrid DC CBs are not just ON/OFF devices with a delay:

- Complex internal structure,
- Interaction with DC Grid,
- Hybrid DC CB as fault current limiting device
  - Enables use of slower DC CBs on other lines,
  - Replaces pre-insertion resistors,
  - Around 1kHz operating frequency,
  - Energy balancing in 4 cells,
  - Self-protection determines exit,

Current control at 1pu (2kA)

Energy limit of absorbers



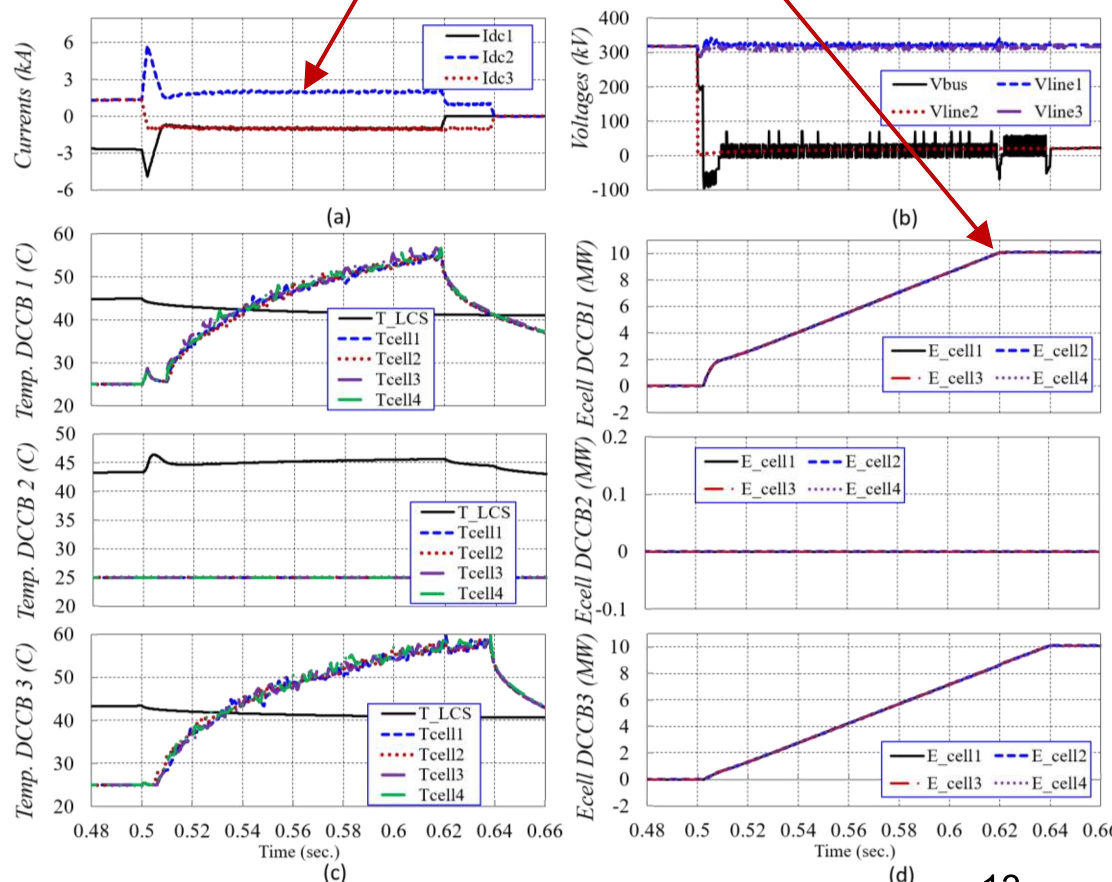


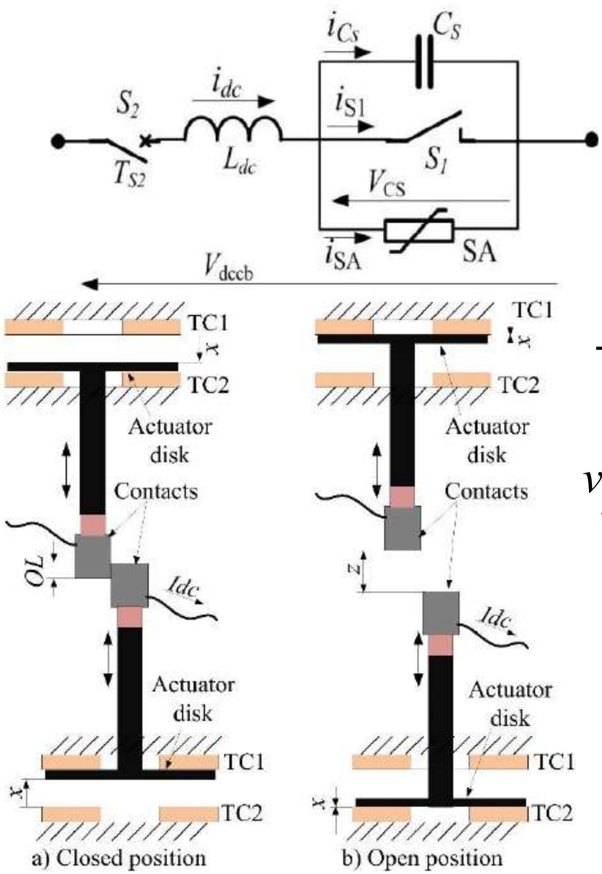
Fig. 12. Hybrid DC CB in fault current limiting mode.

2. DC grid components: DC Circuit Breakers

There is significant worldwide research on new DC topologies,

LC DC Circuit Breaker (Aberdeen):

- Mechanical,
- No arcing,
- Fast (countervoltage insertion at the beginning fo stroke)
- Non-zero velocity at contact separation (lateral contact overlap),



Theoretical basis:

$$v_0 E_b > \frac{I_0}{C_s}, \quad z = 0, \; t = 0$$

Current
Capacitance
Dielectric strength
Velocity at separation

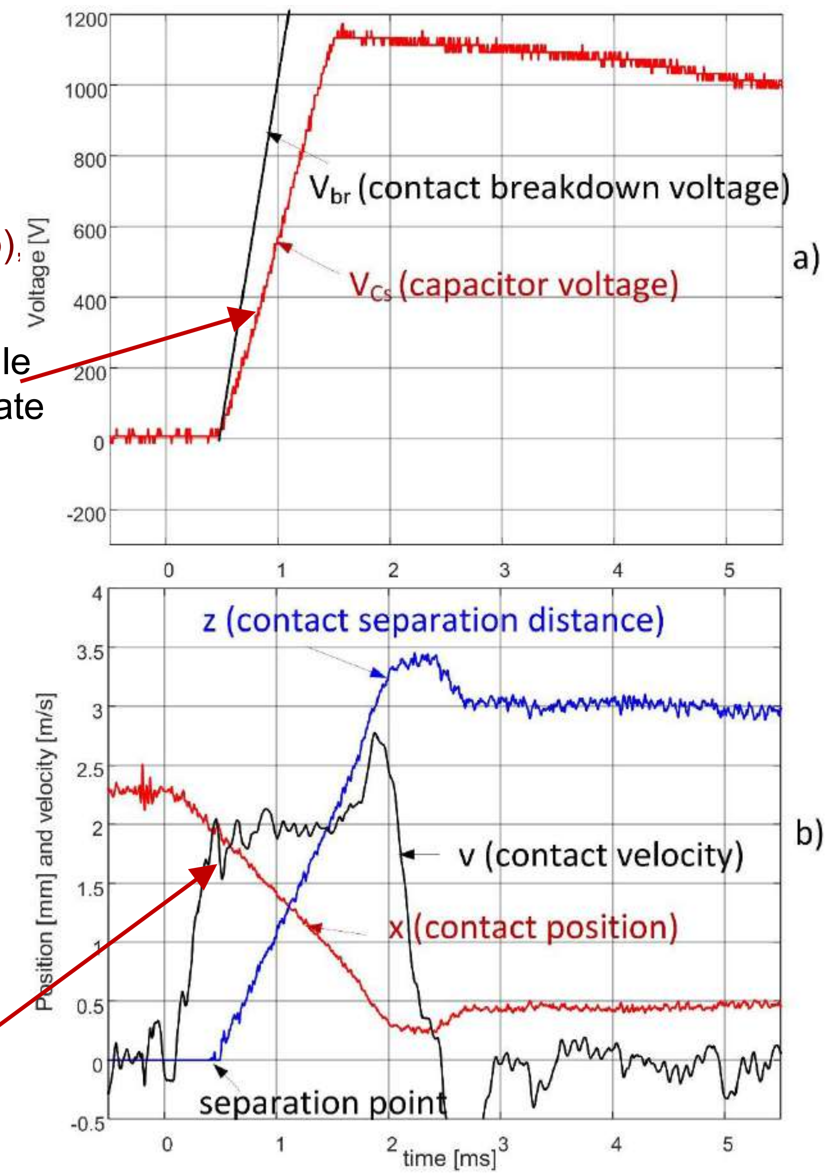
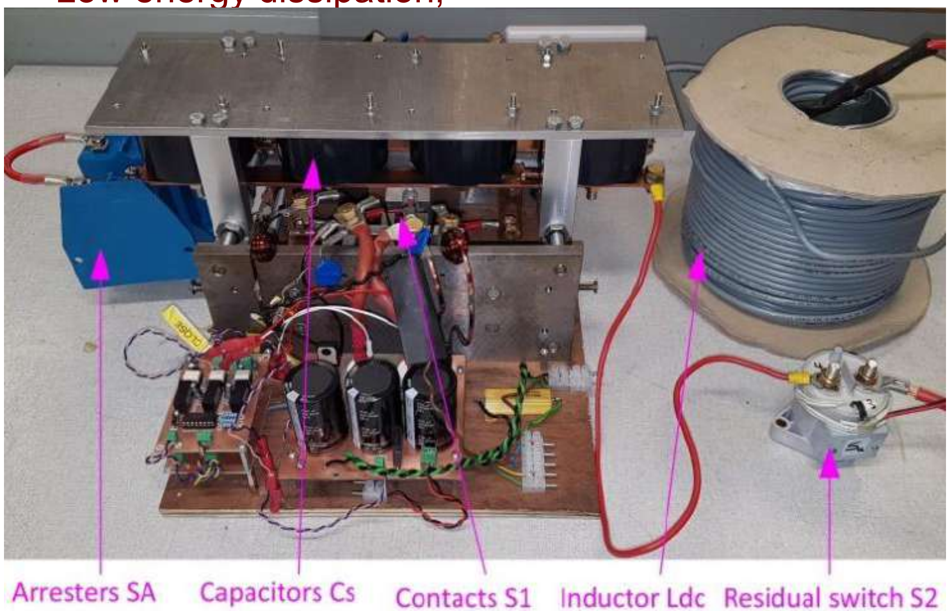
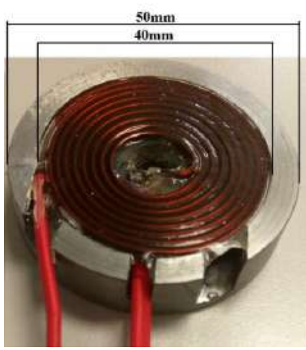


Figure 13. LC DC Circuit Breaker with design details.

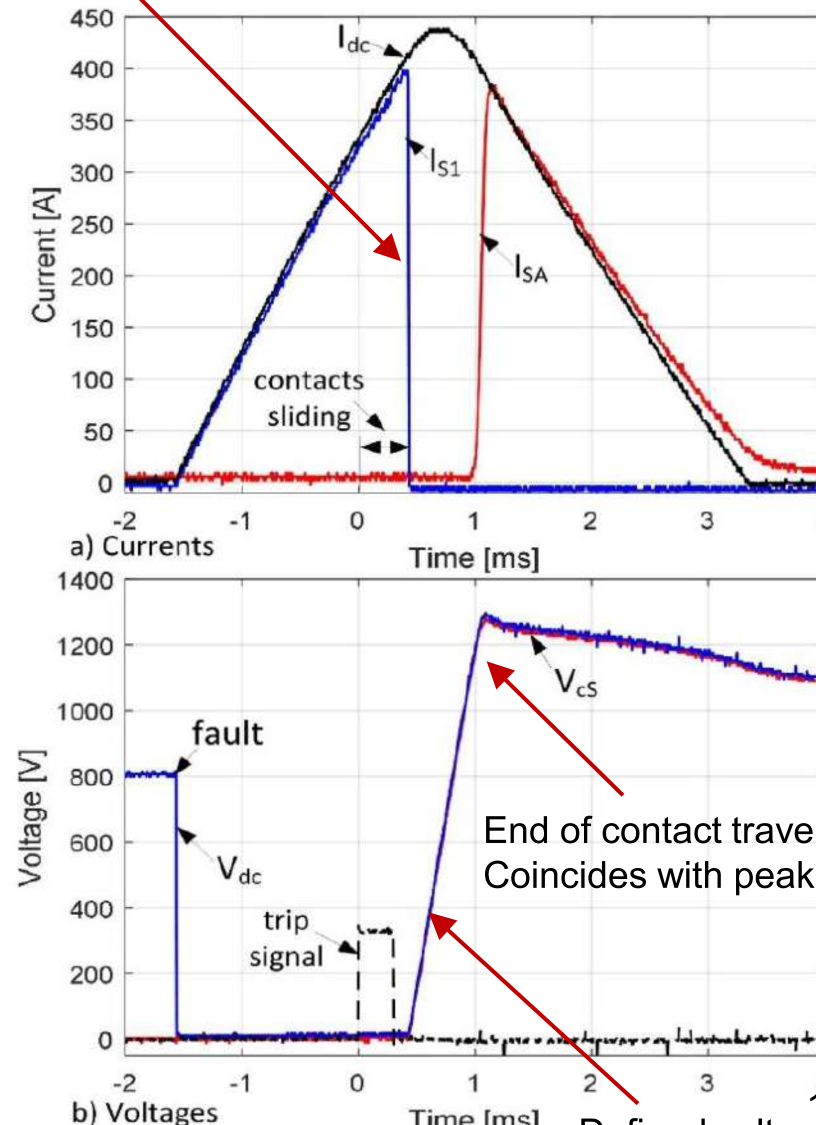
2. DC grid components: DC Circuit Breakers

LC DC Circuit Breaker:
- Mechanical components,
- 1-2ms opening time,
- Converts DC into AC current,
- Low energy dissipation,





Early current commutation,
at the beginning of contact separation (400A)



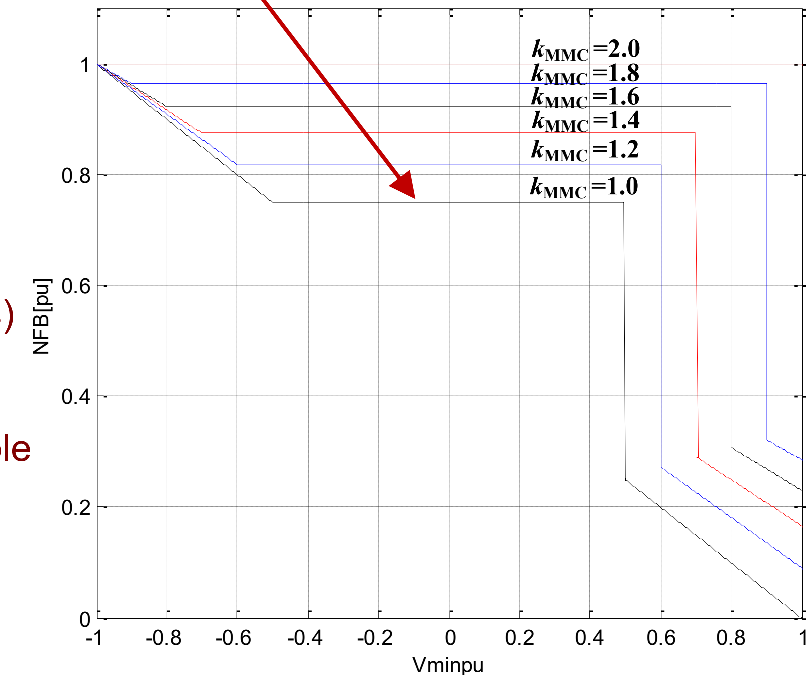
End of contact travel
Coincides with peak voltage

Defined voltage slope,
No restrike

Figure 14. 400A DC current interruption with LC DC Circuit Breaker.

2. DC grid components: New AC-DC converters

At least 75% Full bridge cells are needed for 0 Vdc

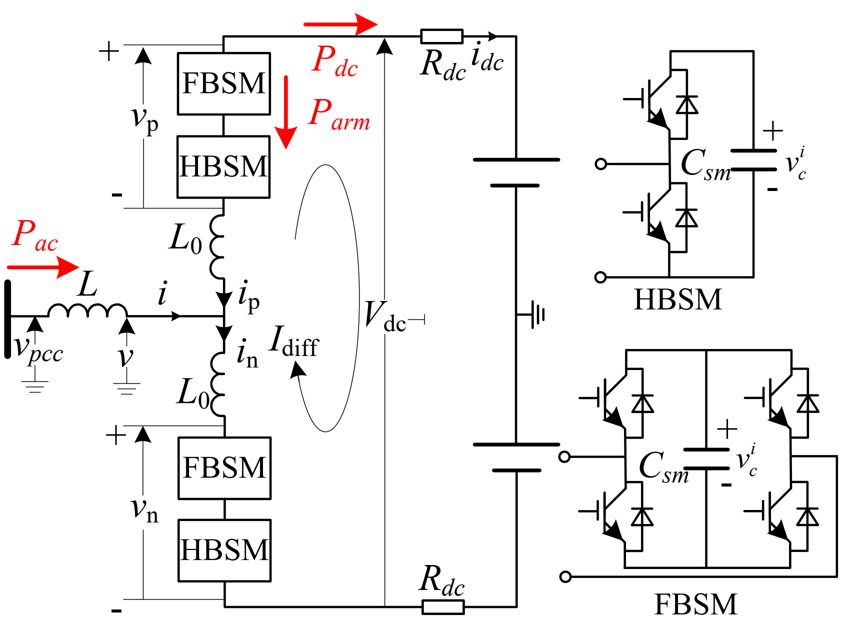


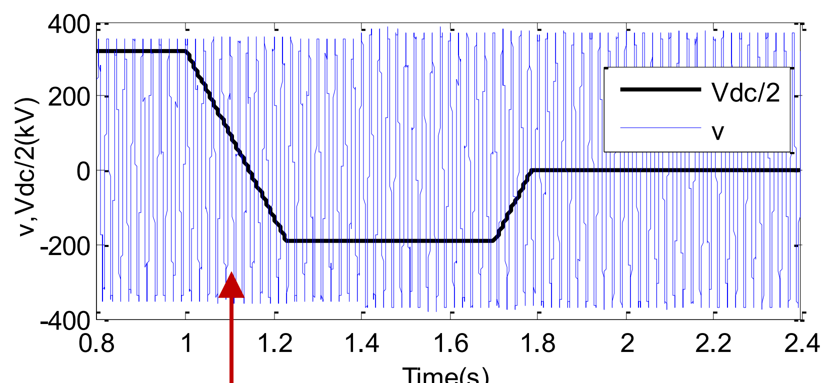
Full Bridge (FB) MMC

- Twice the number of semiconductors compared with HB,
- Each cell can provide +Vdc or –Vdc,
- Enables independent variation of DC voltage,
- DC faults are not issue,

Optimal Design of Full Bridge MMC:

- Not all cells should be FB, (Vdc=-1pu requires 100% FB cells)
- Minimal required DC voltage (Vdc=0 requires 50% FB cells),
- Capacitor voltage balancing requires at least 70% FB cells,
- Overmodulation provides higher AC voltage for given DC cable voltage (using extra FB cells),





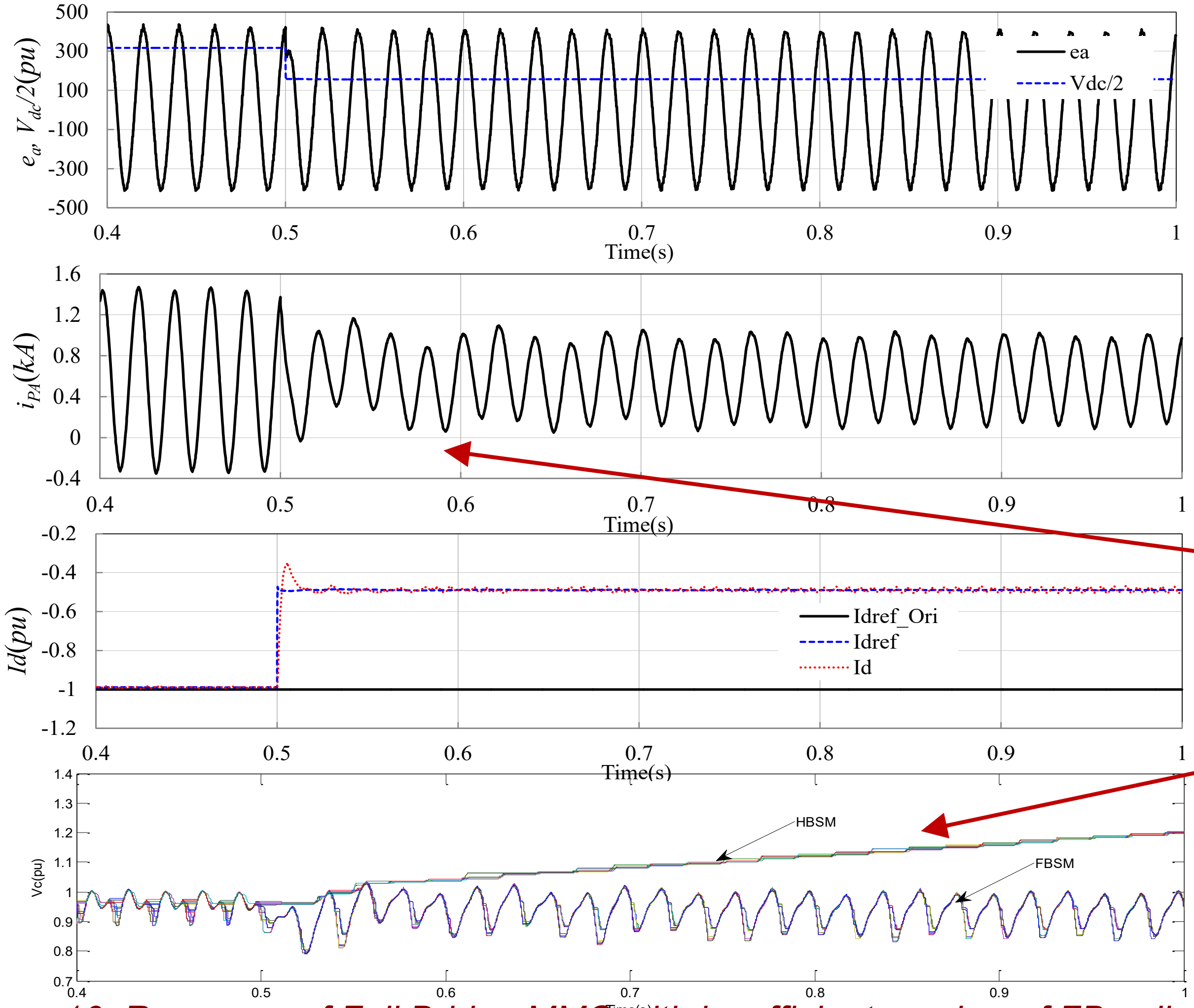
Full AC voltage is generated regardless of Vdc

Figure 15. Optimal design of Full bridge Modular Multilevel Converter.

2. DC grid components: New AC-DC converters

Capacitor voltage balancing is the most stringent requirement :

- FB cell voltage balancing is possible with one-directional current ,
- HB cell voltage balancing requires positive and negative current in each cycle,



No negative current means balancing is impossible

Cell voltages are unbalanced

Figure 16. Response of Full Bridge MMC with insufficient number of FB cells.

2. DC grid components: New AC-DC converters

FB MMC control:

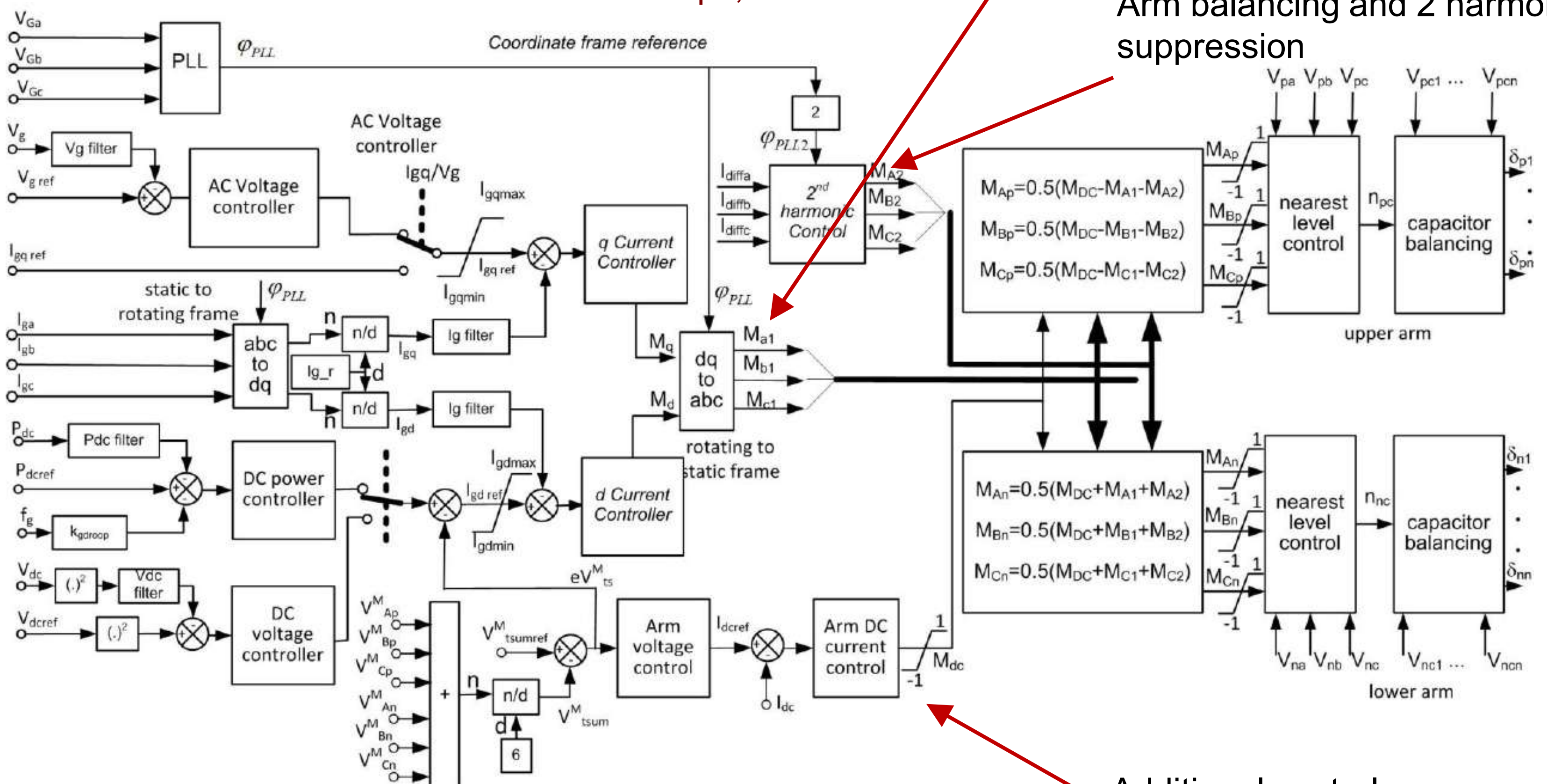
- Control system has three inputs Md, Mq, Mdc,
- Inner AC current control (Id, Iq) but also Idc,
- 4 quadrant control on DC side (Vdc and Idc),
- Energy balancing in MMC is essential,
- Coordination between rectifier and inverter in an HVDC,
- In total each FB MMC has over 30 control loops,

$$m_P = \frac{1}{2}\left(M_{dc} - M_{ac}\cos(\omega t + \theta_m)\right), \quad 0 < M_{ac} < 1, \quad -1 < M_{dc} < 1, \quad -1 < m_P < 1$$

$$m_N = \frac{1}{2}\left(M_{dc} + M_{ac}\cos(\omega t + \theta_m)\right), \quad 0 < M_{ac} < 1, \quad -1 < M_{dc} < 1, \quad -1 < m_N < 1$$

AC voltage control

Arm balancing and 2 harmonic suppression



Additional control for FB MMC

Figure 17. FB MMC control.

2. DC grid components: New AC-DC converters

Operation under DC faults:

1) FB MMC is blocked (not preferred option)

- Fault current is blocked,
- DC line voltage will collapse,
- dangerous arm overvoltage,
- no control of reactive current,

Arm voltage is well bounded

2) FB MMC controlled operation

- Each MMC converter can control local DC current,
- Converter DC voltage reduces to zero,
- Reactive power control is maintained,
- Fast post-fault recovery,

but:

- Adequate safety margin is needed,
- Component stresses can be high,
- Power/Energy balancing is challenge,
- High AC current should be maintained,

Peak transient current is satisfactory

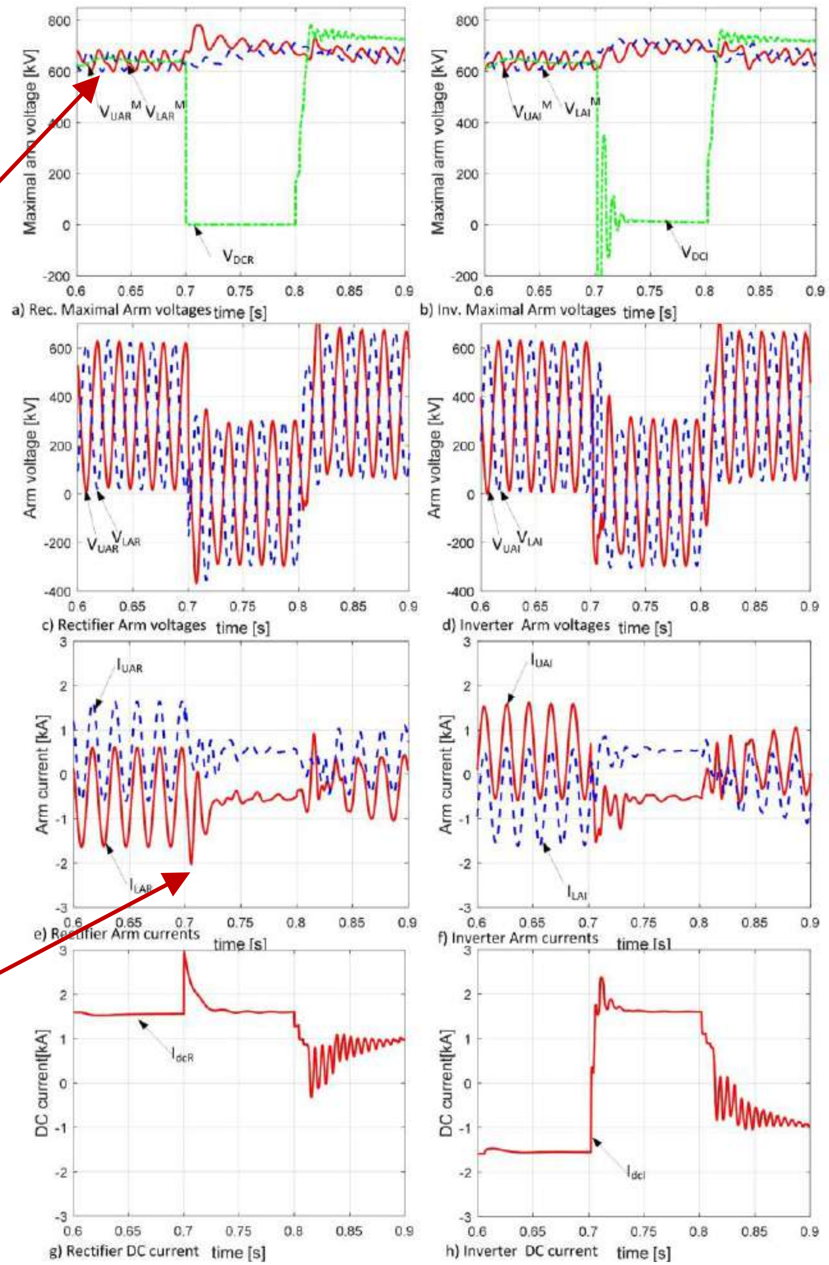


Figure 18. FB MMC HVDC response under DC faults (No blocking).

