Présentation de la Soirée: Les réseaux à courant continu / HVDC grids

La technologie des liaisons à courant continu sur les réseaux de transport a été profondément modifiée avec l'arrivée des convertisseurs à transistors (VSC) et notamment avec la structure qui s'impose actuellement dans les nouveaux projets : le MMC (Modular MultiLevel Converter). Le développement de véritables réseaux courant continu demandera encore des avancées technologiques significatives mais il est largement admis que des réseaux courant continu complexes pourront être construits avec des performances similaires aux réseaux AC en terme de fiabilité, flexibilité, pertes. Ces réseaux courant continu doivent encore relever de nombreux défis technologiques.

Le contrôle de ce type de dispositifs de réseau est l'un des sujets d'étude. L'équilibre des puissances au sein d'un réseau DC est assuré en temps réel par des convertisseurs à très grande dynamique mais l'énergie stockée dans le réseau est faible ce qui rend les variations de tension extrêmement rapides. De plus, les convertisseurs ont des capacités de surintensités très limitées ce qui a des conséquences très importantes sur le comportement dynamique en cas de court-circuit DC.

La gestion des défauts DC est considérée à ce jour comme un des verrous principaux limitant le développement des réseaux HVDC. Il est donc intéressant d'apporter un éclairage sur les différentes problématiques actuelles liées à la protection DC et les différentes stratégies d'élimination du défaut qui sont proposées.

L'implantation de ces liaisons à courant continu dans les réseaux AC nécessite de plus en plus de moyens de test des lois de commande. C'est la raison pour laquelle RTE s'est doté d'un laboratoire de simulation depuis 2012 lui permettant de connecter à des simulateurs Temps Réel des répliques de Contrôle Commande d'équipements à base d'électronique de puissance. Grâce à ces dispositifs, RTE est en mesure de réaliser des études comportementales précises de ses liaisons HVDC mais également d'accompagner au mieux la maintenance de ces ouvrages à fort enjeu.

Organisation et Parrainage

- Chapitre français de l'IEEE PES (Power & Energy Society)
- Avec l'appui de la SEE (Société de l'Electricité, de l'Electronique et des Technologies de l'Information et de la Communication) – Club technique « Systèmes électriques »

Jeudi 27 Avril 2017

de 14h30 à 19h40

RTE - Tour Initiale – 1, terrasse Bellini
Paris - La Défense

14h30	***Tutorial : DC Grids*** Dragan Jovcic, *Chair of Engineering, Université d'Aberdeen, Royaume-Uni.*
17h00	***Pause***
17h30	***Accueil*** Sébastien Henry, *Président du bureau français de l'IEEE PES, Directeur SI & Télécommunications, RTE.*
17h40	***DC Transmission Grids: Components, Modelling, Control and Protection Challenges*** Dragan Jovcic, *Chair of Engineering, Université d'Aberdeen, Royaume-Uni.*
18h10	***La simulation temps réel à RTE,*** *Bertrand Clerc, RTE*
18h40	***Protection des réseaux HVDC : description d'une stratégie sélective basée sur les limiteurs supraconducteurs*** Alberto Bertinato, *Supergrid Institute*
19h10	***La recherche académique française sur le courant continu*** Xavier Guillaud, *Professeur à l'Ecole Centrale de Lille et chercheur au L2EP*
19h40	***Pot de l'amitié***

Renseignements

Après la soirée, les présentations sont disponibles sur http://ewh.ieee.org/r8/france/pes/

Lieu

RTE - Tour Initiale
1, terrasse Bellini, Paris - La Défense
Métro ligne 1– Station : Esplanade de la Défense
Plan : http://bit.ly/1iZ39Jy

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

April 2017

Dragan Jovcic,
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University of Aberdeen,
Aberdeen, UK
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Aberdeen HVDC Research Centre

University of Aberdeen

- Established in 1495. Second in Scotland, UK’s fifth University,
- 150th-170th place in world (Times ranking),
- 5 Nobel Laureates,
- James Maxwell chair in Natural Philosophy, 1856-60, (laid off in 1960),

Aberdeen HVDC Research Centre

- 4 permanent staff,
- 5 post Doctoral fellows,
- 6 PhD students
- Power Systems, Power electronics, Control Engineering,
- Research funding (around £3.6million) :
  - EPSRC, DTI,
  - EU FP 7, Horizon2020,
  - Reseau de Transport d’Electricite, Paris,
  - Scottish and Southern Energy, UK,
- DC Grid laboratory
  - 7x30kW DC Grid demonstrator,
  - RTDS

Outline

1. DC network challenges

2. DC grid components:
    1. DC Circuit Breakers
    2. Full Bridge MMC,
    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 exploitation,
- •Only North Sea can provide the required energy demand,
- •Desertec/Medgrid, EU overlay grid,
- •Also medium voltage collection/distribution DC grids, DC micrigrids, Marine systems,

Why DC?

- •DC has lower losses, no reactive power, fast power control, smaller lines/cables,...
- •Submarine cables over 30km must use DC transmission,
- •War of the currents in early 20th century (Edison versus Westinghouse and Tesla),

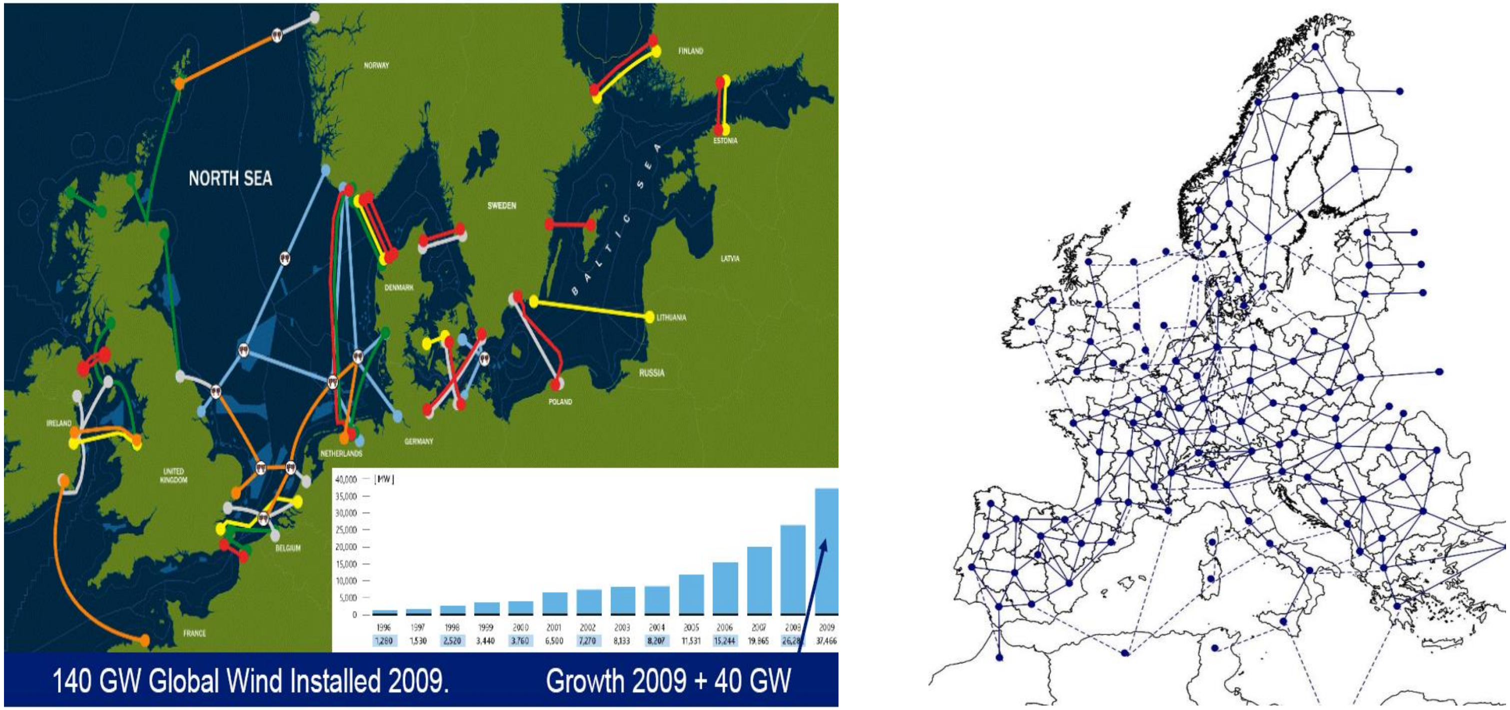


Figure 1. North Sea DC Supergrid (EWEA) and European overlay DC grid.

1. DC network challenges

There are over 150 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). Power reversal by voltage reversal,
- VSC (Voltage source converters) Use IGBTs. Power reversal by current reversal (more suitable for DC grids),
- MMC (Modlar Multilevel Converter) VSC. Improved efficiency, rating and power quality.

Figure 2. INELFE HVDC station and Moyle HVDC valve hall.

1. DC network challenges

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, (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,

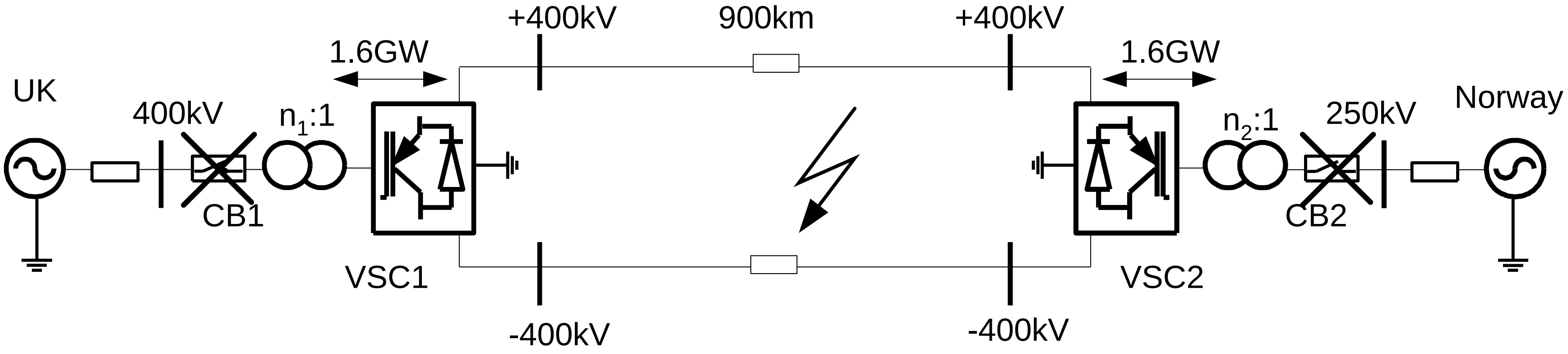


Figure 3. An HVDC link.

1. DC network challenges

- Demand to connect a new load or generator to DC lines
- Multiple HVDC in close proximity,
- We need capability to isolate DC grid segments,

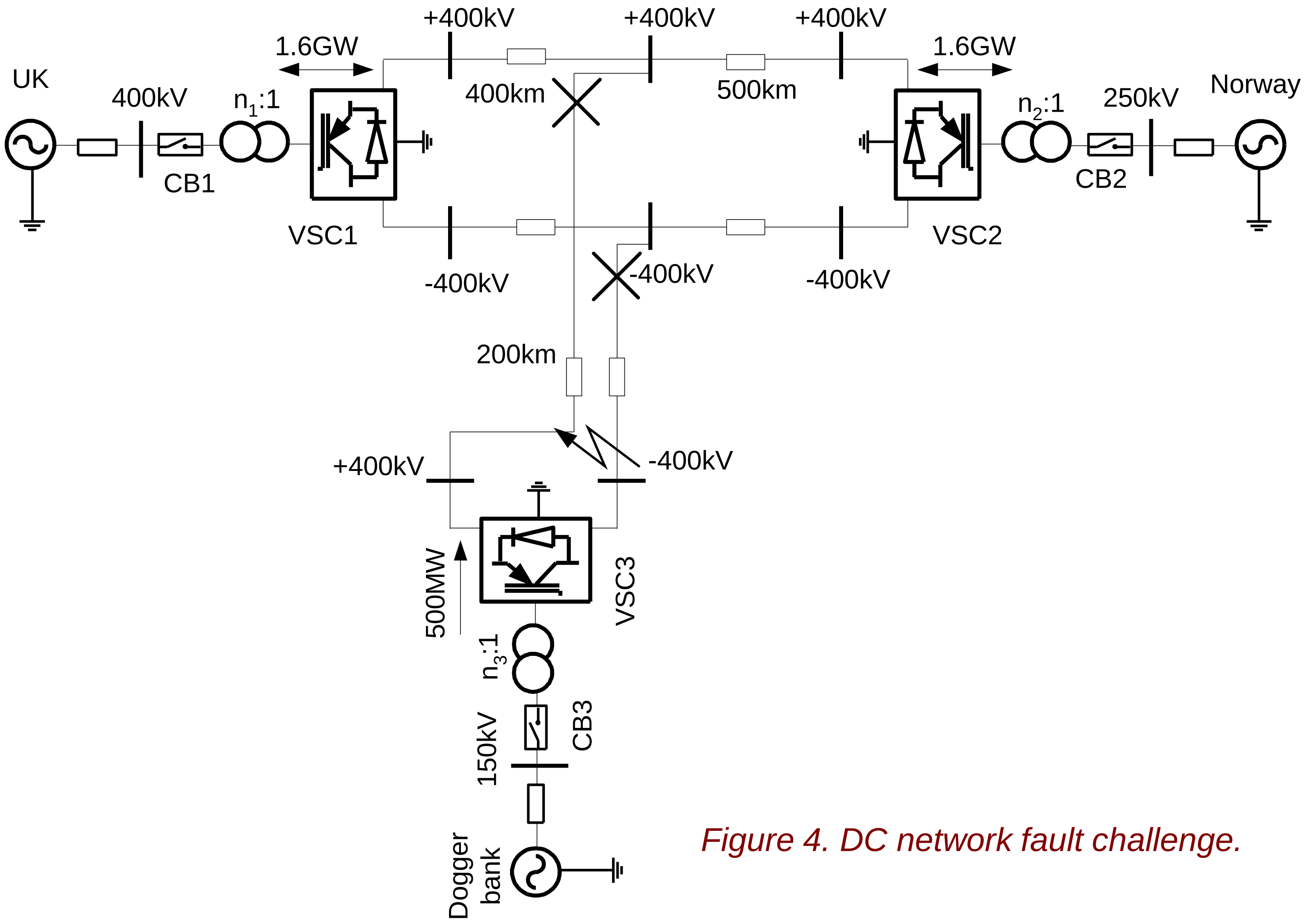


Figure 4. DC network fault challenge.

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),

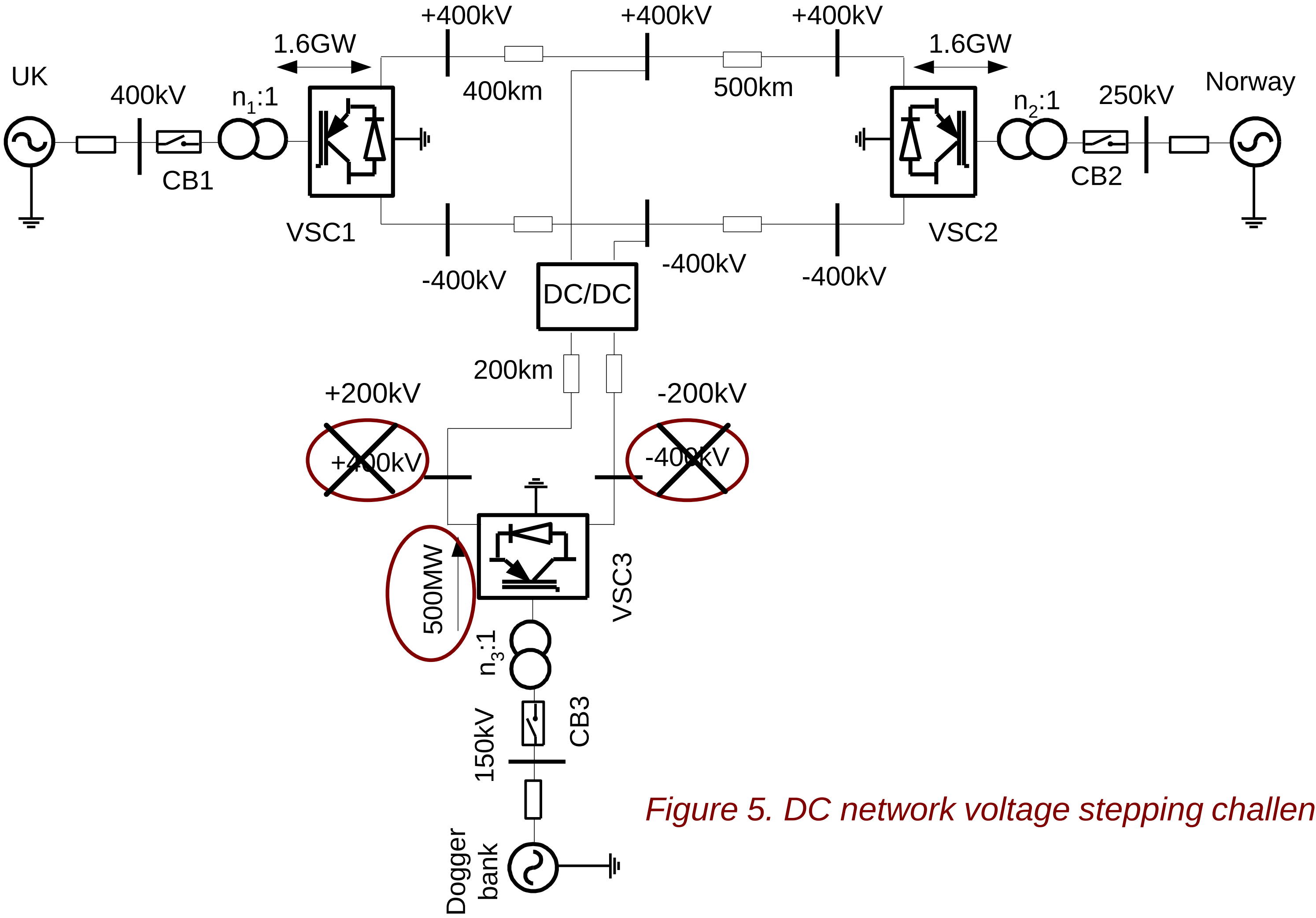


Figure 5. DC network voltage stepping challenge.

1. DC network challenges

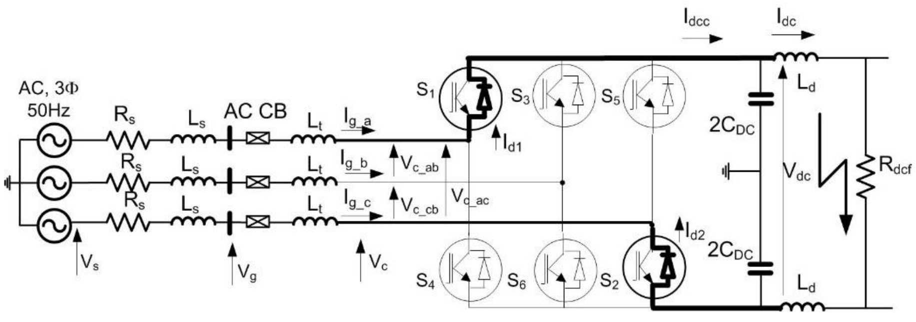
We want DC grids of same reliability and performance as AC grids

•protection challenges

- Diode rectifiers give large fault currents,
- Too many expensive DC Circuit Breakers,
- Converters have no over-current over-voltage capability (self-protection),
- DC lines have low impedance (R+jωL) (ω=0),
- Series reactors and energy dumps,
- DC current has no zero crossings,
- Fast operation is required (2-5ms)

•control challenges

- No inertia,
- Very fast control is required (within 20-50ms)
- Low tripping margin,
- Interaction between many control loops,



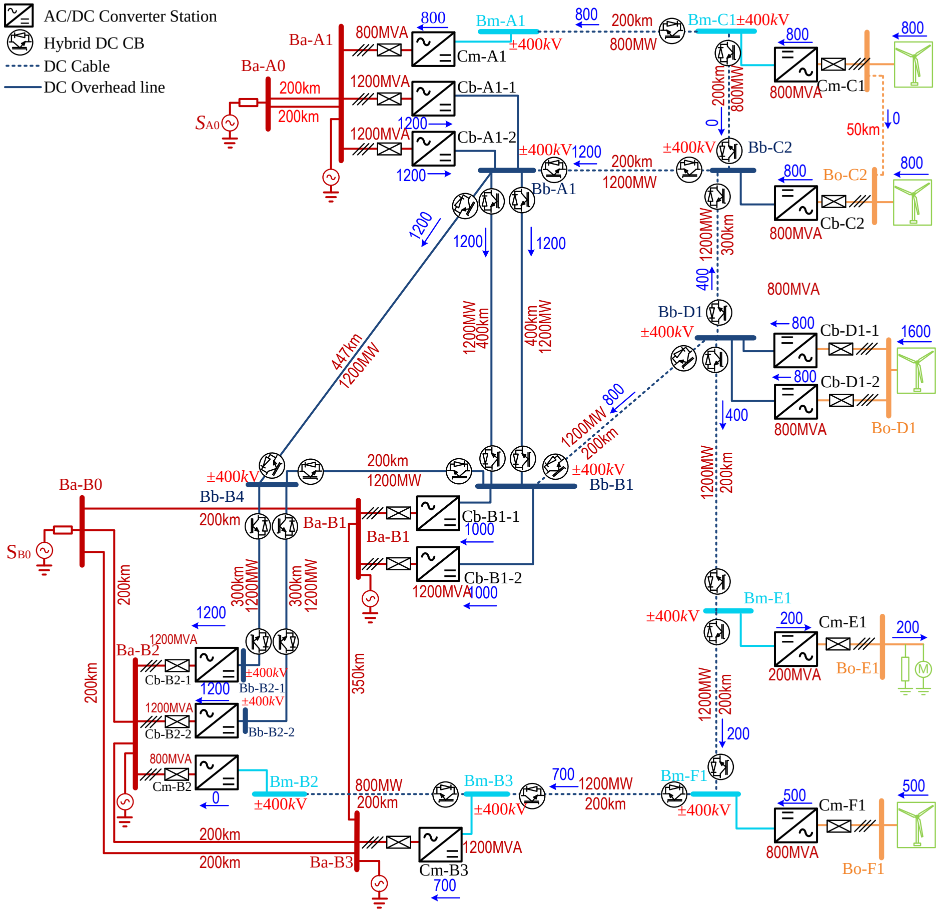
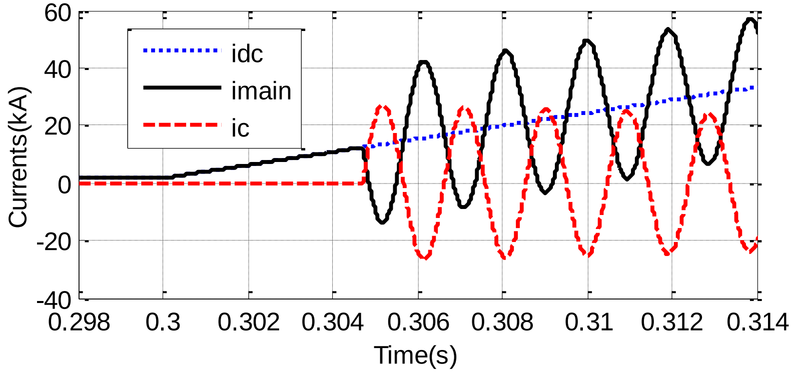
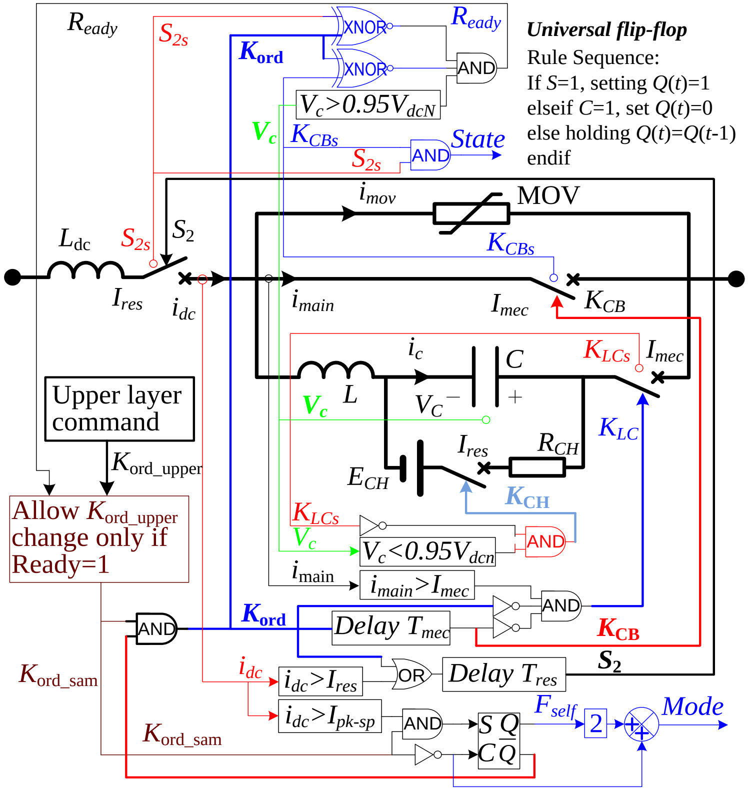


Figure 6. 10 Terminal DC grid (CIGRE B4 Benchmark).

2. DC grid components: DC Circuit Breakers

- AC Circuit Breakers use natural current zero crossing
- DC Circuit Breakers
  - employ series inductors,
  - need large energy absorbers (10-20MJ),
- Mechanical DC CB
  - Opening time around 10ms (slow),
  - Interruption is not certain (3 zero crossings),
  - Cost is low,





Universal flip-flop

Rule Sequence:

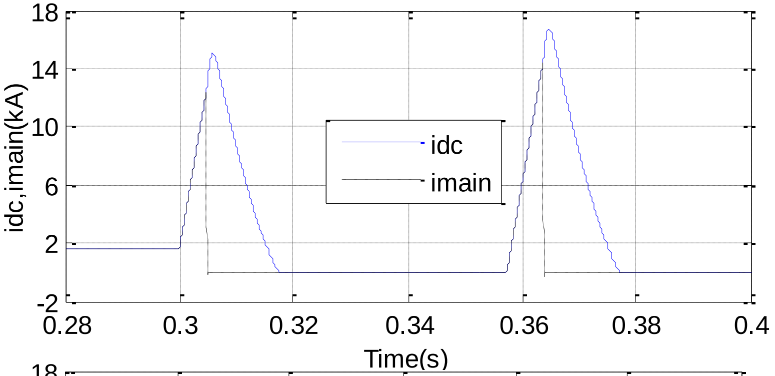
If S=1, setting $Q(t)$=1

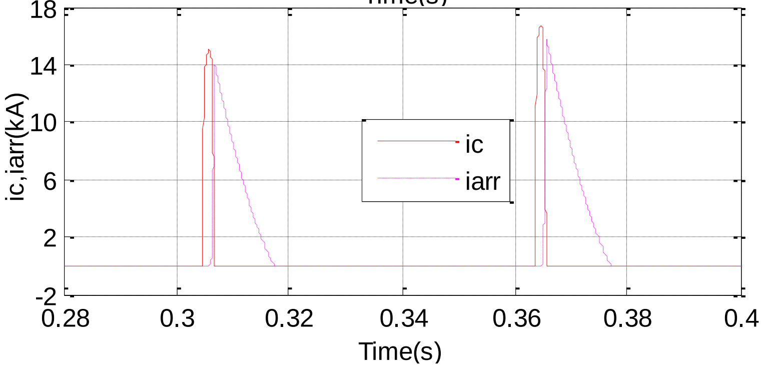
elseif C=1, set $Q(t)$=0

else holding $Q(t)$=$Q(t-1)$

endif

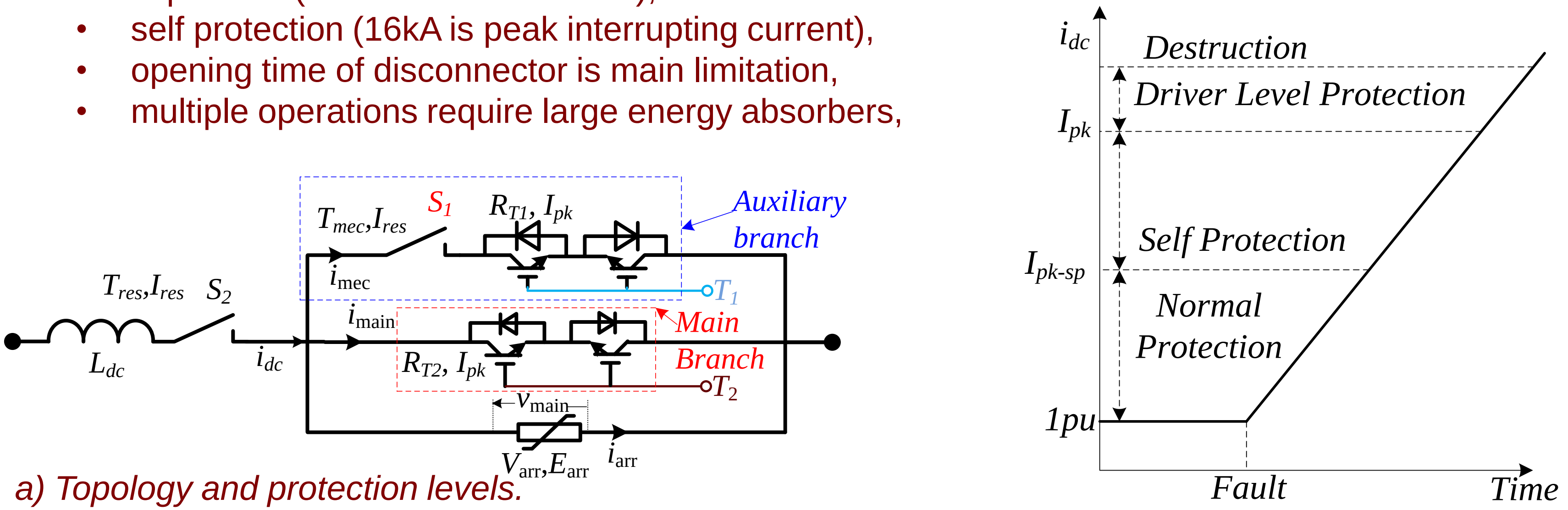
Figure 7. Mechanical DC Circuit Breaker.



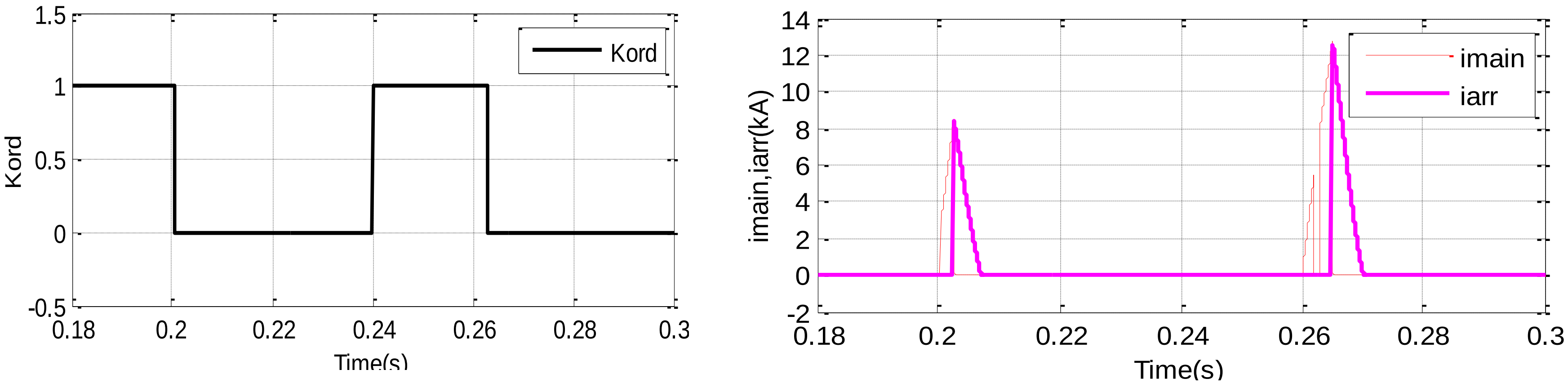


2. DC grid components: DC Circuit Breakers

- **Hybrid DC Circuit Breaker:**
  - 2-5ms opening time,
  - expensive (30% of converter cost),
  - self protection (16kA is peak interrupting current),
  - opening time of disconnector is main limitation,
  - multiple operations require large energy absorbers,



a) Topology and protection levels.



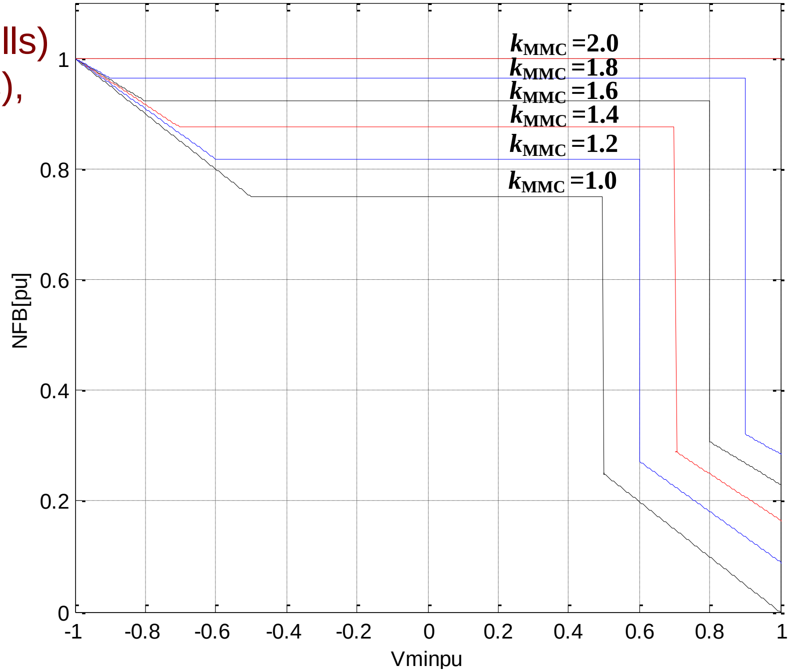
b) Simulation of tripping and reclosing into a permanent DC fault

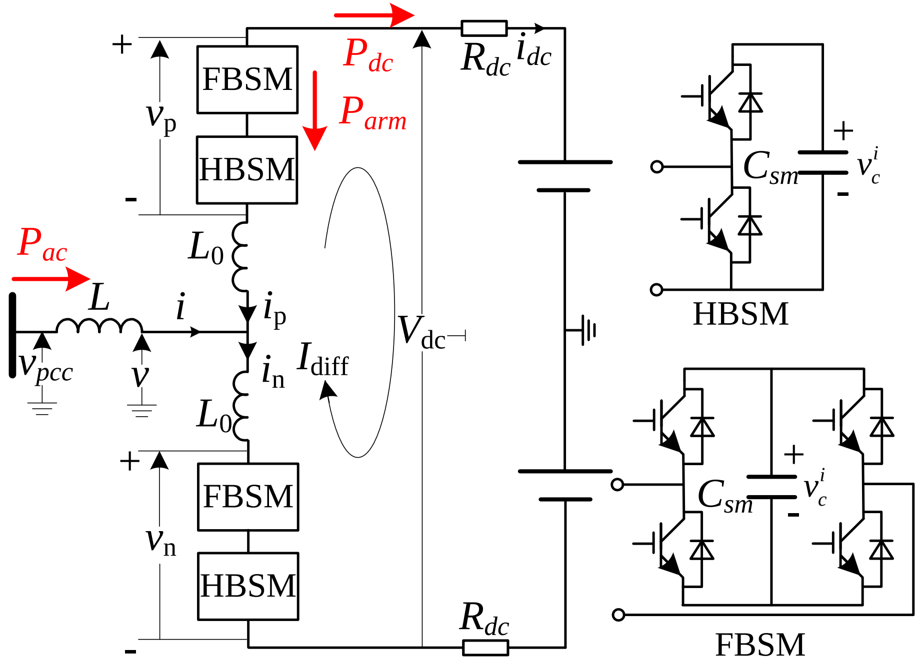
Figure 8. Hybrid DC Circuit Breaker.

2. DC grid components: Full Bridge MMC

Optimal Design of FB 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 more power for given cell current and DC cable voltage (using extra FB cells),





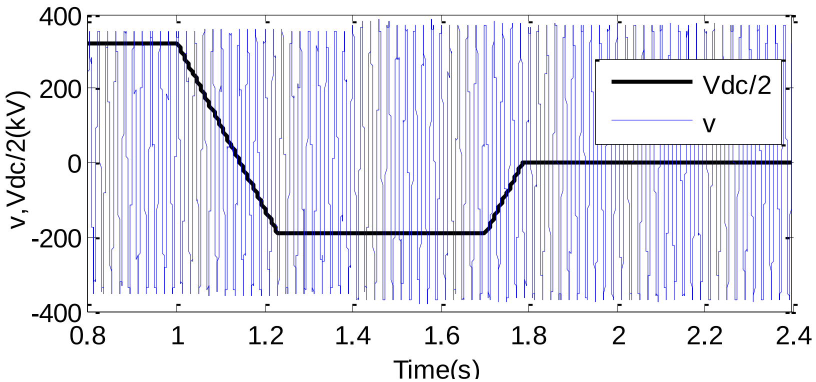


Figure 9. Optimal design of Full bridge Modular Multilevel Converter.

2. DC grid components: Full Bridge MMC

Capacitor voltage balancing is 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,

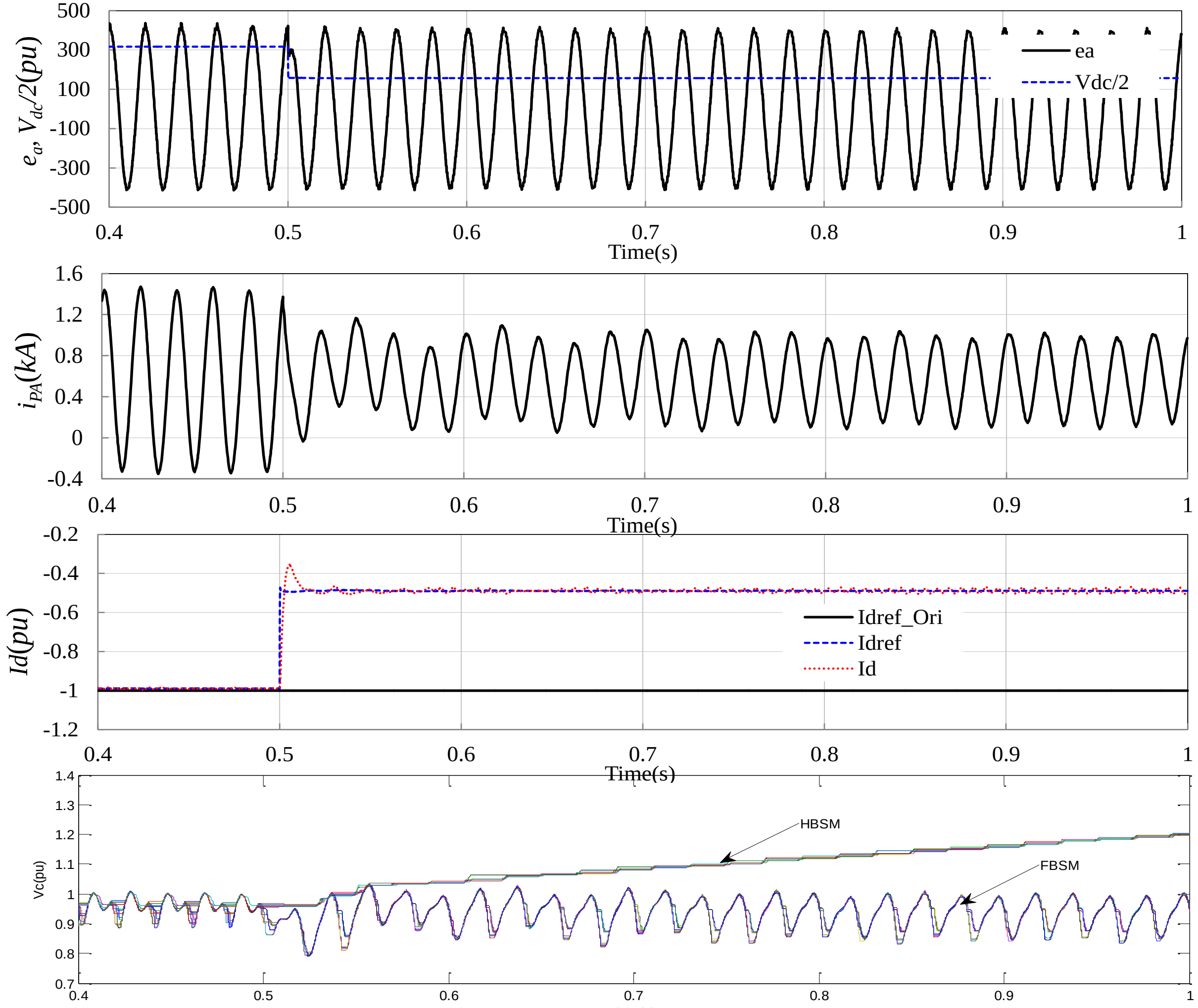


Figure 10. Full Bridge MMC with insufficient number of FB cells.

