Stability Assessment on HVDC Application

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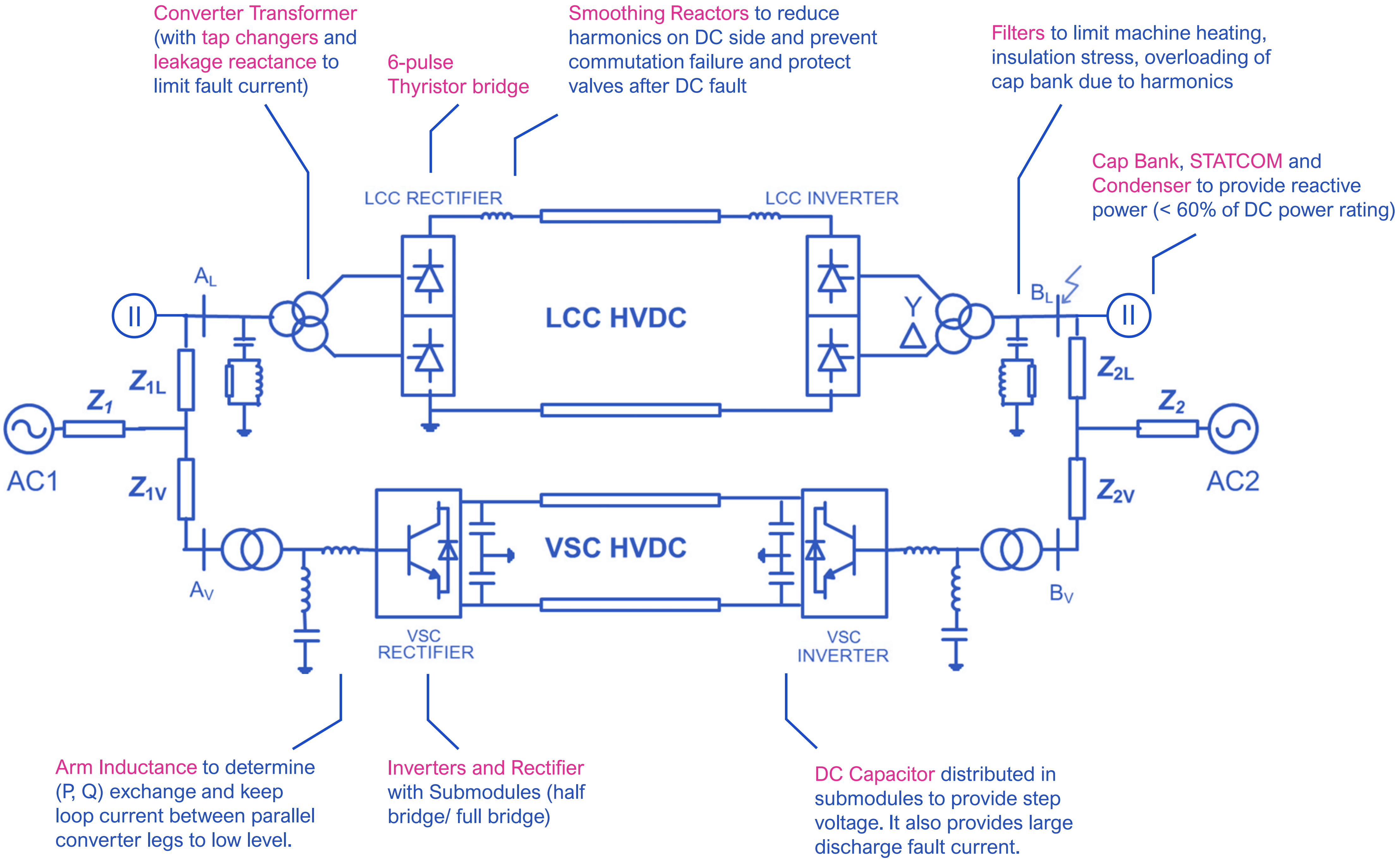

Converter Transformer (with tap changers and leakage reactance to limit fault current)
6-pulse Thyristor bridge
Smoothing Reactors to reduce harmonics on DC side and prevent commutation failure and protect valves after DC fault
Filters to limit machine heating, insulation stress, overloading of cap bank due to harmonics
Cap Bank, STATCOM and Condenser to provide reactive power (< 60% of DC power rating)
LCC RECTIFIER
LCC INVERTER
LCC HVDC
A_L
B_L
Y
Δ
Z_1L
Z_1
Z_2L
Z_2
AC1
AC2
Z_1V
Z_2V
VSC HVDC
A_V
B_V
VSC RECTIFIER
VSC INVERTER
Arm Inductance to determine (P, Q) exchange and keep loop current between parallel converter legs to low level.
Inverters and Rectifier with Submodules (half bridge/ full bridge)
DC Capacitor distributed in submodules to provide step voltage. It also provides large discharge fault current.

Comparison between HVDC and HVAC

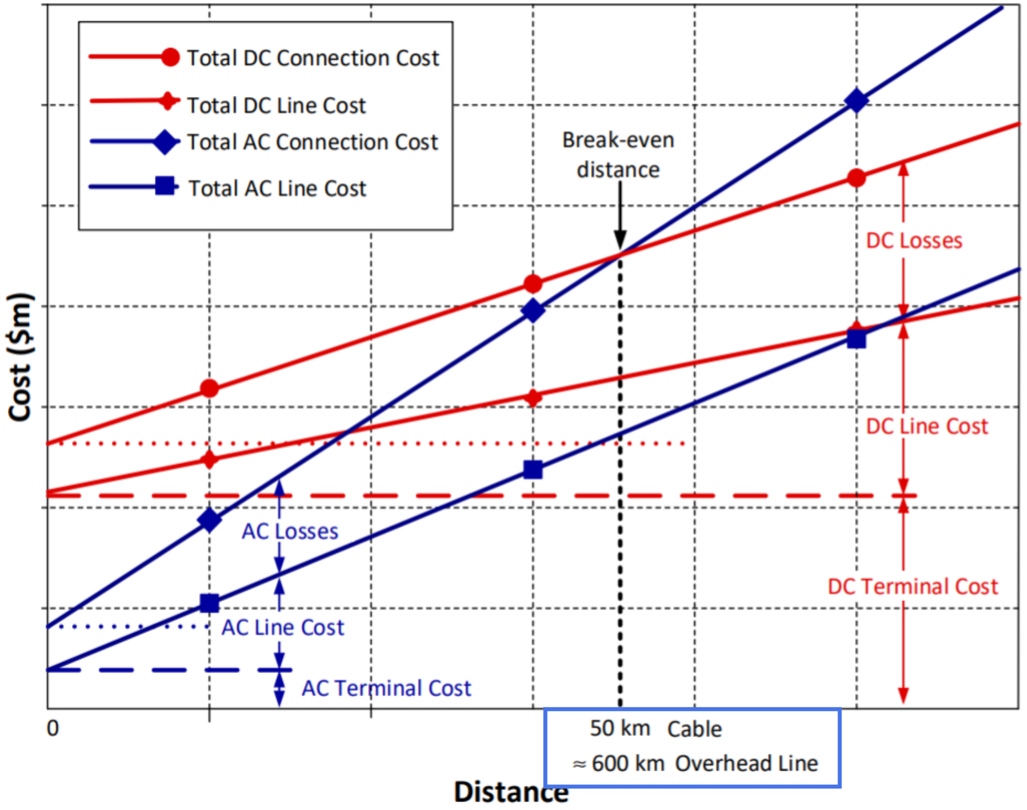
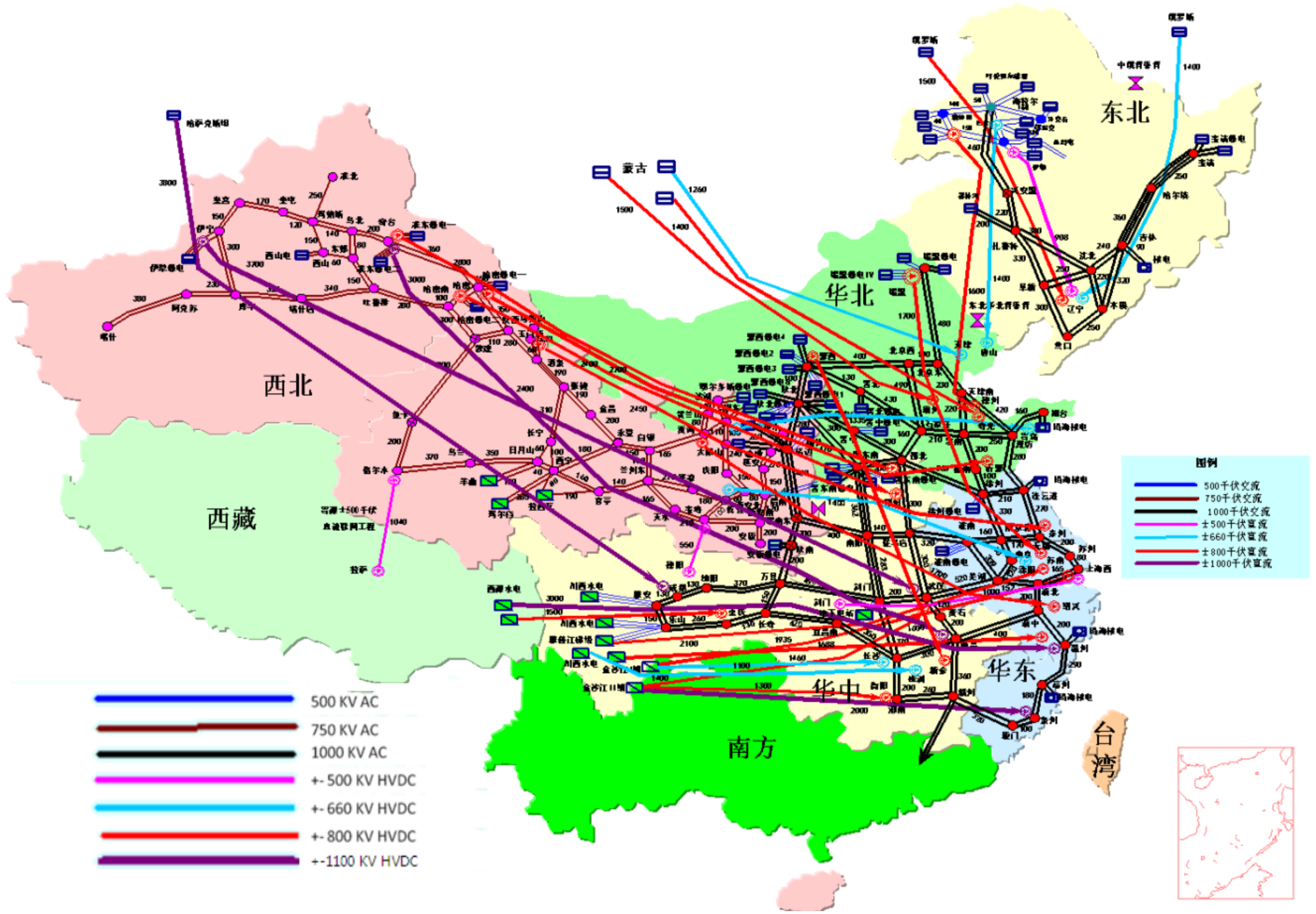


Table 1. Comparison between HVAC, CSC – HVDC and VSC – HVDC

	HVAC	CSC-HVDC	VSC-HVDC
Capacity distance dependent?	✓	×	×
Power losses	Distance dependent	2-4%	5-10%
Black – start capability	✓	×	✓
Voltage level transform	✓	×	×
AC system support	Limited	Limited	Large range
Fault limitation	×	✓	✓
Short-circuit level limitation	×	✓	✓
Evolution in components	Not expected to decrease	Cost of semiconductors tends to decrease with time	Cost of semiconductors tends to decrease with time
Visual impact	Greater as dimensions are larger	HVDC sub-systems require smaller space	HVDC sub-systems require smaller space
Protection systems	More advanced	Limited	Limited
Control strategies	Acceptable under normal operating conditions	Fast control	Fast control both under normal and fault conditions
Corona phenomena	Annual mean Corona losses are much lower in HVDC systems.		
Radio interference	As Corona phenomenon is limited, the radio interference is also limited in DC lines.		
Audible noise	During rainy condition DC lines appear to have lower noise levels than AC lines.		

Statistics – HVDC in China



No.	Commercial operation	Project name	Voltage (kV)	Capacity (MW)
1	1987	Zhoushan	-100	50
2	1990	Gezhouba-Nanqiao	±500	1200
3	2001	Tianshengqiao-Guangzhou	±500	1800
4	2002	Shengsi	±50	60
5	2003	Three Gorges-Changzhou	±500	3000
6	2004	Guizhou-Guangdong I	±500	3000
7	2004	Three Gorges-Guangdong	±500	3000
8	2005	Lingbao Back-to-Back I	120	360
9	2006	Three Gorges-Shanghai I	±500	3000
10	2007	Guizhou-Guangdong II	±500	3000
11	2008	Gaoling Back-to-Back I	±125	2x750
12	2009	Lingbao Back-to-Back II	166.7	750
13	2010	Deyang-Baoji	±500	3000
14	2010	Hulunbuir-Liaoning	±500	3000
15	2010	Xiangjiaba-Shanghai	±800	6400
16	2010	Yunnan-Guangdong	±800	5000
17	2011	Ningdong-Shandong	±660	4000
18	2011	Three Gorges-Shanghai II	±500	3000
19	2011	Nanhui wind farm integration	±30	18
20	2012	Sino-Russia Back-to-Back	±125	750
21	2012	Qinghai-Tibet (Above 10K ft)	±400	600
22	2012	Jinping-Sunan	±800	7200
23	2012	Gaoling Back-to-Back II	±125	2x750

No.	Commercial operation	Project name	Voltage (kV)	Capacity (MW)	
1	2015	Northern Hami-Chongqing	±800	8000	
2	2015	Ningdong-Zhejiang	±800	8000	
3	2015	Ximeng-Jiangsu (Taizhou)	±800	8000	
4	2015	Gansu(Jiuquan)-Hunan	±800	8000	
5	2015	Mengxi-Hubei	±800	8000	
6	**2015**	**Zhundong-Sichuan**	**±1100**	**10000**	
7	2015	Humeng-Shandong	±800	8000	
8	2014	Xiamen island in-feed	±320	1000	HBSM
9	2014	Zhoushan multi-terminal (5)	±200	1000	HBSM
10	2014	Xiluodu-Zhejiang	±800	8000	
11	2014	Southern Hami-Zhengzhou	±800	8000	
12	2013	Nan'ao multi-terminal (3)	±160	200	HBSM
13	2013	Nuozhadu-Guangdong	±800	5000	
14	2013	Xiluodu-Guangdong	±500	6400	
15	—	Dalian city in-feed	±320	1000	HBSM
		Yunnan (Luoping)			HBSM
	2020	Wudongde			Hybrid

Statistics – HVDC Worldwide

TABLE I. POTENTIAL INTERCONNECTIONS GIVEN THE CURRENT HVDC INSTALLATIONS

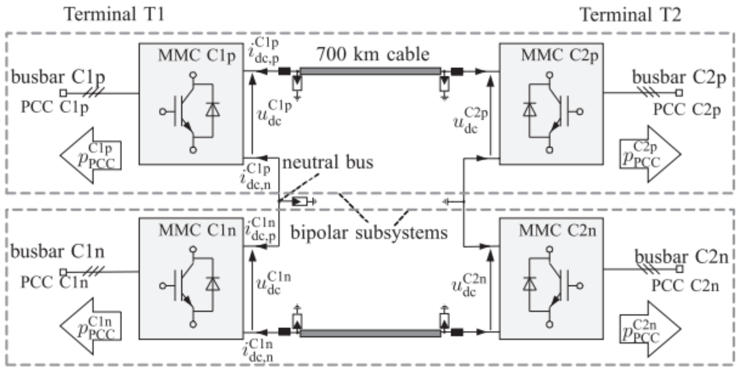
Potential interconnection	*Link 1*	*Link 2*	*Voltage ratio*	*Technology*	*Topology (grounding)*	*Countries / TSO*	*Comments*
1	Baltic Cable 450kV - 600MW (Sweden - Germany)	Kontek 400kV - 600MW (Germany - Denmark)	1.13	LCC - LCC	Asymmetric monopole (both lines)	3	Crossing point available
2	SwePol 450kV - 600MW (Sweden - Poland)	NordBalt 300kV - 700MW (Sweden - Lithuania)	1.5	LCC-VSC	Asymmetric monopole - Bipole	3	No crossing point.

TABLE II. POTENTIAL INTERCONNECTIONS INCLUDING FUTURE HVDC PROJECTS

Potential interconnection	*Link 1*	*Link 2*	*Voltage ratio*	*Technology*	*Topology (grounding)*	*Countries / TSO*	*Comments*
3	COBRA Cable ±320kV - 700MW (Netherlands – Denmark)	NordLink 525kV - 1400MW (Germany – Norway)	1.64	VSC - VSC	Symmetric monopole – Rigid Bipole	4	Crossing point available
4	NordLink 525kV - 1400MW (Germany – Norway)	Viking link 400-500kV - 1000-1400MW (Denmark - UK)	1.31 -1.05	VSC - VSC	Rigid Bipole – Bipole	4	Crossing point available
5	Viking link 400-500kV - 1000-1400MW (Denmark – UK)	NorNed 450kV - 700MW (Norway – Netherlands)	1.11 - 1.13	VSC - LCC	Bipole – Symmetric monopole	4	Crossing point available
6	Nemo Link 400kV - 1000MW (Belgium - UK)	BritNed 450kV - 1000MW (UK - Netherlands)	1.13	VSC - LCC	Symmetric monopole - Bipole	3	No crossing point
7	SuedLink 2000 MW (Germany)	SuedOstLink ⩾ 2000 MW (Germany)	Unknown	Unknown	Unknown	3	No crossing point.
8	Ultranet 380 kV 2000 MW (Germany)	SuedLink 2000 MW (Germany)	Unknown	VSC - Unknown	Unknown	2	No crossing point.
9	Viking – NordLink - NorNed (UK- Denmark – Germany -Norway – Netherlands)		1.05 - 1.31	VSC - LCC -VSC	Bipole – Rigid Bipole – Symmetric monopole	5	Two crossing points available for 2 dc-dc converters

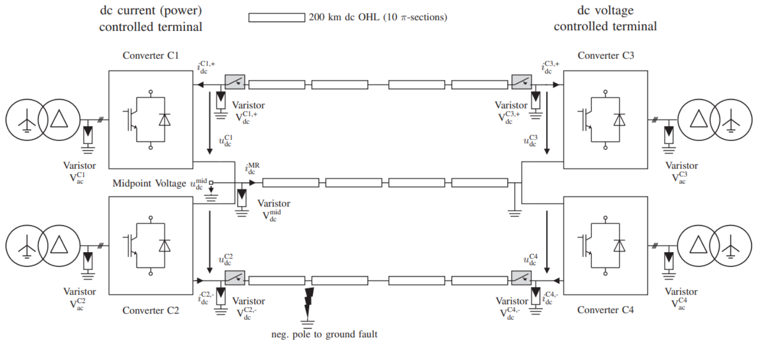
Rigid Bipolar

- Reconfiguration Capability (vs Monopolar)
- High Transmission Capacity & Converter Redundancy to Asymmetric Monopole (vs Monopolar)
- Reduced Cable Cost (vs Bipolar with metallic return)



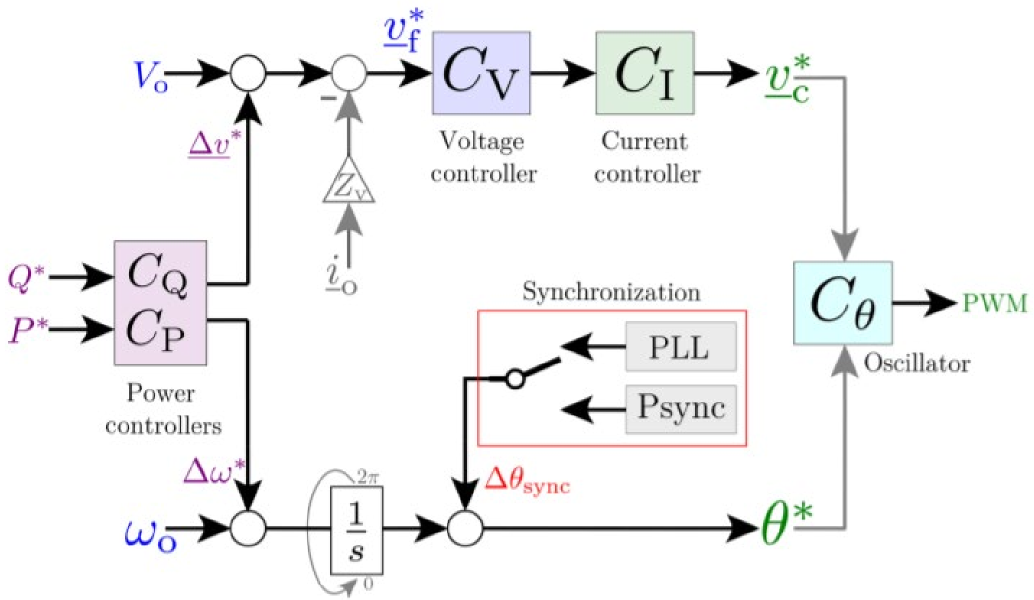
Bipolar (with Metallic Return)

- Reduced Insulation Requirement
- No corrosion in Surrounding Material
- Reduced Touch Voltage During Fault
- Limited Voltage and Current Rating in Returning Path



Functionality of HVDC

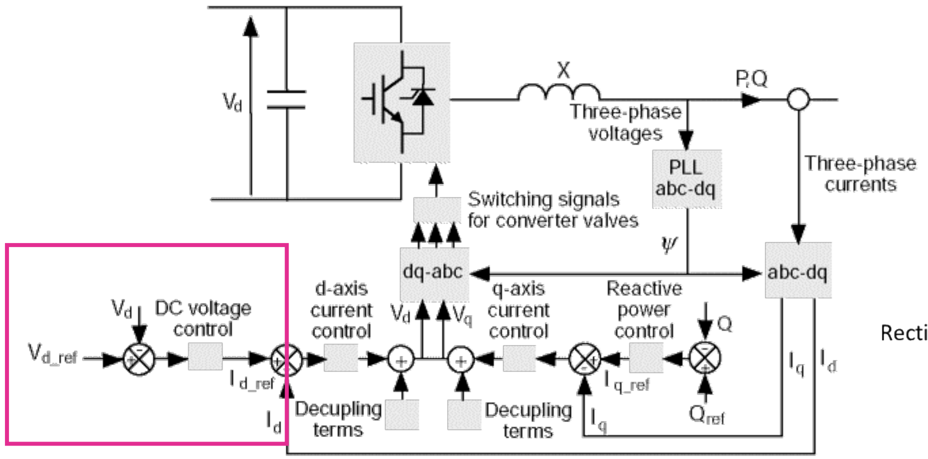
Black Start Capability



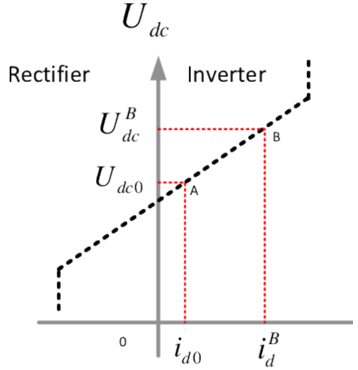
Able to energize a bus to sustain frequency and voltage transient (e.g. ramps, step load, **synchronization**) and to provide P – Q control capability.

HVDC Converter should also be capable of resynchronize small islands (mode: islanded operation → resynchronization) with fast change in power flow.

Voltage Control Capability



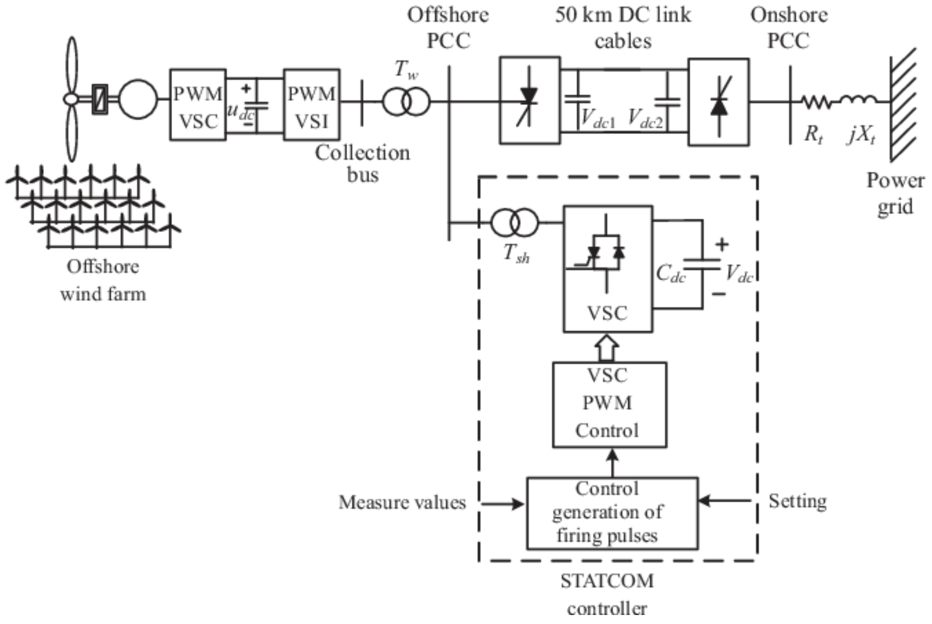
Fast in step response



Once the HVDC is energized at receiving end, it must be possible to ramp up voltage from a low value (0 Un) to 0.9 Un within 3 – 5 sec to avoid Ferroresonance. This can either provide a **power plant with auxiliary power** or a **transmission corridor with large power transformer**. The HVDC must be able to make successive attempt to ramp up voltage in case of failure.

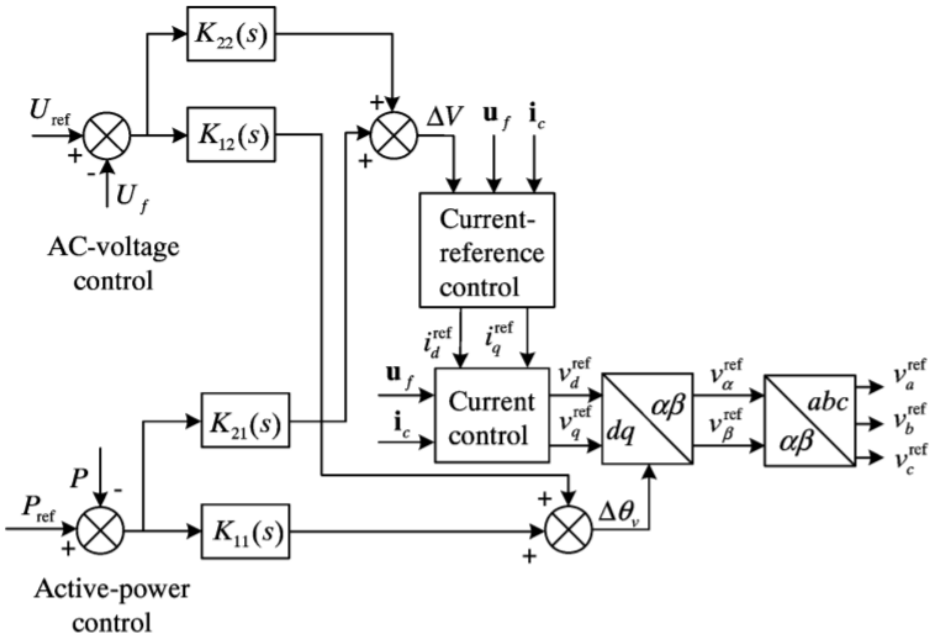
Functionality of HVDC

HVDC as STATCOM



Able to act as STATCOM in restoration process. Only VSC technology can provide **reactive power capability** that allows both reactive power and voltage control of the restoration path. It is used as top-down strategy to **stabilize the voltage profile** on AC corridors. Yet, HVDC requires complete discharge of power modules when changing state (to STATCOM operation, with 5 – 90 min)

Synchronization



Due to **increase in distribution generation** and **system decoupling**, more island may form, and can survive after a blackout. The islands must be re-synchronized.

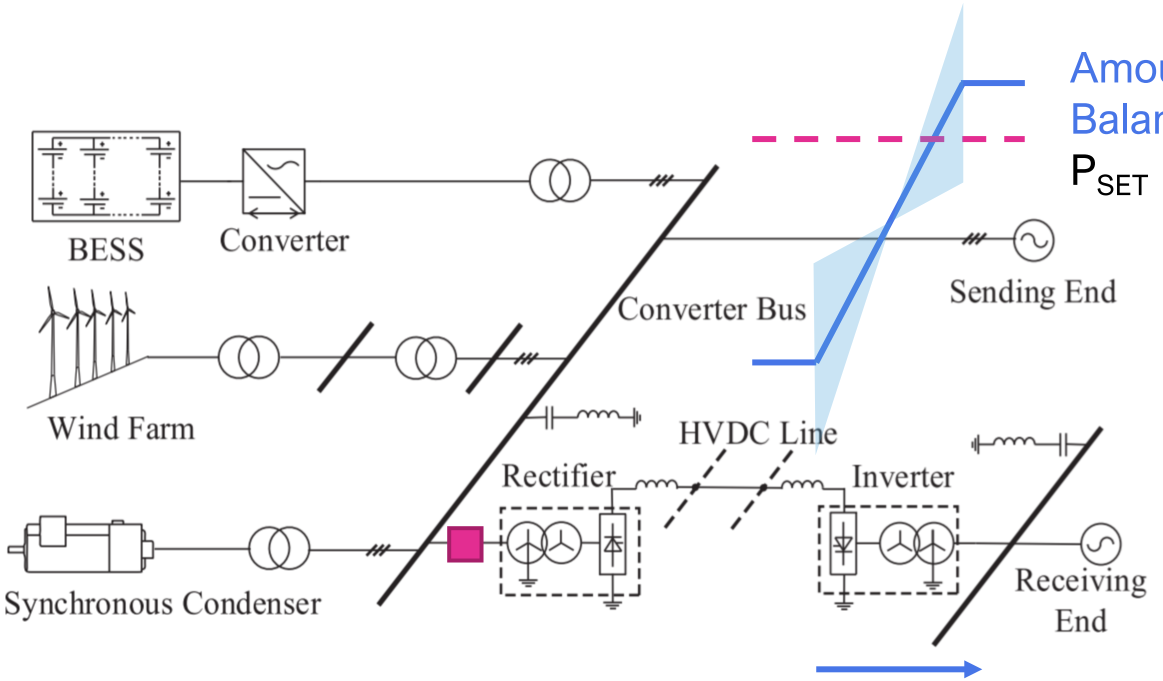
It is noted that synchronization can be one source of instability (e.g. coupled sequence synchronization during asymmetric fault) and inter-area oscillation with low damping ratio and resonance.