2. DC grid components: New AC-DC converters

HVDC and DC Grids with FB MMC:

- DC fault currents are controlled and fault extinguishing is possible,
- Full control range for DC voltage,
- Need for DC CB (mechanical) on each DC line,
- Series inductors can be small (5mH), (low energy dissipation)

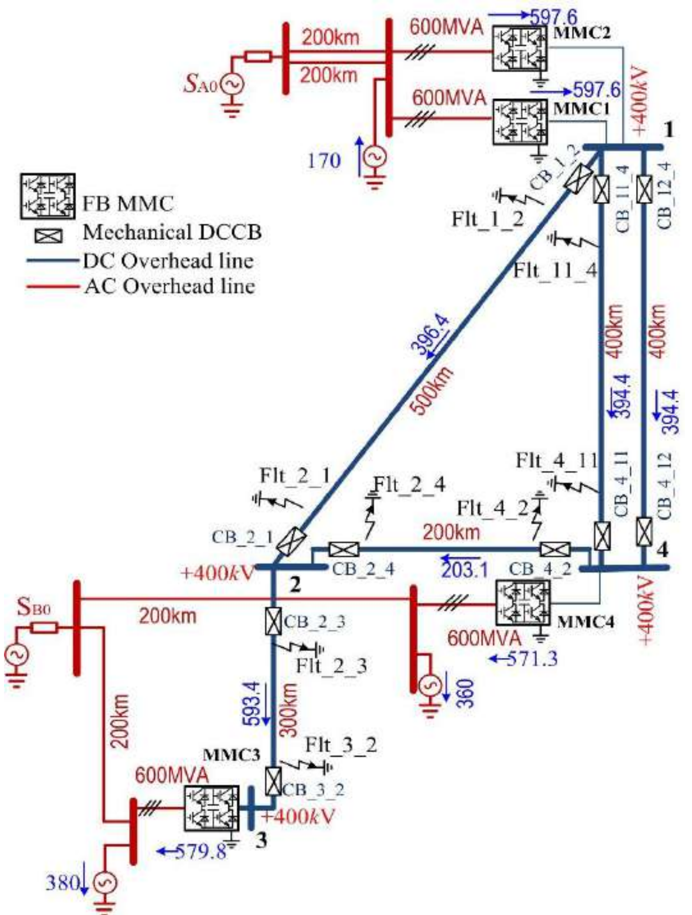


Figure 19. 4-terminal DC grid with FB MMC.

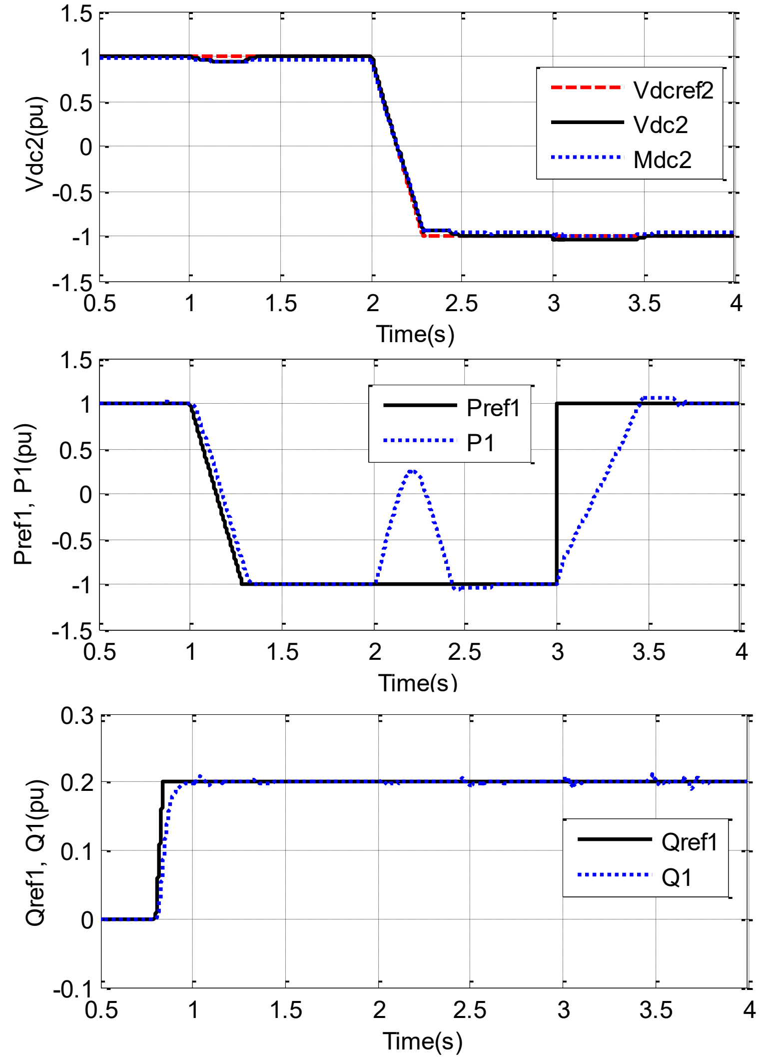


Figure 20. 100% FB MMC HVDC 4-quadrant operation.

2. DC grid components: New AC-DC converters

Hybrid HVDC (LCC and MMC):

- Terminal Hybrid, (Wodonge HVDC in China 2019)
- Pole hybrid (Skagerrak HVDC in Denmark HVDC 2010),
- Converter hybrid,
  - Series converter hybrid (8GW Baihetan-Jiangsu HVDC in construction in China),
  - Parallel converter hybrid,

Series Hybrid AC-DC converter (Thyristor valves and MMC valves),

- MMC valve may have smaller voltage than LCC valve (1/2Vdc in Baihetan-Jiangsu HVDC),
- Hybrid converter is better justified at receiving end (inverter),
- Advantages of thyristor valves
  - Low cost,
  - Low losses,
  - High current
  - Good overcurrent capability,
  - Good DC fault ride through,
- Advantages of MMC valves
  - Supply of reactive power (even during faults),
  - Controllable reactive current (voltage control),
  - Lowers commutation failure risk with LCC,
  - Operation with passive systems,
  - Black start capability,
  - Grid forming control,
- FB MMC valve enables
  - DC Voltage reversal,
  - HVDC power reversal,
  - Better DC fault ride through,
- MMC valve
  - May need parallel switches to support high current,
  - 3 parallel valve used in Baihetan-Jiangsu HVDC,

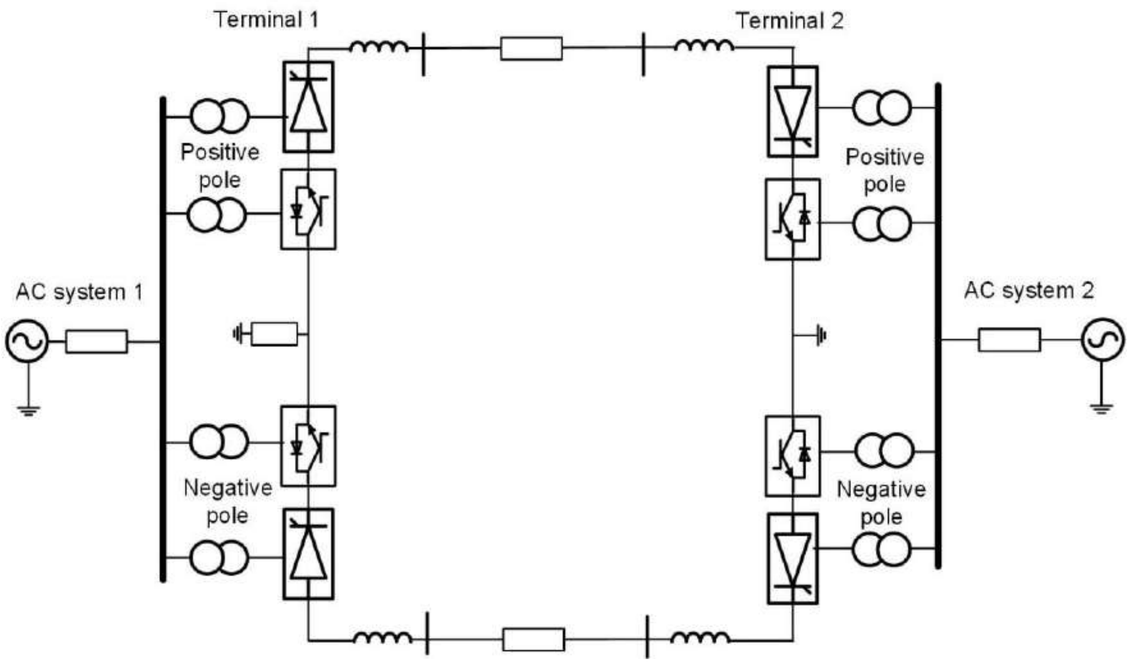


Figure 21. Series, converter-hybrid bipolar HVDC.

2. DC grid components: DC/DC converters

DC/DC converter functions:

- Controllable DC voltage stepping,
- Power flow control,
- DC CB and DC fault current control,
- Interconnection of different DC systems:
  - different manufacturers,
  - VSC with LCC,
  - helps with interoperability,
  - flexibility and standardisation,

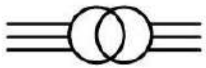
DC/DC converter types:

- Low stepping ratio (direct conversion, non-isolated),
- Autotransformers,
- High stepping ratio (isolated or non-isolated),

DC/DC converter isolation:

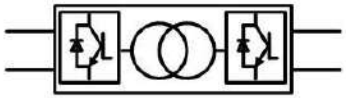
- Isolated with internal transformer
  - galvanic isolation enables flexible grounding on two DC sides,
  - at high frequency transformer losses can be high
- Non isolated
  - same performance as with isolated,
  - losses are usually lower,
  - lower semiconductor count.

AC system



- Voltage stepping,
- Galvanic isolation
- Fault current limiting

DC system

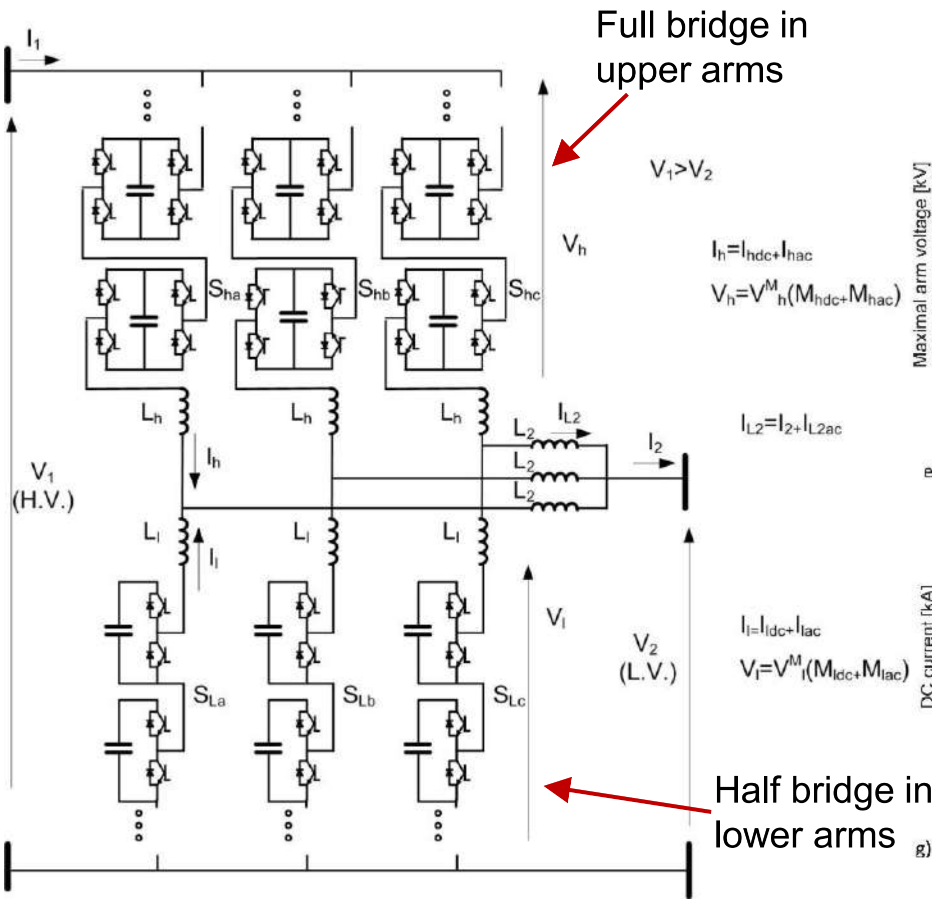


- Controllable Voltage stepping,
- DC Circuit Breaker,
- Power flow control,
- Galvanic isolation,
- Controllable fault current limiting,

2. DC grid components: DC/DC converters

Non-isolated MMC based DC/DC:

- Moderate number of semiconductors, (1-1.3pu),
- DC fault tolerant on LV and HV side,
- 0.5 voltage stepping ratio is cost-optimal,
- Upper and lower arms have unequal DC power,
- Energy balancing using AC power,



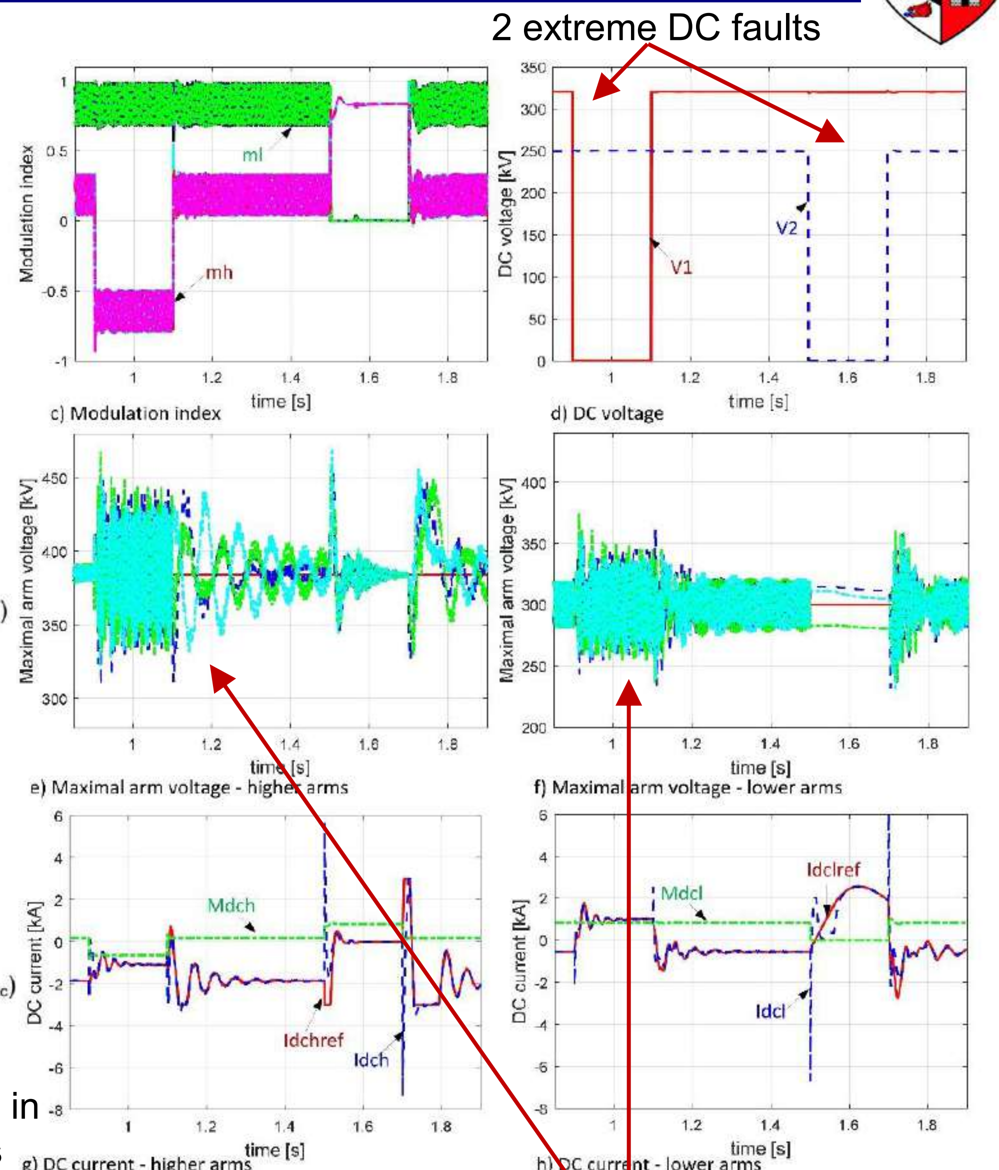


Figure 22. Non-isolated MMC-based DC/DC converter, and responses to DC faults.

2. DC grid components: DC/DC converters

MMC-based isolated DC/DC converter,
- Different grounding options on each DC system (connecting bipolar and monopolar DC grids),
- Controllable ride through DC faults (one bridge is blocked),
- Operating frequency 50-300Hz,
- Internal AC Transformer can be an issue (high power high frequency transformers, limitation <150Hz)

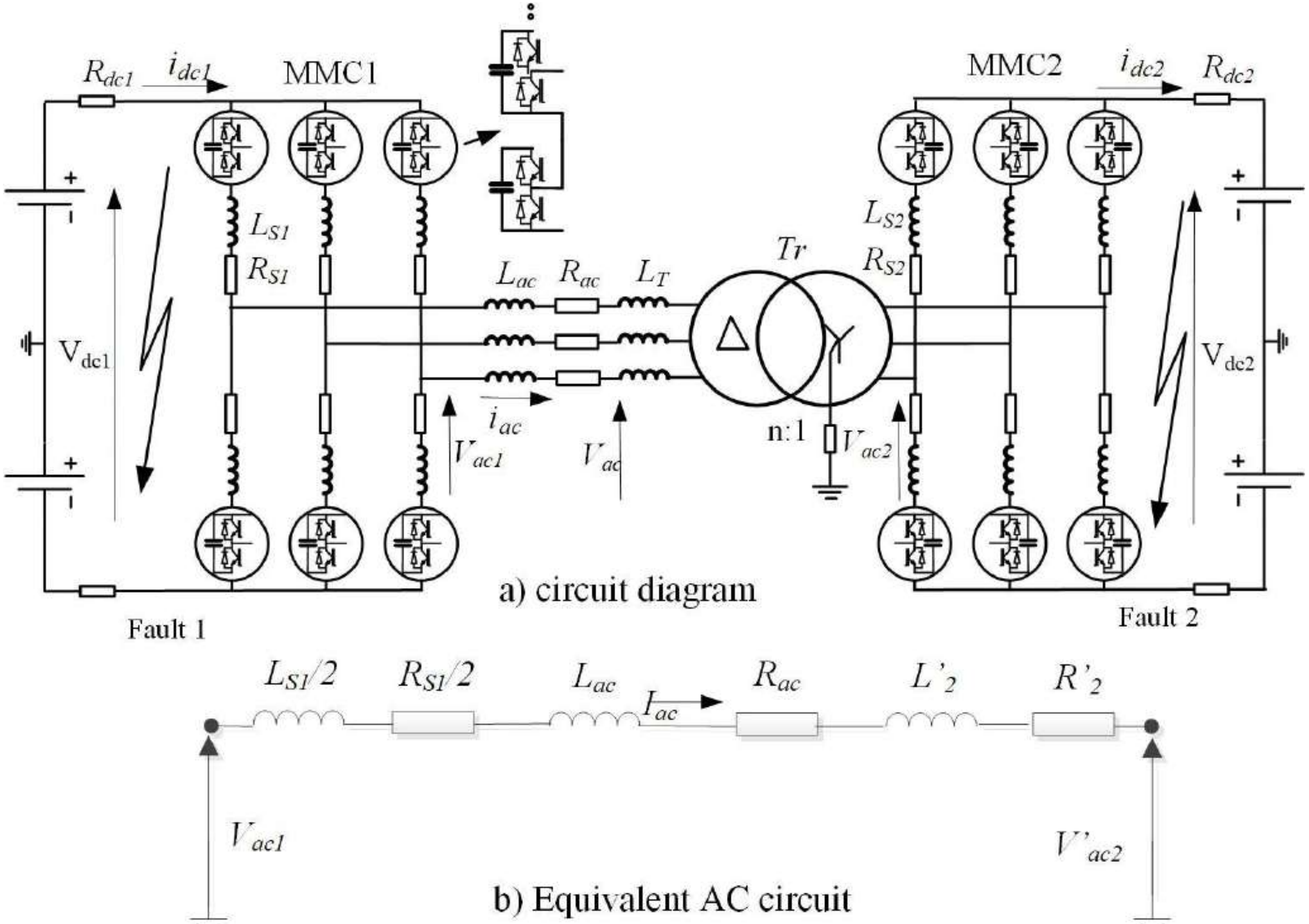


Figure 23. Isolated, MMC-based, 3-phase, DC/DC Converter.

2. DC grid components: DC/DC converters

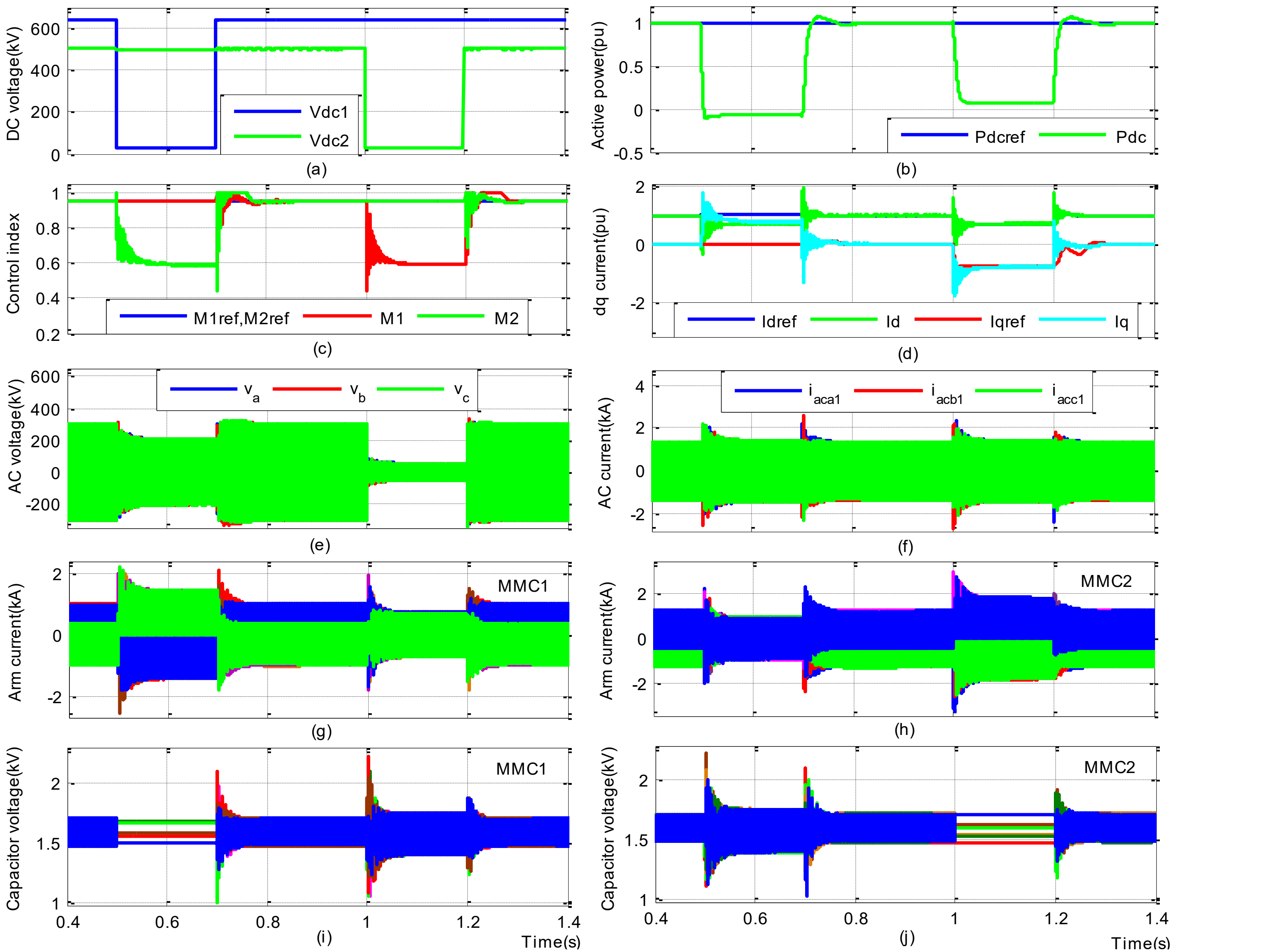


Figure 24. Response to DC faults at HV and LV sides (Isolated, MMC-based, DC/DC Converter).

2. DC grid components: DC/DC converters

Many new high-power DC/DC topologies are studied worldwide.

- Thyristor LCL DC/DC converter enables connection of LCC or VSC with DC grid
- Transformer is not needed (core losses are high at higher frequencies)

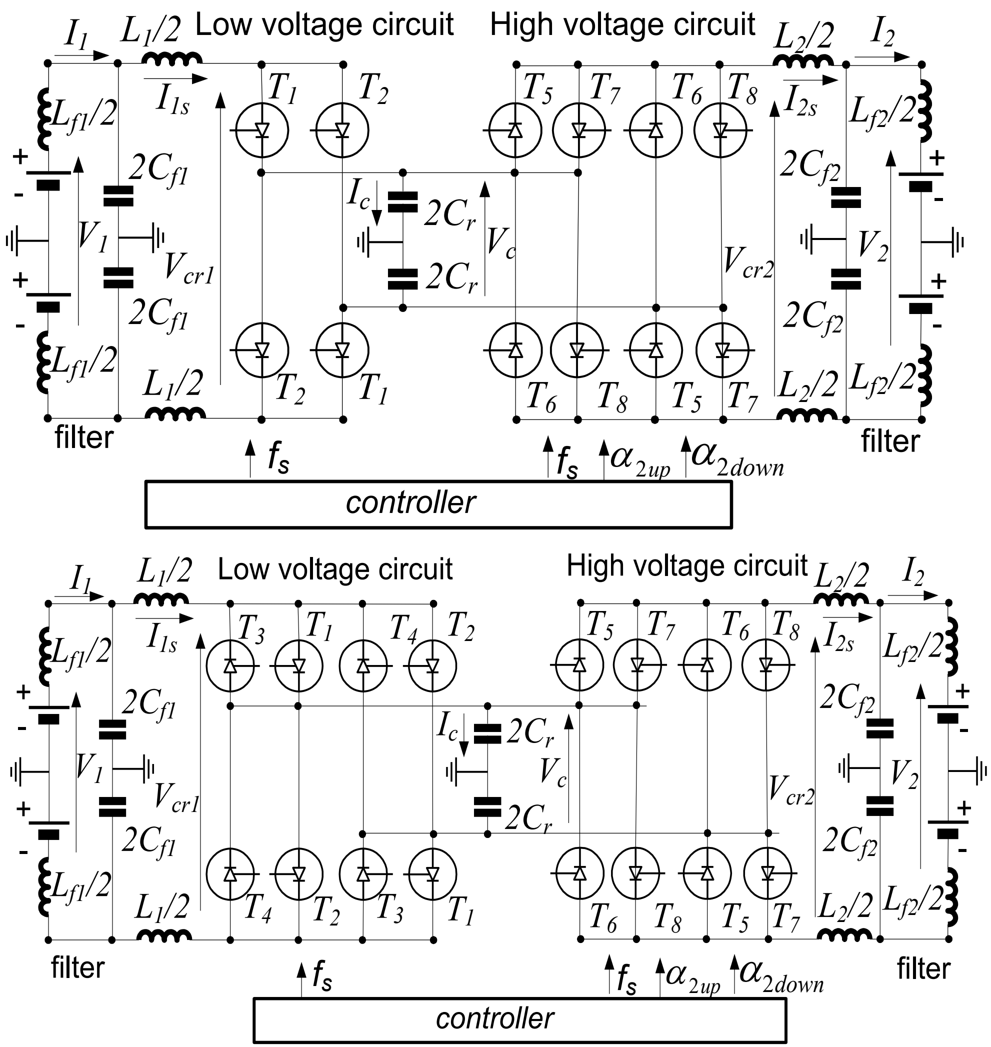


Figure 25. Bidirectional thyristor-based DC/DC converter.

Table 4 Connecting LCC with DC grid (Type I).

Power direction	V_1	I_1	V_2	I_2
V_1 to V_2 (step-up)	+	+	+	+
V_2 to V_1 (step-down)	-	+	+	-

Table 5 Connecting VSC with DC grid (type II).

Power direction	V_1	I_1	V_2	I_2
V_1 to V_2 (step-up)	+	+	+	+
V_2 to V_1 (step-down)	+	-	+	-

2. DC grid components: DC/DC converters

IGBT based LCL DC/DC converter,

- High DC voltage stepping ratio with good efficiency,
- No transformers, implies low weight and core losses,
- Capacitors and air core reactors allow high frequency operation,
- Zero reactive power circulation (at one operating point),
- Excellent switch utilisation,
  - HV-side switches are rated for high voltage and low current,
  - LV-side switches are rated for low voltage and high current,
  - Current can be in phase with voltage at each bridge,
- Excellent inherent DC fault tolerance,
- Full-range power control,
- Can be expanded to multiport topology.

LCL inner circuit works as AC transformer

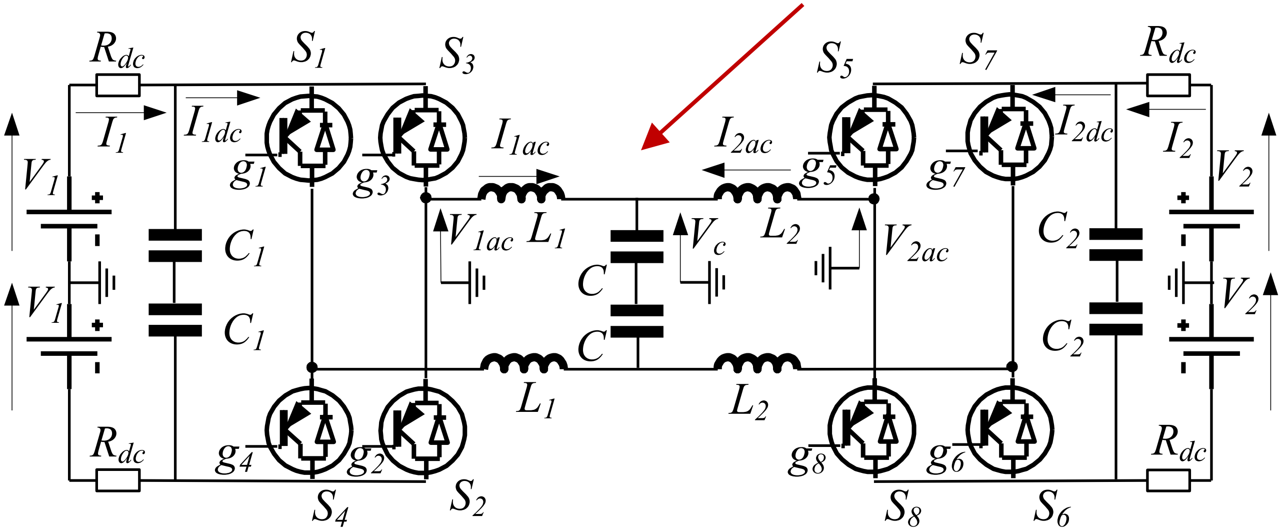


Figure 26. IGBT based LCL DC/DC converter .