2. DC grid components: Full Bridge MMC

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),
- Coordination between rectifier and inverter in an HVDC,
- In total each FB MMC has over 30 control loops,

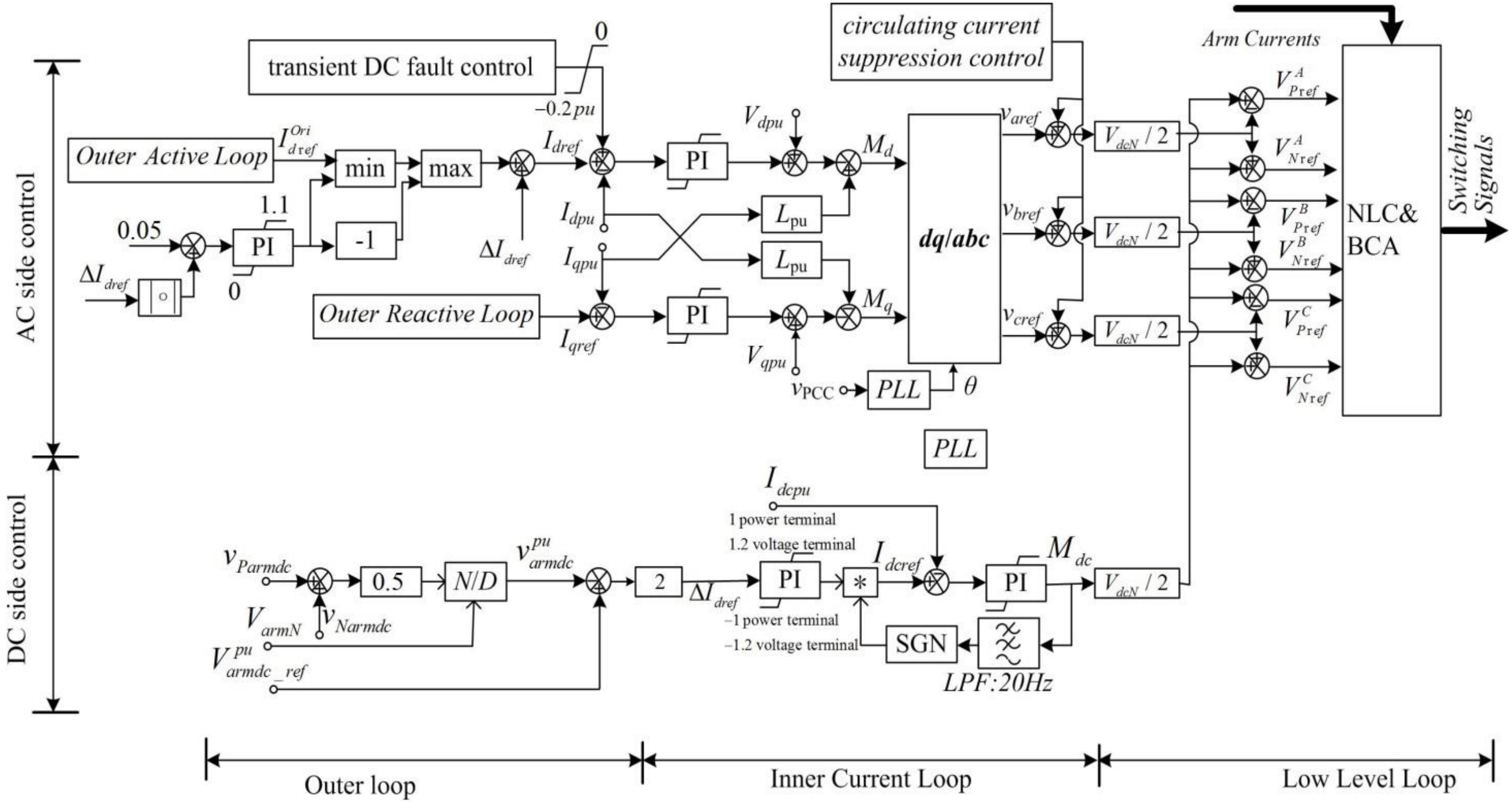


Figure 11. FB MMC control.

2. DC grid components: Full Bridge MMC

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,

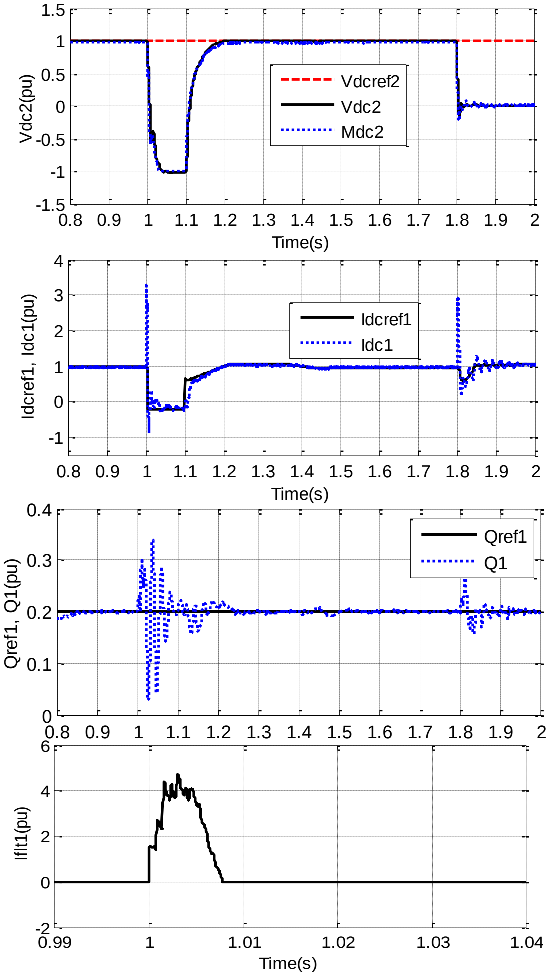


Figure 12. FB MMC HVDC response to DC faults.

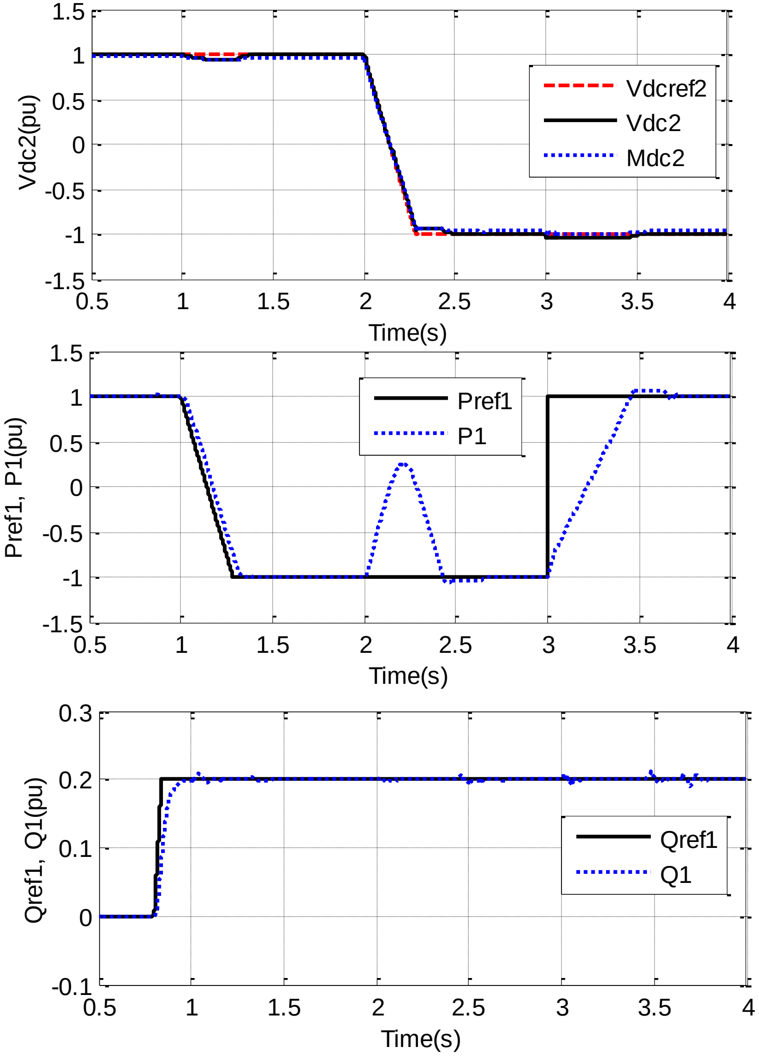


Figure 13. FB MMC HVDC 4-quadrant operation.

2. DC grid components: DC/DC converters

DC/DC converter functions:

- Enable DC voltage stepping,
- Enable power flow control,
- DC fault current control and DC fault isolation,
- Interconnection of different DC systems:
    - different manufacturers,
    - VSC with LCC,
    - helps with interoperability and standardisation issues,

DC/DC converter types:

- Low stepping ratio (chopper),
- 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,
    - central grounding (symmetrical monopole) only.

2. DC grid components: DC/DC converters

Thyristor LCL DC/DC converter enables connection of LCC or VSC with DC grid

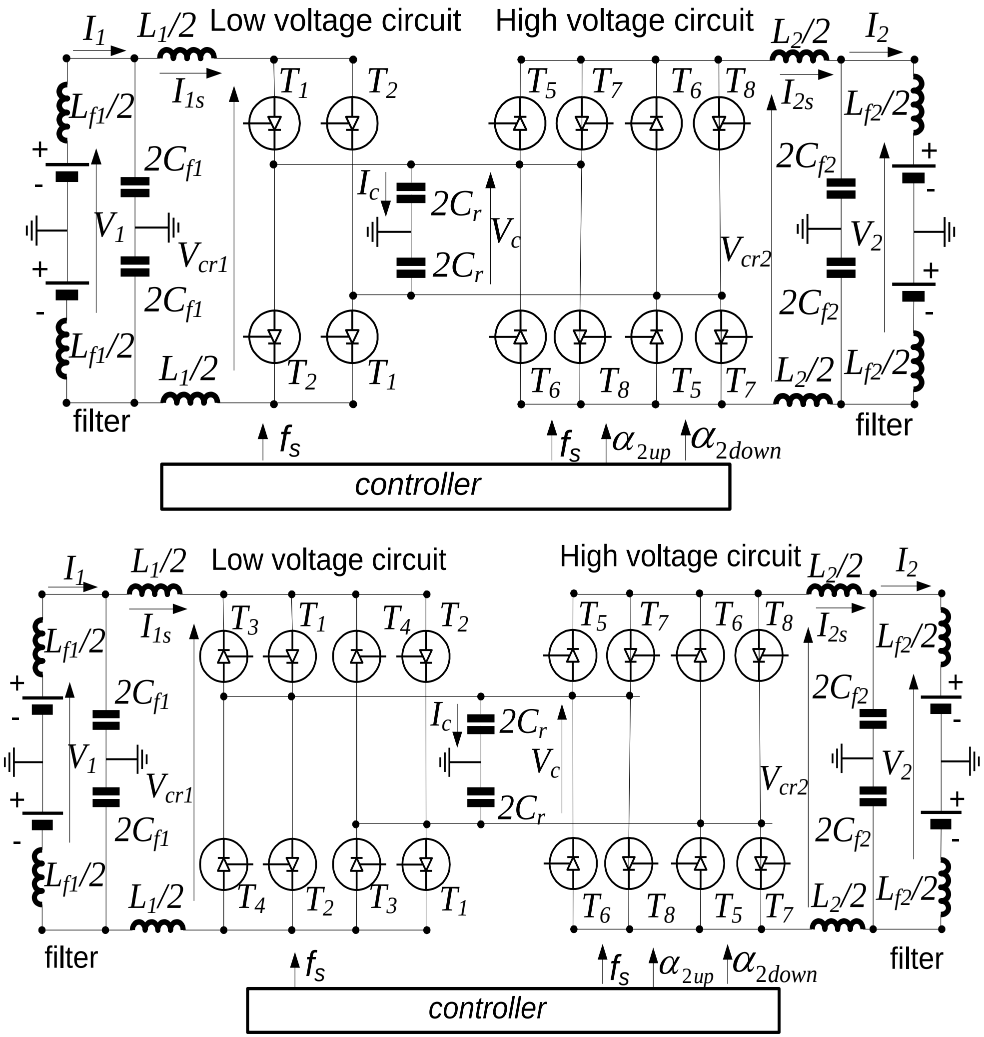


Figure 14. Bidirectional thyristor-based DC/DC converter.

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

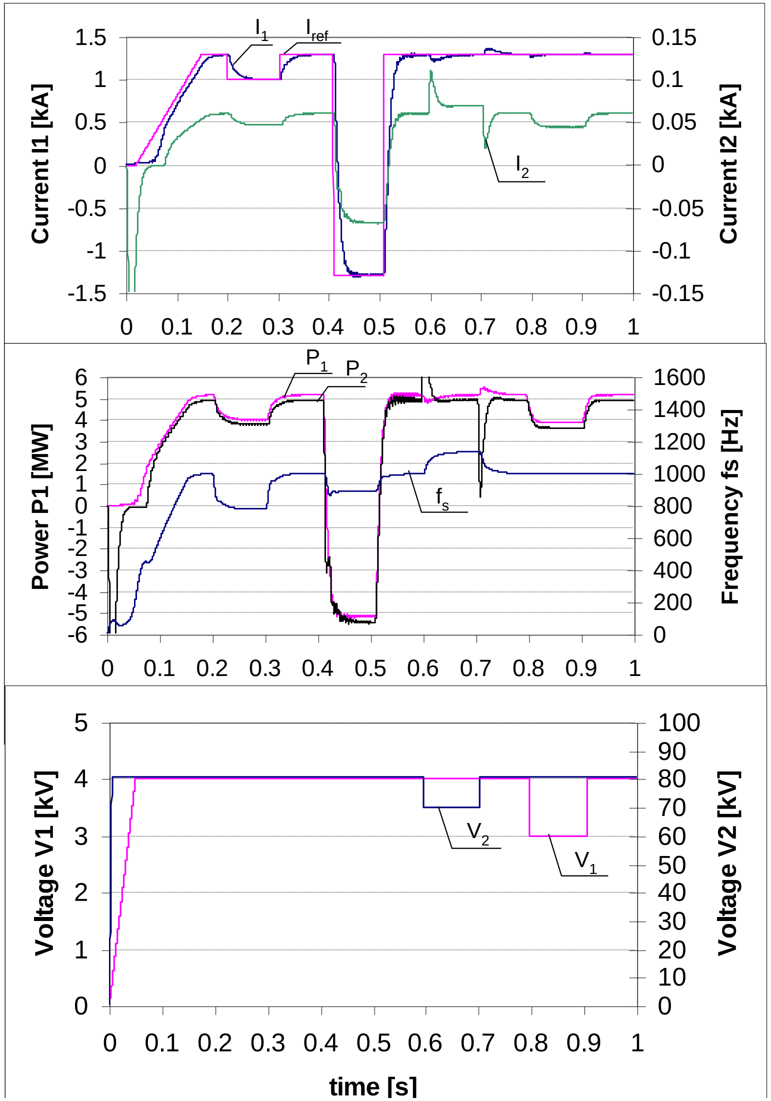
Power direction	V_1	I_1	V_2	I_2
V_1 to V_2 (step-up)	+	+	+	+
V_2 to V_1 (step-down)	-	+	+	-

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

Interfacing VSC converters with DC grids



DC/DC for wind energy integration

- P=5MW
- V1=4kV
- V2=80kV

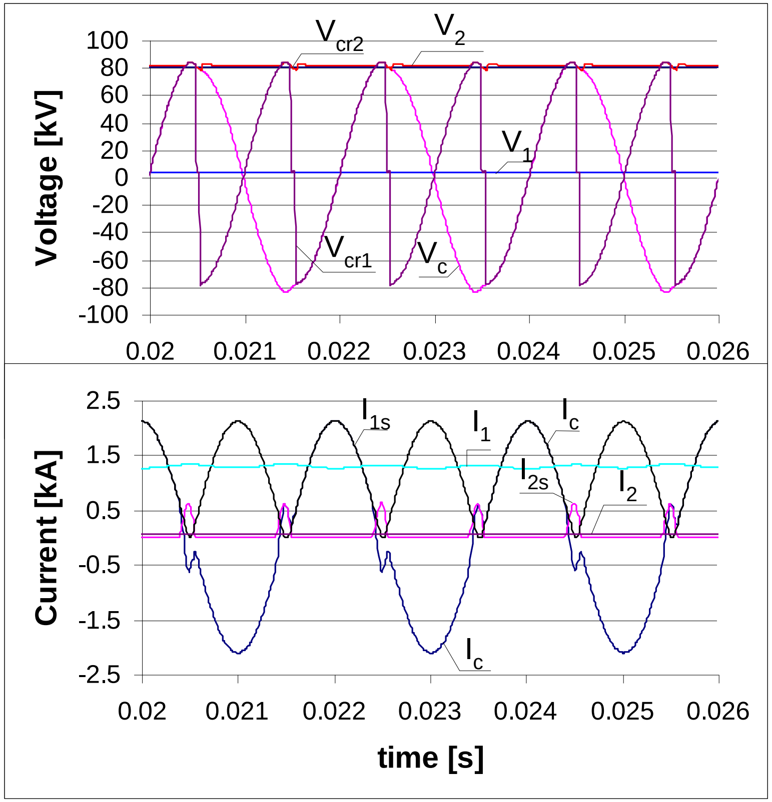


Figure 15. Simulation results; converter with current polarity change on V1. At 0.2s current step, at 0.4-0.5s power reversal, at 0.6s V2 disturbance, at 0.7s V1 disturb.

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,
- 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 multiterminal topology.

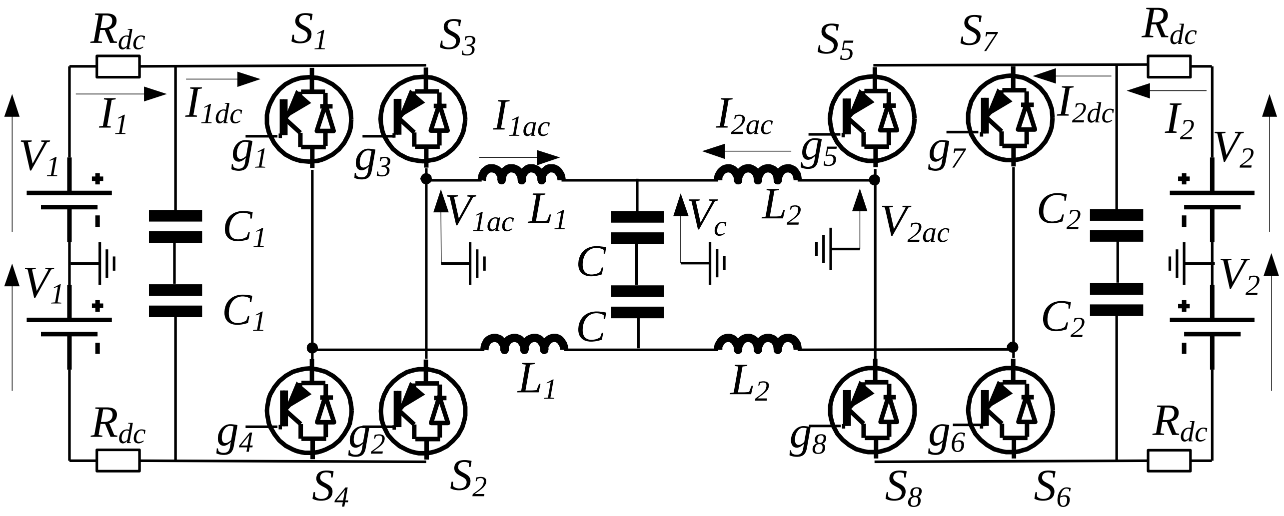


Figure 16. IGBT based LCL DC/DC converter .

2. DC grid components: DC/DC converters

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

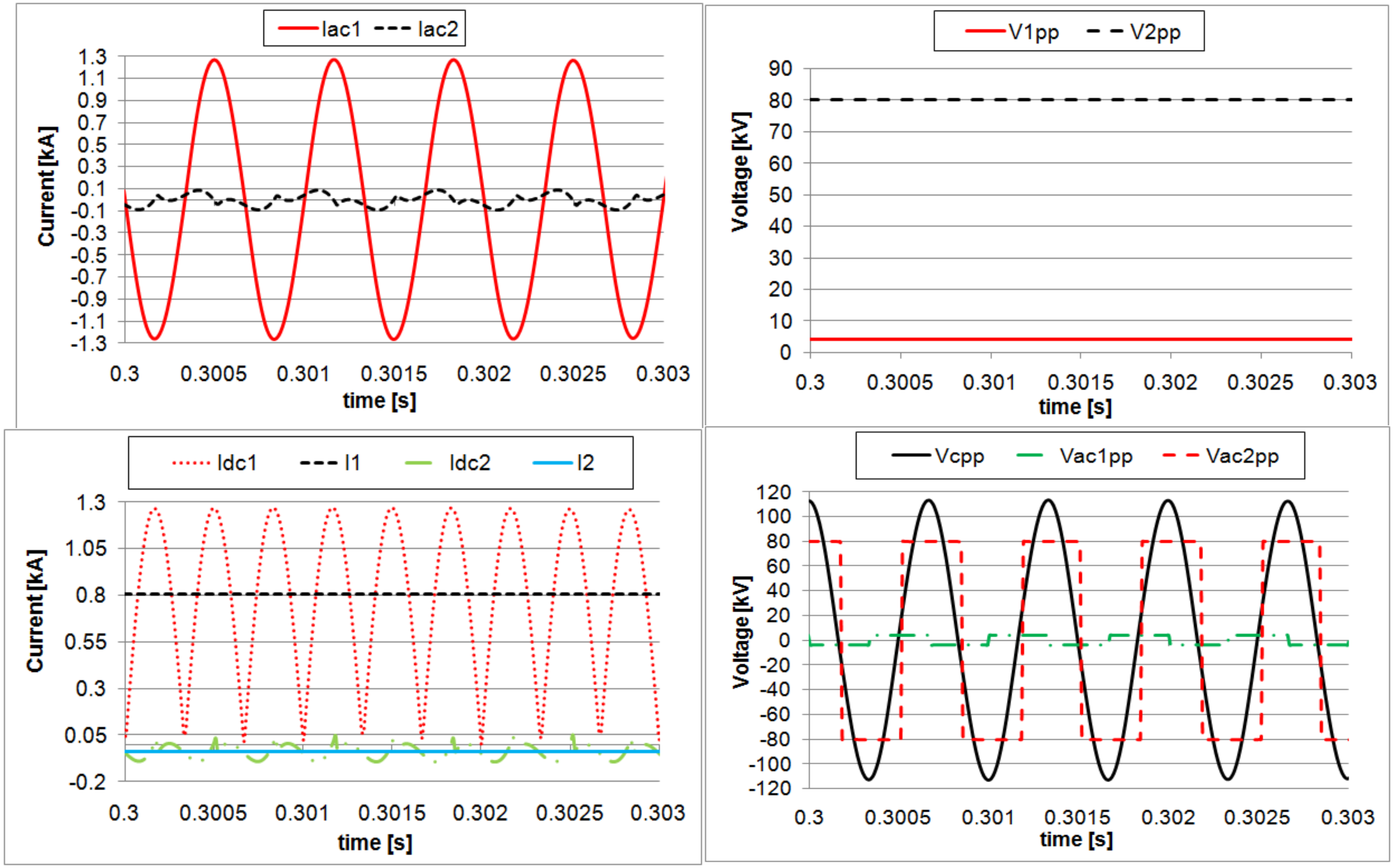


Figure 17. LCL DC/DC converter 5/80kV simulation of steady-state operation.

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),
- Ride through DC faults,
- Operating frequency 50-300Hz,

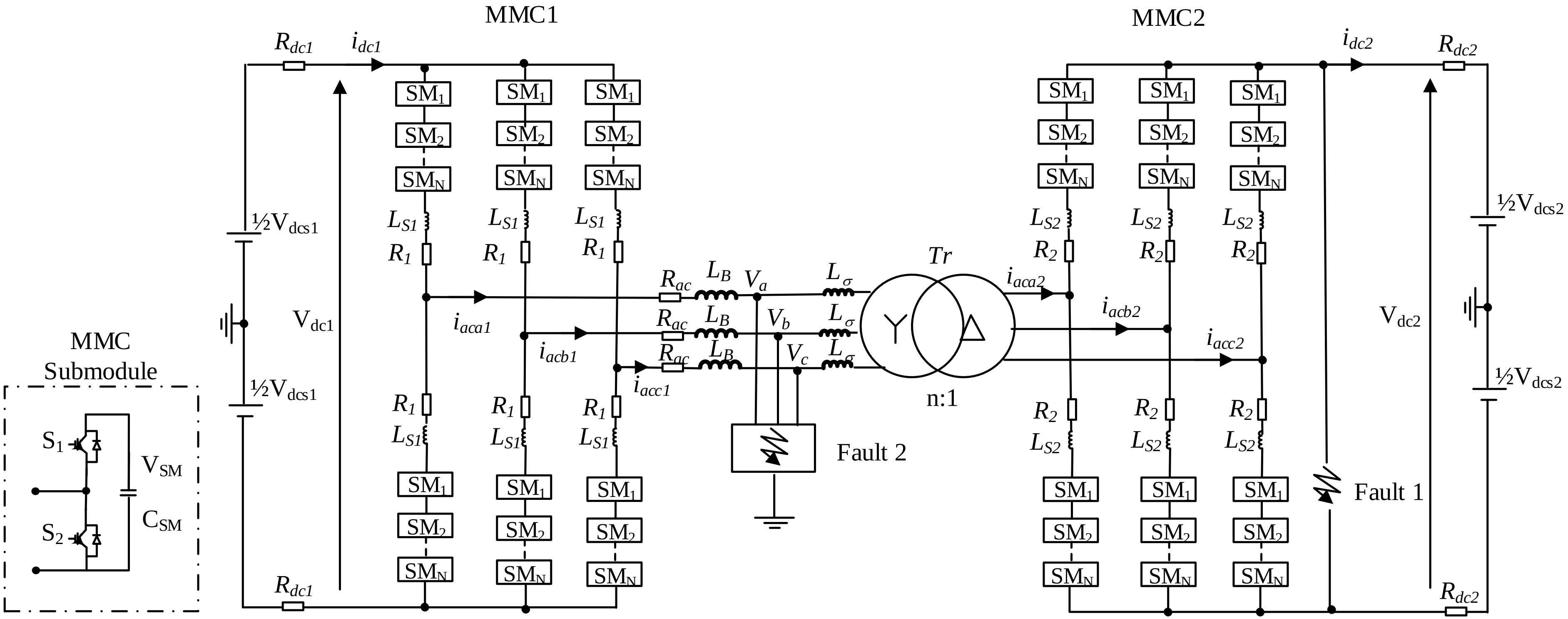
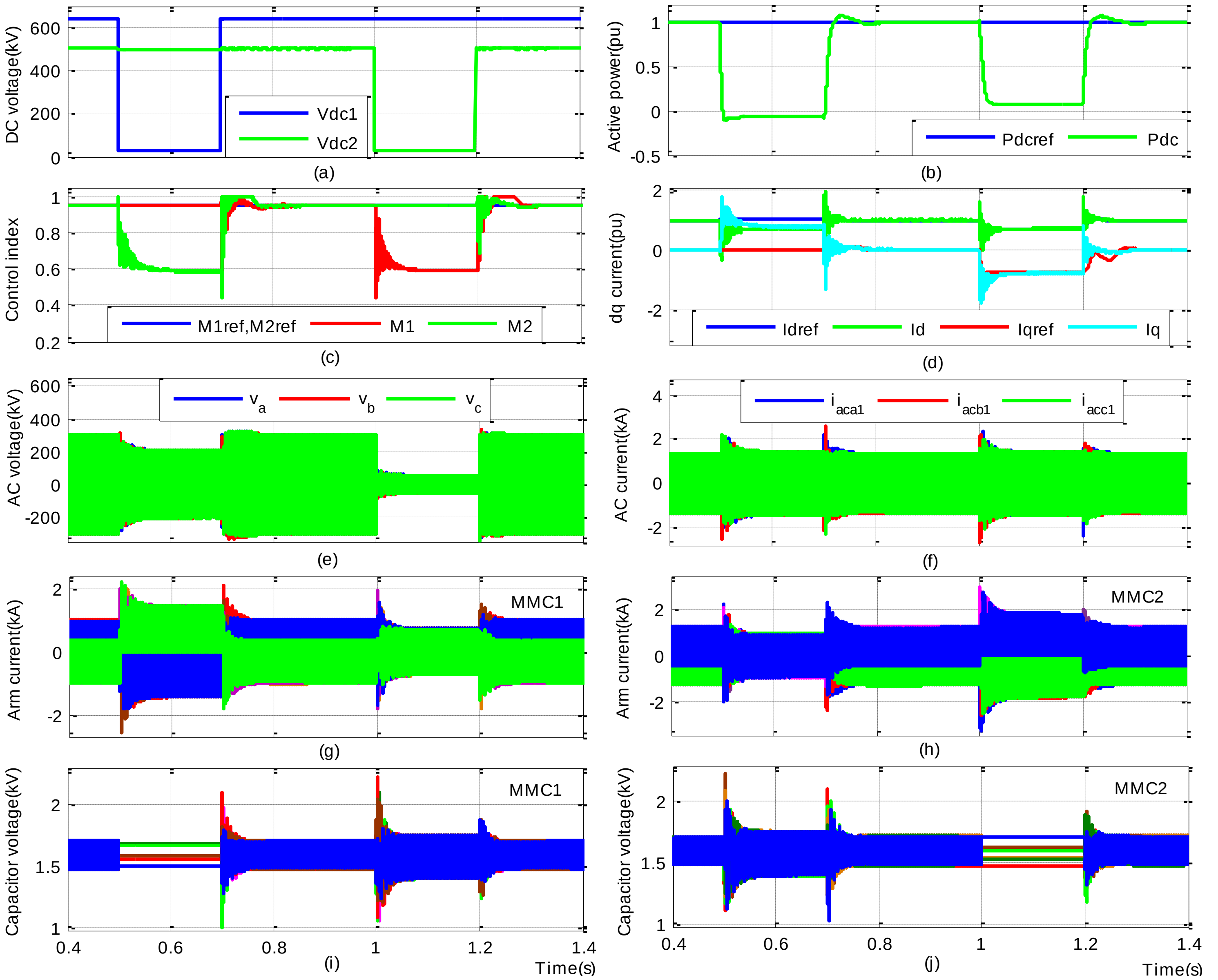


Figure 18. Isolated, MMC-based, 3-phase, DC/DC Converter.

2. DC grid components: DC/DC converters



(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

Figure 18. Response to 2 DC faults (Isolated, MMC-based, DC/DC Converter.

2. DC grid components: DC/DC converters

MMC-based DC/DC design

- DC/DC involves 2 MMC AC/DC converters, front to front connected,
- MMC VSC enables low losses and good power quality,
- Power quality in inner AC circuit is not essential,
- Lower number of cell rotations (voltage balancing) leads to lower losses,
- Lower number of cells gives lower losses,
- 20-50 cells gives optimal design (single switching per half-cycle)

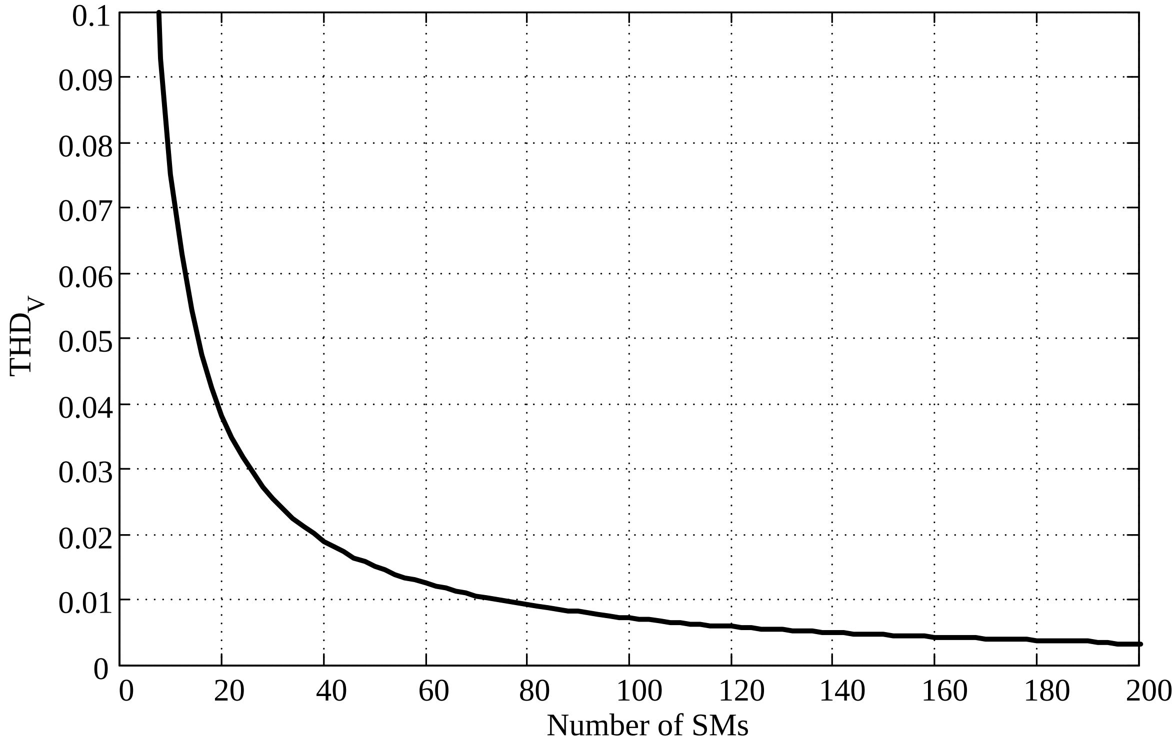


Figure 19. AC voltage THD versus number of cells (1GVA, 640kV MMC VSC).

2. DC grid components: DC/DC converters

MMC-based DC/DC design

- Total loss for DC/DC is 1.24%-2.1% (200-500Hz)

Table 2 Total power losses, weight and volume of 1GVA, 640kV, LCL DC-DC converter

Freq. (Hz)	LCL weight[1] (Ton)	LCL volume[1] (m^3)	LCL inductors conduction losses (MW)	Total Weight[2] (Ton)	Total volume[2] (m^3)	Total power losses (MW)	Total power losses (%)
50	458	379	1.16	4040	3605	9.32	0.93
100	256	196	0.77	2062	1816	10.35	1.04
200	145	99	0.5	1061	913	12.36	1.24
300	105	69	0.39	721	619	15.17	1.52
400	91	54	0.34	561	470	18.08	1.81
500	71	43	0.29	447	373	20.97	2.1
600	62	37	0.26	368	350	23.72	2.37
700	55	32	0.24	325	268	26.94	2.69
800	49	28	0.22	289	236	29.72	2.97
1000	42	23	0.19	230	187	36.17	3.62

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.

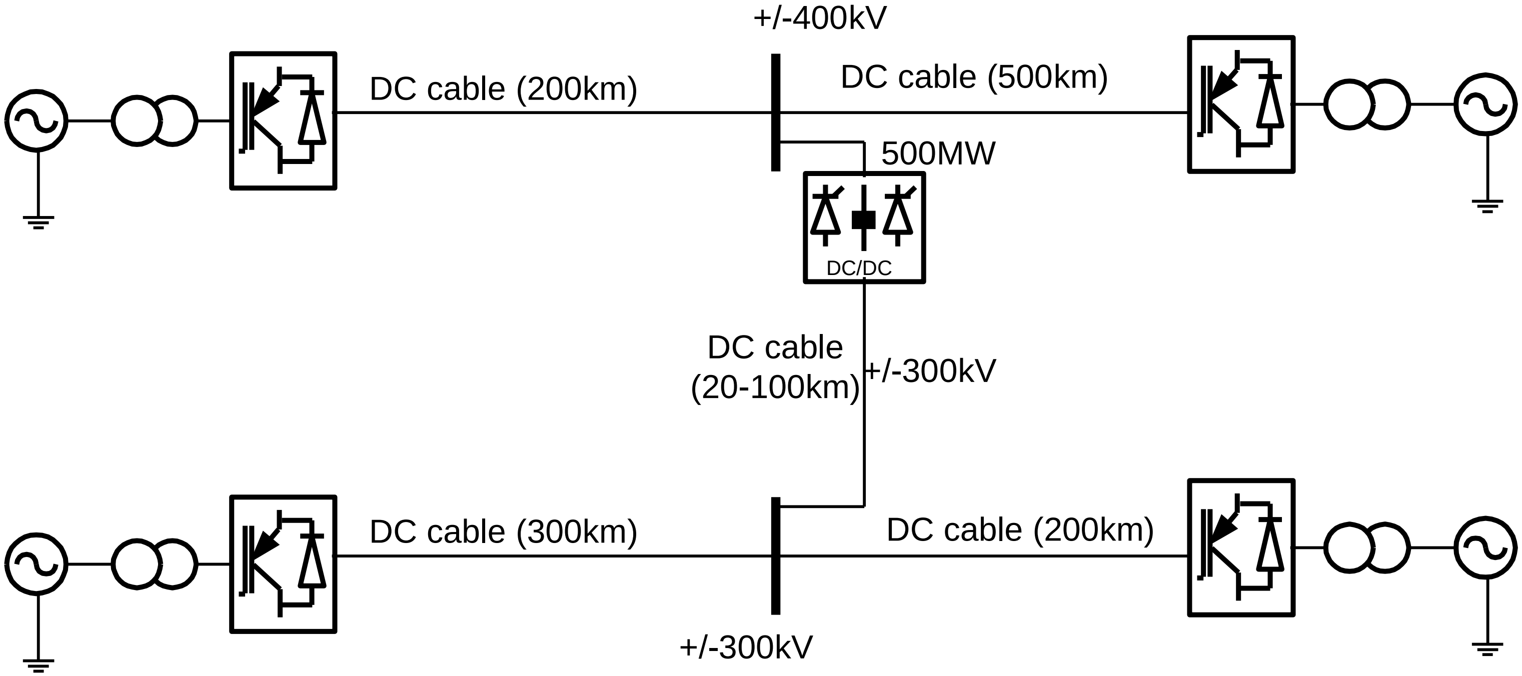


Figure 20. Connecting two existing HVDC using a DC/DC converter.