Functionality of HVDC

Frequency Control

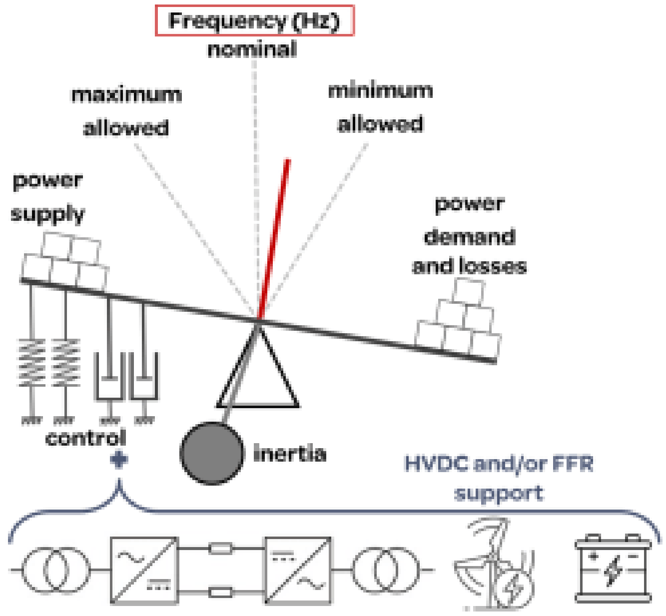
Max. Ramp Rate of Active Power Change (Start & Stop)
dP/dt_{MAX}, dP/dt_{MIN}

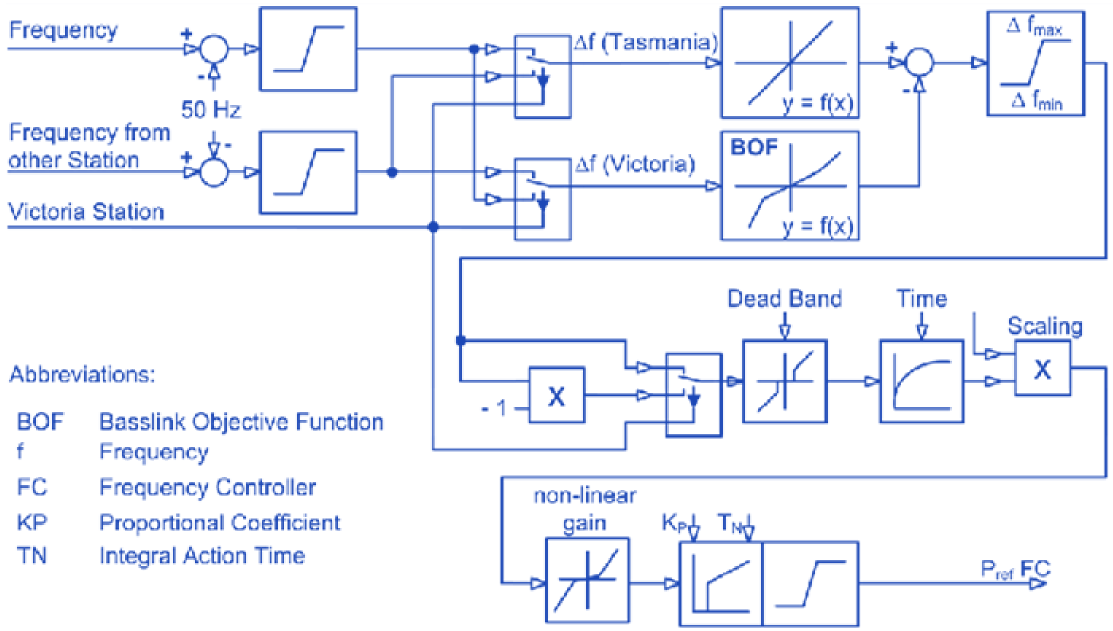
Amount of Balancing Power
P_{SET}



Trigger for (De) Activating Balancing Power Support

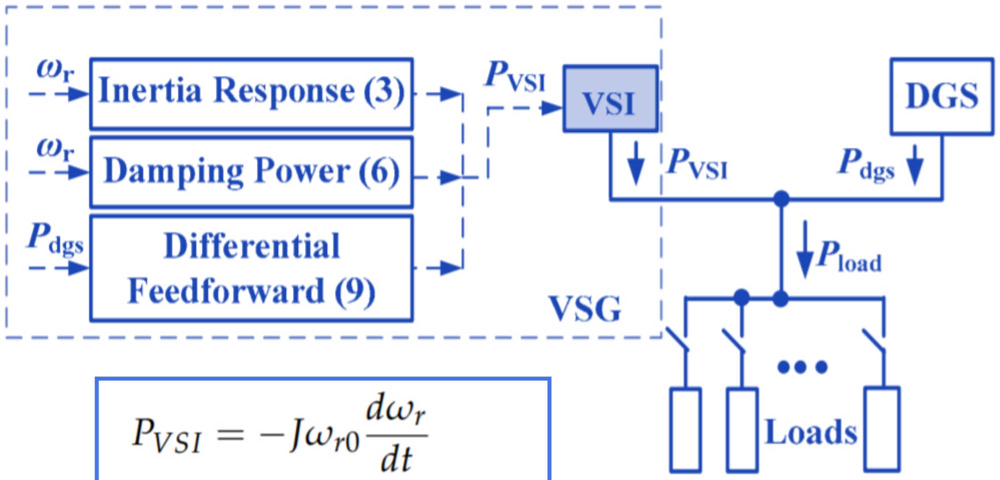
Max. Balancing Power (for each direction)
P_{MAX_IN}, P_{MAX_OUT}



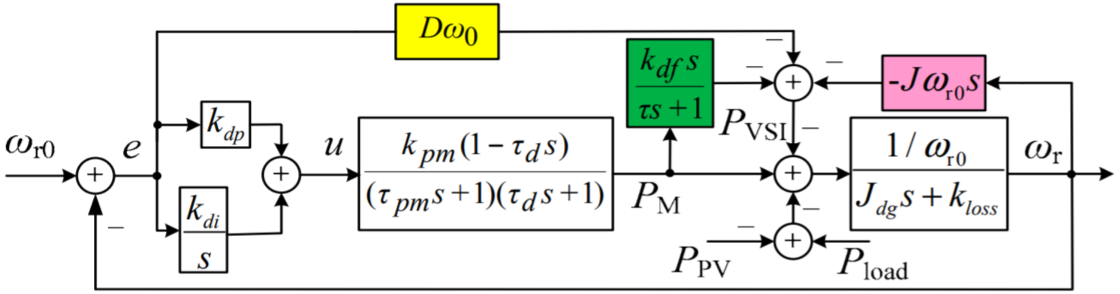


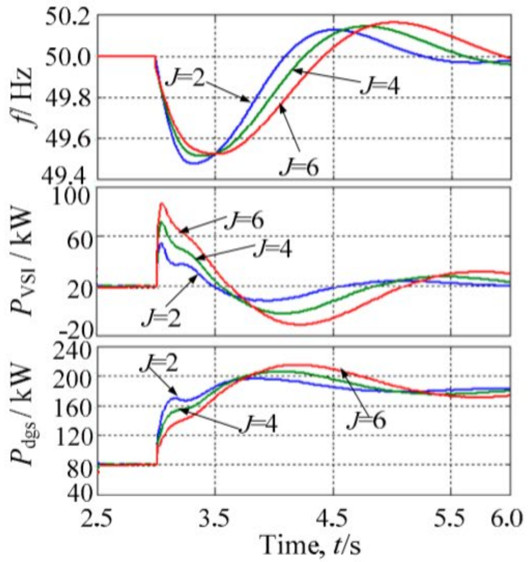
Functionality of HVDC

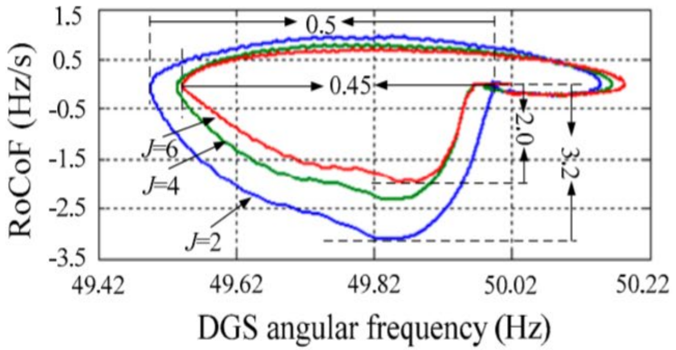
Frequency Control

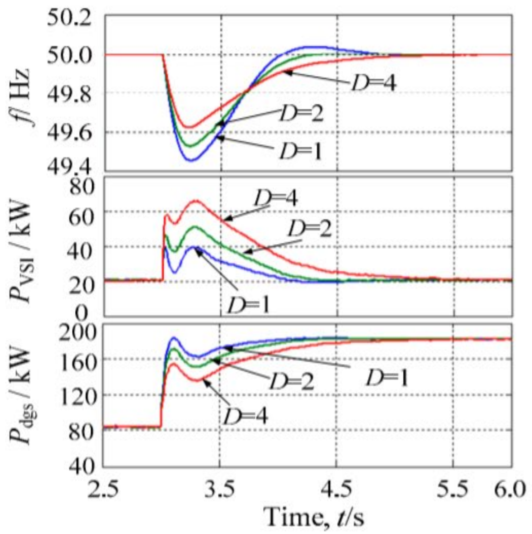


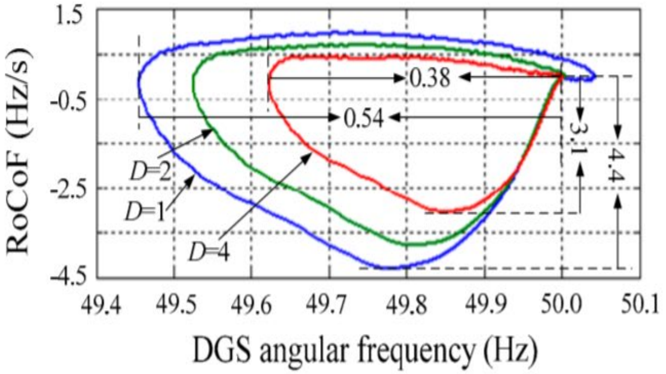
$$P_{VSI} = -J\omega_{r0}\frac{d\omega_r}{dt}$$
$$P_{VSI} = D\omega_0(\omega_{r0} - \omega_r)$$
$$P_{VSI} = \frac{k_{df}s}{\tau s + 1}P_{dgs}$$











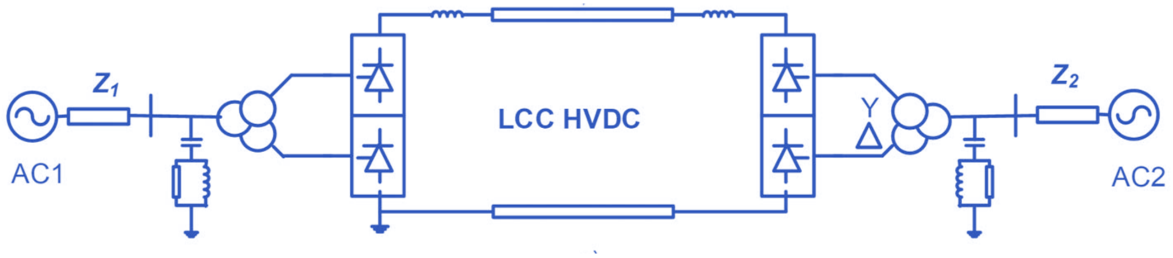
Technical Challenges on HVDC

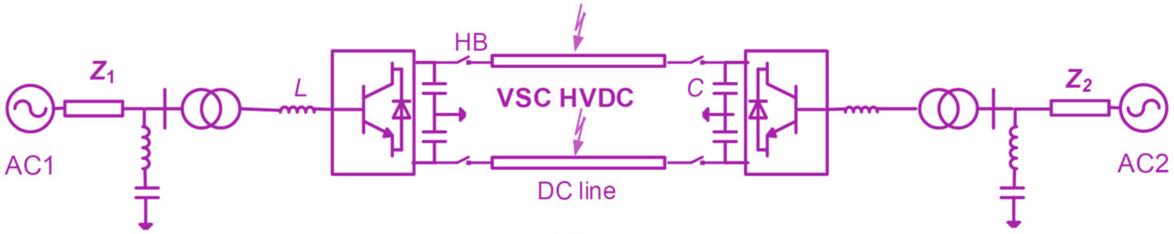
Technical
- Power Reversal
- HVDC Circuit Breaker
- Commutation Failure
- Communication Failure
- Voltage Control Strategies
- Protection Coordination
- Hybrid Grid Code
- Overvoltage

Protection
- Fast HVDC Protection
- Short Circuit Current
- No Zero Crossing
- HVDC Converter Fault Bearing Capacity
- DC Fault from HVAC System

Modelling
- Reliability and Accuracy
- Real Time Simulation
- Unbalanced Condition
- Connection with External Equipment
- Stability Evaluation

Technical Challenges towards LCC – HVDC and VSC – HVDC





Traditionally HVDC grid were realized as LCC as a current source converter (CSC), but was practically infeasible with the following reason.

LCC

- Difficult current reversal
- Dependent on HVAC system strength for whole system recovery
- Need for DC and AC Filters with harmonics
- Prone to Commutation Failure
- Only works when inverter is in active state

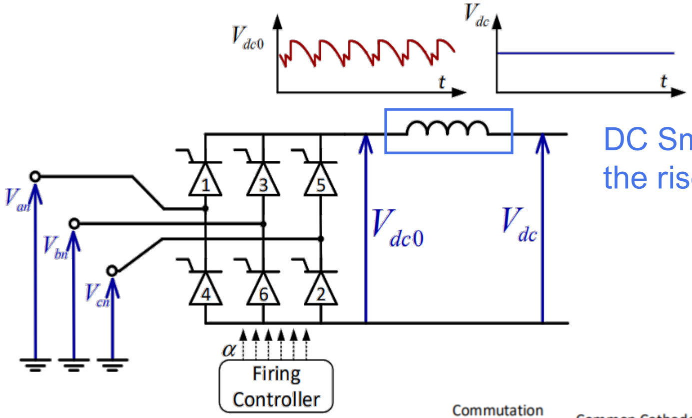
With the advent of IGBTs, VSC for HVDC system was introduced to overcome drawbacks for LCC. Yet, there are new technical challenge.

VSC

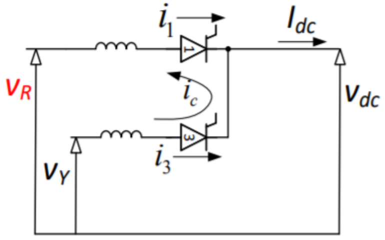
- Protection Coordination
- Fast Fault Removal with Fault Location
- Sophisticated DC Voltage Control & Power Flow
- Functions during Communication Failure
- Load Supply after Isolating a Section of HVDC grid

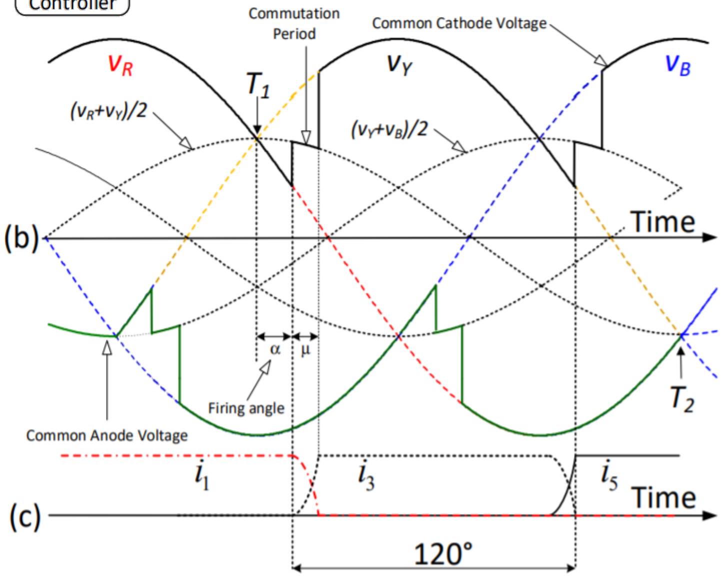
Comparison between LCC – HVDC and VSC – HVDC

LCC – HVDC

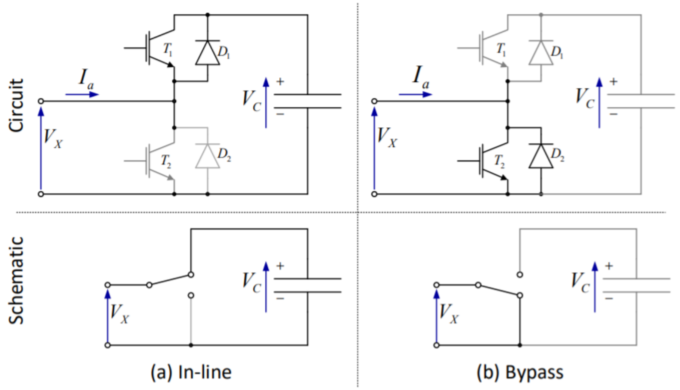


DC Smoothing Reactor limits the rise of fault current



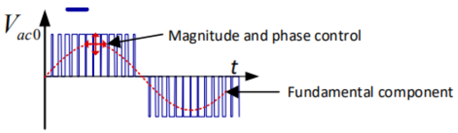


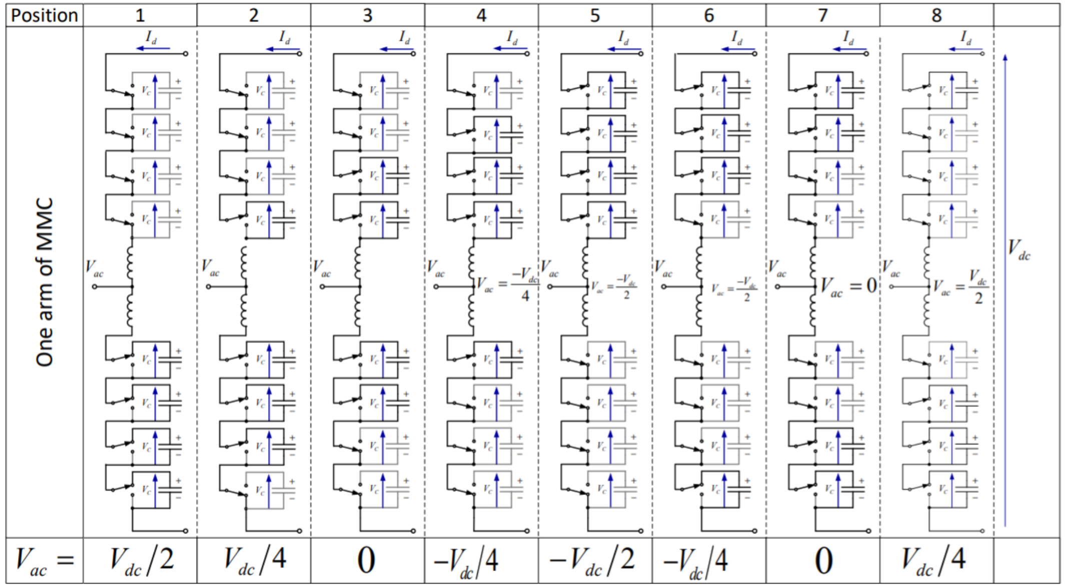
VSC – HVDC



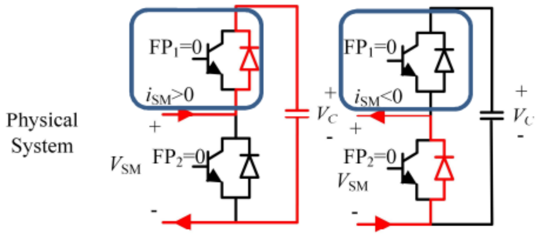
Capacitor discharges rapidly

No commutation failure, but incapable of limit overvoltage and current

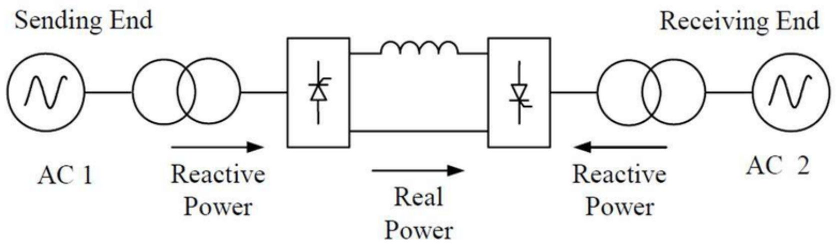




Power Flow in LCC – HVDC and VSC - HVDC



LCC – HVDC

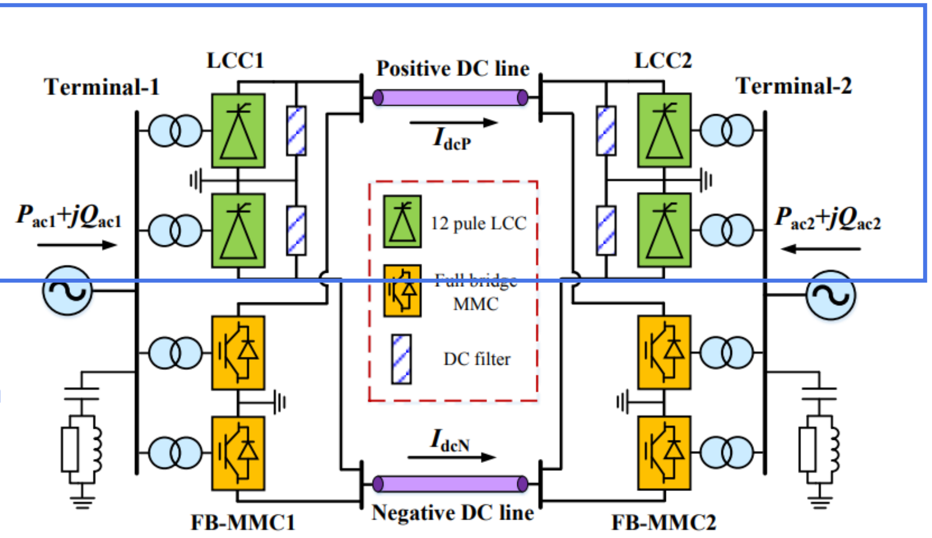


$$P_{\mathrm{LCC}} = (V_{\mathrm{dc}0} \cos\alpha - d_x I_{\mathrm{dcLCC}}) I_{\mathrm{dcLCC}}$$

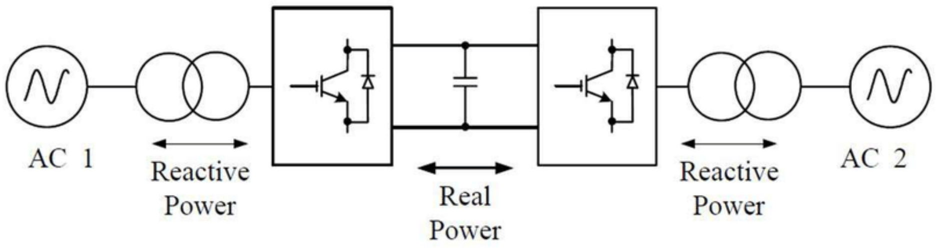
$$Q_{\mathrm{LCC}} = V_{\mathrm{dc}0} I_{\mathrm{dcLCC}} \sqrt{1 - \left(\cos\alpha - \frac{d_x I_{\mathrm{dcLCC}}}{V_{\mathrm{dc}0}}\right)^2}$$

Require large reactive power

VSC – HVDC can transmit Q for LCC – HVDC

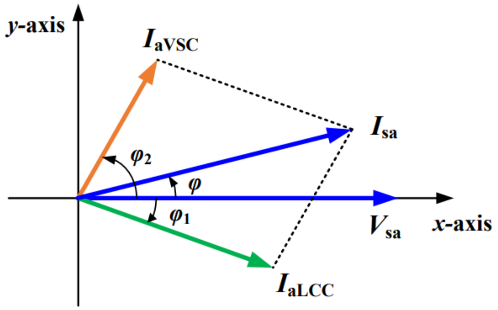


VSC – HVDC



$$P_{\mathrm{VSC}} = 1.5 u_{\mathrm{sd}} i_{\mathrm{vd}}$$
$$Q_{\mathrm{VSC}} = -1.5 u_{\mathrm{sd}} i_{\mathrm{vq}}$$

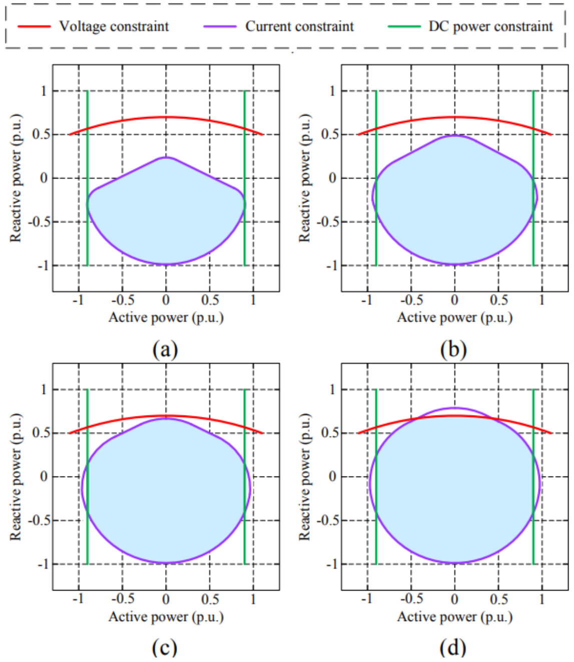
Given that d-axis is aligned with AC voltage, so u_{sd} = AC voltage and $u_{sq} = 0$



$$P^2 + Q^2 = \left(\frac{3}{2} V_{\mathrm{sa}} I_{\mathrm{sa}}\right)^2$$
$$= (P_{\mathrm{VSC}} + P_{\mathrm{LCC}})^2 + (Q_{\mathrm{VSC}} - Q_{\mathrm{LCC}})^2$$

$$k = \frac{S_{\mathrm{VSC}}}{S_{\mathrm{LCC}}}$$

↑ k



Commutation Failure in Multi-Terminal LCC – HVDC System

Commutation Failure is failure of current transfer from one valve to next due to the reduction in commutation voltage of converter after any significant fault or disturbance.

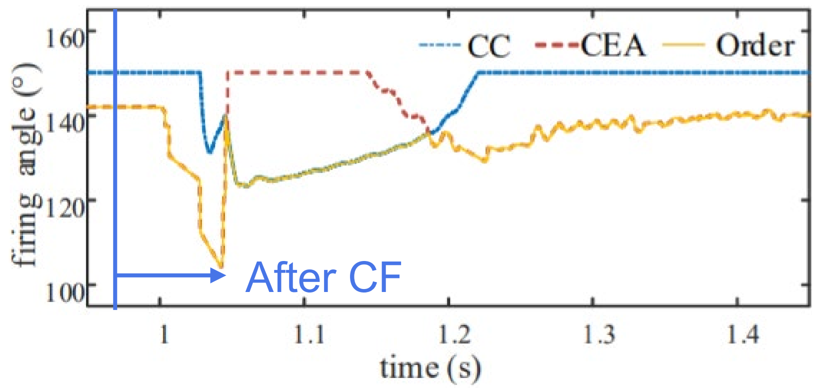
Method to Reduce Commutation Failure:

1. Installation of Voltage Support Equipment, e.g. STATCOM, Synchronous Condenser, Capacitor Bank.
2. Increase of AC System Strength
3. Stabilize Input Voltage e.g. with Capacitor Commutator Converter (CCC)
4. Reduce Fault Impact e.g. with Superconducting Fault Current Limiter
5. Advanced Control in Firing Angle e.g. Reduce Firing Angle

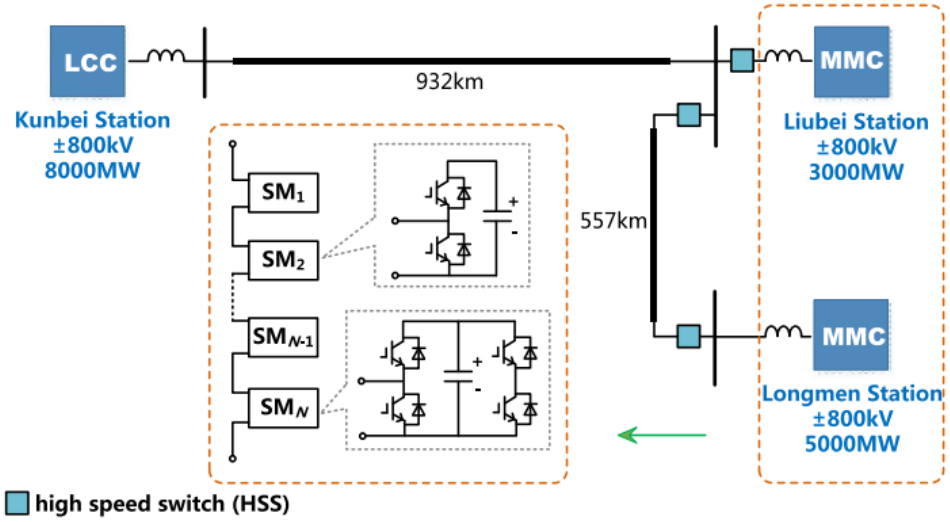
Yet, it often requires accurate commutation failure detection or even CF prediction.

Detection of Commutation Failure

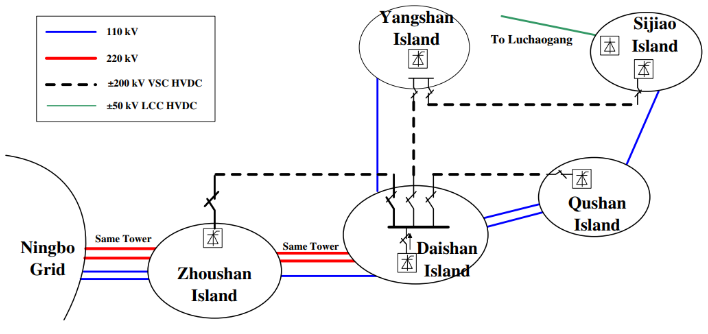
1. Calculation of Maximum Acceptable Voltage Drop
2. Electromagnetic Transient (EMT) Simulation
3. Examination of Valve Conduction Status
4. Comparing Valve Current with DC Current
5. Estimate AC Current of All Phase in Transformer
6. Inspection of DC current of Converter
7. Observation of Extinction Angle



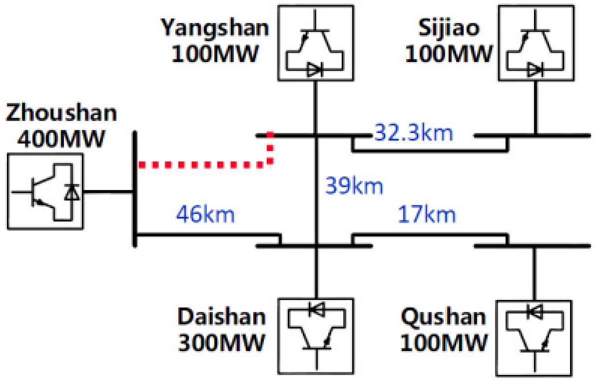
Multi-Terminal HVDC System

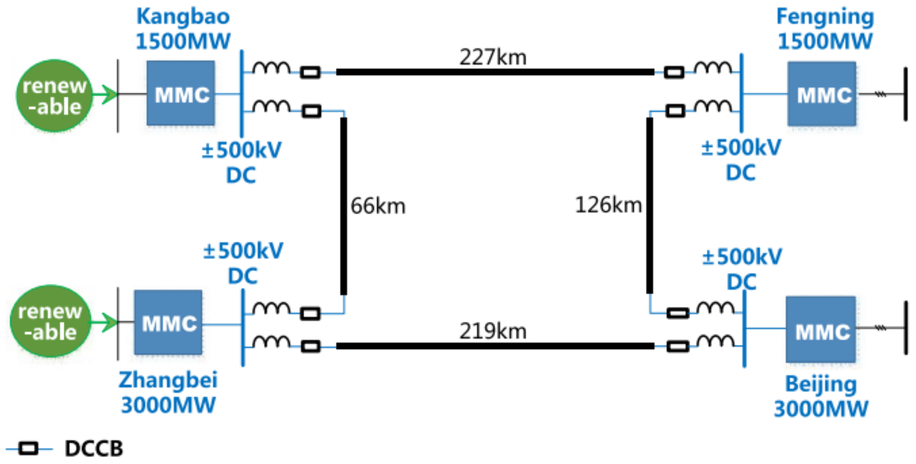


(a) Wudongde three-terminal HVDC system

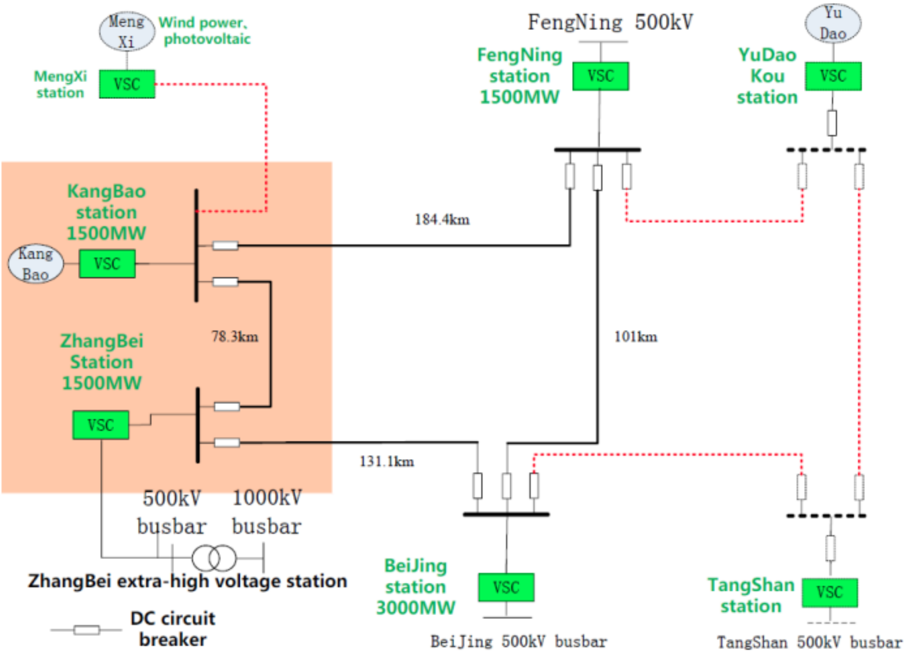


(c) Zhoushan five-terminal DC grid





(b) Zhangbei four-terminal DC grid

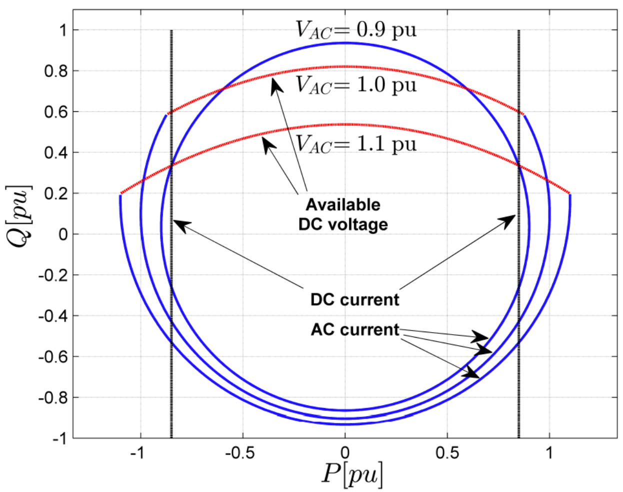


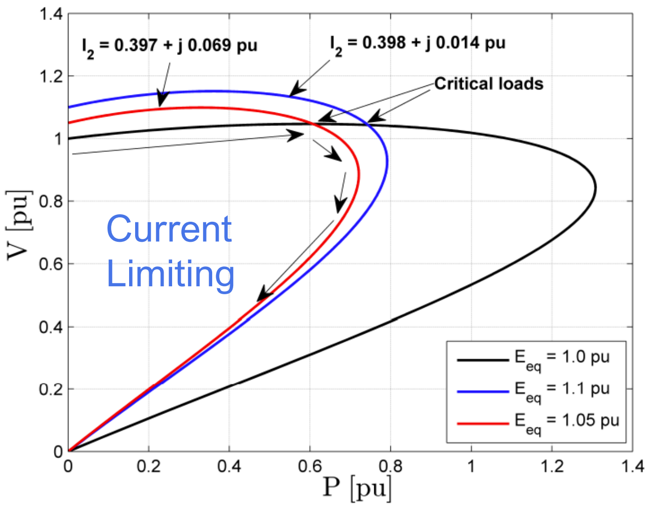
Operation Features of VSC - HVDC

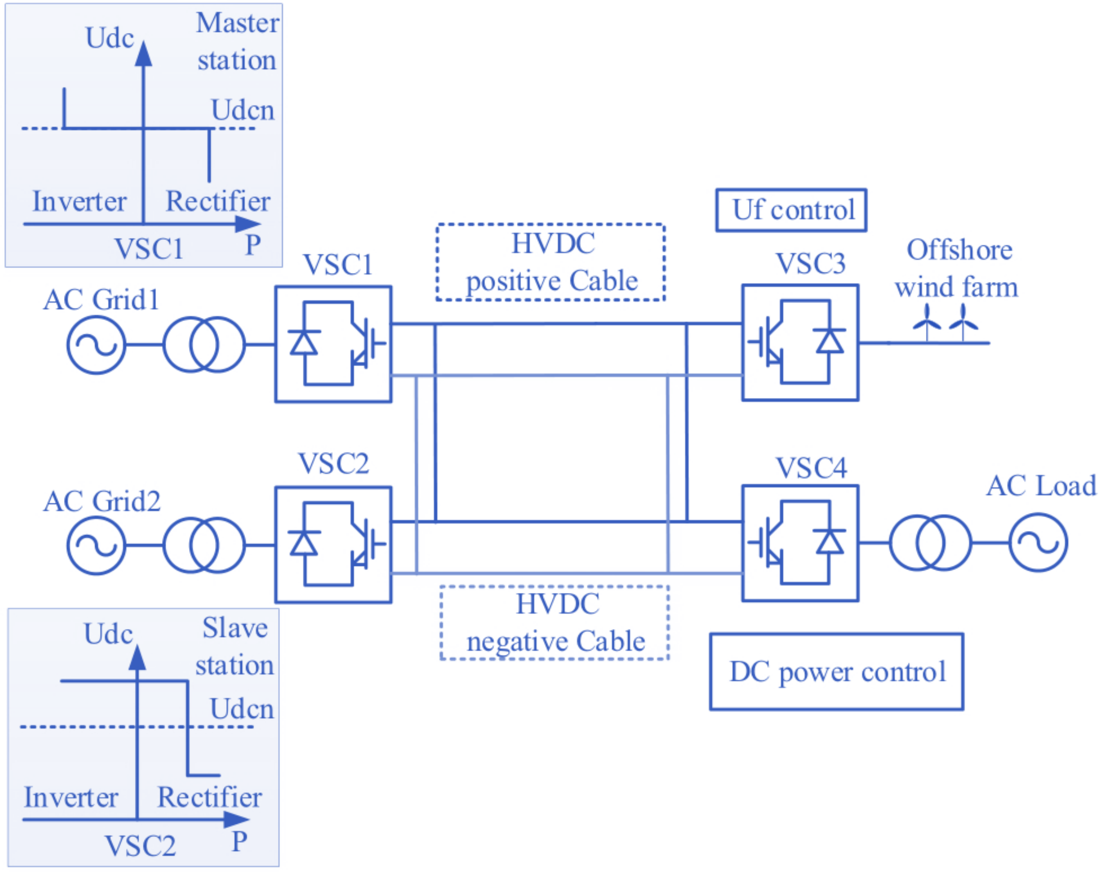
In point-to-point HVDC systems, one converter operates as **rectifier** (sending end, control DC voltage) and another end operates as **inverter** (receiving end, control power flow).