2. DC grid components: DC/DC converters

- **IGBT based LCL DC/DC converter,**
  - Good switch utilisation ratio (optimal stresses),
  - Power factor of 1 at each bridge at any power level,

Figure 27. LCL DC/DC converter 5/80kV simulation of steady-state operation.

2. DC grid components: DC/DC converters

Using DC/DC converter to connect two HVDC lines

- Interconnect two HVDC lines of different voltage levels,
- Improved operating flexibility,
- Two protection zones,
- DC faults are not transferred across DC/DC,
- DC/DC becomes:
    - transformer,
    - power flow regulator,
    - DC Circuit Breaker.

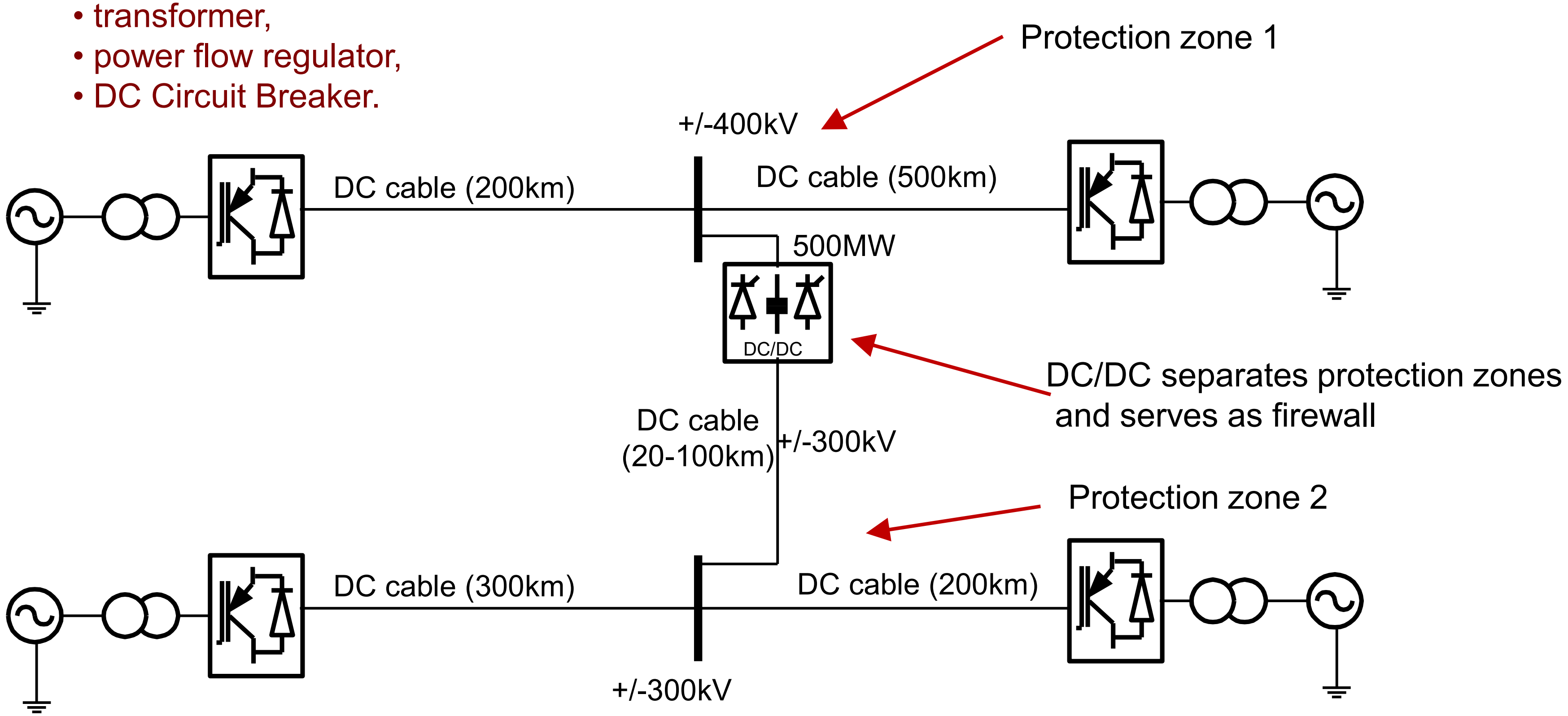


Figure 28. Connecting two existing HVDC using a DC/DC converter.

2. DC grid components: DC/DC converters

Connecting 3 offshore wind farms with 3 onshore terminals with n-1 security:

Items	*Numbers and Rated*	*Cost est./unit*	*Cost est.*
AC stations	3 (1.5GW)	165 M€	495 M€
DC cable (pair)	3 (1.5 GW) + 2 (1GW)	1.4M€/GW/km	630 M€ + 280 M€
Mech. DC/CB	3 (1.5GW) + 2 (1GW)	0.0003 M€/MW	1.35 M€ + 0.6 M€
DC/DC converter	2 (1GW)	0.18 M€/MW	360 M€
Total Cost (2011) to transmit 3GW			1767 M€, 589 M€/GW

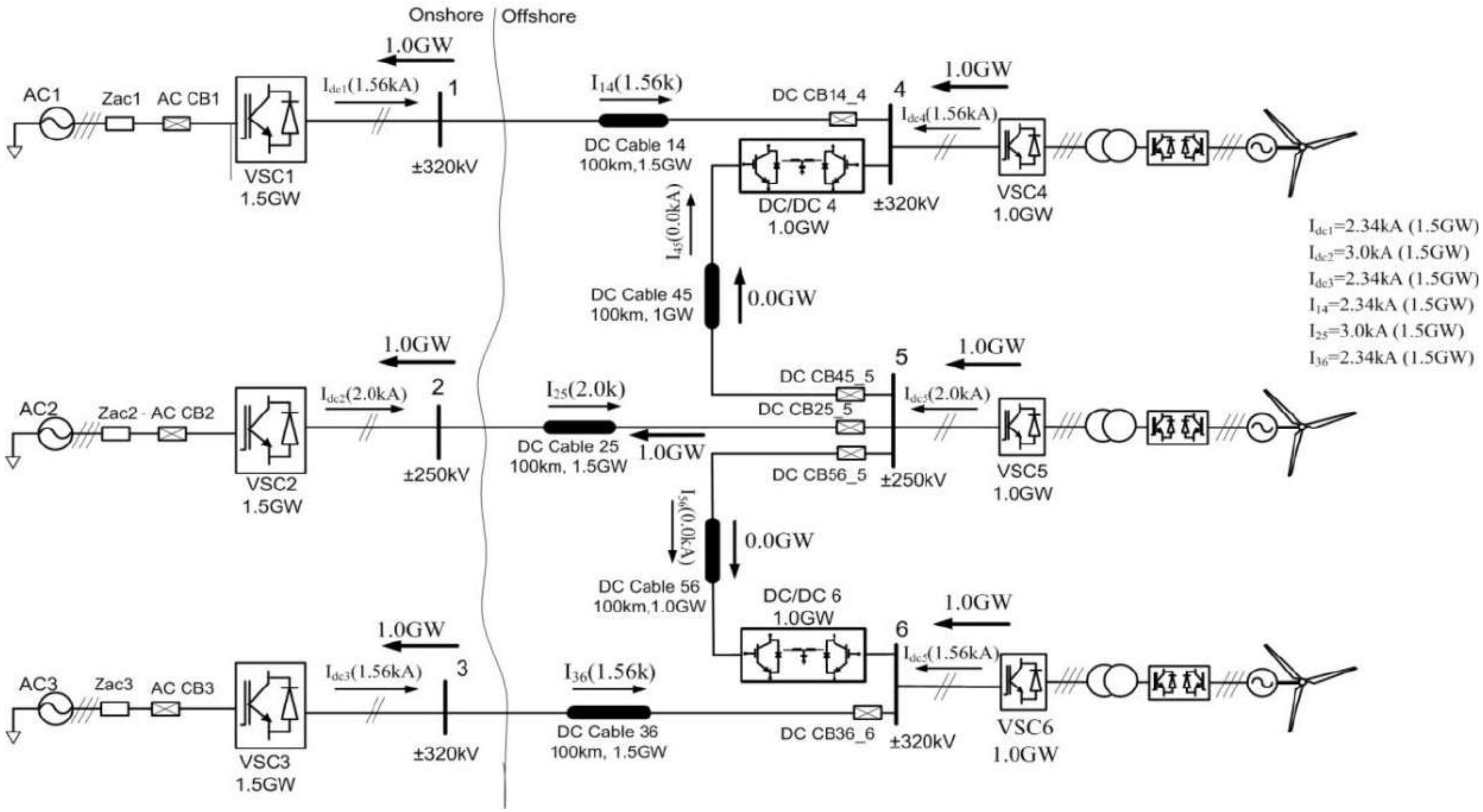
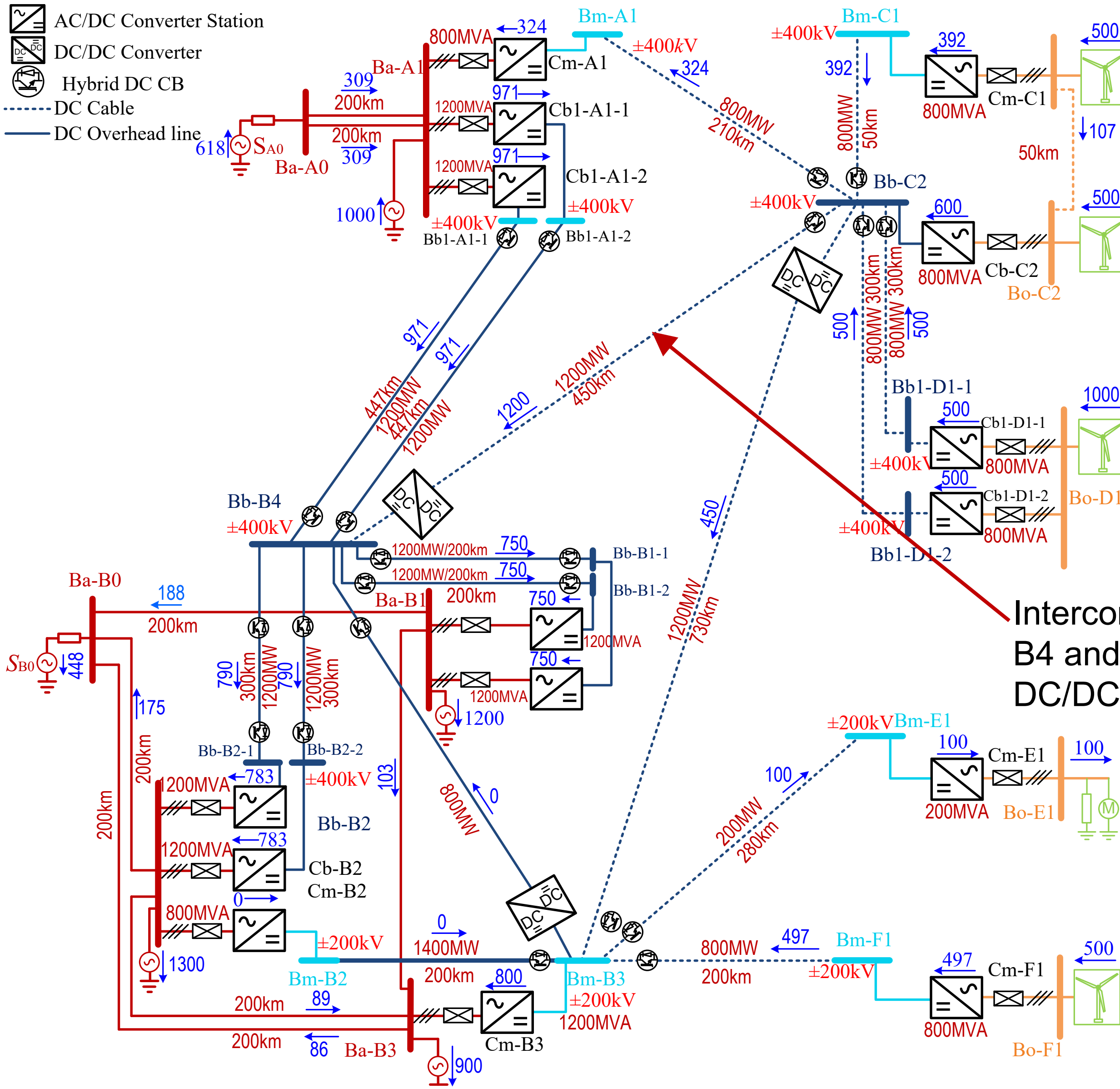


Figure 29. Connecting 3-offshore VSC converters using DC/DC.

2. DC grid components: DC/DC converters



Interconnection between DC bus Bb-B4 and Bb-C2 consisting of: DC/DC, DC line and DC CB

Fig.30. 10-terminal DC grid with 3 local radial DC systems and 3 DC/DC.

2. DC grid components: DC hubs

Multiport, Multiphase DC hub

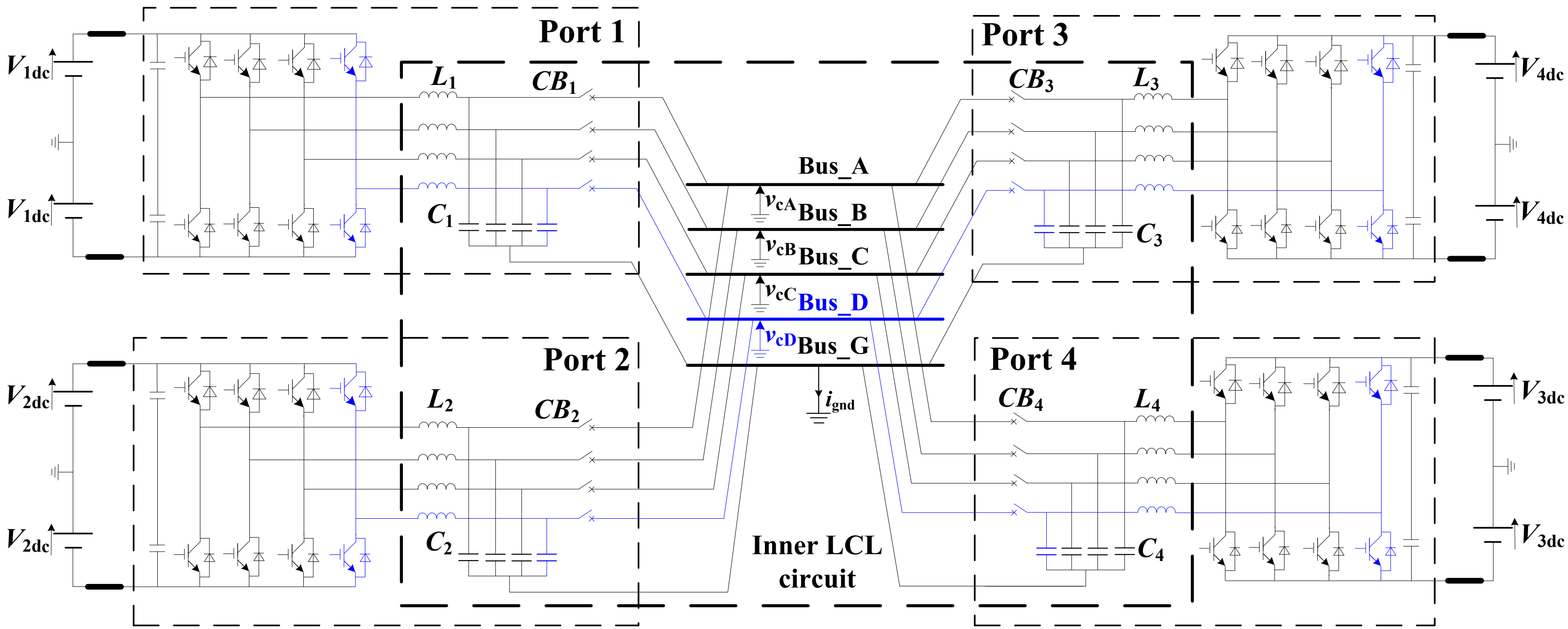


Fig.31. 4-port, 4-phase DC hub

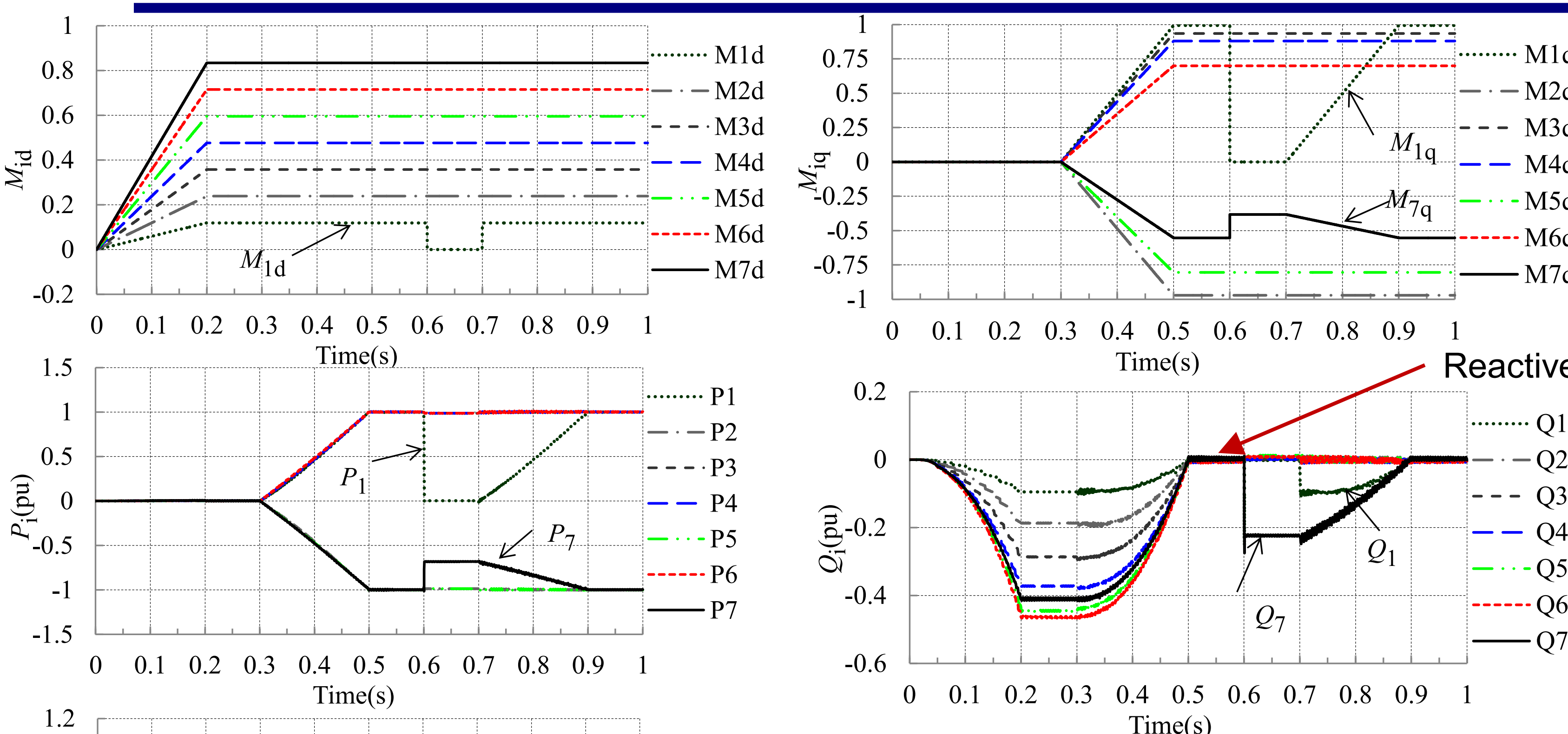
Functionality/Flexibility

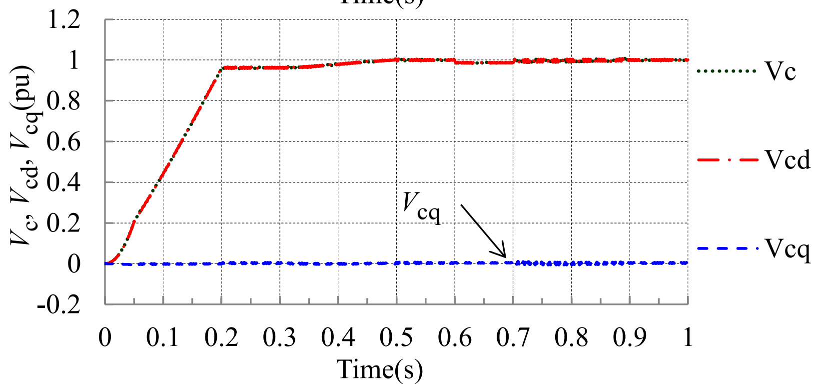
- Each port has different DC voltage,
- Ports can be connected/disconnected without affecting operation of other ports,
- DC fault isolation on each port,

Reliability/Redundancy (n-1 phase operation)

- Disconnect one phase on all ports, and operate as n-1 phase balanced system.
- Operate a redundant phase in stand-by to meet *N*-1 criterion in case single phase fault,
- Use redundant phase to substitute faulted phased/scheduled maintenance of a phase,
- Similar to redundant single ac transformer at transmission substation,

2. DC grid components: DC hubs





- Test system has 7 different DC voltage levels on 7 ports,
- Port1 tripped at 0.6s and reconnected to the hub at 0.7s
- Port7 acts as balancing port
- Reactive power at all ports are zero at rated power
- V_{cd} maintained to 1pu, V_{cq} maintained to 0
- Operation of other ports is not affected

Fig.32. Response of a 7-port test DC Hub to tripping and reconnecting a port

2. DC grid components: DC hubs

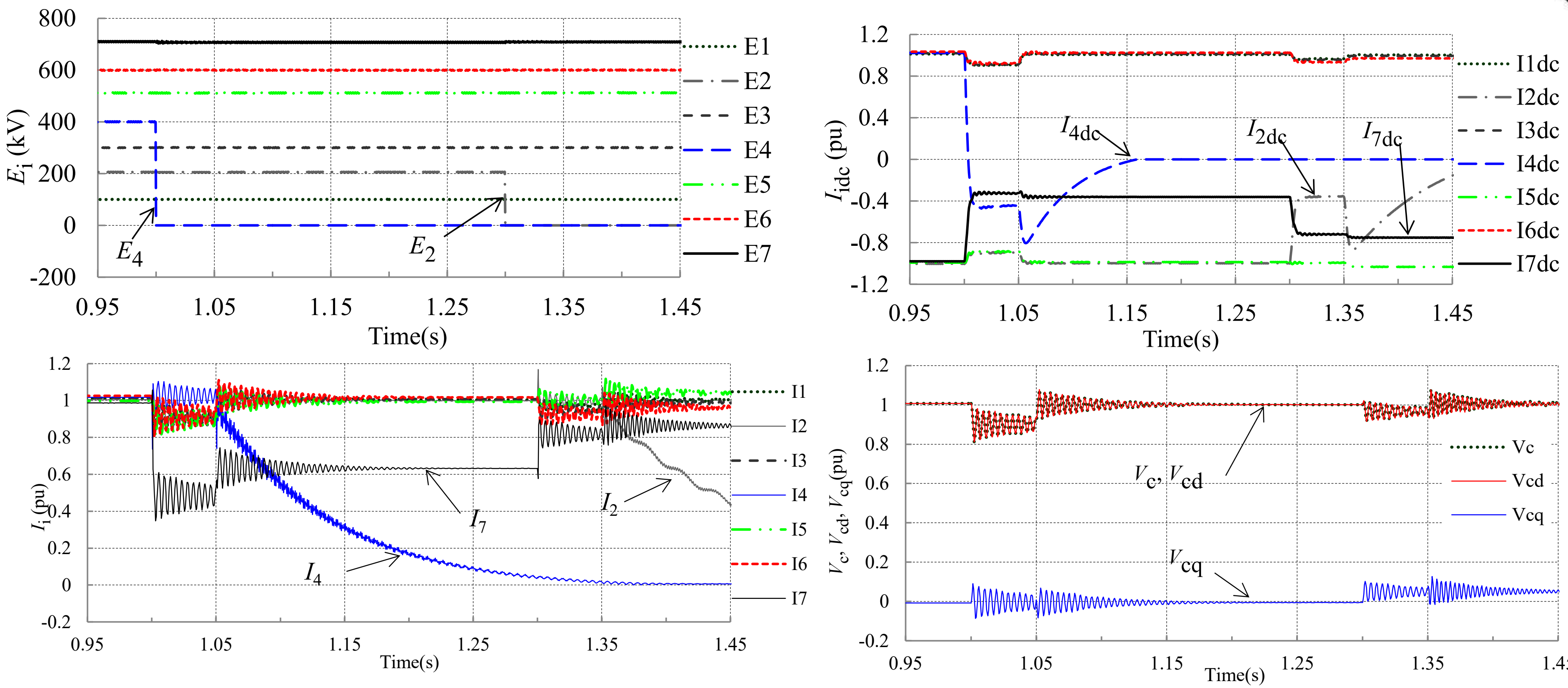
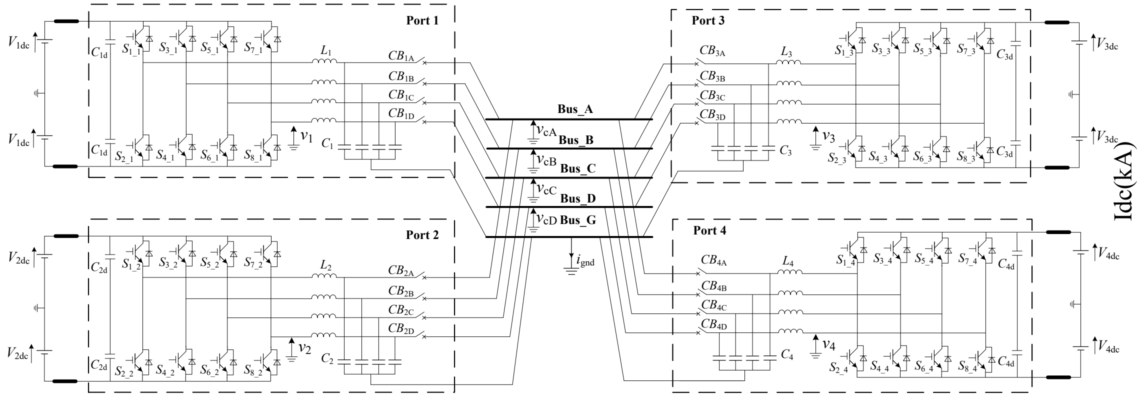


Fig.33. Response of 7-port DC hub to DC faults on two DC lines.