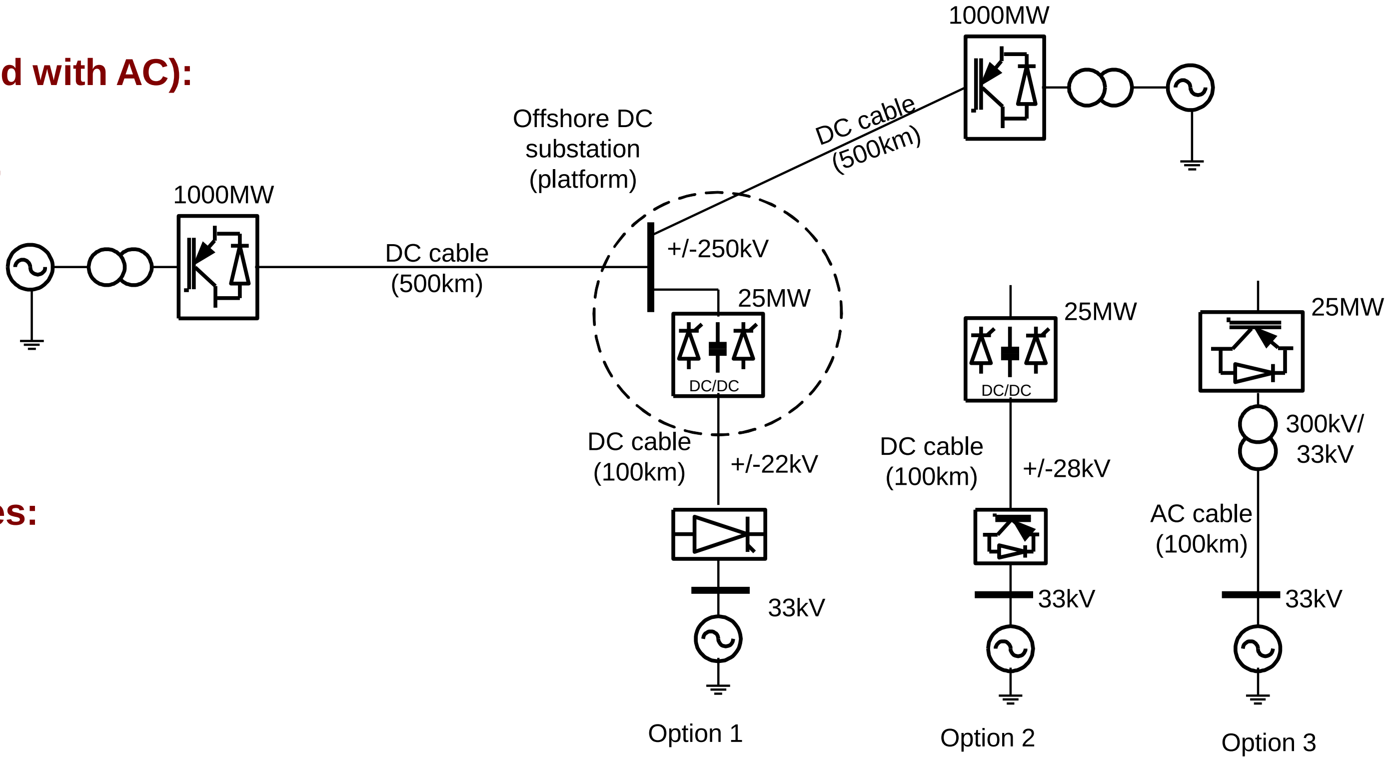
2. DC grid components: DC/DC converters

Case study: 25MW Tap on a 1GW, +/-250kV HVDC

interface	Option 1	Option 2	Option 3 (default)
AC transformer	x	x	300kV/33kV
DC/DC converter	12 thyristors 500kV	16 thyristors 500kV	x
AC/DC converter	6 thyristors 44kV	6 IGBTs 56kV	6 IGBTs 500kV

DC advantages (compared with AC):

- Unlimited distance,
- No reactive power issues,
- Smaller cables,
- Better control,
- Smaller transformers,
- Simpler fault isolation,



DC/DC converter provides:

- DC voltage stepping,
- DC fault isolation,
- DC power control

Figure 21. 25MW tap study on a 1GW HVDC.

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 to transmit 3GW			1767 M€
Total cost per GW			589 M€/GW

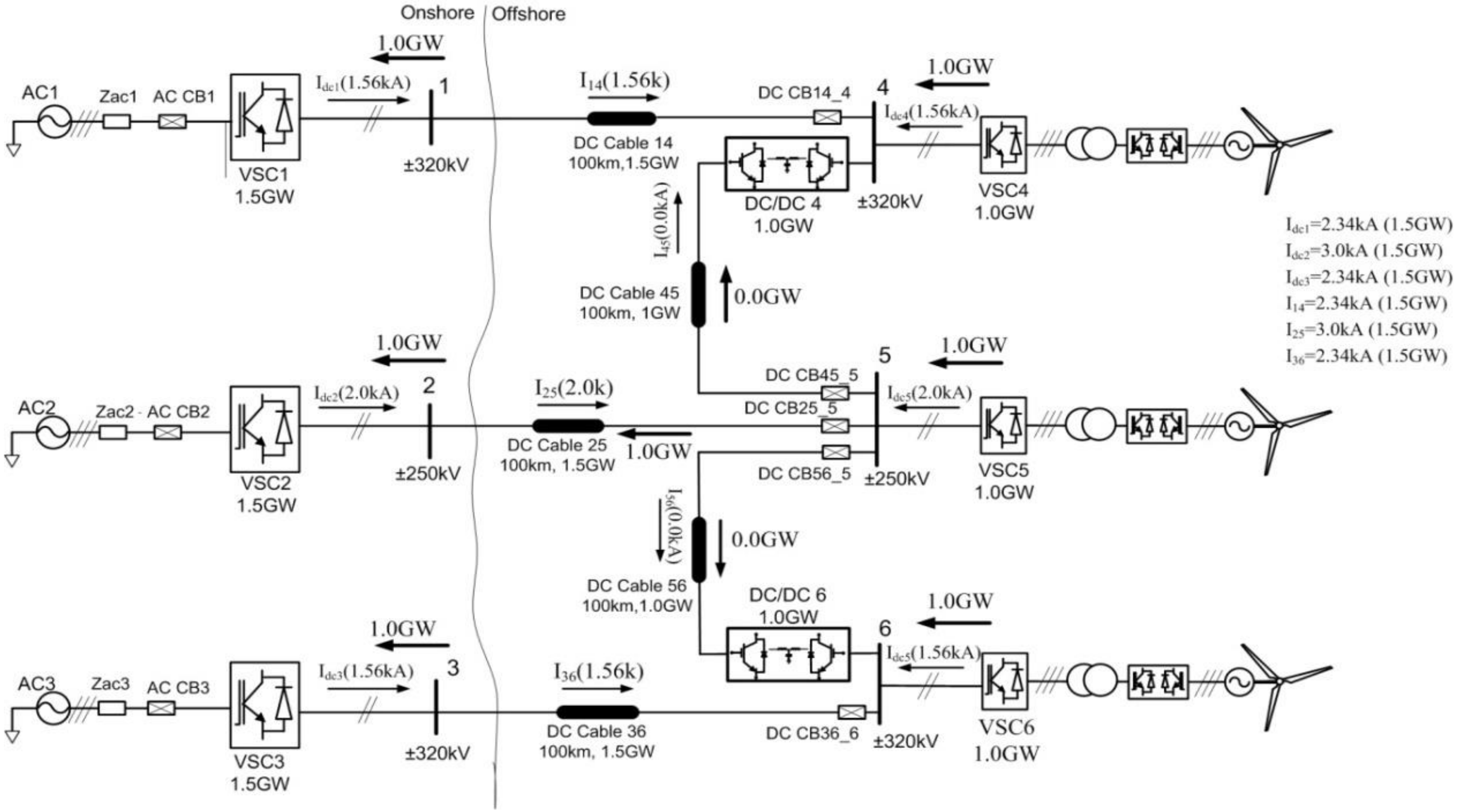


Figure 22. Connecting 3-offshore VSC converters using DC/DC.

2. DC grid components: DC/DC converters

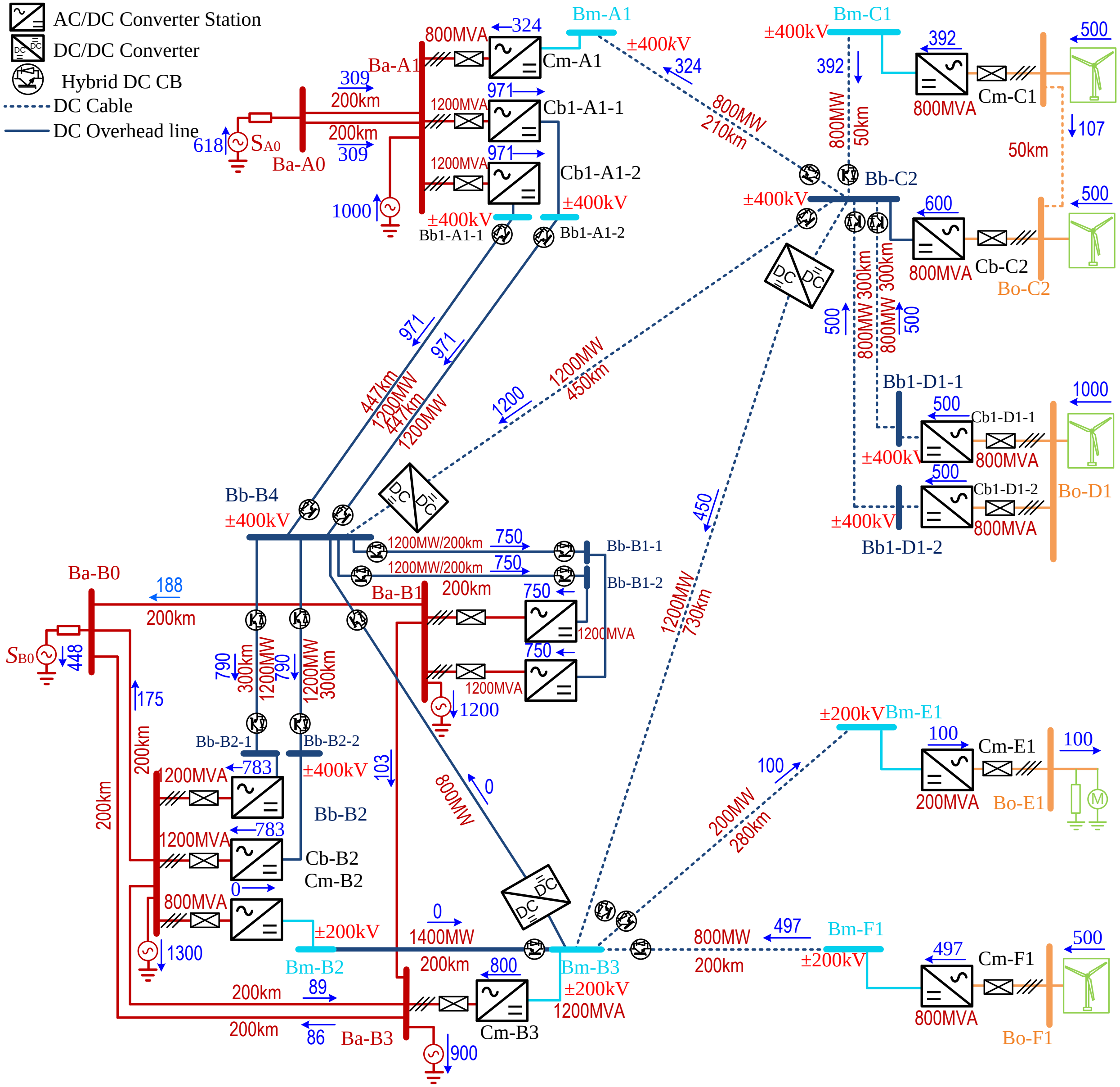


Fig.23. 10-terminal DC grid with 3 local radial DC systems and 3 DC/DC

2. DC grid components: DC hubs

Multiport, Multiphase DC hub

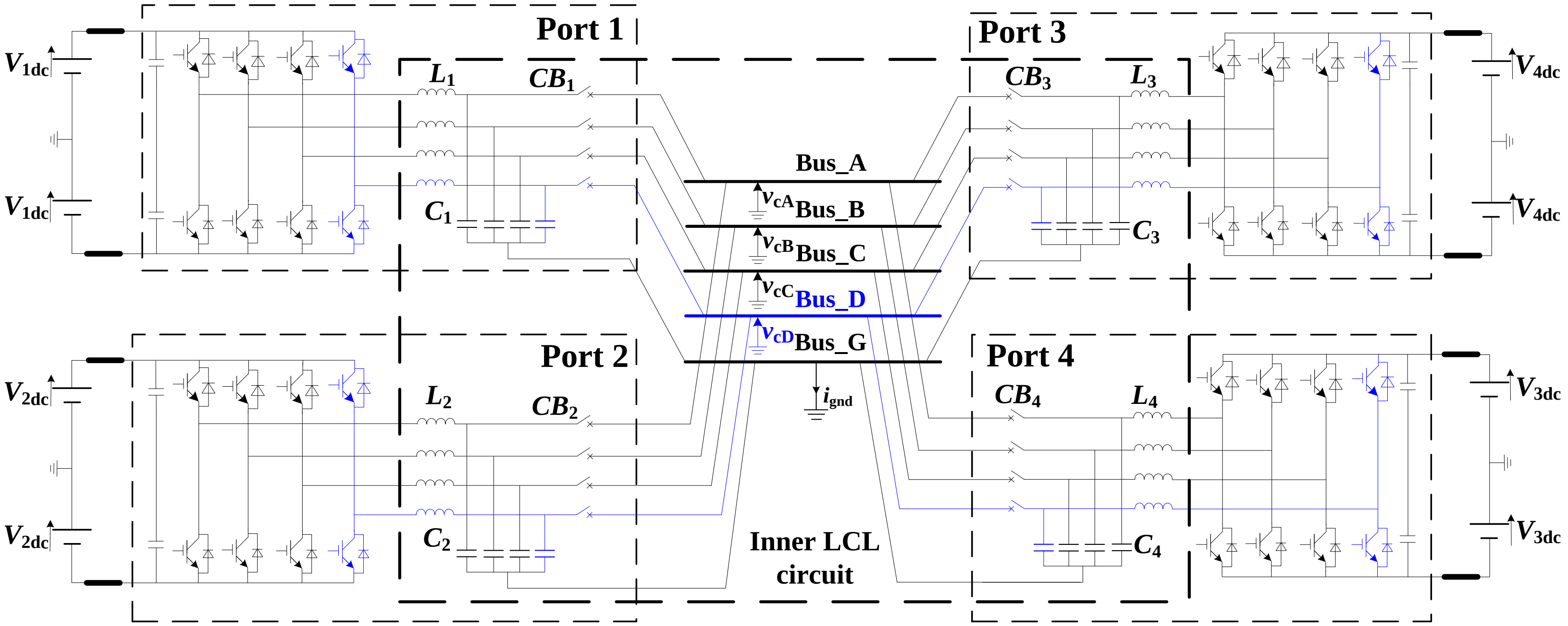


Fig.24. 4-port, 4-phase DC hub

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

- Reconfigure the inner LCL circuit to new balanced AC circuit with reduced number of phases in case of one-phase fault
- Keep redundant phase to meet *N*-1 criterion in case one phase of a port at 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

DC hub test system is purposely designed to represent worst conditions.

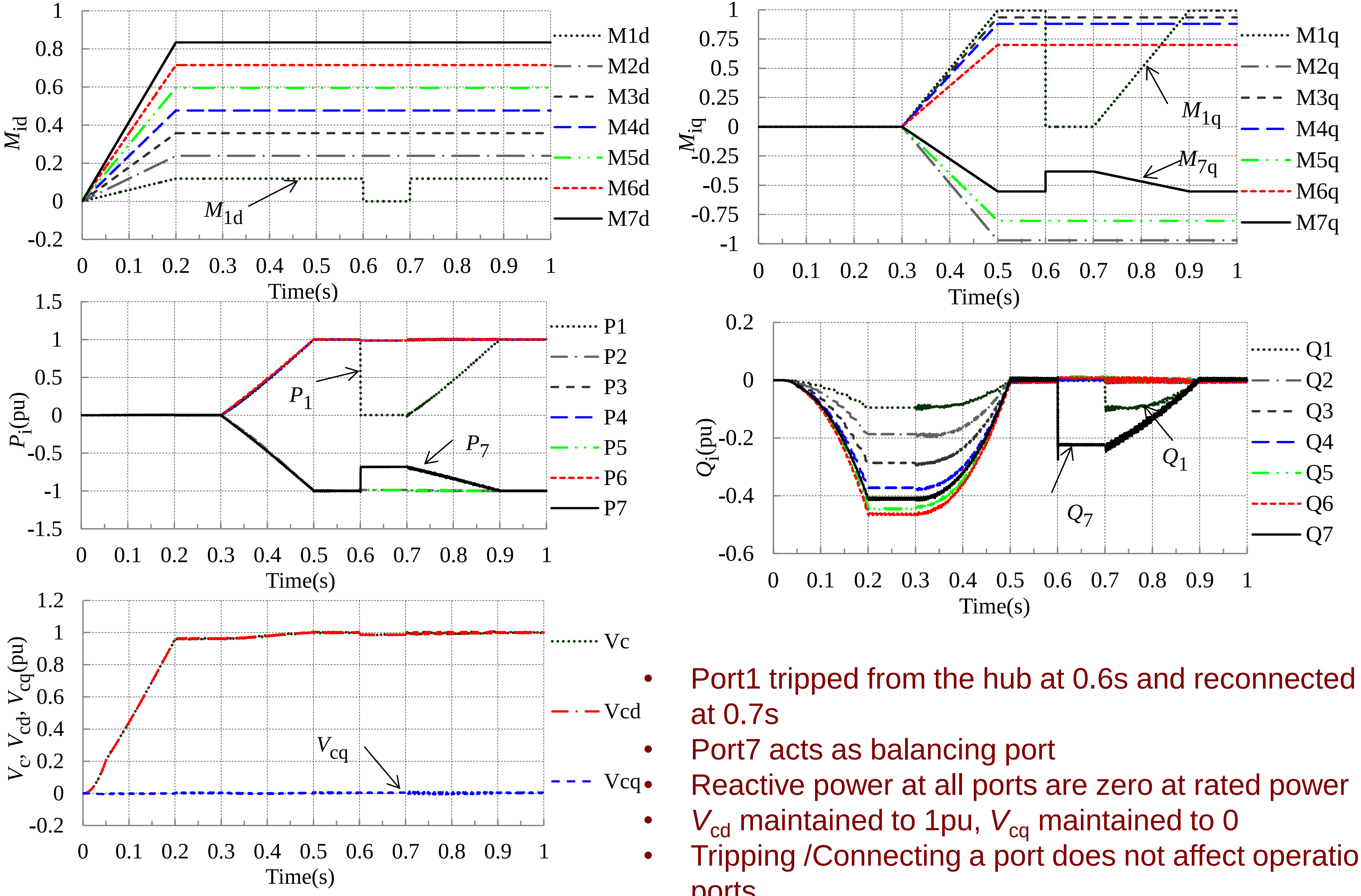
Table 1 Parameters of 7 port test system

Port	**1**	**2**	**3**	**4**	**5**	**6**	**7**
E_i(kV)	100	200	300	400	500	600	700
P_i (MW)	200(+)	300(-)	200(+)	400(+)	350(-)	500(+)	650(-)
L_i(H)	0.086	0.112	0.243	0.152	0.199	0.145	0.103
C_i(uF)	0.186	0.136	0.058	0.082	0.053	0.055	0.048
f_n(kHz)	1.30	1.34	1.41	1.38	1.40	1.37	1.33

Table 2 Common parameters of 7 port test system

V_{cm}(kV)	**p**	**f_o(kHz)**	**f_s(kHz)**	**f_n(kHz)**
755.9	2	1.25	3.75	1.47

2. DC grid components: DC hubs



- Port1 tripped from the hub 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
- Tripping /Connecting a port does not affect operation of other ports

Fig.25. DC Hub response to tripping and reconnecting a port

2. DC grid components: DC hubs

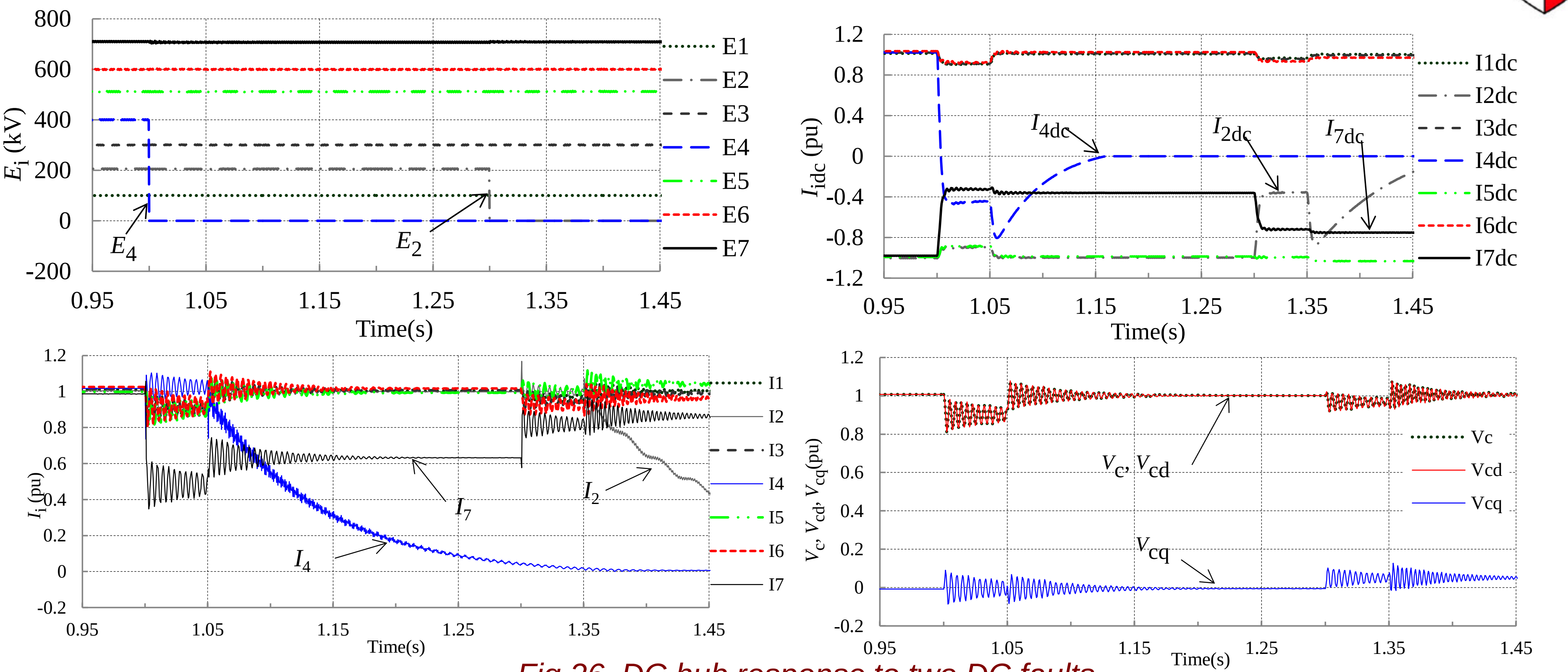
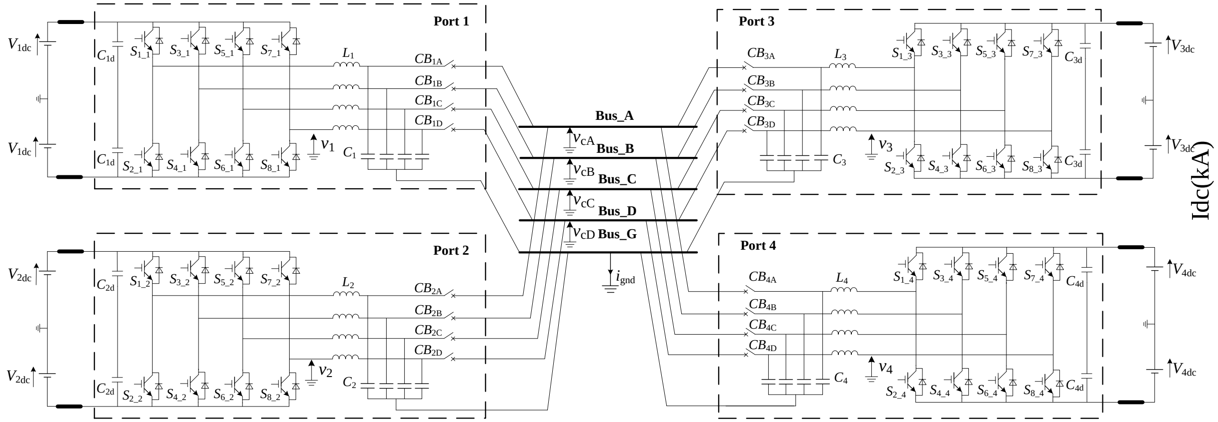


Fig.26. DC hub response to two DC faults.

- 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,
- Capacitor voltage maintained during and after dc fault,

2. DC grid components: DC hubs



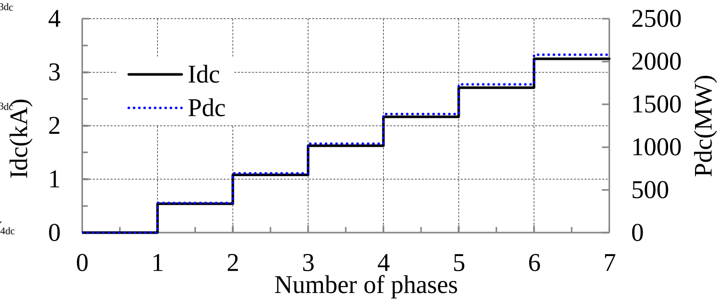
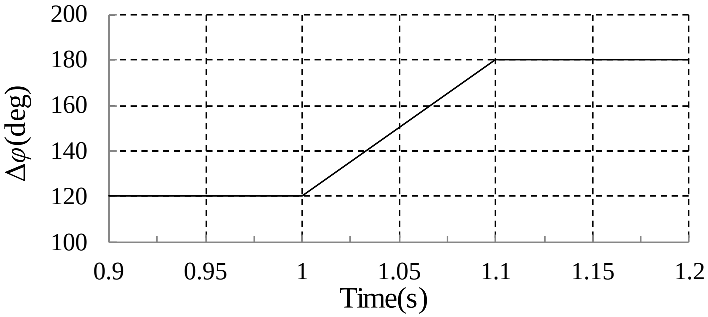
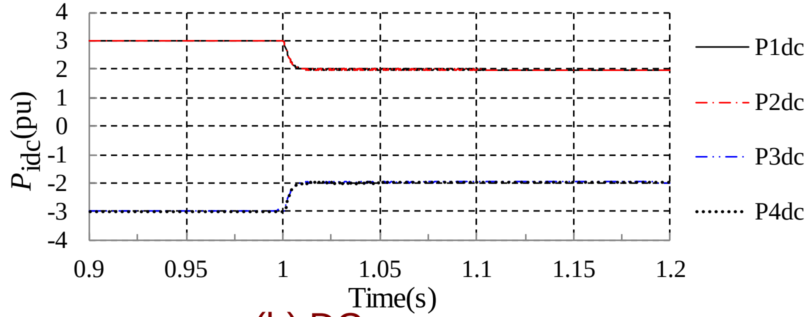


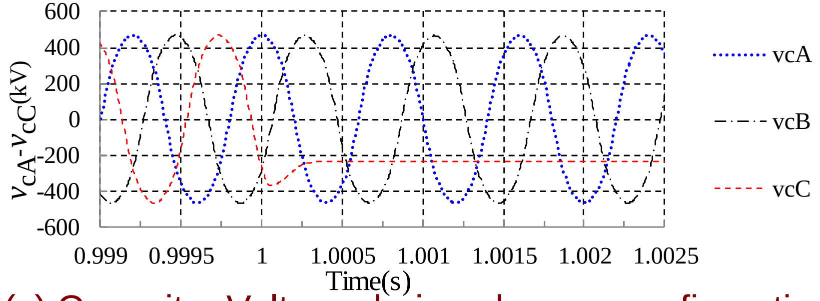
Fig.27. DC Hub power versus number of phases



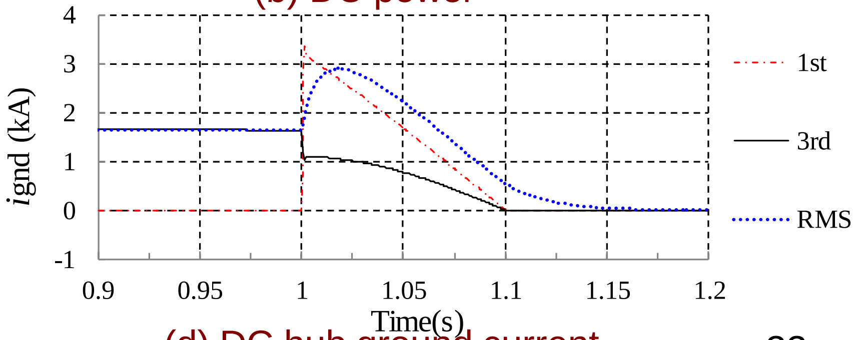
(a) Phase angle difference between each phase



(b) DC power



(c) Capacitor Voltage during phase reconfiguration

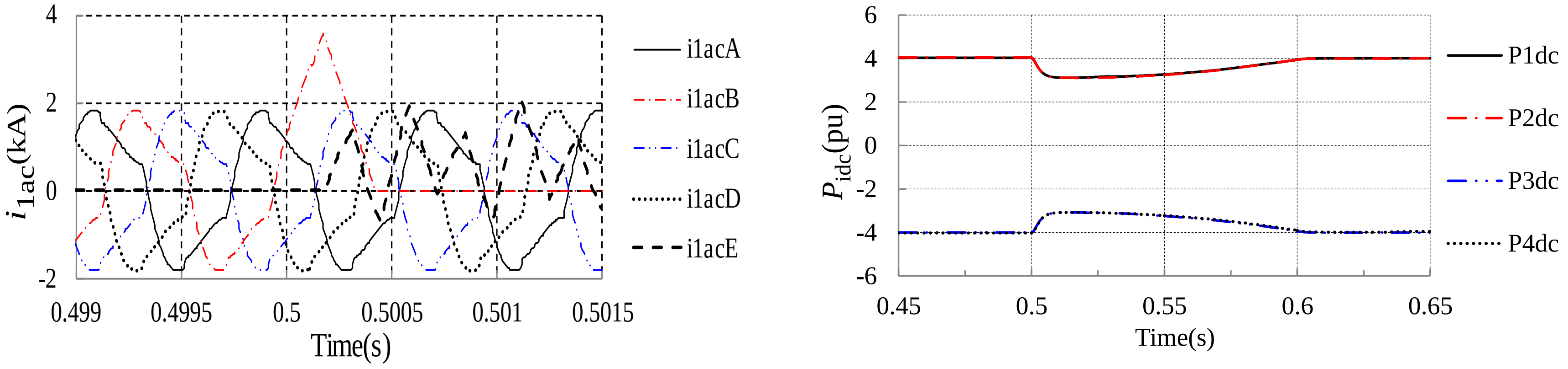


(d) DC hub ground current

Fig.28. Tripping phase C on all 4 ports (3-phase DC Hub)

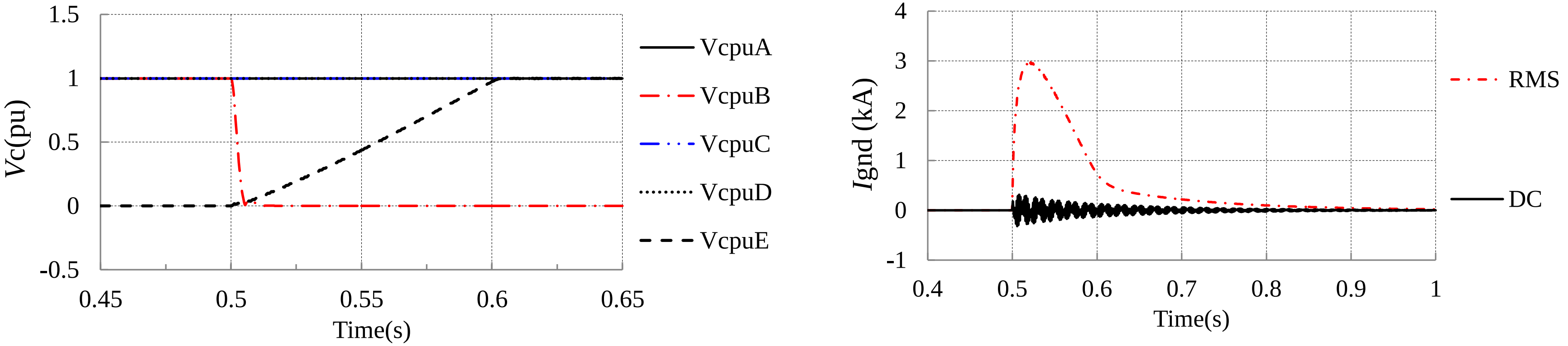
2. DC grid components: DC hubs

Redundant phase improves reliability.



(a) AC current of port 1

(b) DC power



(c) Capacitor voltage of each phase

(d) DC hub ground current

Fig.29. Replacing phase B with redundant phase E on all ports (4-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,

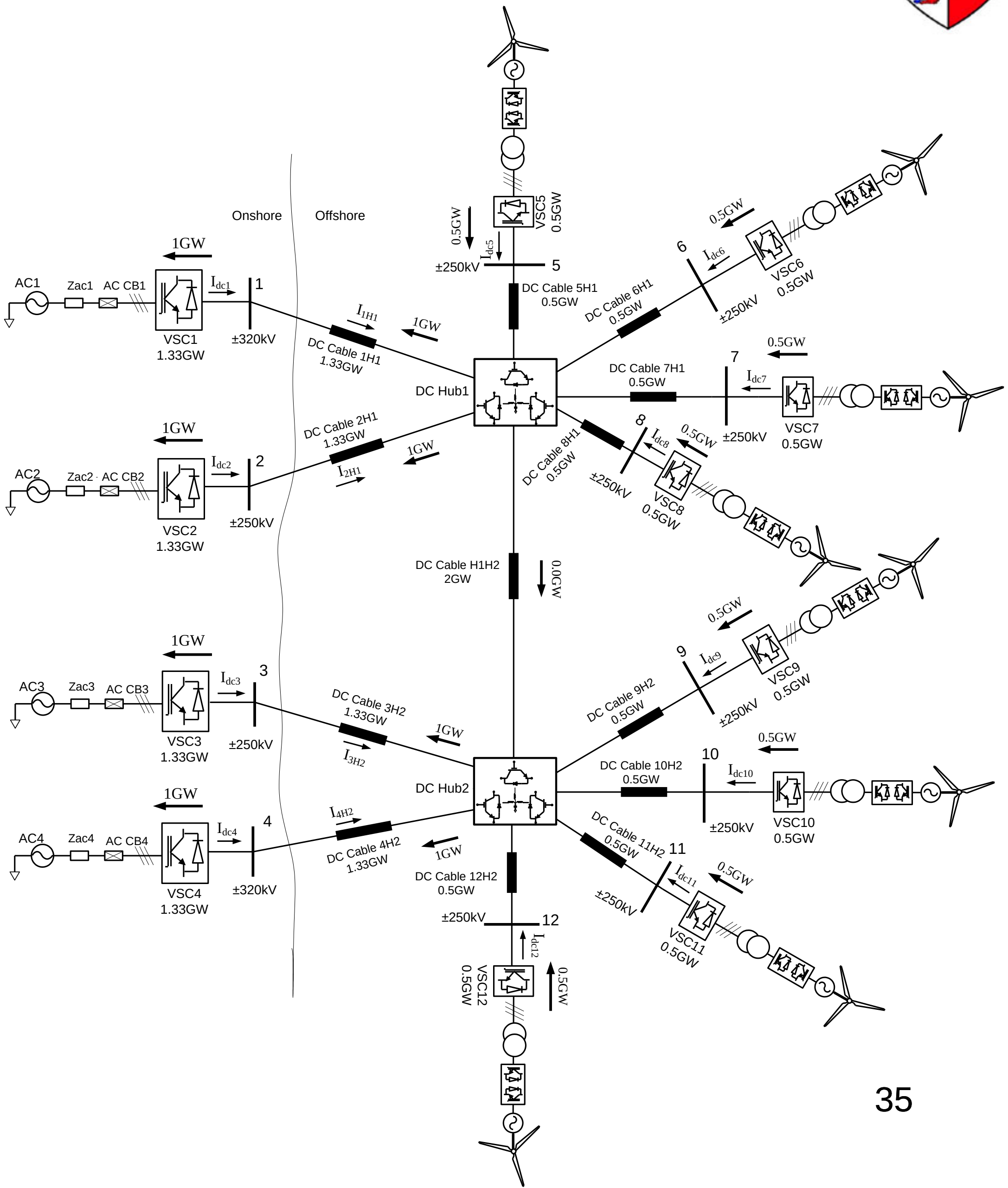


Figure 30. 8-terminal DC grid with 2 DC hubs.