Power Capability (P-Q Curve) of VSC Converter is as shown. The limits depends on rating of converter and the conditions in connected AC system

- **Converter Rating** (IGBTs) determines the size of the circle (Blue Line)
- **Maximum Active Power Transmission Capacity** from overhead line (Black Line)
- **Maximum Reactive Power** (Capacitive) **Capability** from AC voltage of the grid (red line)



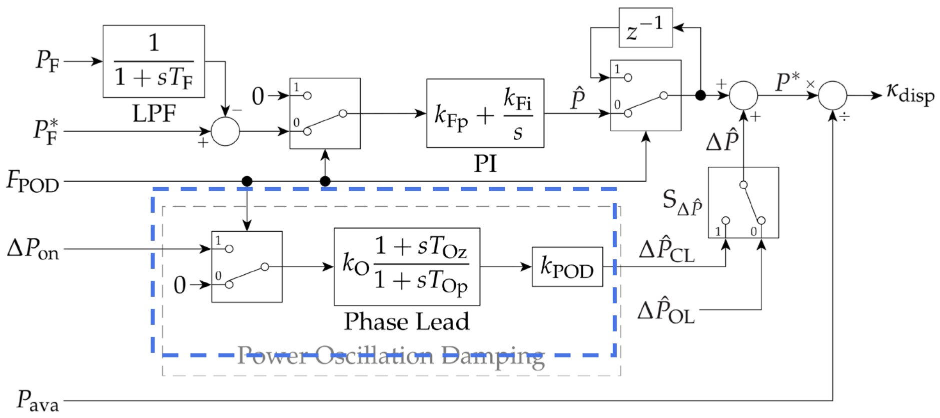




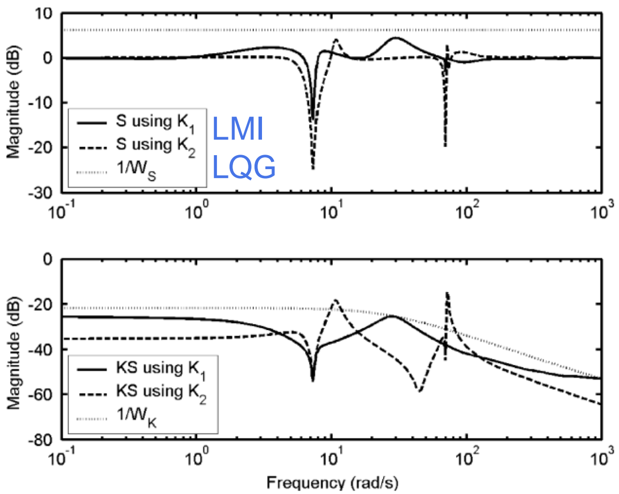
Operation Features of VSC – HVDC: Advanced Application

Based on the fundamental control function for P-Q curve, more advanced application can be developed

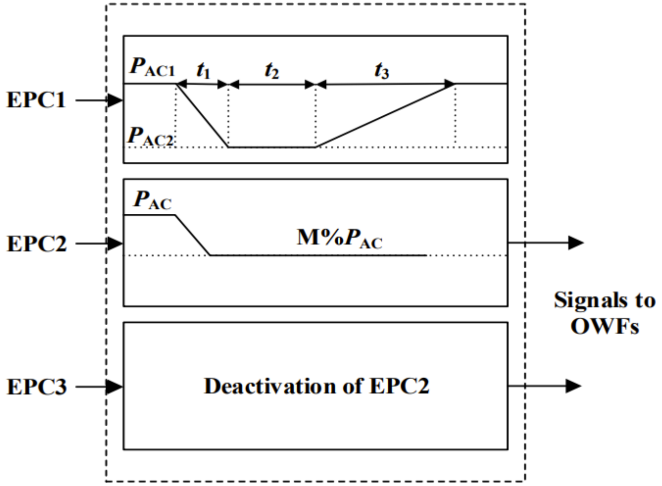
Power Oscillation Damping (POD)



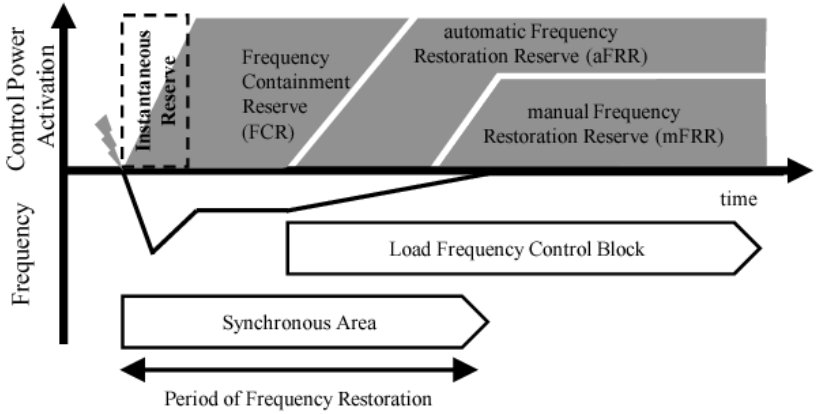
Sub-Synchronous Damping (SSD)



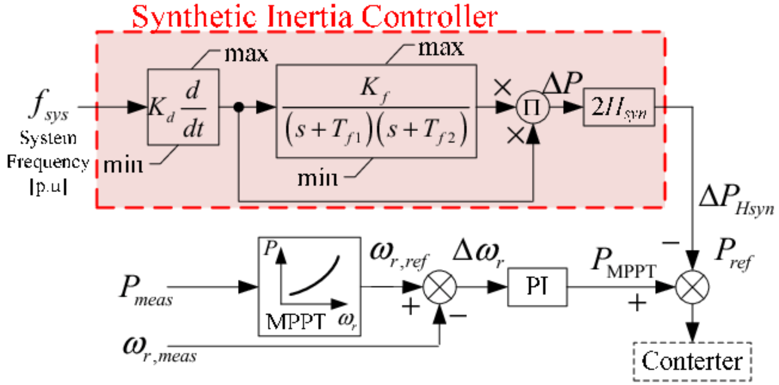
Emergency Power Control (EPC)



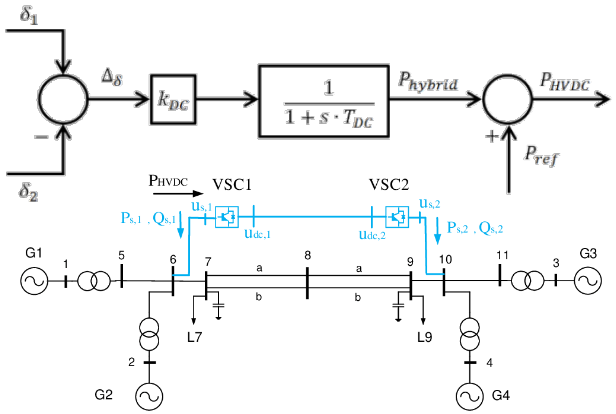
Frequency Containment Reserves (FCR)



Virtual Inertia(FCR)



AC Line Emulation



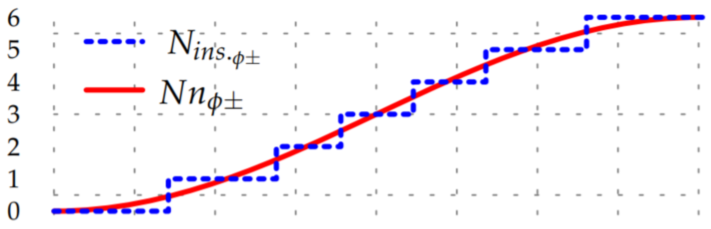
Comparison between LCC – HVDC & VSC – HVDC

LCC	VSC
Thyristor-based Technology	IGBT-based Technology
Withstand Voltage in either polarity	Withstand Current in either polarity
Constant Current Direction (**Current Reversal** by Changing Voltage Polarity)	Current Direction changes with Power
Energy is stored inductively	Energy is stored capacitively
High Power Capability per Converter	**Low Power Capability** per Converter
Strong Overload Capability	**Weak Overload** Capability
Limited in Reactive Power Control	**Good Reactive Power Control**
Requires Converter Transformer	Requires only Conventional Transformer
Higher Voltage Capability of >1000kV	**Lower Voltage Capability** around 600kV
Inverter side suffer Commutation Failure	**Immune** to any voltage dip or transient AC disturbance
Less terminal in LCC can be connected	**High number** of VSC in multi-terminal is possible
Control of Thyristor firing angle limit DC fault current	Body diode contributes fault current in DC side
Need for Short Circuit Power (**Strong SCR** needed for Thyristor Commutation)	Short Circuit Power during normal operation, in STATCOM operation, and/or in black start operation may be required.

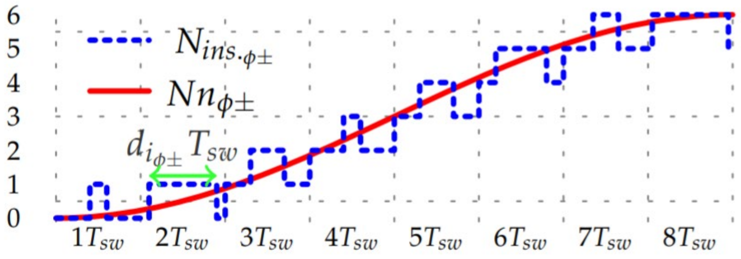
Module-Level Modulation

Module Level Modulation (MLM) is to translate reference values from the arm-level modulation to the gate signals for each submodule. Switching signals for individual SM not only influence the **voltage waveform** on the AC and DC sides, but also control **charging and discharging of SM capacitors**. It needs to be conformed with the arm-level modulation and voltage balancing control.

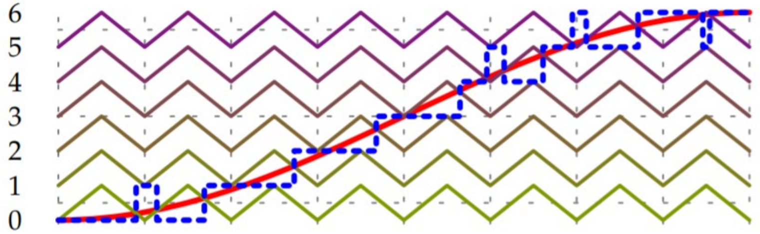
Nearest Level Control

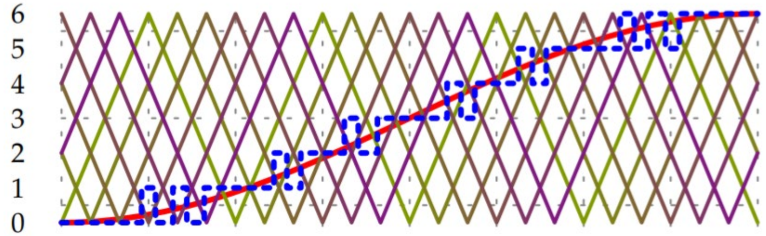


Nearest Level Modulation

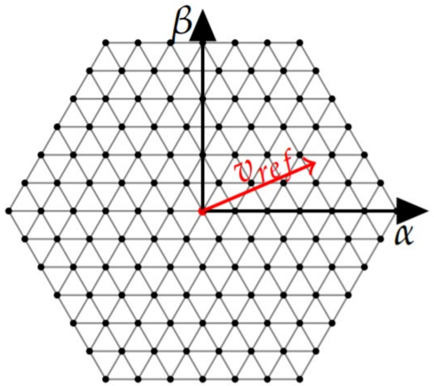


Multi-Carrier PWM

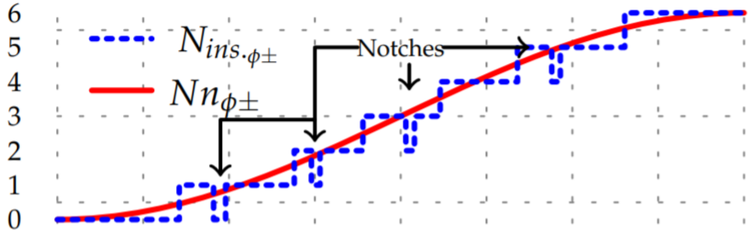




Space Vector Modulation

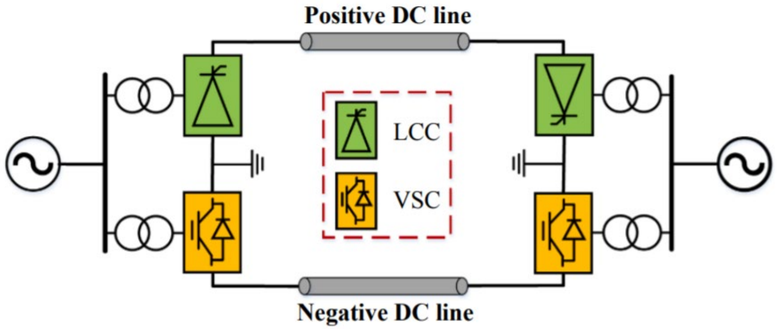


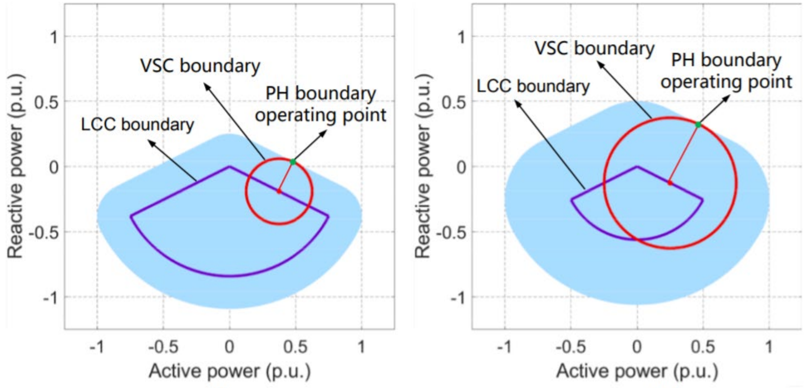
Selective Harmonic Elimination



Operation Boundary of Hybrid LCC – HVDC and VSC – HVDC: Configuration

Pole Hybrid HVDC (PH)

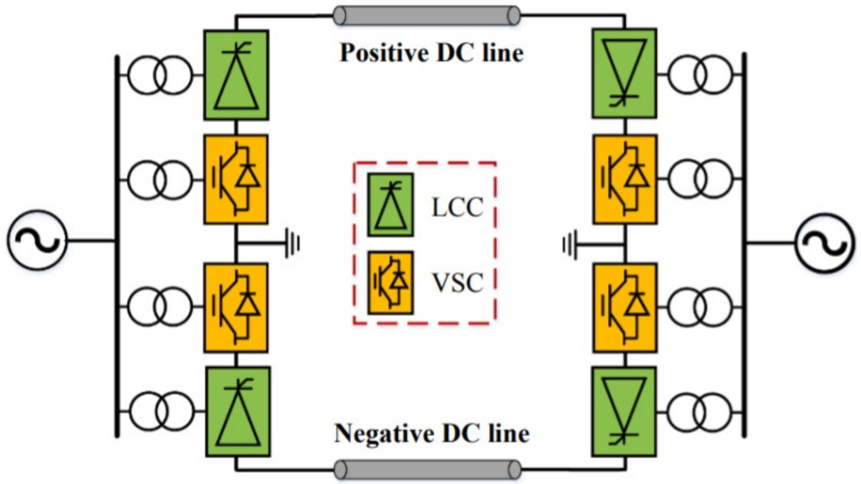


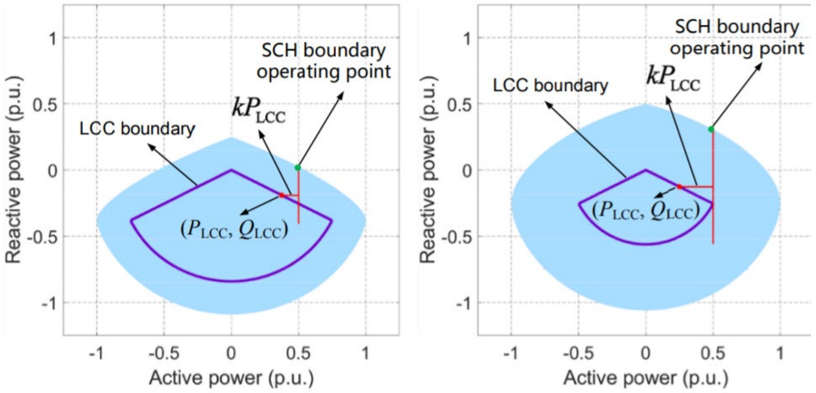


(a) (b)

(a) LCC Terminal (b) VSC Terminal

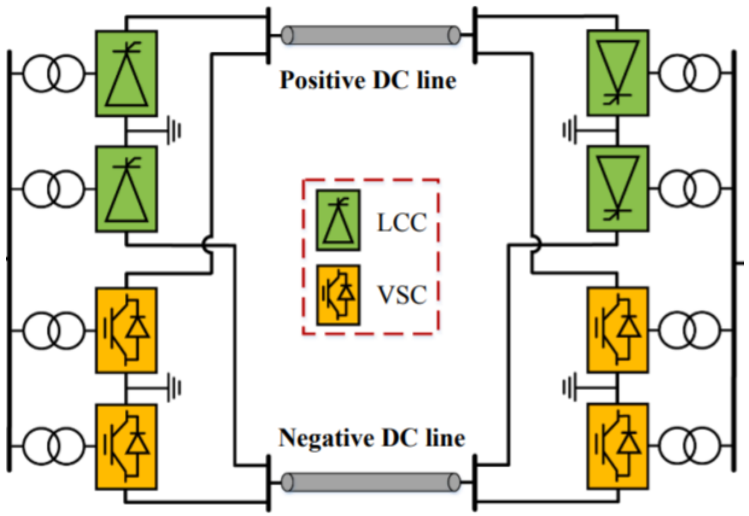
Series Combined Hybrid (SCH)

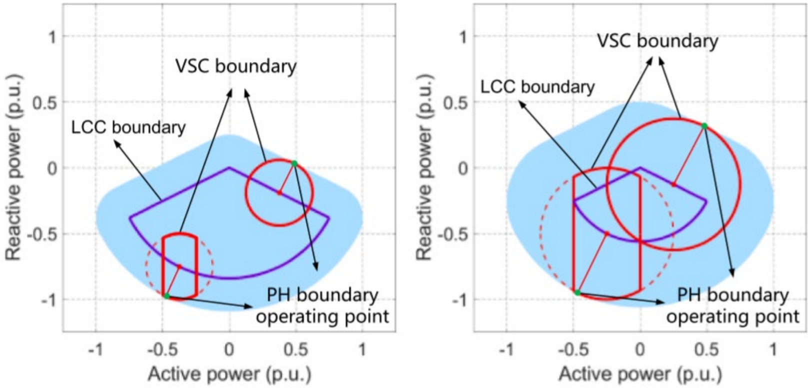




(a) (b)

Parallel Combined Hybrid (PCH)





(a) (b)

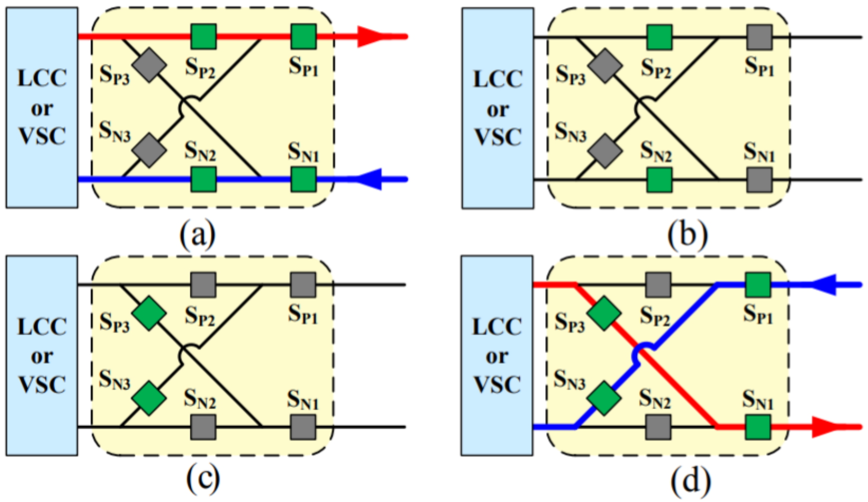
Operation Boundary of Hybrid LCC – HVDC and VSC – HVDC: Consideration

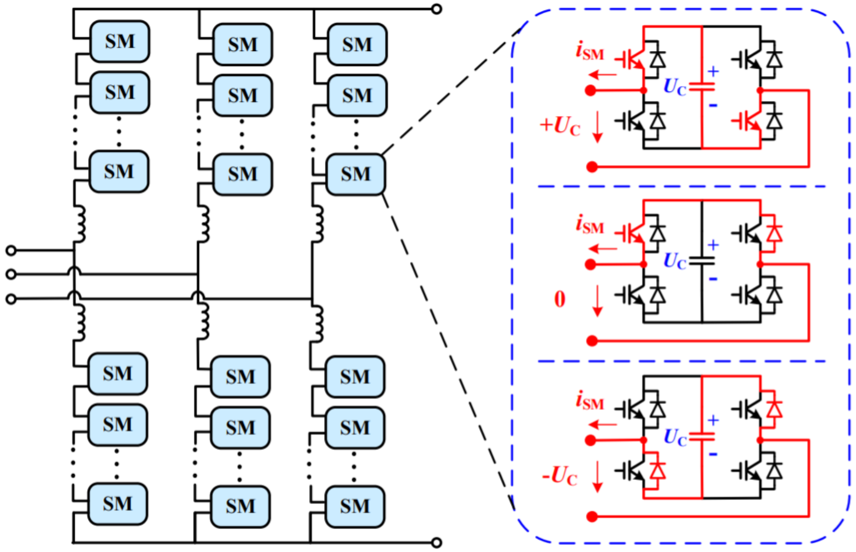
Power Flow Reversal

In PCH Topology, LCC and VSC are connected in parallel in each terminal. When LCC is disconnected by reversal switch, the remaining part is a VSC. Then power direction can be easily reversed by changing DC current. After LCC is reconnected to the system, shutdown is required for LCC.

Adopting Full-Bridge MMC is another solution. PCH topology can perform power flow reversal without shutdown of either LCCs or FB-MMCs. The sequence of power flow reversal is as follows.

1. Reduce P of two FB – MMCs to zero.
2. Keep DC current of LCCs to reasonable value
3. Adjust voltage reference of FB – MMC from 1 pu to – 1 pu linearly. As LCC and FB – MMC are connected to the same DC line, DC voltage of LCC is also changed.
4. Increase the transmitted power the desired level by adjusting DC current reference of LCC and active power of FB-MMC





Operation Boundary of Hybrid LCC – HVDC and VSC – HVDC: Consideration

Power Flow Reversal

1. Need shutdown?
2. Earth Current Present?

Power flow reversal method	PH topology	TH topology	SCH topology	PCH topology
Installing reversal switch	Need LCC shutdown, earth current presents	Need system shutdown	Need system shutdown	Need LCC shutdown, no earth current
Adopting FB-MMC	Need LCC shutdown	No shutdown	Need system shutdown	No shutdown

DC Fault Ride-Through

Fault Blocking Capability?

DC fault ride-through strategy	PH topology PTP fault can be cleared with LCC force retardation; extra device or control action is required to clear VSC PTG fault	TH topology Install diodes on the DC lines or on the low-voltage side of the VSC

SCH topology Both PTP and PTG faults can be cleared with LCC force retardation	PCH topology Trip ACCB, use DCCB or adopt fault-blocking converter is required

Overall Comparison

Items	PH topology	TH topology
PQ operating zone	★★★★	★★
Power flow reversal	★★★	★★★
DC fault ride-through	★★★	★★★

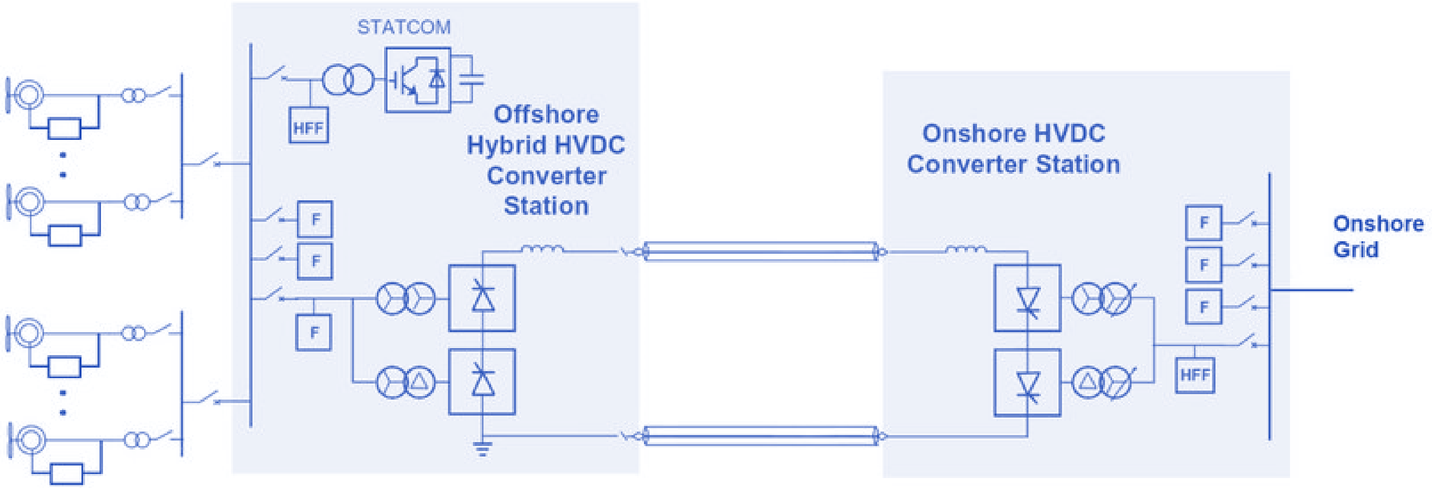
Items	SCH topology	PCH topology
PQ operating zone	★★★	★★★★
Power flow reversal	★★	★★★★
DC fault ride-through	★★★★	★★

Note:
VSC DC Cap leads to sharp rise in fault current, while **LCC Smoothing Reactor** limits fault current

Weak AC Infeed (2 < SCR < 3) with low inertia to LCC-HVDC

Weak AC Infeed (2 < SCR < 3) with **low system inertia** has an impact on operation of LCC-HVDC links. It includes:

- Voltage Instability
- Small Signal Instability
- Commutation Failure
- Harmonics Resonance
- Limitation on Power Transfer

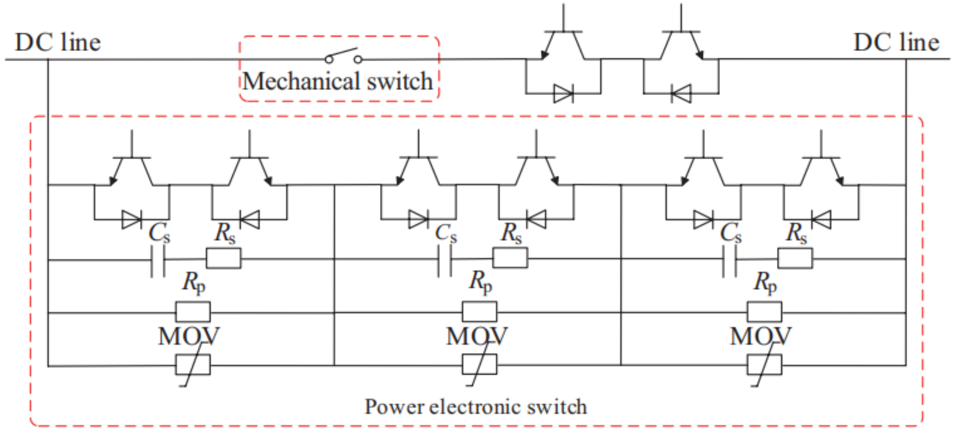


To mitigate the problems,

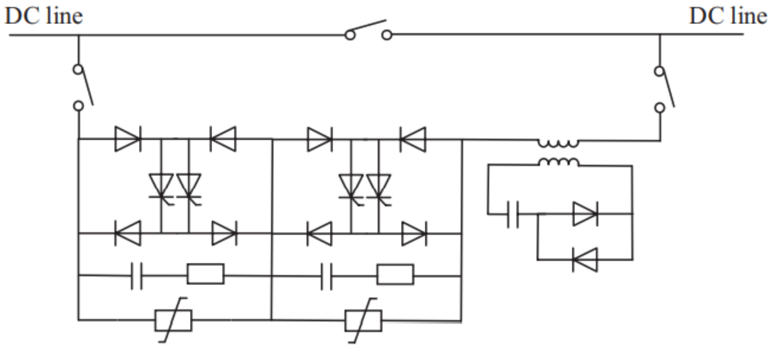
- Application of **Capacitor Commutated Converter (CCC)** with series connected capacitor to provide stable commutation voltage with less coupling to AC grid. [Note: CCC provides reactive power supply proportional to line current, hence required less reactive power compensation.]
- Application of **Synchronous Condensers** and VAR compensator such as **STATCOM** to provide voltage support [Note: Failure of DC Link can lead to **overvoltage** if NOT instantaneously tripped]

Fault Capability for VSC – HVDC in FBSM + HBSM

Hybrid HVDC Breaker



Breaker with Magnetic Coupling



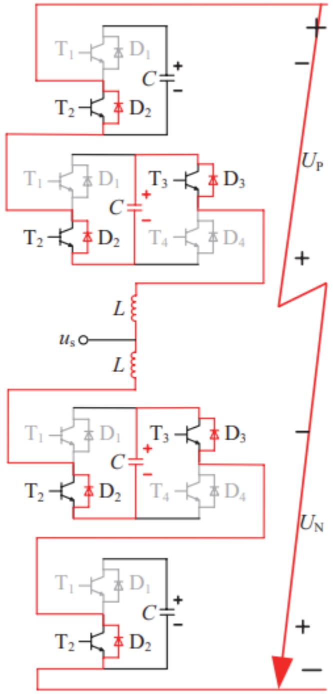


Fig. 11 Blocking current limiting operation

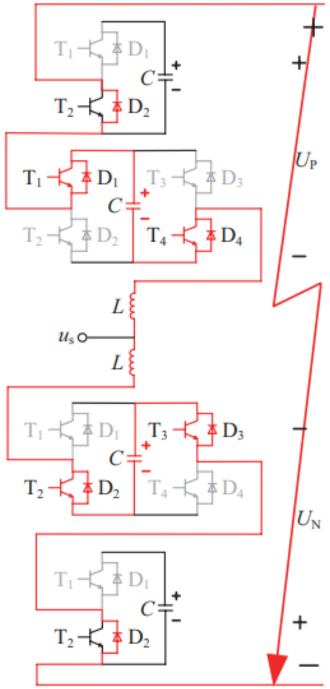


Fig. 12 Fault ride-through limiting operation

Blocking: Detecting the fault, all switching devices of SMs of the converter are blocked, so that SM capacitors are reversely connected into the fault circuit. Fault current charges the sub-module capacitors. The fault point is subjected to reverse voltage, hence blocking the DC fault current.

Fault Ride-through Mode: It controls and limits DC side current actively by reducing the DC side voltage of the converter station. It operates in STATCOM mode during fault period, which can provide reactive power support to the AC system. After the fault is isolated, the power supply can be quickly restored through this operation mode.

Half – Bridge Vs Full – Bridge on Fault

DC Fault Ride Through on DC Fault:

- Combination of half-bridge MMC with DC breakers
  Half-bridge valves experience a **high overcurrent** and block their control operation for protection. As a result, the MMC operates as a **diode-bridge rectifier**, losing its control capability.
- Full-bridge MMC with mechanical disconnectors for isolation
  DC fault blocking: After all the switching devices are switched off during a DC fault, series capacitors in FBSMs have opposite polarity to direction of fault current flown from AC side and blocked the fault if **arm capacitor voltage** is still **sufficiently high to block the fault current**. Therefore, blocking voltage formed by the two arm voltages and the ac line-to-line voltage has the following relationship:

$$u_{max} = \frac{\sqrt{3}}{2} \frac{N+M}{(N-M)} V_{dc} < \frac{2N}{(N-M)} V_{dc} = 2u_{arm}$$

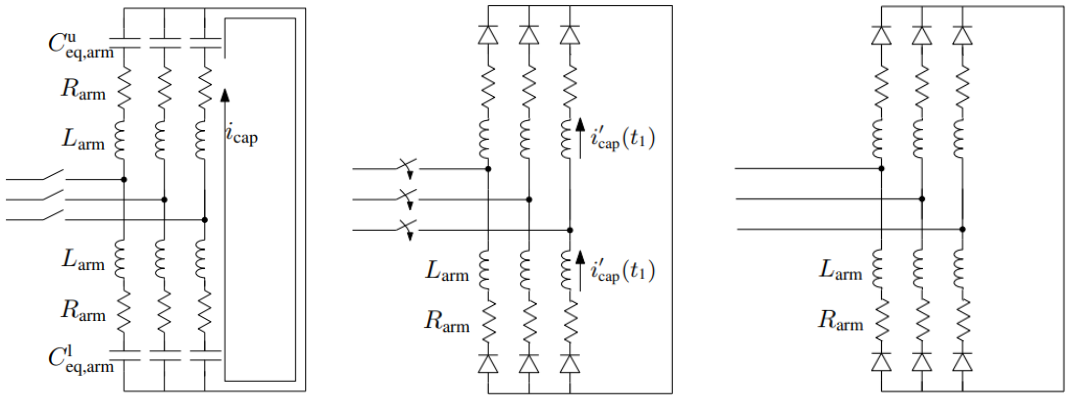
Stage 1: When a DC fault occurs, $V_{DC} = 0$, $I_{d,\,AC} = 0$, only $I_{q,\,AC} = I_{q,\,SET}$ is controllable for voltage support

Stage 2: Try $V_{DC} = V_{DC,\,SET}$. If V_{DC} recovers successfully, DC fault is cleared. If NOT, put $V_{DC} = 0$.

Stage 3: A ramp signal for V_{DC} is set for controlling d-axis and q-axis AC current.

Note: FBSM operates at HBSMs at normal condition.

Note: Free-wheeling diode may damaged

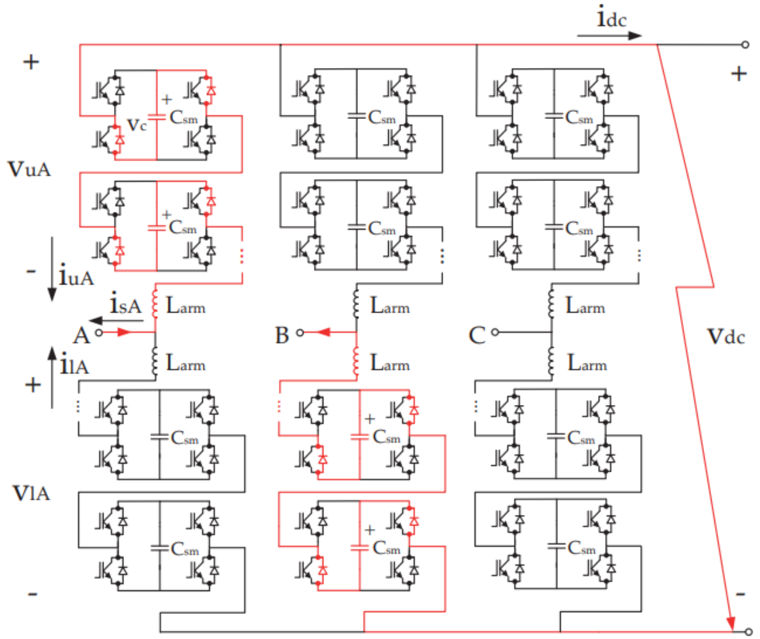


(a) Dc capacitive discharge (stage (i))

(b) End of dc capacitive discharge (stage (i))

(c) Ac steady-state infeed (stages (ii) and (iii))

Note: Blocking Voltage, but loss of control (no AC grid support function).



Half – Bridge Vs Full – Bridge on Fault

When DC fault occurs, overcurrent develops in the DC grid line and DC fault detection is triggered ($I > I_{SET} = 2$ pu). The converter cannot maintain control at V_{DC} or P_{AC}. To avoid converter energy collapse:

- V_{DC} or P_{AC} mode is changed to converter energy control (W_{CONV}) mode. Although control of V_{DC} is lost as it drops to zero, the voltage of submodule v_C can be controlled independently. Modulation technique is needed to ensure SM capacitor remain charged at nominal voltage level independent of DC grid state. Decoupling V_{DC} and v_C, each arm acts as virtual DC link even during DC fault and MMC remain controllable by acting as a STATCOM and provides reactive power support to AC grid.
- It is necessary to **drive i_{DC} to zero** and decouple AC from DC side operation.
- Arm and Leg energy controller are necessary for STATCOM operation.
- When i_{DC} is brought to zero, mechanical disconnector is used to isolate faulty lines. If it is a single-in-single-out topology, it is important to keep its **controllability** to continue supporting the AC grid. If it is a multi-in-multi-out topology, the healthy part can have their MMC return to normal pre-fault condition mode.

Difference in Arm Energy:

$$\frac{\partial W_{\Delta,j}}{\partial t} = -\hat{v}_{sj}\hat{i}_{c1j}cos(\phi_{cj})$$

Difference in Leg Energy:

$$\frac{\partial W_{\Sigma,j}}{\partial t} = i_{c0j}v_{dc} - \hat{v}_{sj}\hat{i}_{sj}cos(\phi_{ij})$$

→ Control circulating current.