- Port4 subject to dc fault at 1.0s and isolated by CB4 at 1.05s,
- Port2 subject to dc fault at 1.3s and isolated by CB2 at 1.35s,
- No significant overcurrent occurs at the faulted ports and healthy ports,
- Healthy ports do not contribute fault current to faulted port,
- DC voltages at healthy ports stay unaffected,
- Central capacitor voltage maintained during and after dc fault,

2. DC grid components: DC hubs



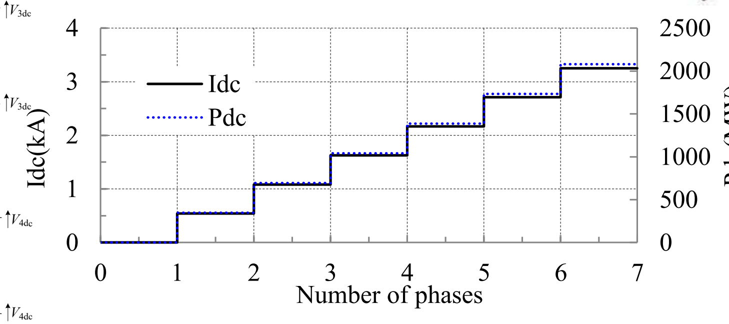
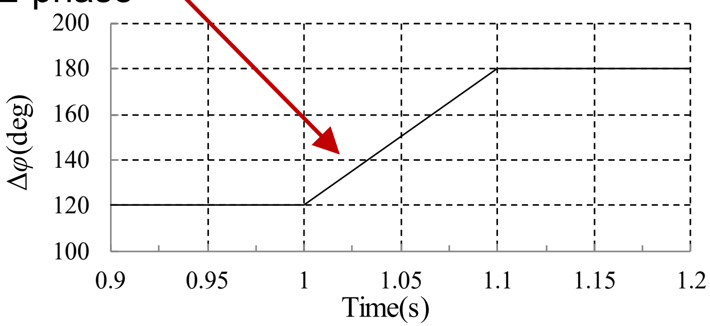


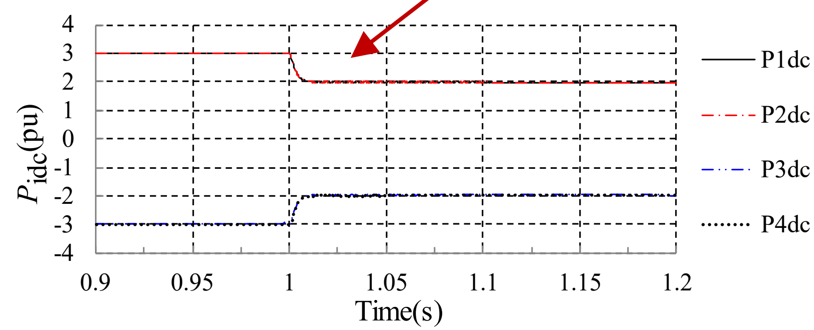
Fig.32. DC Hub power versus number of phases

Transition from 3-phase to 2-phase

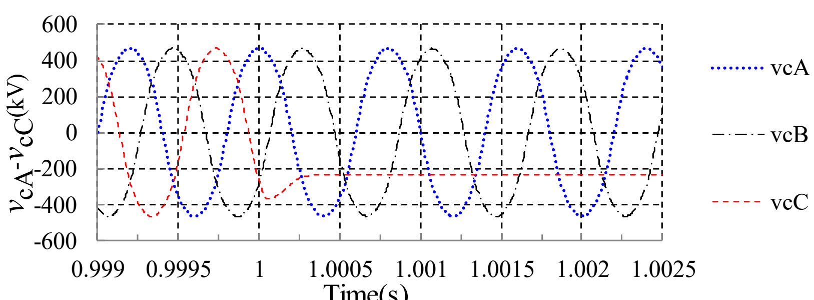
Power reduces by 1/3



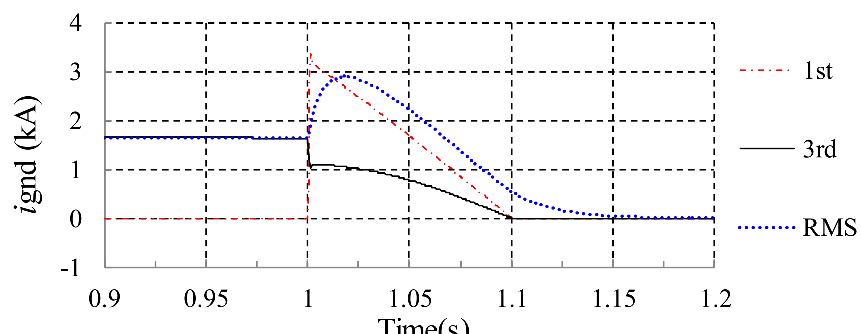
(a) Phase angle difference between each phase



(b) DC power



(c) Capacitor Voltage during phase reconfiguration



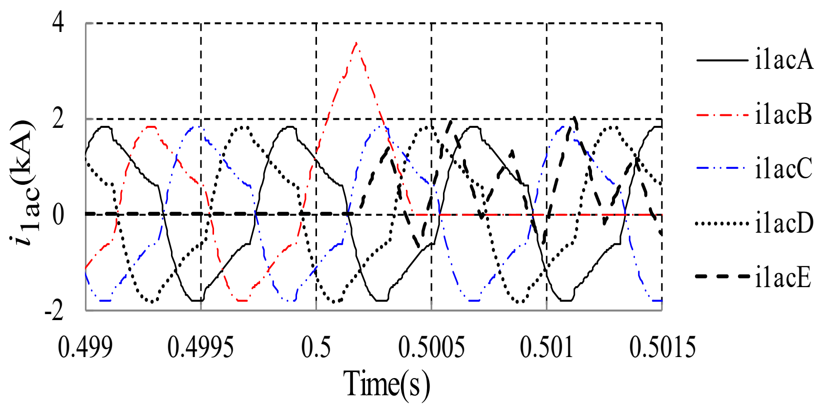
(d) DC hub ground current

Fig.34. Tripping phase C on all 4 ports (Reconfiguration 3->2 phase while in operation)

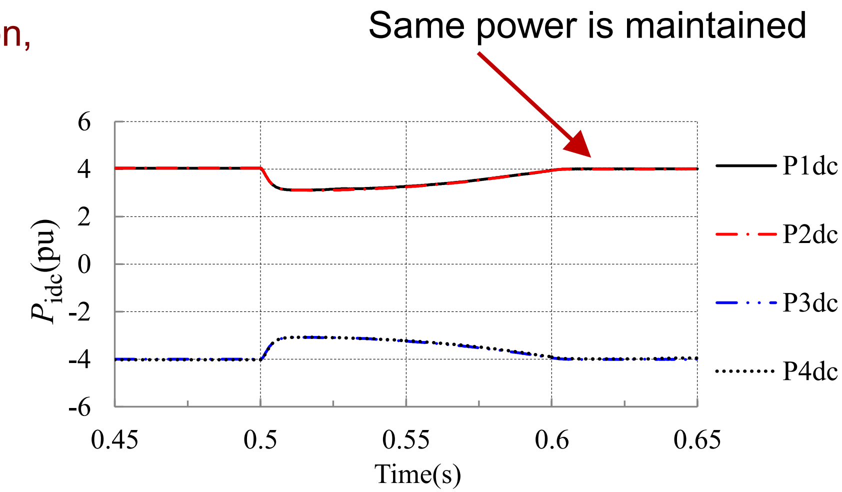
2. DC grid components: DC hubs

3-phase DC hub with a redundant phase

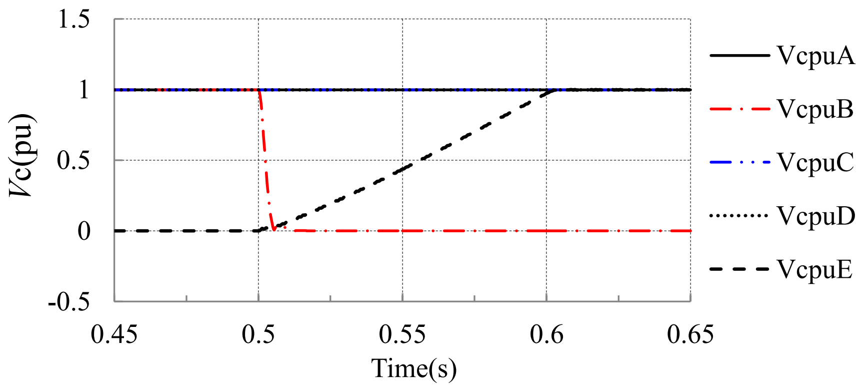
- Redundant 4th phase improves reliability,
- Maintenance of any phase is possible in operation,



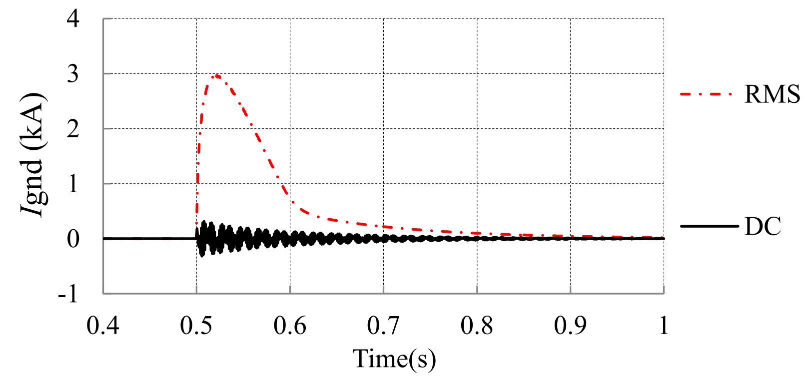
(a) AC current of port 1



(b) DC power



(c) Capacitor voltage of each phase



(d) DC hub ground current

Fig.35. Replacing phase B with redundant phase E on all ports (3-phase, 4 port, DC hub)

2. DC grid components: DC hubs

Multiport DC substations (DC hub) enables:

- Power control in each DC line,
- Faults on each DC line are readily isolated,
- Each DC line can have optimised DC voltage,
- No DC Circuit Breakers,
- Expansion to additional terminals is simple,
- Integration of different VSC/LCC technologies,

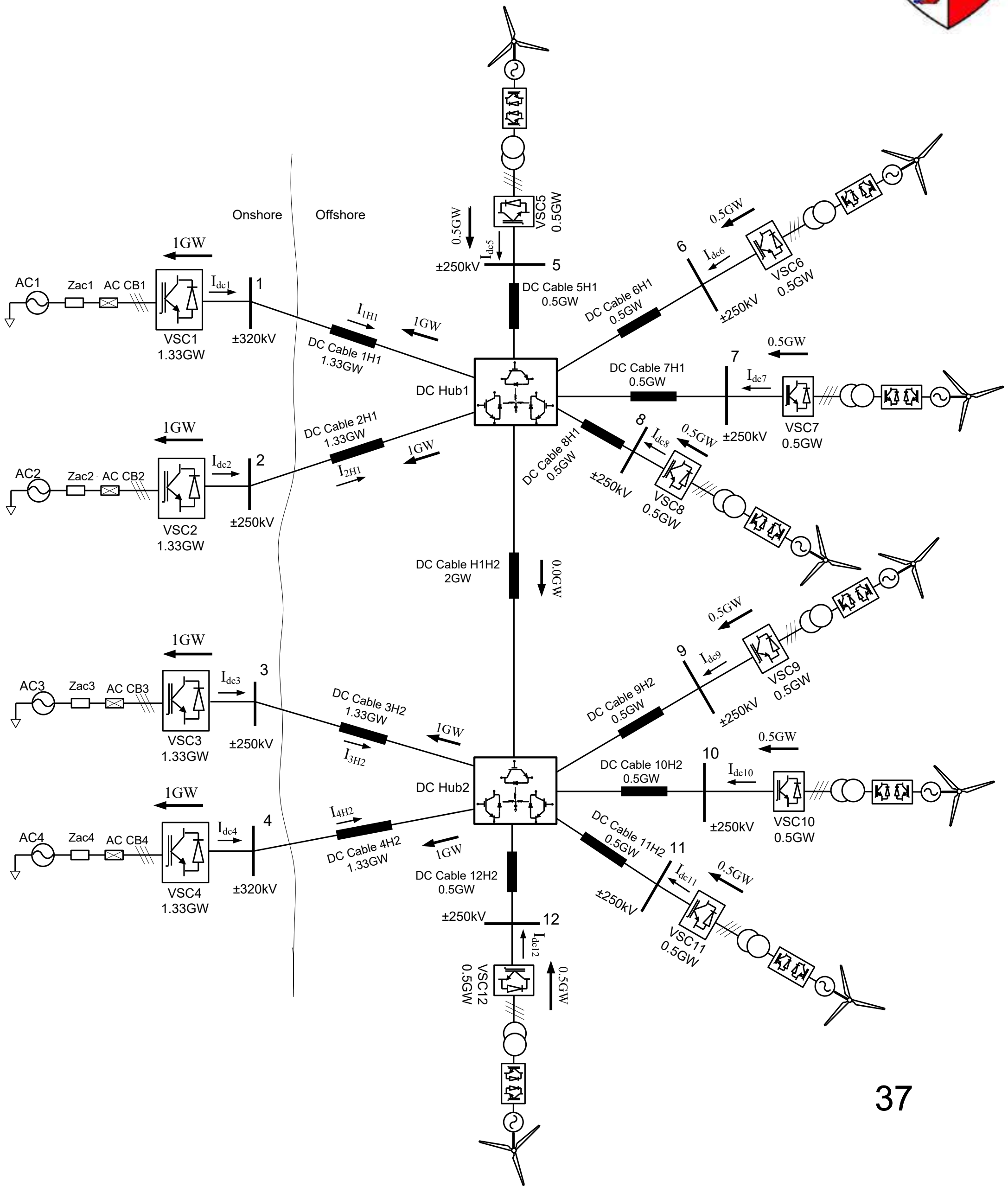


Figure 36. 8-terminal DC grid with 2 DC hubs.

2. DC grid components: DC hubs

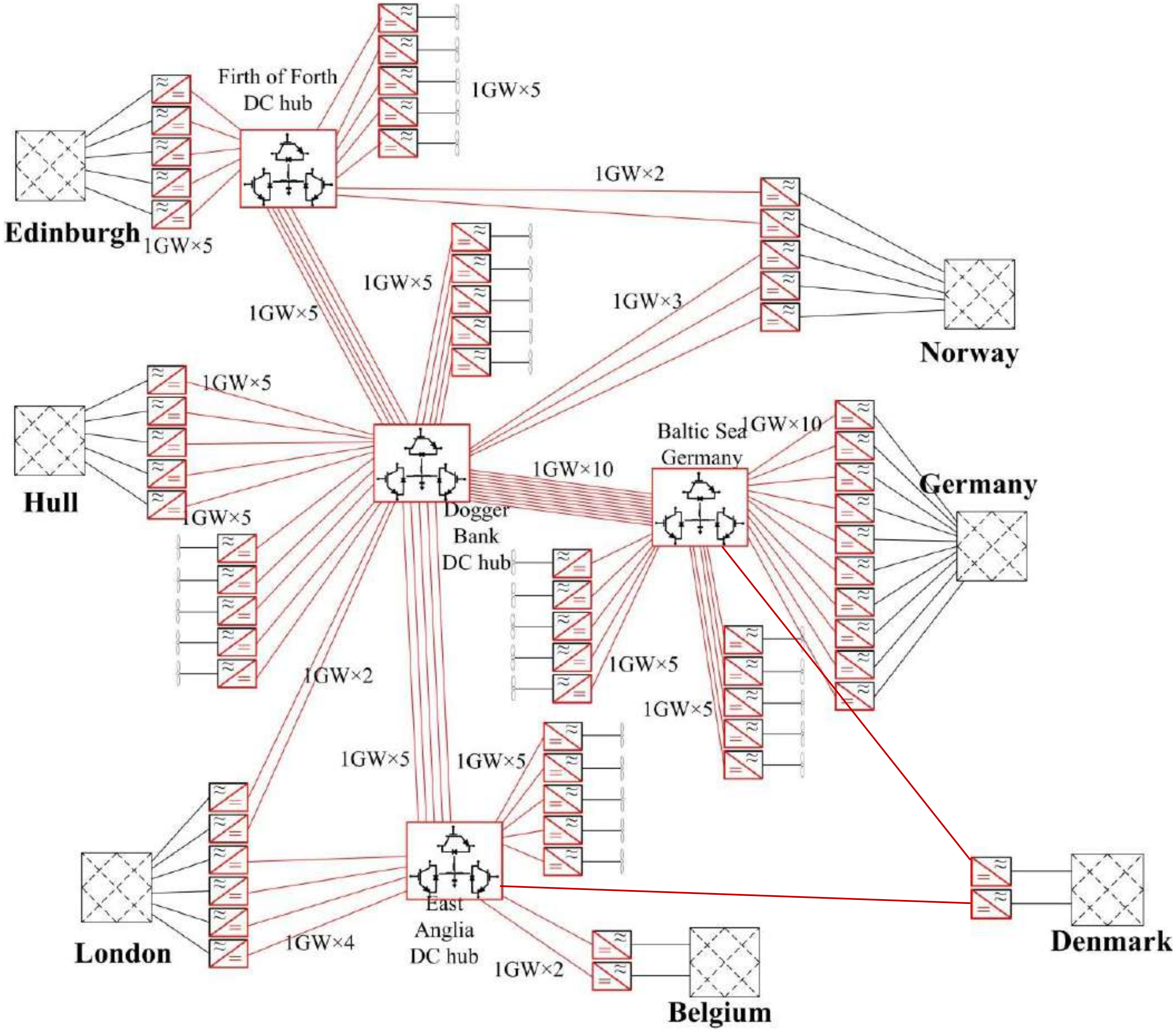


Figure 37. DC supergrid based on multiple DC hubs (no DC CBs).

2. DC grid components: DC hubs

Radial DC grid with onshore DC bus:

- DC bus (hub), and terminals with DC line and DC CB,
- Easily expandable,
- Power trading between terminals (no congestion),
- Ownership framework is simple,
- Protection is reliable and simple,
- Operation and control is based on MMC terminals,
- Interoperability challenge is reduced,

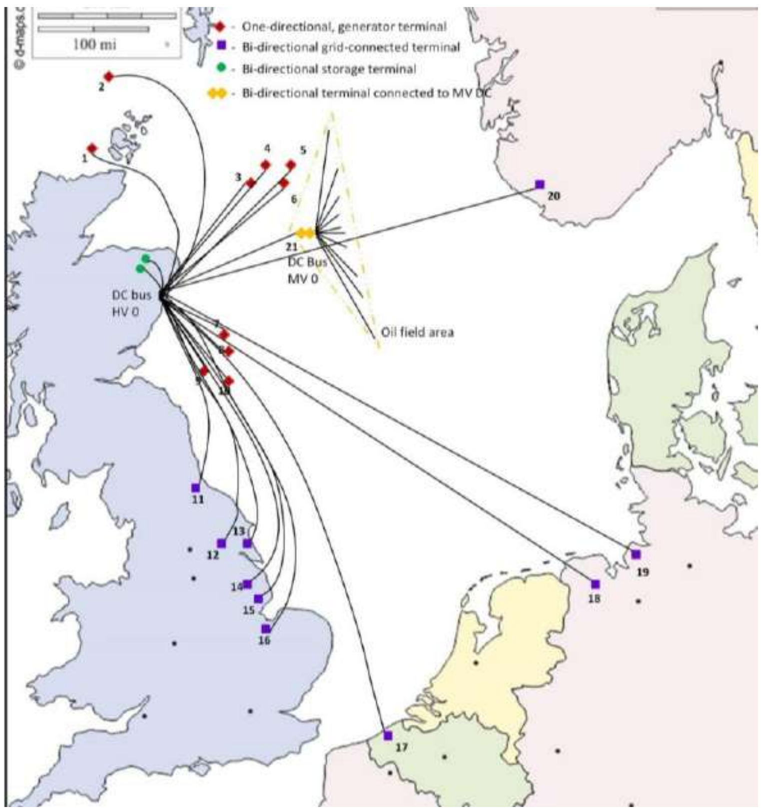
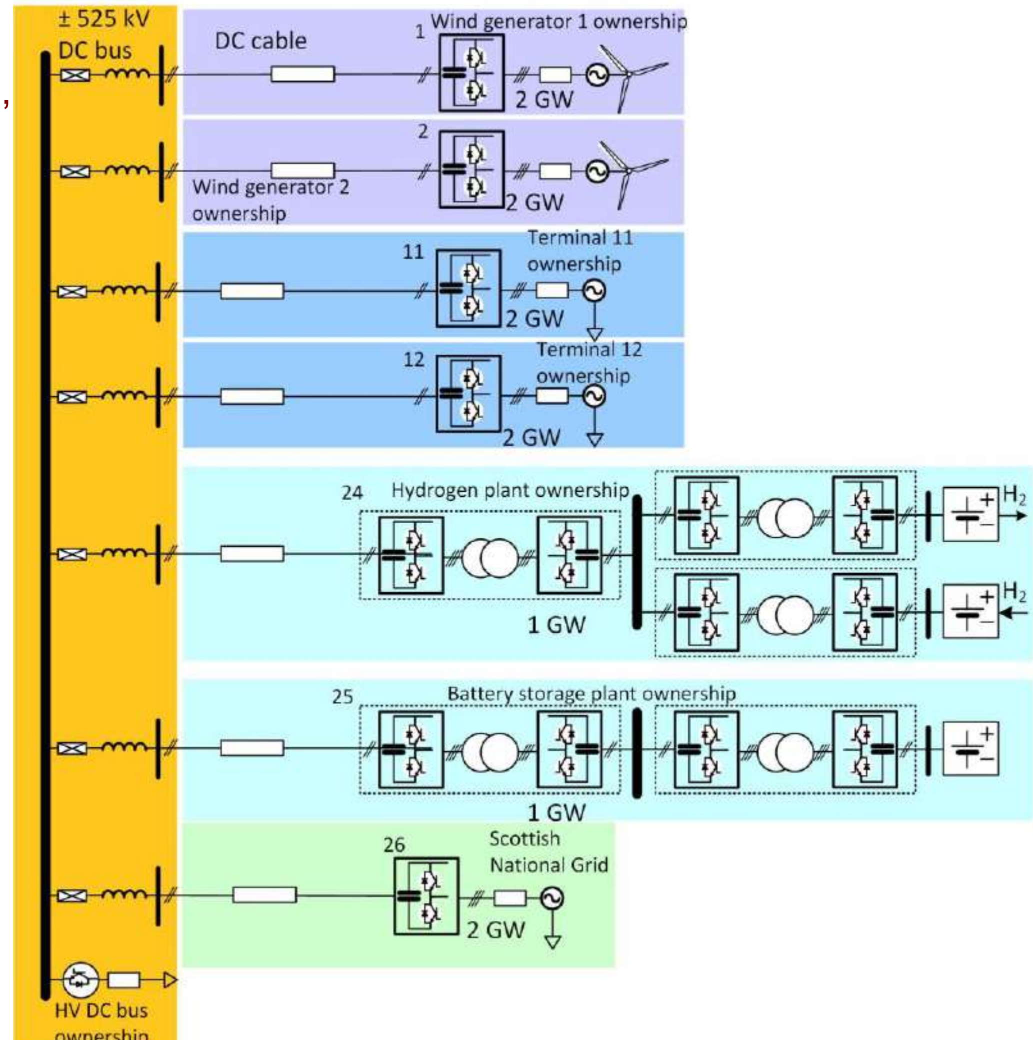
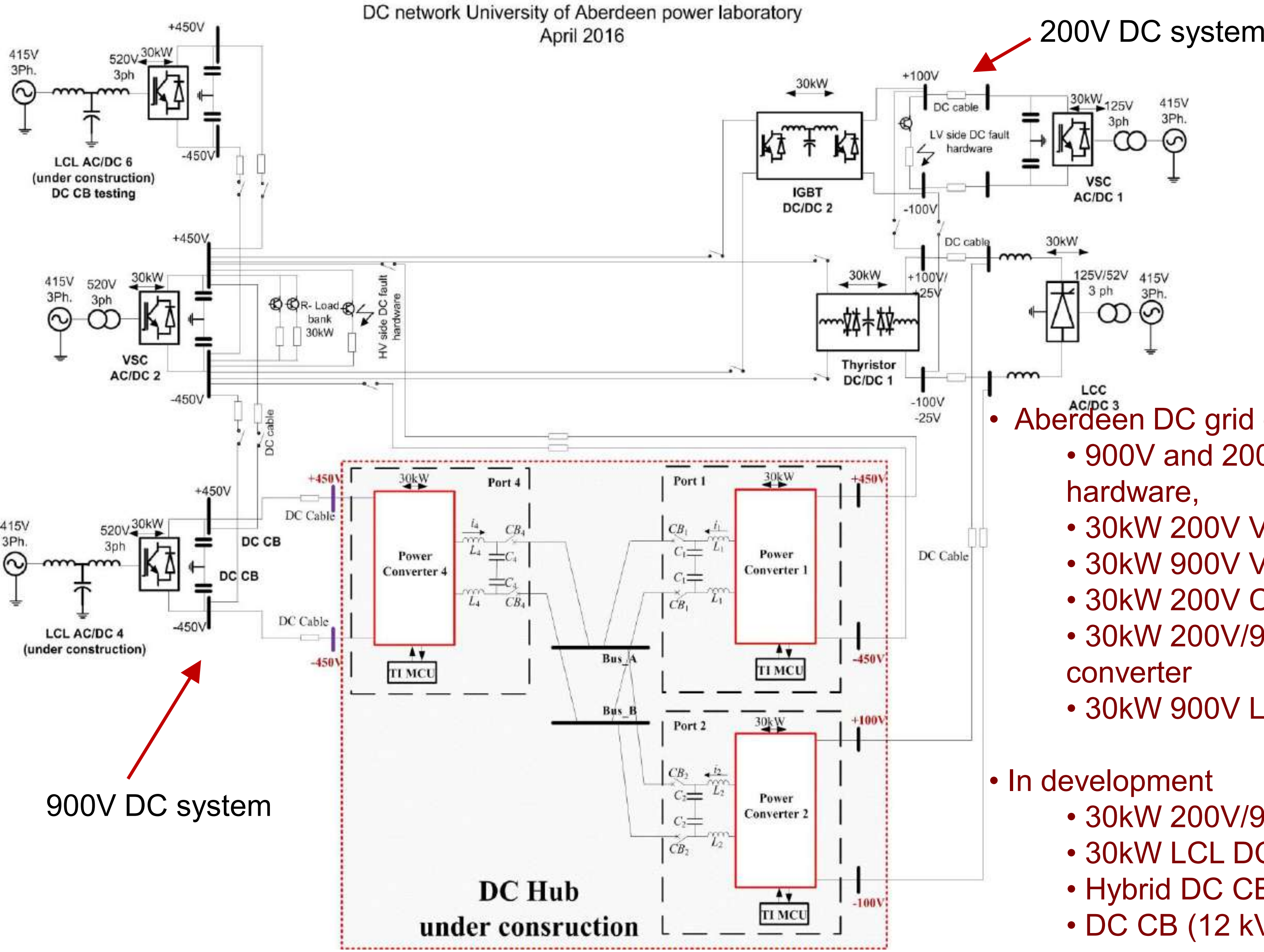


Figure 38. Proposed DC grid in north of Scotland with onshore DC bus (DC hub).



2. DC grid components: hardware demonstrations



- Aberdeen DC grid demonstrator
  - 900V and 200V DC bus with fault hardware,
  - 30kW 200V VSC converter
  - 30kW 900V VSC converter,
  - 30kW 200V CSC converter,
  - 30kW 200V/900V DC/DC converter
  - 30kW 900V LCL VSC converter,
- In development
  - 30kW 200V/900V LCL DC/DC
  - 30kW LCL DC/DC hub,
  - Hybrid DC CB (900V, 500A),
  - DC CB (12 kV 6 kA),

Figure 39. Aberdeen laboratory, 900V DC grid demonstrator schematic.

2. DC grid components: hardware demonstrations

Aberdeen DC grid demonstrator

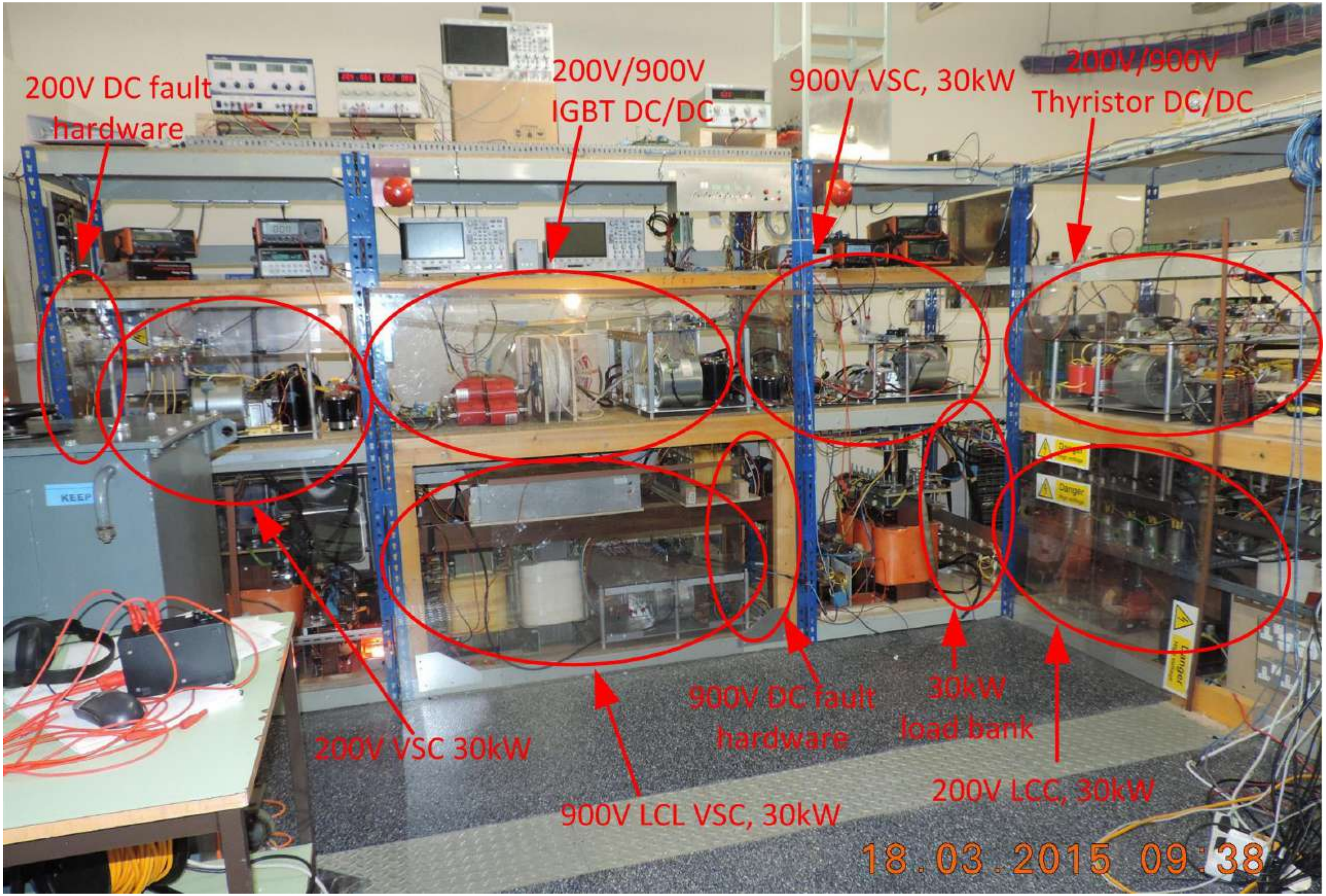
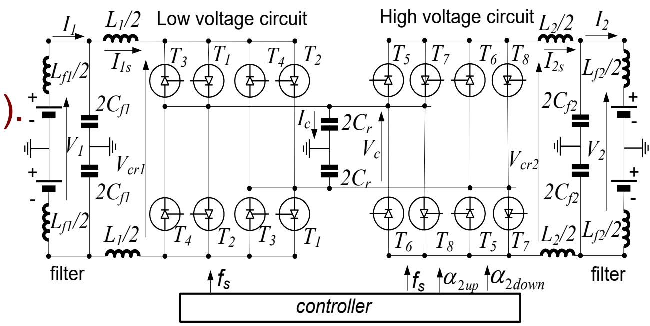


Figure 40. Aberdeen DC test grid. 4 AC/DC converters and 2 DC/DC converters

2. DC grid components: hardware demonstrations

30kW, 200V/900V, thyristor DC/DC converter prototype,

- Semikron 1.8kV, 4x270A and 4x70A, phase control thyristors,
- Litz-wire air-core inductors,
- Texas Instruments microcontroller,
- Efficiency 92-95%. Further improvement might be possible,
- Bidirectional operation. Fast reversal is demonstrated (type I, II).
- Ride through and isolation of DC faults demonstrated,
- Total weight is around 42kg,
- Operating frequency 580Hz,



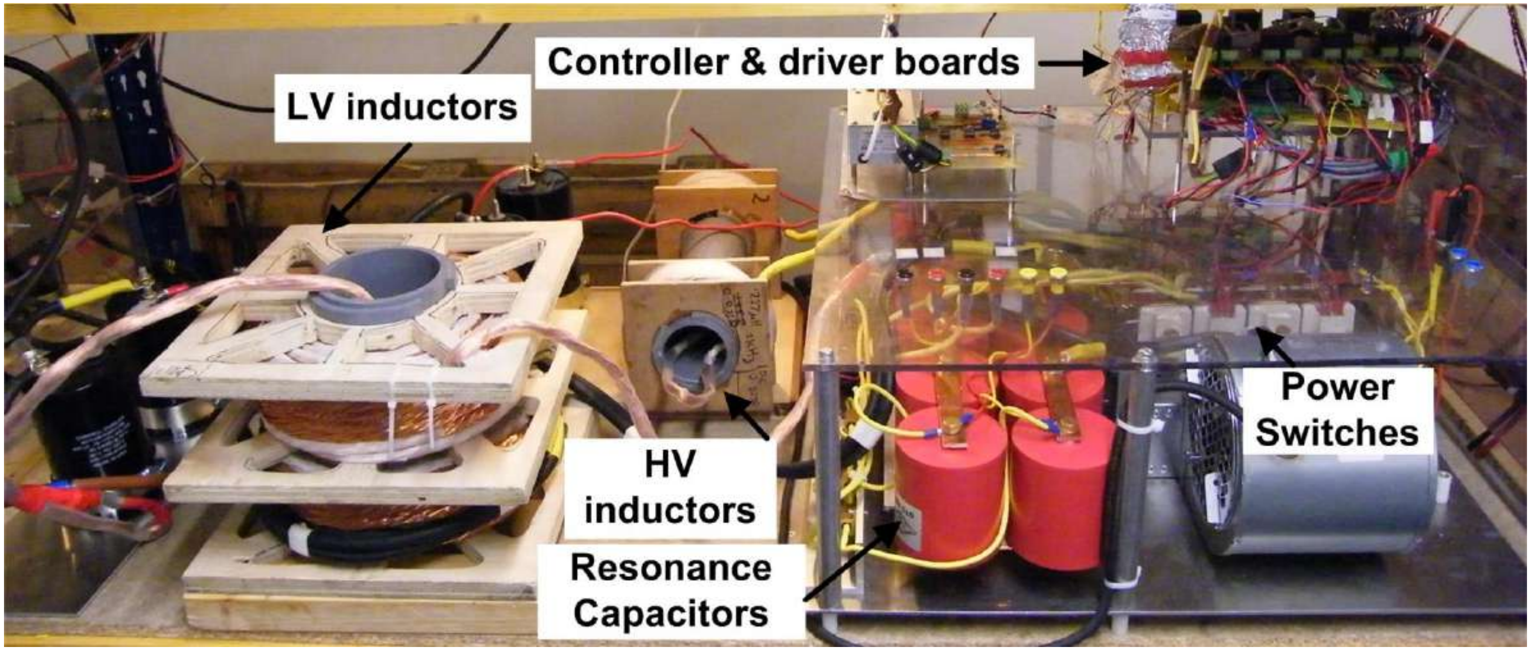
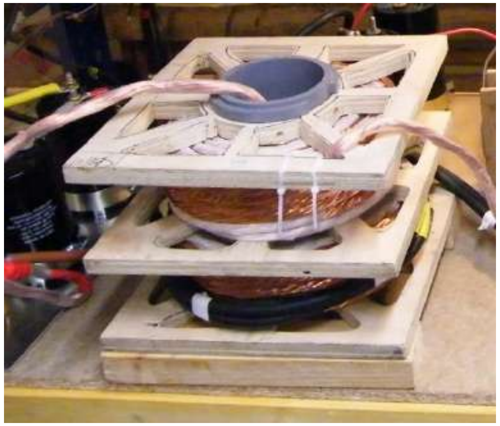


Figure 41. 30kW, 200V/900V, non-isolated, thyristor DC/DC converter.