2. DC grid components: DC hubs

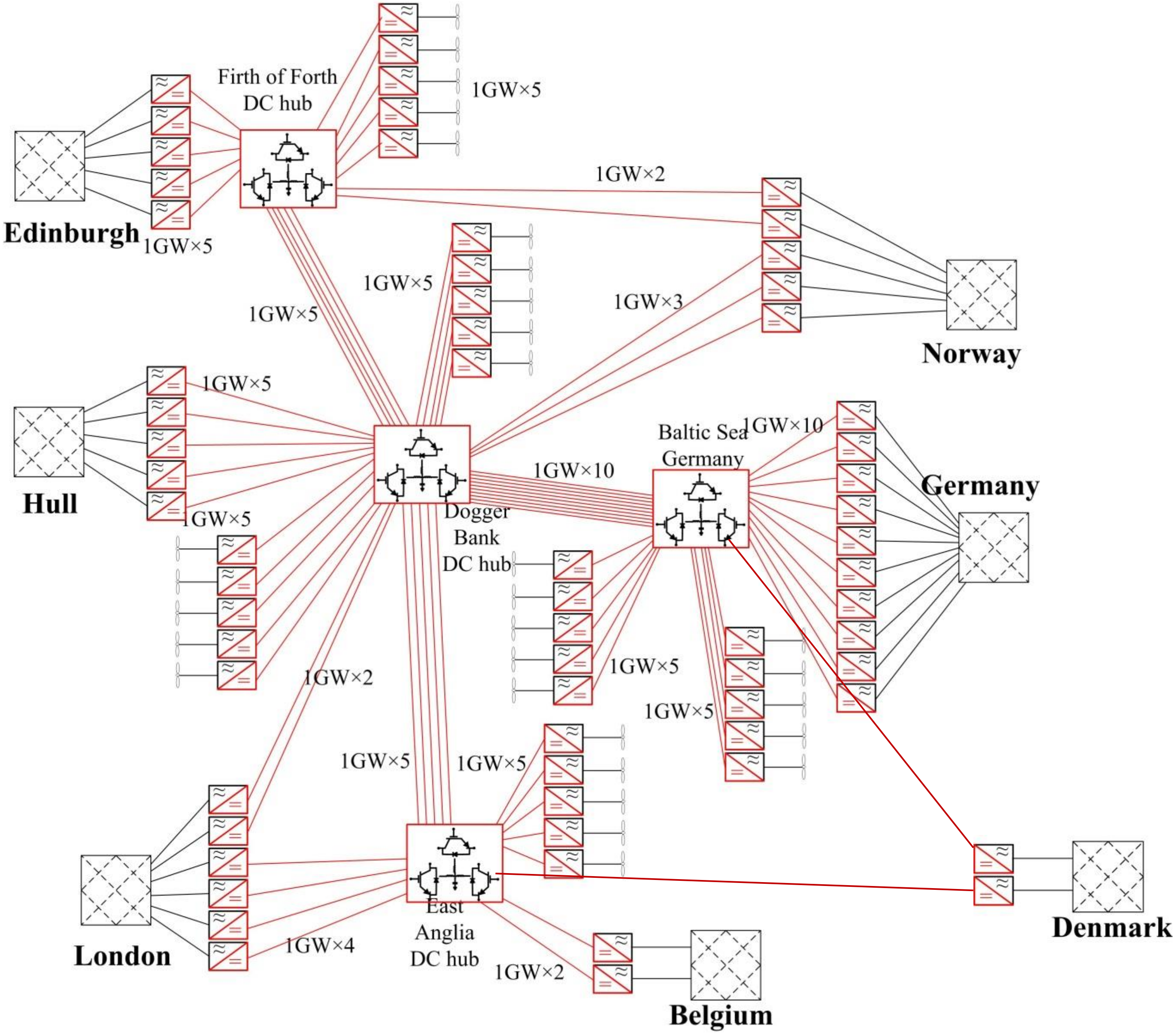
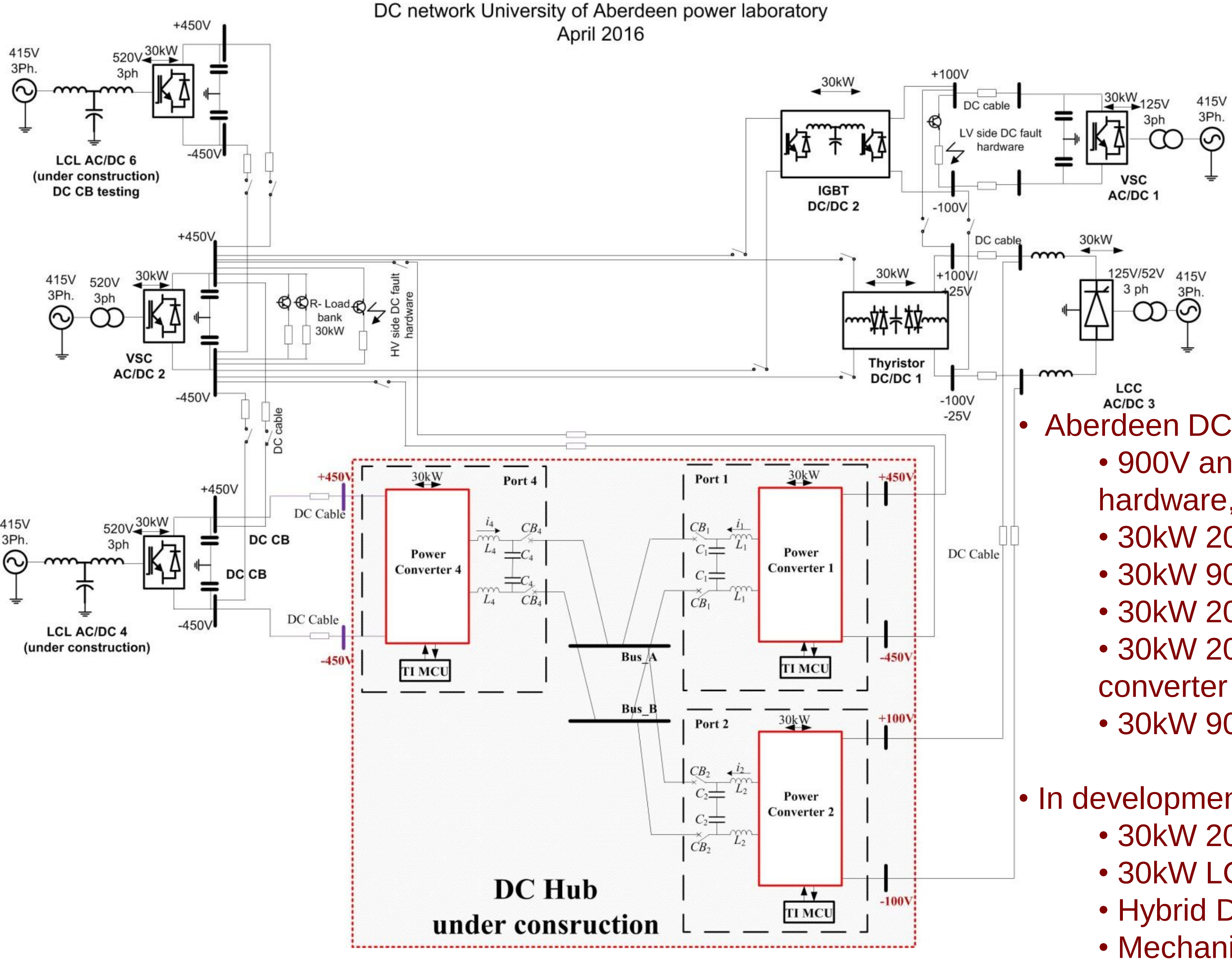


Figure 31. DC supergrid based on multiple DC hubs (no DC CBs).

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),
  - Mechanical DC CB (900V 500A),

Figure 32. Aberdeen DC test grid schematic.

2. DC grid components: hardware demonstrations

Aberdeen DC grid demonstrator

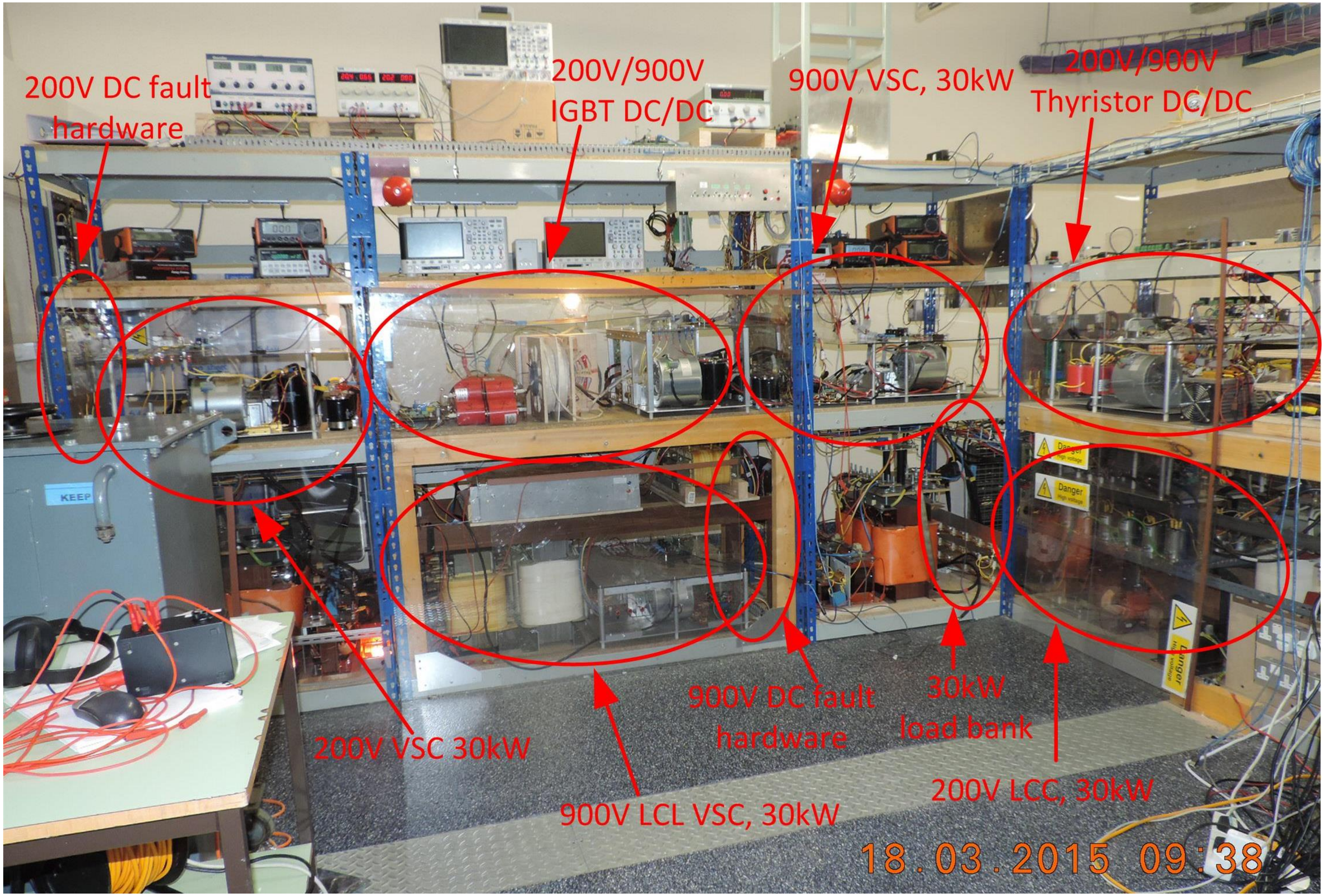
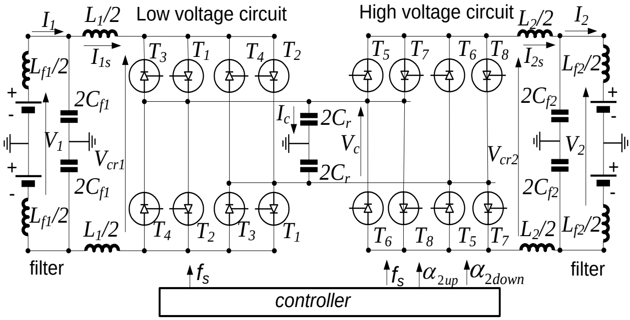


Figure 33. Aberdeen DC test grid. 4 AC/DC converters and 2 DC/DC converters

2. DC grid components: hardware demonstrations

- 30kW, 200V/900V, 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,



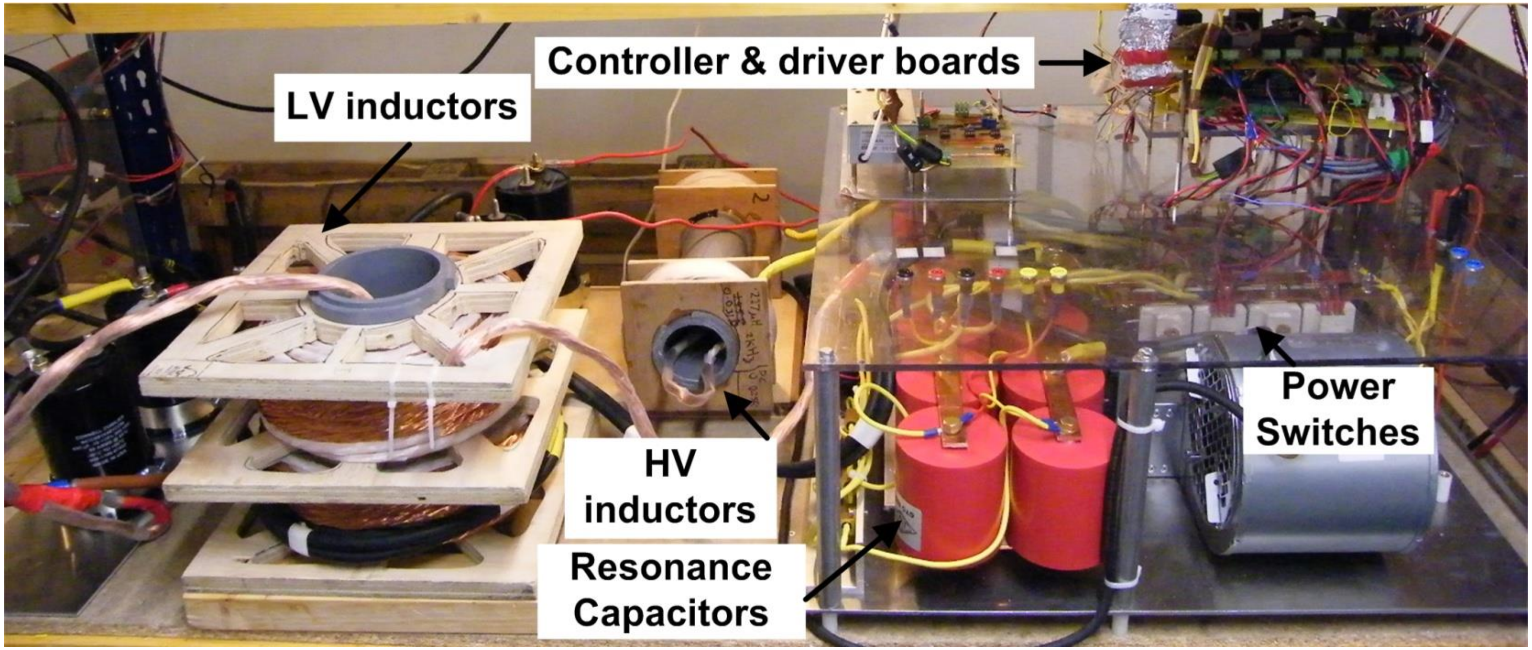


Figure 34. 30kW, 200V/900V, non-isolated, thyristor DC/DC converter.

2. DC grid components: hardware demonstrations

DC/DC prototype efficiency testing:

- 92-96% at full power with 200V/900Voperation,
- Strongly dependent on stepping ratio,

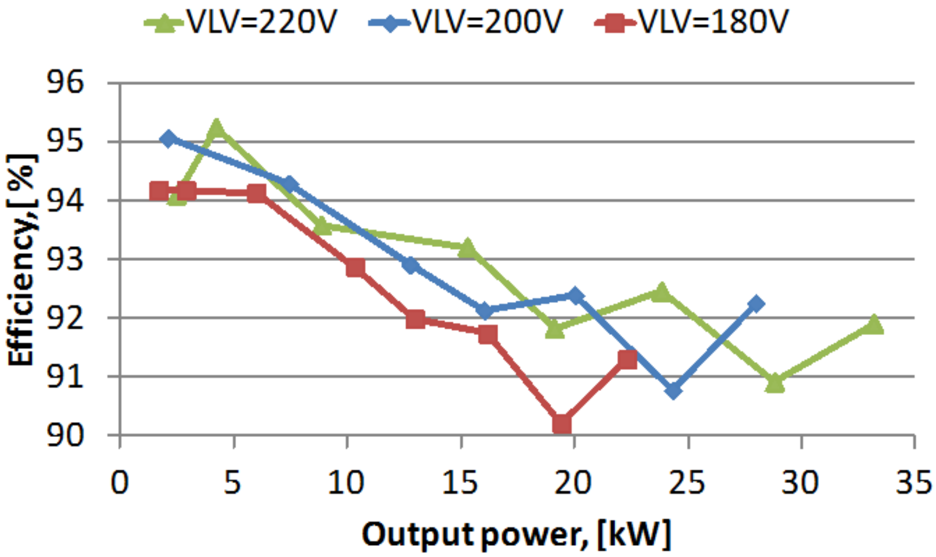


Figure 35a. Prototype efficiency testing: V1=180-220V, V2=900V

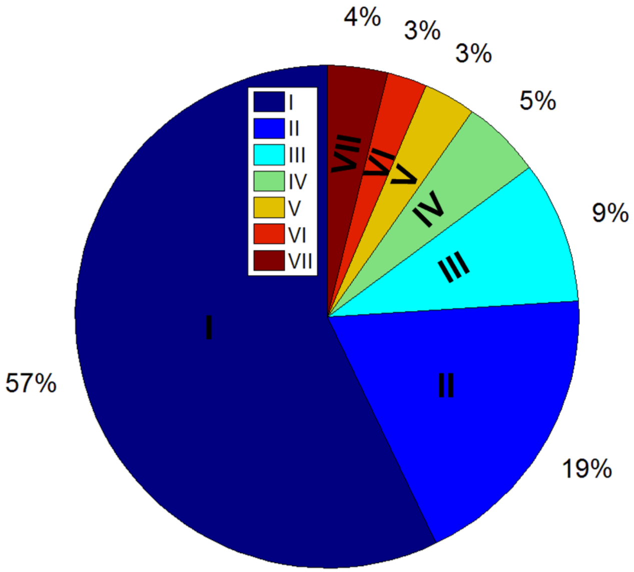
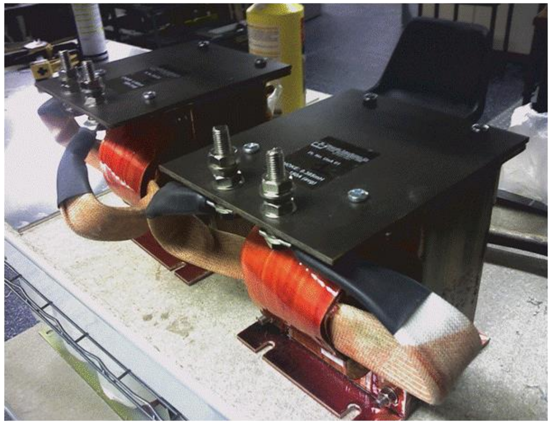


Figure 35b. Loss components at 580Hz,

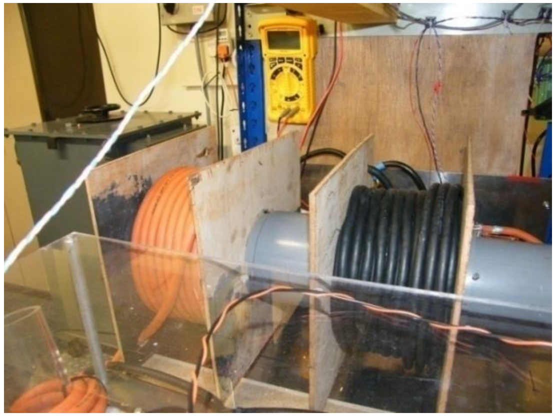
I: *LV* side inductor, II: *LV* side switch conduction, III: *LV* side switch reverse recovery, IV: *HV* side inductor, V: *HV* side switch conduction, VI: *HV* side switch reverse recovery, VII: Resonant capacitor.

2. DC grid components: hardware demonstrations

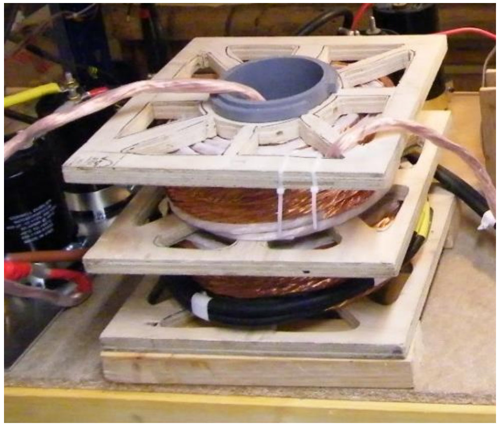
Inductor design for high current and high frequency:



Iron core inductors
Inductance: 385 µH
Weight: 22 kg (x2)
Volume: 6800 cm^3



Air core inductors
(stranded copper)
Inductance: 290 µH
Wire Area: 33 mm^2
Weight: 10 kg (x2)
Volume: 8750 cm^3



Air core inductors
(Litz wire 275x0.4mm)
Inductance: 325 µH
Wire Area: 42 mm^2
Weight: 12 kg (x2)
Volume: 7840 cm^3

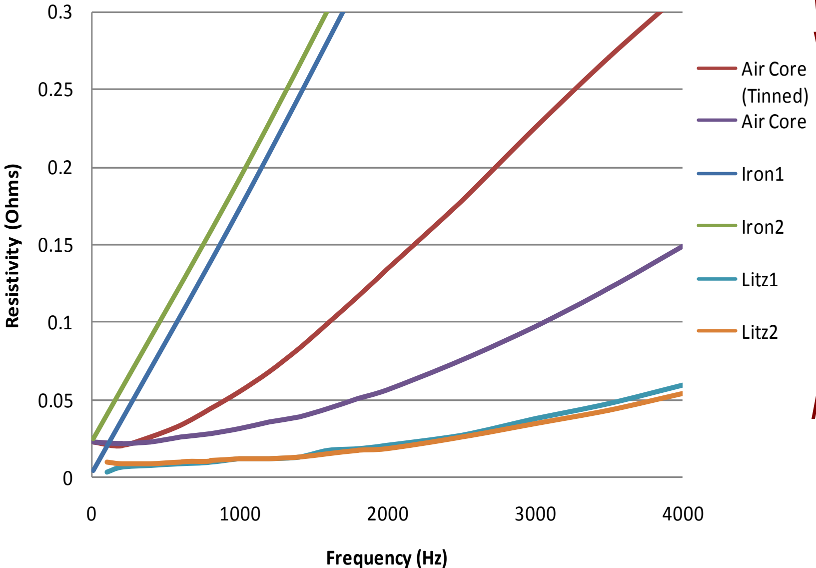


Figure 36. Inductor resistance versus frequency

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.

DC/DC type I power reversal:

- LV Voltage reversal (200V -> -200V),
- HV current reversal (30A -> -30A),
- 25kW to -25kW reversal in around 100ms,

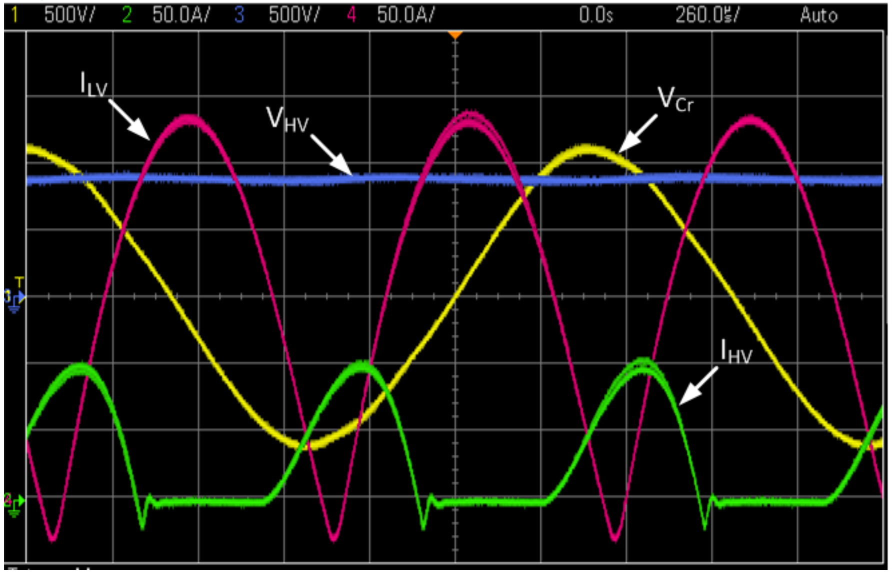


Figure 37. full power operation in step up mode

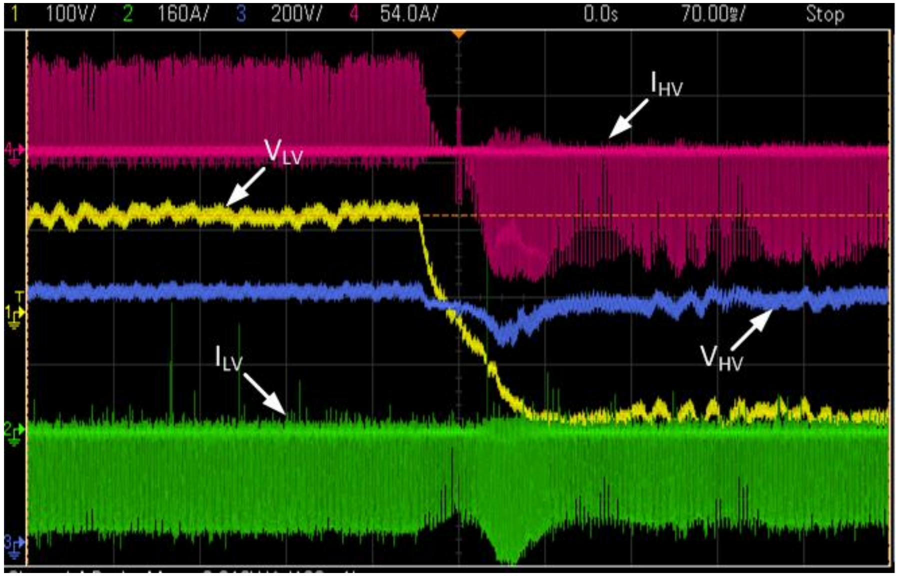


Figure 38. power reversal in type I operation (step up to step down)

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 special fault controls,
- Power transfer is inherently reduced for DC faults,

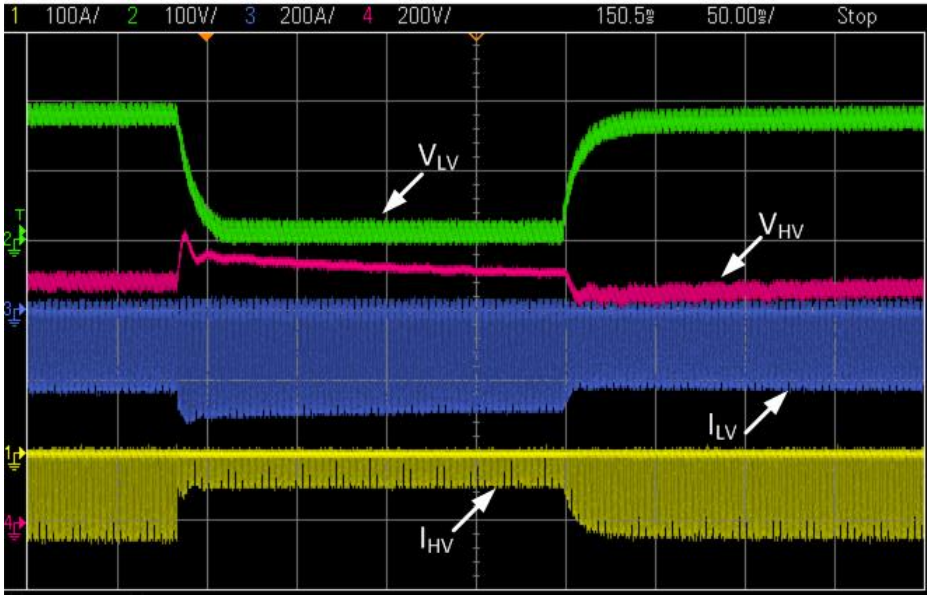


Figure 39. 200V DC bus fault

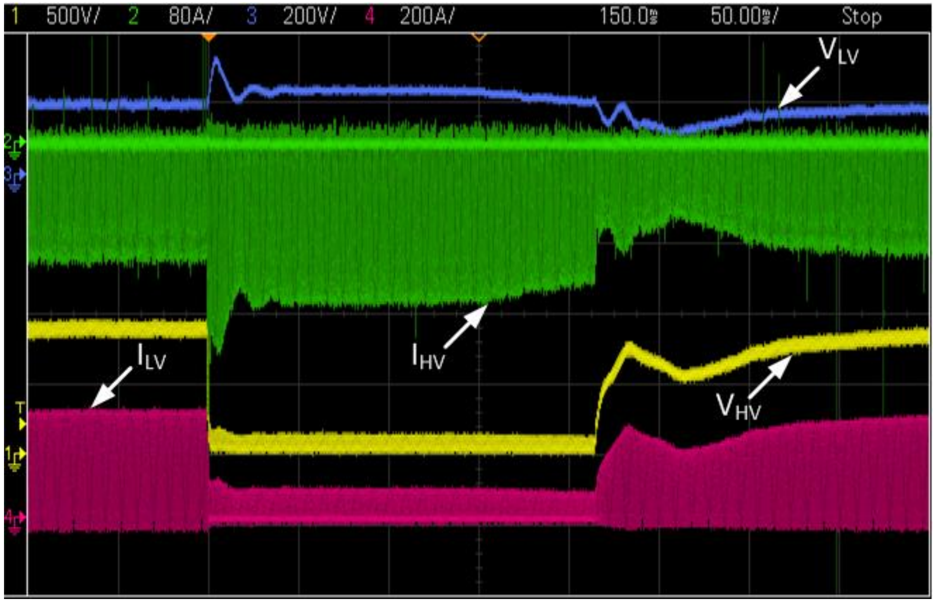
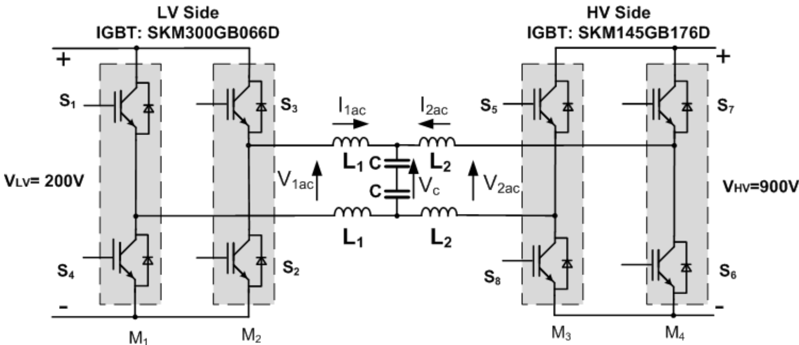


Figure 40. 900V DC bus fault

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



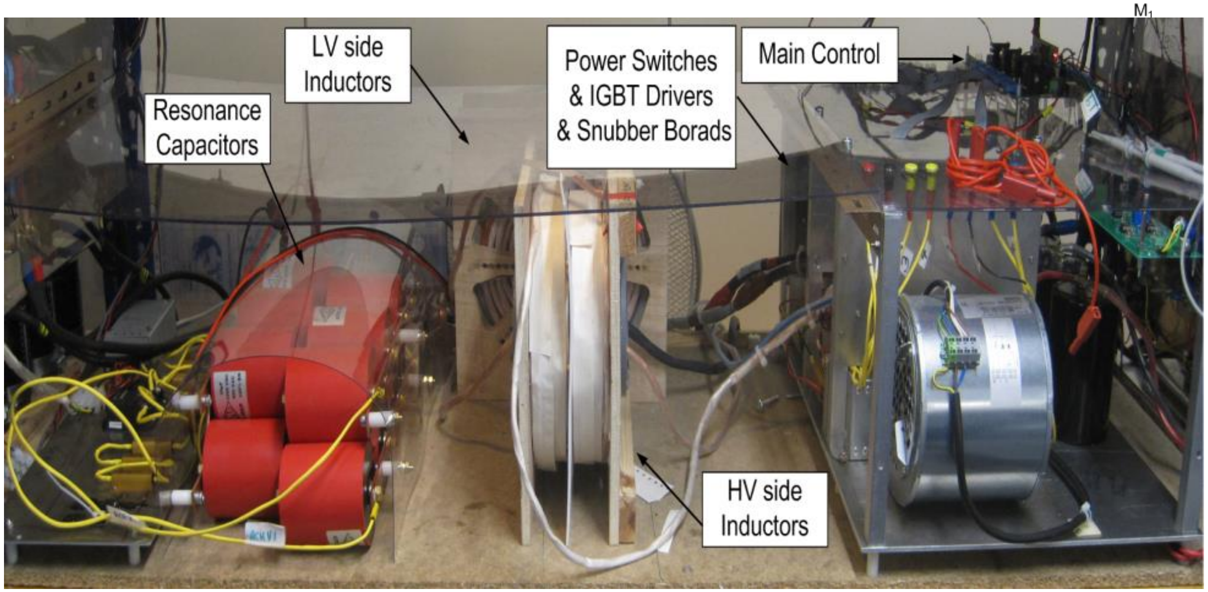


Fig.41. 35kW 200V/900V prototype IGBT based LCL DC/DC converter

2. DC grid components: hardware demonstrations

- New PWM method leads to lower conduction and switching losses,
- Switchings are located at low current segments,
- However, it is difficult for real time implementation using popular TI microcontrollers,
- Sinusoidal control signal is converted to a flat constant signal equal to $M_1=2/3(1-M_a)$,
- A triangular signal with double main frequency is generated for carrier,
- The switching criteria is toggled in each half cycle of the main frequency.

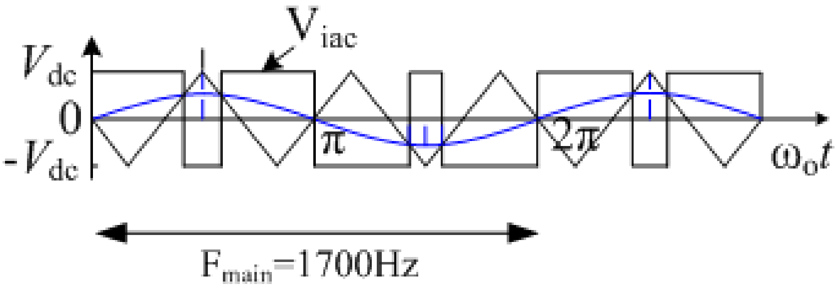


Fig.42. Conventional SPWM pattern generation with mf=3

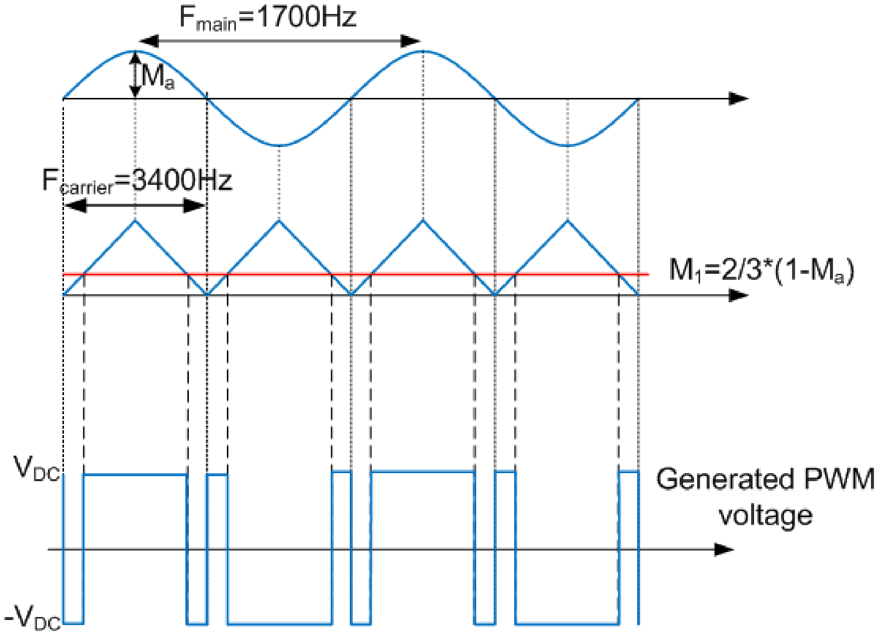
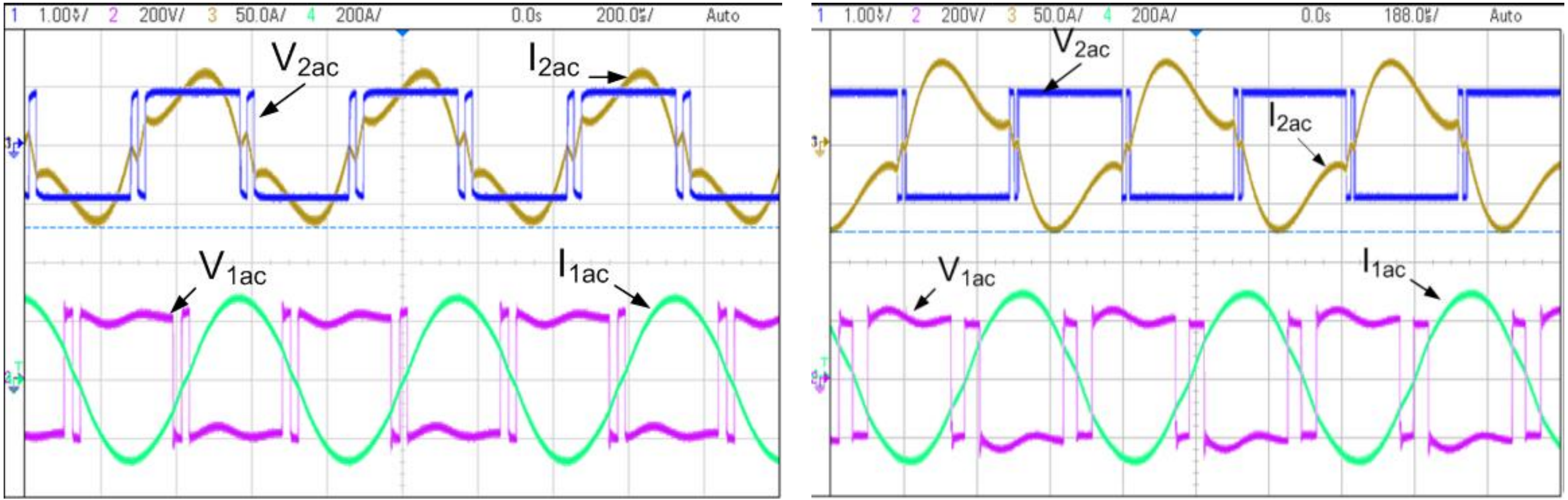


Fig.43. Proposed PWM pattern generation

2. DC grid components: hardware demonstrations



Step up mode

Step down mode

Fig. 44. Steady state experimental test results at 30kW.

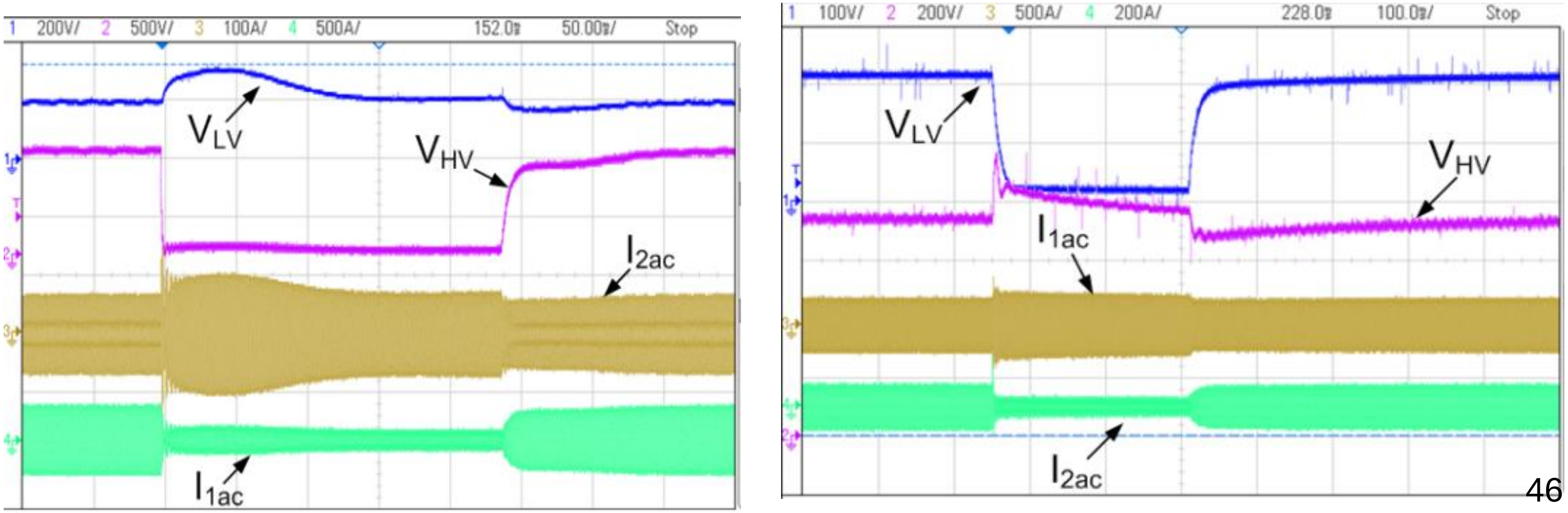
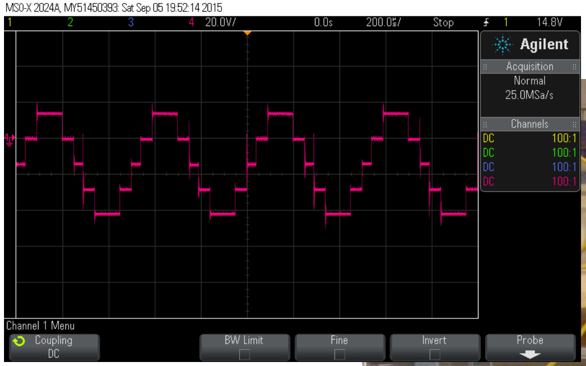


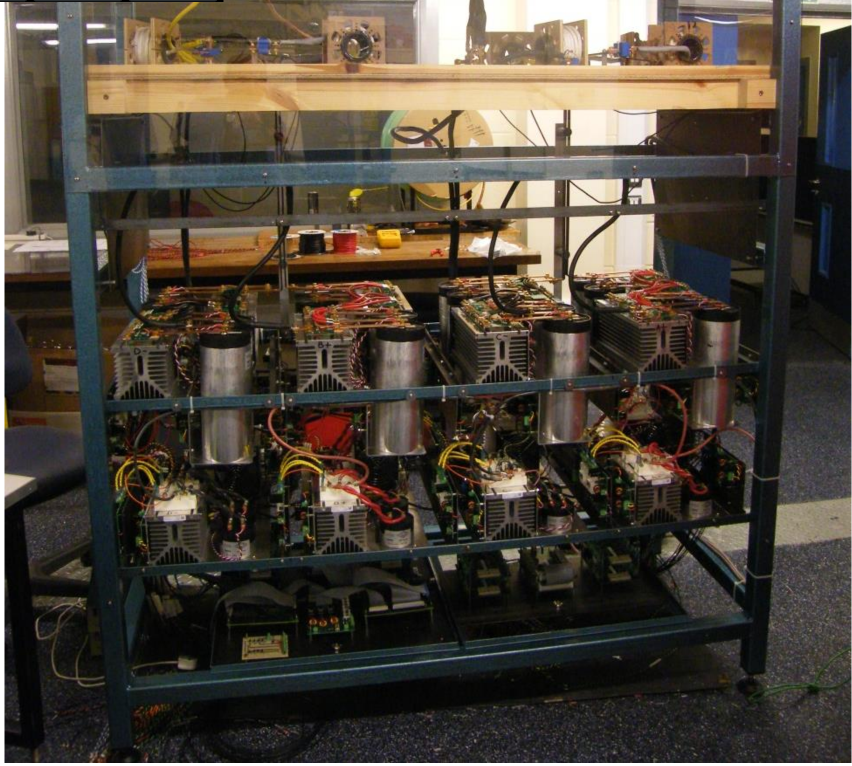
Fig. 45. Experimental DC fault response at full power.