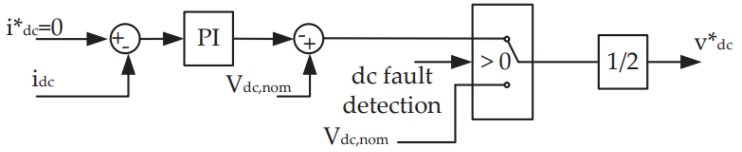


Fig. 3. DC current controller

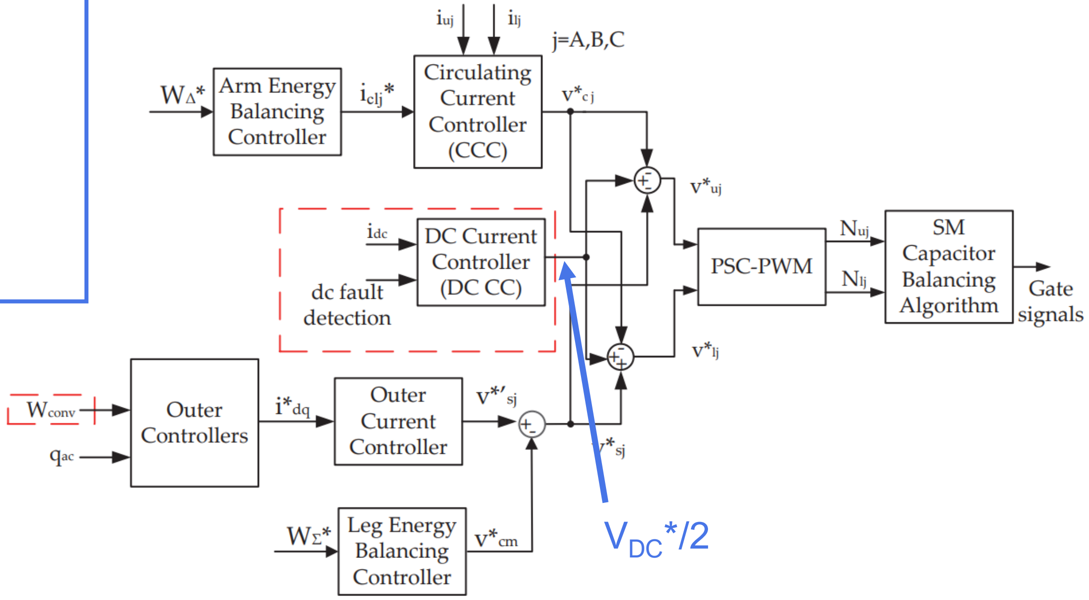
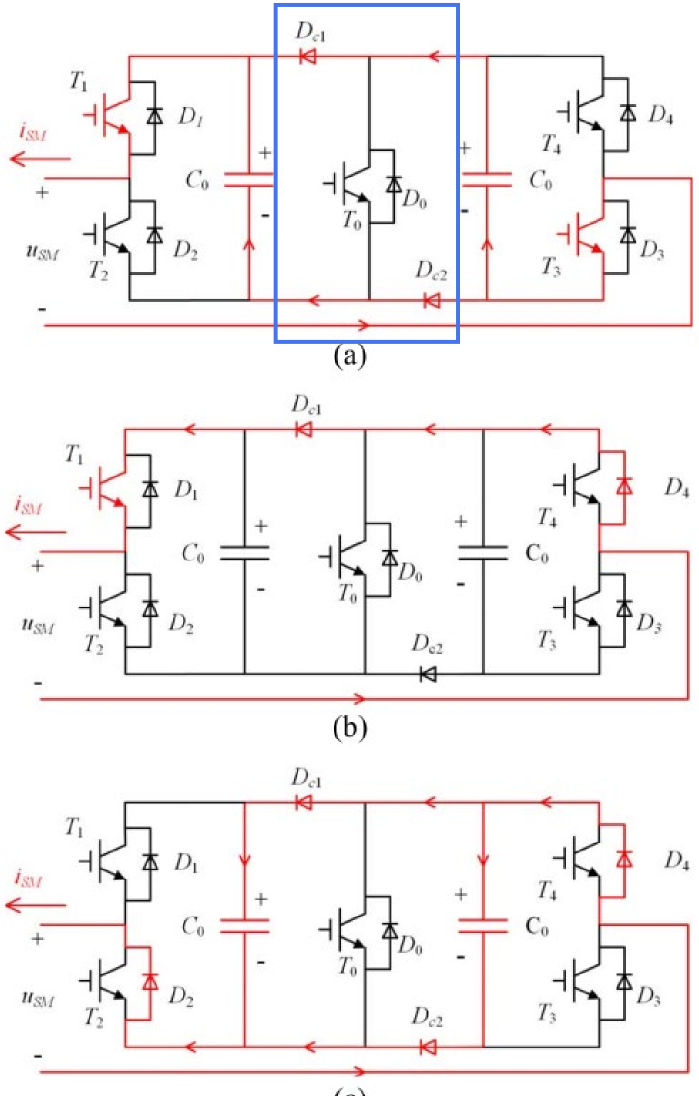


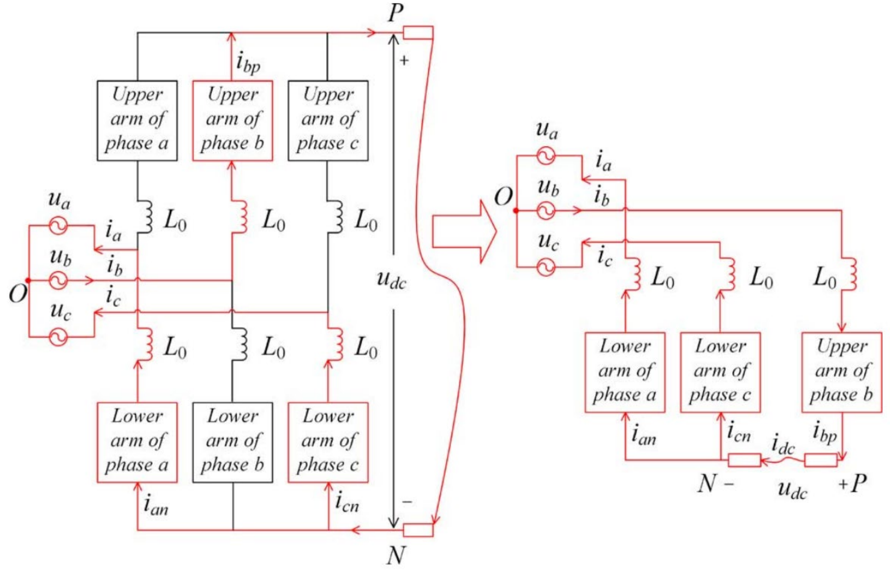
Fig. 5. Control structure of MMC in STATCOM operation

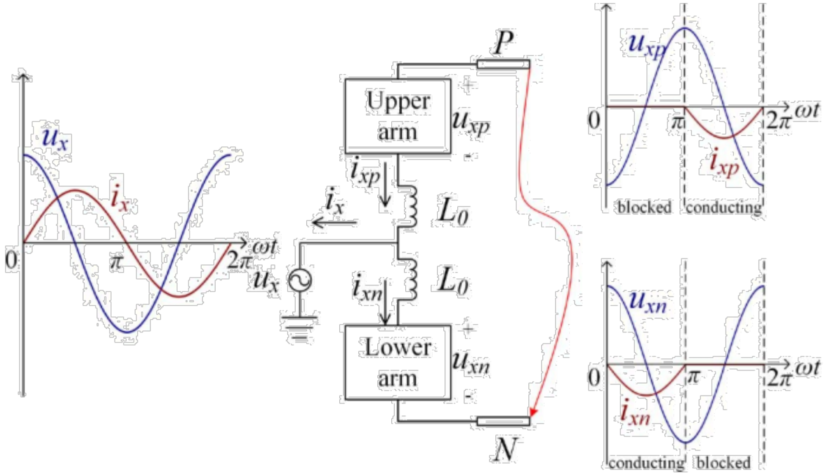
STATCOM Operation on Fault

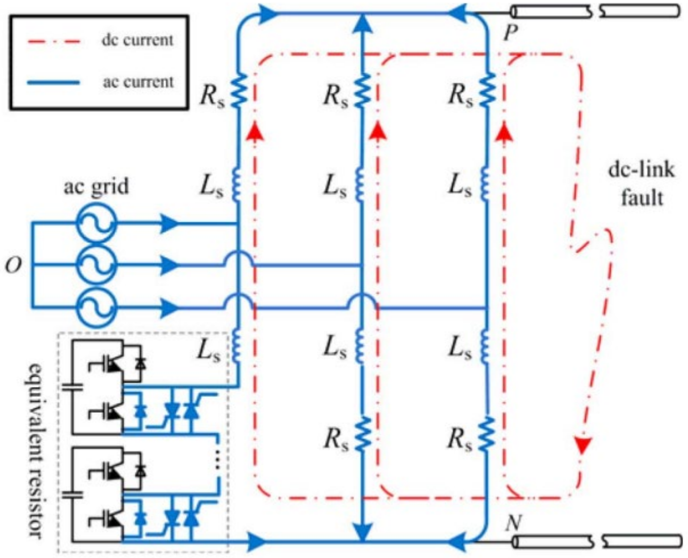


(a)
(b)
(c)

SM state	T_1	T_2	T_3	T_4	T_0	i_{SM}	u_{SM}
Positive	1	0	1	0	0	<0	U_c
Bypassing	1	0	0	1	0	<0	0
Negative	0	1	0	1	0	<0	$-U_c$
Blocked	0	0	0	0	0	>0	$2U_c$
Blocked	0	0	0	0	0	<0	$-U_c$
Blocked	0	0	0	0	0	=0	--







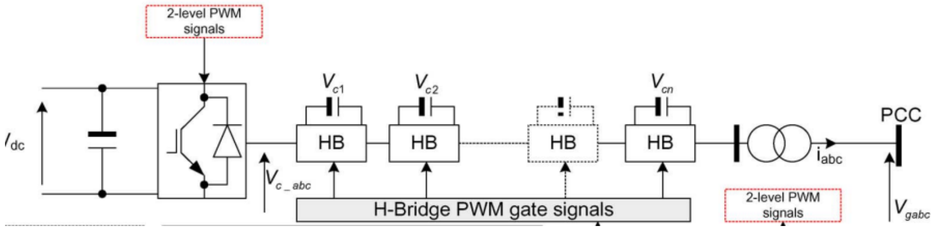
DC Blocking Capability

DC Fault Reverse-Blocking Capability

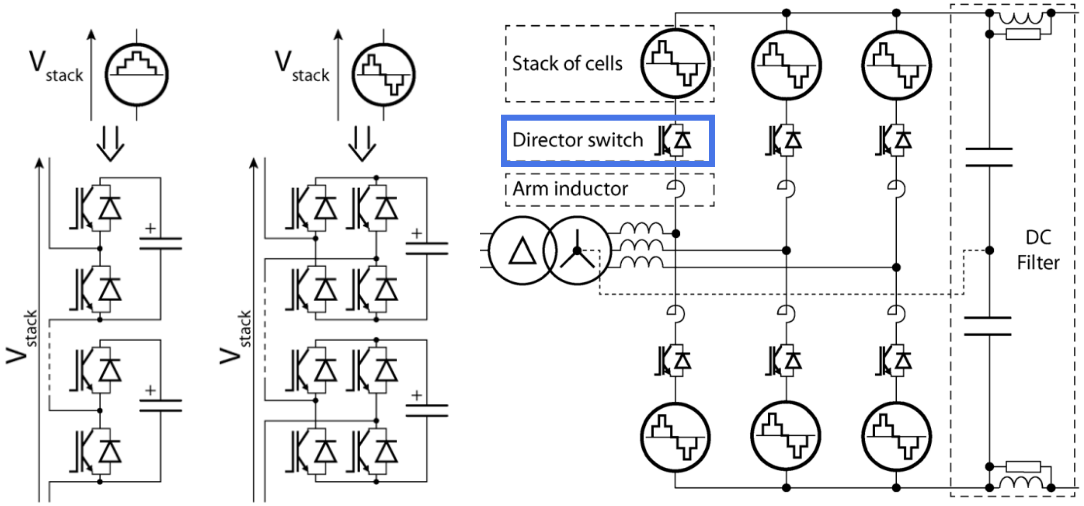
- Eliminate AC grid contribution to DC fault, hence converter failure
- Facilitate controlled recovery without opening AC CB
- Simplify DC CB design with reduction in magnitude and duration of DC fault current
- Improved voltage stability of AC network with reduced Q consumption in converter during DC side fault.

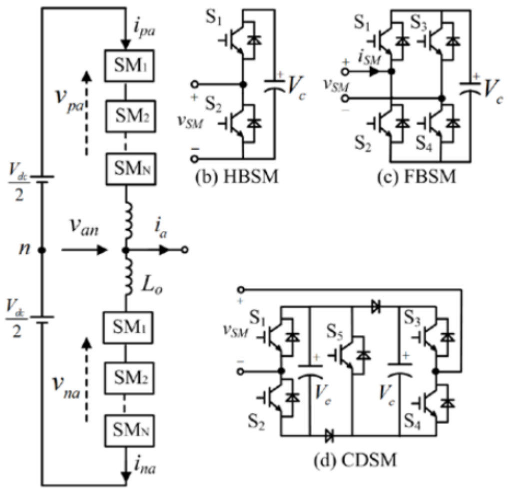
Converter type	Hybrid multilevel converters		Modular multilevel converters			
	HCMC	AAC*	CDSM-MMC	FBSM-MMC	Hybrid FBSM-MMC[12]	Boost FBSM-MMC[12]
Rated dc-link voltage	U_{dc}	U_{dc}	U_{dc}	U_{dc}	U_{dc}	U_{dc}
Rated voltage of IGBTs	$U_{dc}/(2N)$	$U_{dc}/(2N)$	$U_{dc}/(2N)$	$U_{dc}/(2N)$	$U_{dc}/(2N)$	$U_{dc}/(2N)$
No. of SMs in each arm	N FBSMs	$4N/\pi$ FBSMs	N CDSMs	$2N$ FBSMs	N FBSMs and N HBSMs	$2N$ FBSMs and N HBSMs
No. of IGBTs in total	$24N$	$36N$	$30N$	$48N$	$36N$	$60N$
Output voltage levels	$4N+1$	$4N/\pi+1$	$2N+1$	$2N+1$	$2N+1$	$4N+1$
Capability of boosting voltage	Yes	Yes	No	No	No	Yes
Series operation of large numbers of IGBTs	Yes	Yes	No	No	No	No
Size of dc filters	large	large	small	small	small	small
Capability of blocking dc faults	Yes	Yes	Yes	Yes	Yes	Yes
Capability of working as a STATCOM to ride through dc faults	Yes	Yes	Yes	Yes	Yes	Yes

Hybrid Cascaded Multilevel Converter: H-bridge at AC side



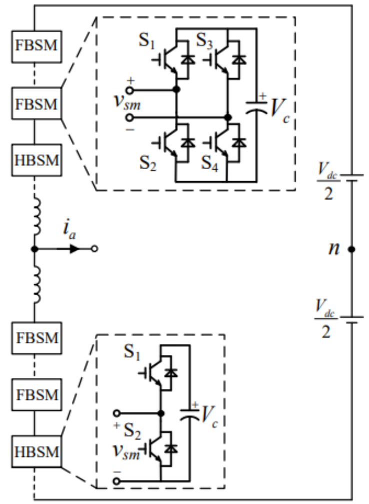
Alternate Arm Converter (AAC)



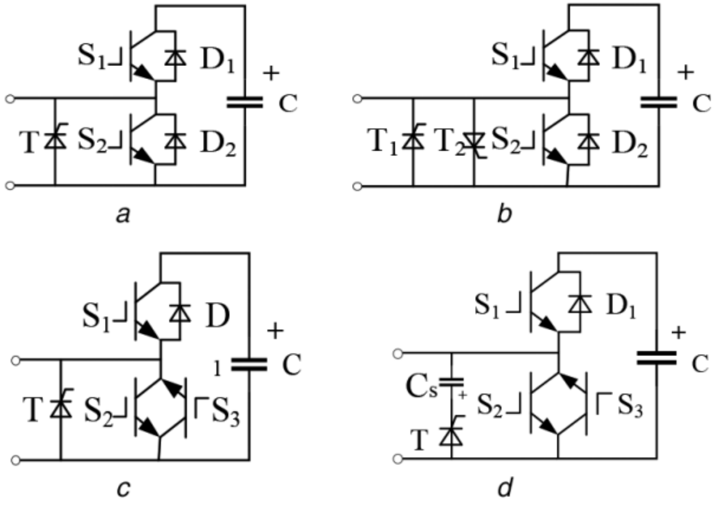


Hybrid (Boost) FBSM-MMC

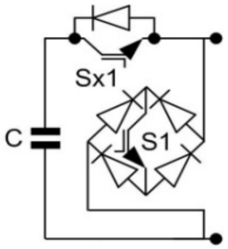
Boost allows some SM operating with $-V_C$

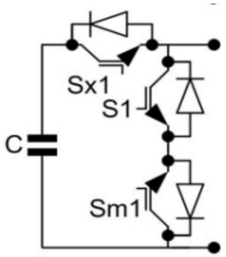


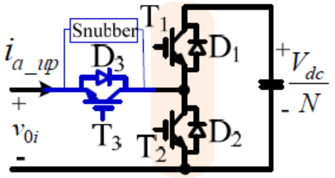
Modified Topology with DC Blocking Capability

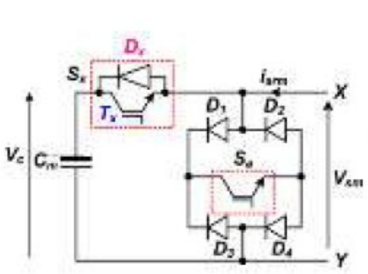


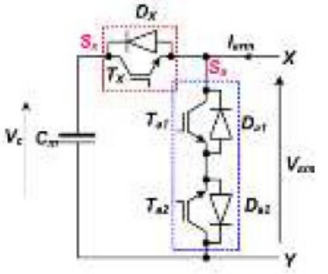
(a) STSS, (b) DTSS, (c) BBSM, (d) RBSM

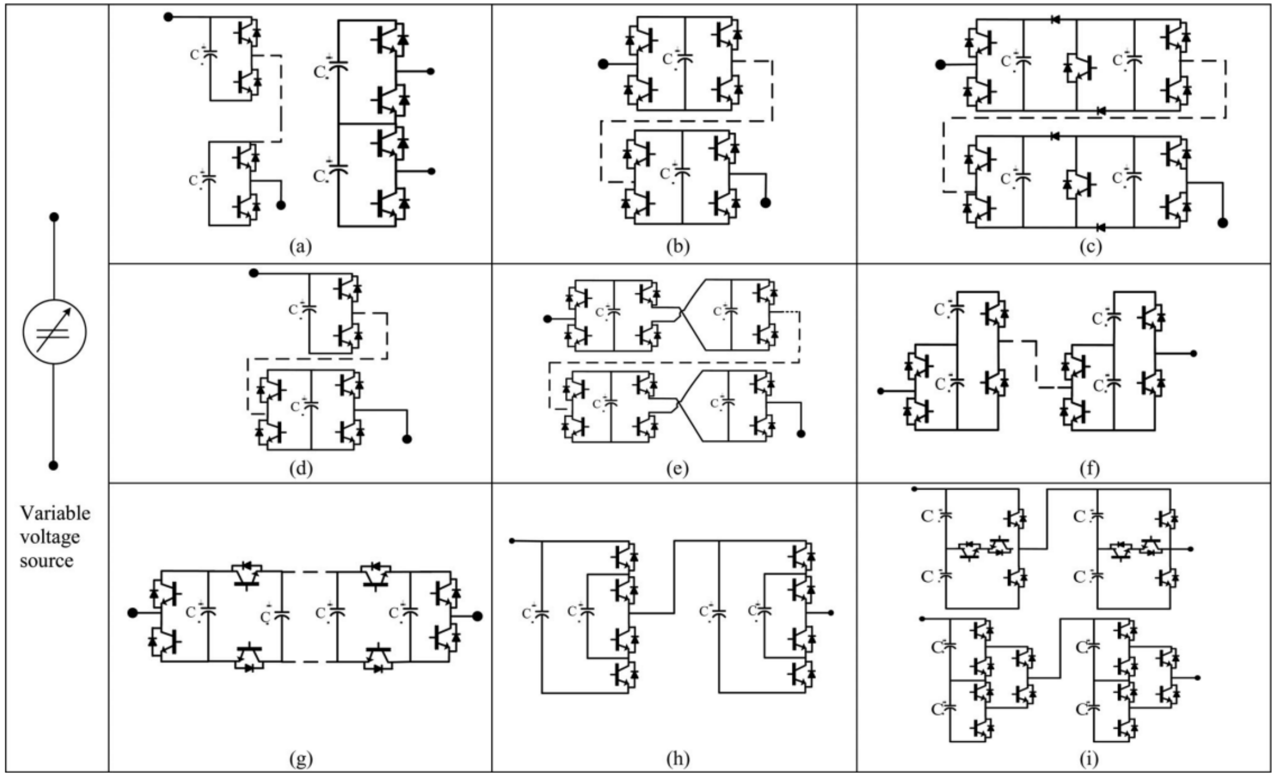






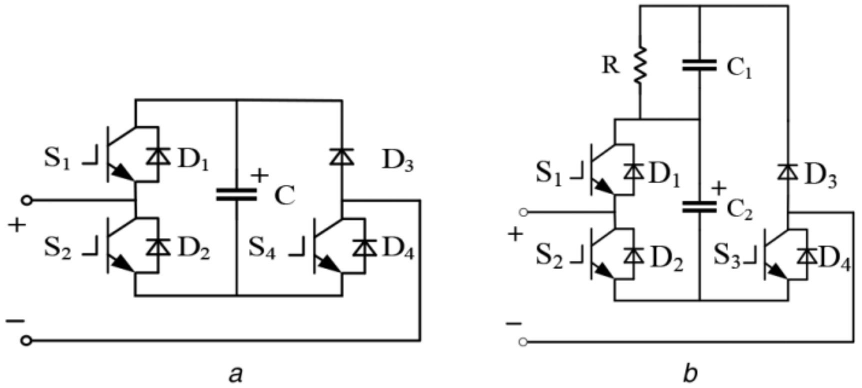




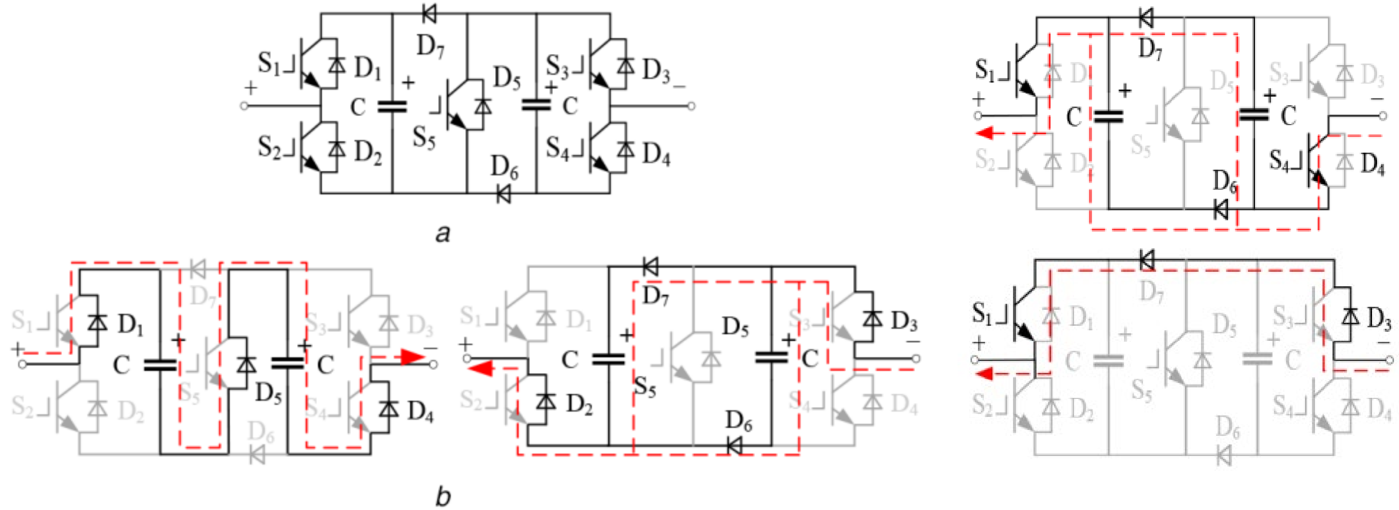


M2LC with chain-link arm	(a)	(b)	(c)	(d)	(e)	(f)	(h)	(i)
Number of cells	$2N$	$2N$	N	N	N	N	N	N
Total No. of switches normalized Uc	$8N$	$16N$	$14N$	$12N$	$16N$	$12N$	$8N$	$12N$
Max No. of switches in conduction	$4N$	$8N$	$7N$	$6N$	$8N$	$6N$	$4N$	$4N$
Bipolar voltage operation of the arm	No	Yes	Yes	Yes	Yes	Yes	No	No
Dc fault short-circuit current limitation	No	Yes	Yes	Yes	Yes	Yes	No	No
Capacitor voltage balancing in M2LC	Yes	Yes	Yes	Yes	Yes	Limited	Yes	Limited
PQ controllability	Yes	Yes	Yes	Yes	Yes	Limited	Yes	Limited

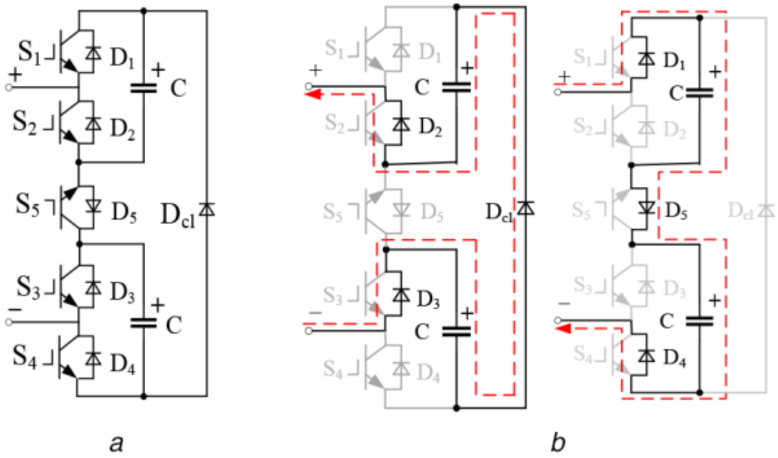
Other Modified Topology



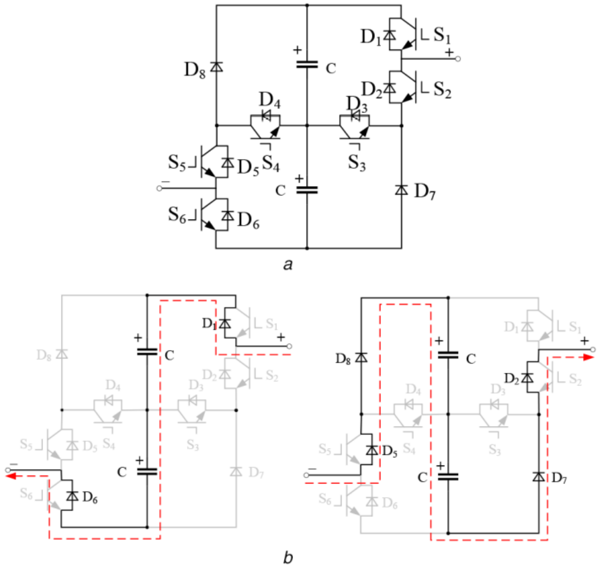
(a) UFBSM, (b) AUFBSM



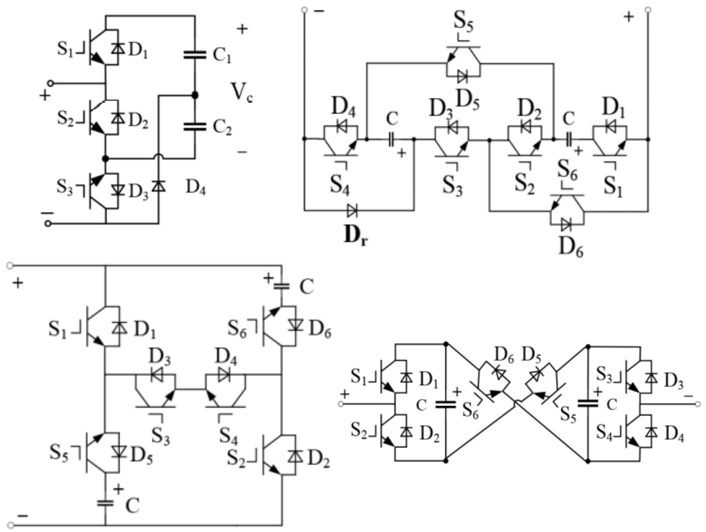
Clamp double SM (a) Basic structure, (b) Fault operation, (c) STATCOM mode



Series-connected double submodule
(a) Basic structure, (b) Fault operation

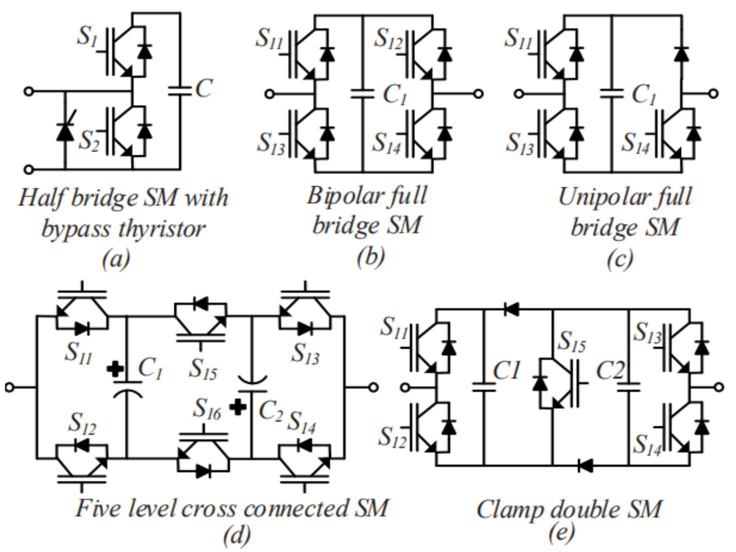


Active clamped T-type submodule
(a) Basic structure, (b) Fault operation

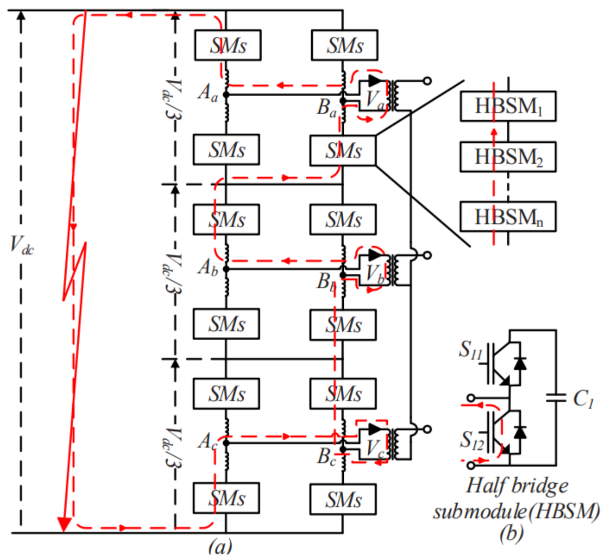


(a) HVCSM (b) SCSM
(c) Modified SCSM (c) 5LCCSM

Other Modified Topology



	MMC with HBSMs	SMMC with HBSMs	SMMC with 100% FBSMs	SMMC with 50% HBSMs and 50% FBSMs	PHMC	Proposed SSHMC	Series-HBHMC
dc voltage	V_{dc}	V_{dc}	V_{dc}	V_{dc}	V_{dc}	V_{dc}	V_{dc}
Max ac voltage	$V_{dc}/2$	$V_{dc}/3$	$V_{dc}/3$	$V_{dc}/3$	$V_{dc}/2$	$V_{dc}/3$	$V_{dc}/3$
Output voltage levels	N+1	2N/3+1	2N/3+1	2N/3+1	N+1	2 N/3 +1	(2N/3)+1
No. of switches (3 phase)	12N	8N	16N	12N	9N	10.67N	8N
No. of switches in conduction path	6N	12N	9N	6N	4.5N	4N	4N
No. of capacitors (3 phase)	6N	4N	4N	4N	1.5N	4N	N
Voltage stress of switches	V_{dc}/N	V_{dc}/N	V_{dc}/N	V_{dc}/N	V_{dc}/N	V_{dc}/N	V_{dc}/N
Soft switching of DSs	NA	NA	NA	NA	Yes	NA	No
dc Fault tolerant	No	No	Yes	Yes	No	Yes	Yes
Overmodulation	No	No	Yes	Yes	No	Yes	Yes
dc link capacitor	No	No	No	No	No	No	Yes



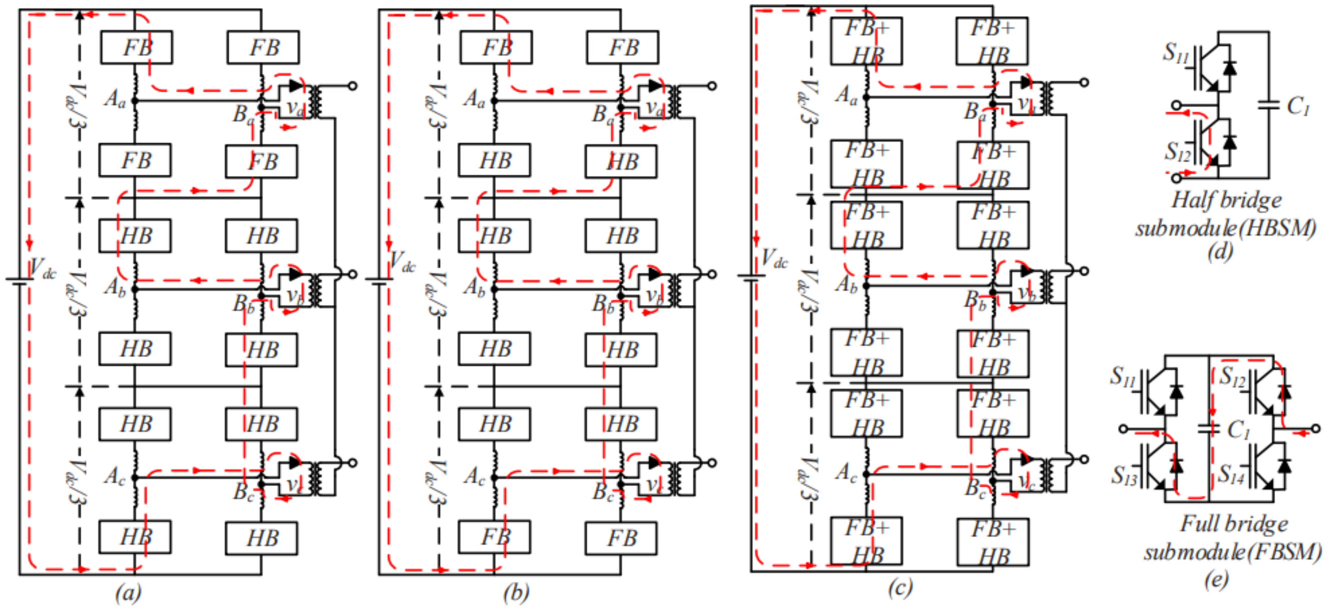
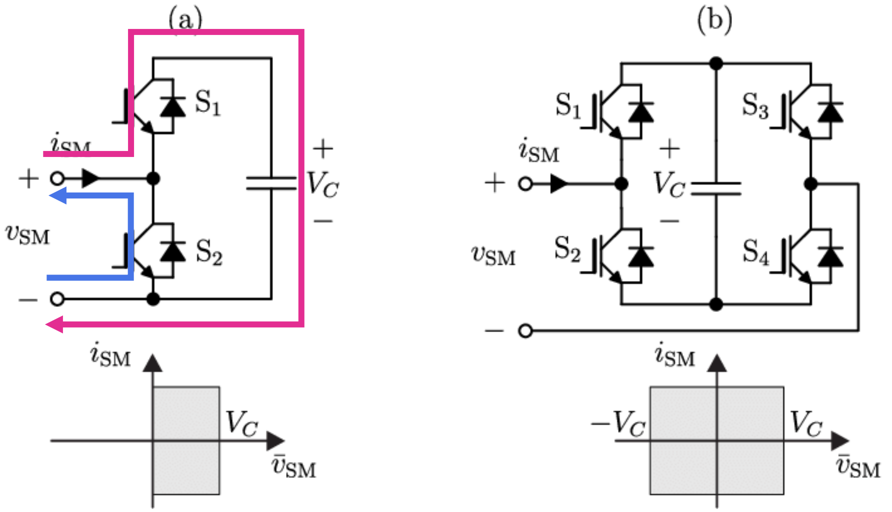