2. DC grid components: hardware demonstrations

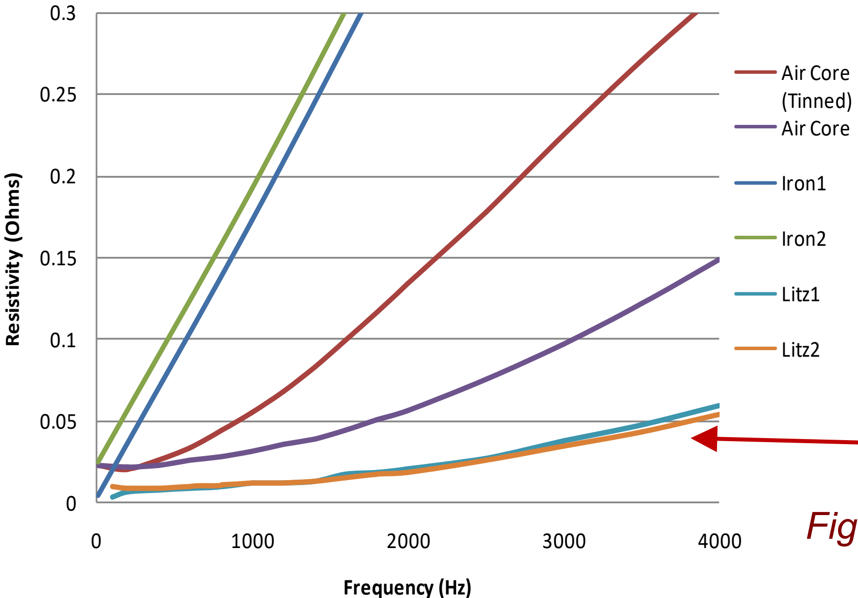
Inductor design for high current and high frequency:



Iron core inductors
Inductance: 385 μH
Weight: 22 kg (x2)
Volume: 6800 cm³

Air core inductors
(stranded copper)
Inductance: 290 μH
Wire Area: 33 mm²
Weight: 10 kg (x2)
Volume: 8750 cm³

Air core inductors
(Litz wire 275x0.4mm)
Inductance: 325 μH
Wire Area: 42 mm²
Weight: 12 kg (x2)
Volume: 7840 cm³



Reducing losses in high-power high-frequency inductors:

- Air core eliminates core loss,
- Litz wire reduces skin effect and copper losses,

Only Litz wire provides low loss at high frequency

Figure 42. Inductor resistance versus frequency

2. DC grid components: hardware demonstrations

DC grid component testing:
- DC/DC converter full power operation in step up mode
- DC/DC converter full power operation in step down mode
- Peak LV current is 283A, peak HV current is 101A.
- Thyristor reverse recovery increases losses and limits operating frequency (<600Hz).

DC/DC type I power reversal:
- LV Voltage reversal (200V -> -200V),
- HV current reversal (30A -> -30A),
- 25kW to -25kW reversal in around 100ms,

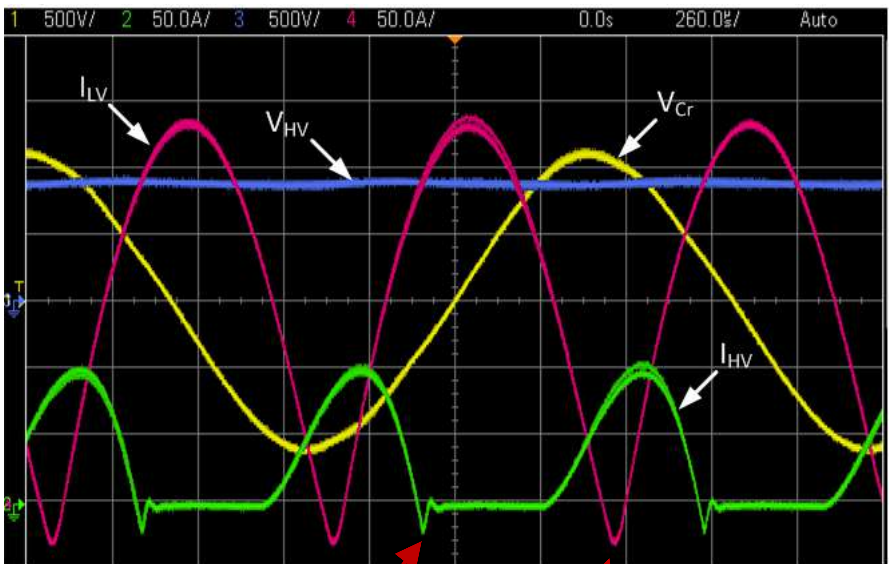


Figure 43. full power operation in step up mode

Thyristor reverse recovery

Zero current switching

DC current reversal

DC voltage reversal

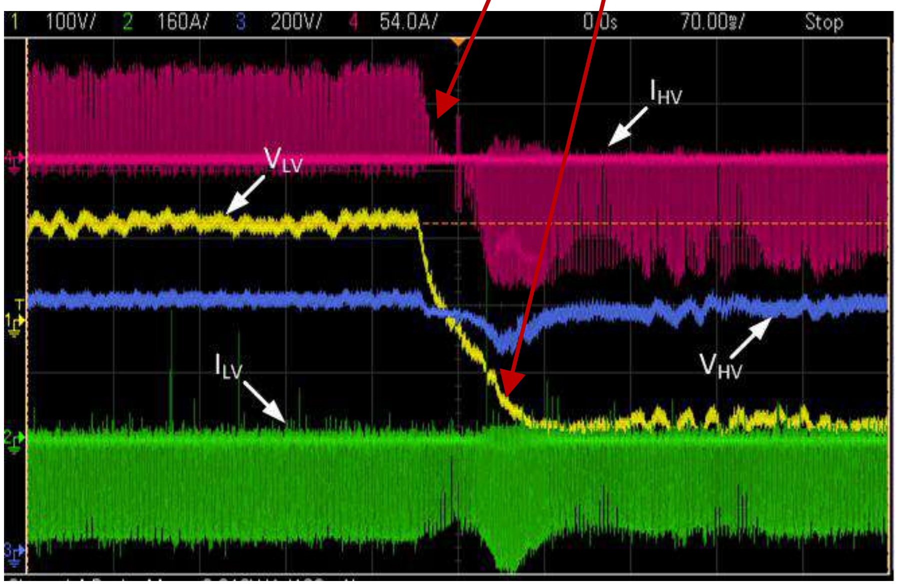


Figure 44. power reversal in type I operation (step up to step down)

2. DC grid components: hardware demonstrations

DC/DC converter testing for DC faults:

- Almost zero impedance DC faults at 25kW power transfer,
- Converter rides through DC faults,
- No need for DC Circuit Breakers,
- No need for special fault controls in DC/DC,
- Power transfer is inherently reduced for DC faults,

Peak Current is acceptable

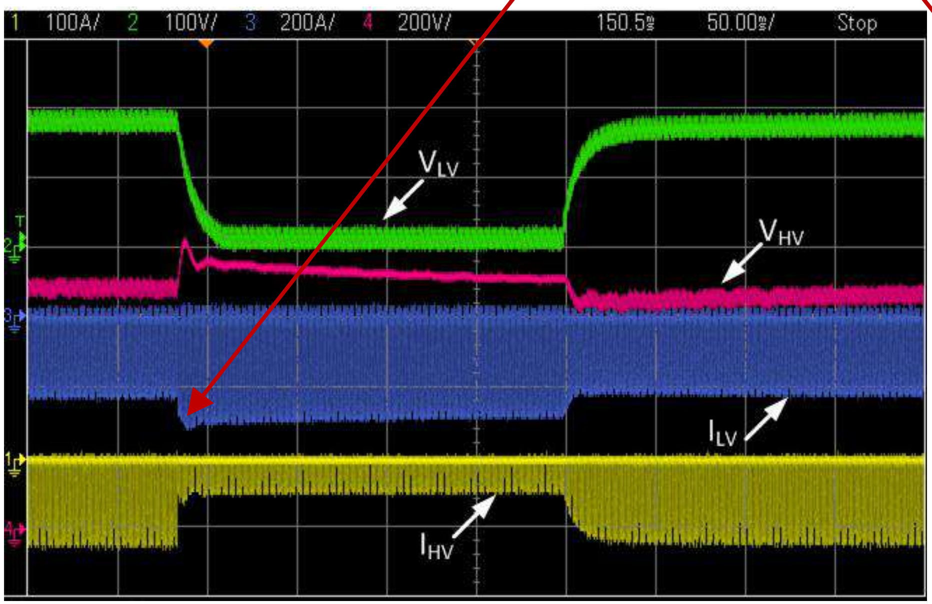


Figure 45. 200V DC bus fault

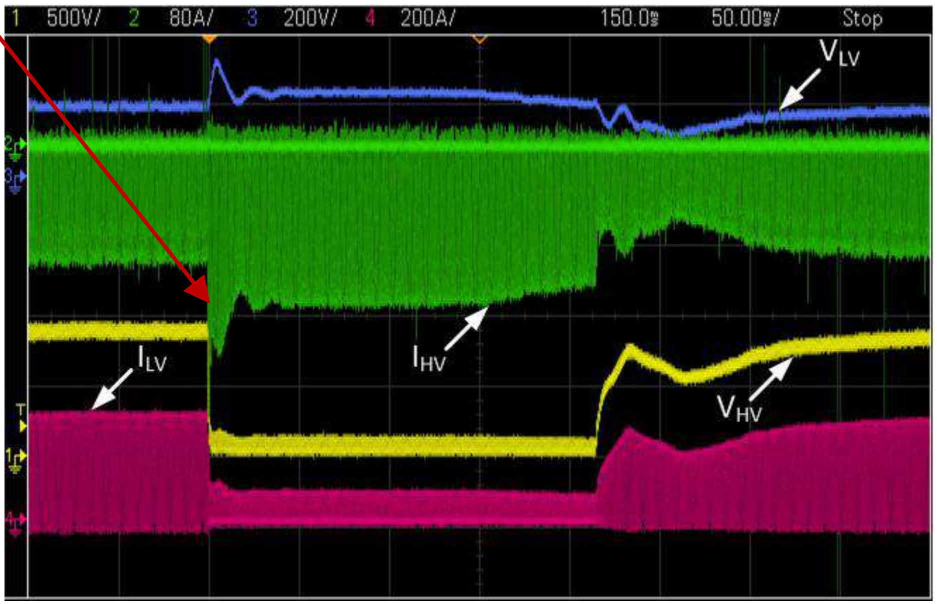
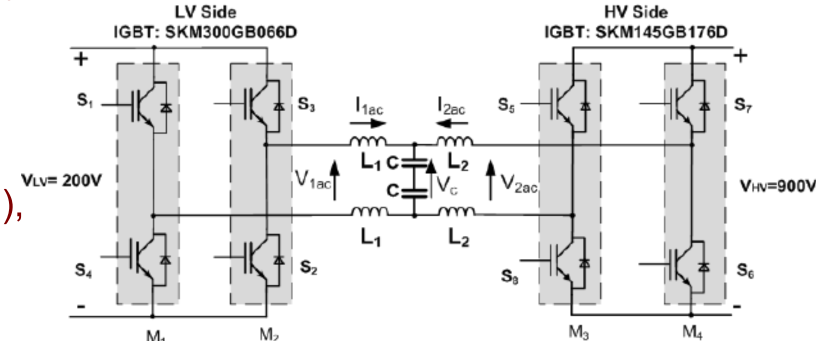


Figure 46. 900V DC bus fault

2. DC grid components: hardware demonstrations

LCL IGBT-based DC/DC converter prototype

- VLV=200V. VHV=900V. P=35kW.
- Operating frequency is 1.7kHz. Switching frequency 3x1.7kHz.
- Low voltage switches: IGBT SKM 300GB066D, (300A, 600V).
- High voltage switches: IGBT SKM 145GB176D, (120A, 1700V).
- AC capacitor of 22μF, (3x2x2) film capacitors, 10kg,
- LV side inductor of 2x205μH, 200A, Litz Wire, 14kg,
- HV side inductor of 2x390μH, 44A, Litz wire, 7kg,
- Total weight is around 35kg,
- Only symmetrical voltage reduction (no monopolar application),



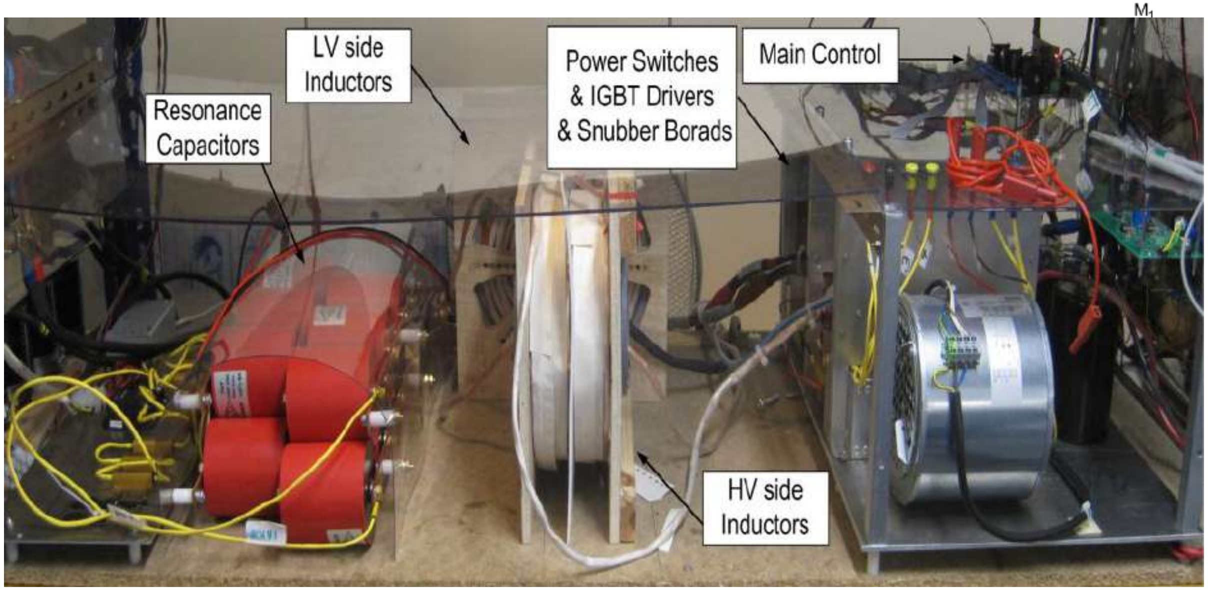
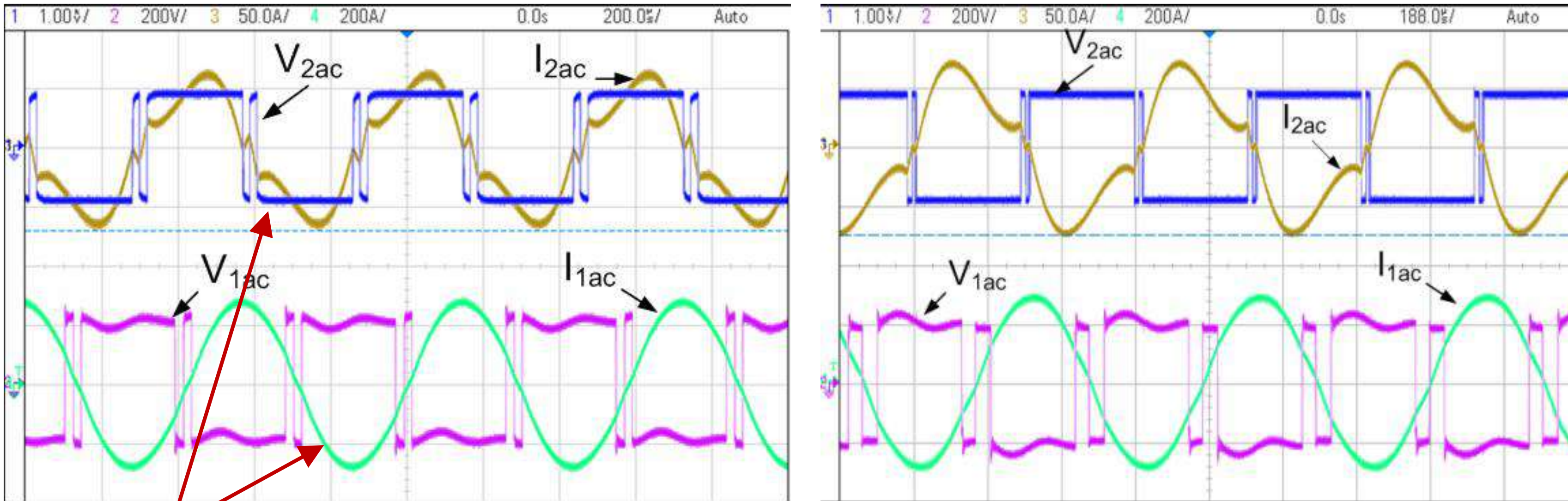


Fig.47. 35kW 200V/900V prototype IGBT based LCL DC/DC converter

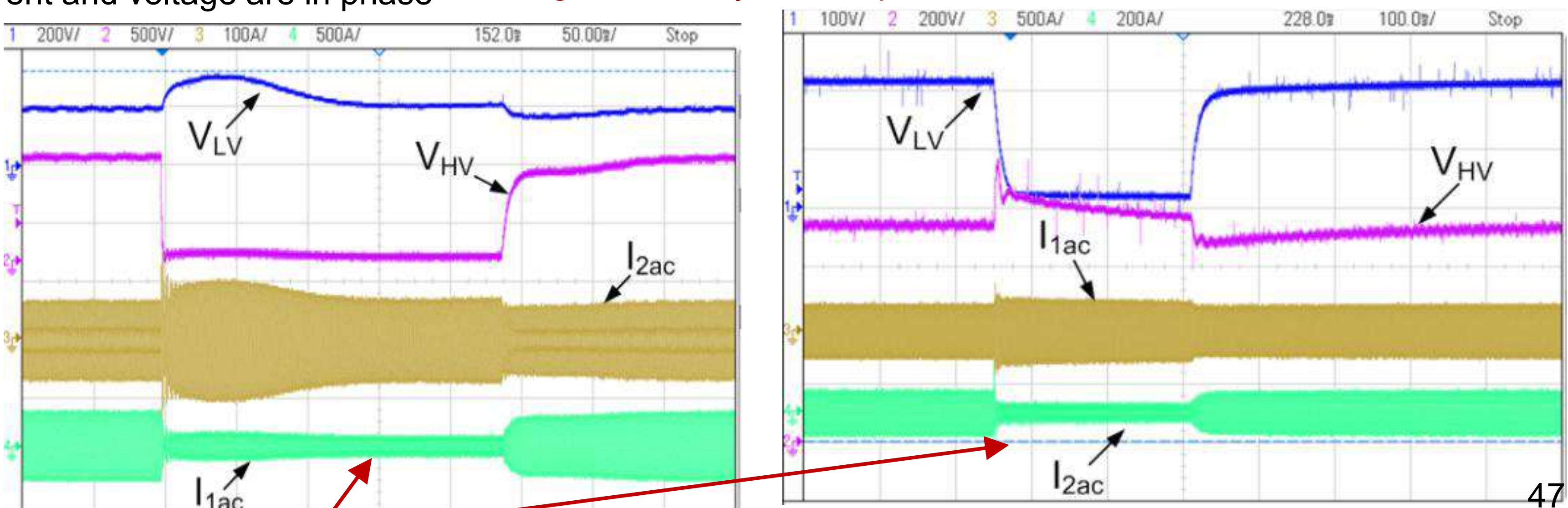
2. DC grid components: hardware demonstrations

Step up mode | **Step down mode**



Current and voltage are in phase

Fig. 47. Steady state experimental test results at 30kW.



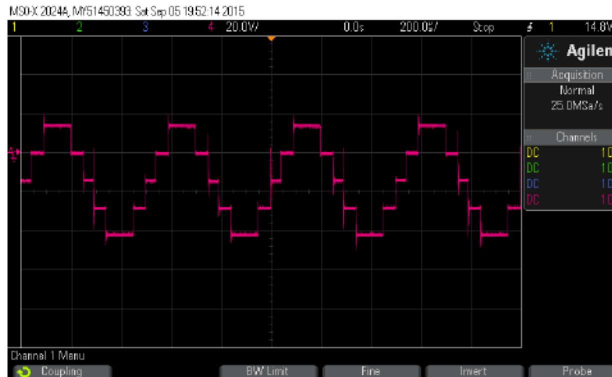
Good current response for DC faults

Fig. 48. Experimental DC fault response at full power.

2. DC grid components: hardware demonstrations

Modular Multilevel DC/DC converter

- 2, 30kW MMC,
- 5-level MMC,
- 8 HB cells in each arm,
- 2-phase configuration,
- 1700Hz fundamental frequency,
- LCL inner circuit,
- controlled by 4 FPGAs,
- Third terminal in development,



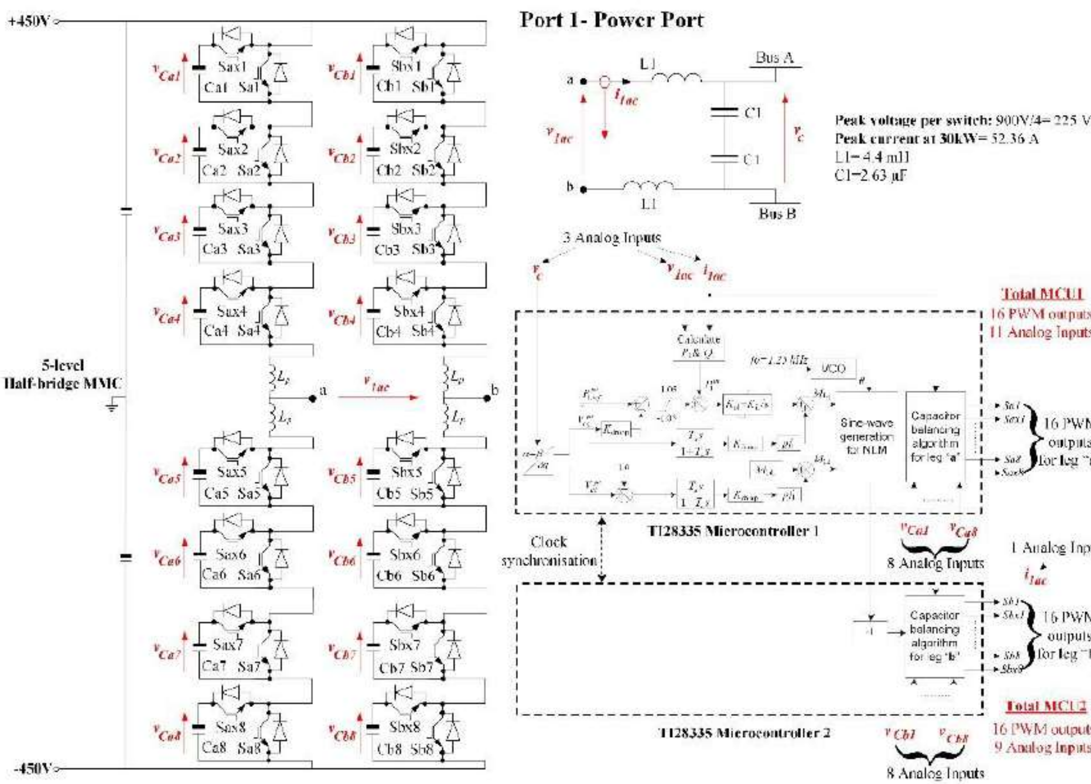
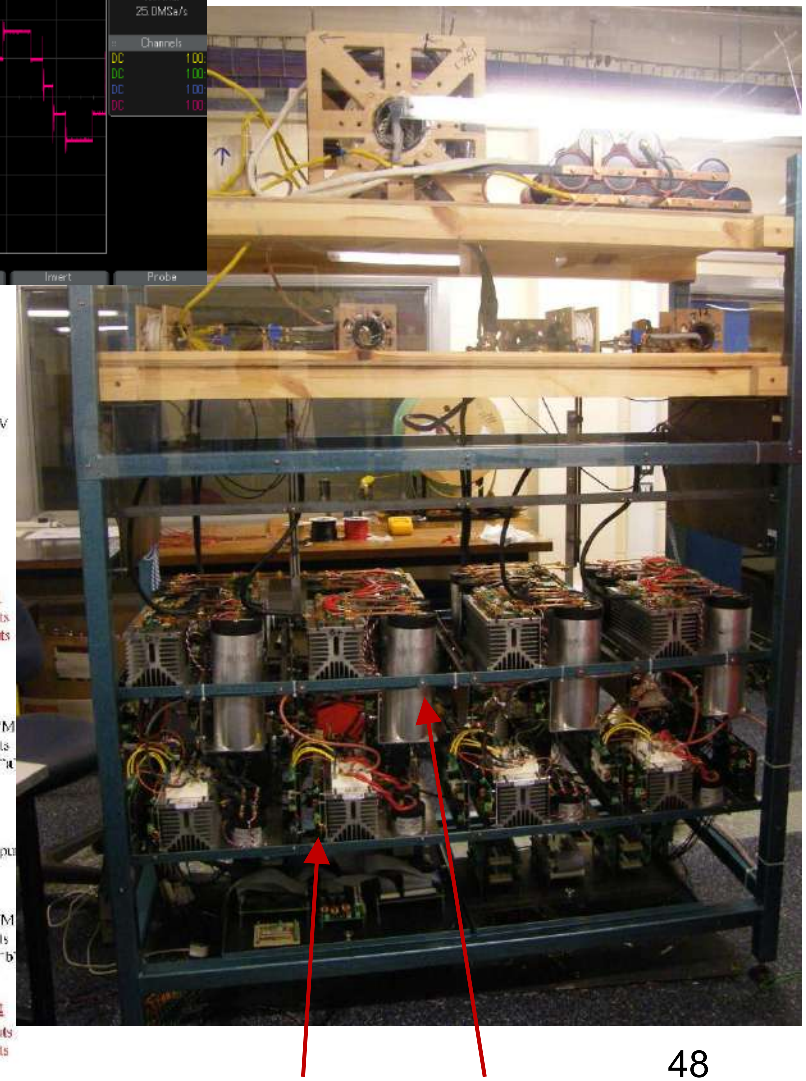


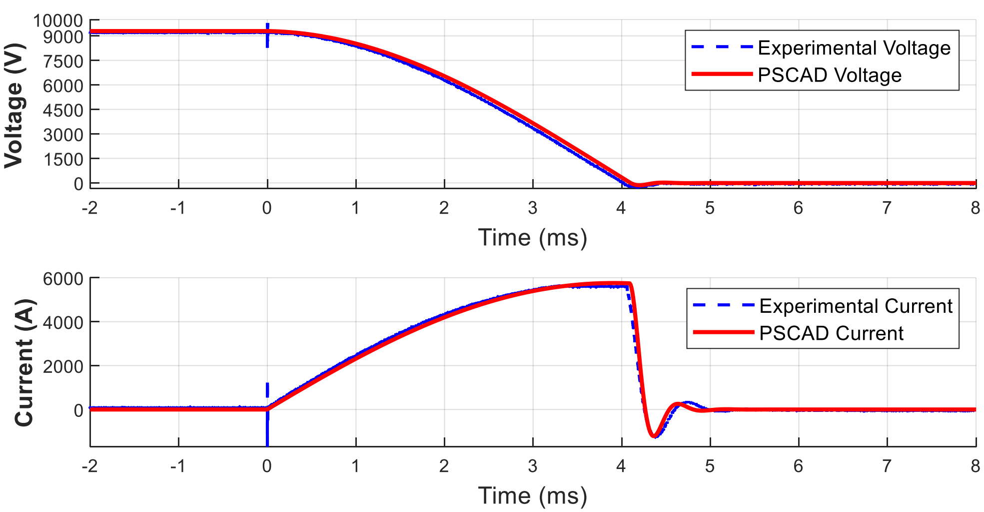
Figure 49. 30kW, 200V/900V, 5-level MMC based DC/DC converter



2. DC grid components: hardware demonstrations

12 kV, 5-15 kA DC test circuit and Medium Voltage DC CB development

- Flexible DC CB test circuit:
  - 3-12 kV,
  - 5-15 kA,
  - 144 kJ,
- MISSION EU project
  - LCL DC CB 12 kV TRL3-5,
  - G&W commercial prototype 12 kV, 6 kA, TRL 6,
- MoWiLife EU project,
  - Hybrid DC CB with SiC MOSFETS,
  - Infineon 2.6 kV, 1 kA SiC MOSFETs,
  - 3-9 kV, 5-15 kA
- DC CB for railways,
  - 0.8-3.6 kV, 10- 30 kA

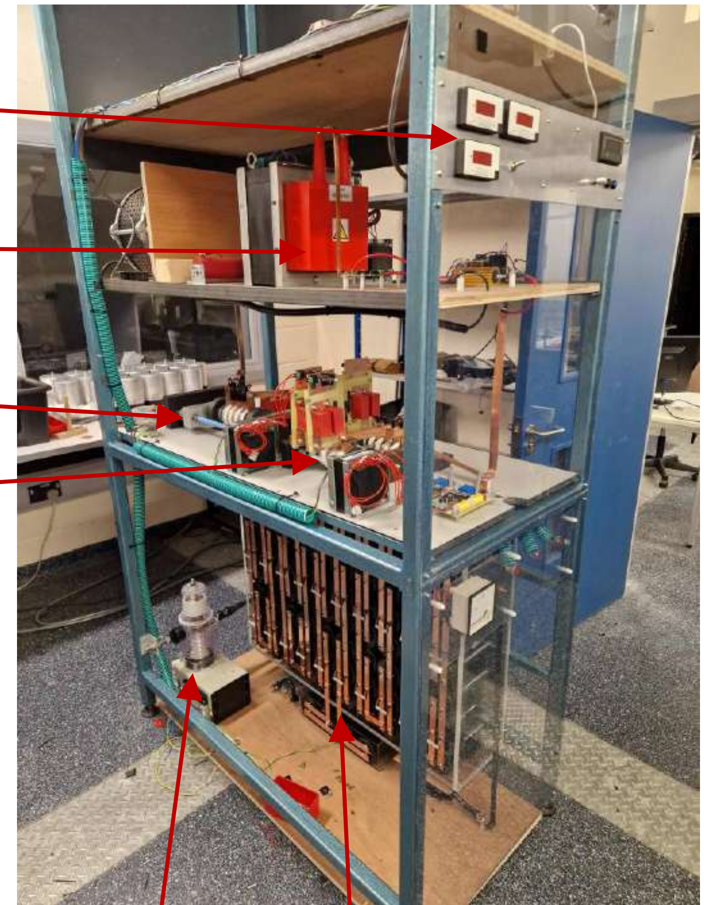


Control panel

12 kV charging circuit

21 kV discharge thyristor valve

21 kV bypass diode valve



Safety 12 kV AC CB

30x3, 12 kV, 144 kJ DC capacitor bank

Figure 50. 12 kV, 7 kA, 144 kJ, DC CB test circuit and discharge response.