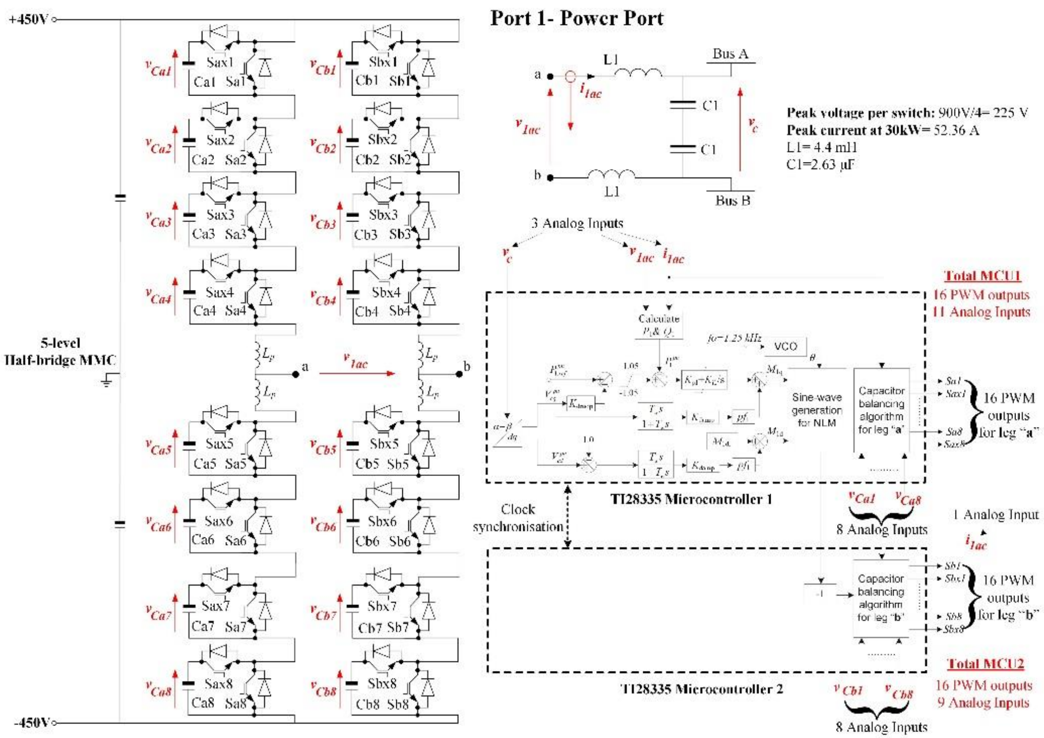
2. DC grid components: hardware demonstrations

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,







Peak voltage per switch: 900V/4= 225 V
Peak current at 30kW= 52.36 A
L1= 4.4 mH
C1=2.63 µF

Figure 46. 30kW, 200V/900V, 5-level MMC based DC/DC converter

3. DC grid modelling challenges

- Future DC grids will include numerous MMC AC/DC converters,
- Average modeling (PSCAD,EMTP) 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,
- 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,
- Modelling in the rotating DQ frame transfers the AC quantities into DC quantities and improves speed,
- Multiple DQ frames are required at different frequencies,
- Non-linear elements can not be directly transferred to DQ frame,

3. DC grid modelling challenges

ABC frame average MMC model

- Only time domain simulation
- Eigenvalue study is not possible
- Power flow (phasor) study is not possible
- Frequency domain study is not possible

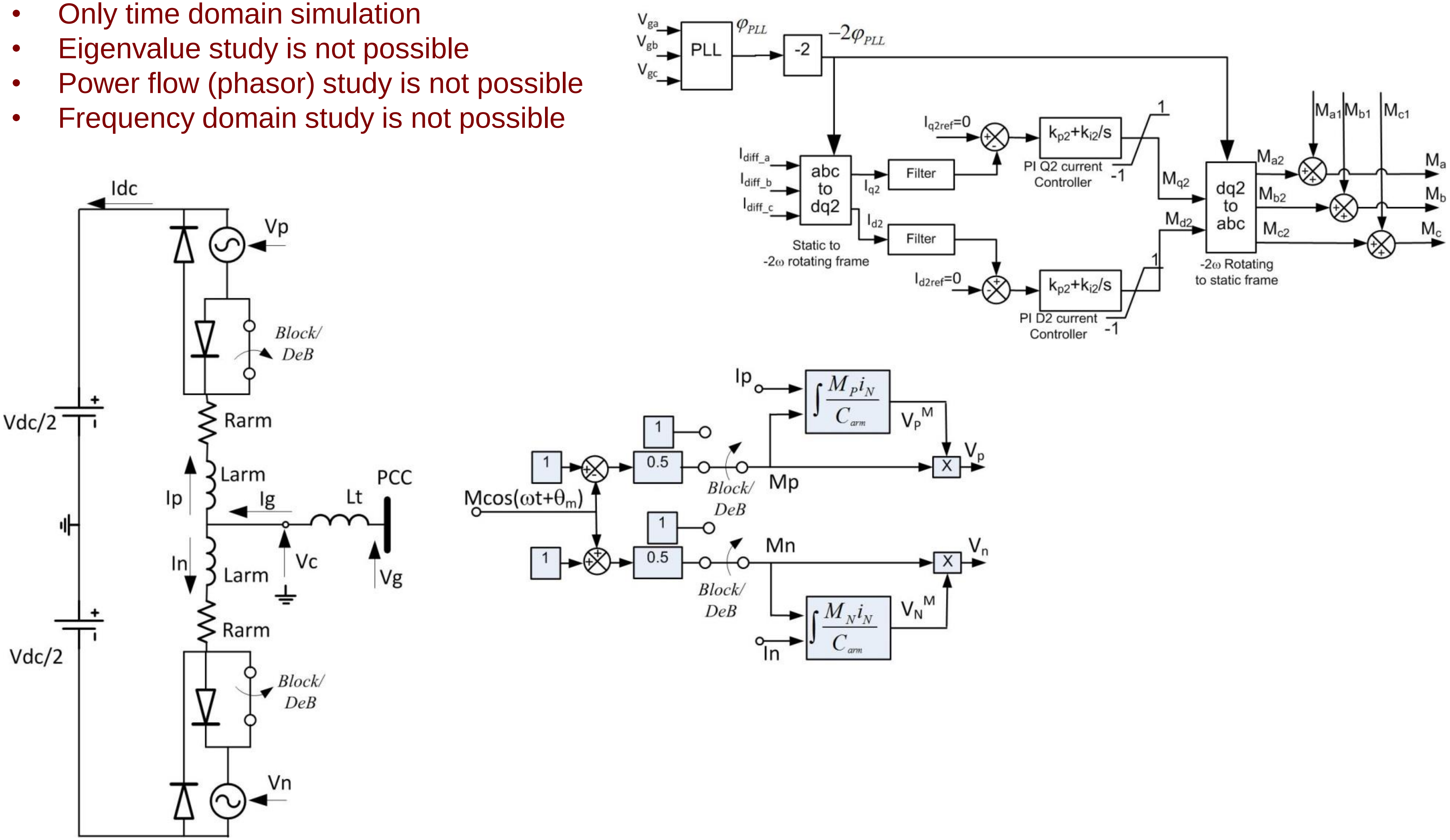
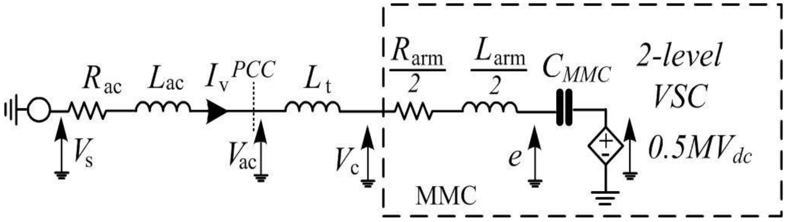


Fig. 47. Average MMC model in ABC frame, with blocked state and including circulating current controller

3. DC grid modelling challenges

DQ frame linearsed MMC model

- Includes three DQ coordinate frames
- CCSC control
- 10th order in state space form
- MMC responds like VSC with a series capacitor.



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

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

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

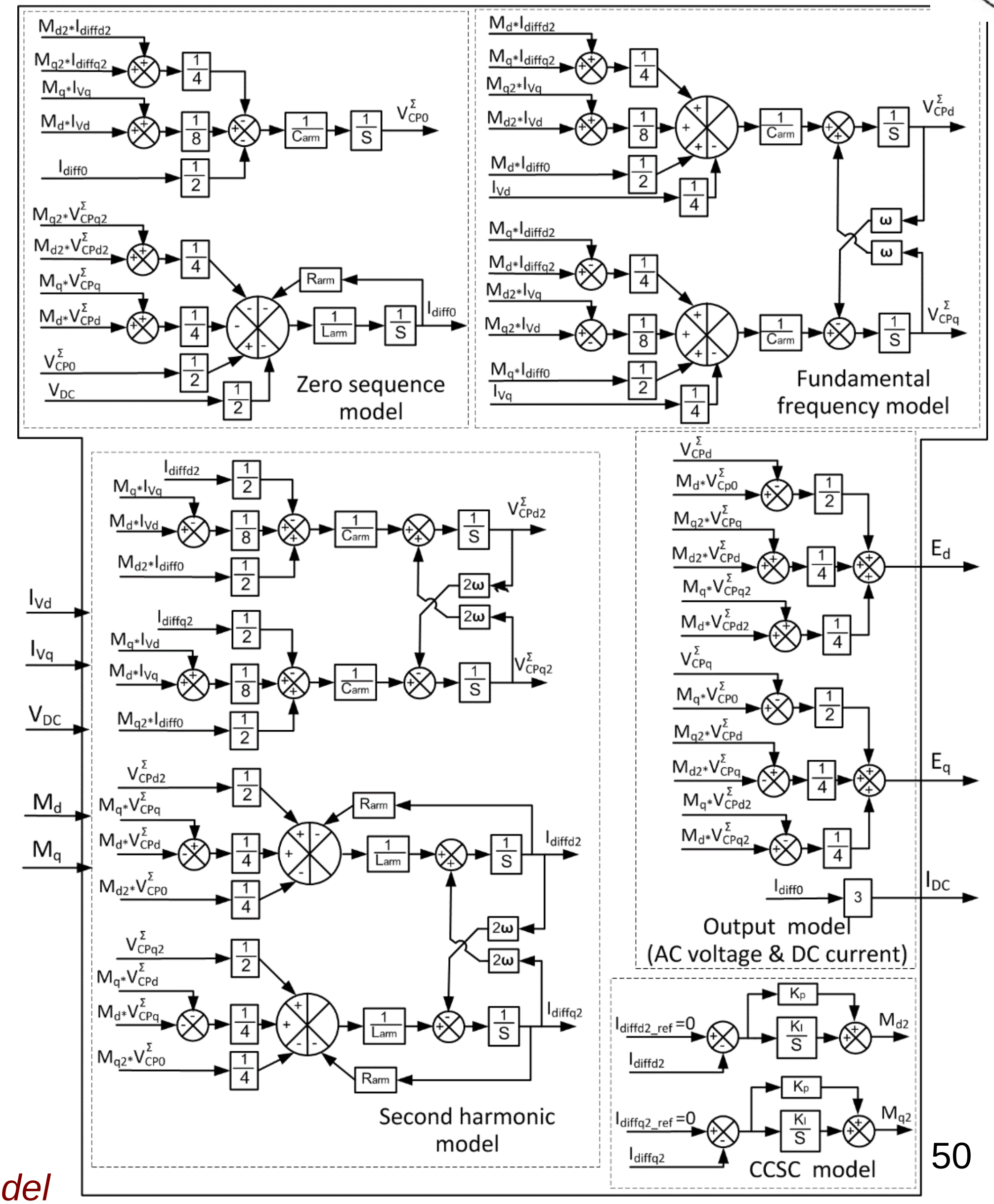


Fig. 48. MMC DQ frame average model

3. DC grid modelling challenges

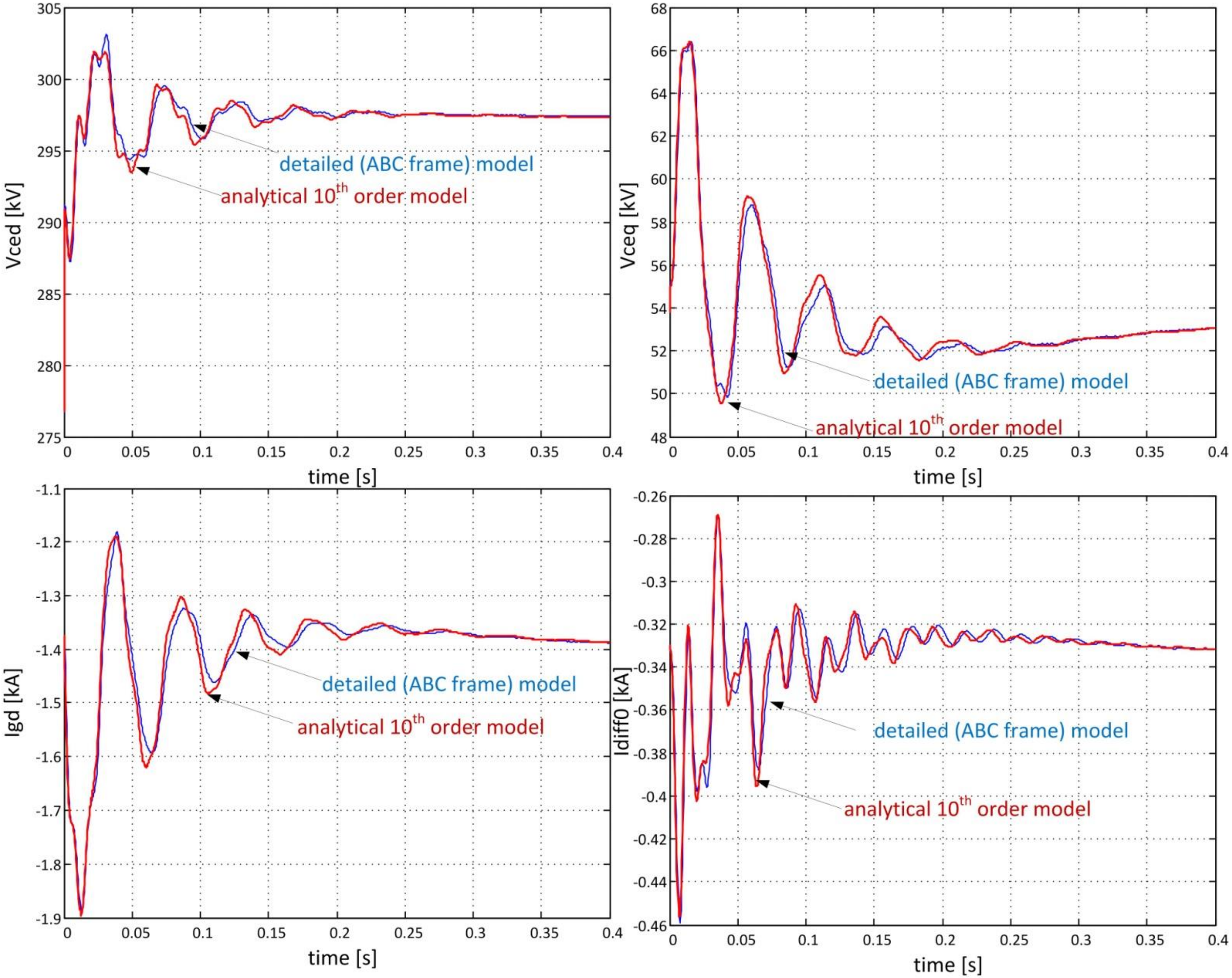


Fig. 49. MMC 10th order DQ analytical model testing

3. DC grid modelling challenges

DQ frame average 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 ± j313.2 -17.82± j129.5	-6.98 ± j317 -33.74± j101.3

- High CCSC gains 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 ± j122.2 -155.0± j637.8	-6.2 ± j129.7 -165.2± j681.6

- MMC average modelling status

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

3. DC grid modelling challenges

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

- 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,

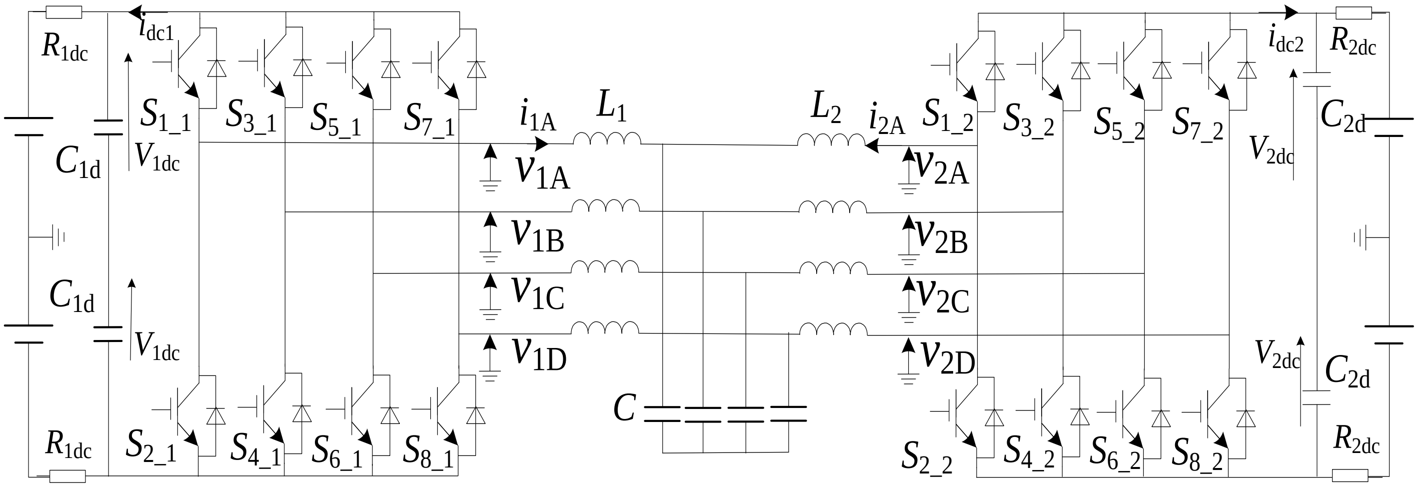


Fig.50. Circuit diagram of 4-phase high frequency LCL DC/DC converter

3. DC grid modelling challenges

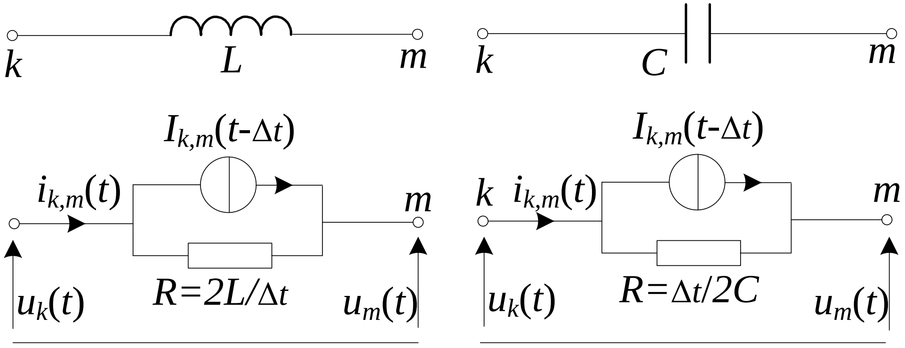
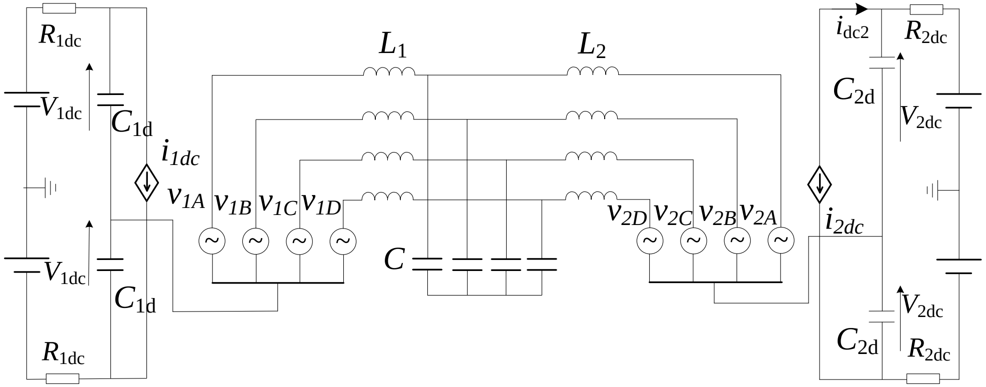


Fig.51. Representation of inductor and capacitor in Dommel's method



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

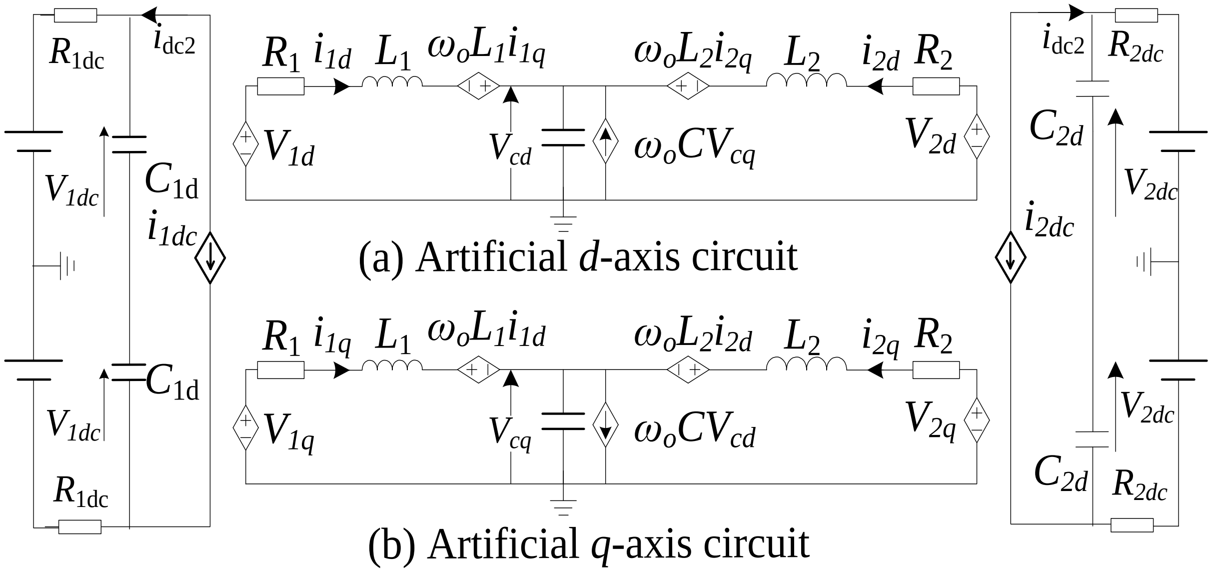
$$v_{1C} = m_{1C}V_{1dc}, \quad v_{1D} = m_{1D}V_{1dc}$$

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

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

Fig. 52. Average Model using Dommel's method in ABC frame (Model1)

3. DC grid modelling challenges



(a) Artificial *d*-axis circuit

(b) Artificial *q*-axis circuit

Fig. 53. Average model using Dommel's method in dq frame(Model 2)

- Requires artificial d-axis and q-axis circuit
- Controlled voltage source to represent *dq* coupling of inductor current
- Controlled current source to represent dq coupling of capacitor voltage

State Equations:

$$\frac{dI_{id}}{dt} = \frac{1}{L_i}(-R_i I_{id} + \omega_o L_i I_{iq} + V_{id} - V_{cd})$$

$$\frac{dI_{iq}}{dt} = \frac{1}{L_i}(-R_i I_{iq} - \omega_o L_i I_{id} + V_{iq} - V_{cq})$$

$$\frac{dV_{cd}}{dt} = \frac{1}{C}(I_{1d} + I_{2d} + \omega_o C V_{cq})$$

$$\frac{dV_{cq}}{dt} = \frac{1}{C}(I_{1q} + I_{1q} - \omega_o C V_{cd})$$

AC/DC Link Equations:

$$V_{id} = M_{id} V_{idc}$$

$$V_{iq} = M_{iq} V_{idc}$$

$$I_{idc} = \frac{M_p}{4} k_m (M_{id} I_{id} + M_{iq} I_{iq})$$

3. DC grid modelling challenges

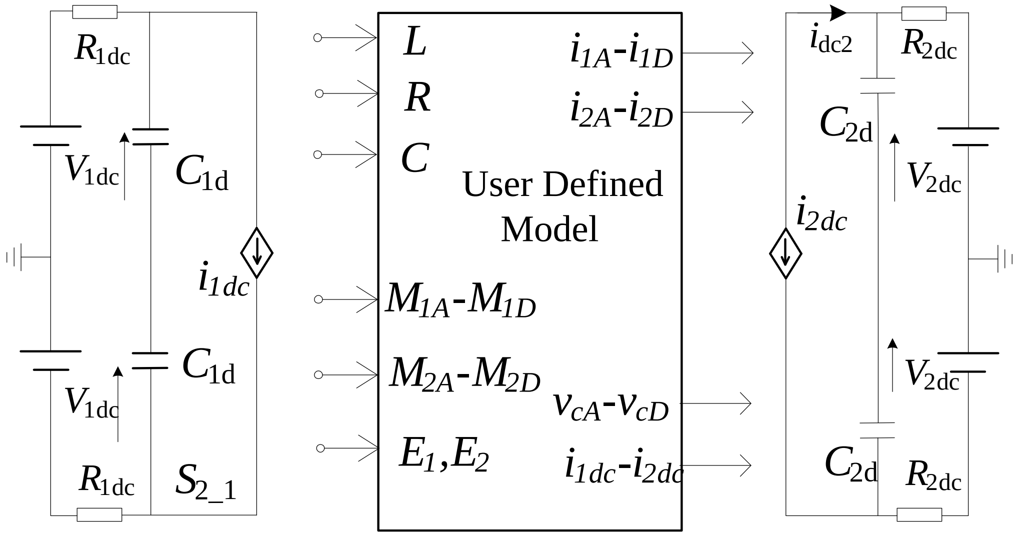


Fig. 54. AVM of Runge Kutta method in ABC frame (Model 3)

Steps of solving $dx/dt=\boldsymbol{f}(\boldsymbol{x},\boldsymbol{u})$
Using Runge-Kutta's method

1) $calculate\ \boldsymbol{k}_1 = \Delta t\boldsymbol{f}(\boldsymbol{x}(t),\boldsymbol{u}(t))$
2) $calculate\ \boldsymbol{x}_1 = \boldsymbol{x}(t) + 0.5\boldsymbol{k}_1$
3) $calculate\ \boldsymbol{k}_2 = \Delta t\boldsymbol{f}(\boldsymbol{x}_1,\boldsymbol{u}(t))$
4) $calculate\ \boldsymbol{x}_2 = \boldsymbol{x}(t) + 0.5\boldsymbol{k}_2$
5) $calculate\ \boldsymbol{k}_3 = \Delta t\boldsymbol{f}(\boldsymbol{x}_2,\boldsymbol{u}(t))$
6) $calculate\ \boldsymbol{x}_3 = \boldsymbol{x}(t) + \boldsymbol{k}_3$
7) $calculate\ \boldsymbol{k}_4 = \Delta t\boldsymbol{f}(\boldsymbol{x}_3,\boldsymbol{u}(t))$
8) $\boldsymbol{x}(\mathrm{t}+\Delta\mathrm{t}) = \boldsymbol{x}(\mathrm{t}) + 1/6(\boldsymbol{k}_1 + 2\boldsymbol{k}_2 + 2\boldsymbol{k}_3 + \boldsymbol{k}_4)$

State Equations:

$$\frac{d}{dt}\begin{bmatrix} i_{1A} \\ i_{2A} \\ v_{cA} \end{bmatrix} = \begin{bmatrix} -R_1/L_1 & 0 & -1/L_1 \\ 0 & -R_2/L_2 & -1/L_2 \\ 1/C & 1/C & 0 \end{bmatrix}\begin{bmatrix} i_{1A} \\ i_{2A} \\ v_{cA} \end{bmatrix} + \begin{bmatrix} 1/L_1 & 0 \\ 0 & 1/L_2 \\ 0 & 0 \end{bmatrix}\begin{bmatrix} m_{1A}E_1/2 \\ m_{2A}E_2/2 \end{bmatrix}$$

AC/DC Link Equations:

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

- ○ 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

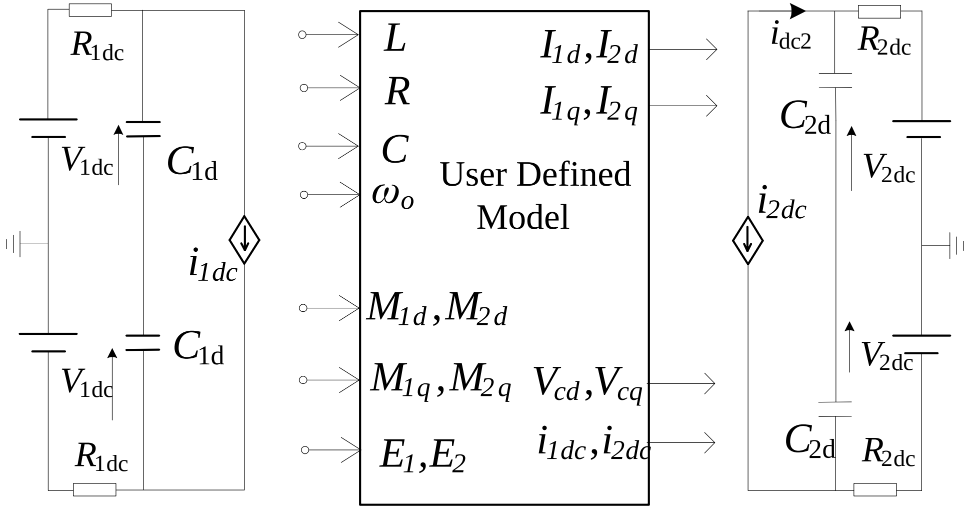
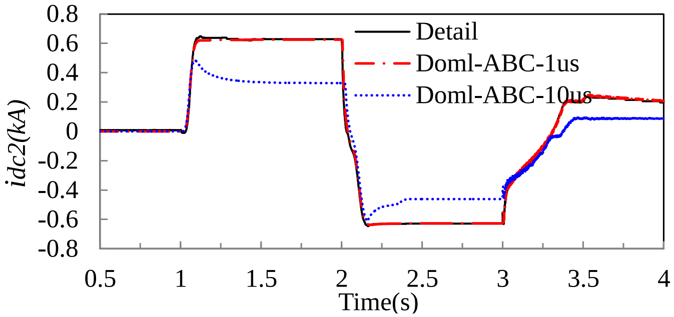


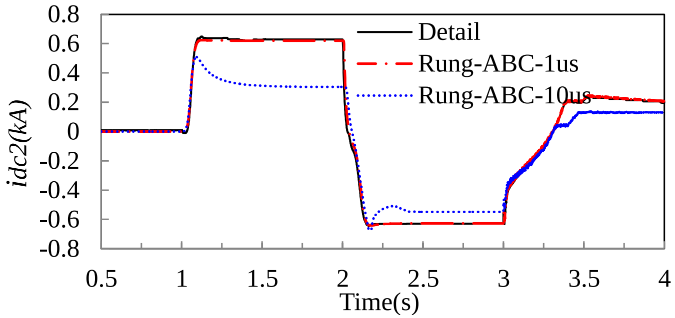
Fig. 55. AVM of Runge Kutta method in dq frame(Model 4)

- 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,

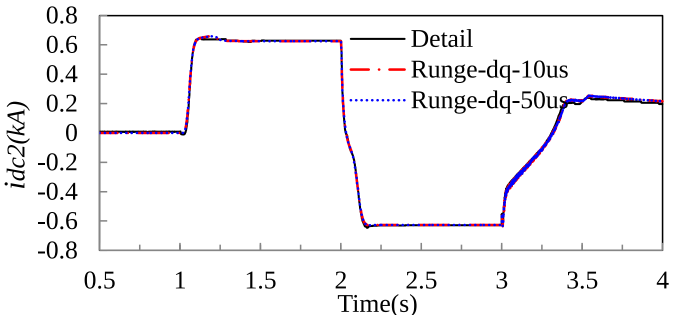
3. DC grid modelling challenges



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



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



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

Fig. 56. Model comparisons for 2kHz DC/DC (power step at 1s and at 2s, DC fault at 3s)

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

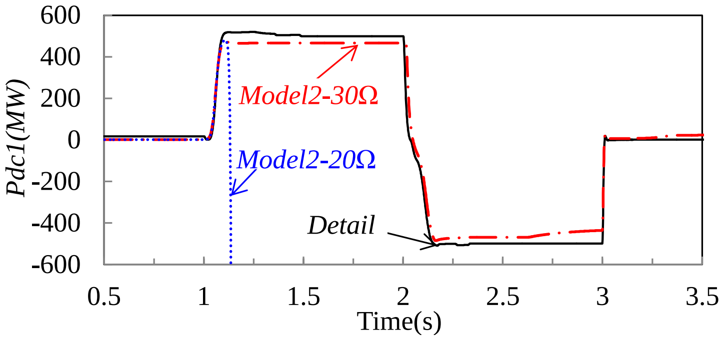


Fig. 57. Numerical instability of Model2 (Dommel's modelling in the dq frame)

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

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

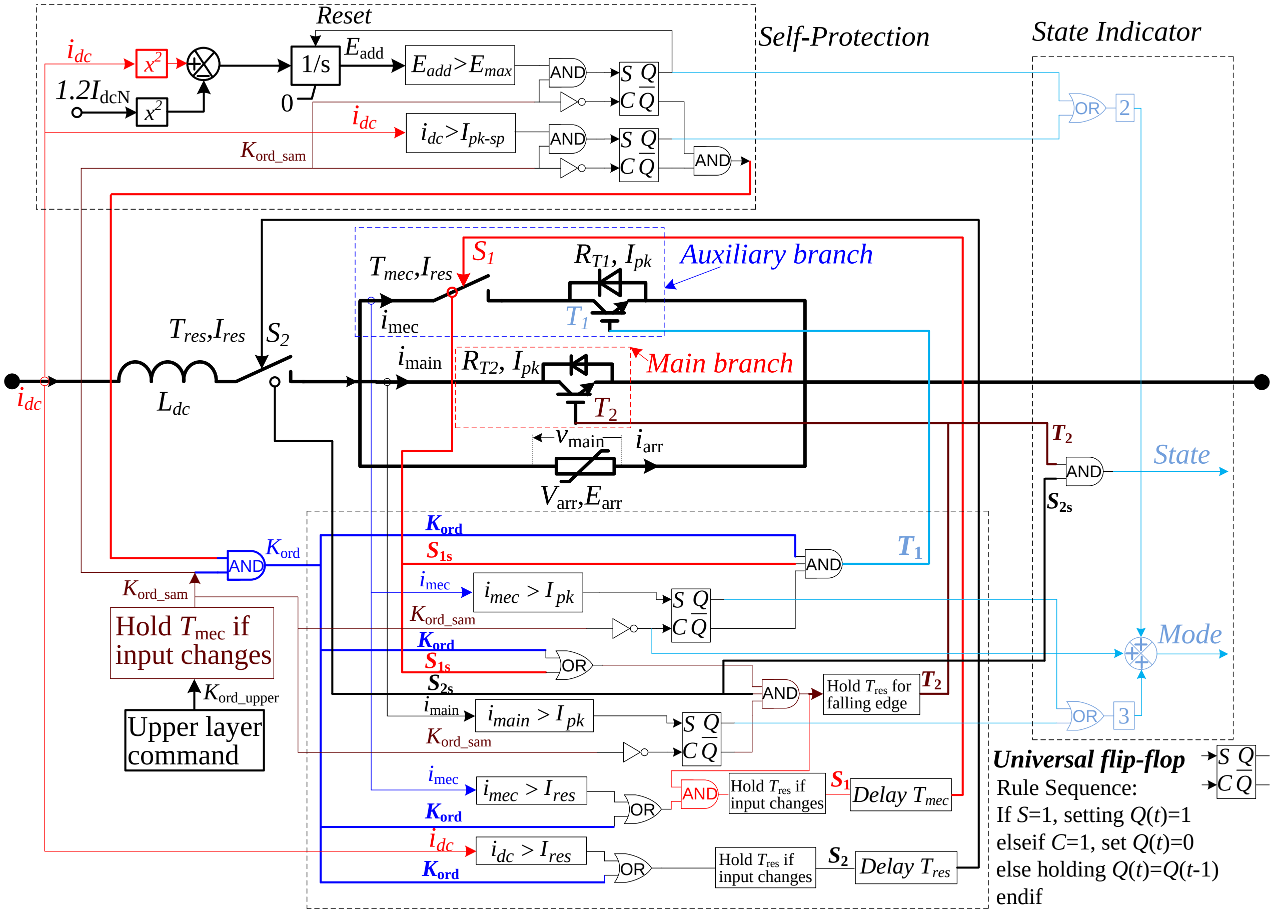
Solution Method	**Models**	**Simulation time for 4s real time**	**Accuracy is good for time step**	**Numerical stability**
Dommel's Method	**Detailed Model**	**216.3s**	**≤1μs**	**stable**
	Model 1 (ABC, 1us)	**201.3s**	**≤1μs**	**stable**
	Model 2 (DQ, 1us)	****	****	**unstable**
Runge-Kutta Method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

3. DC grid modelling challenges

Hybrid DC CB modelling

- 5 components,
- Complex control sequence

Opening process (all are closed initially)			Closing process (all are open initially):		
NO.	Operation	Duration	NO.	Operation	Duration
1.	Open T1,	0-40μs	1.	Close S2	20ms
2.	Open S1	2ms	2.	Close T2	0-40μs
3.	Open T2	0-40μs	3.	Close S1	2ms
4.	Open S2	20ms	4.	Close T1	0-40μs



Universal flip-flop

Rule Sequence:

If S=1, setting $Q(t)$=1

elseif C=1, set $Q(t)$=0

else holding $Q(t)$=$Q(t$-1)

endif

Fig. 58. Hybrid DC CB model

4. DC grid Control Challenges

- DC grid is more difficult to control than traditional AC systems,
- There is no common frequency, which indicates power unbalance,
- DC voltage indicates global power unbalance but it also changes with local power flow,
- DC grid dynamics are 2 orders of magnitude faster than AC grid dynamics,
- DC grid components have low range of operating DC voltage (trip at 0.85pu),
- There are no passive loads with stabilising feedback (lower voltage implies lower power),
- All components are controllable. Numerous control loops,
- No inertia. GW powers should be balanced within 1-2ms.