Fig. 5. (a), (b), and (c) Different topologies of SSHMC with dc fault tolerant, (d) half bridge SM, and (e) full bridge SM

Double Direction Controllable Switches (DDCS)



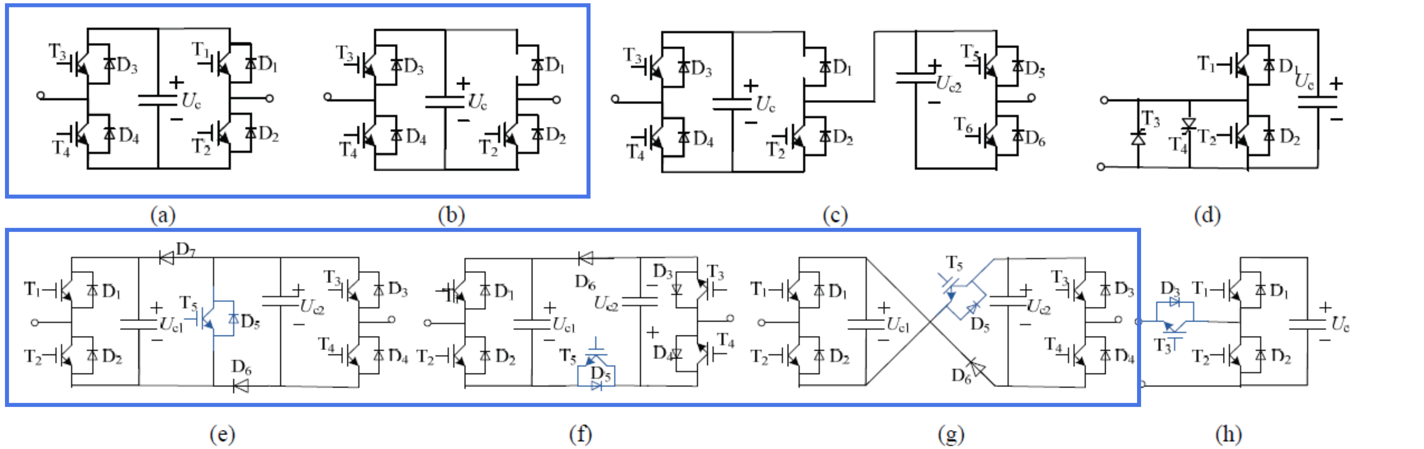
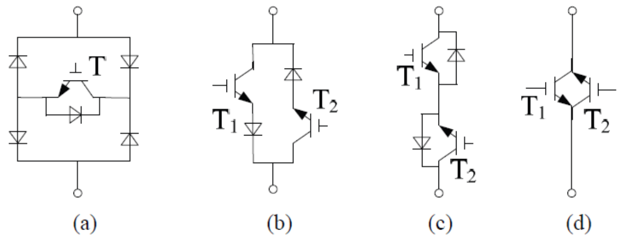
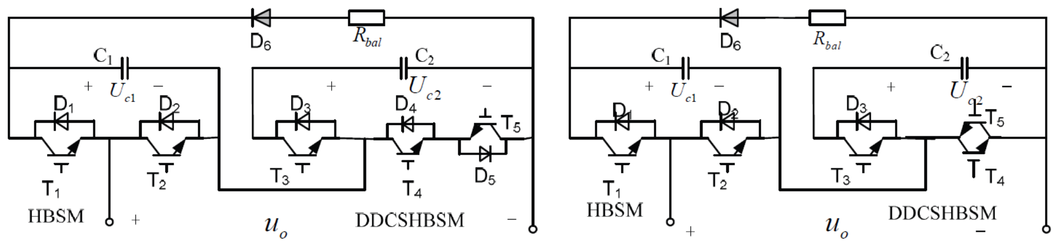


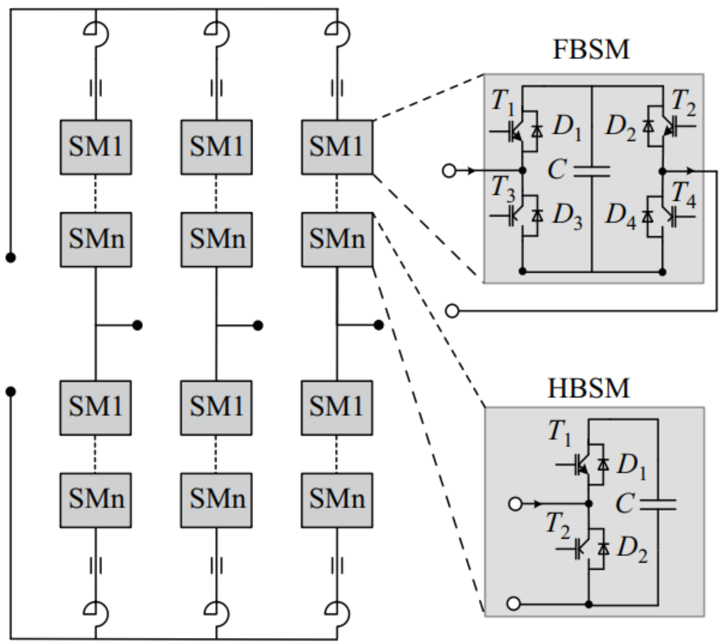
Fig. 1. Different sub-module topologies. (a) FBSM. (b) SPFBSM. (c) SPFBSM+HBSM. (d) Double parallel thyristor sub-module. (e) CDSM. (f) SDSM. (g) CTSM. (h) Self-cutting off sub-module.

- MMC must be able to **cut off fault current path** from the AC side to the DC side and **dissipate inductance storage energy**.
- Active self-blocking fault suppression topologies use the capacitor charging effect to absorb part of the energy in the fault loop and provide reverse voltage to turn the diode into a reverse bias state.
- Hybrid Self-Blocking with HBSM in Fig 1(c) is to reduce conduction loss to minimum, but it suffers unbalanced capacitor charging.
- AC CB shutdown is required for passive inhibition topology (thyristor clamped). Yet, the huge energy consumption and possible overvoltage during turning OFF are the problems to be considered.
- **Freewheeling diode effect** of S_2 lacks DC fault suppression capability and it requires DDCS for controllability.

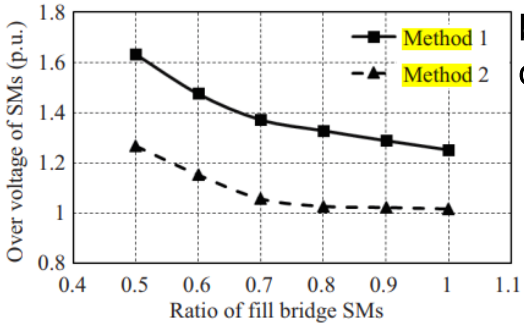




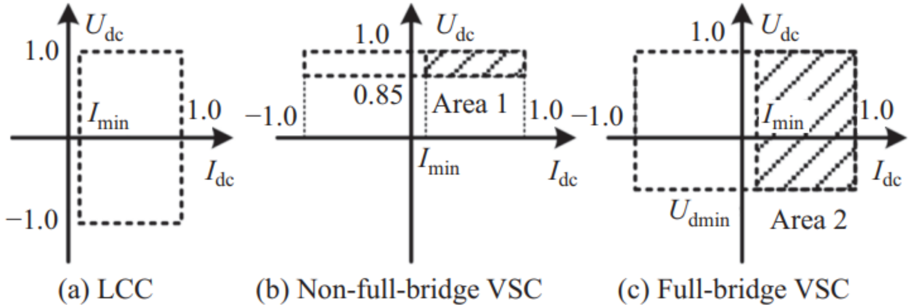
Hybrid Submodules



- SM such as FBSM and Clamped Double SM (CDSM) has fault clearance ability.
- To clear OHL fault, it is either to **block the VSC converter**, or control DC current by means of **zero DC voltage operations** or even negative voltage operation such as FBSM-MMC or (Half/Full bridge) Hybrid MMC.
- Voltage regulation or reduced DC voltage operation (70 – 80% p.u.) should be considered as basic operation modes. DC voltage of VSC can vary between 0 p.u. to 1.0 p.u.
- With less investment and lower power loss, hybrid MMC is proposed.
- Clearing OHL fault primarily depends on FBSM in hybrid MMC. The power impact of OHL and AC system will cause overvoltage of FBSMs. The overvoltage closely related to the parameters of OHL, operation mode, fault location and power level.
- For Wudongde HVDC, the proposed number of FBSM is at least 70%.



blocking
current control



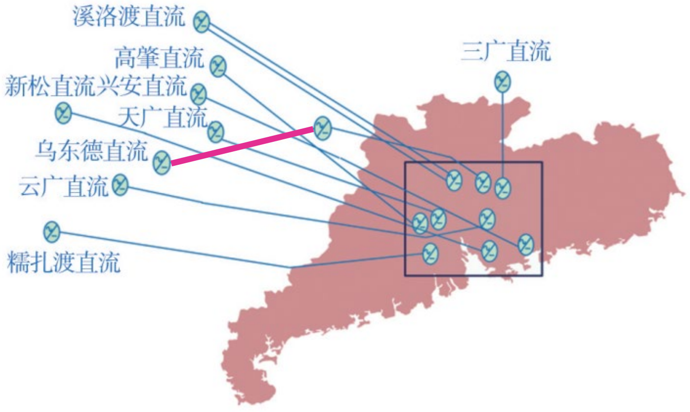
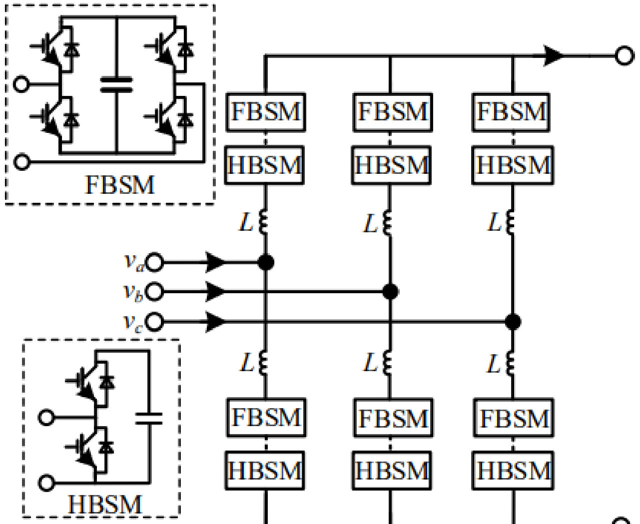
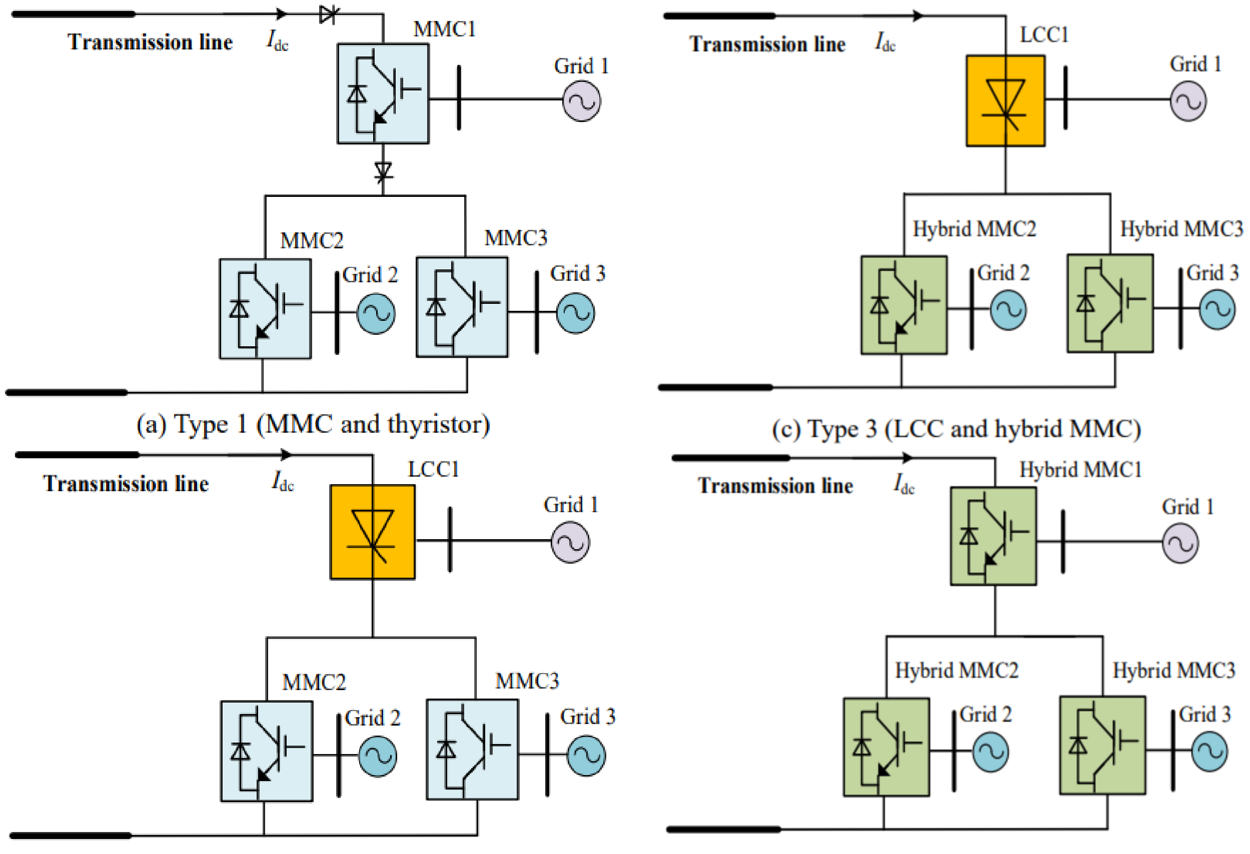


图1 2035年送广东直流示意图

Comparison of Hybrid Converter

Technical features	Type 1	Type 2	Type 3	Type 4
DC fault blocking capability	Yes	Yes	Yes	Yes
DC fault ride through	No	No	Yes	Yes
commutation failure	No	Yes	Yes	No
Operating power loss	0.6%	0.47%	0.57%	0.8%
Cost	medium	lowest	medium	highest





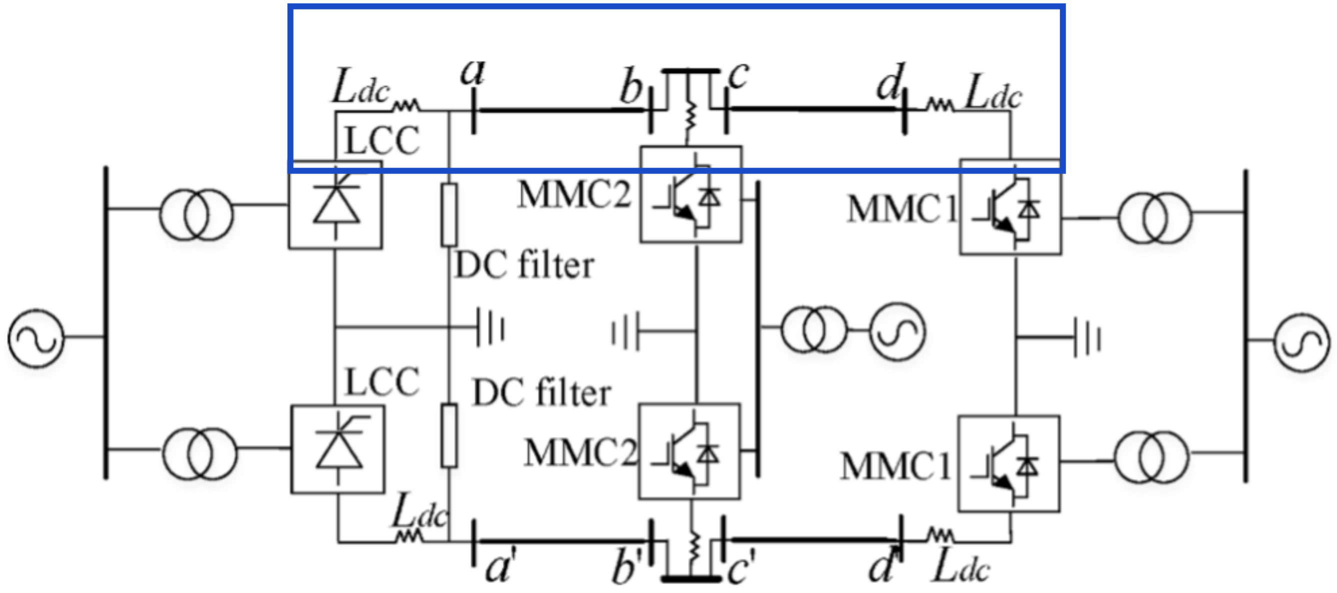
(a) Type 1 (MMC and thyristor)

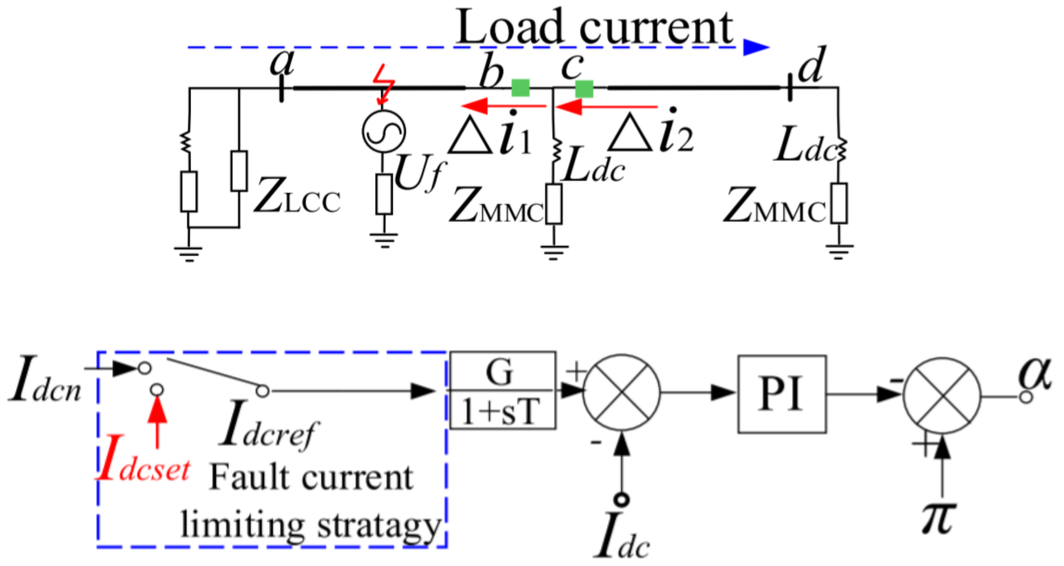
(b) Type 2 (LCC and MMC)

(c) Type 3 (LCC and hybrid MMC)

(d) Type 4 (hybrid MMC)

HVDC Protection – Control Affecting Fault Current and Stability





Fault Current Limiting by Gate Shutting

With **Full Bridge** Submodules, it provides **negative voltage level** output capacity, the sum of differential equation of 3-phase bridge arm current can be obtained by

$$-R_{arm}i_{dc} - L_{arm}\frac{di_{dc}}{dt} + \frac{3}{2}U_{dref} = \frac{3u_{dc}}{2}$$

When fault impedance exists in fault branch, the equation of DC side fault is as follows.

$$R_{dc}i_{dc} + R_f i_{dc} + L_{dc}\frac{di_{dc}}{dt} = \frac{u_{dc}}{2}$$

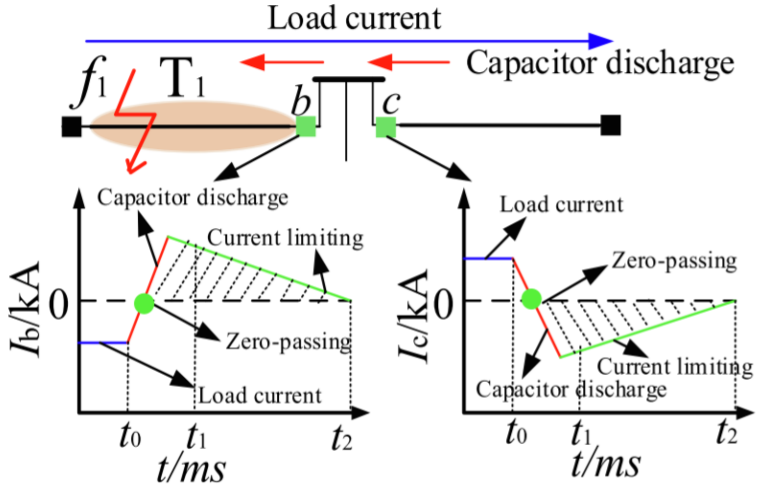
Combining the equations, the DC side current $i_{dc}(t)$ of the DC side port of MMC can be expressed as

$$i_{dc}(t) = [i_{dc(2)} - i_1(t_1)]e^{-\frac{(R_{arm}+3R_{dc}+3R_f)}{L_{arm}+3L_{dc}}(t-t_1)} + i_1$$

$$i_1 = \frac{3}{2}\frac{U_{dcref}}{R_{arm} + 3R_{dc} + 3R_f}$$

HVDC Protection – Control Affecting Fault Current and Stability

Fault at T_1

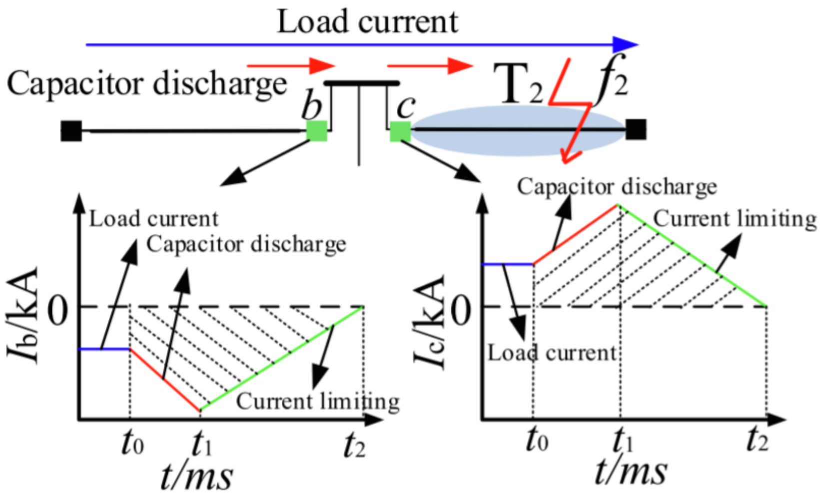


Due to **load current** at initial moment of fault, fault current cannot be changed suddenly with inductance. When load current is ignored, *b* should have current in greater **magnitude** than *c* with **opposite polarity**. Hence

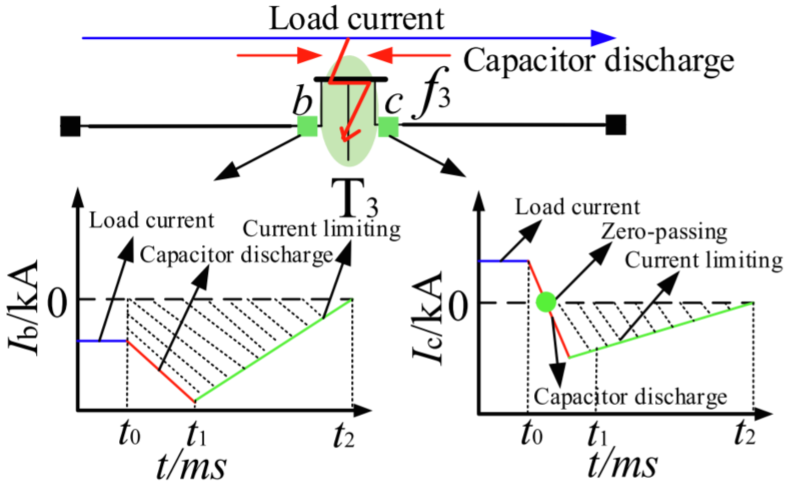
$$\sum_{i=1}^{n} \frac{I_b(i)}{I_c(i)} < 0, \qquad \sum_{i=1}^{n} I_b(i) > 0, \sum_{i=1}^{n} I_c(i) < 0$$

Where n is the sampling point.

Fault at T_2



Fault at T_3



Similarly for T_2,

$$\sum_{i=1}^{n} \frac{I_b(i)}{I_c(i)} < 0,$$

$$\boxed{\sum_{i=1}^{n} I_b(i) < 0, \sum_{i=1}^{n} I_c(i) > 0}$$

Conclusion

HVDC with multiple sections allow **fault sectionalizing** with current sum polarity.

HVDC Protection – Control Affecting Fault Current and Stability

Trigger Criterion

$$\frac{1}{m}\sum_{k=1}^{m}|I(k)| > I_{set} \quad \text{or} \quad \frac{1}{m}\sum_{k=1}^{m}|U(k)| < U_{set}$$

Consider the coupling effect of bipolar, it is necessary to increase the criterion of **fault pole selection**.

Positive PTG: $$\frac{\frac{1}{m}\sum_{k=1}^{m}|I_p(k)|}{\frac{1}{m}\sum_{k=1}^{m}|I_N(k)|} > k_{set1}$$

Negative PTG: $$\frac{\frac{1}{m}\sum_{k=1}^{m}|I_p(k)|}{\frac{1}{m}\sum_{k=1}^{m}|I_N(k)|} < k_{set2}$$

PTP: $$k_{set2} < \frac{\frac{1}{m}\sum_{k=1}^{m}|I_p(k)|}{\frac{1}{m}\sum_{k=1}^{m}|I_N(k)|} < k_{set1}$$

where k_{set1} and k_{set2} are set to 1.2 and 0.8 respectively.

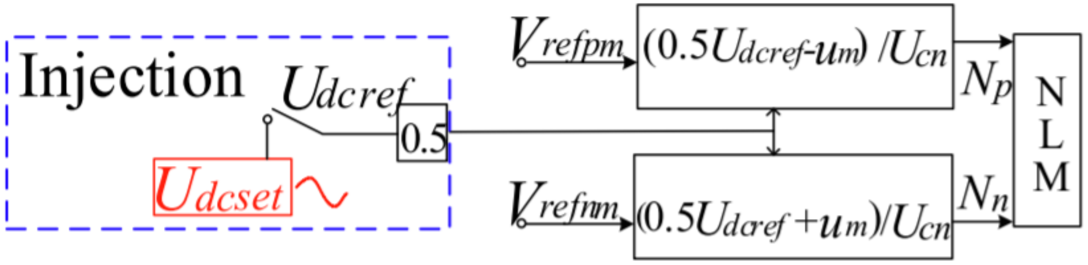
Protection Criterion

When a positive PTG fault or PTP fault occurs on DC system, combining with the result of fault pole selection, the polarity characteristics of b and c helps **identify faulty area**.

$$T_1: \begin{cases} \sum_{i=1}^{n}\frac{I_b(i)}{I_c(i)} < 0 \\ \sum_{i=1}^{n} I_b(i) > 0, \sum_{i=1}^{n} I_c(i) < 0 \end{cases} \qquad T_2: \begin{cases} \sum_{i=1}^{n}\frac{I_b(i)}{I_c(i)} < 0 \\ \sum_{i=1}^{n} I_b(i) < 0, \sum_{i=1}^{n} I_c(i) > 0 \end{cases}$$

Signal Injection Process

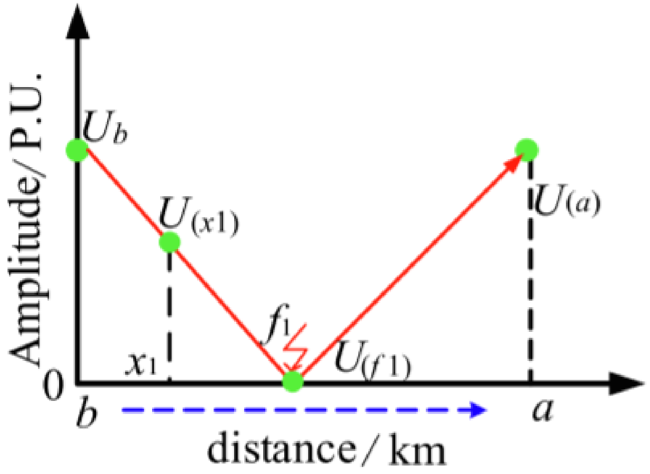
It is to aid converter blocking with signal injection.

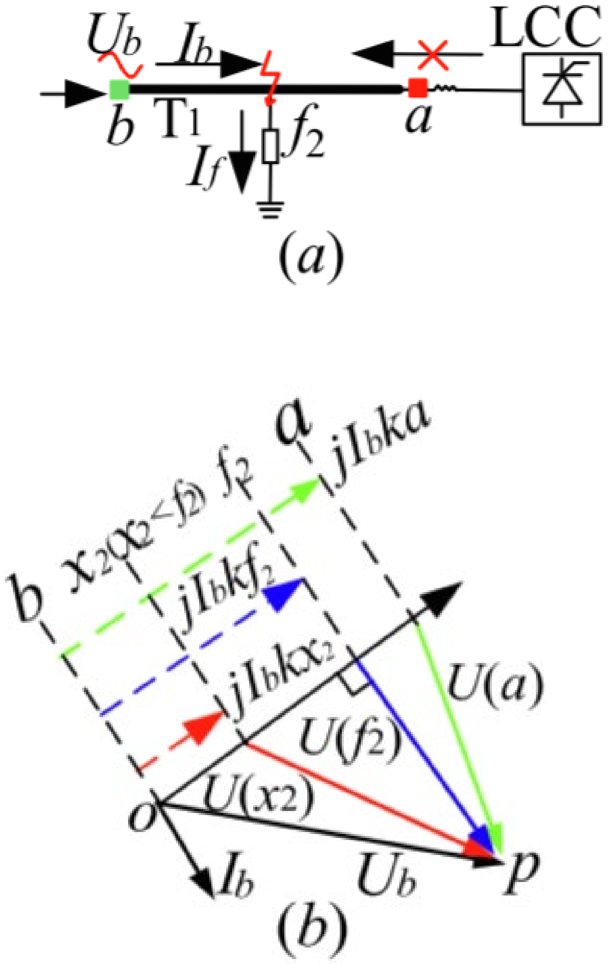


HVDC Protection – Control Affecting Fault Current and Stability

Voltage Based Fault Location

Considering the amplitude of signal injection, fault location can be executed.





Impedance Based Fault Location

When x_2 is shorter than the fault distance f_2, the amplitude of voltage $U(x_2)$ can be expressed as

$$|U(x_2)| = |U_b - jI_b k x_2|$$

Condition under AC Faults vs DC Faults

AC fault:

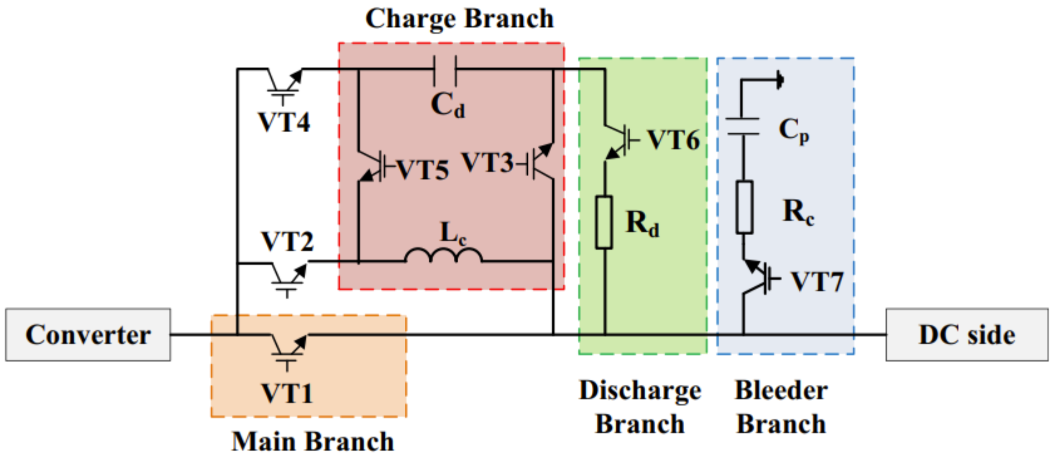
- Voltage drops at PCC and the converter supplies a voltage dependent reactive current to stabilize the voltage.
- Converter is capable to supply short circuit current up to the rating of the converter until it changes to another state (e.g. current limiting).

DC fault:

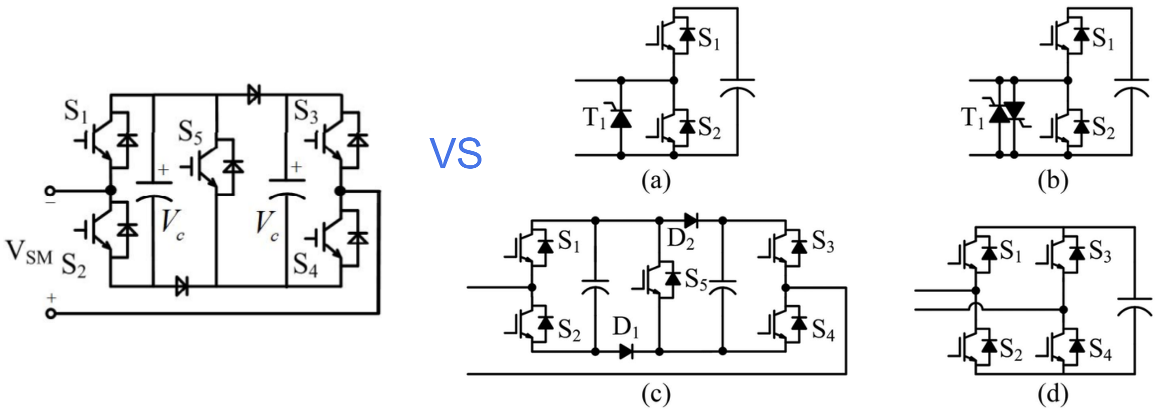
- DC Fault is harmful with large capacitor discharge current with large rate-of-rise.
- Converter Action: Fault current blocking time depends on submodule topology. Yet, fast blocking means difficulties in fault location.
- In Half-bridge (HB) SM, IGBT is blocked and AC CBs at both end must interrupt fault current. It is detrimental to converter. In Full-bridge (FB), fault current can be controlled similar to LCC based system.

Note: Some VSC designs require complete discharge of capacitors before the converter can change the operating state. It can lead to a shutdown of 90 min.