3. DC grid modelling challenges

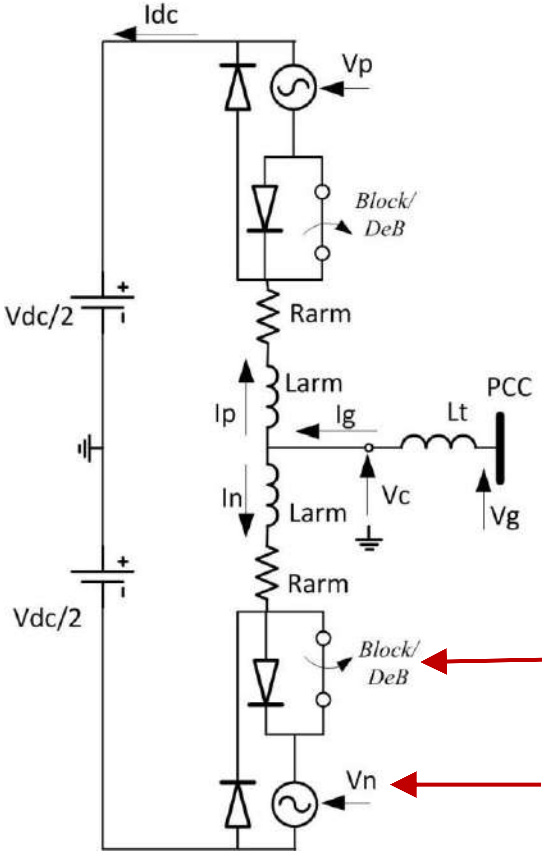
- Future DC grids will include numerous MMC AC/DC converters,
- Detailed EMT- models may not have adequate simulation speed and capacity,
- Average EMT modeling (PSCAD,EMTP)
  - Nodal approach (Dommel method). Good for system that frequently change topology.
  - Significantly improves simulation speed, but simulation is still very slow,
  - CIGRE 10 terminal DC grid model, 20s of real time takes 4 hours simulation using average model (20μs).
  - Only trial and error is available in time domain,
  - Simulation time directly depends on the system size.
  - Eigenvalue studies or frequency domain studies are not possible,
  - Medium frequency (300Hz-1000Hz) will be used in the dc/dc converter to reduce size,
  - Simulation step needs to be small enough to comply with the fastest sampling in the dc/dc converter,
- Analytical state-space (non-) linear models
  - State-space model format, (simultaneous solution of dynamic equations).
  - Significantly faster simulation,
  - Eigenvalue studies,
  - Challenges with systems that frequently change topology,

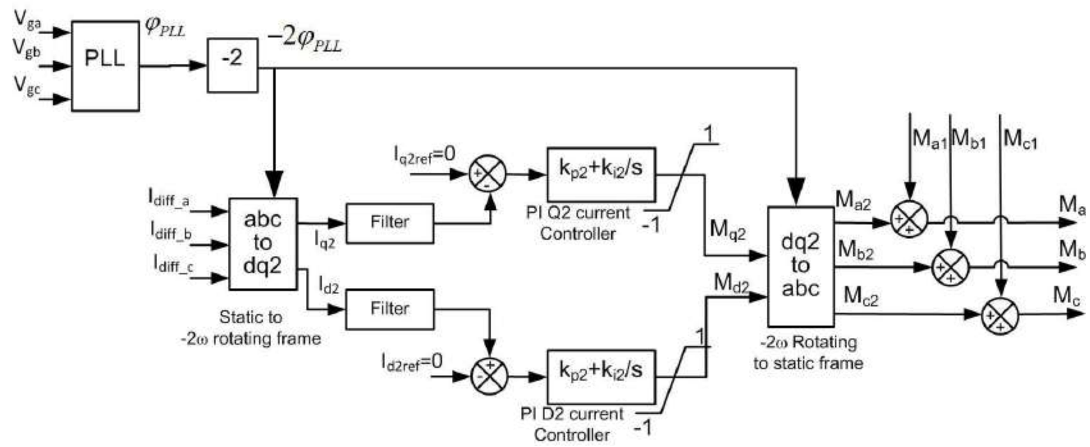
MMC model	Cell faults	Capacitor balancing	Blocked state	Eigenvalue studies	Simulation speed
Detailed cells	yes	Yes	Yes	No	Very slow
Average arm	No	Yes	Yes	No	Slow
Average arm equivalent	No	No	Yes	No	Acceptable
Analytical DQ linearized	No	No	No	yes	Fast

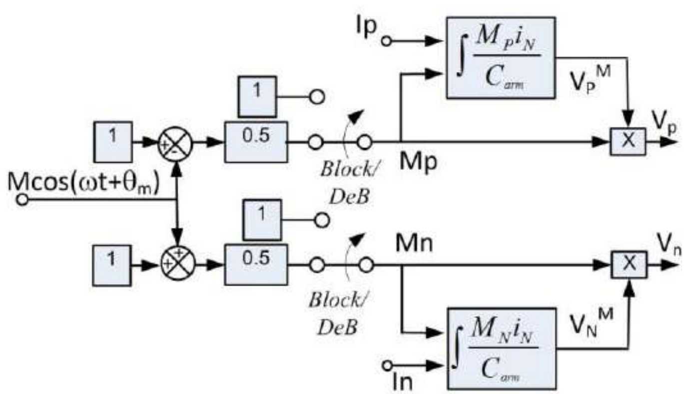
3. DC grid modelling challenges

ABC frame average HB MMC model

- Only time domain simulation,
- Eigenvalue study is not possible,
- Power flow (phasor) study is not possible,
- Frequency domain study is not possible,
- Parametric studies are not possible,
- Unbalanced operation is possible,







Only one topology change (block/deblock)

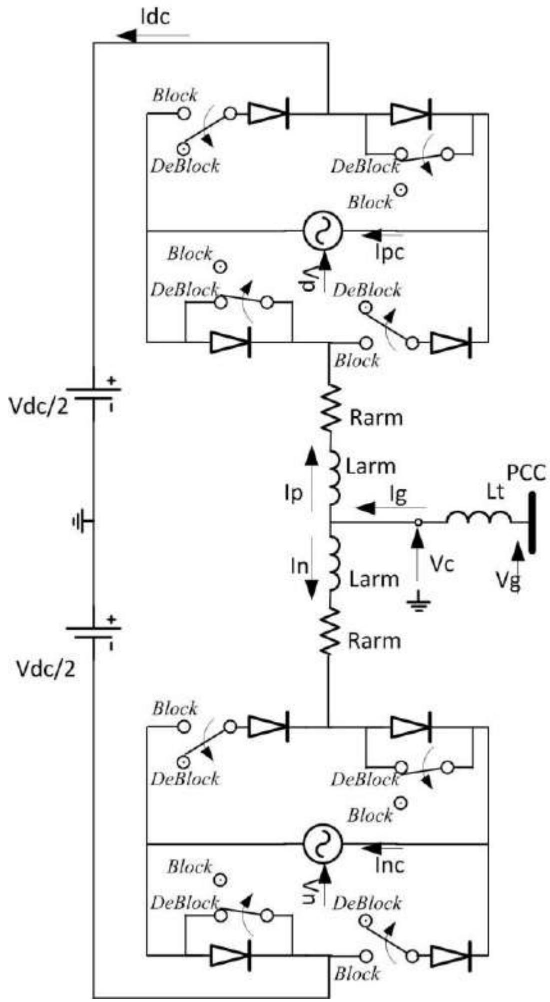
Arm is replaced with a controllable voltage source (DC, first and second harmonic, positive sequence)

Fig. 51. Average HB MMC model in ABC frame, with blocked state and including circulating current controller

3. DC grid modelling challenges

ABC frame average FB MMC model

- Normal operation and blocked state,
- Only time domain simulation,



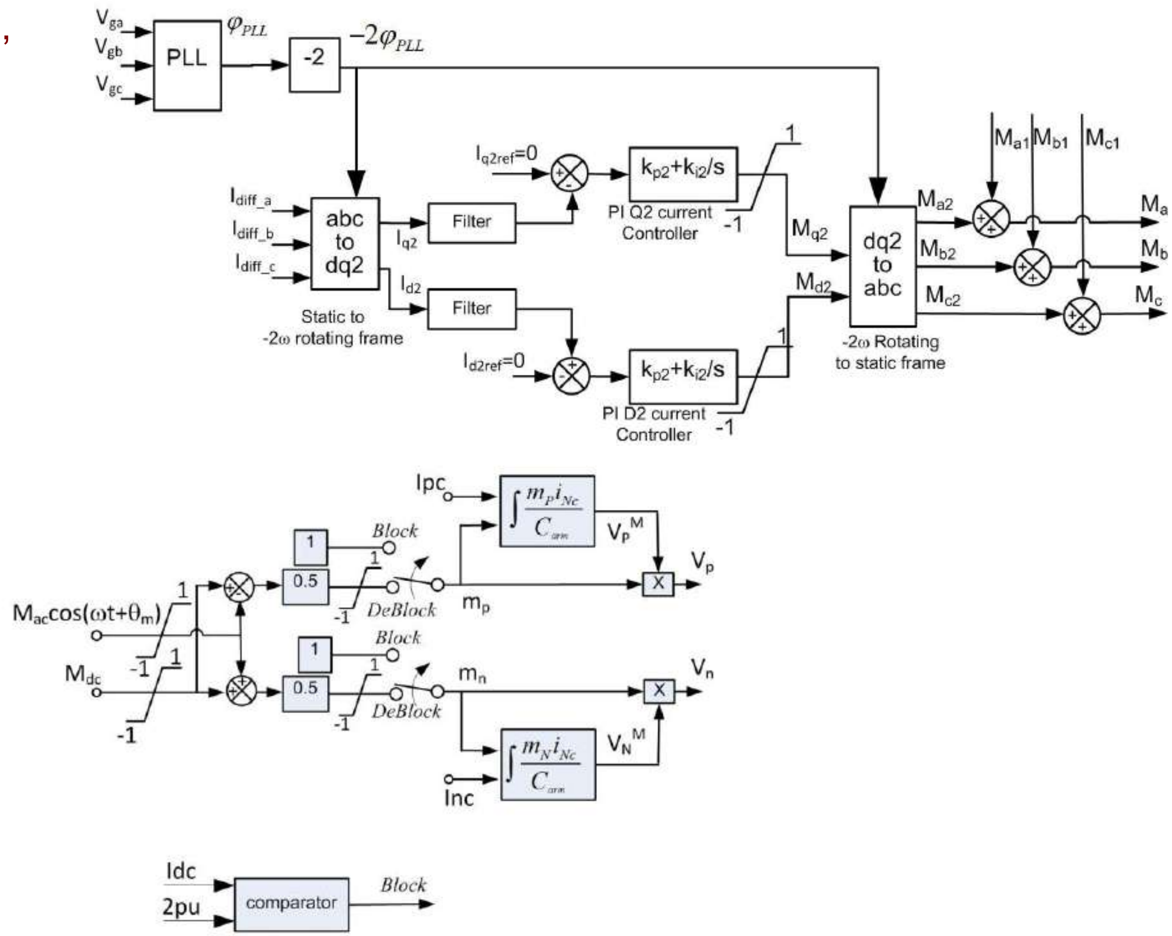


Fig. 52. Average FB MMC model in ABC frame, with blocked state and including circulating current controller

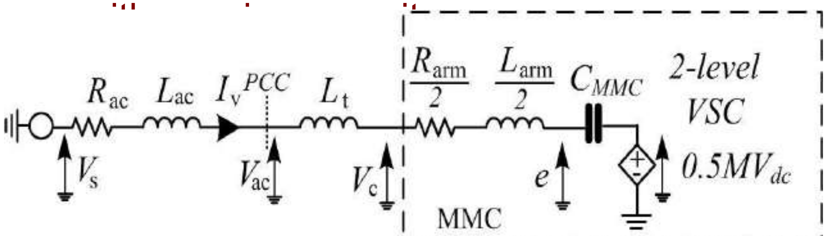
3. DC grid modelling challenges

DQ frame analytical linearised MMC model

- Simulation speed is very fast,
- Parametric/stability studies are simple,
- All oscillating variables are converted to DQ,
- Model in three DQ coordinate frames,
- Unbalanced operation requires negative DQ,

Analysis of MMC dynamics:

- 10^{th} order model in state space form,
- 2^{nd} order model: MMC responds like VSC



$$e_d = -\frac{I_{Vq}}{\omega C_{MMC}} + \frac{M_d V_{dc}}{2}$$

$$e_d = \frac{I_{Vd}}{\omega C_{MMC}} + \frac{M_q V_{dc}}{2}$$

$$C_{MMC} = 64C^{arm} / \left(8 - 3\left(M_d^2 + M_q^2\right)\right)$$

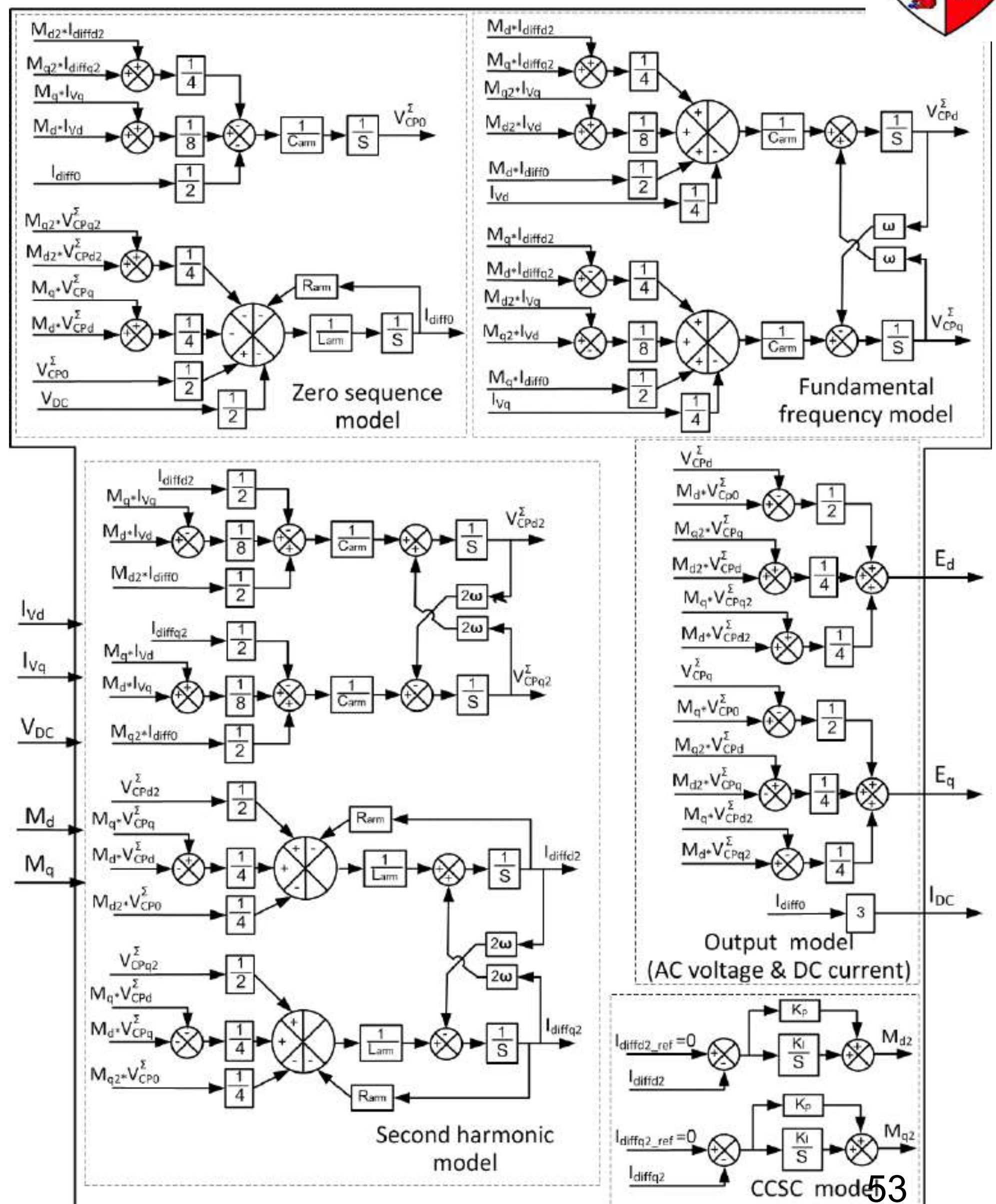
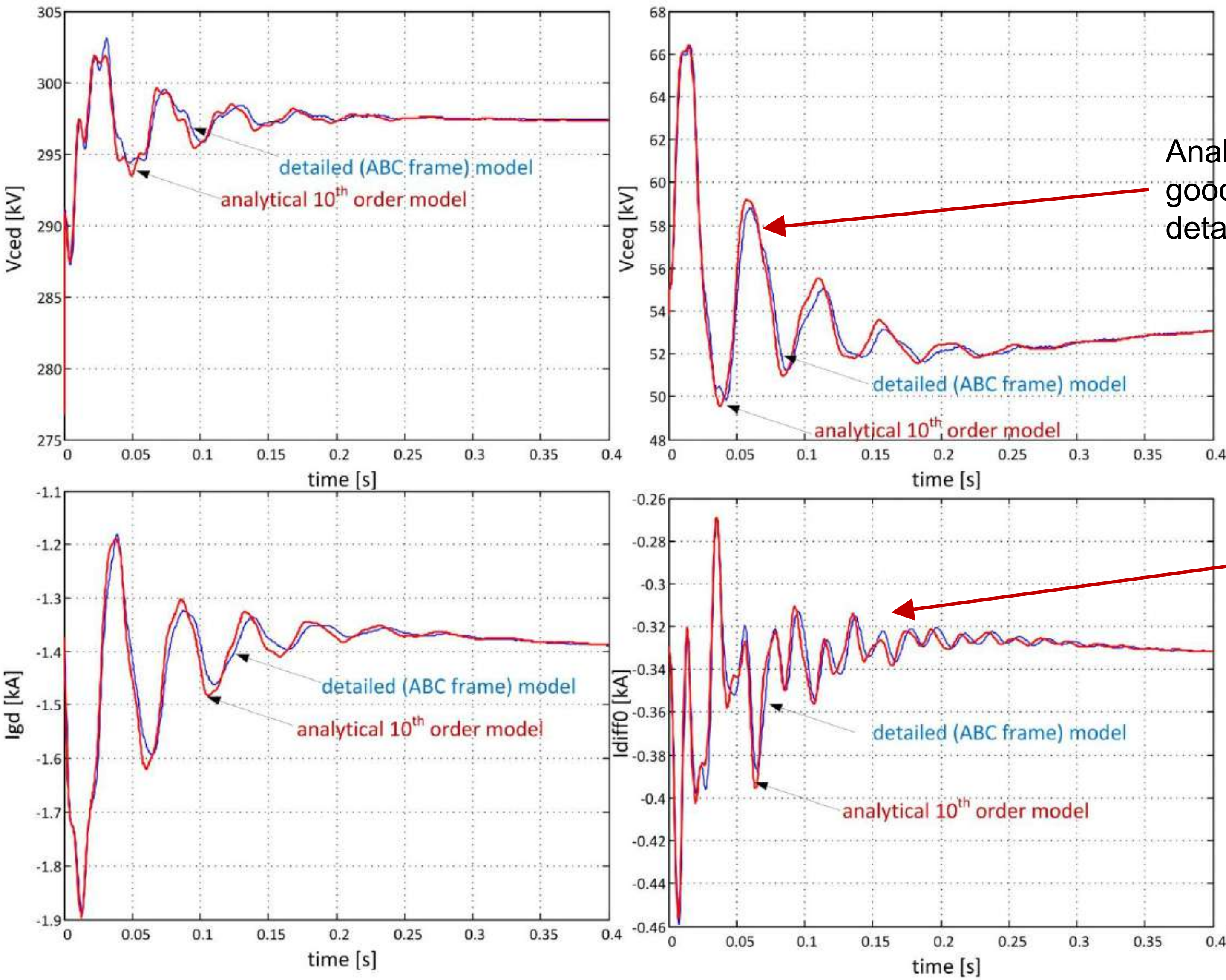


Fig. 53. MMC DQ frame 10^{th} order average model and simplified 2^{nd} order model

3. DC grid modelling challenges



Analytical model shows good matching with detailed model <150Hz

good matching for all AC and DC variables

Fig. 54. MMC 10th order DQ state-space analytical model verification.

3. DC grid modelling challenges

DQ frame state space linearized model enables eigenvalue studies

- High PLL gains cause subsynchronous frequency instability (45Hz)

Original system (Kp_PLL=30, Ki_PLL=500)	System with increased PLL gains (Kp_PLL=300, Ki_PLL=5000)
$-14.56 \pm j313.2$ $-17.82 \pm j129.5$	$-6.98 \pm j317$ $-33.74 \pm j101.3$

- High gains of circulating current controller deteriorate stability at 20Hz

System 1 (K_{P_CCSC}=0.5, K_{I_CCSC} =50)	System 2 (K_{P_CCSC}=10, K_{I_CCSC}=50)
$-20.1 \pm j122.2$ $-155.0 \pm j637.8$	$-6.2 \pm j129.7$ $-165.2 \pm j681.6$

- MMC average analytical modelling status

Average model	ABC frame (non-linear)	DQ frame (linear)
Normal operation	solved	solved
Blocked state	solved	difficult

3. DC grid modelling challenges

MMC operation with unbalanced AC system

Internal converter balancing controls,

- Vertical balancing (between arms),
- Horizontal balancing (between phases),
- Energy control,
- Over 30 control loops,

Unbalanced grid conditions

- Detecting unbalance,
- AC grid sequence control,

Analytical model (at each harmonic):

- Positive sequence,
- Negative sequence,
- Zero sequence,

Operator control strategy

- Priority on negative sequence under AC faults,

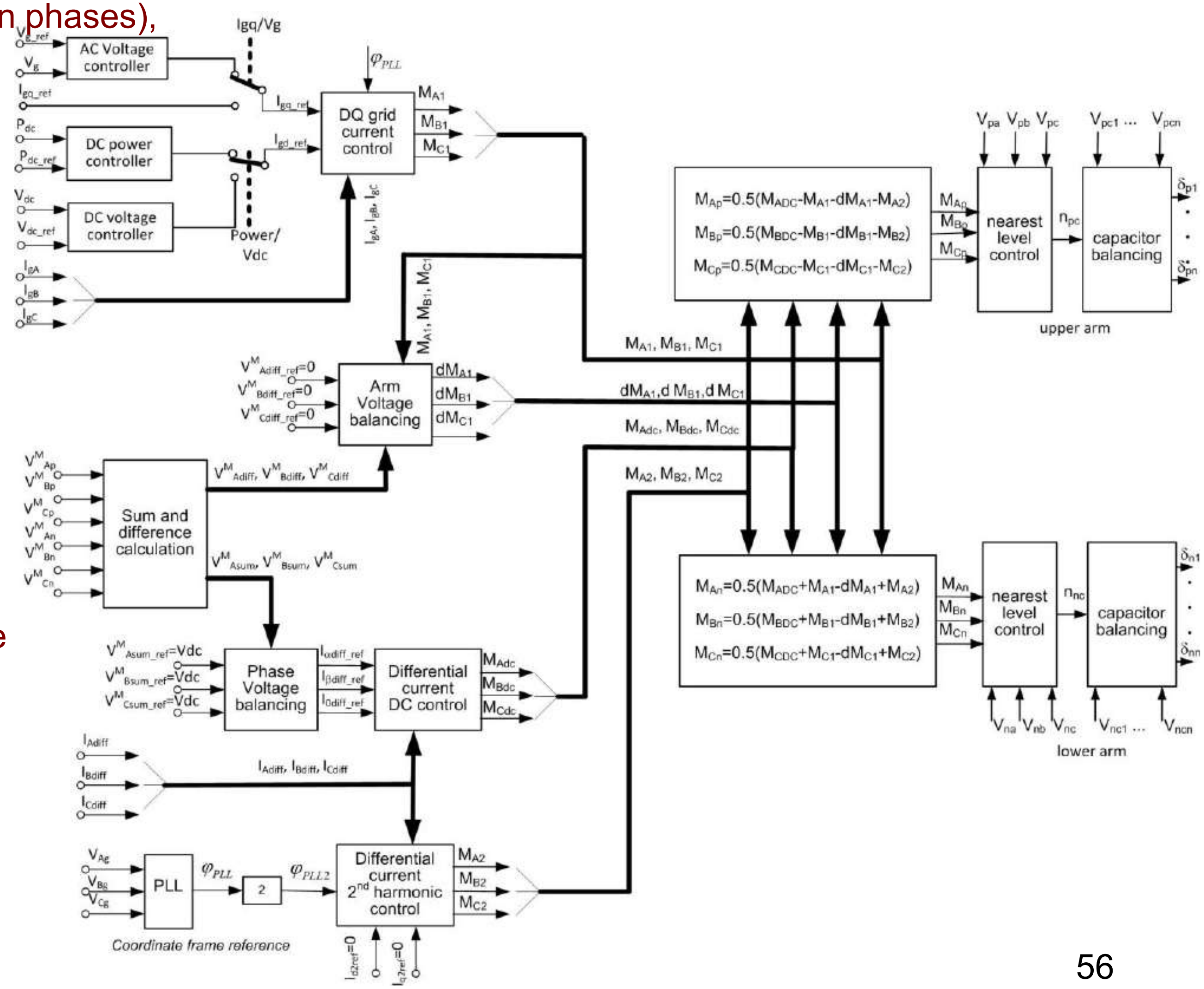


Fig.55. MMC converter structure including balancing controllers

3. DC grid modelling challenges

DC/DC converters are particularly difficult for simulation/modelling (as part of DC grids),

- EMT programs are optimised for 50-60Hz systems,
- Medium frequency inner AC circuit (300Hz-1000Hz),
- Simulation step must be very low (below 1μs),
- Two AC/DC MMC converters,
- Numerous control loops,
- Blocked state modelling,

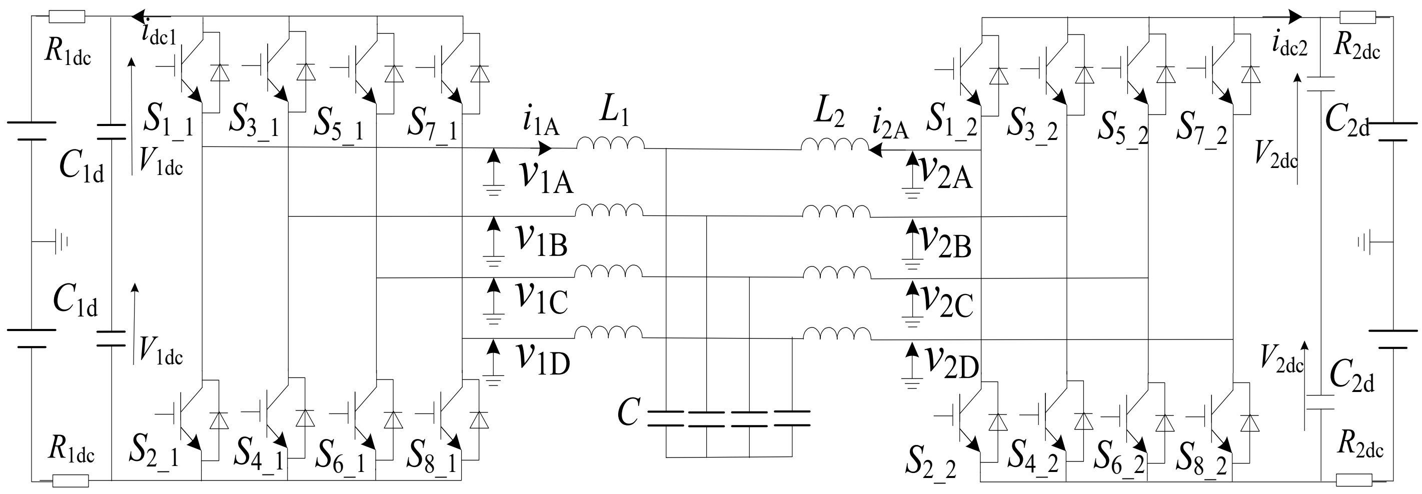


Fig.56. Circuit diagram of 4-phase high frequency LCL DC/DC converter

3. DC grid modelling challenges

DC/DC modelling options:

1. Dommel's method in ABC frame (model 1), - used in all EMTP platforms,
2. Dommel's method in rotating DQ frame (model 2),
3. Runge Kutta method in ABC frame (model 3), state-space method used in SIMULINK,
4. Runge Kutta method in rotating DQ frame (model 4),

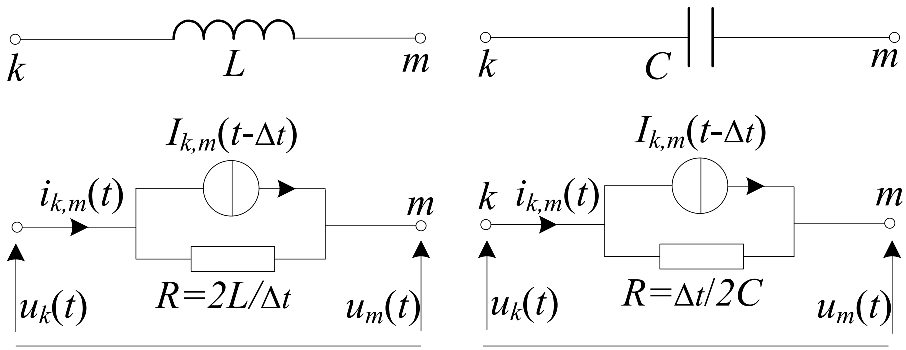
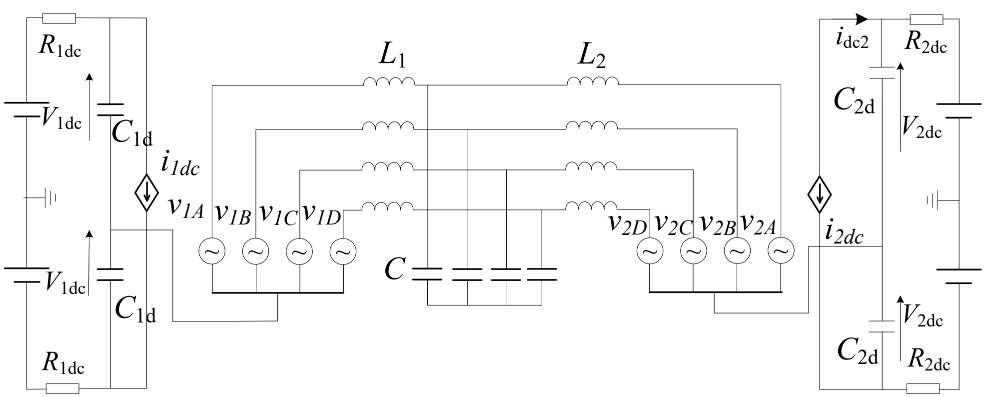


Fig.57. Representation of inductor and capacitor in Dommel's method



$$v_{1A} = m_{1A} V_{1dc}, \quad v_{1B} = m_{1B} V_{1dc},$$

$$v_{1C} = m_{1C} V_{1dc}, \quad v_{1D} = m_{1D} V_{1dc}$$

$$i_{1dc} = \frac{k_m}{2}\left(M_{1A} i_{1A} + M_{1B} i_{1B} + M_{1C} i_{1C} + M_{1D} i_{1D}\right)$$

- Use controlled AC voltage source and controlled DC current source to link AC circuit and DC circuit,

Fig. 58. Average Model using Dommel's method in ABC frame (Model1)