4. DC grid Control Challenges

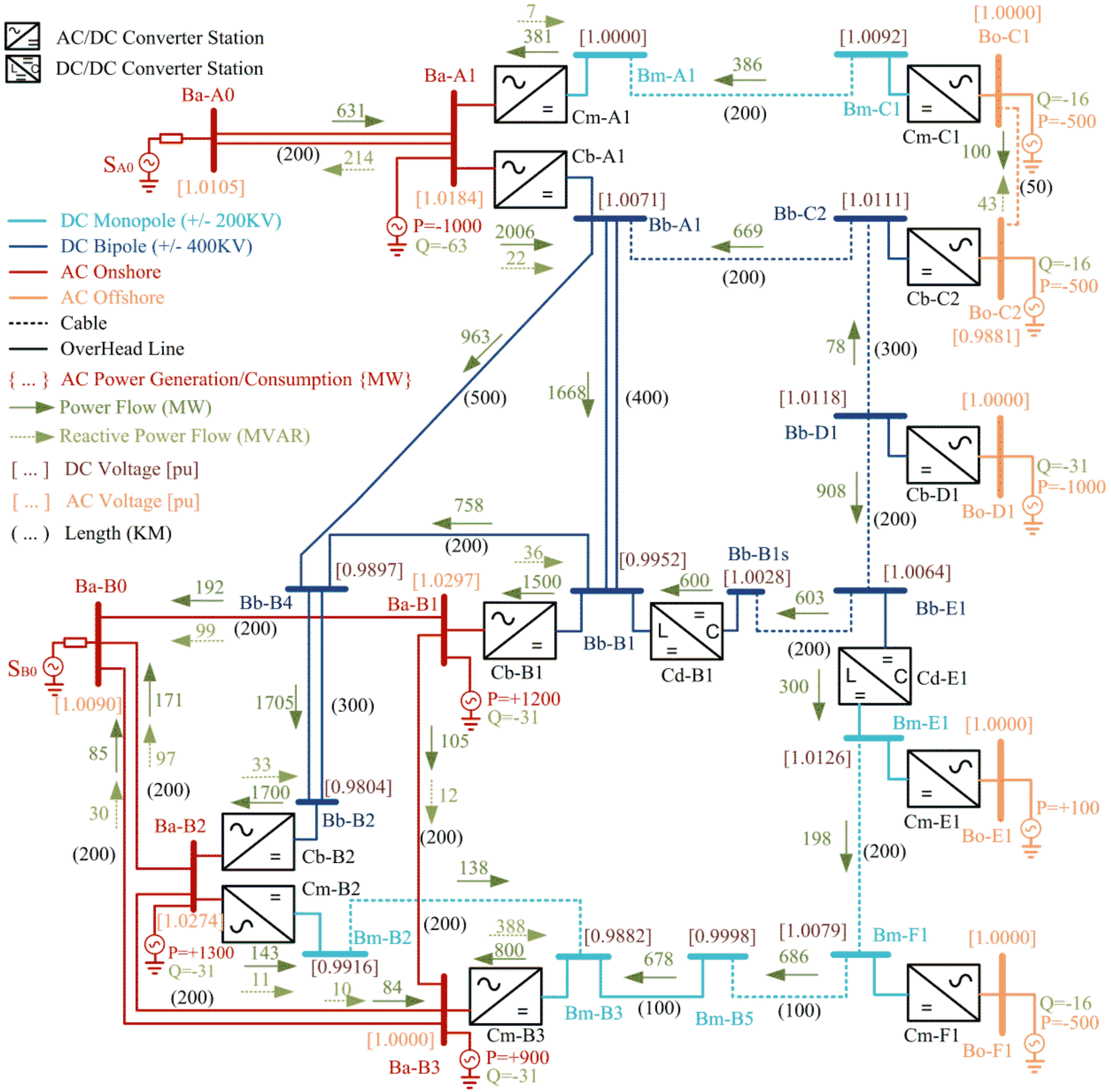


Fig. 59. CIGRE DC grid benchmark

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 stable without communication with despatcher. Distributed primary response,
- ○ Converters should contribute grid power balancing for a disturbance. Secondary response (automatic),
- ○ Optimisation and re-dispatching by dispatcher. Tertiary response (human intervention),
- ○ Droop based control enables power balancing but dynamic stability may not be good,
- ○ Fast DC voltage control is required at each terminal,

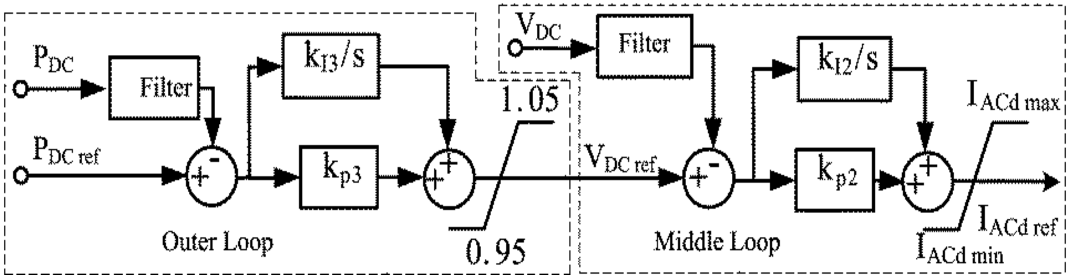


Fig. 60. 3-level controller for VSC terminals

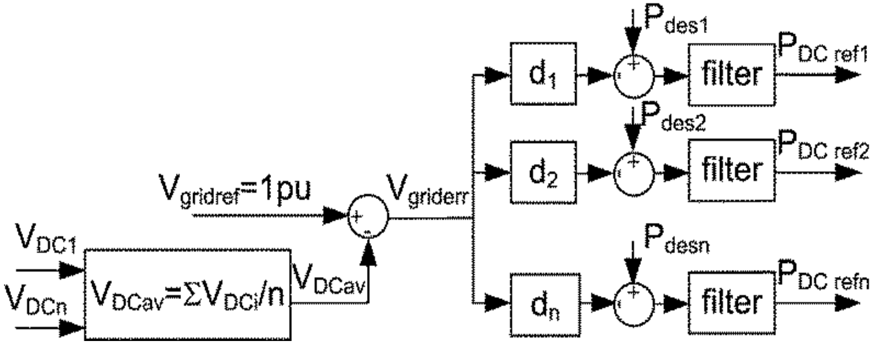


Fig. 61. Dispatcher Controller

4. DC grid Control Challenges

Following outage of a large VSC terminal:

- Primary response maintains stability. All variables are within operating limits. No VSC tripping.
- Secondary response balances power. A new operating point within 0.5s.
- Tertiary response establishes 1pu average DC voltage within 2s.

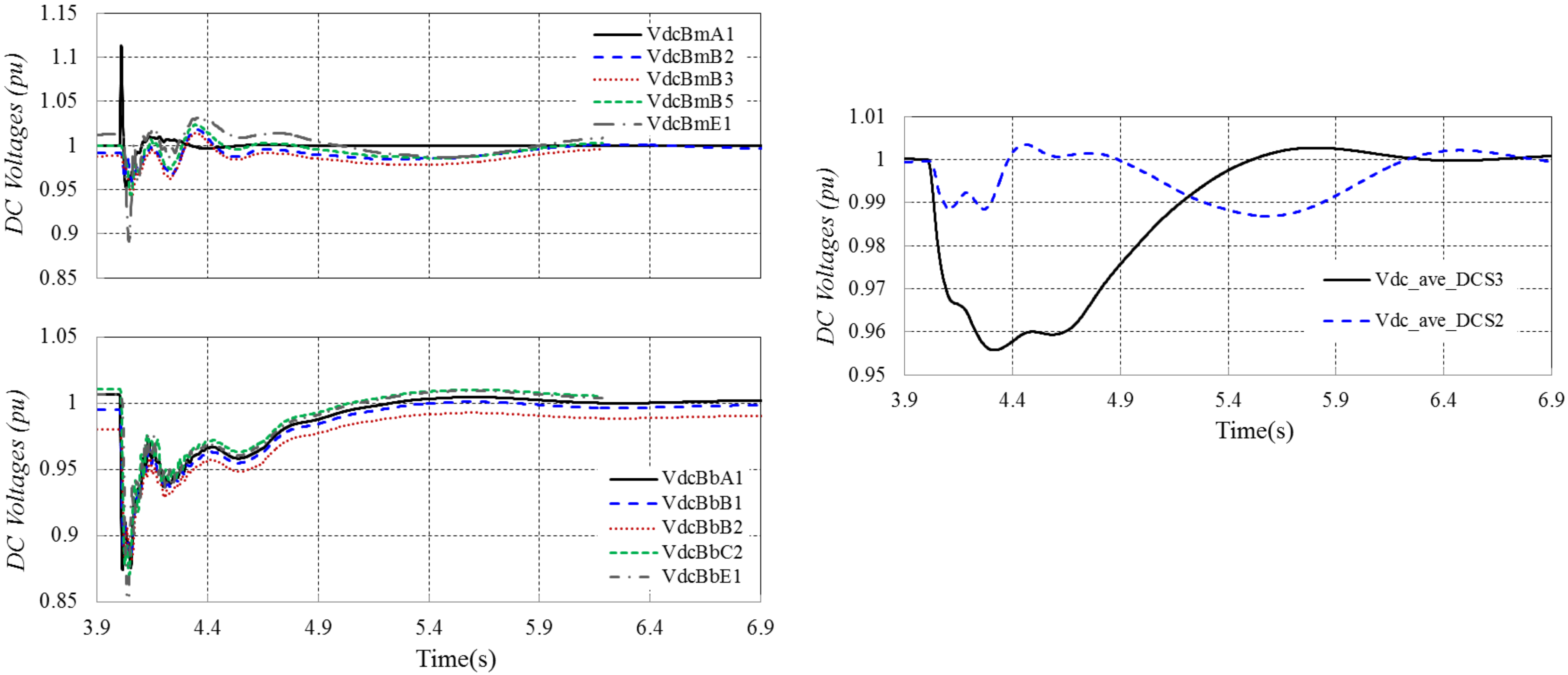


Fig. 62. DC voltages after terminal Cb-A1 outage (1GW loss),

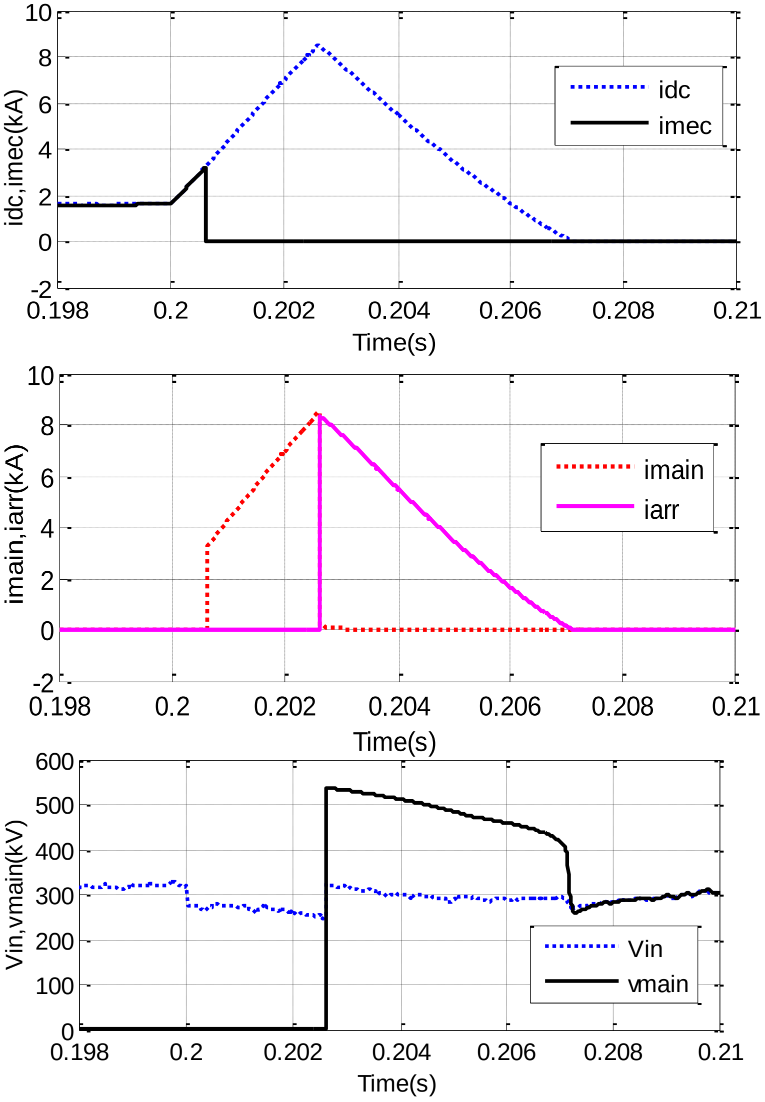
5. DC grid Protection Challenges

DC Grid protection using DC CBs:

- DC CB:
  - Limited speed of operation (2-7ms),
  - Self protection (8kA-15kA),
  - Inserting arrester reduces DC current in 2-5ms,
  - Inserting arrester causes large disturbance,

- VSC converters :
  - Self protection (current 2.5-4kA or voltage 0.8pu),
  - If blocked, they become a diode bridge,
  - After converter blocking AC CB is also tripped,

- DC grid protection system:
  - selectivity (very fast),
  - reliability (sufficient margin),
  - robustness (no false tripping),
  - back-up protection,



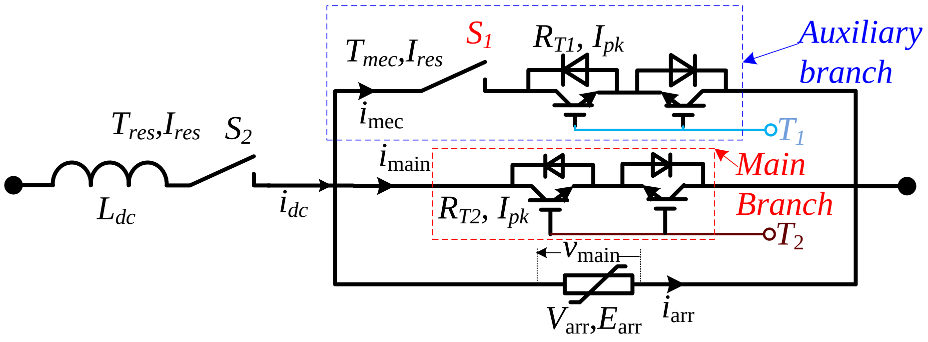


Fig. 63. DC fault isolation using Hybrid DC CB,

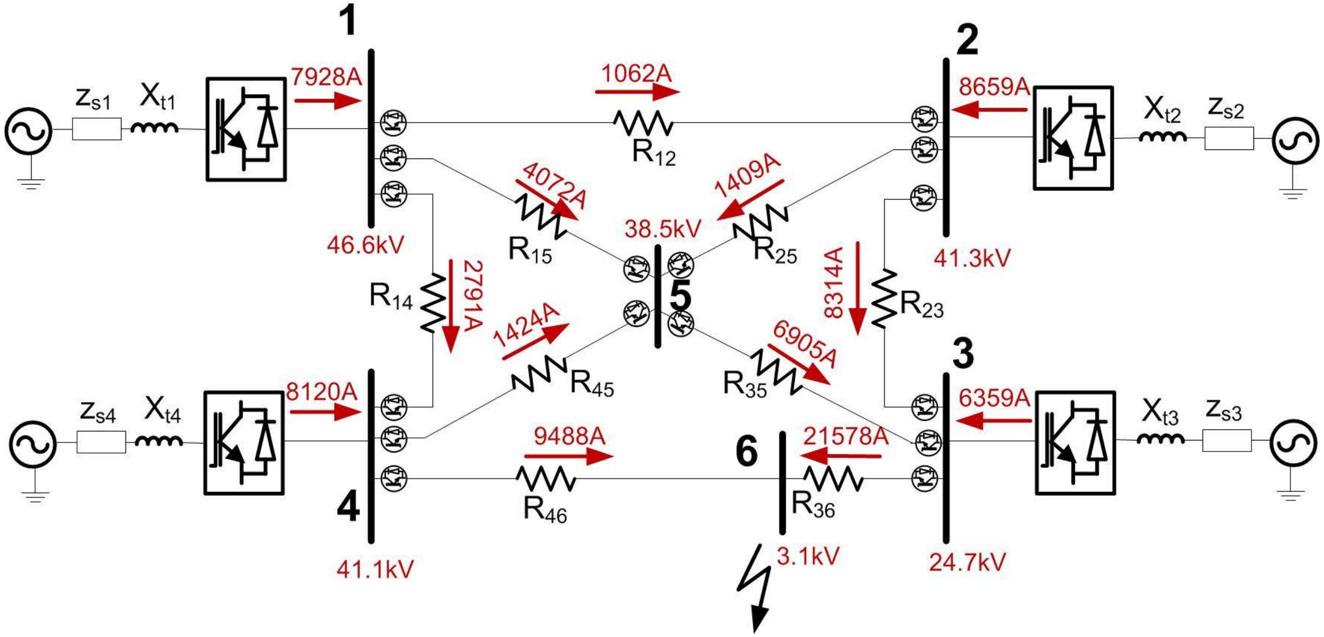
5. DC grid Protection Challenges

- DC fault currents are large, rise fast, and spread fast grid-wide
- Case study: 4-terminal 400kV meshed DC grid under a DC fault.

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

- Blocked VSC converters generate high DC fault currents,
- 8 DC lines, 16 DC CBs (cost of each is 0.3pu),
- Total DC CB cost is 5pu (total VSC cost is 4pu),
- How to locate fault (reliably and fast)?
- How to build back-up protection?
- Trip DC CBs before VSCs trip (2-5ms)



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

Figure 64. DC network fault study (assuming all VSCs are blocked).

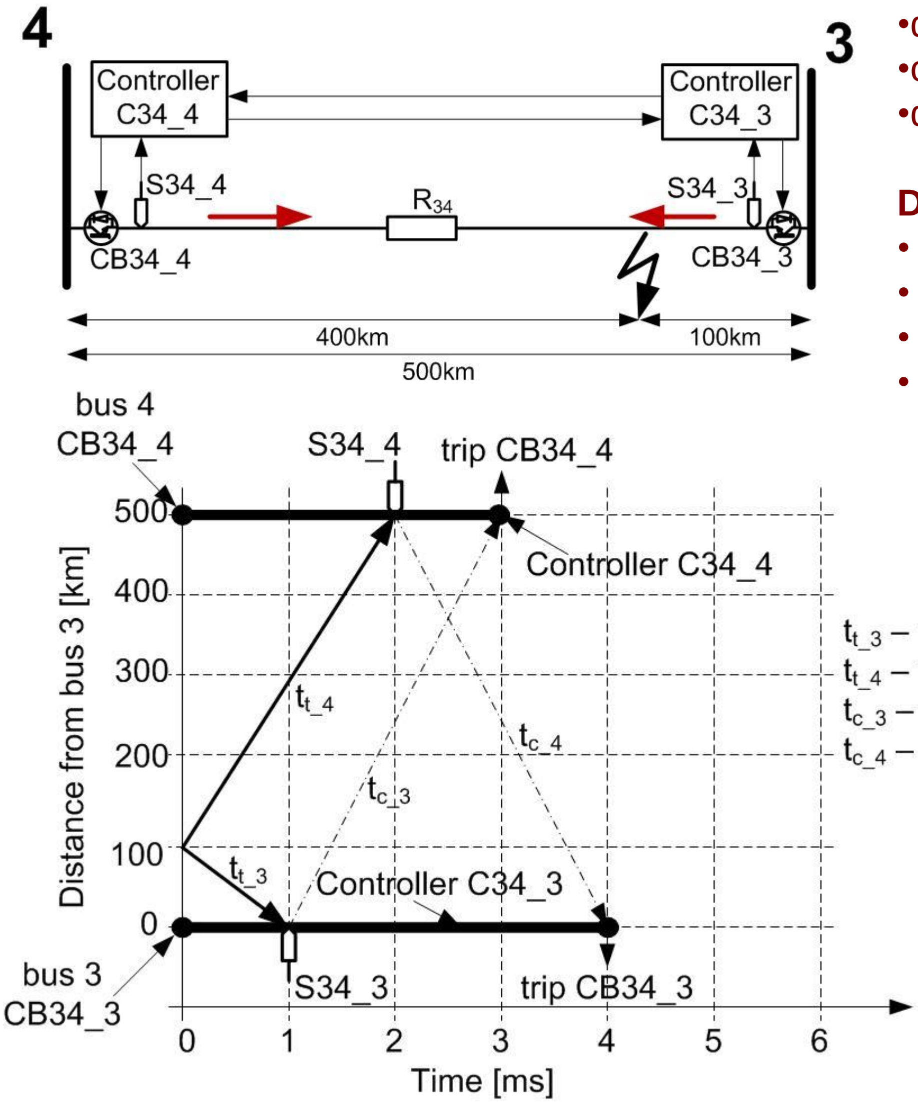
5. DC grid Protection Challenges

AC protection

- distance protection (R+jωL)
- overcurrent protection (radial lines)
- differential (communication between line ends)

DC line differential protection.

- excellent selectivity,
- excellent reliability,
- each DC CB receives signals from other line end,
- too slow for long lines (3-10ms),



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 65. 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,
- A positive fault current over a threshold immediately initiates trip signal,
- At one end fault is isolated with DC CB,
- At the converter end fault is isolated with AC CB,

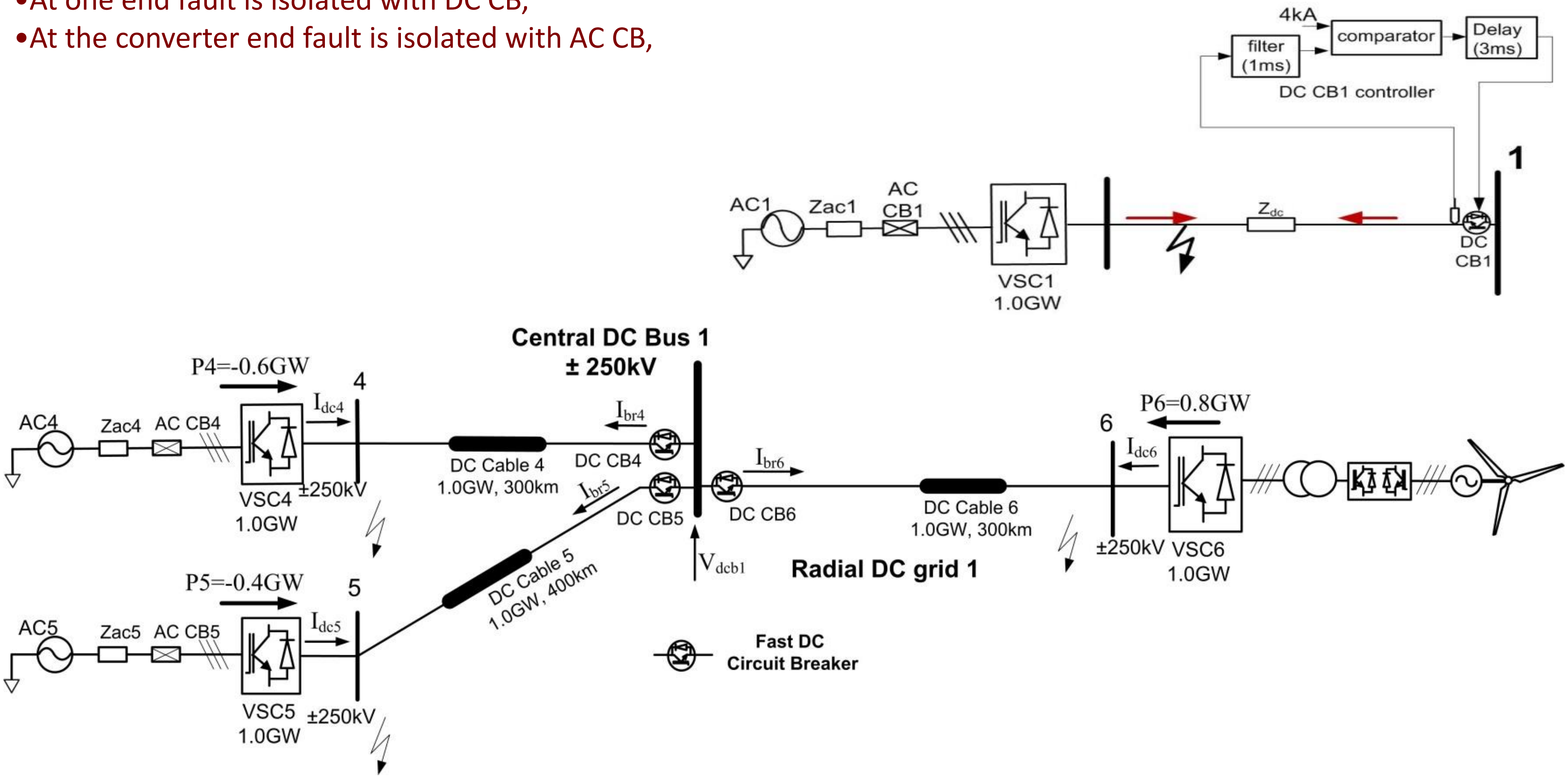
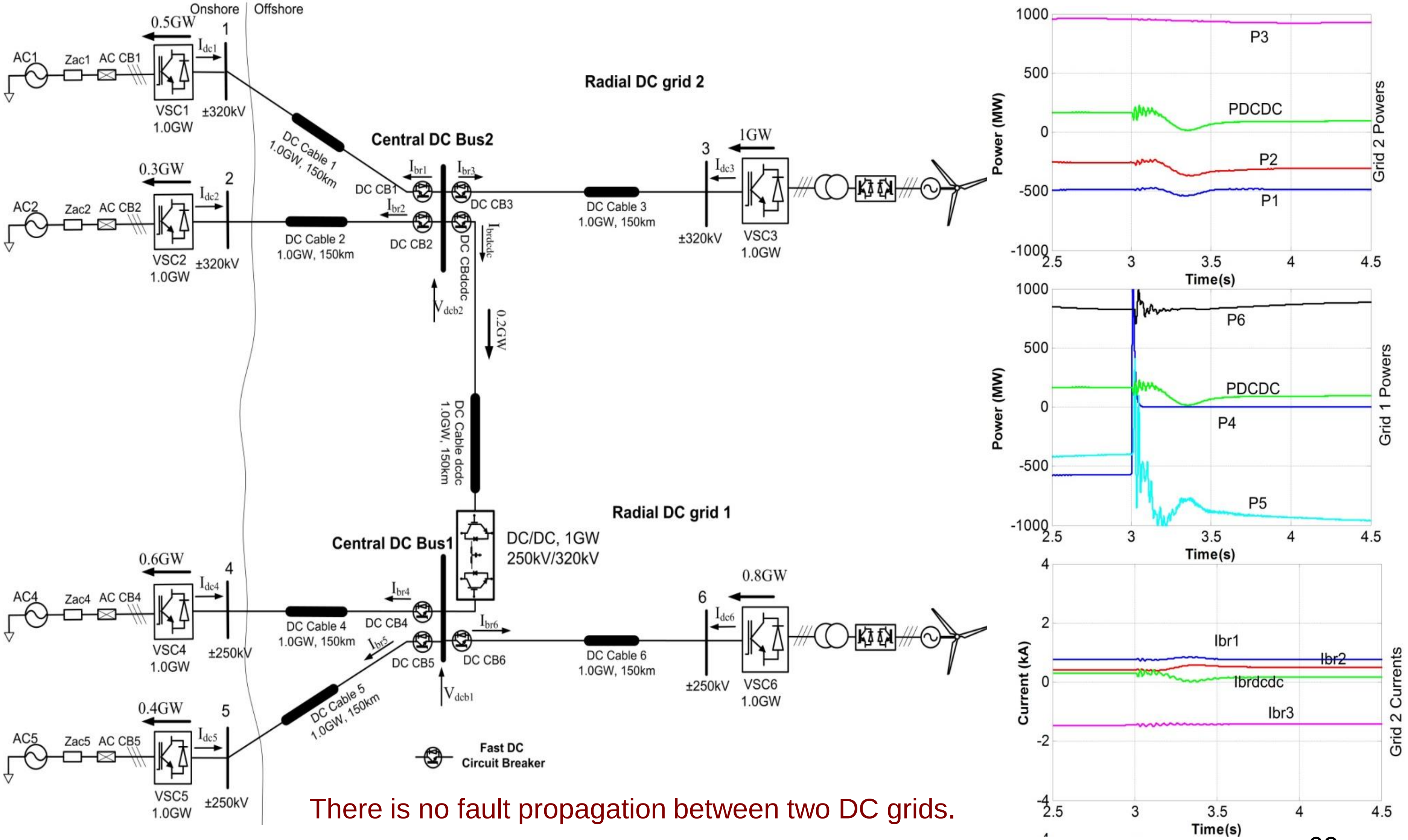


Figure 66. Protection system for radial DC grids.

5. DC grid Protection Challenges

Radial DC grids with DC/DC converters



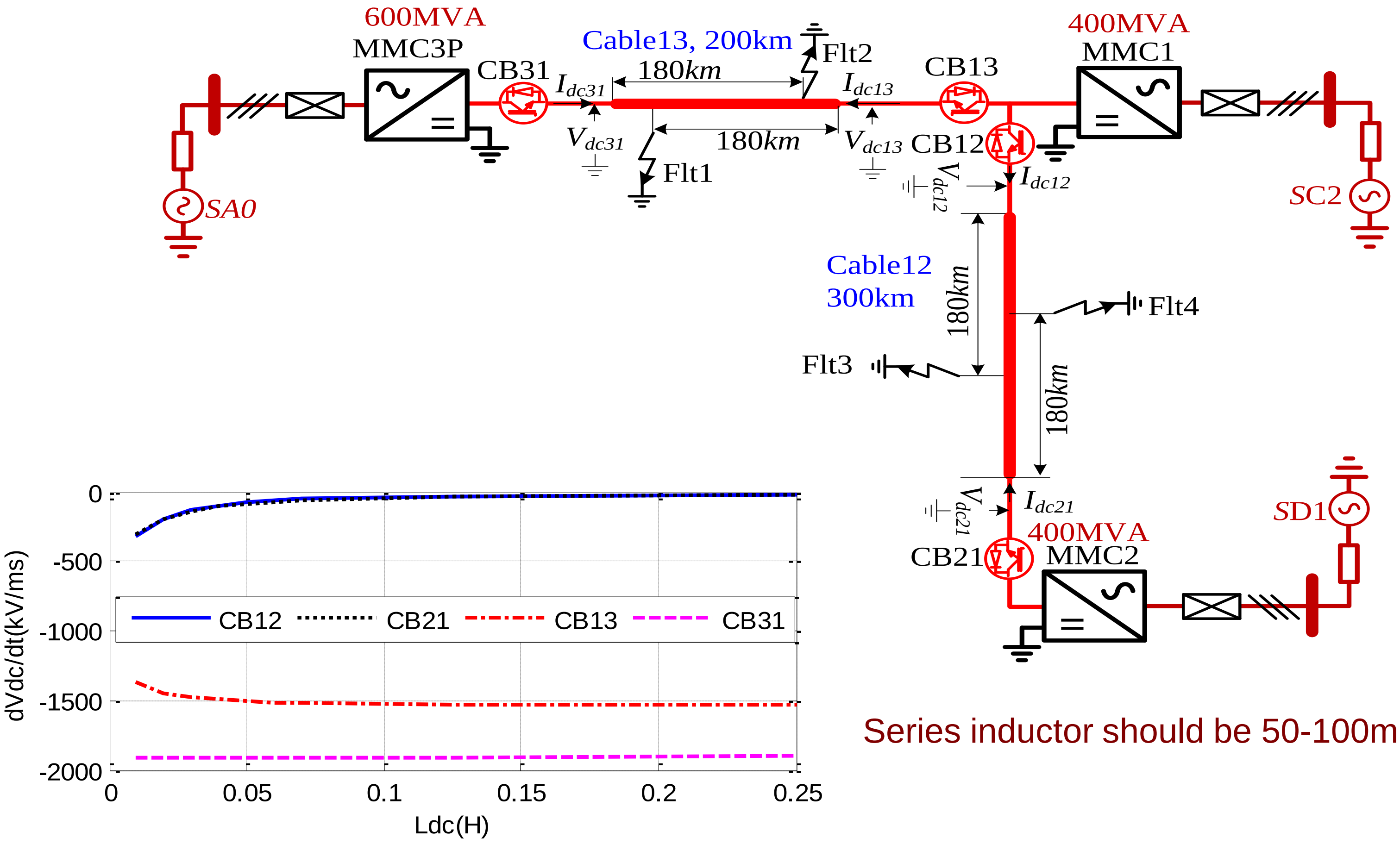
There is no fault propagation between two DC grids.

Figure 67. Interconnecting local radial DC grids with DC/DC converters.

5. DC grid Protection Challenges

DC Grid protection based on local traveling wave measurements

- Enables meshed DC grids,
- Selectivity requirements need careful design,
- Should not block local VSC terminals,
- ROCOV (Rate of change of local DC voltage) is input signal for protection relays,



Series inductor should be 50-100mH.

Fig. 68. Selecting threshold voltage rate of change for Flt1.

5. DC grid Protection Challenges

Local VSC terminal will see large current for DC cable faults, and terminal tripping results. The options to avoid loss in capacity are:

- Install large DC inductors of around 500-800mH,
  - Will be issue for offshore systems because of size,
  - May cause stability problems,

- Temporarily block VSC terminal:
  - Diodes require larger fault rating,
  - IGBTs may require cool-off period,
  - VSC blocking may not always occur (depends on fault location).

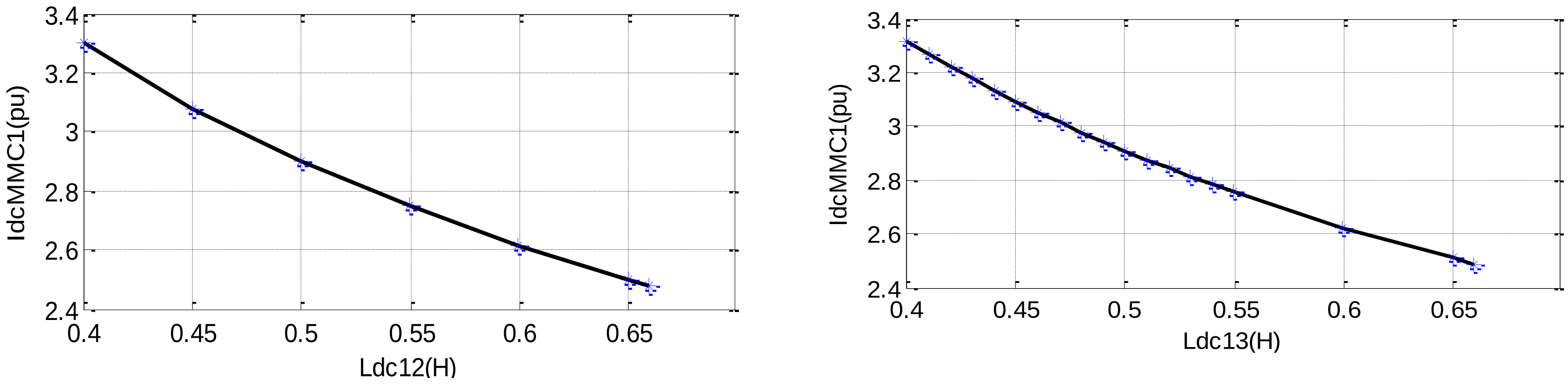


Fig. 69. Peak DC fault current at VSC terminal, assuming 2ms clearing time in DC CBs.