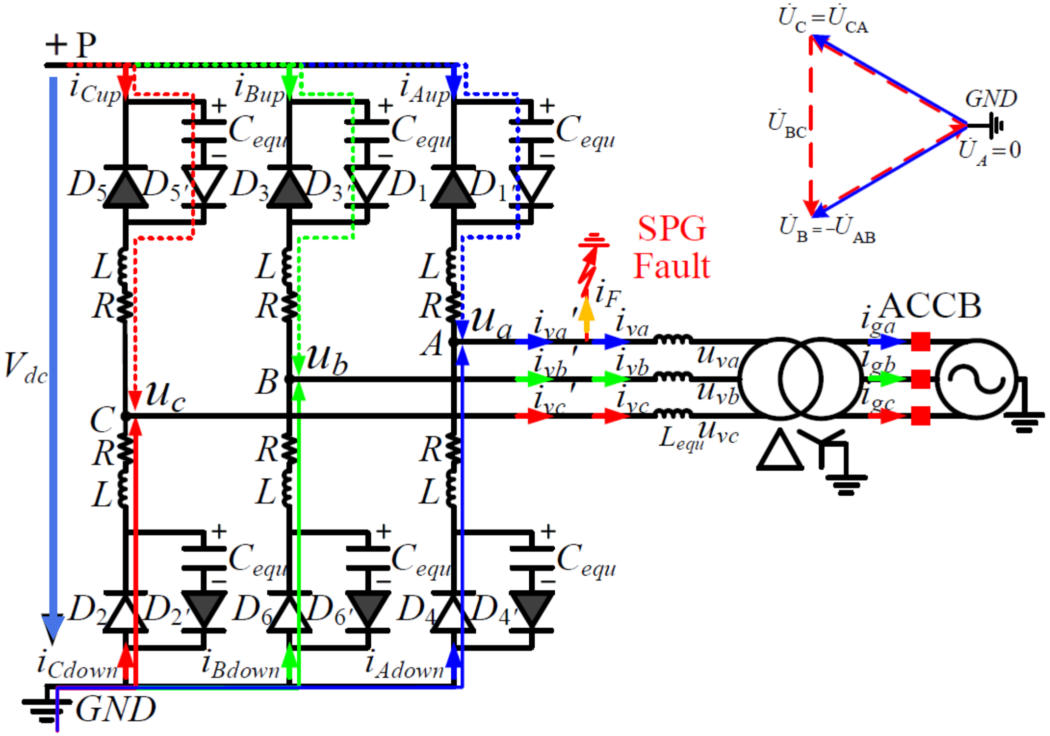
Fault Clearance Module

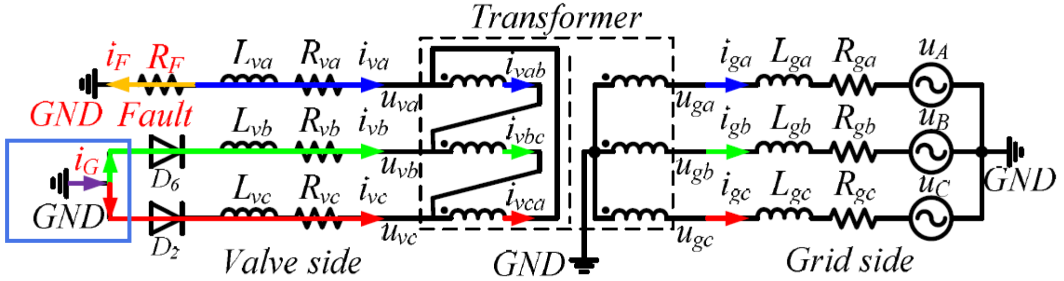


Clamped Double Submodule (CDSM)



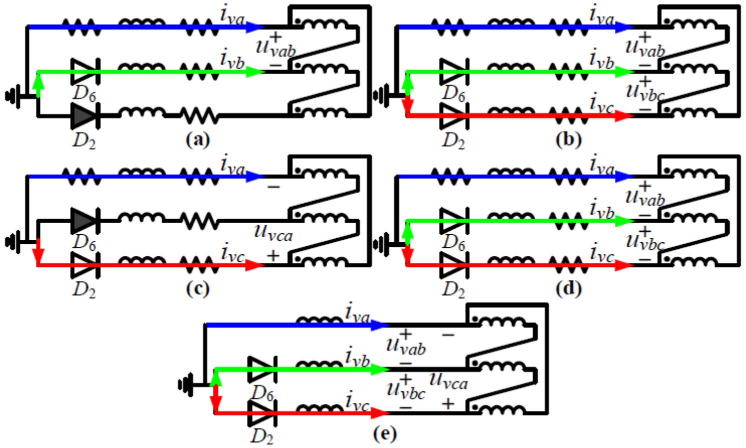
Valve Side Fault





CONDUCTING MODES OF THE DIODES D_2 AND D_6

Conducting modes	I	II	III	IV	I	…
Conducting diode(s)	D_6	D_2&D_6	D_2	D_2&D_6	D_6	…



Upper Arm Overvoltage

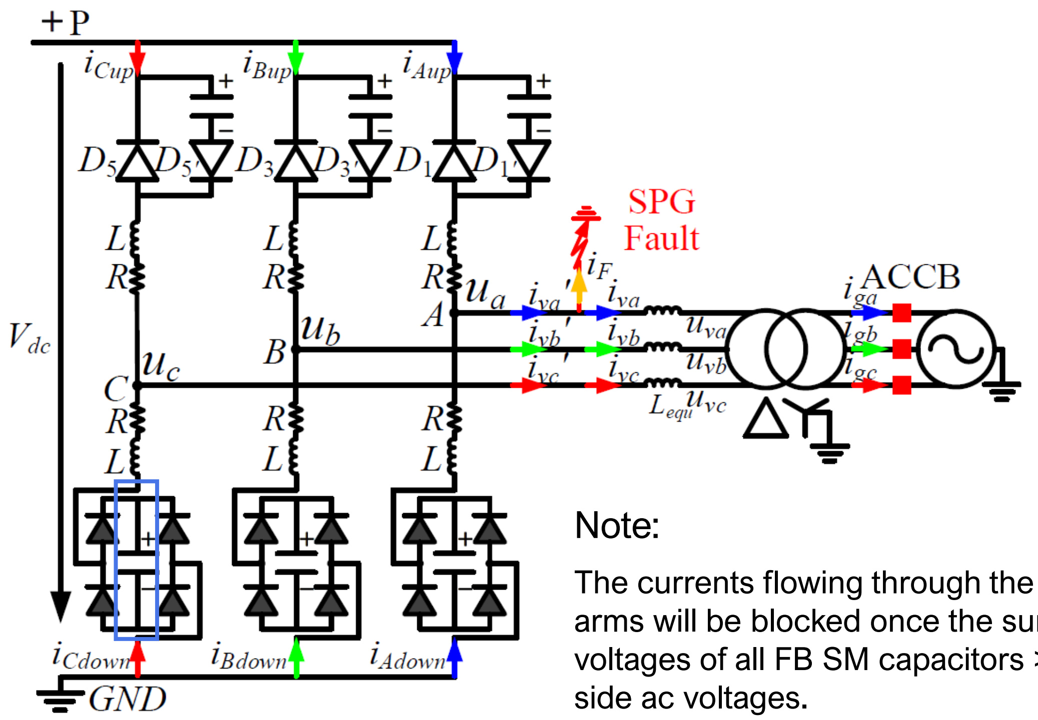
- Diode D_1, D_3, D_5 is reverse-biased once the converter is blocked. Upper arm capacitors are charged due to DC side transient overvoltage caused by the fault. The upper arm capacitor of non-faulted phase are **charged** in every negative half-cycle. Large arm reactance L and transformer leakage reactance L_{equ} increases the overvoltage.

No Zero-Crossing Fault Current

- With post-fault voltage $u_a = 0$, diode $D_{4'}$ is reverse-biased and current decays to zero naturally. With total voltage at each arm equals to V_{dc} at normal operation, $D_{2'}$ and $D_{6'}$ are reverse-biased and lower arm SM capacitors voltage remain constant.

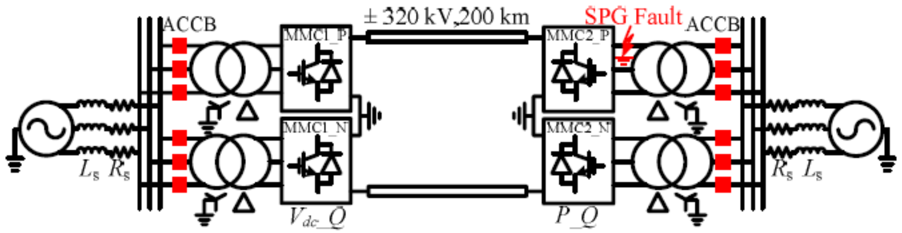
- Yet, lower arm of non-faulted phase will conduct large fault current in negative half cycle with no zero-crossing due to its high DC components.

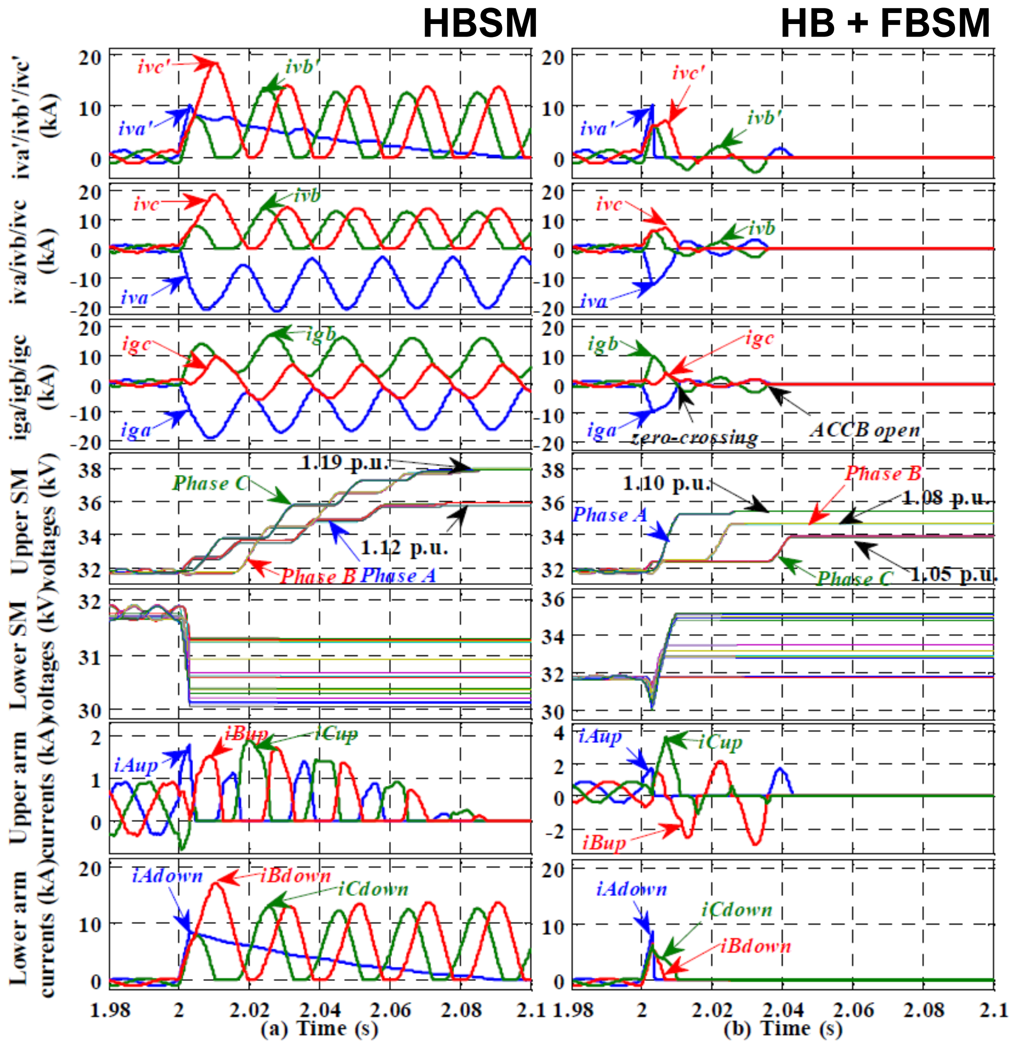
Valve Side Fault – Hybrid MMC



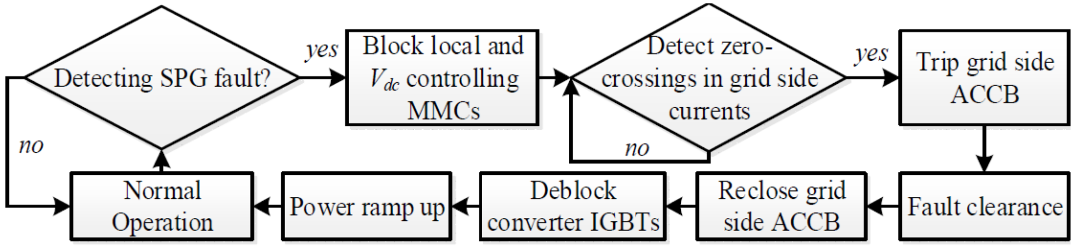
Note:

The currents flowing through the lower arms will be blocked once the sum of the voltages of all FB SM capacitors > valve-side ac voltages.

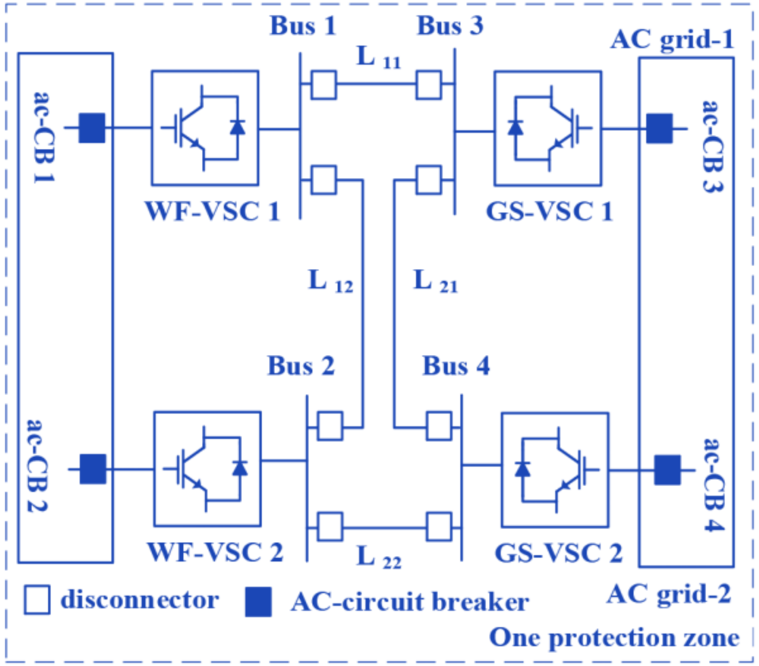




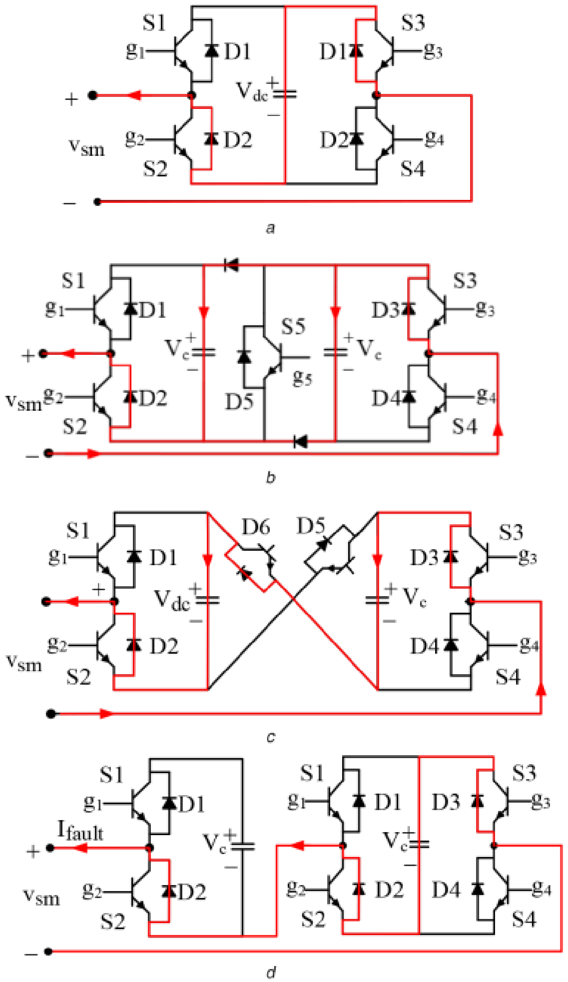
Protection Scheme under Valve side fault



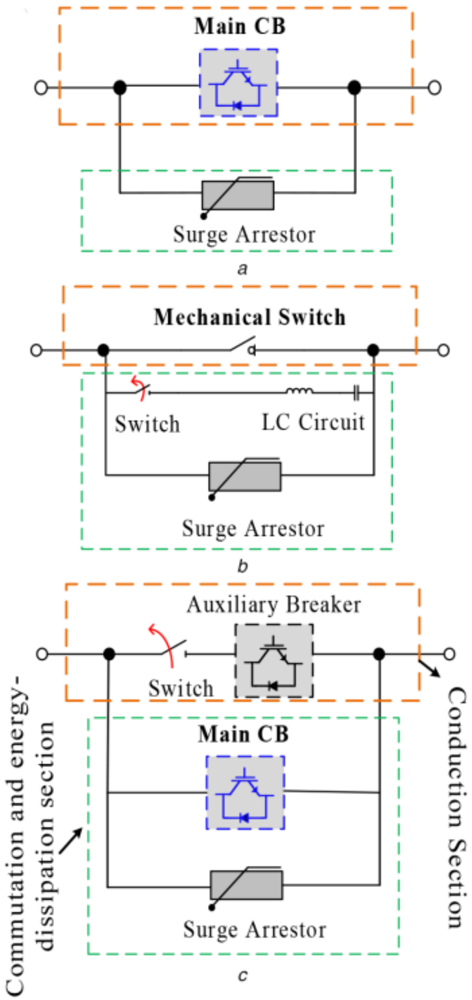
DC Fault Clearance



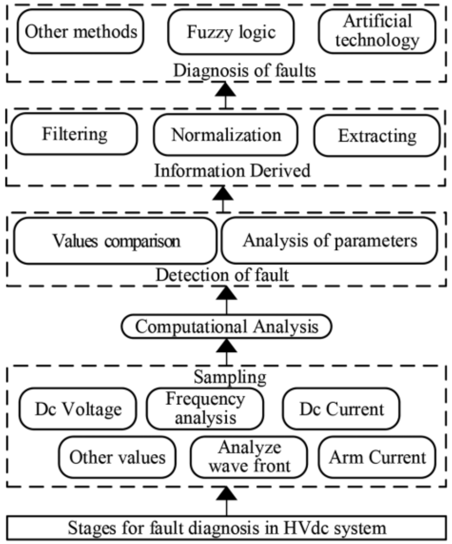
Fault Current Path with Blocked SM



Types of DC Circuit Breaker



Fault Diagnosis Process



DC Fault Clearance requires:

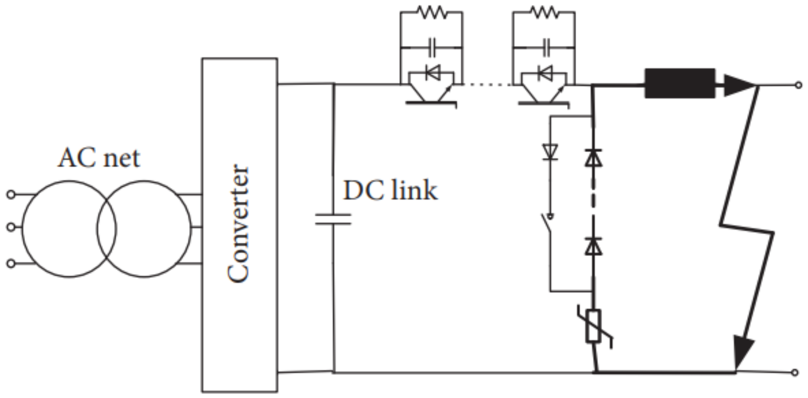
- Disconnection of Capacitor
- Isolation to DC side
- Isolation to AC side
- Action towards fault energy (dissipate by resistance / absorbed by source)

Detection Method:

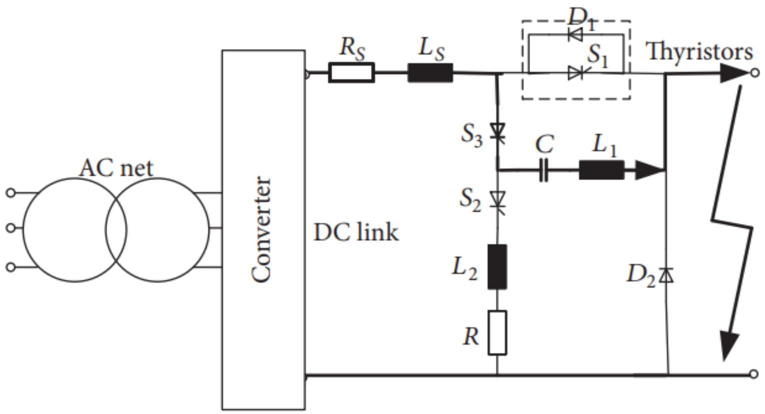
- MMC arm current
- DC Overvoltage
- Capacitor Discharge
- Converter Output I
- Rate-of-Rise of DC
- DC Reactor Voltage
- Travelling Wave Theory
- Machine Learning

DC Fault Clearance: Other Types of CB

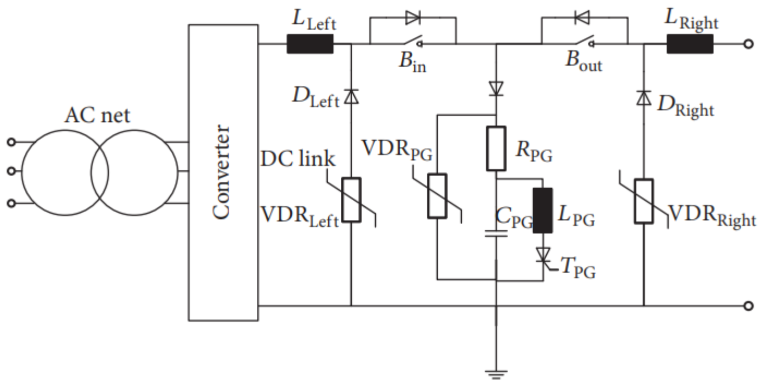
All Solid Breaker



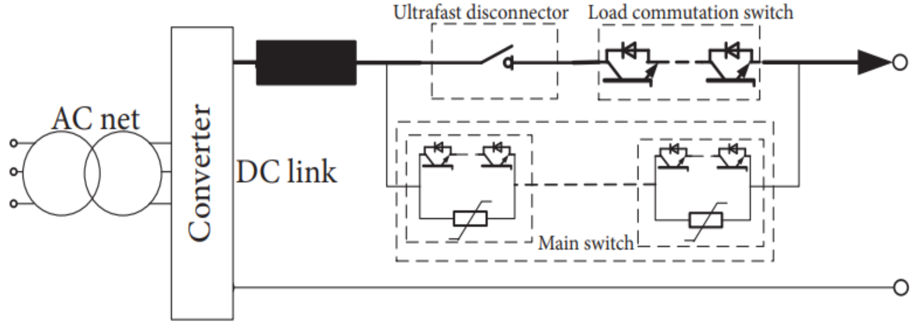
All Solid Breaker (2nd Type)

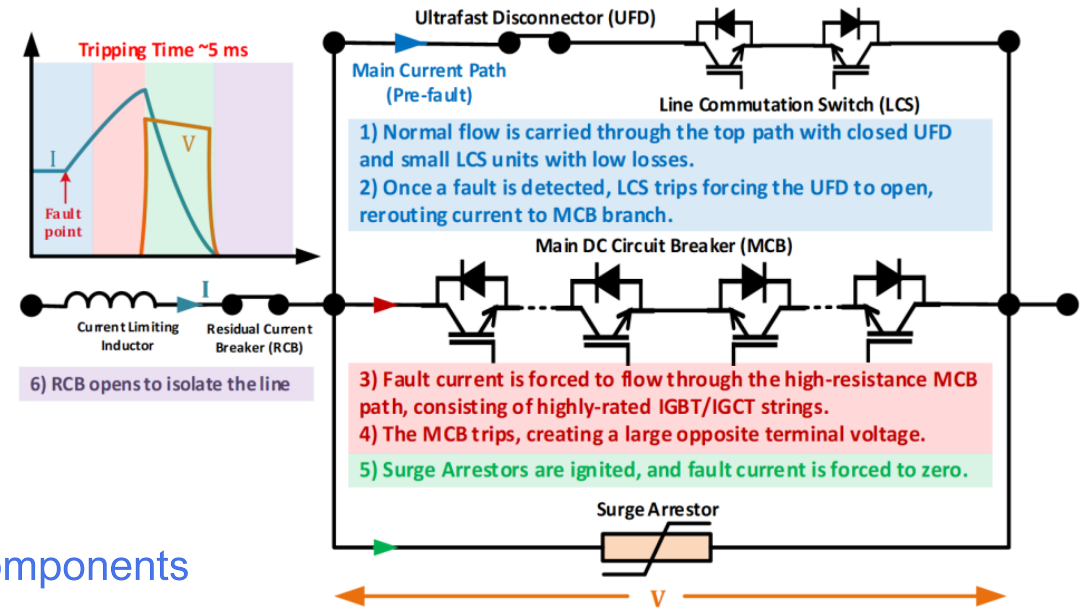


Resonant Breaker



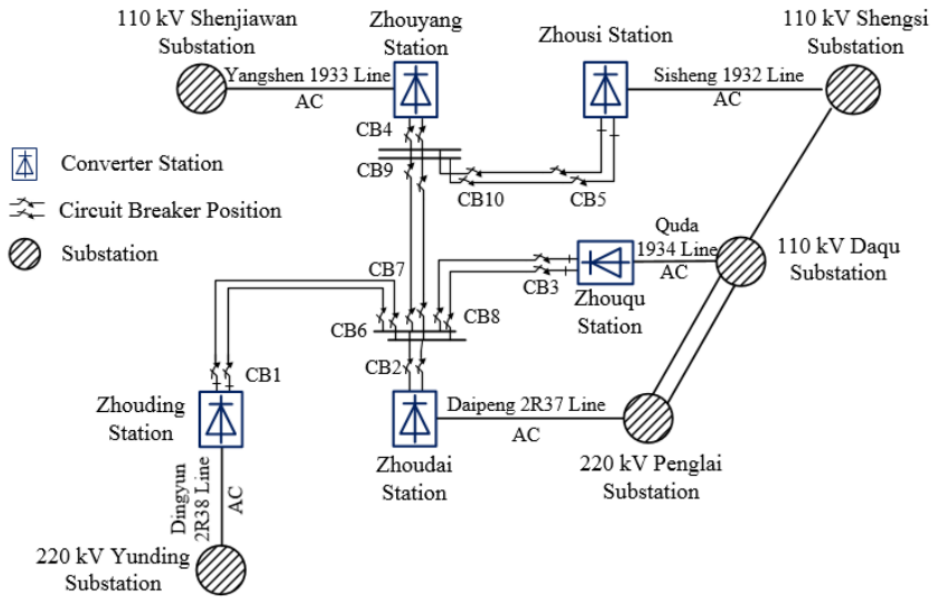
Hybrid Breaker





Other Components

DC Fault Clearance: Other Types of CB



Zhaoshan Project – HVDC CB

Main branch: Conduct the load current
Commutation branch: Interrupt the short-circuit fault current
Energy absorption branch: Absorb the short-circuit current

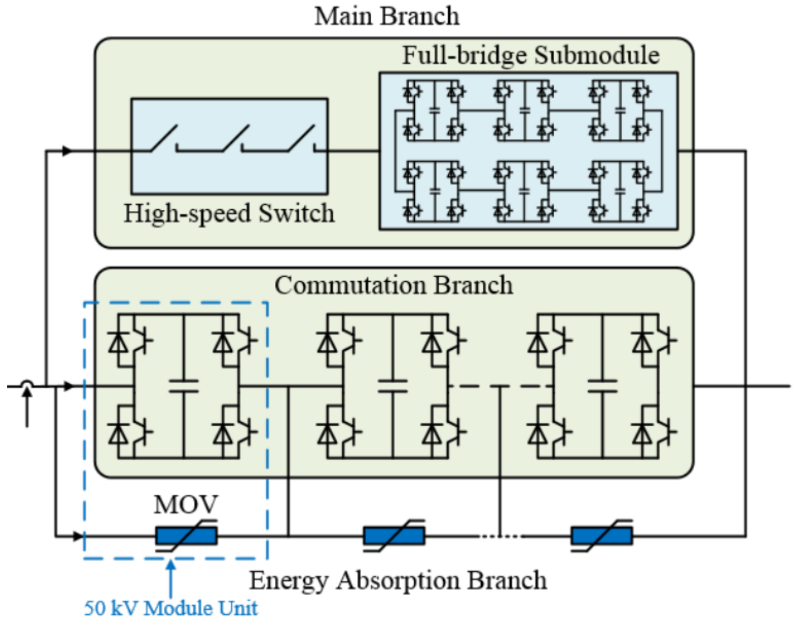
Steady-State Operating Condition

Load current mainly passes through the main branch due to its lower conducting resistance.

DC Short-Circuit Fault

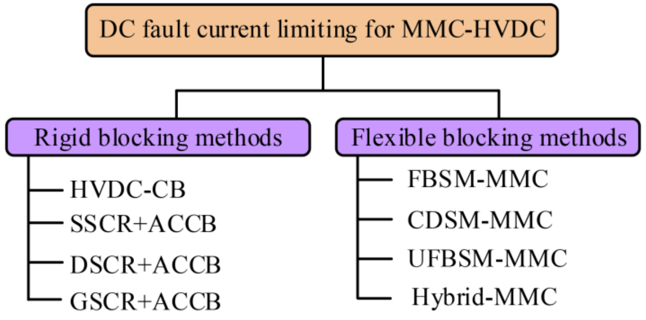
IGBTs of full-bridge modules in the main branch will turn off, then the current is transferred to the commutation branch and drops rapidly to 0, and the high-speed switches are open. When the CB voltage reaches the protection threshold of the arrester, the current will be transferred to the energy absorption branch until it drops to 0, achieving current interruption and fault isolation.

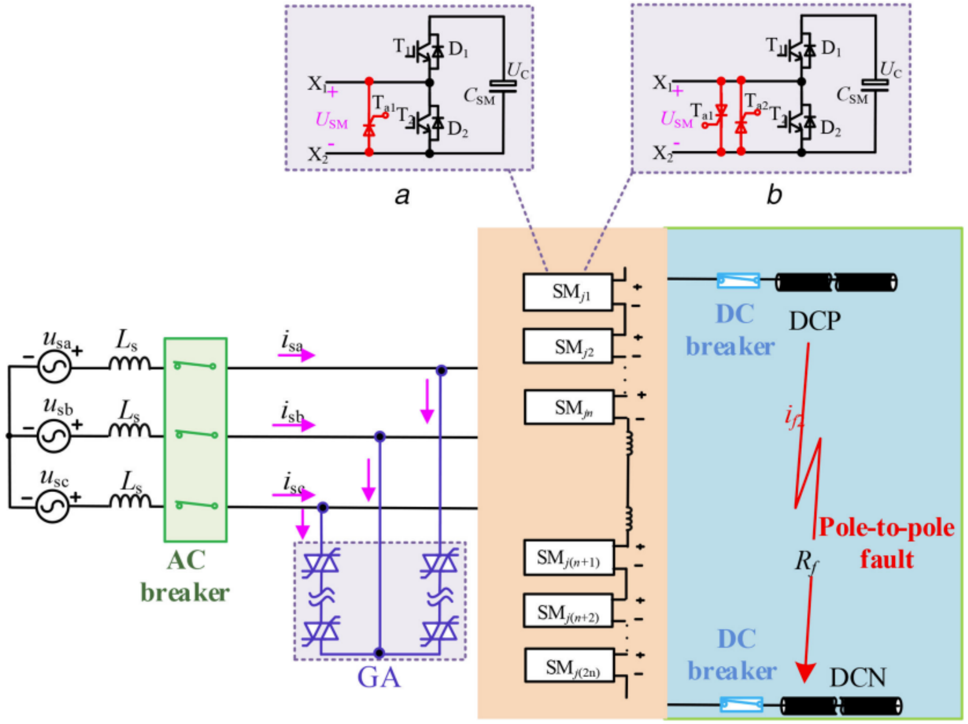
Interruption current of HVDC CB: 15kA 3ms.
Withstand current of HVDC CB: 15kA, 5s; 40kA, 5ms
Thermal Capacity: 8kA



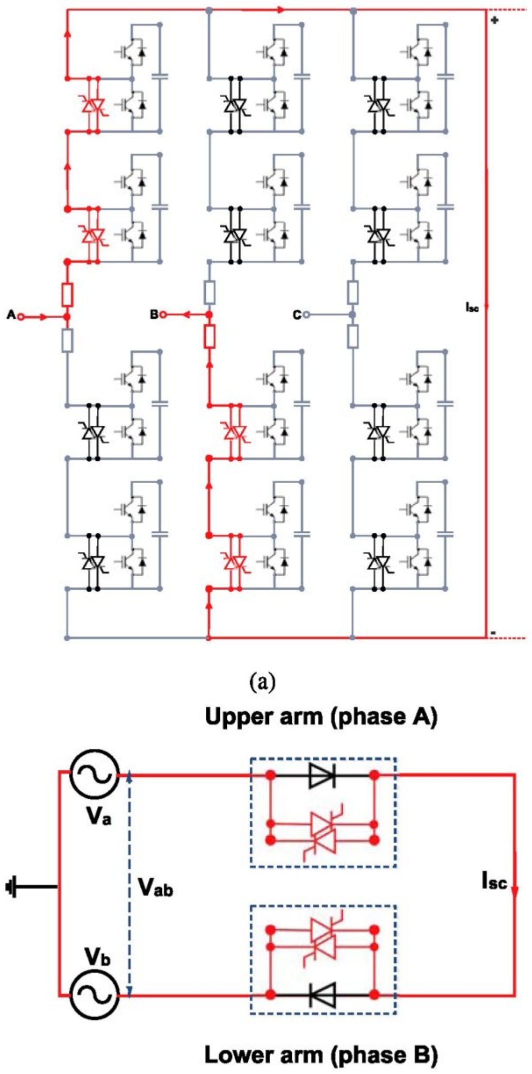
DC Fault Clearance

Note: DC Current Blocking is to block current from AC source continuous feeding.