3. DC grid modelling challenges

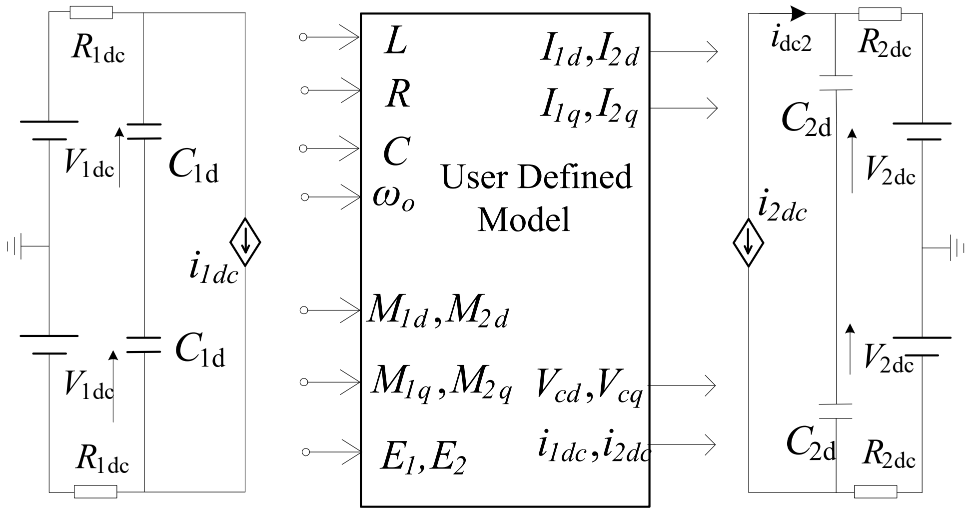
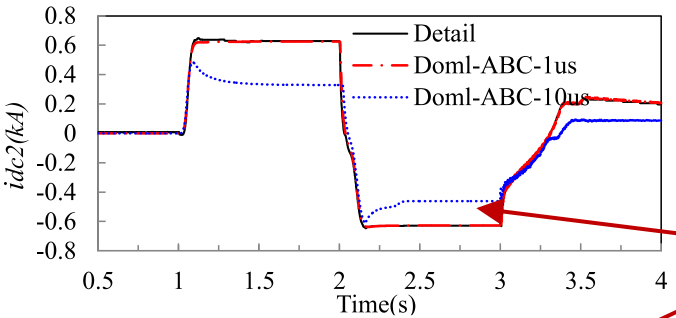


Fig. 59. AVM of Runge Kutta method in dq frame(Model 4)

- State-space model in the dq frame,
- All AC quantities converted to dc quantities,
- Simulation step can be increased,
- State-space equations solved simultaneously at each time step using user defined subroutine,
- The user defined subroutine adopts Runge-Kutta's Method,

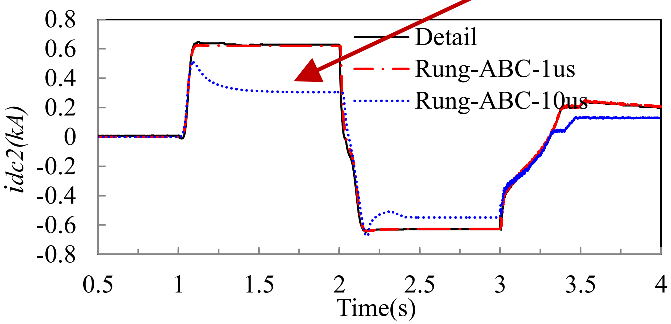
3. DC grid modelling challenges

- Only Runge-Kutta method shows good accuracy.
- Simulation step can be large with Runge-Kutta method



(a) Dommel's Method in ABC frame(Model1)

Significant modelling error



(b) Runge-Kutta Method in ABC frame(Model3)

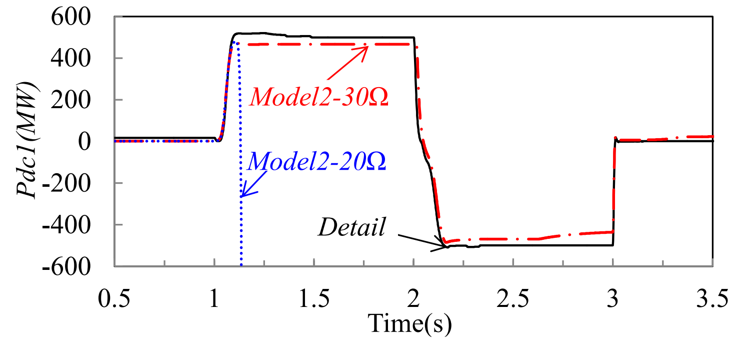
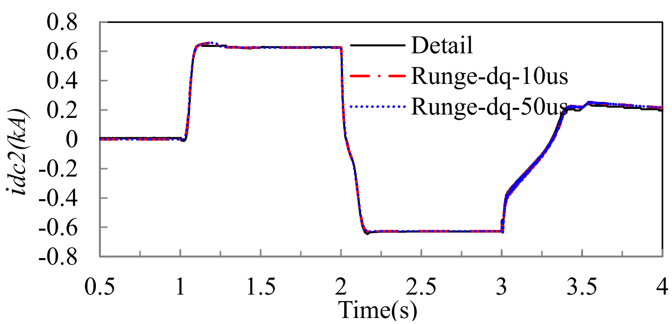


Fig. 61. Numerical instability of Model2 (Dommel's modelling in the dq frame)



(c) Runge-Kutta Method in dq frame(Model4)

Only DQ state-space modelling gives good performance for converters operating at high frequencies

Fig. 60. Model comparisons for 2kHz DC/DC (power step at 1s and at 2s, DC fault at 3s)

3. DC grid modelling challenges

DC/DC converter modelling:

- Average value models with accurate blocked states (static ABC frame or rotating DQ frame),
- Preferably DQ frame modelling,
- State-space (Runge-Kutta solver) if high-frequency DC/DC are present

We may use Dommel method for 50Hz systems and State-space method for converters at high frequencies

Table 3 Overall comparison of the 4 average models for 2kHz DC/DC Converter

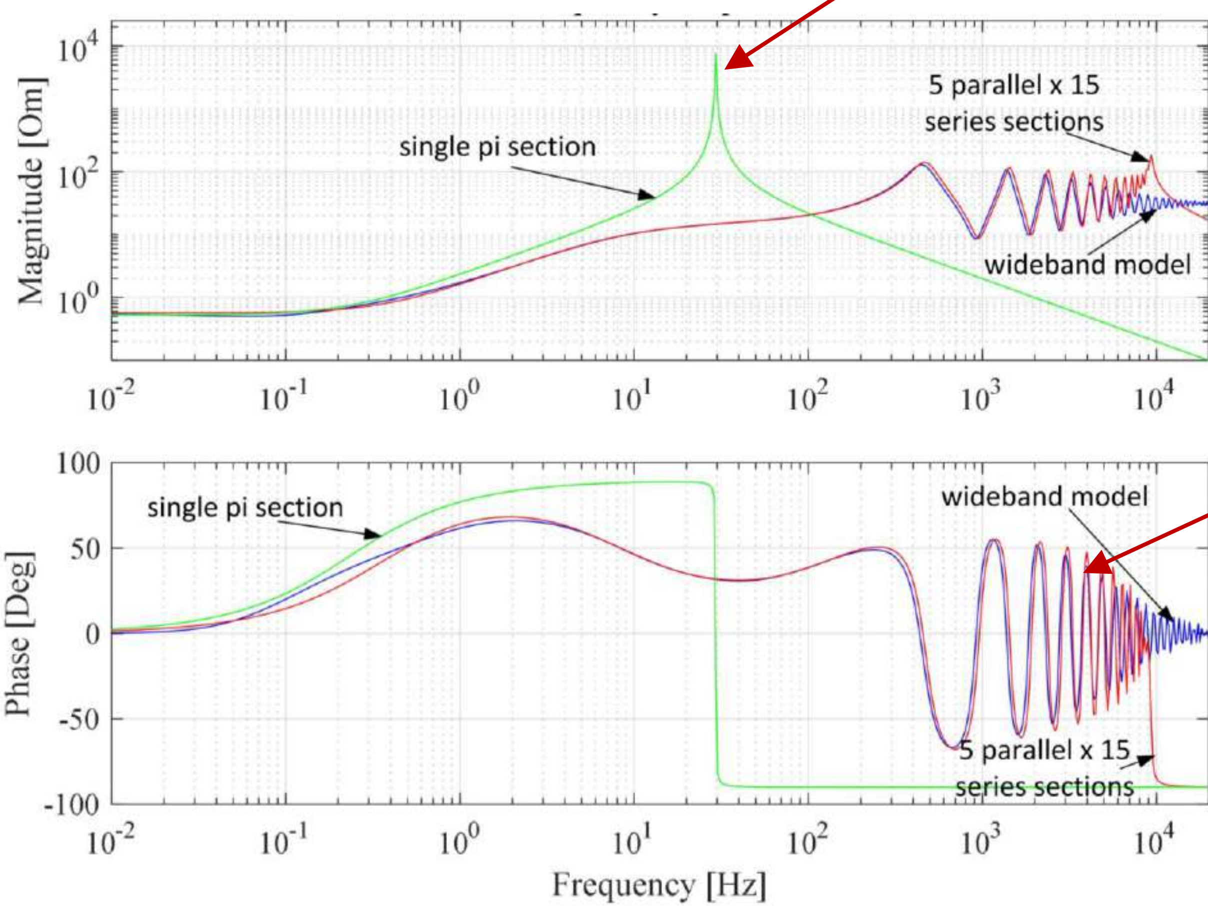
Solution Method	Models	Simulation time for 4s real time	Accuracy is good for time step	Numerical stability
Dommel's Method	Detailed Model	216.3s	≤1μs	stable
	Model 1 (ABC, 1us)	201.3s	≤1μs	stable
	Model 2 (DQ, 1us)	\	\	unstable
Runge-Kutta Method (State-space DQ)	Model 3 (ABC,1us)	65.8s	≤1μs	stable
	Model 4 (DQ,50us)	2.1s	≤50μs	stable

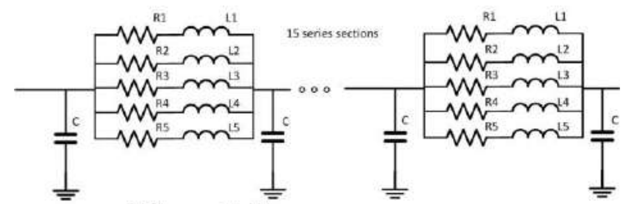
3. DC grid modelling challenges

DC cable analytical modelling :

- High order dynamics because of frequency dependence of per-unit parameters,
- Single pi-section with lumped parameters is not sufficiently accurate,
- State-space model of high order (over 100) gives good accuracy,
- Model order is much higher if multiple cable layers are considered,

Accuracy of single “pi” section is poor





	R [Ω]	L [mH]
Branch 1	1518.4	43.66
Branch 2	47.48	12.80
Branch 3	1.255	1.367
Branch 4	6.0347	36.08
Branch 5	0.0393	16.99
C [μF]	0.54	

Analytical model of at least 75^{th} order is needed (15 sections, each with 5 RL elements).

Fig. 62. Comparison of wideband, 75^{th} order state-space, and 2^{nd} order model for 100km, 320kV cable.

4. DC grid Control Challenges

- DC grid is more difficult to control (and probably operate) than traditional AC systems,
- There is no common frequency, which would indicate grid power unbalance,
  - DC voltage indicates global power unbalance but it also changes with local power flow,
  - Average grid-wide DC voltage will be dependent on numerous measurements and communication
- DC grid dynamics are 2 orders of magnitude faster than AC grid dynamics,
- DC grid components have narrow range of operating conditions (converter tripping)
  - DC voltage self-protection at 0.85pu<Vdc<1.3pu,
  - DC current self protection at 2 pu.
- There are no passive loads with stabilising feedback
  - Constant power loads,
  - Lower voltage does not imply lower power,
- All components are controllable.
  - Numerous control loops,
  - Control priority should be carefully regulated,
- No inertia. GW powers should be balanced within 10ms.

4. DC grid Control Challenges

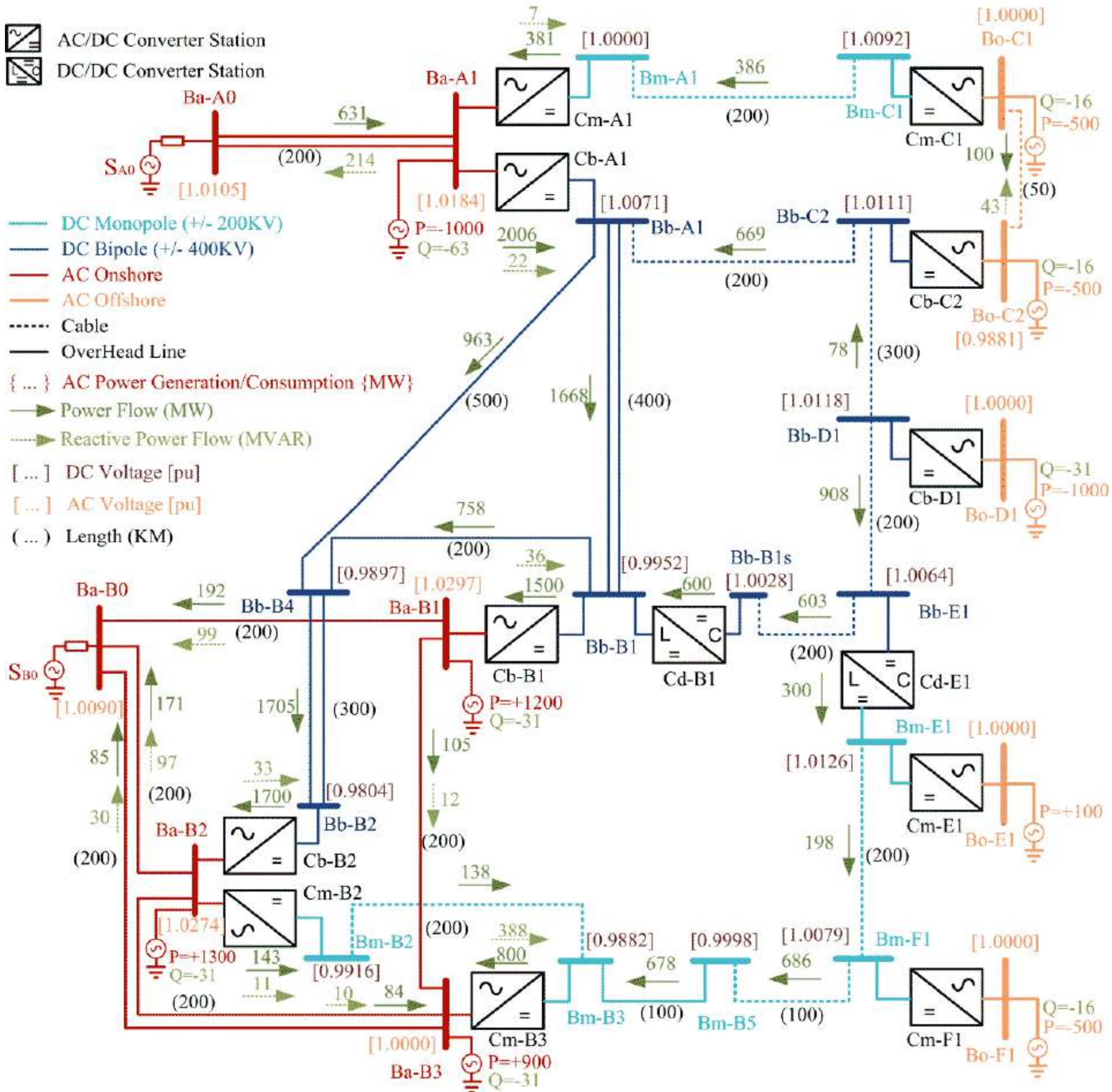


Fig. 63. CIGRE DC grid benchmark (B4.57 and B4.58)

CIGRE DC Grid:

- 5 Offshore VSC terminals,
- 6 onshore VSC terminals,
- 2 DC/DC converters,
- 2 separate DC systems
- One DC system is bipolar,
- Meshed DC lines,
- Onshore AC systems,

Control system requirements:

- automatic power balance,
- optimal operating point,
- stable recovery for large disturbances,

4. DC grid Control Challenges

DC Grid control:

- Must be safe and secure:
  - Inner fast current control at each converter,
- Must be stable without communication with despatcher.
  - Distributed primary response,
  - Fast DC voltage control is required at each terminal,
  - Commonly used DC-voltage droop (static gain) feedback is not ideal,
- Converters (but not all) should contribute local power balancing for a disturbance.
  - Secondary response (automatic),
- Optimisation and re-dispatching by central dispatcher.
  - Tertiary response (human intervention and automatic) enables global and optimal power balancing,
  - Start up, restoration,

Outer (slower) power control ensures local power balancing

Middle (fast) DC voltage control ensures dynamic stability

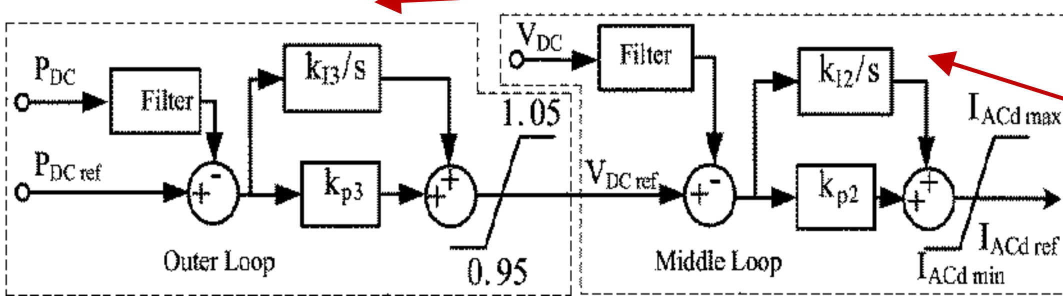
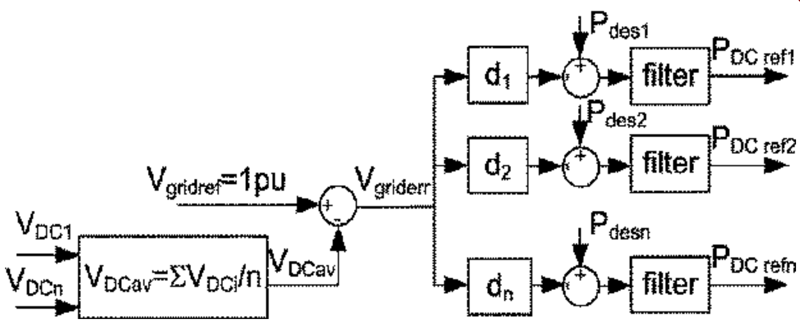


Fig. 64. 3-level controller for VSC terminals, using local signals and dispatcher references.



Dispatcher average DC voltage control ensures global power balance, but requires signals from DC grid nodes

Fig. 65. Dispatcher Controller, using pilot DC grid control

4. DC grid Control Challenges

Controller testing on CIGRE DC Grid for an outage of a large VSC terminal:

- Primary response maintains stability. All variables are within operating limits. No VSC blocking.
- Secondary response balances power. A new operating point within 0.5s. Optimal DC voltage in 2s.
- Tertiary response (if required) would dispatch another converter.

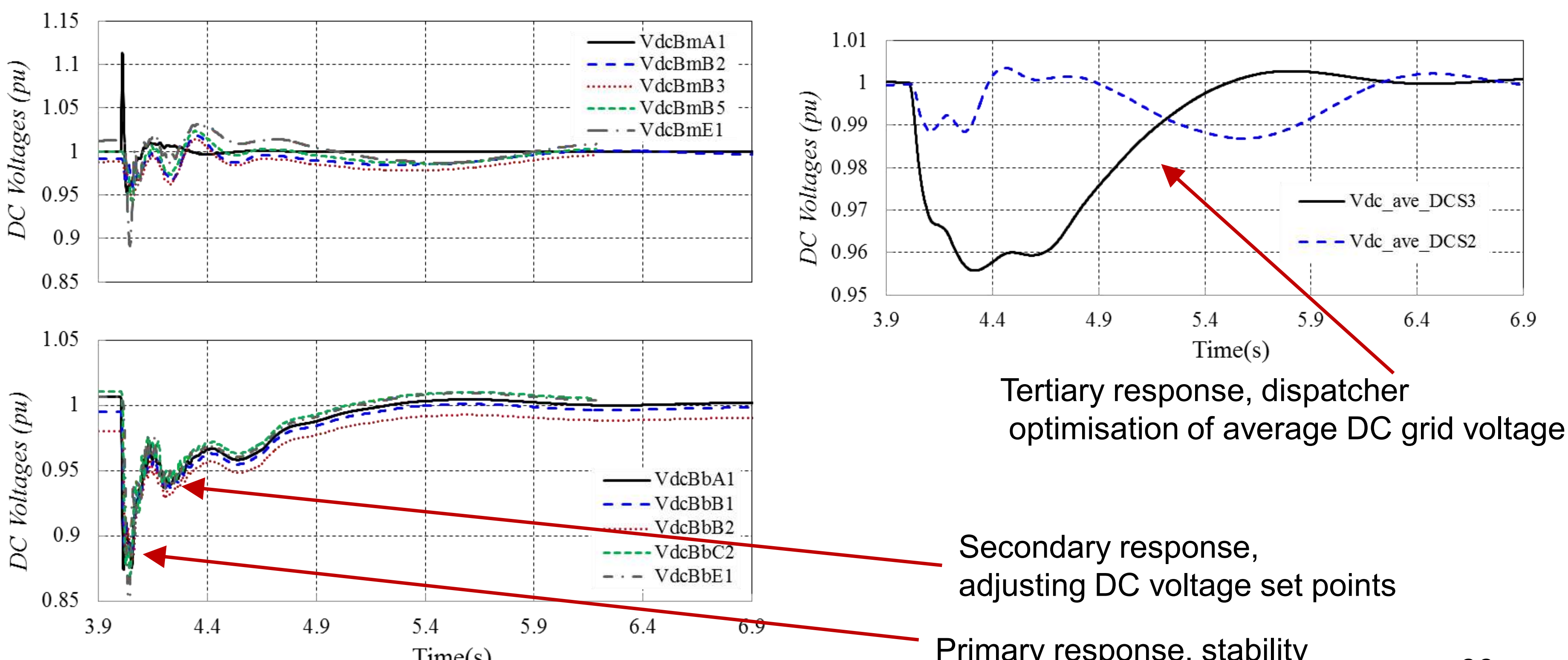


Fig. 66. Voltages in DC grid after terminal Cb-A1 outage (1GW loss),

5. DC grid Protection Challenges

DC Grid protection:

- AC protection methods can not be used,
  - distance protection (R+jωL),
  - overcurrent protection (radial lines),
  - differential protection
- DC grid protection system general requirements :
  - selectivity (very fast),
  - reliability (sufficient margin),
  - robustness (no false tripping),
  - back-up protection,

Some DC grid protection challenges:

- DC CB:
  - Limited speed of operation (2-7ms),
  - Limited peak current (self-protection at 8kA-15kA),
  - Inserting arrester is required (1.5 pu voltage, additional 2-30 ms, large disturbance)
- VSC converters have self protection:
  - Blocking threshold on current 2.5-4kA or voltage 0.85pu,
  - They become an uncontrollable diode bridge,
  - AC CB is automatically tripped (implies loss in capacity for at least 1s),
  - Temporary VSC blocking may be possible,
- DC currents are very large and spread very fast,
- Series inductors are needed on each DC line,
- System cost (around 5-10% of the grid cost),
- Reliability and security,
- Interoperability, standardisation, transparency, ownership/operation model, …..

5. DC grid Protection Challenges

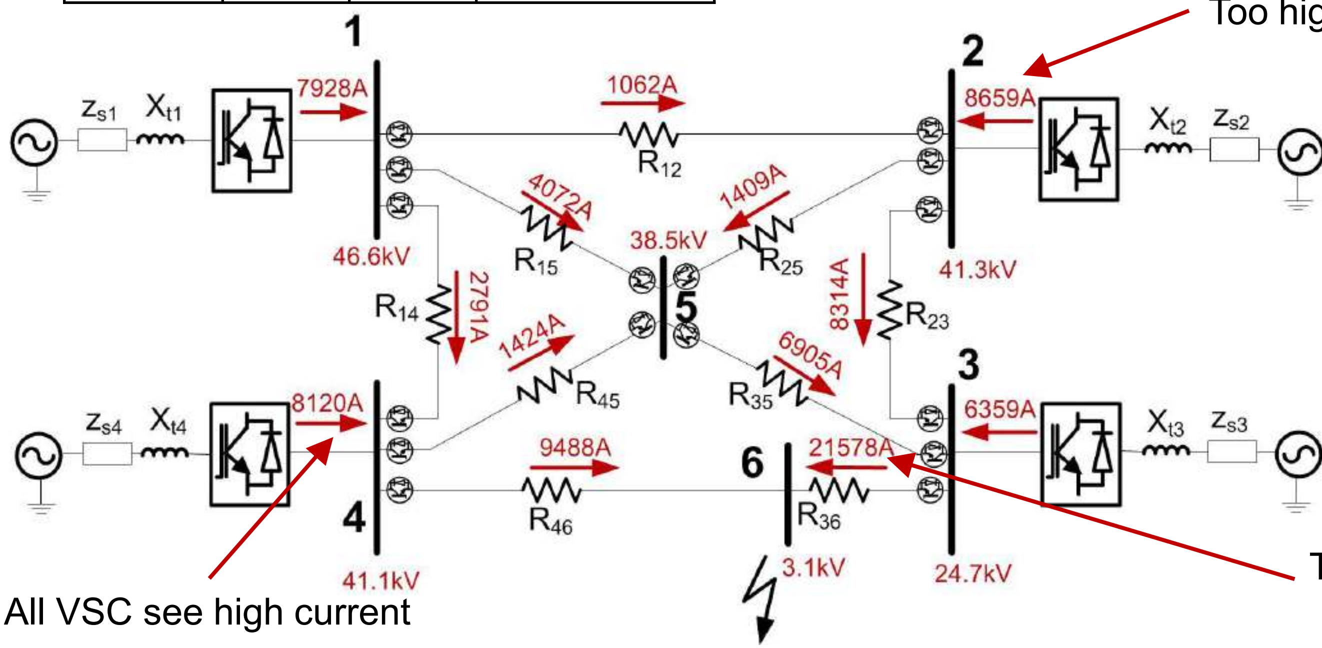
- Case study 4-terminal 400kV meshed DC grid under a DC fault.
  - 8 DC lines, 16 DC CBs (cost of each is 0.3pu),
  - Total DC CB cost is 5pu (total VSC cost is 4pu),

- DC fault currents are large, rise fast, and spread fast grid-wide
  - All VSC converters are blocked and generate high DC fault currents,
  - DC cables see up to 21kA
  - converters see up to 8.5kA in 10-30ms
- How to detect DC fault (reliably)?
- How to locate fault (reliably and fast)?
- How to avoid converter blocking?
- Can temporary converter blocking be used (not permanent)?
- How to build back-up protection?

Table 1. AC system parameters

Terminal	SCR	X/R	$P_{dcnominal}$ [MW]
1	20	9	1000
2	30	20	1000
3	10	10	1000
4	22	12	1000

Too high current for VSC converters



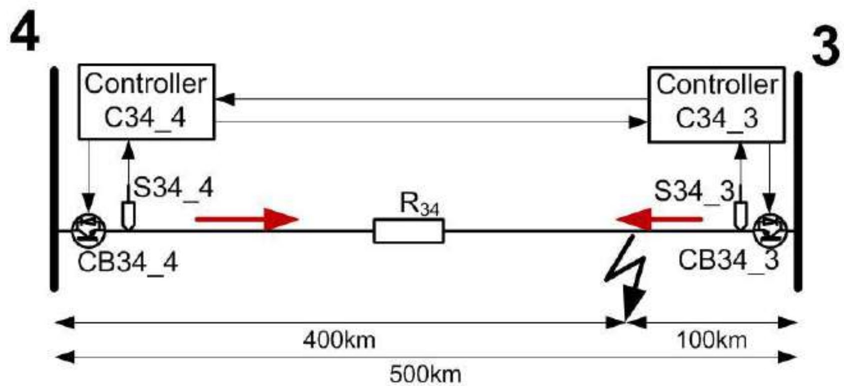
$$
R\,[\Omega] = \begin{bmatrix} 3e6 & 5 & \infty & 2 & 2 & \infty \\ 5 & 3e6 & 2 & \infty & 2 & \infty \\ \infty & 2 & 3e6 & \infty & 2 & 1 \\ 2 & \infty & \infty & 3e6 & 1.8 & 4 \\ 2 & 2 & 2 & 1.8 & 3e6 & \infty \\ \infty & \infty & 1 & 4 & \infty & 0.1 \end{bmatrix}
$$

Too high current for DC CBs

All VSC see high current

Figure 67. DC network fault study, steady-state currents assuming all VSCs are blocked.

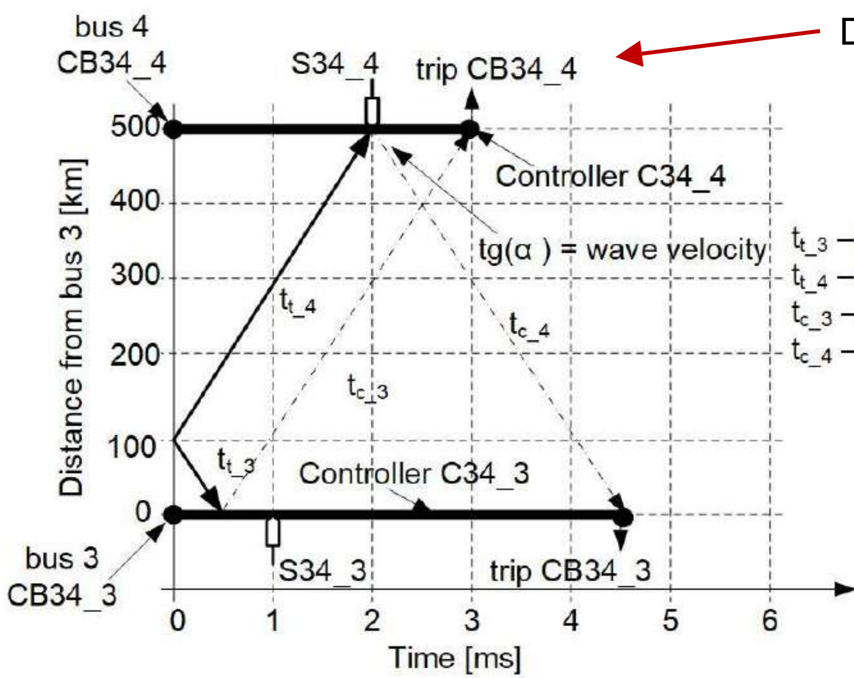
5. DC grid Protection Challenges



DC line differential protection.

- DC current direction detection is simple,
- excellent selectivity,
- excellent reliability,
- each DC CB receives signals
  - local traveling wave,
  - from the other line end,
- too slow as primary protection (3-10ms),
- will be used for back-up protection,

DC CB further away from fault always trips first



t_{t_3} – travelling wave delay to sensor S_{34_3}

t_{t_4} – travelling wave delay to sensor S_{34_4}

t_{c_3} – communication delay from C_{34_3} to C_{34_4}

t_{c_4} – communication delay from C_{34_3} to C_{34_4}

Figure 68. DC line differential protection .