5. DC grid Protection Challenges

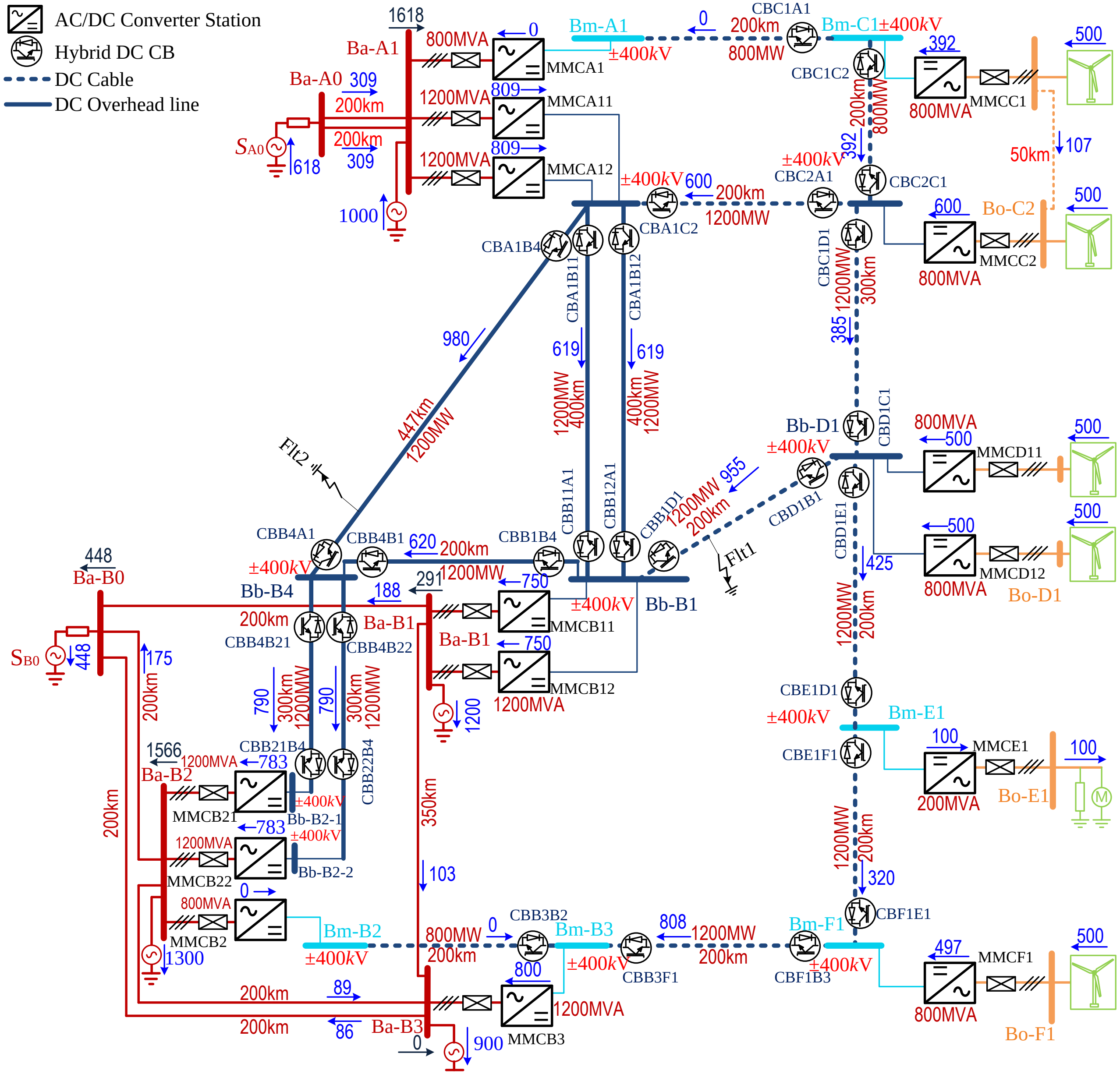
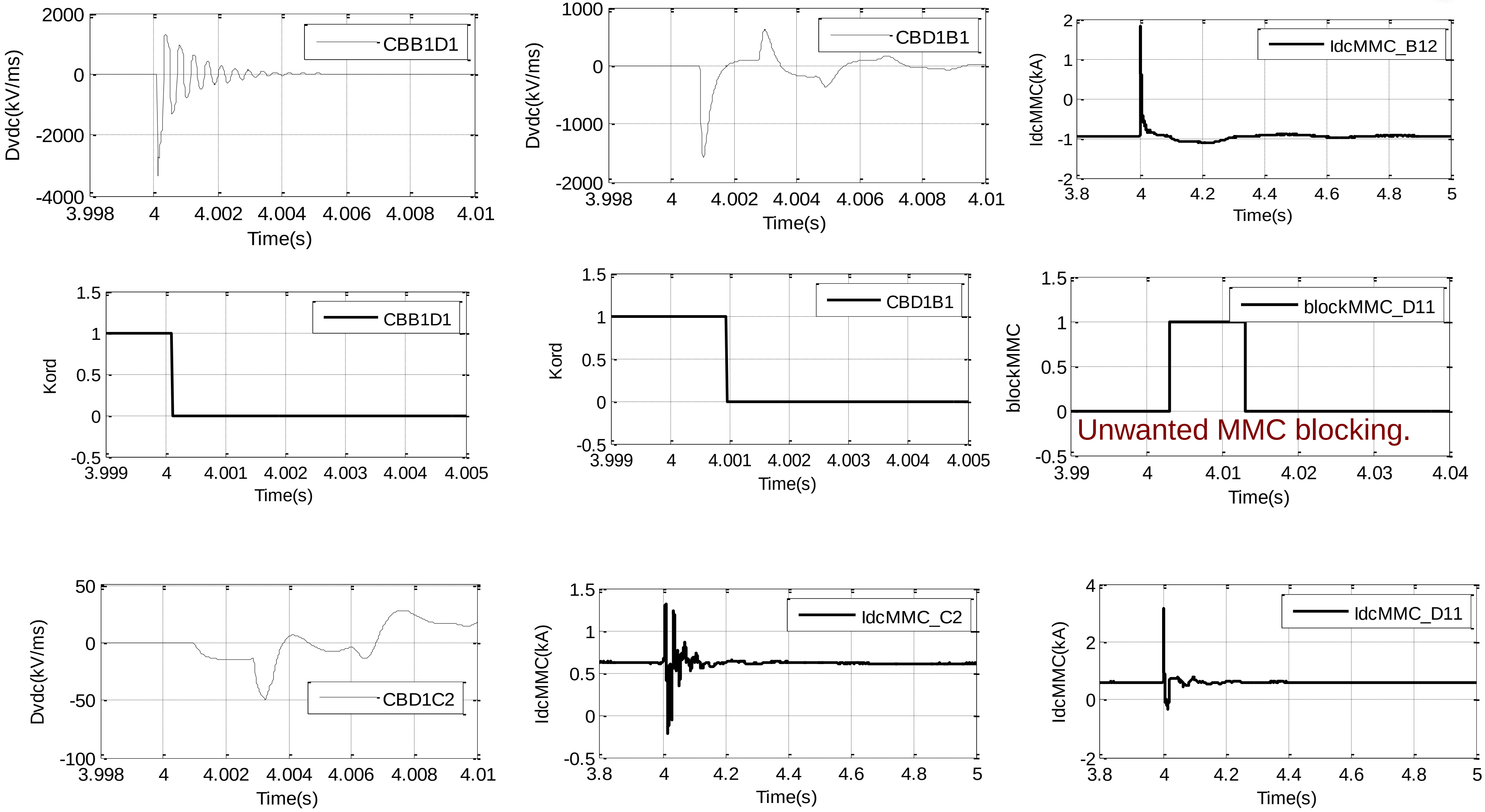


Fig. 70. DC test grid with single DC voltage level (29 DC CBs).

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



Unwanted MMC blocking.

Fig. 71a). DC grid simulation for permanent DC fault flt1 (125mH inductors).

5. DC grid Protection Challenges

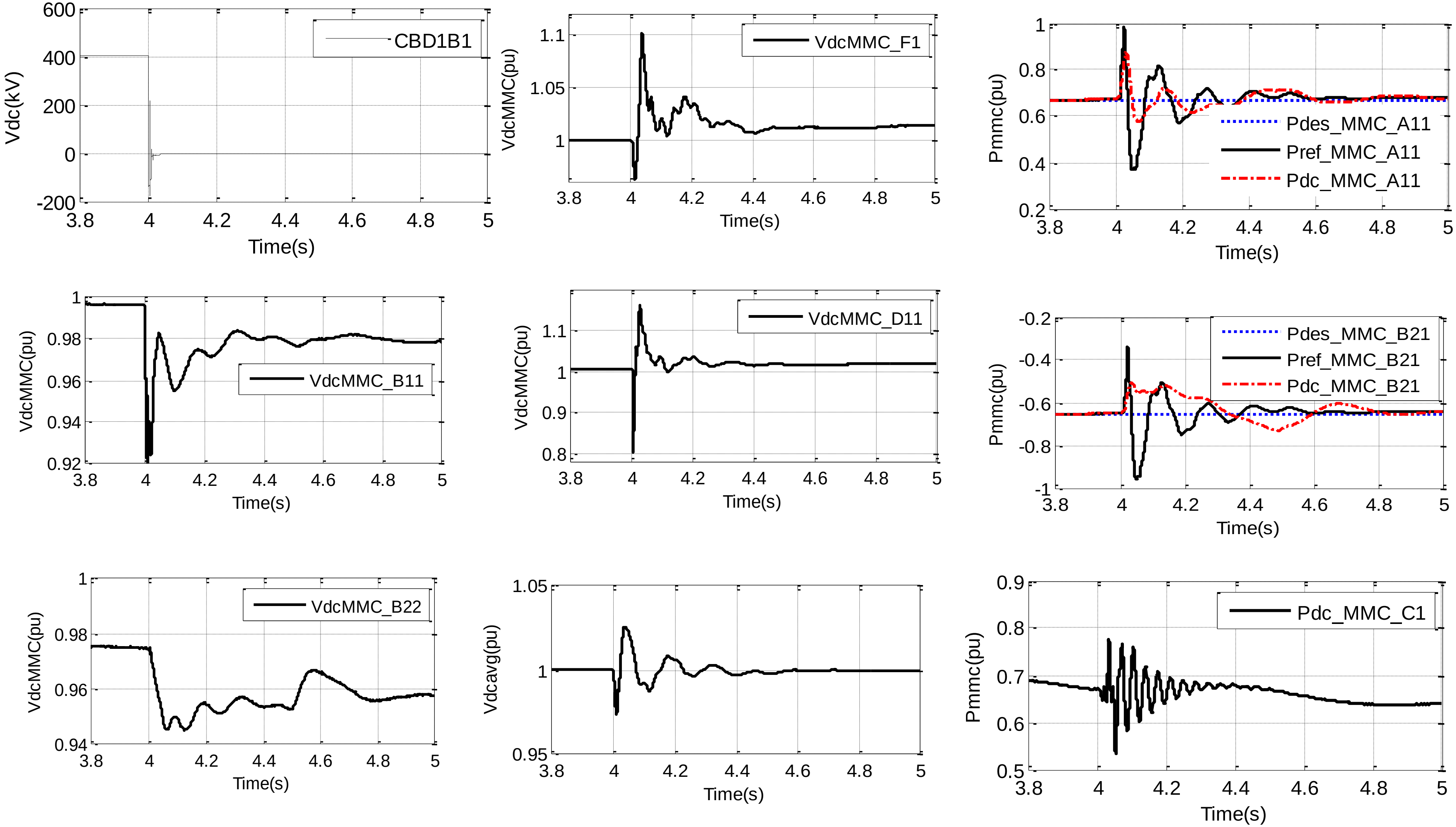


Fig. 71b). DC grid simulation for permanent DC fault flt1

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,
- **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.

Further Information

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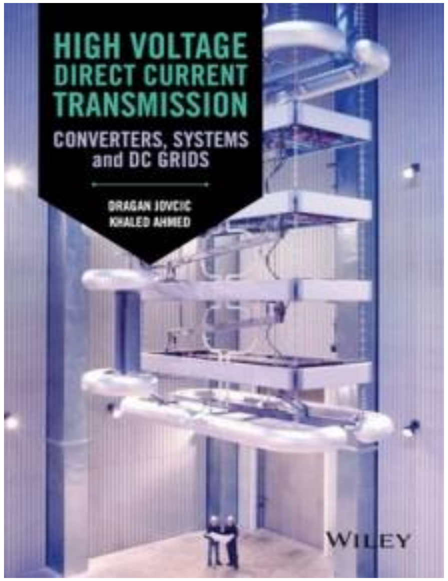
https://www.abdn.ac.uk/

Aberdeen HVDC research centre:
https://www.abdn.ac.uk/engineering/research/aberdeen-hvdc-research-centre-472.php



HIGH VOLTAGE
DIRECT CURRENT
TRANSMISSION
CONVERTERS, SYSTEMS
and DC GRIDS
DRAGAN JOVCIC
KHALED AHMED
WILEY

Dragan Jovcic and Khaled Ahmed “High-Voltage Direct Current Transmission: Converters Systems and DC Grids” Wiley, 2015

27/04/2017 – Les réseaux à courant continu

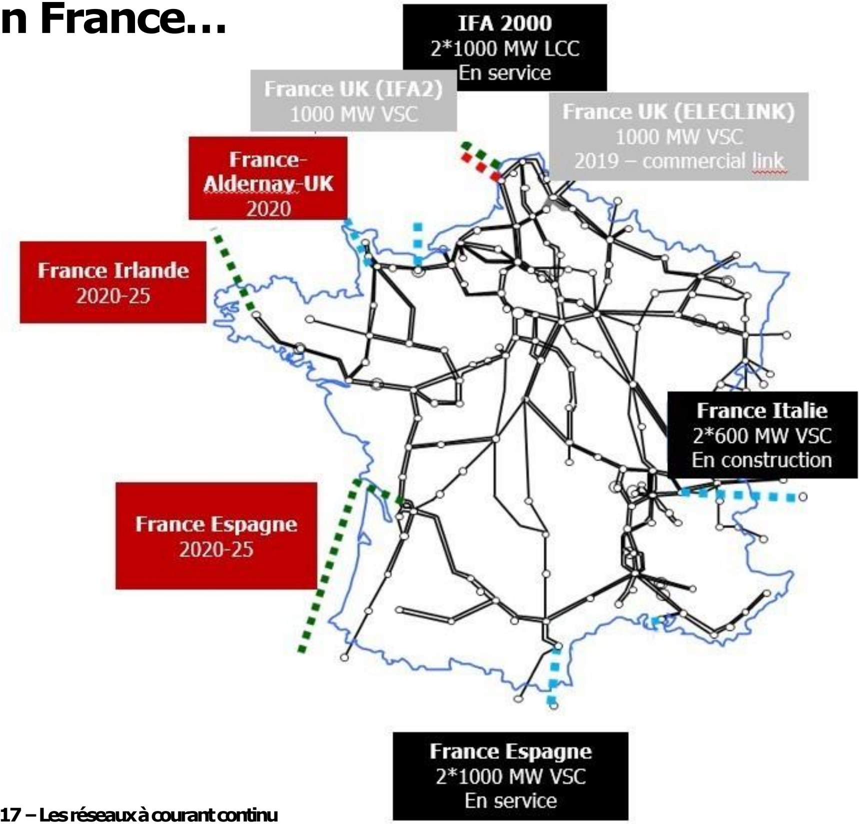
La simulation Temps Réel des systèmes HVDC à RTE

Bertrand CLERC

Rte – Centre National d'Expertise Réseaux

La multiplication des liaisons HVDC

En France…



IFA 2000
2*1000 MW LCC
En service

France UK (IFA2)
1000 MW VSC

France UK (ELECLINK)
1000 MW VSC
2019 – commercial link

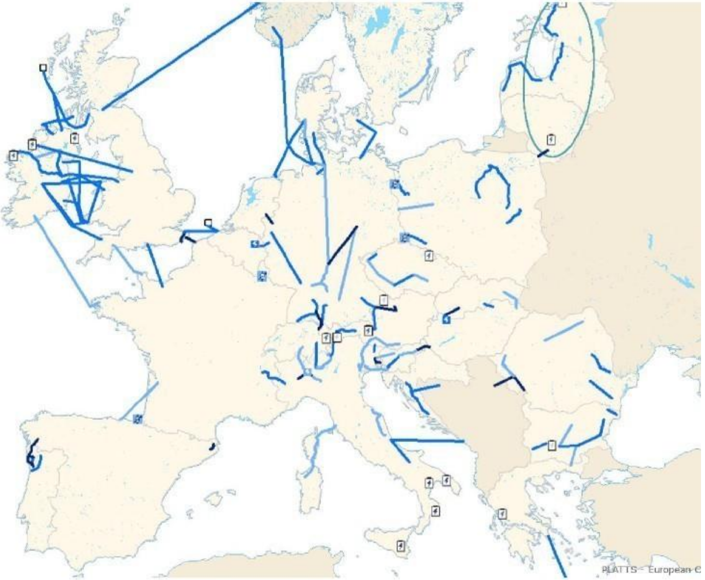
France-Aldernay-UK
2020

France Irlande
2020-25

France Italie
2*600 MW VSC
En construction

France Espagne
2020-25

France Espagne
2*1000 MW VSC
En service



… Comme dans toute l'Europe

De nouveaux défis pour les GRT

Garantir l'insertion en exploitation dans le système électrique de ces liaisons HVDC

- Être en capacité d'exprimer les besoins statiques et dynamiques au sein des spécifications fonctionnelles
- Disposer de moyens pour vérifier l'absence d'interactions avec d'autres composants du réseau

Identifier une stratégie de maintenance de ces composants particuliers

- Conjuguer la maîtrise des coûts de maintenance et l'exigence de disponibilité des liaisons HVDC
- Disposer de moyens d'analyse d'incidents et d'adaptation de ces composants au contexte évolutif

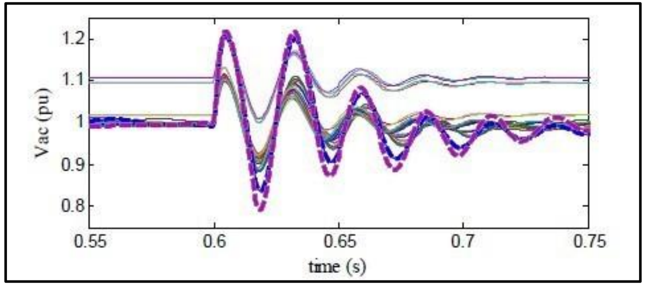
Intégrer le HVDC dans la planification Long Terme du réseau

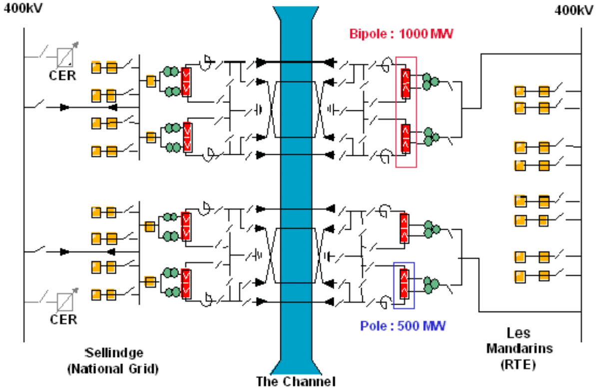
- Réfléchir aux opportunités et aux difficultés de création d'un réseau HVDC

La simulation au service de la maîtrise du système

Nécessité de réaliser des simulations électromagnétiques transitoires (EMT) pour analyser le comportement des systèmes HVDC

- Calculs électriques sur les 3 phases avec prise en compte de la propagation des ondes, des dépendances fréquentielles, des phénomènes non linéaires, …

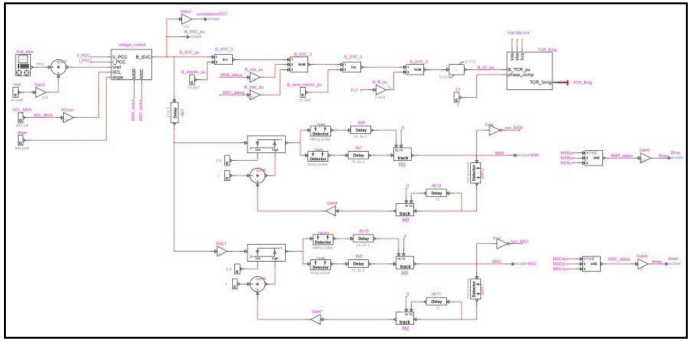




Requiert une modélisation fine du réseau et des stations de conversion

- Obtenir les paramètres détaillés des différents composants
- Disposer d’un modèle du Contrôle Commande des équipements à base d’électronique de puissance

Les limites de la modélisation numérique



La modélisation numérique du Contrôle Commande des équipements à base d'électronique de puissance est une solution limitée

- Les Contrôles Commande sont développés sur des systèmes informatiques spécifiques dont le comportement est difficile à reproduire sur des processeurs standards
- Certains algorithmes des constructeurs ne sont pas ouverts pour des raisons de protection de la propriété intellectuelle
- Les modèles numériques fournis par les constructeurs sont imparfaits et difficiles à utiliser ainsi qu'à maintenir

Plutôt que de modéliser numériquement le Contrôle Commande, il est possible de raccorder une réplique du Contrôle Commande reel à un simulateur Temps Réel

Le principe de la simulation Temps Réel

Armoires du Contrôle Commande réel

Stations de conversion

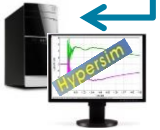
Sous-modules des convertisseurs

Equipements sur site

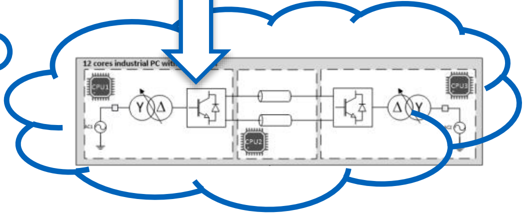
Réplique du Contrôle Commande

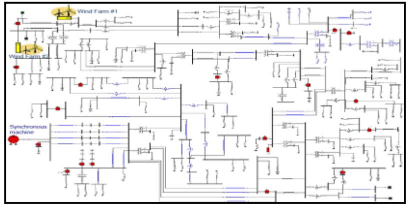
Mesures courants/tensions

Commandes interrupteurs



Simulateur Temps Réel

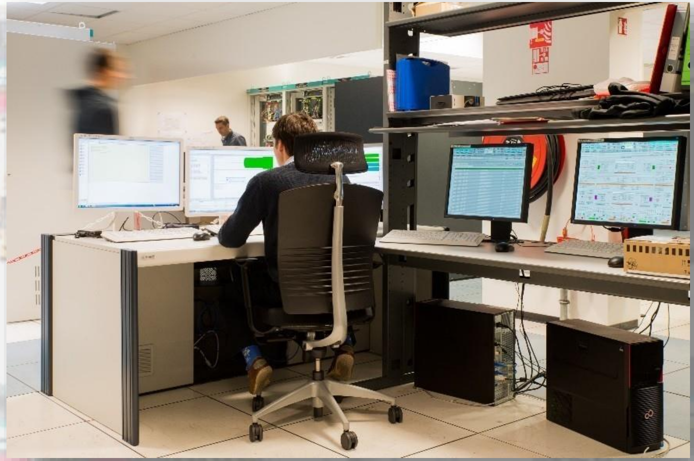




Modélisation possible d'un réseau étendu

Equipements sur la plateforme de simulation Temps Réel

La simulation Temps Réel à RTE



Créée en 2012 à Courbevoie, la plateforme SMARTE accueille désormais plusieurs systèmes de simulation Temps Réel d'équipements à base d'électronique de puissance

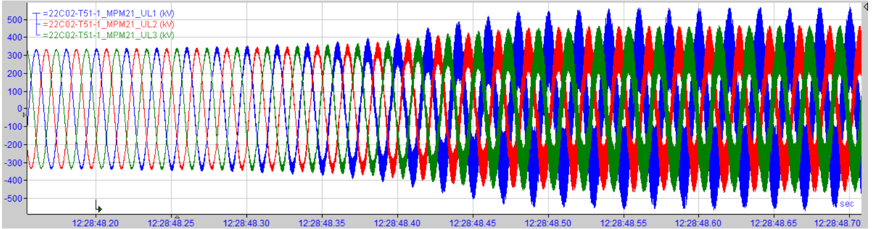
- 3 répliques de Contrôle Commande de liaisons HVDC : France-Espagne (Siemens – technologie VSC) et IFA 2000 (GE – technologie LCC)
- 5 répliques de Contrôle Commande de Compensateurs Statiques de Puissance Réactive

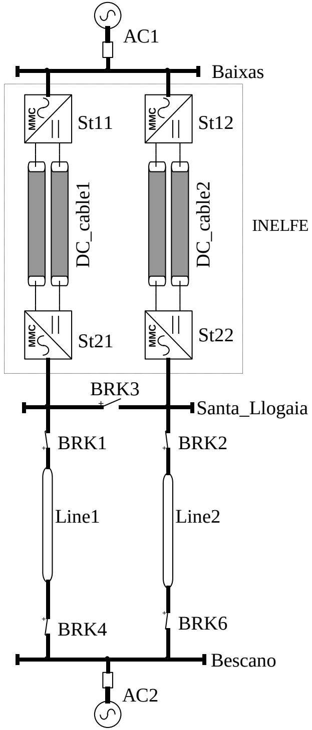
RTE possède 6 simulateurs Temps Réel dédiés à l'utilisation des répliques de Contrôle Commande pour un total de 170 CPU

L’utilisation de la simulation Temps Réel

Reproduction d’un incident sur la liaison France-Espagne : Déclenchement de la liaison suite à l’apparition d’un phénomène de résonance (1.8 kHz)

- Simulation avec le logiciel EMTP non concluante
- Phénomène reproduit avec la réplique et le simulateur Temps Réel Hypersim
- Réalisation d’une modification du Contrôle Commande par le constructeur
- Tests de non regression sur la plateforme



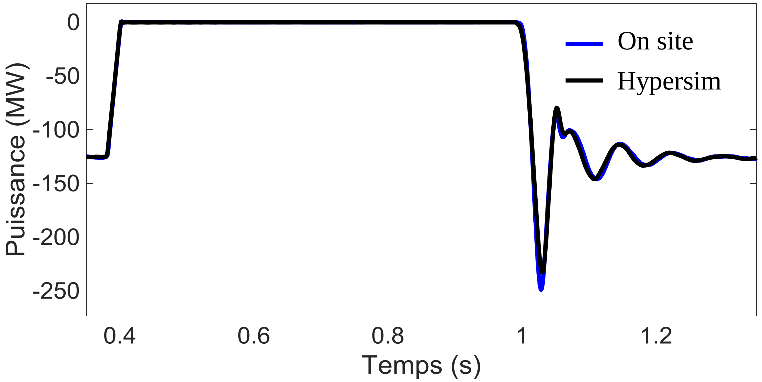


L’utilisation de la simulation Temps Réel

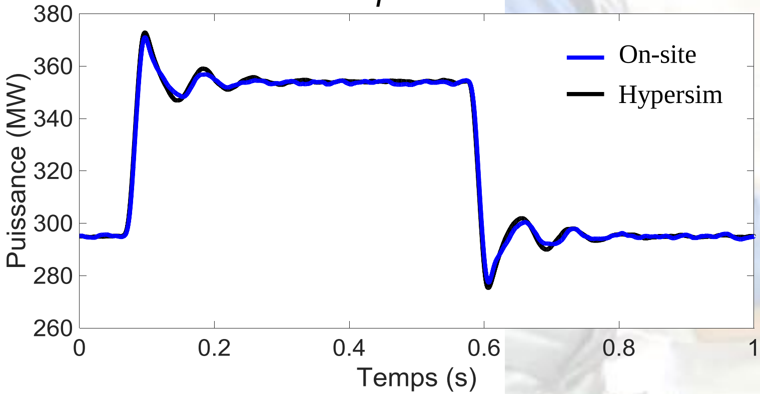
La maîtrise de la simulation Temps Réel nécessite des travaux préalables

- Préparation des modèles du réseau et des matériels HT HVDC : validation offline puis en Temps Réel
- Mise au point d’une interface avec la réplique de Contrôle Commande
- Reproduction des essais réalisés en usine du véritable Contrôle Commande (FAT & SAT)
- Reproduction d’essais réels sur site lors de la phase de mise en service de l’équipement réel

Blocage d’un convertisseur



Echelon de puissance active



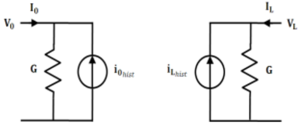
L’utilisation de la simulation Temps Réel

RTE a choisi de maîtriser les logiciels de simulation EMT

- Collaboration avec Hydro-Québec et EDF sur le développement d’EMTP
- Collaboration avec Hydro-Québec sur le développement d’HYPERSIM

RTE développe des fonctionnalités dans HYPERSIM pour ses besoins de simulation Temps Réel

- Développement d’un modèle d’équations d’état pour les composants de puissance permettant notamment de modéliser des équivalents de réseaux à dépendance fréquentielle
- Intégration d’une fonctionnalité d’interfaçage de codes de contrôle issus de MATLAB/Simulink
- Développement d’un modèle de ligne / cable WideBand



$$\mathrm{x}_{i,k} = \hat{p}_{i,k}\, \mathrm{x}'_{i,k} + \widehat{\mathbf{R}}_{i,k}\left[\mathbf{i}_{\mathbf{fw}_\mathrm{L}}(t-\tau_i) + \mathbf{i}'_{\mathbf{fw}_\mathrm{L}}(t-\tau_i)\right]$$

L’utilisation de la simulation Temps Réel

Le développement des réseaux DC requiert une capacité des constructeurs à créer des systèmes interopérables

- Apparition de projets de liaisons HVDC avec des stations de conversion de technologies différentes ou avec des options d’extension ouvertes à d’autres constructeurs

Le lot 2 du projet Best Paths vise à étudier l’interopérabilité de stations de conversion de plusieurs constructeurs équipant une même liaison HVDC

- Une première étape sous EMTP mettant en évidence 15% de situations simulées présentant des problèmes d’interopérabilité

- Une seconde étape avec l’objectif de réaliser des études complémentaires avec des contrôles commande réels

La simulation TR au service de la maintenance

La plateforme SMARTE constitue un outil puissant pour optimiser l'exploitation et la maintenance des liaisons HVDC

Développer les compétences sur le HVDC

Former les opérateurs

Préparer les gestes de maintenance

Rejouer les incidents pour les analyser

Tester les évolutions du Contrôle Commande

Epauler les équipes sur le terrain

Accueillir des partenaires et échanger

Des questions en temps réel ?

Recherches sur les systèmes HVDC au GeePs

Axes de recherche

- Convertisseurs modulaires multiniveaux (MMC)
- Conduite de systèmes HVDC multi-terminaux
- Maquette physique de réseau MTDC

Contrôle de MMC

- Thèse de Gilbert Bergna (2011-2014)
  - Nouvelle approche de contrôle des courants circulants
  - Contrôle de la puissance DC en conditions déséquilibrées
  - Utilisation du MMC en “firewall contre les oscillations de puissance”
  - Contrôleur PI avec méthode de passivité

Contrôle MMC

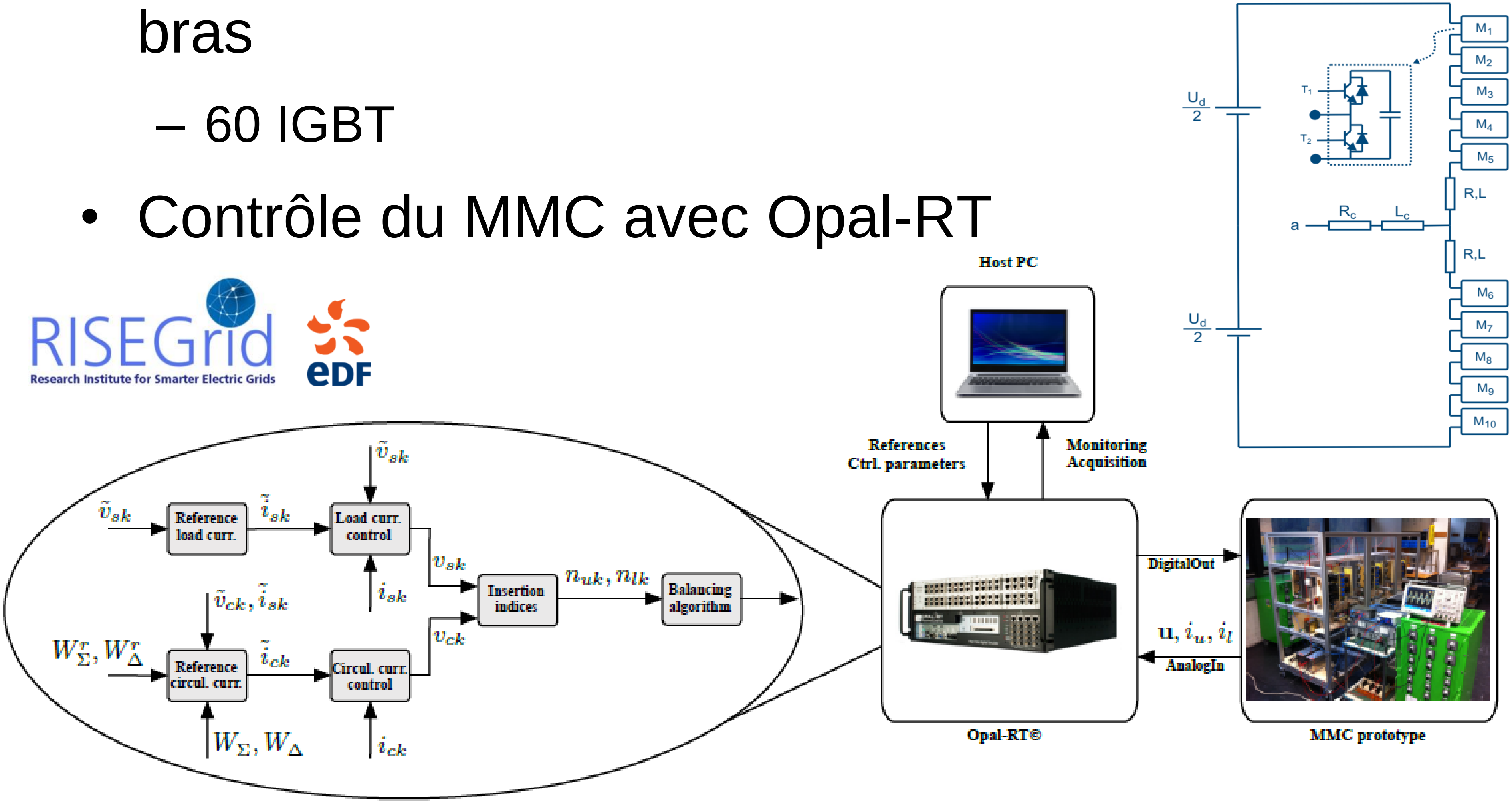
- Post doc de Nikola Stankovic (2013-2016)
  - Optimisation des références des courants circulants avec prise en compte de contraintes antagonistes (courant circulants et oscillation de tensions de bras)
  - Plateforme expérimentale avec un MMC piloté via Opal-RT

Plateforme MMC

- Construction d'un MMC avec 10 submodules / bras
  - – 60 IGBT
- Contrôle du MMC avec Opal-RT

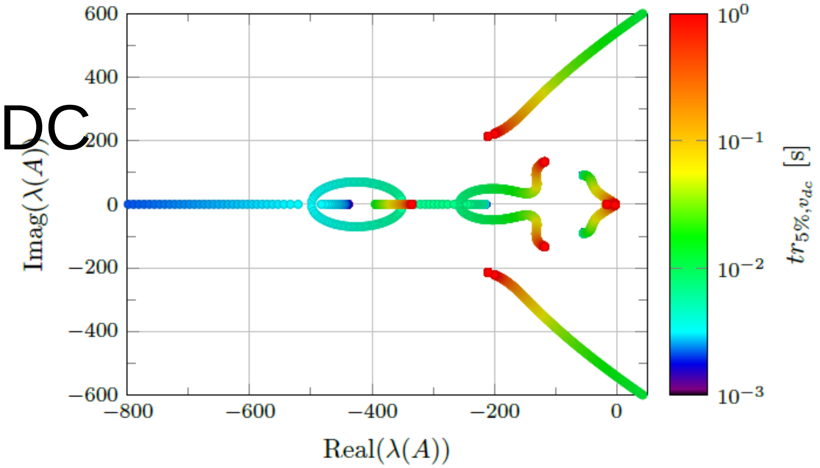
RISEGrid
Research Institute for Smarter Electric Grids

eDF



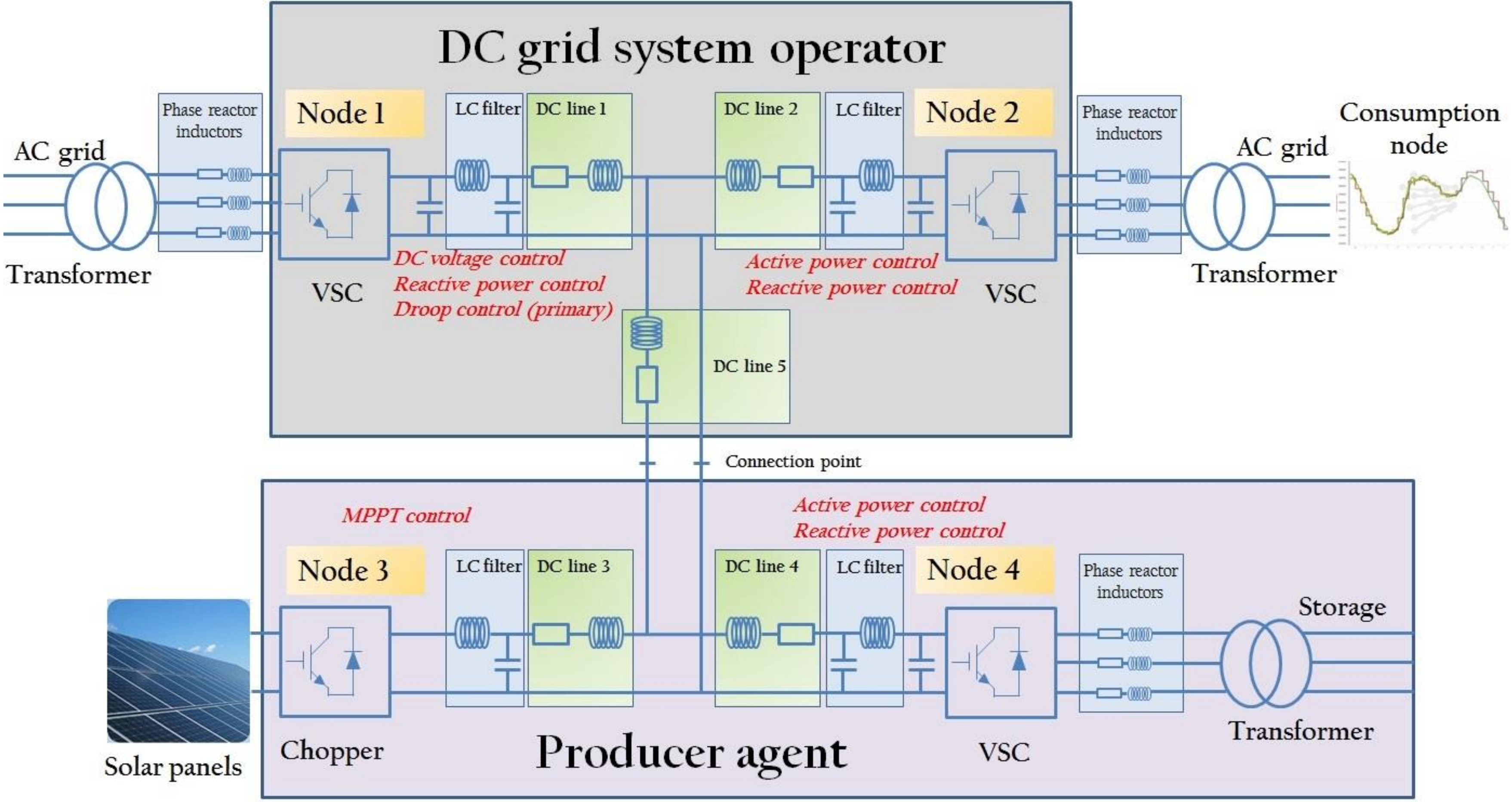
Système Multiterminaux HVDC

- Thèse de Samy Akkari (2013-2016)
  - Définition du paramètre de droop pour V_{dc}
  - Modélisation d’état d’un VSC et d’un MMC
  - Analyse des valeurs propres et trajectoires selon les valeurs du droop. Identification des facteurs d’influence
  - analyse petits-signaux par décomposition en valeurs singulières
  - Impact du modèle de câble DC
  - Interaction entre les droop tension et fréquence



Plateforme MTDC

- Système MTDC avec convertisseurs physiques (VSC and MMC)

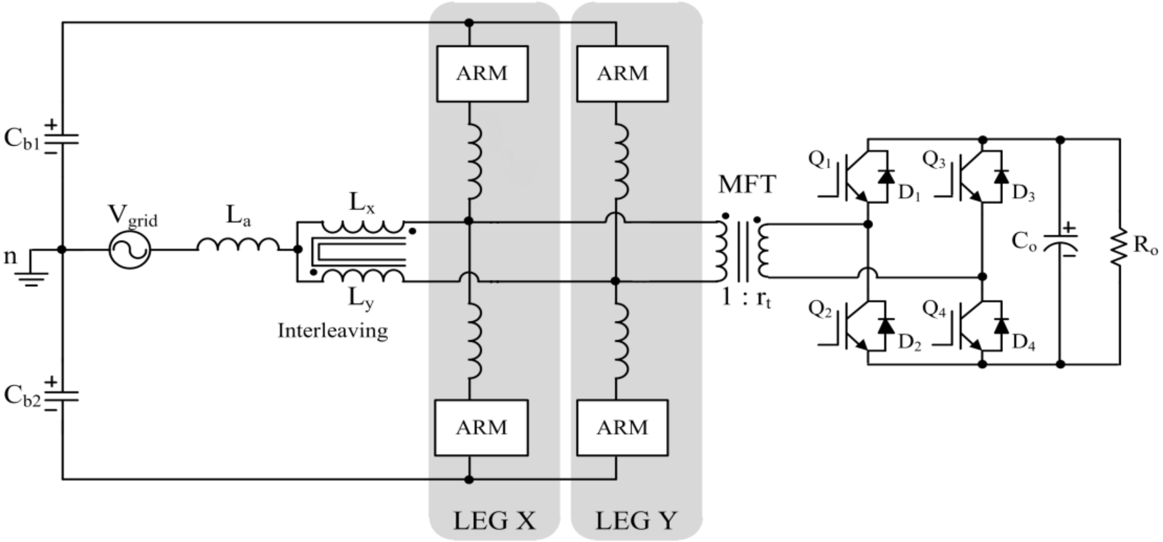


Autres recherches DC

- Étude de nouvelles topologies de MMC
  → MMC entrelacé (10 kHz transformer)
  - Partenariat avec le Brésil

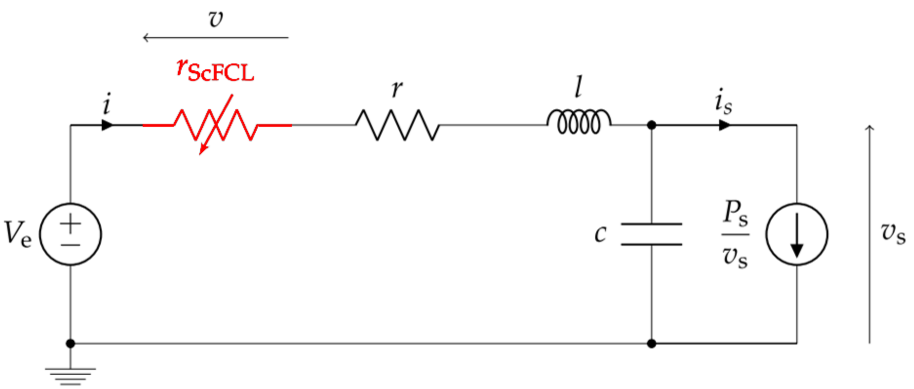
UNIVERSIDADE FEDERAL DO CEARÁ

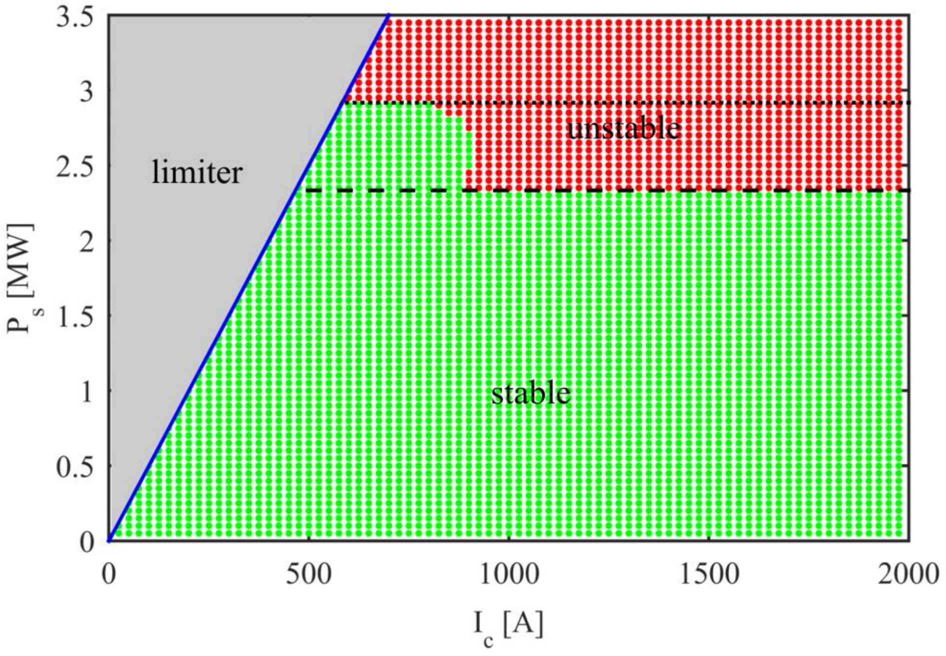
GRUPO DE PROCESSAMENTO DE ENERGIA E CONTROLE

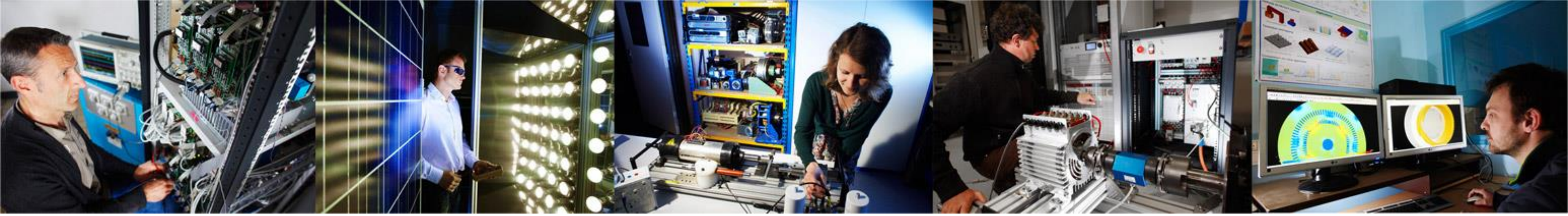


Autres recherches DC

- Utilisation de limiteurs supra sur réseaux DC
  - Partenaria avec le GREEN et UNAM (Mex)
  - Utilisation du FCL pour stabilisation du réseau DC en condition sans défauts







Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Synthèse sur les activités du L2EP autour de l'électronique de puissance sur les réseaux de transport

Xavier Guillaud – professeur Ecole Centrale de Lille

xavier.guillaud@centralelille.fr

Introduction

Le L2EP est un laboratoire de génie électrique à Lille réparti sur 4 établissements : Université de Lille 1, Ecole Centrale de Lille, Arts et Métiers – Campus de Lille, HEI

Depuis la création du L2EP dans les années 90 (et même avant), il y a toujours eu une **activité d'électronique de puissance** à Lille.