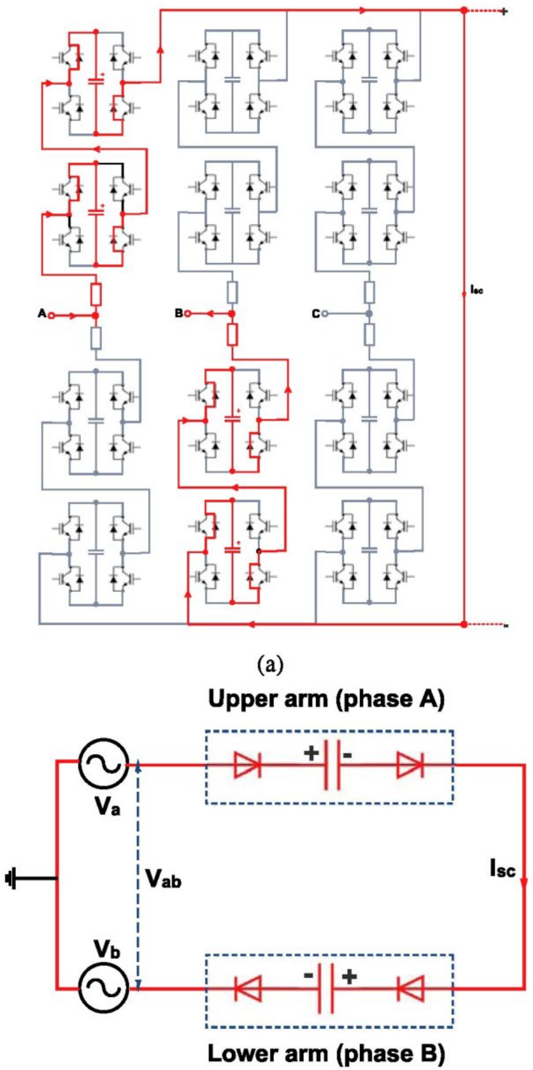




c



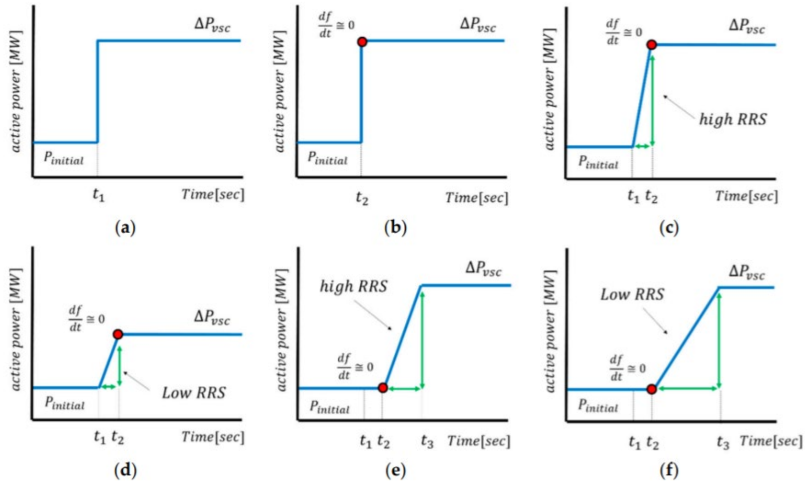
(b)



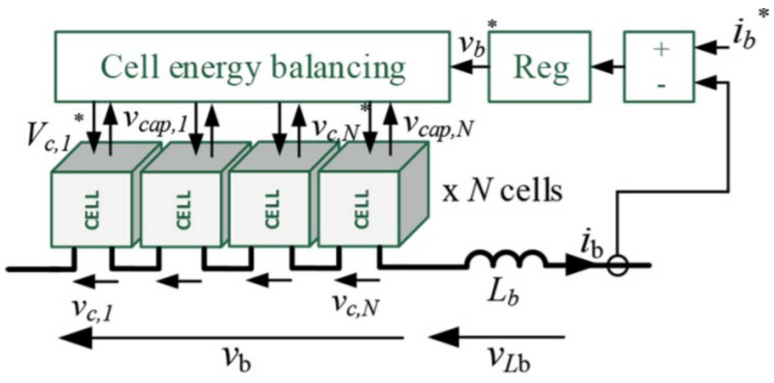
(b)

Requirement on Converter Control

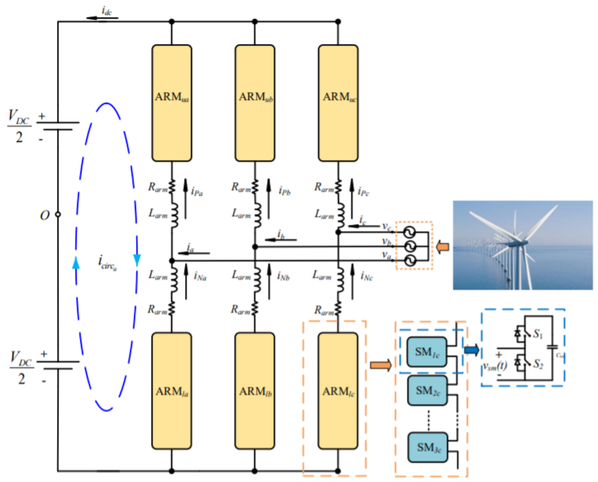
Active Power Control



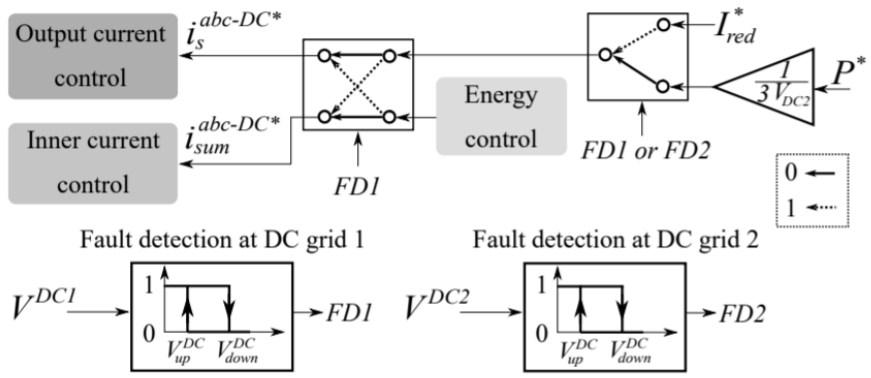
Energy Balance within Converter



Circulating Current Minimization



DC Fault Capability



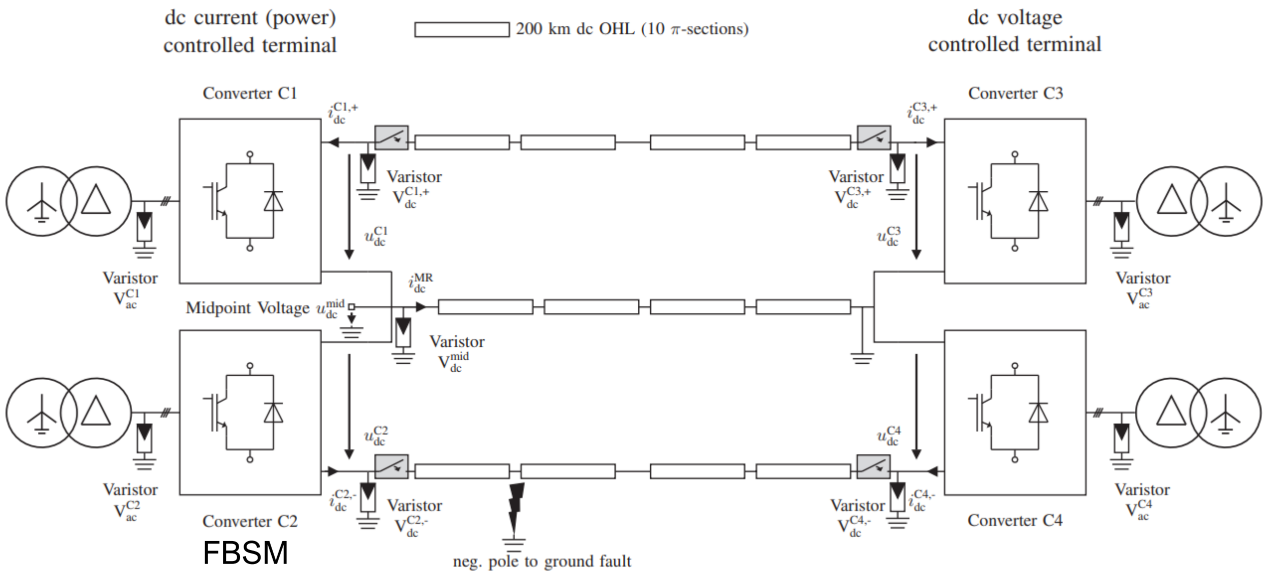
Note:

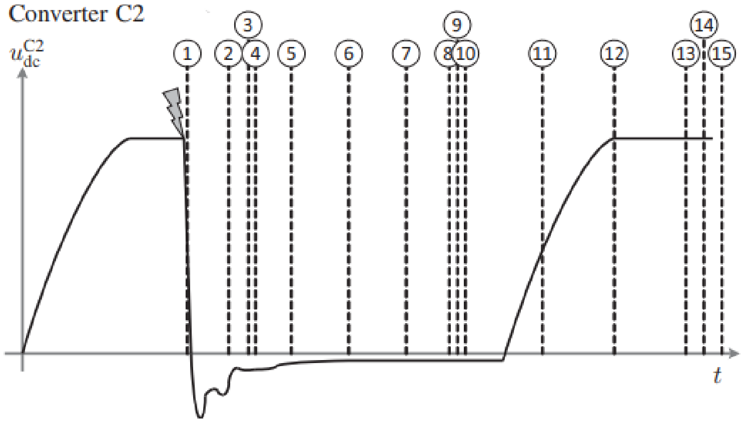
- Energy Balance is enabled under fault condition with appropriate controller design (with FRT capability) and converter (e.g. FBSMs).
- To minimize AC circulating current, AC side voltage for FB and HB can be selected as:

$$V_{FB}^{AC} = \min(N_l V_{SM} - V^{DC2}, N_u V_{SM} - V^{DC1} + V^{DC2})$$

$$V_{HB}^{AC} = \min(N_l V_{SM} - V^{DC2}, N_u V_{SM} - V^{DC1} + V^{DC2}, V^{DC2}, V^{DC1} - V^{DC2})$$

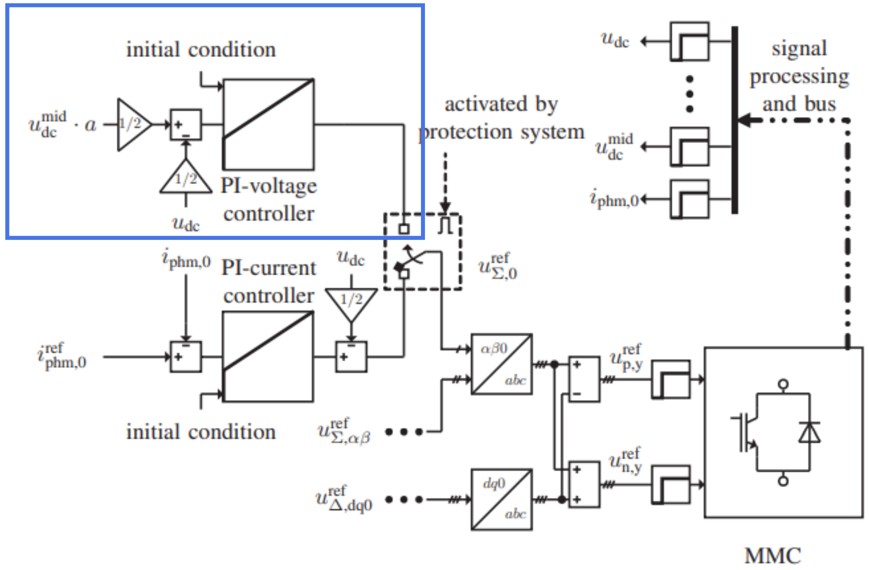
Active Fault Management on Bipolar FBSMs with Metallic Return

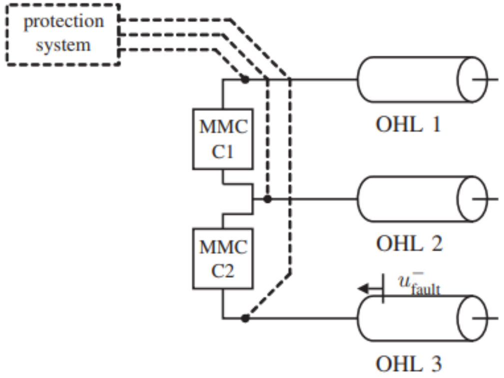




Fault ride through sequence of Terminal C1/C2:

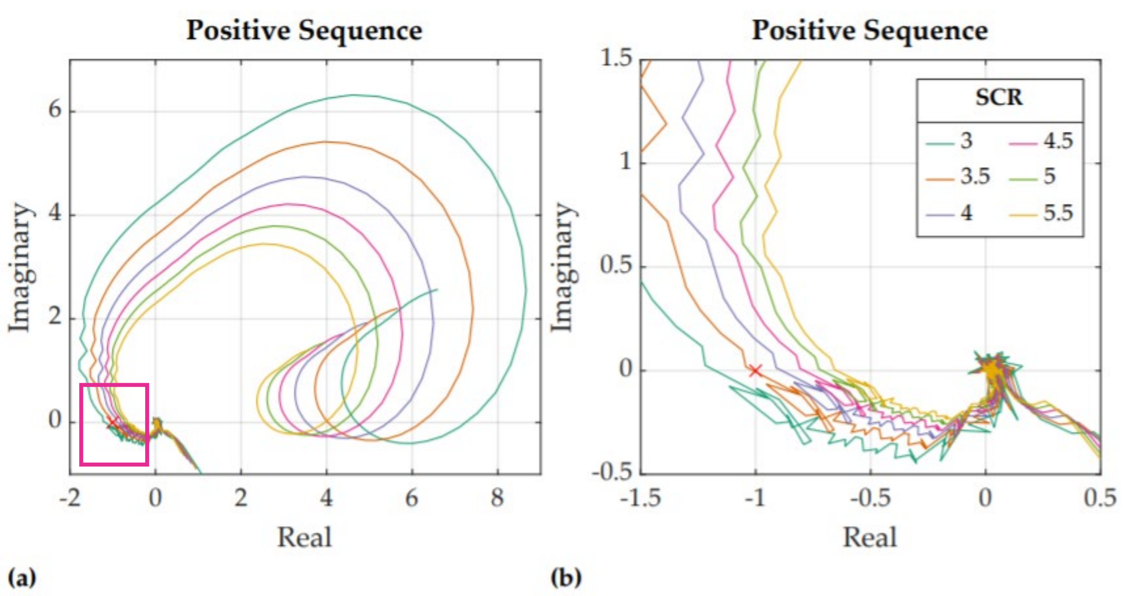
- t_1: fault detection
- t_2: $i_{dc}^{C2,-} = 0$ A, disconnector C2 opens
- t_3: start midpoint control
- t_4: power ramp up of converter C1
- t_5: midpoint control steady state reached
- t_6: *earthing of disconnected line (triggered by Terminal C3/C4)*
- t_7: *earthing of disconnected line completed*
- t_8: disconnector C2 reclosure
- t_9: return to dc current control mode
- t_{10}: wait for dc voltage to return
- t_{11}: $u_{dc} = 0.5pu$
- t_{12}: reactivate total energy balancing
- t_{13}: reactivate horizontal balancing
- t_{14}: reactivate vertical balancing
- t_{15}: power ramp up





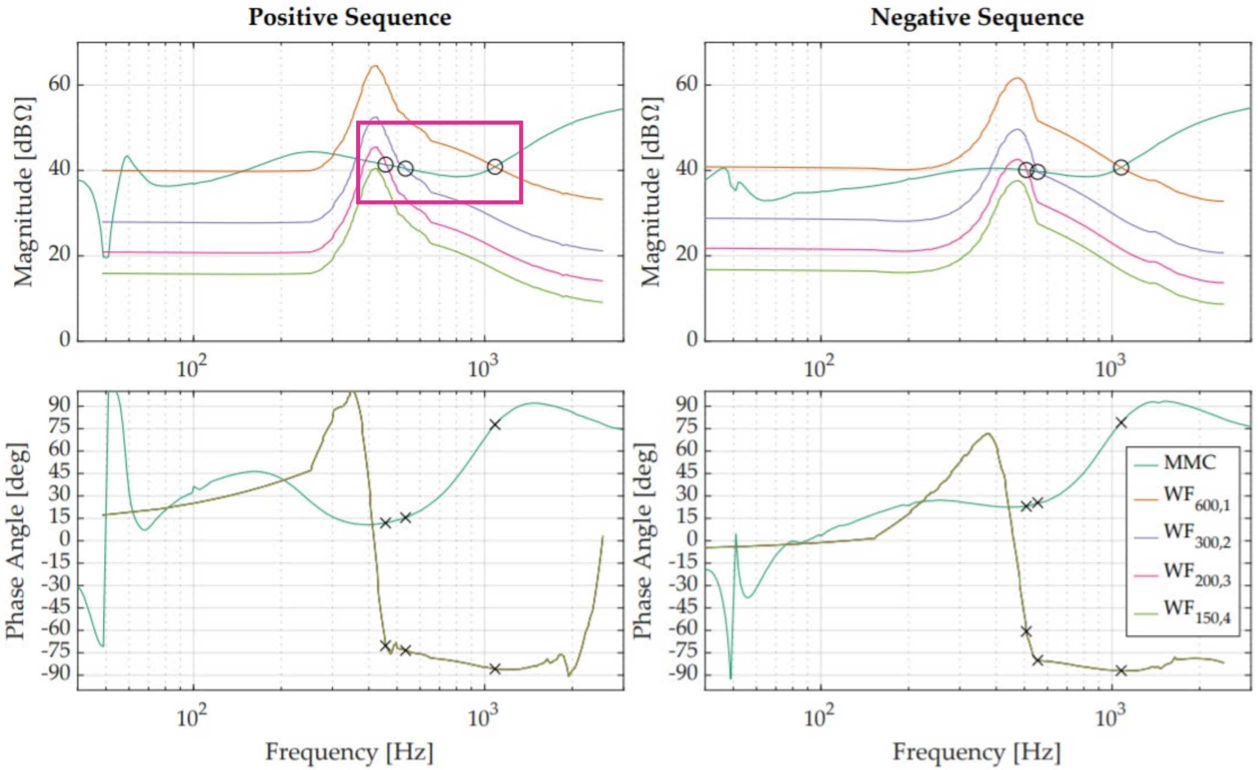
Interaction between Wind Power and HVDC Converters

MMC in grid-following mode and AC grid with positive sequence perturbation:



Note:
For a short circuit ratio (SCR) = 3.5 (or > 3.5), the (-1, j0) point is encircled and it indicates an **unstable system**.

Interaction between grid forming MMC and offshore wind farm impedance ratio for different farm layout.

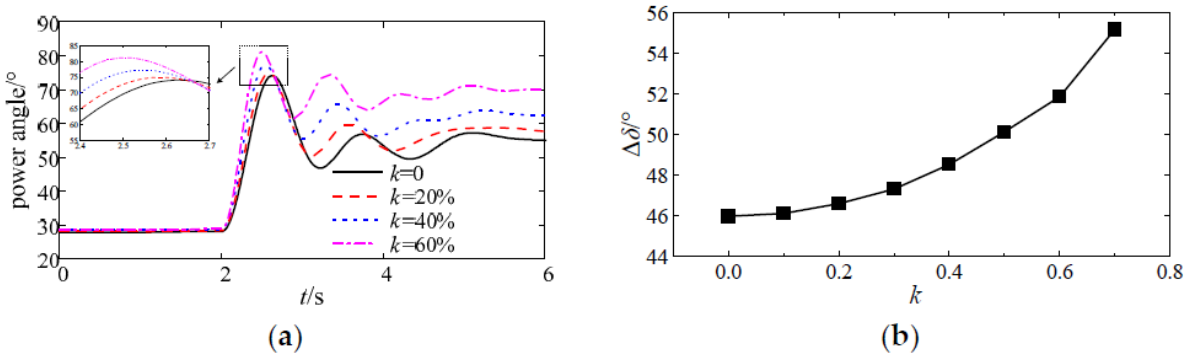


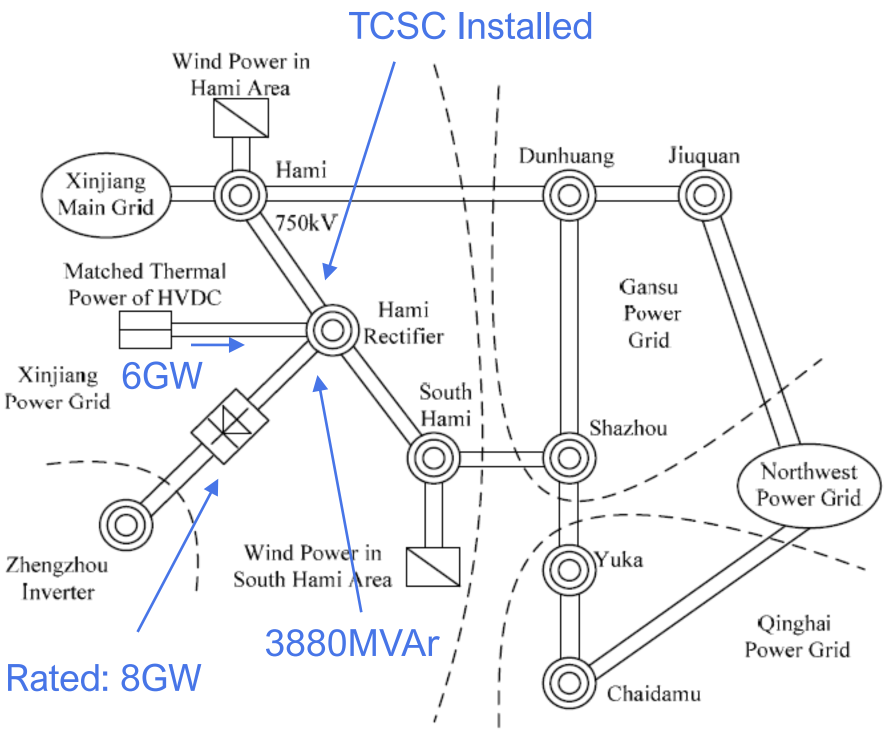
Note:
Small change in VSC and MMC impedance trajectory can cause system instability. Change in Control system can modify its system impedance and leading to negative PMs.

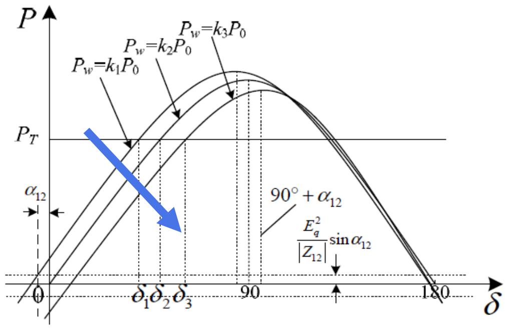
Interaction between Wind Power and HVDC Converters

- Normal Operation:
  Increase of Wind Power will increase initial rotor angle with increasing k when P_M and operating condition of thermal plant unchanged.
- UHVDC Block:
  Trend of Rotor Angle Stability under different wind power is affected by HVAC line reactance. With low reactance value, rotor angle stability worsen with increasing wind.
- UHVAC Fault:
  With a bolted fault, rotor angle stability first improves and then worsen with an increasing wind power. Increase in HVDC capacity or decrease in HVAC line reactance causes optimal wind power penetration ratio to increase.

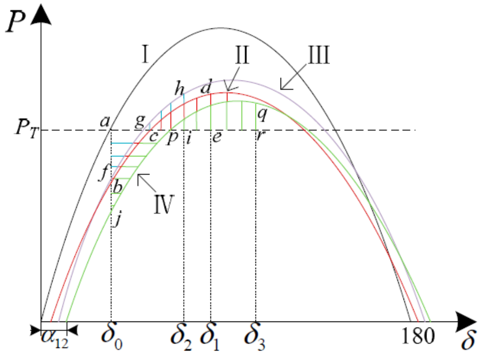
UHVDC Block when x_L is decreased by TCSC: (a) Rotor Angle (b) Max. Rotor Angle Difference.



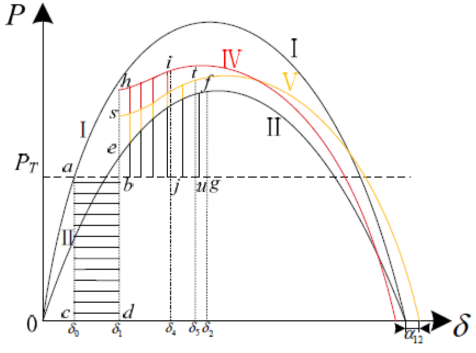




Normal, ↑ P_W



HVDC Block, ↑ P_W



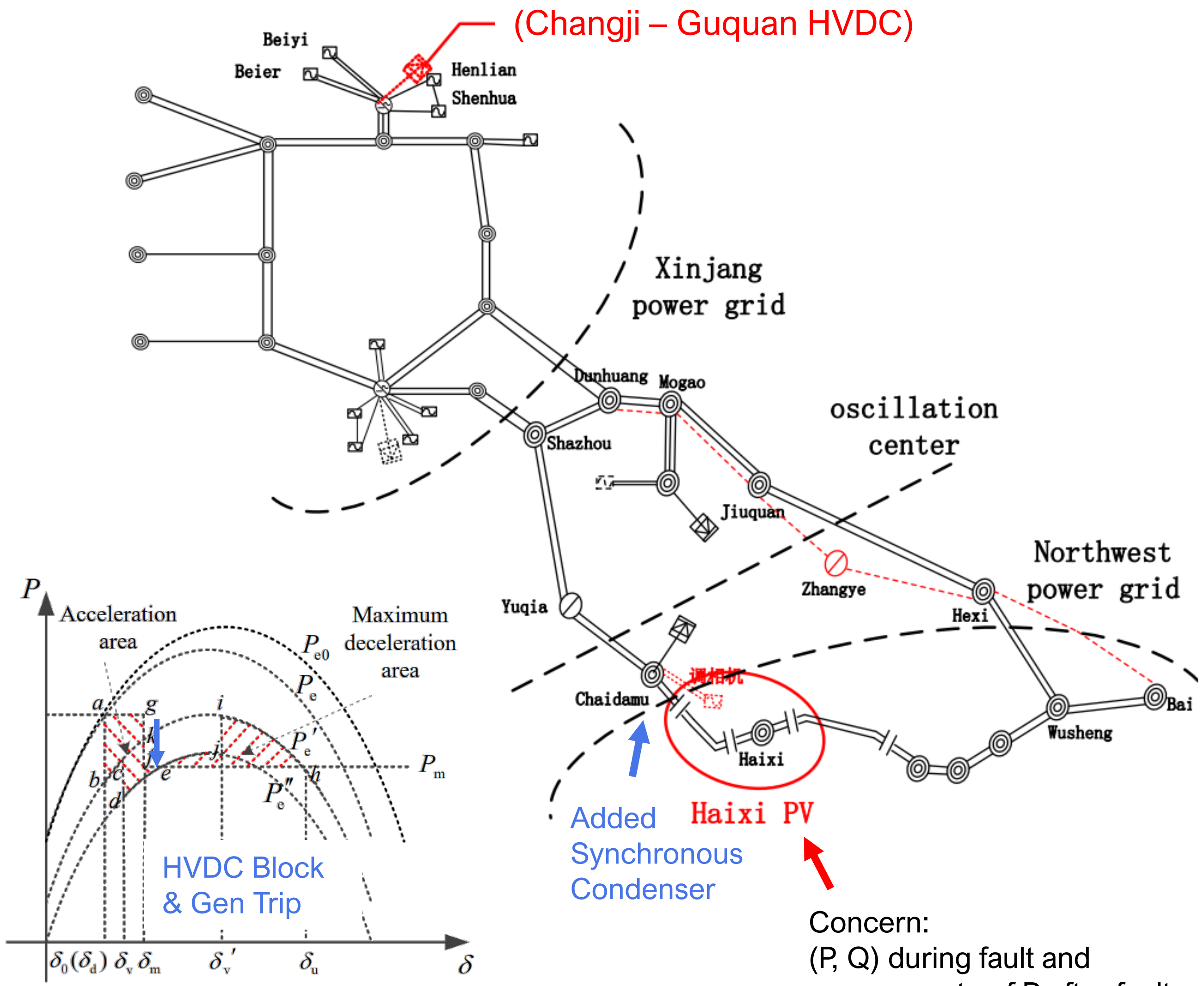
HVAC Short circuit, ↑ P_W

Interaction between PV Generation and HVDC Converters

- PV in LVRT Operation:
  If PVG terminal voltage < 0.9 pu resulted from nearby system disturbances, it will enter **LVRT process**. During LVRT, in order to avoid overcurrent of the inverter, the PVG will decrease active current to 0.1 – 0.5 pu, and increase reactive current in scale with the voltage drop (K = 1 – 2).
- Variation of PM and PE :
  HVDC block and generator trip leads to drop of mechanical power and increases deceleration area.
- Impact of Angle Increase to Voltage Stability:
  Electromagnetic torque Te decreases, and motor slip s continuously increase with decreased equivalent resistance r. Thus, if relative rotor angle continuously increases, it deteriorates the voltage stability close to the oscillation centre.

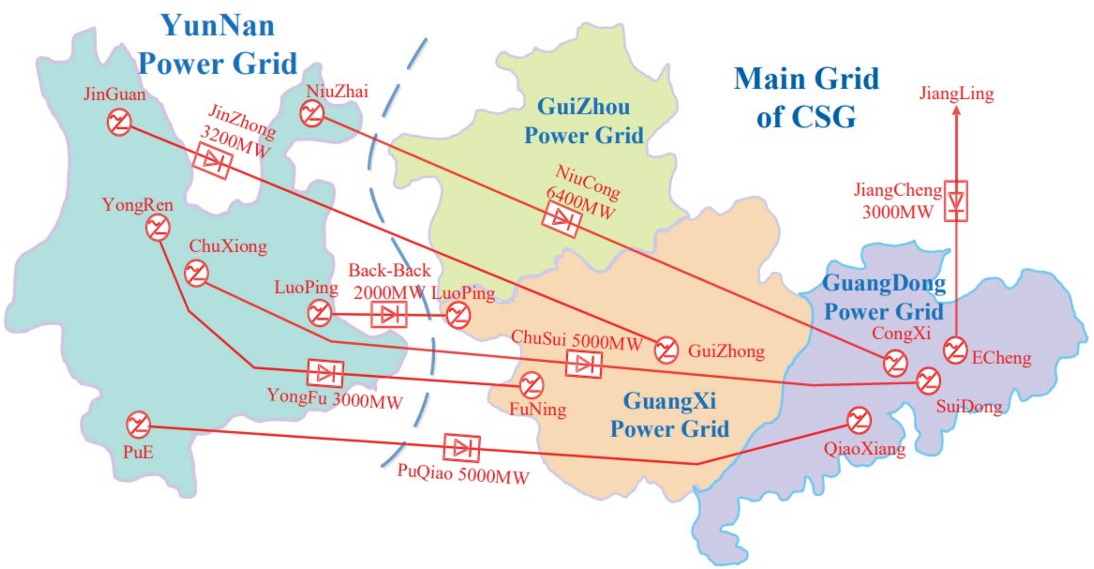
Requirement

1. Synchronous Condenser is added at Chaidamu for voltage support and allow 11GW transmission at HVDC. [Voltage instability occurs with HVDC block and > 8500MW.]
2. Added line on Dunhuang – Mogao – Jiuquan – Zhangye – Hexi – Bai to reduce X and increase angle stability margin.



Concern:
(P, Q) during fault and recovery rate of P after fault.

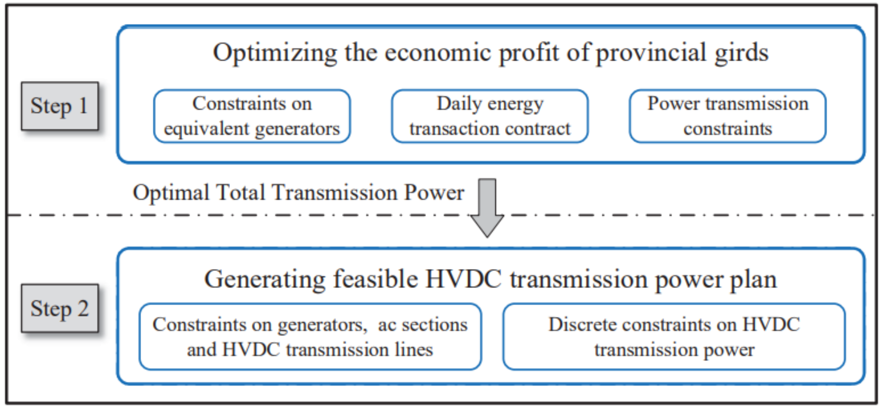
HVDC Scheduling



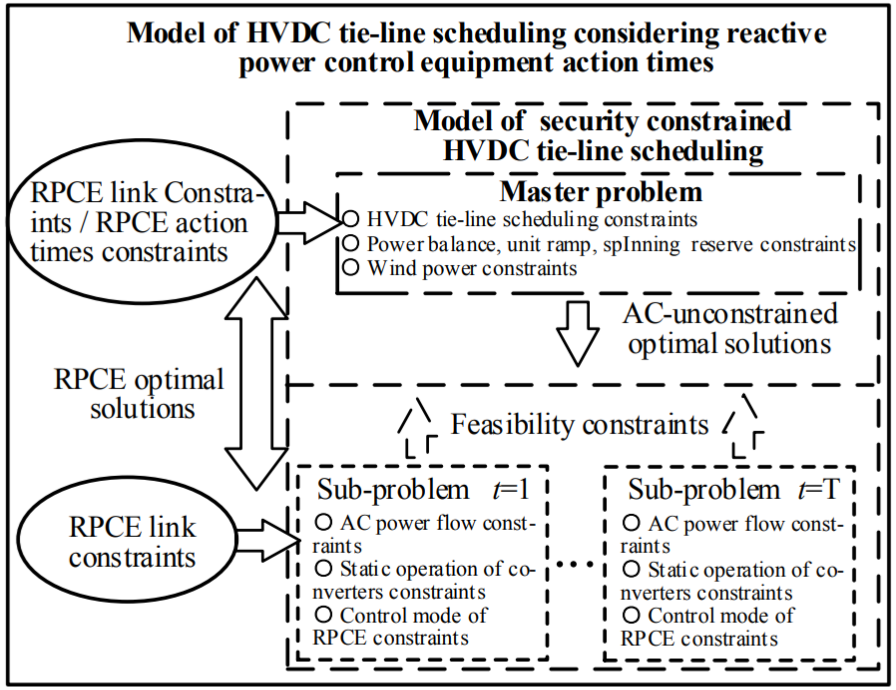
Active Power Transmission is often scheduled to HVDC (Multi-terminal) Converters and Links based on **power balance**, **regulation reserves** and **operation constraints** (line, converter rating, generation and load). The schedule may also be derived from market results or as a solution of optimization problems.

Other than active power, Reactive Power Schedule may also be defined during operational planning phases as:

- Reactive Power may limit the use of active power (restricting active power schedule)
- Reactive Power Contribution of a converter when providing active power may need to be planned according to a given schedule.



Consider also Reactive Power



DC Loop Flow with HVDC Scheduling

Congestions can be voltage, or current-related. DC loop flows transfer a power flow that causes congestion from one AC grid node to another AC grid node via at least two DC links and at least one asynchronous grid.

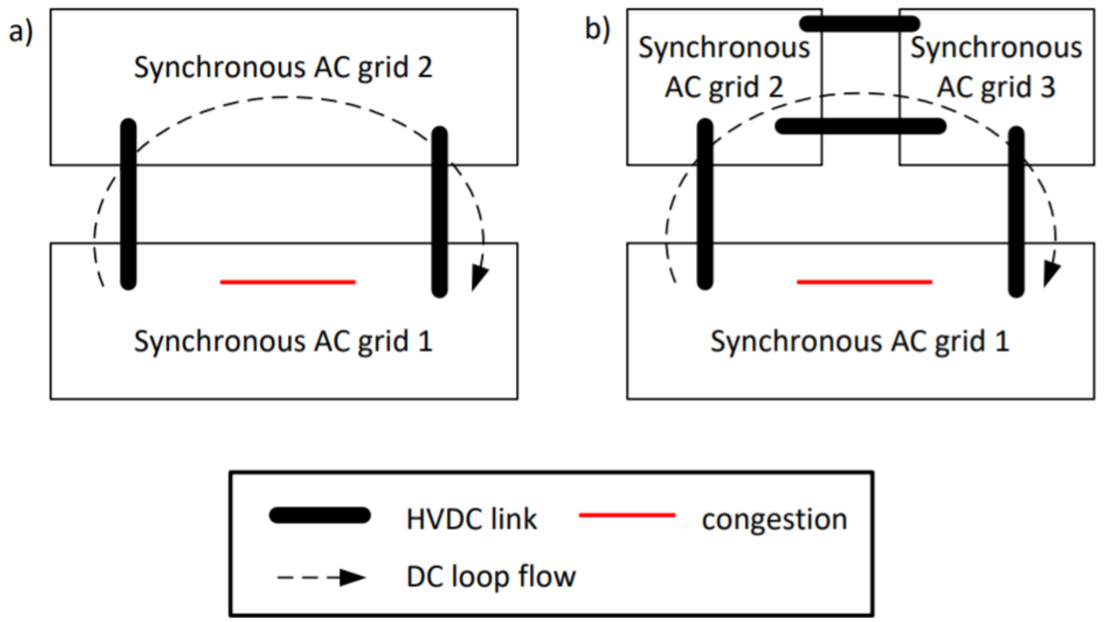
In effect, DC loop flows move power within an AC grid without loading AC equipment, thus **avoiding costly congestion management**.