5. DC grid Protection Challenges

Radial DC grids:

- Protection is simple and reliable,
- Trip decision can be made using local signals only,
- Tripping can be very fast (below 1ms), limited only by the speed of components,
- Sign of fault is reliable indicator for selective trip decision ,
- At one end fault is isolated with DC CB,
- At the converter end fault is isolated with AC CB,

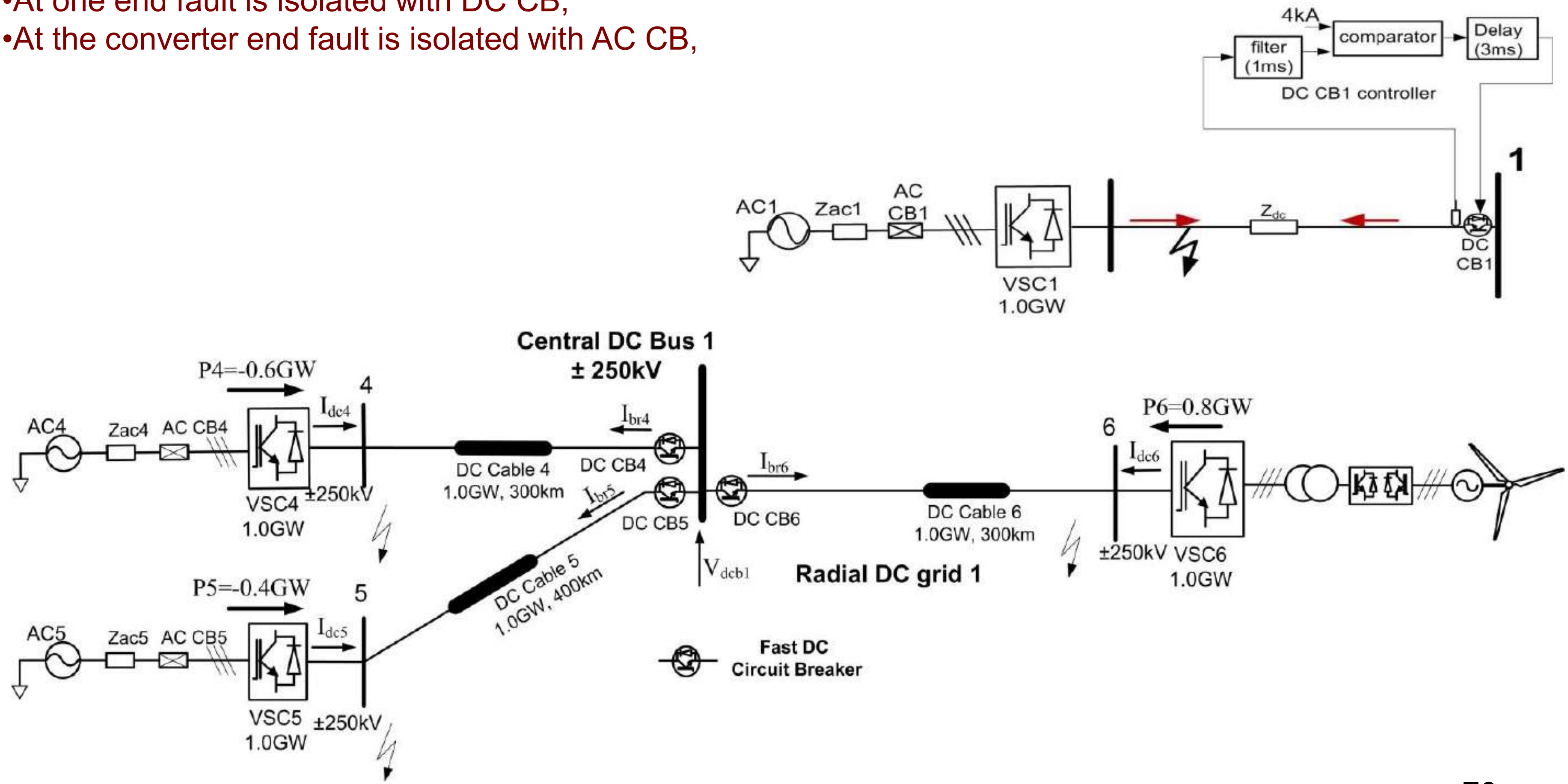
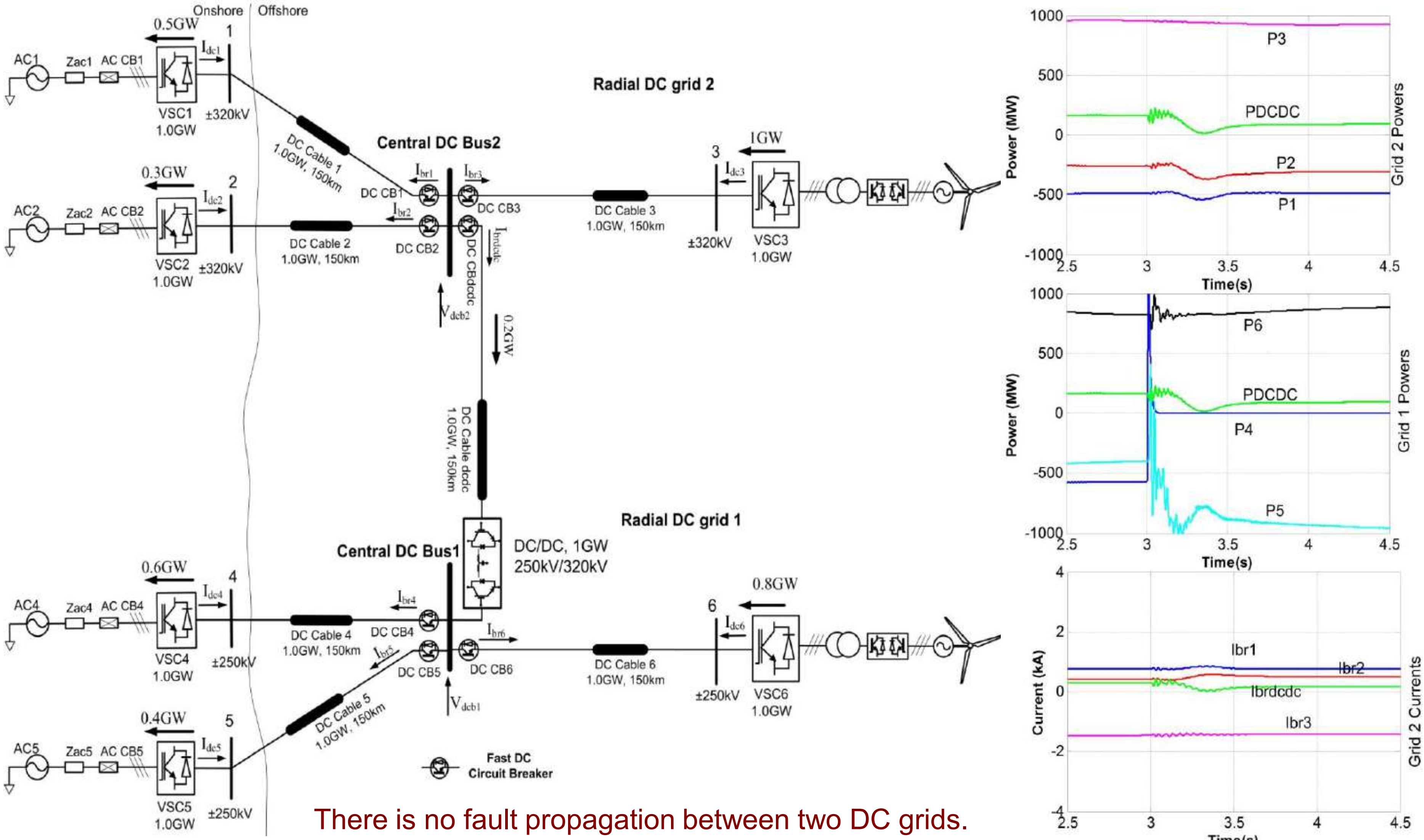


Figure 69. Protection system for radial DC grids.

5. DC grid Protection Challenges

Radial DC grids with DC/DC converters



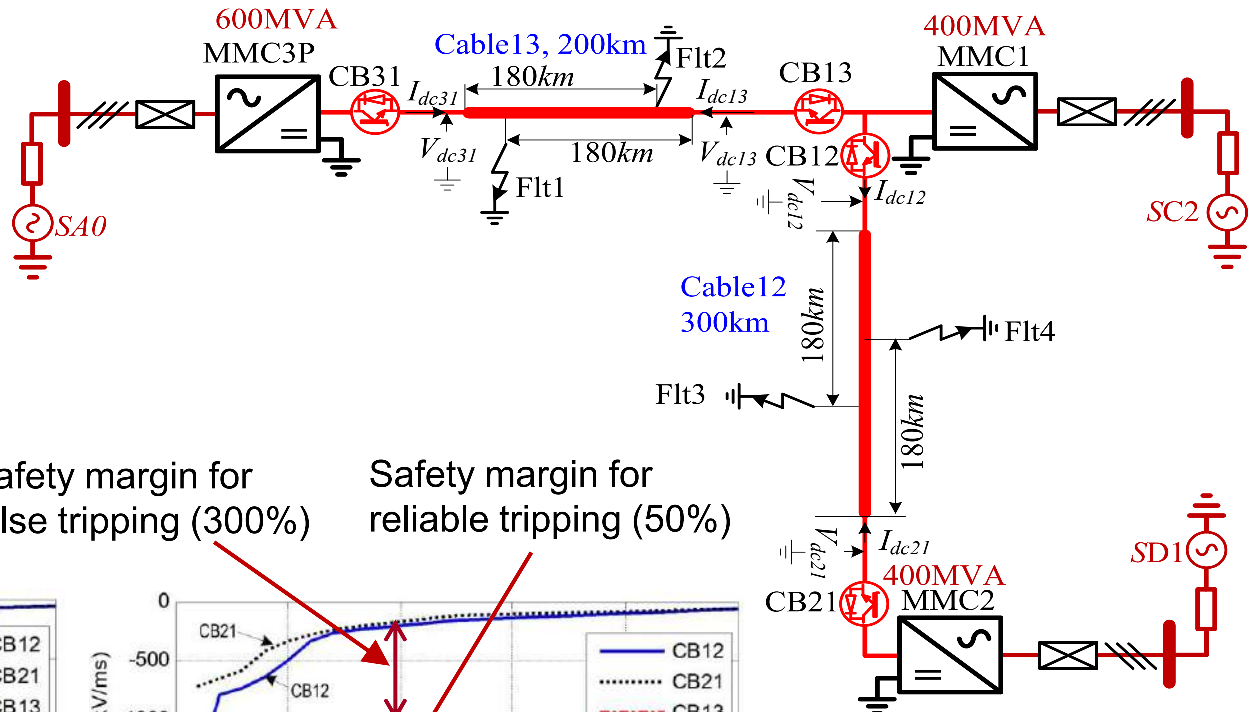
There is no fault propagation between two DC grids.

Figure 70. Interconnecting local radial DC grids with DC/DC converters.

5. DC grid Protection Challenges

DC Grid protection based on local traveling wave measurements

- Suitable for meshed DC grids,
- Selectivity requirements need careful design,
- ROCOV (Rate of change of local DC voltage) is input signal for protection relays,
- Wavelet transform might be required,
- Possible challenges:
  - safety margin in general,
  - long DC cables,
  - short lines,
  - high impedance faults,



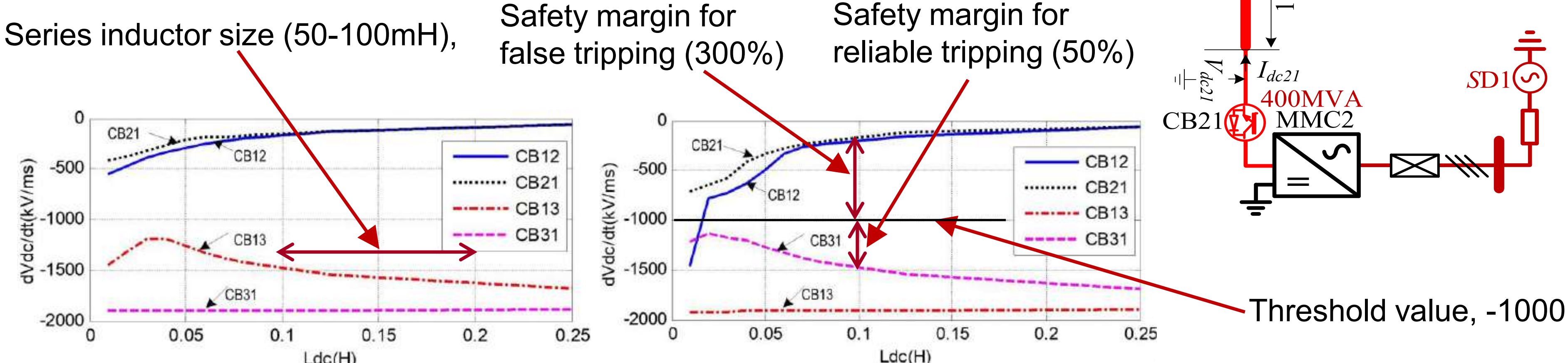


Fig. 71. Selecting threshold voltage rate of change for Flt1, left - DC cable, right – DC overhead line.

5. DC grid Protection Challenges

Converter self-protection results in blocking and therefore loss in capacity

- Converters will see large current for DC cable faults,
- Converter blocking threshold is around Idc=2.0pu.
- The blocking margins should be acceptable for TSOs (operators).

To avoid loss in capacity (MMC blocking), two design options are available:

- Install large series DC inductors (of around 500-800mH),
  - Will be issue for offshore systems because of size,
  - May cause stability problems,
- Temporarily block MMC terminal:
  - Block converter for 10-30ms,
  - Diodes require larger fault rating,
  - IGBTs may require some cool-off period,
  - MMCs do not discharge cell capacitors,

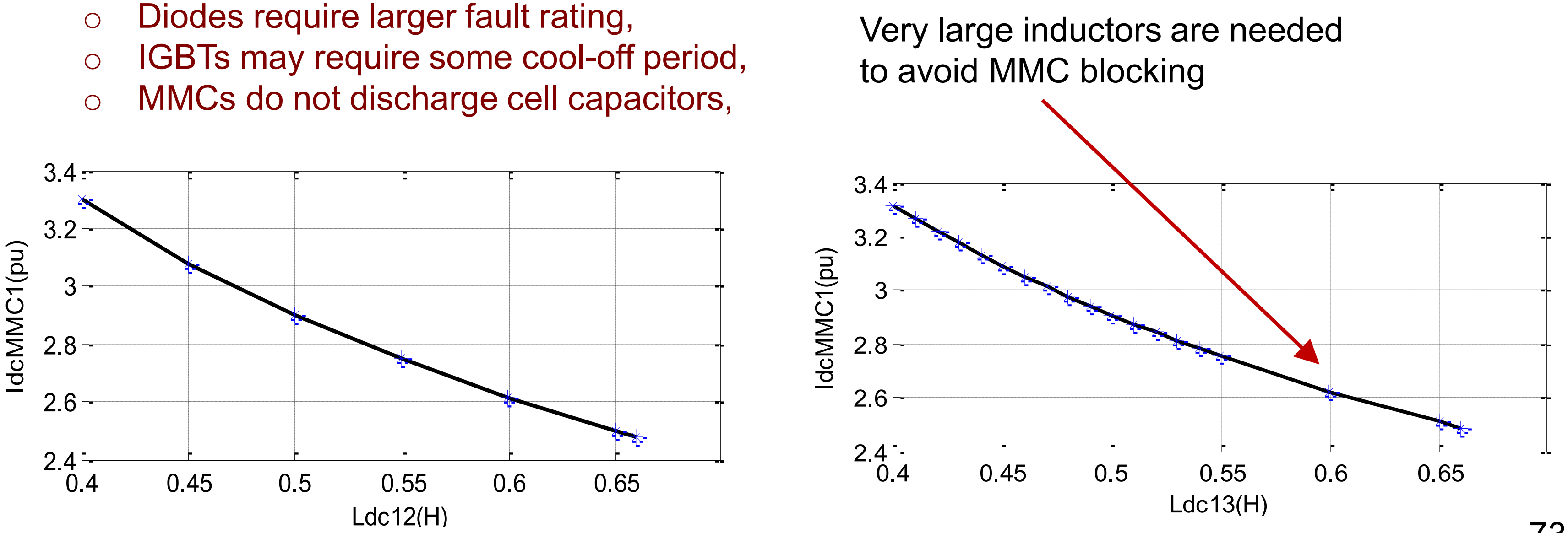


Fig. 72. Peak DC fault current at 2 VSC terminals, assuming 2ms operating time in DC CBs.

5. DC grid Protection Challenges

Manufacturing protection relays
- DC CB manufacturers are developing their own protection relays,
- Do we need independent relay manufacturers?

DC grid protection relays should be operated by TSOs,
- Open source (converter, DC CB, Cable …) models are needed,
- Protection algorithm should be transparent,

There is need for:
- Standardisation, (inputs outputs, parameters, ..)
- Interoperability,

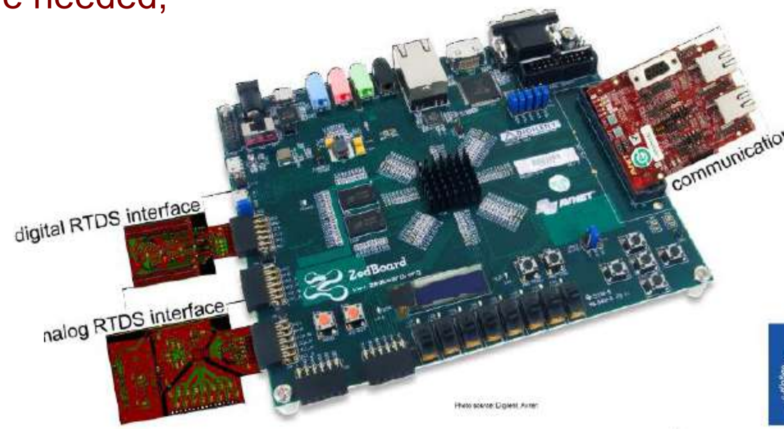
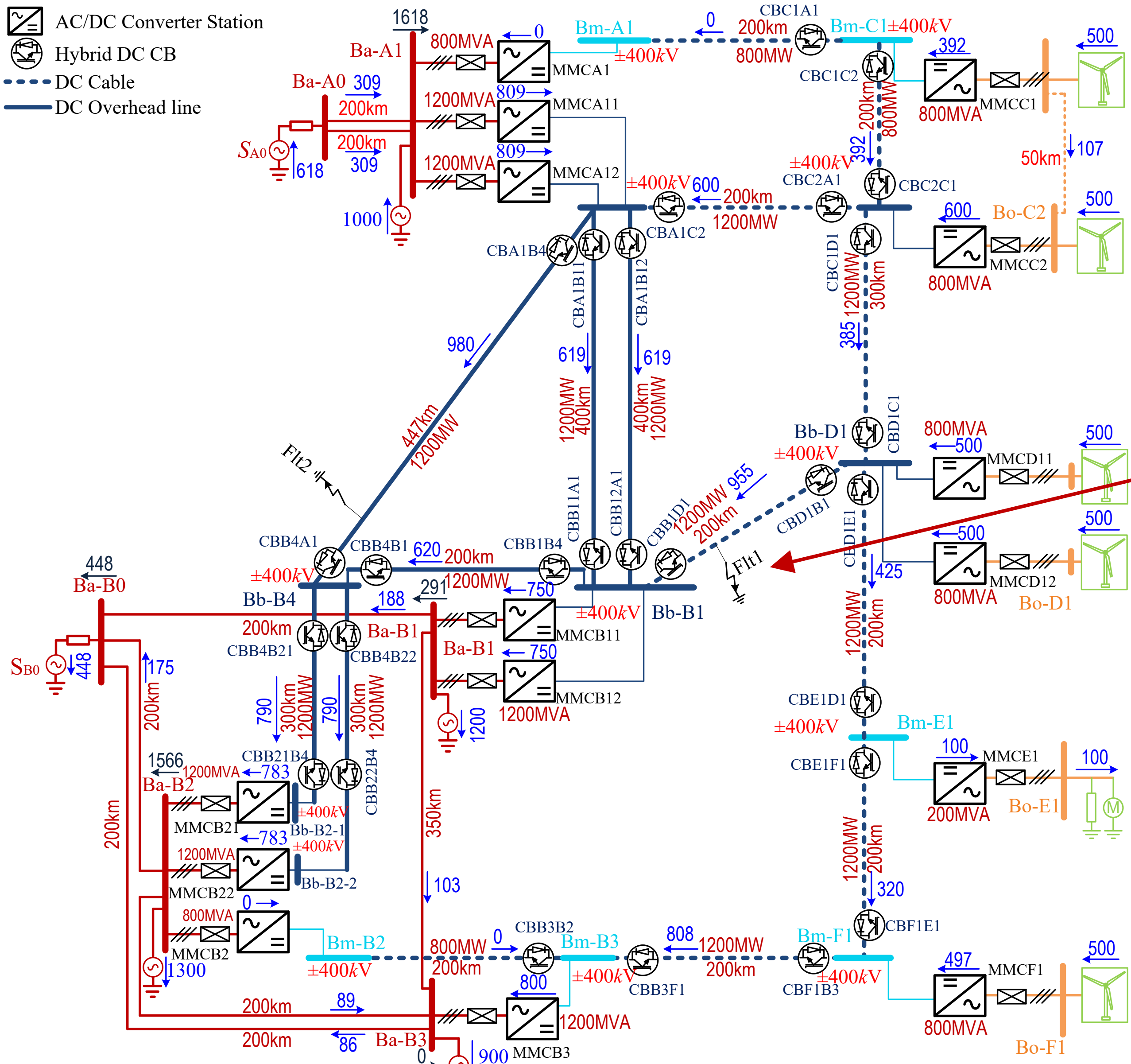


Fig. 73. Intelligent electronic device developed in EU Horizon2020 Promotion project.
https://www.promotion-offshore.net/

5. DC grid Protection Challenges



Fault on highly loaded DC line

Fig. 74. DC test grid with single DC voltage level (15 terminals and 29 DC CBs).

For Flt 1 we want:

- tripping of only: CBB1D1 and CBD1B1.
- no VSC blocking,
- post-fault power balance,
- stable post-fault recovery,

5. DC grid Protection Challenges

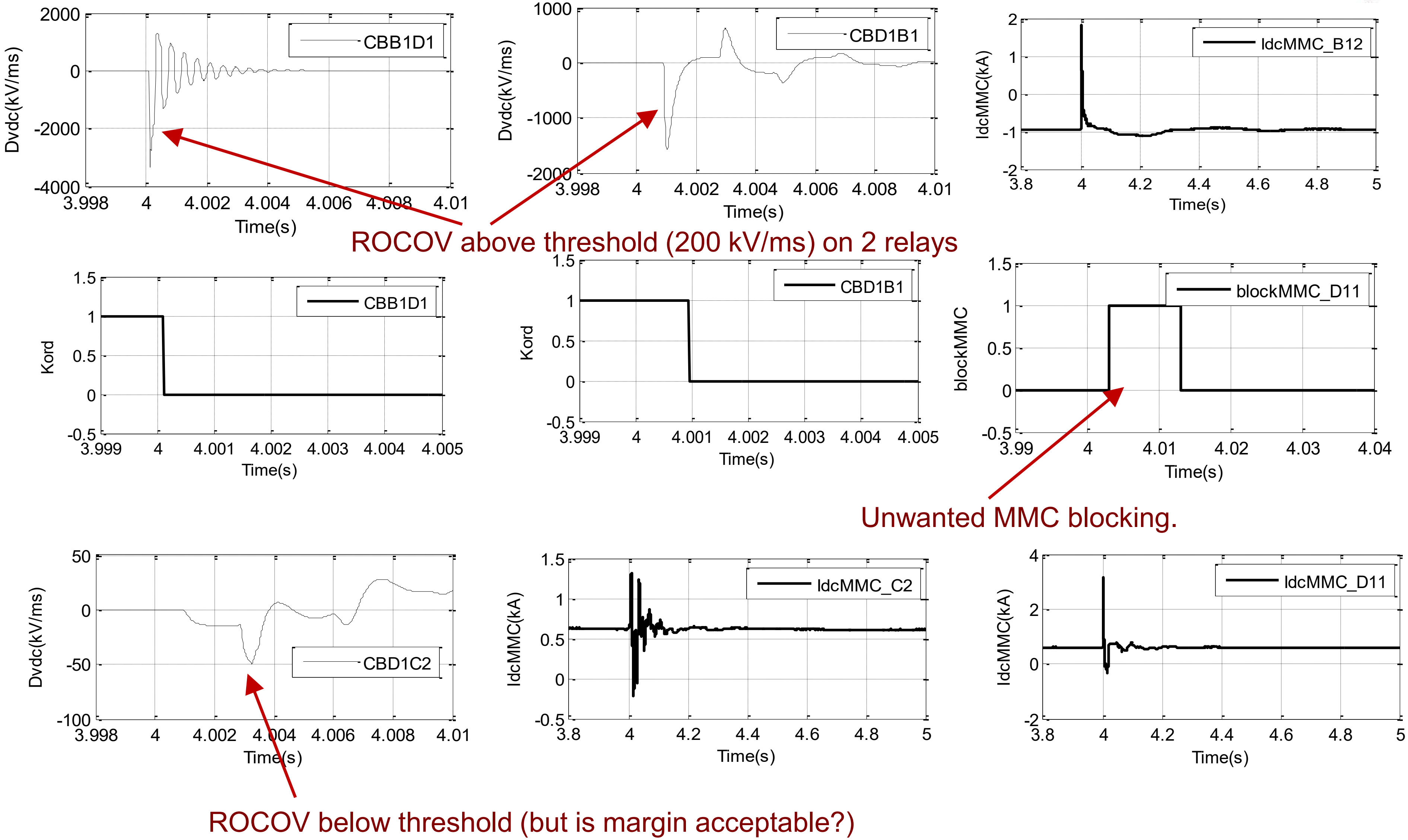


Fig. 75a). DC grid simulation for permanent DC fault flt1 (125mH inductors).

5. DC grid Protection Challenges

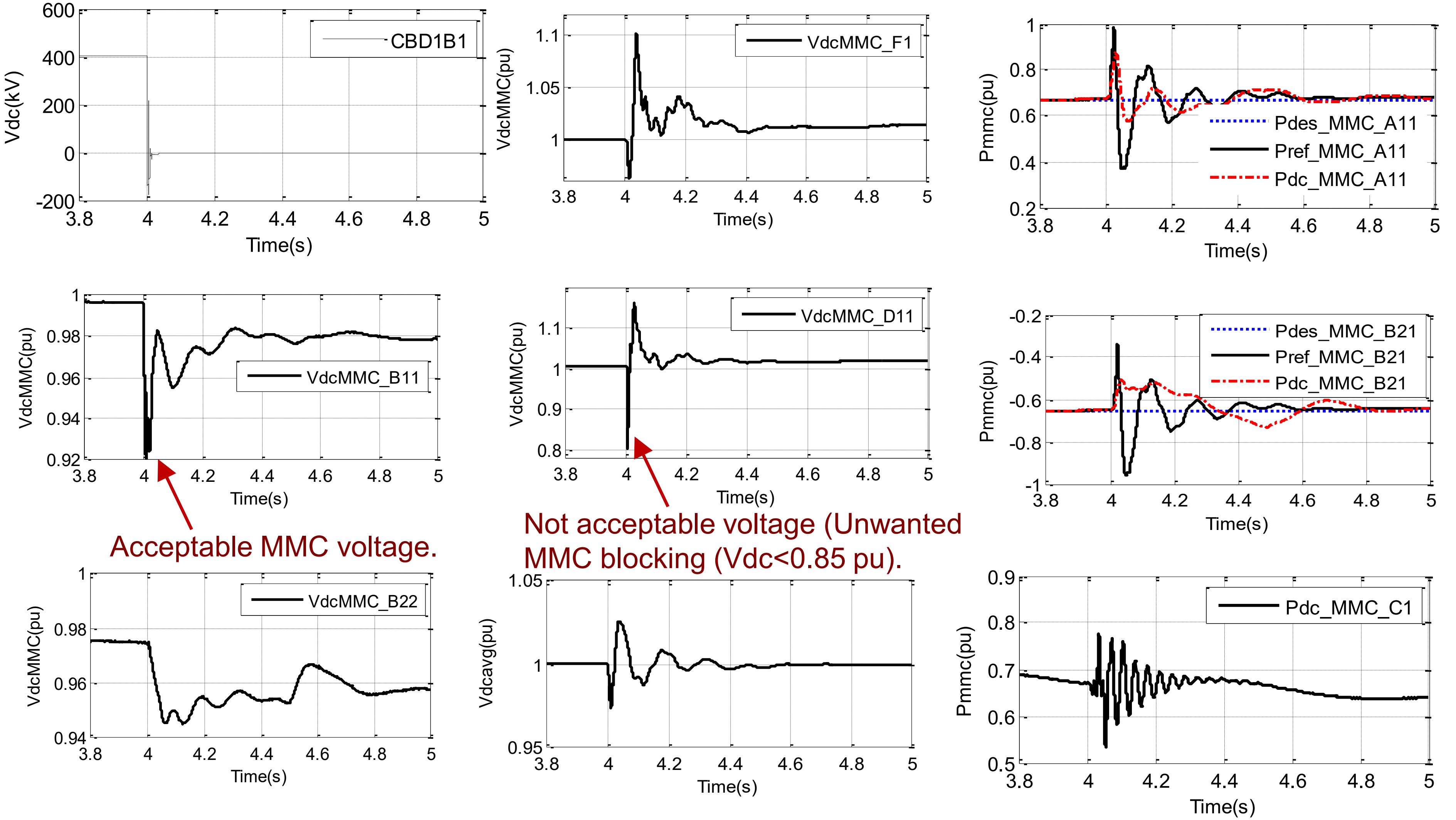


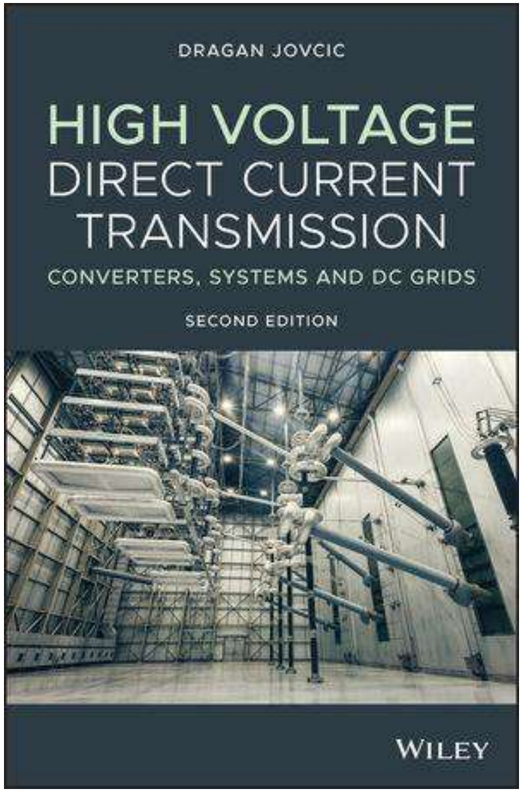
Fig. 75b). DC grid simulation for permanent DC fault flt1

6. Conclusions

- **DC grids will require new components, new operating and control methods,**
- **The main DC grid components:**
  - AC/DC converters,
  - DC Circuit Breakers,
  - DC/DC converters,
  - DC Hubs,
- **DC grid modelling challenges:**
  - Average analytical modelling,
  - Medium frequency DC/DC and DC hubs,
  - DQ frame modelling,
  - Unbalanced operation,
- **DC grid control:**
  - Distributed power balancing within 5-10ms,
  - Local DC voltage control for all VSC converters,
  - Optimal control by dispatcher,
- **DC grid protection:**
  - High speed,
  - Excellent selectivity and reliability,
  - Security margin (before self protection activates),
  - Back up protection.

Many Thanks to:

Funders:
- Engineering and Physical Sciences Research Council (EPSRC), UK,
- European Research Council (ERC), EU,
- Horizon 2020, EU
- Scottish Enterprise, UK,
- Royal Society, UK,
- Scottish and Southern Energy (SSE), UK,
- Réseau de Transport d'Électricité, France,



All collaborators

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List of publications:
https://scholar.google.co.uk/citations?user=O2CFBK8AAAAJ&hl=en&oi=ao

Text book:
https://www.wiley.com/en-gb/High+Voltage+Direct+Current+Transmission%3A+Converters%2C+Systems+and+DC+Grids%2C+2nd+Edition-p-9781119566618