Une équipe s'est aussi développée sur les aspects **contrôle commande des systèmes électrotechniques**

L'activité **réseau** a démarré en 2001 au L2EP.

Les travaux d'électronique de puissance sur les réseaux de transport sont à l'intersection entre ces 3 axes de recherche : réseau, commande des systèmes électrotechnique et électronique de puissance

Axe de recherche développés au L2EP

- Réseau HVDC

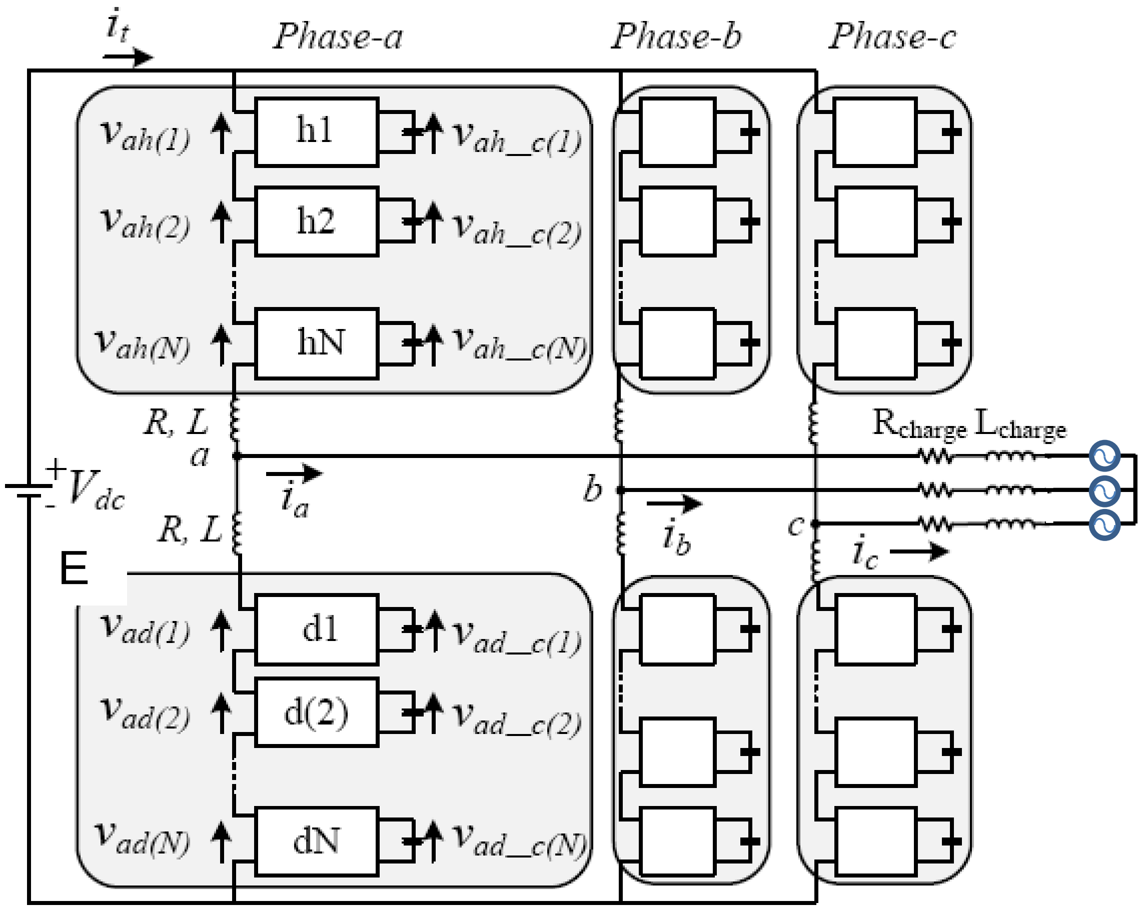
  Les convertisseurs AC/DC de forte puissance

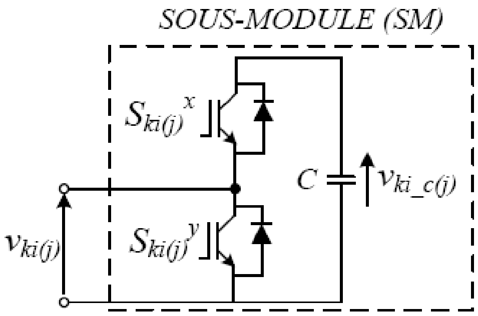
  Contrôle-commande des réseaux courant continu multiterminaux (MTDC)

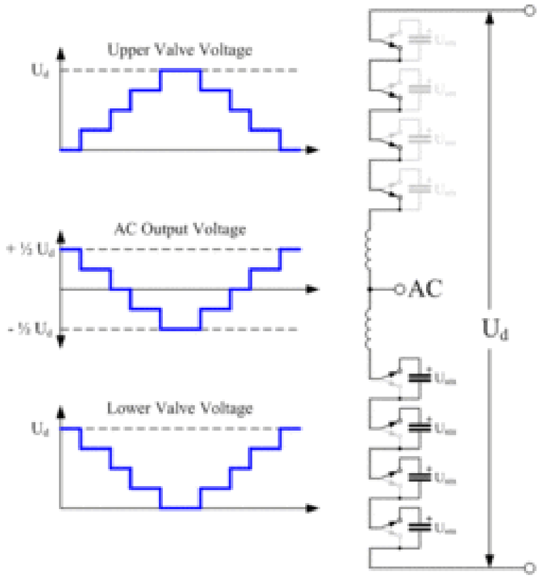
  Participation au service système des réseau MTDC

- Réseau AC avec forte pénétration d’électronique de puissance

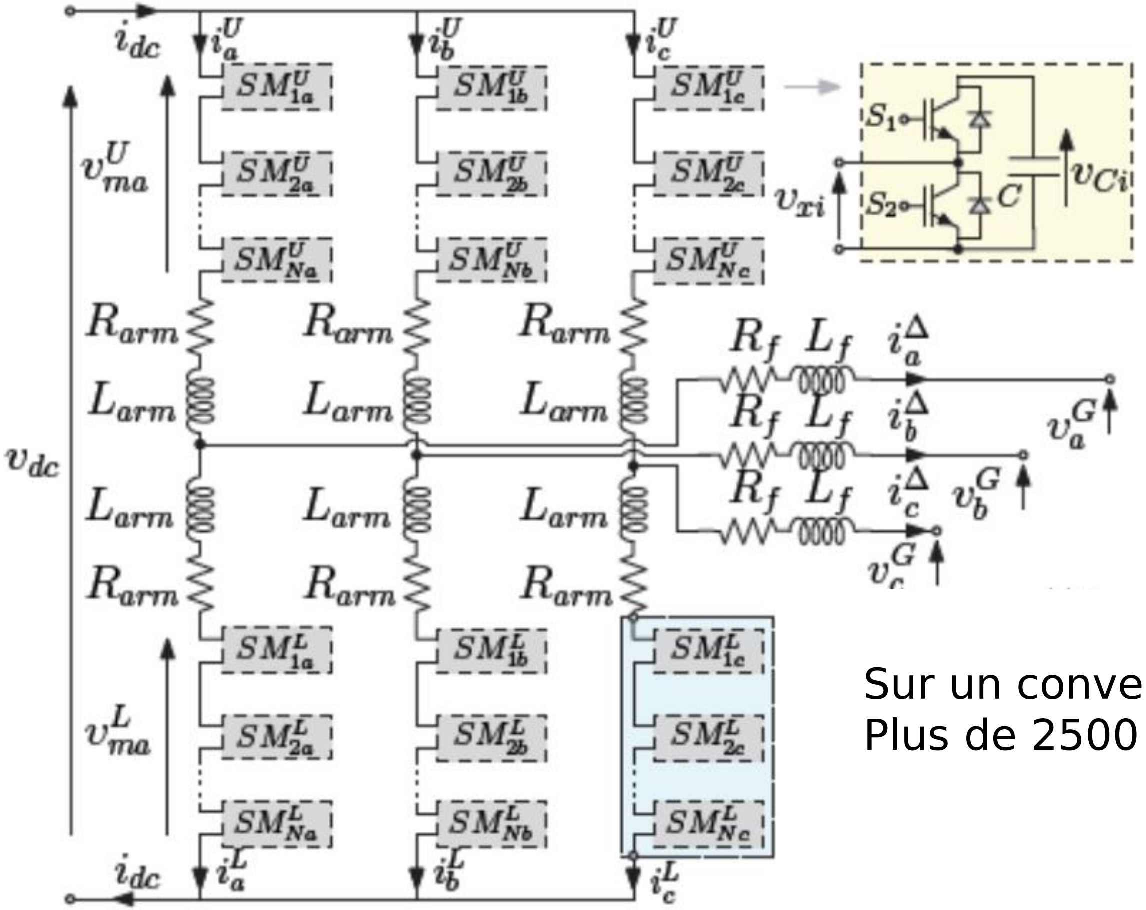
Convertisseur AC/DC de forte puissance : le MMC







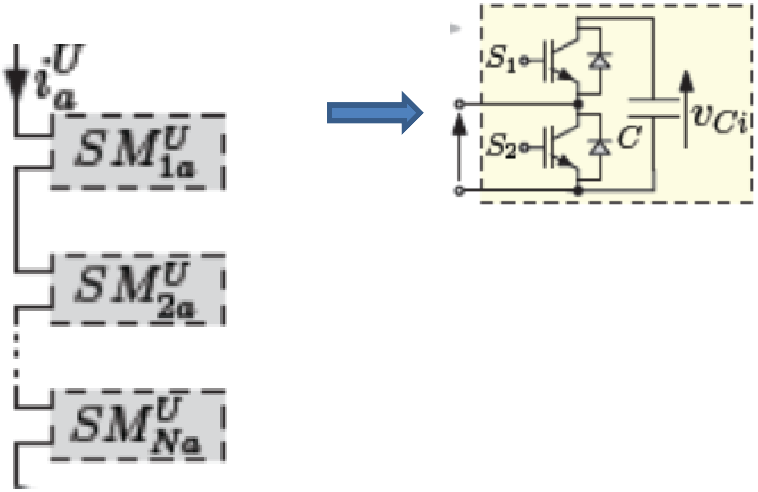
Convertisseur AC/DC de forte puissance : le MMC



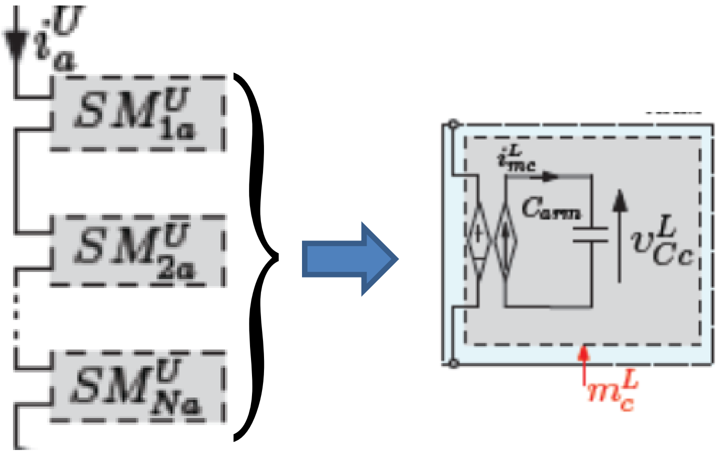
Sur un convertisseur de forte puissance
Plus de 2500 sous-modules (SM)

Comment étudier une structure aussi complexe ?
Quelle commande ?

Convertisseur AC/DC de forte puissance : le MMC



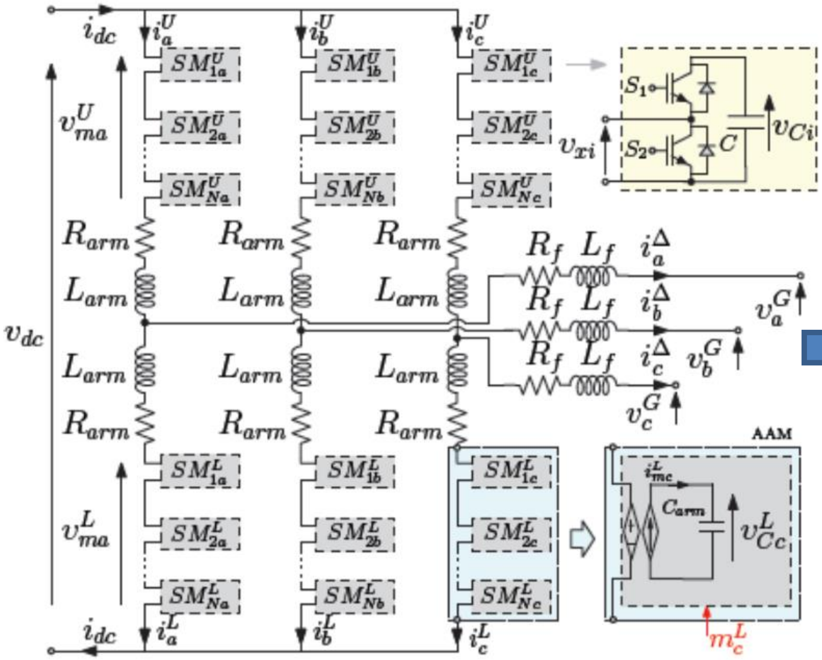
Objectif : pilotage des différents sous module d’un bras :
Nécessité d’avoir un modèle assez détaillé

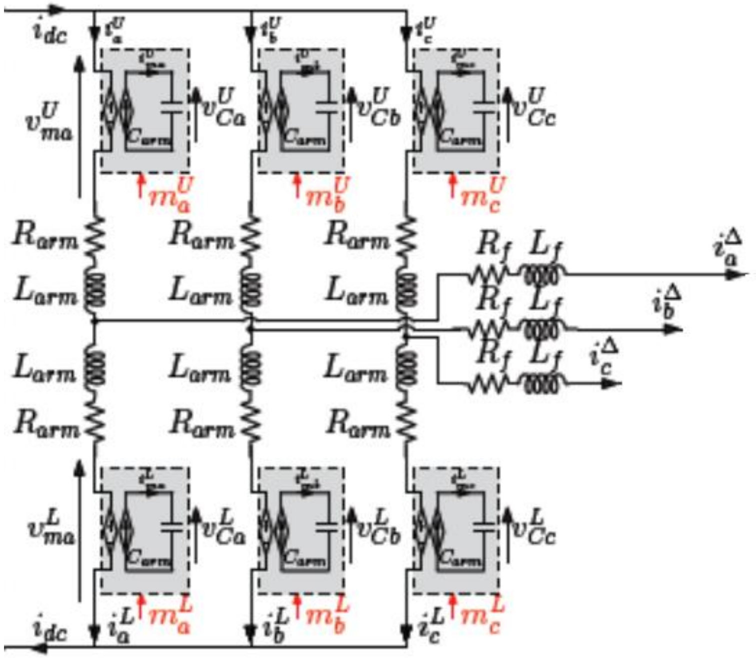


Objectif : commande de l’ensemble du convertisseur
Possibilité d’avoir un modèle simplifié :

L’ensemble d’un bras est modélisé par un condensateur équivalent + un modulateur

Convertisseur AC/DC de forte puissance : le MMC





Simulation complexe et lourde
Possibilité d’étudier les questions d’équilibrage de sous-modules

Simulation beaucoup plus rapide
Pas de possibilité d’étudier l’équilibrage de sous-modules

Convertisseur AC/DC de forte puissance : le MMC

Principaux résultats :

- Proposition d’un modèle simplifié pour l’étude de la commande « haut niveau » d’un convertisseur MMC
- Démarche de formalisation de la commande
- Etude de différents niveaux de modélisation en vue d’une intégration dans des simulations de grands réseaux
- Gestion de l’énergie dans le convertisseur MMC
- Développement d’une maquette expérimentale (5 kW - 400 V , 120 modules)

Convertisseur AC/DC de forte puissance : le MMC

Principaux travaux sur le MMC :

Thèse H. Saad : « Modélisation et commande d'une liaison HVDC de type VSC-MMC
2011 – 2015 Ecole Polytechnique de Montréal -

Thèse de S. Samimi : « Modélisation et Commande des Convertisseurs MMC en vue de leur Intégration dans le Réseau Electrique »
2012 – 2016 Université de Lille 1

Thèse de K. Shinoda 2014 – 2017
Supergrid

Thèse de J. Freytes 2014 – 2017
Best path – RTE
Collaboration avec NTNU – Trondheim

Projet DO-MMC : développement de la maquette MMC

Convertisseur AC/DC de forte puissance : perspectives

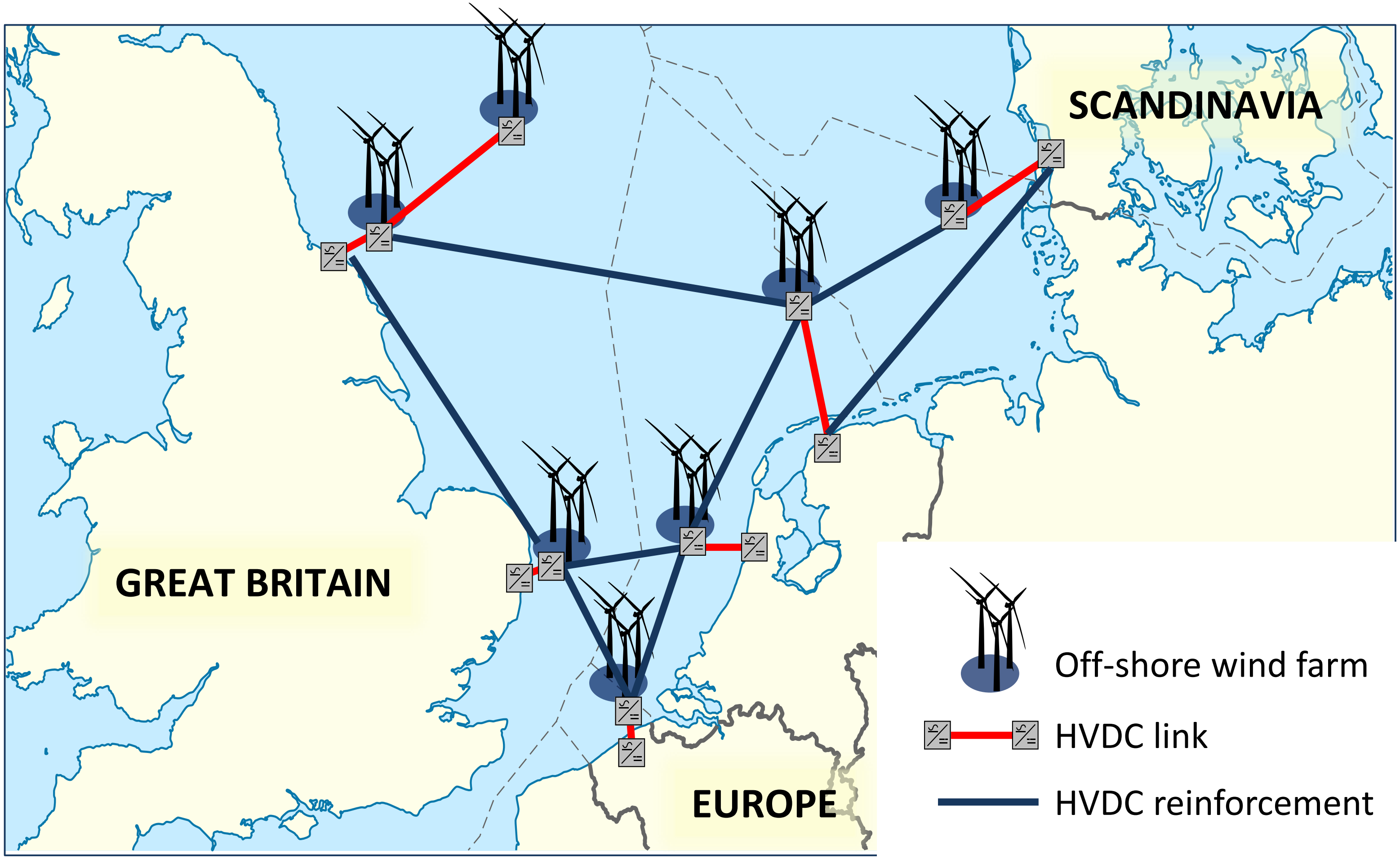
De nombreuses perspectives :

Approfondissement des lois de commande en situation dégradée, court-circuit AC, DC …

Etudes d’autres structures en émergence

Contexte – Pourquoi des réseaux MTDC ?

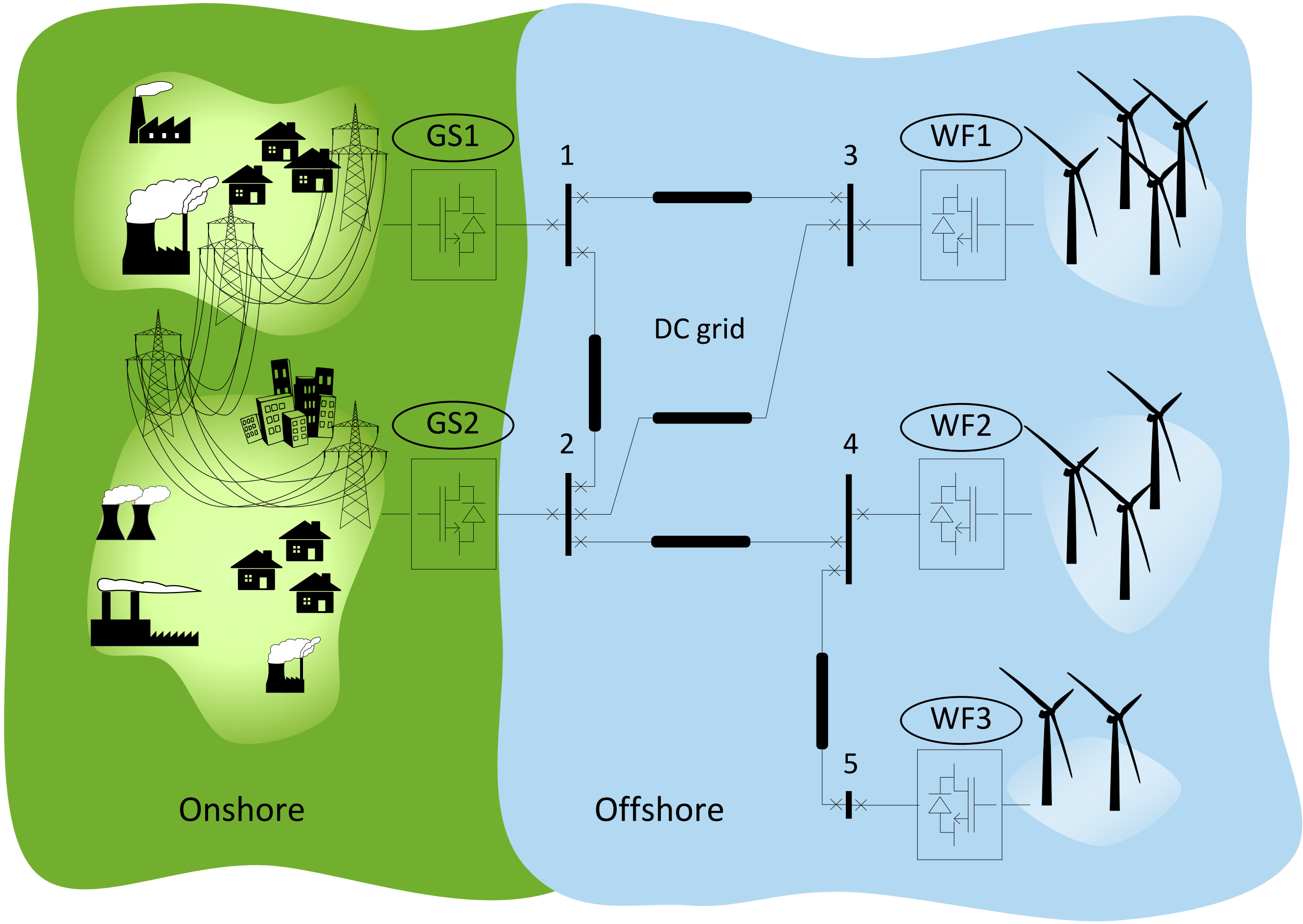
Développement de fermes éoliennes offshore
Possibilité d’augmenter les échanges entre des zones asynchrones



Réseau courant continu multi terminaux

Comment gérer les flux de puissance dans un réseau MTDC ?

Condition de stabilité pour ce type de réseau ?



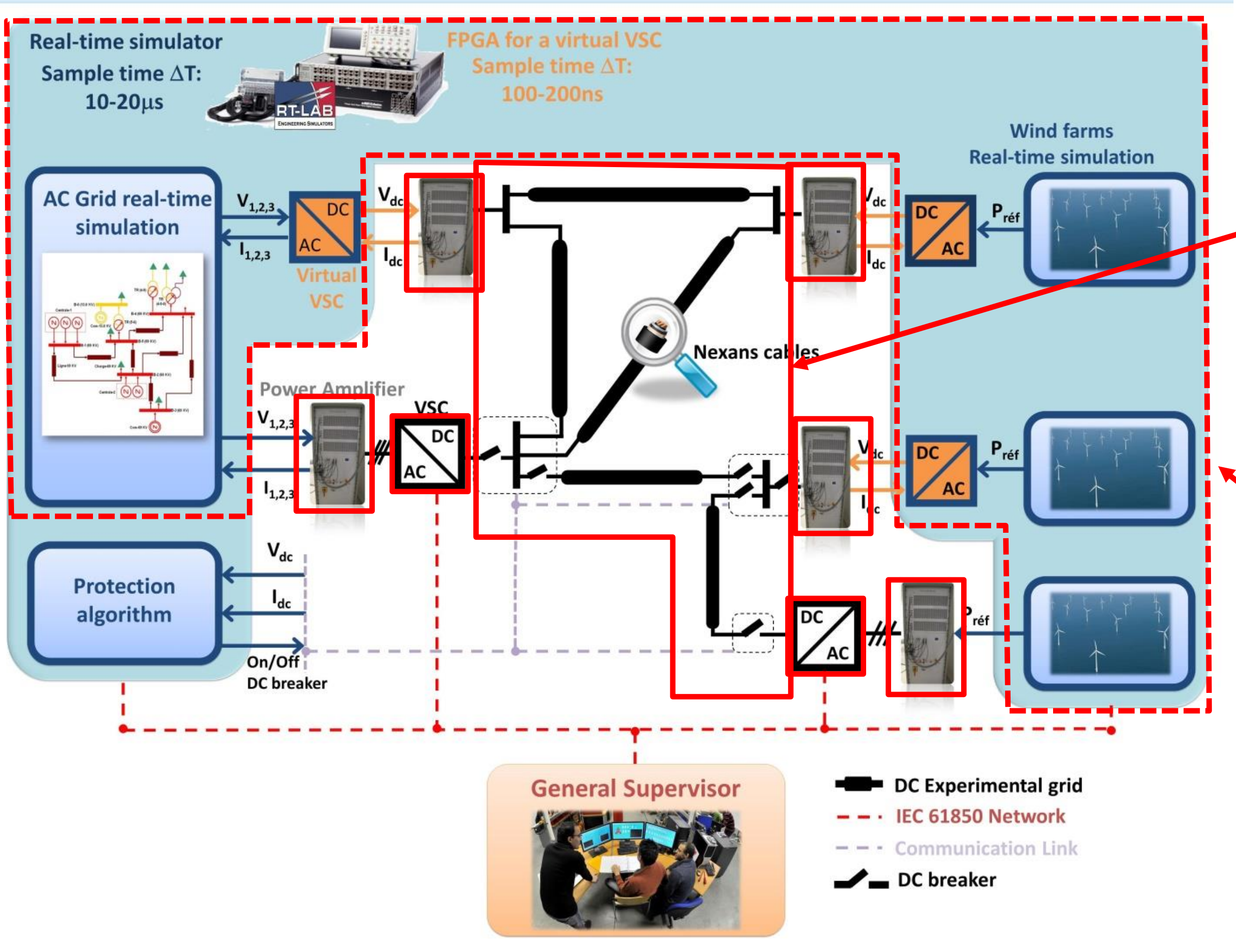
Réseau courant continu multi terminaux

Principaux travaux sur les MTDC:

Thèse P. Rault : Modélisation dynamique et la commande des réseaux courant continu multiterminaux. 2010 – 2014 – Financement Rte

Projet Twenties : Développement d’un réseau courant continu multi terminal

Réseau courant continu multi terminaux



Le réseau courant continu est composé de 15 km de cables

2 convertisseurs AC/DC

Simulation temps réel des fermes éoliennes et du réseau AC

5 points de connexion (ampli de puissance) entre les systèmes réels et la simulation temps réel

Réseau courant continu multi terminaux

Thèse de J. Freytes 2014 – 2017

Projet européen Bestpath
Travail sur l'interopérabilité entre les principaux constructeurs de matériel d'électronique de puissance présents en Europe (ABB, Siemens, General Electric)

Approfondissement des modèles MMC pour l'étude de la stabilité des réseaux courant continu multiterminaux

Thèse de K. Shinoda 2014 – 2017
Dans le cadre de Supergrid

Limites opérationnelles des réseaux courant continu et proposition d'une nouvelle manière de gérer l'énergie dans les convertisseurs MMC pour améliorer la stabilité des réseaux MTDC

Réseau courant continu multi terminaux

Thèse de S. Akkary 2013 – 2016

Etude de stabilité d’un réseau courant continu
Développement d’un outil pour l’analyse de stabilité des réseaux MTDC

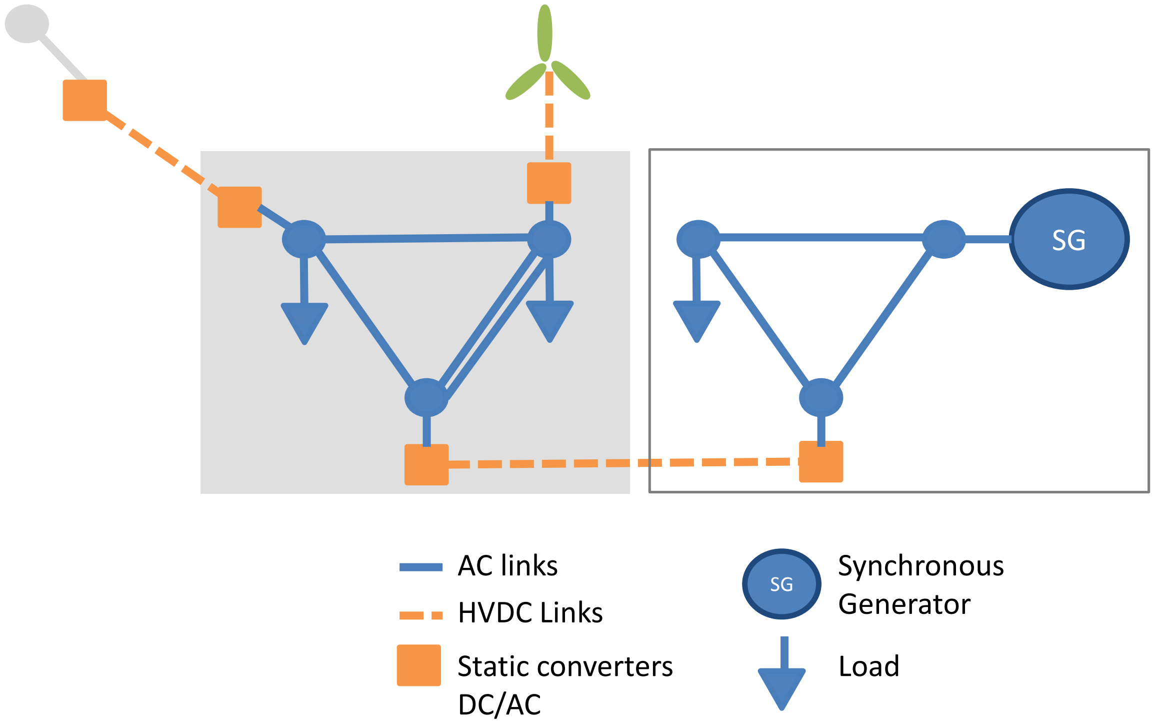
Réglage de la fréquence d’un réseau AC à l’aide d’un réseau MTDC
Test sur la plateforme courant continu

Ce travail a été poursuivi par une collaboration avec l’université de Liège (thèse L. Papangelis - RTE) qui a développée une commande plus avancée.
Prochains test sur la plateforme courant continu

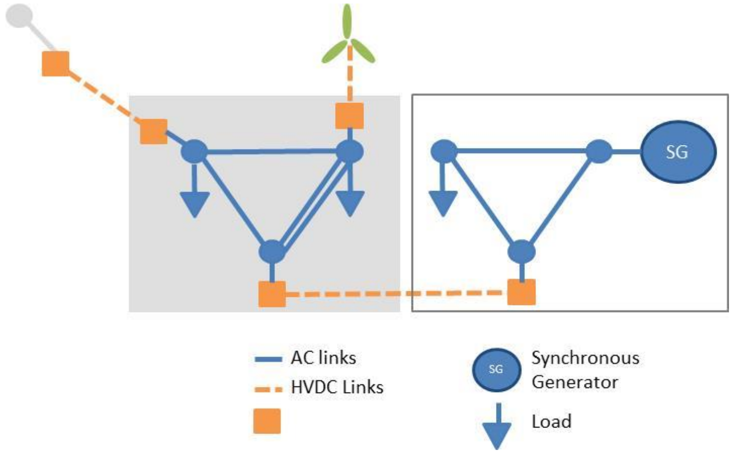
Réseau AC sans machine synchrone

Nouveaux type de réseaux transport AC alimentés uniquement par de l'électronique de puissance

Centrale classique raccordée au réseau par l'intermédiaire de machines synchrones



Réseau AC sans machine synchrone



Thèse de G. Denis –2014 – 2017

Etude des nouvelles problématiques posées par ces réseaux AC uniquement avec des machines synchrones

Contrôle commande de convertisseur dits « grid forming » (création de l'onde de tension)

Réseau AC sans machine synchrone

Projet européen Migrate 2016 - 2020

Thèse de T. Qoria 2017 - 2020

Approfondissement de la thèse de G. Denis
Applications des lois de commande « grid forming » au MMC
Test expérimentaux sur maquette hybride : convertisseur réel + simulation temps réel

Thèse Q. Cossard 2016 - 2019

Réduction de modèle pour intégration dans des études grands réseaux
Application sur le réseau irlandais

Conclusion

- Des champs d’investigation complètement nouveaux pour les réseaux de transport
- Des méthodologies d’analyse dynamique à repenser complètement tant les modèles des convertisseurs d’électronique de puissance sont différents des modèles de machine synchrone
- Des méthodes pour continuer d’avoir une approche expérimentale pour ce type de système.
- Un contrat cadre de 5 ans signé en début d’année 2017 entre le L2EP et RTE pour continuer ces travaux

Merci pour votre attention

L2EP
Laboratoire d'électrotechnique et
d'électronique de puissance de Lille