Yet, the **advanced control function** of HVDC system offers the possibility of integrating **disturbance**, the local or global remedial effect can be

- Thermal Overloading (Flipping DC flow back to original AC line)
- Voltage Collapse
- Frequency Deviation

The corresponding actions introduced by the converter can be

- Full run-back / full run-up of active power
- Inductive/capacitive reactive power boost
- Parameter modification of power control (e.g. AC power control)



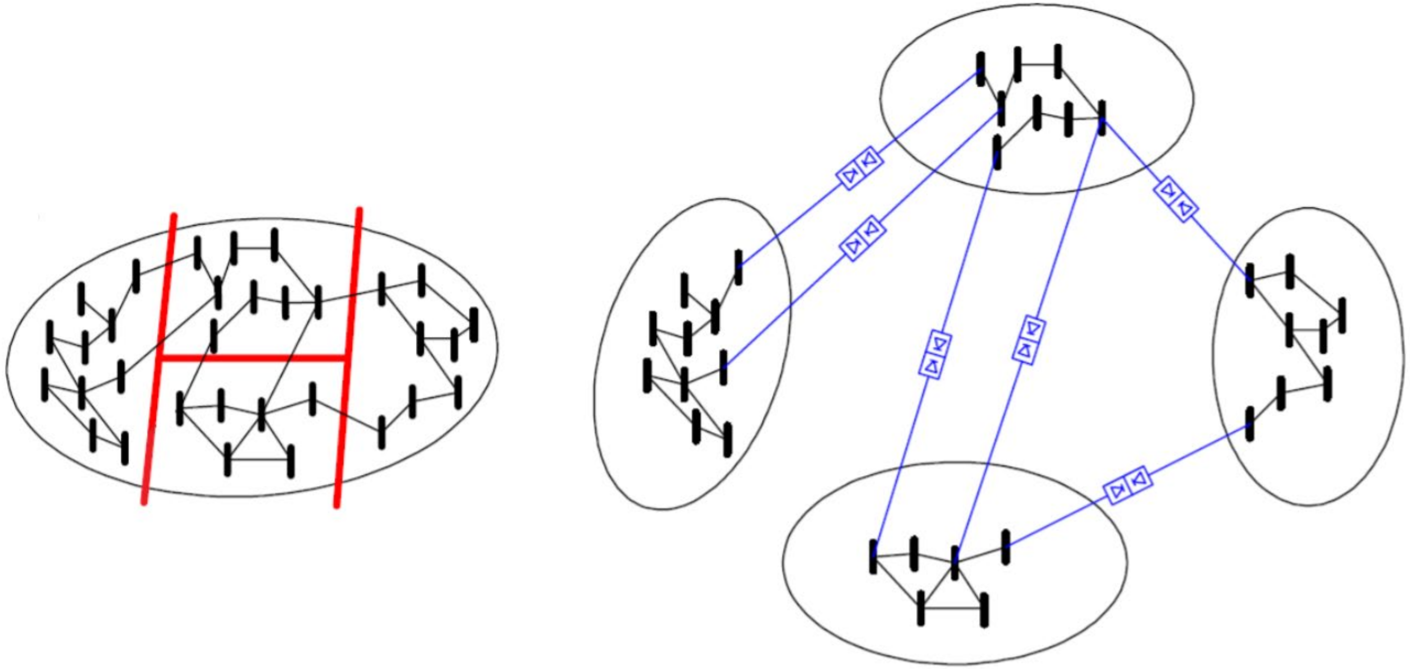
Grid Segmentation

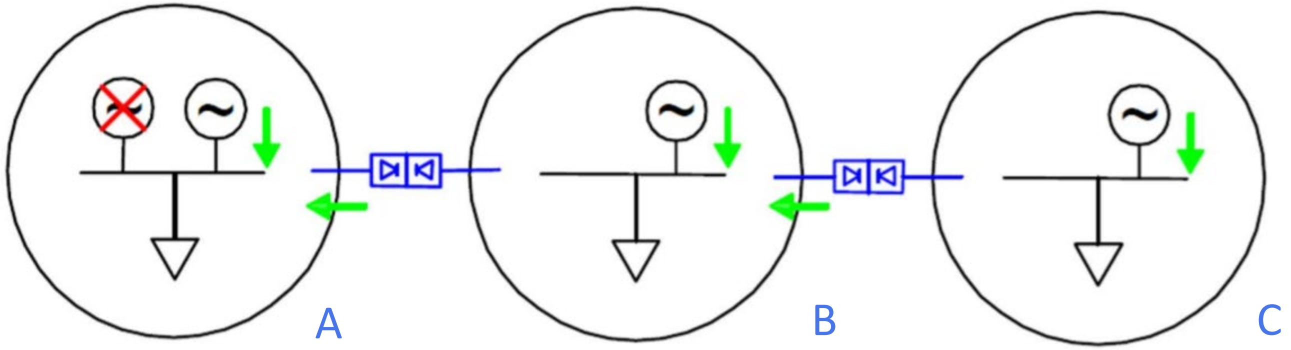
DC Segmentation on AC grid is decomposition of any inter-regional AC network in a set of sectors asynchronously operated and interconnected by DC links to

- Minimize Cascade Interruption
- Increase Energy Transfer Capacity between Sectors
- Solve Interconnection Issues
- Strengthen Local Oversight of Regional Network.

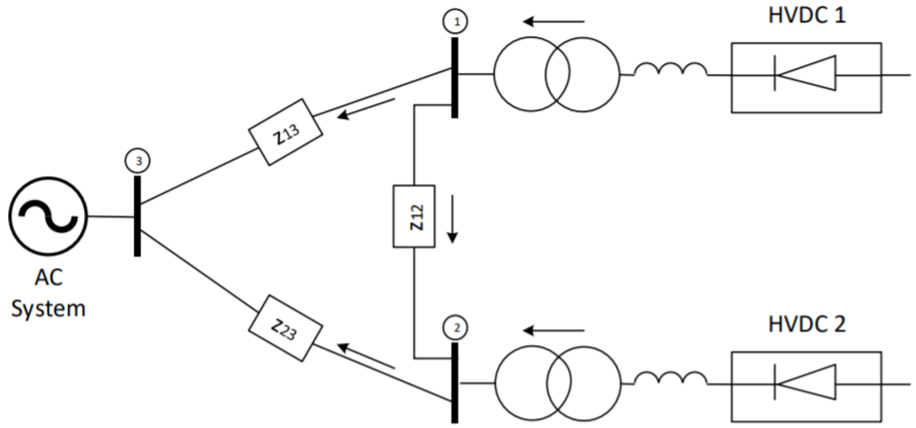
Under normal conditions, power level changes with the setpoint from operators. When a disturbance occurs, *controller* on each back-to-back S/S and each HVDC line increases the power flow from system with higher frequency difference.

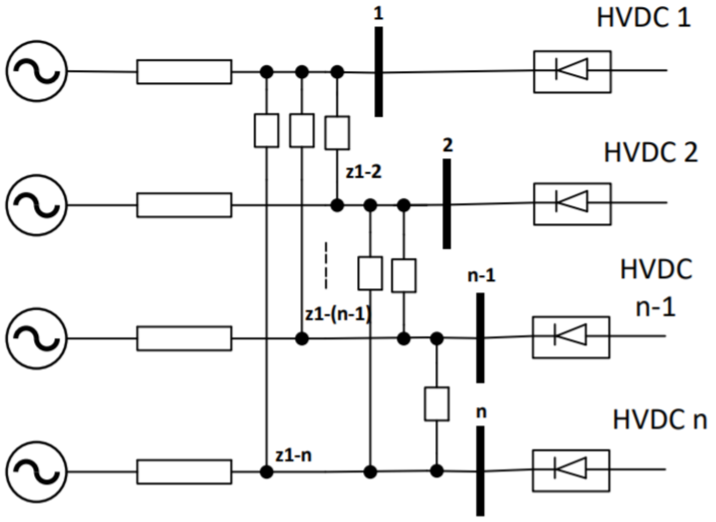
Loss of generation in area A can have support through HVDC link from B and C with capacity limit. Hence, it does NOT affect security and stability of B and C and hence whole system.

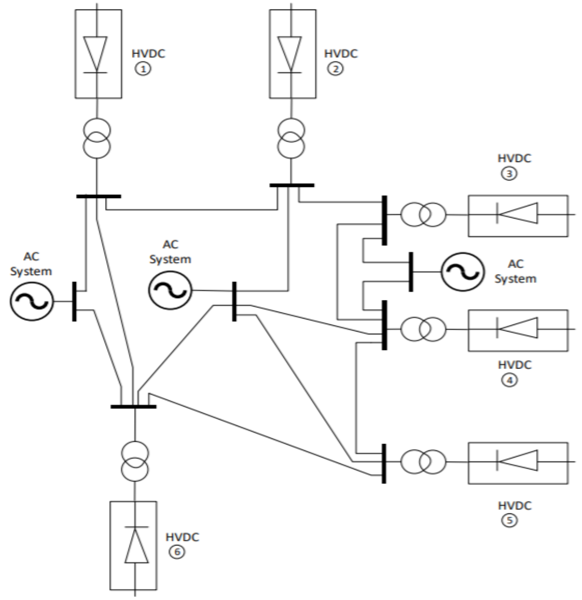




Multi-Terminal HVDC







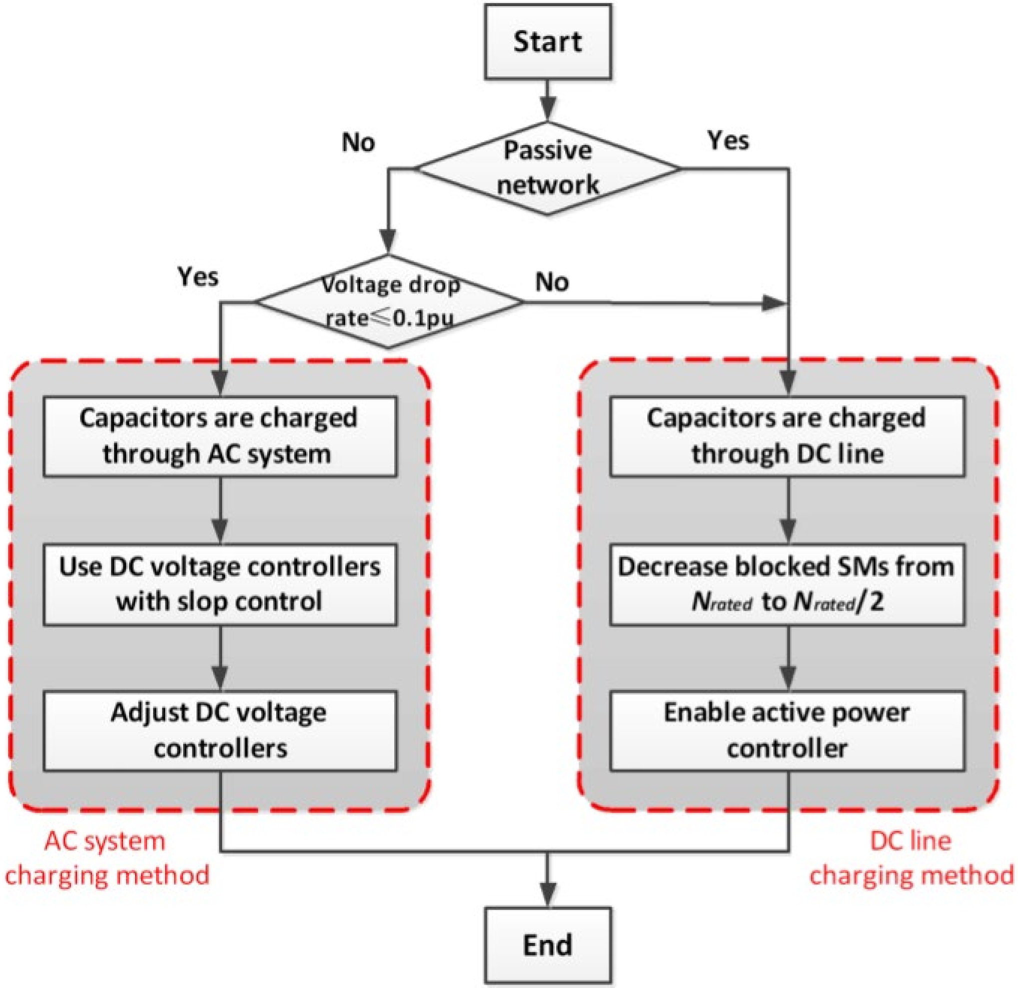
Serious Challenge in Evolution of Multi-Infeed HVDC system is **lack of data** and **knowledge** about steady state and dynamic behavior of multiple DC infeed system.

The performance of multi-infeed HVDC is largely influenced by interaction between DC converter and other allied phenomena. **Reactive power support**, **commutation failure**, **transient overvoltage** and **fault recovery time** are also valid for multi-infeed HVDC. Beside the issues in single HVDC line, **inter-converter voltage interaction**, **voltage stability**, **local and concurrent commutation failure**, **inter-converter direct current interaction** and **discrete tap position** are new challenge for multi-infeed HVDC system.

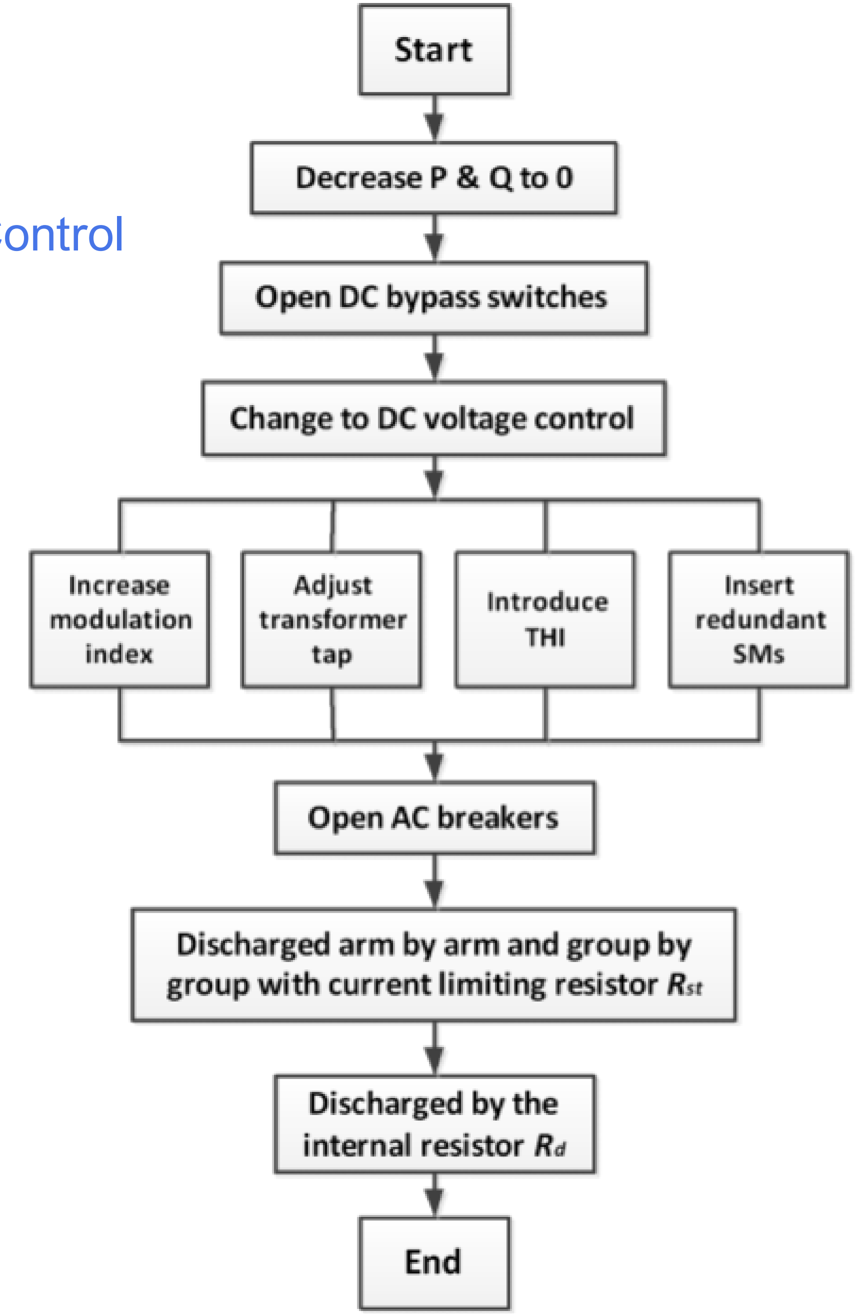
Worse transient overvoltage occurs when all converters in proximity are simultaneously *blocked* due to fault.

Start-Up and Shut-Down Process of HVDC

Start-Up Control



Shut-Down Control



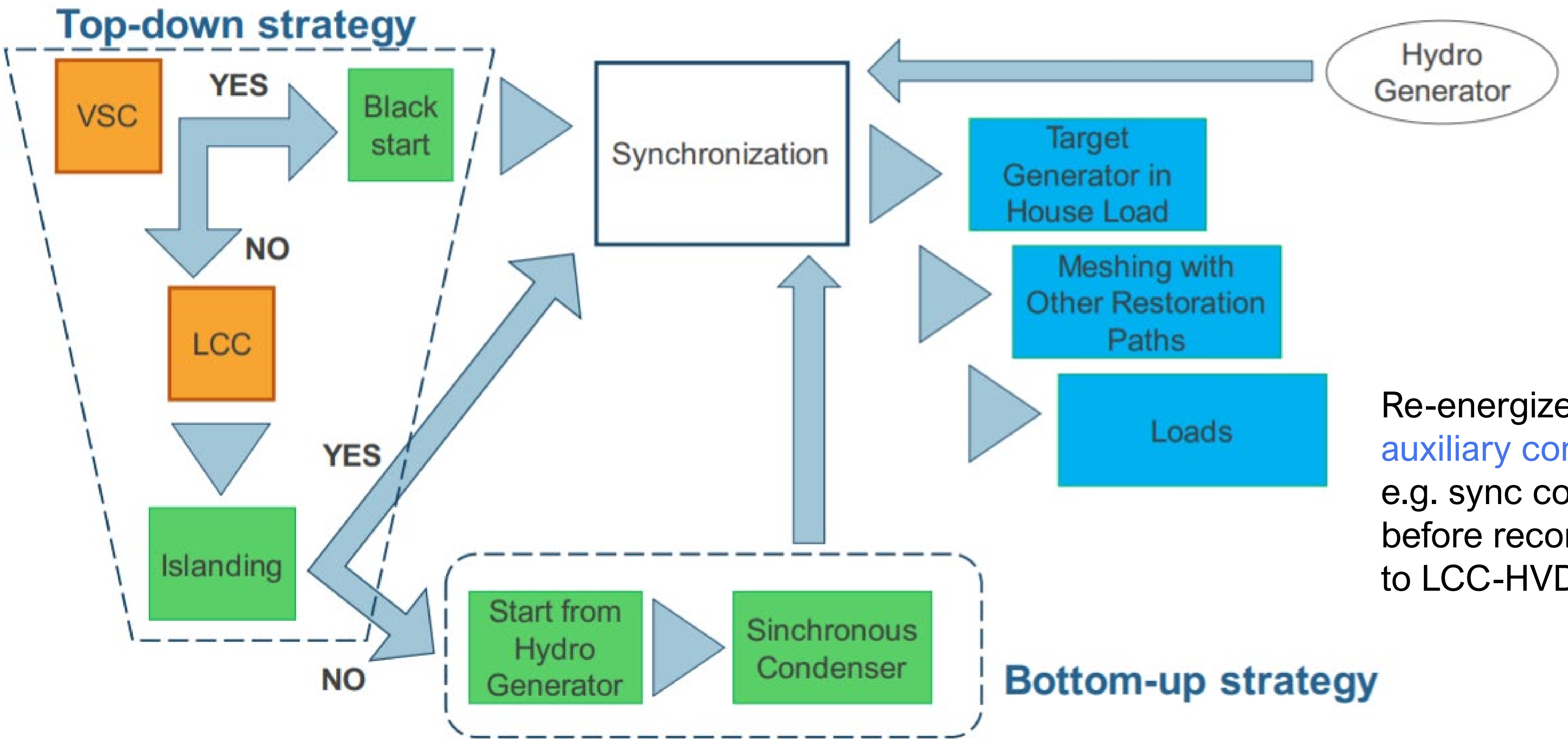
System Restoration and Re-connection of Asynchronous Grids

TSO and synchronous area should have a restoration plan for blackout and other islanding condition. The restoration process, top-down or bottom-up strategies is introduced in case of a partial or total blackout. Each strategy can be implemented depending on **blackout area**, **status of neighboring grid**, **availability of house-loaded unit** and **HVDC interconnection**.

Require External Voltage Source

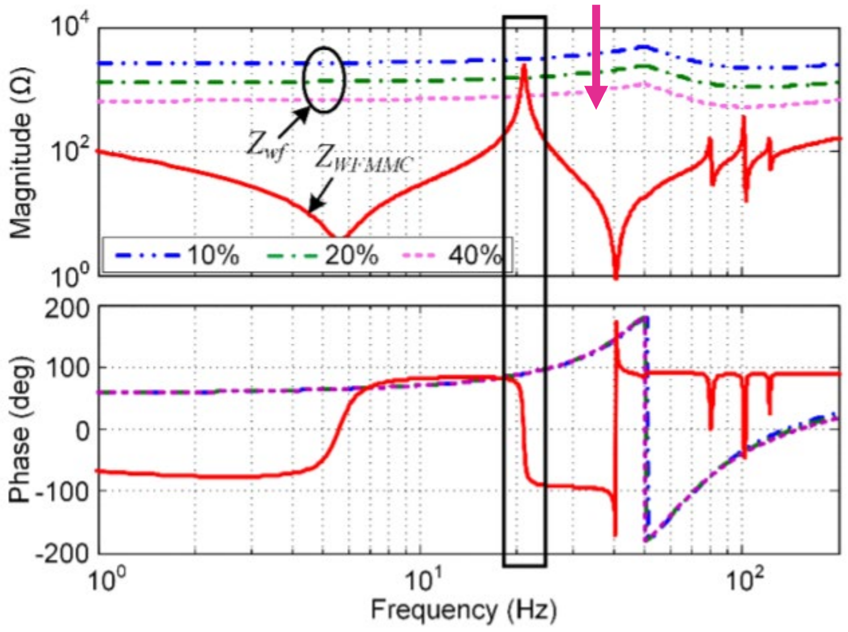
Note:
Require secure and stable source to re-energize step-by-step an isolated area in blackout condition starting from tie-line.

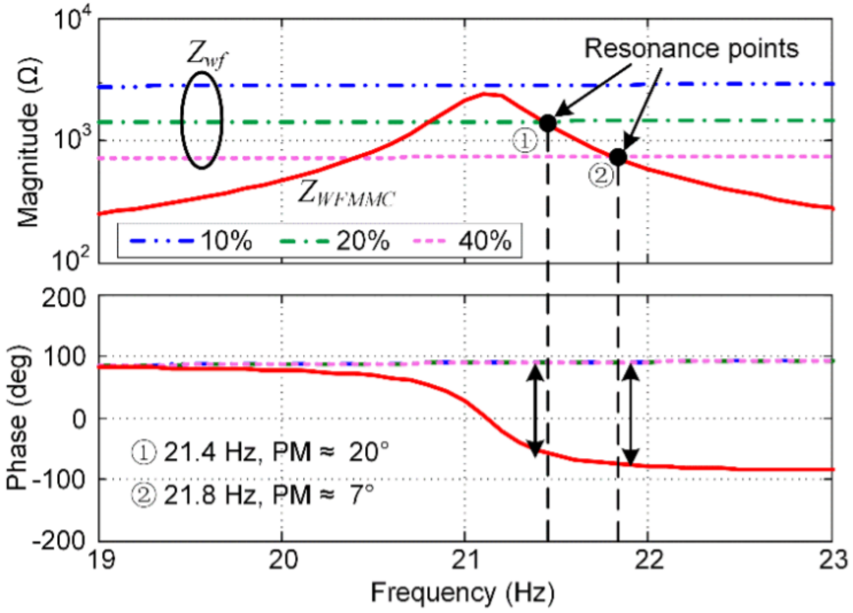
"Grid Forming"

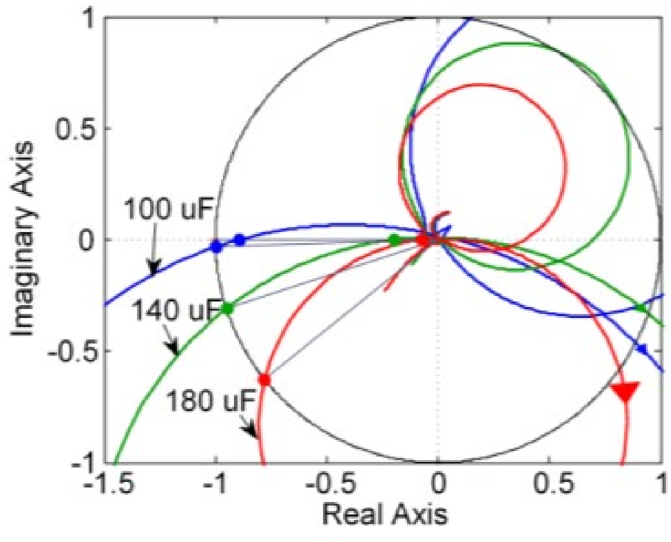


Re-energize auxiliary component e.g. sync condenser before reconnecting to LCC-HVDC

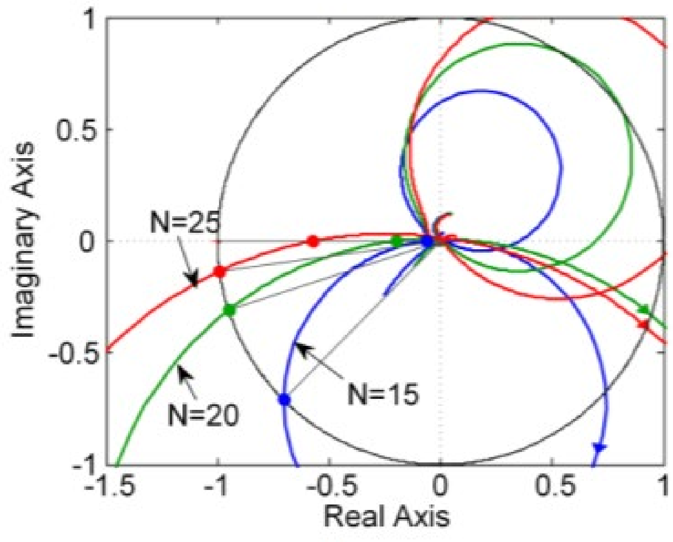
Sub-synchronous Oscillation with PLL Controller







b



c

b SM capacitance
c SM number per arm

- PLL-based Grid Synchronization is used in wind power inverter. It is concluded that large proportional gain of current controller or **small proportional gain of PLL control** could lead to to the stability of interconnected system.
- dq-domain current control with PLL dynamics requires separate analysis on positive sequence (dominating instability) and negative sequence response. Yet, it is possible that negative sequence input can affect positive sequence stability.
- Output Power Level has a significant impact on stability of interconnected system.

Power Flow and Transient Instability Issues after Unsynchronized with HVDC Link

It is necessary to implement southwest power grid and central east four provinces power grid asynchronous networking (**decoupling** two grids).
It can bring many advantages:

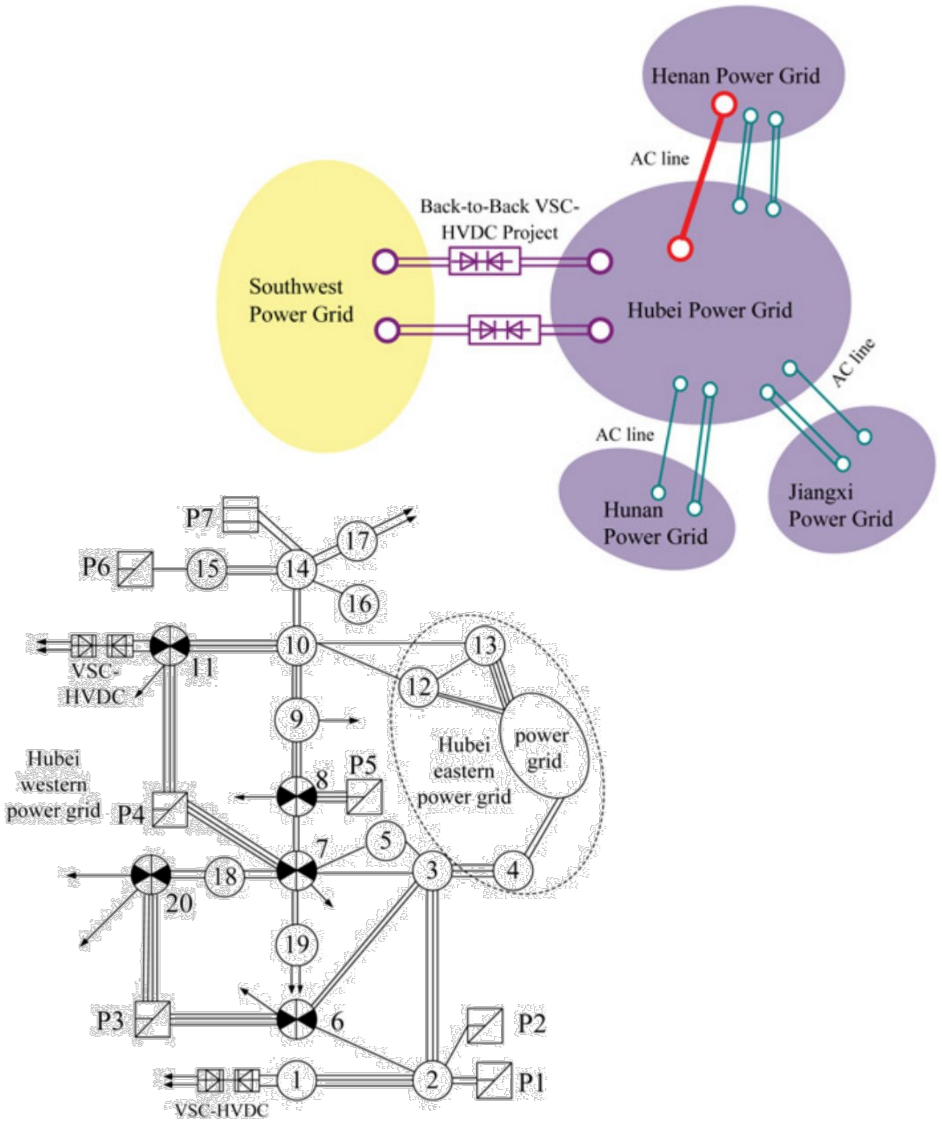
- **Hydropower transport** from Sichuan province
- Full utilization of power transmission line capacity
- Improved controllability of power grid operation
- Reduce risk of security and stability operation of power grid

After Introduction of HVDC Link,

1. Power Flow > Thermal Capacity
   At **Summer Peak Load**,
   1-2 delivers 3030 MW > limit = 2200MW
   2-3 and 3-4 deliver 4450MW and 4600MW, significantly larger than before.
   10-11 delivers 5260MW > limit 4000MW

2. Transient Instability
   AC channel between Chongqing and Hubei is interrupted, which decreases the equivalent moment of inertia of central east. The transmitted power from west to east increase, hence the transient stability of 500kV Hubei from west to east deteriorates.
   N – 1 fault of any lines of 2-3, 3-6, 3-4, 3-7, 2-6 and 10-11 can lead to transient instability.]

Solution
500kV Enshi East S/S is proposed to build ahead and synchronize with back-to-back VSC-HVDC.



Transient Stability Analysis for Hu-Liao HVDC and AC Parallel Transmission

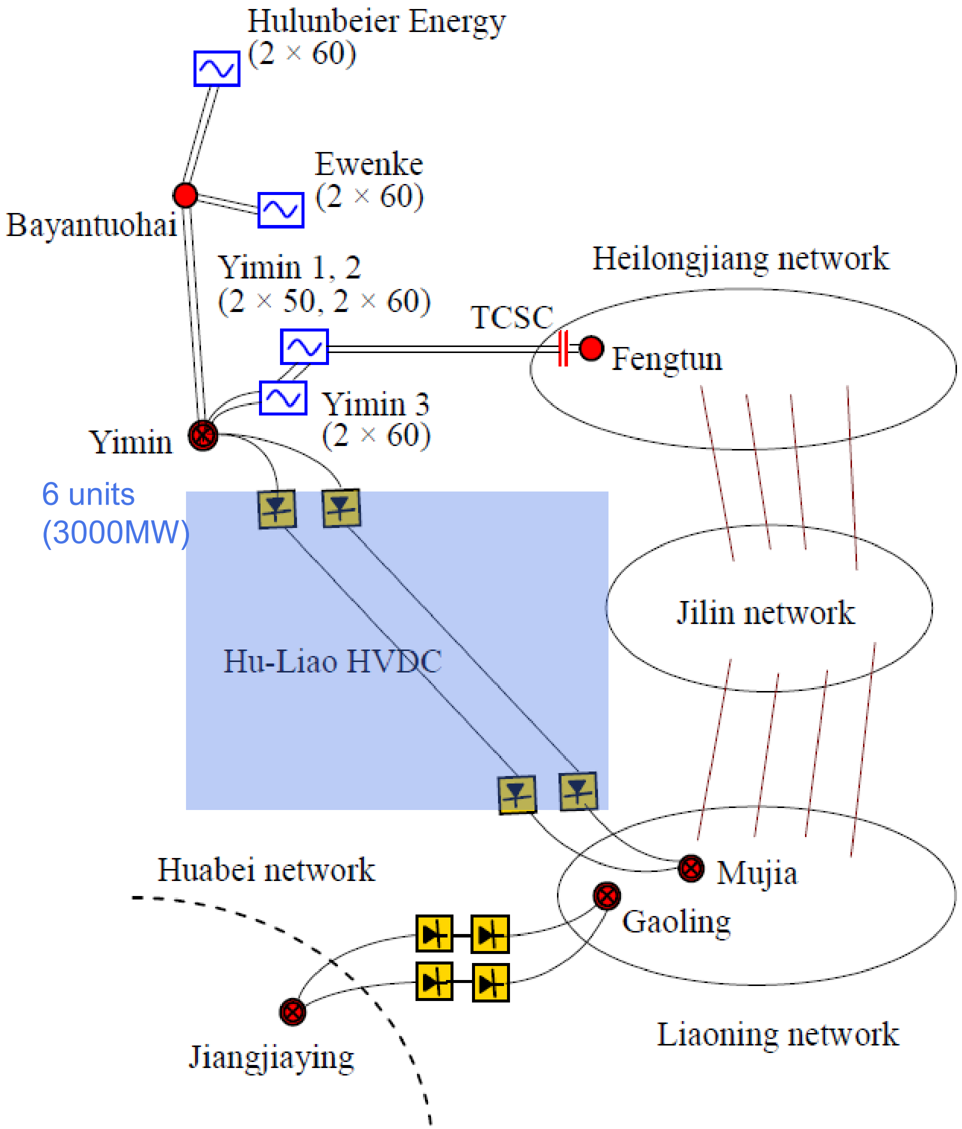
Hu-Liao HVDC line project is introduced and dynamic performance between AC and DC system during serious disturbance were analysed.

1. Dynamic Behaviour during AC Fault
   Permanent 3 phase fault at exit of 500kV Yi-Feng Line was simulated.
   3 units tripped in Yimin plants. AC bus voltage of Yimin converter reduced a lot and the **rectifier quitted temporarily**. The unbalance between energy and power of AC system in Yimin and Hulunbeier was further increased and **system instability** became worse. When AC voltage is recovered, DC system restarted and DC power is restored.
2. Dynamic Behaviour during DC Fault
   When fault occurred in DC line, bipolar blocking shifts most power to Yi-Feng lines and make a great impact to AC system. If DC can restart successfully, AC system can be stable, or else AC side will lose stability without secure control. In simulation, DC system experiences restart failure at first, and a success start over a lowering voltage for the second time.

To keep frequency stability, Transmission capacity of Yimin – Yimin Converter should be constrained by local generation:

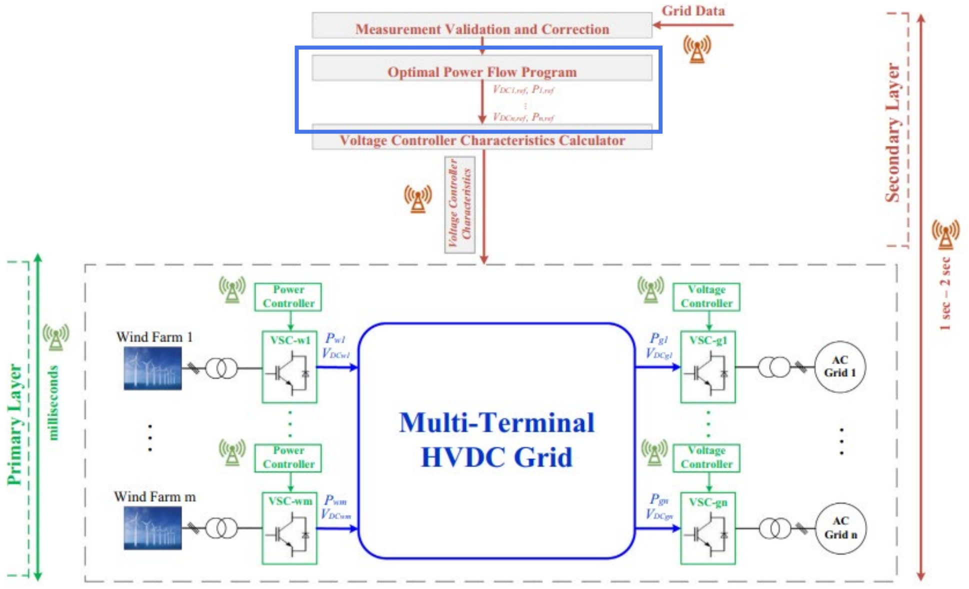
DC island generation		Line transmission limit of Yimin-Yimin converter (MW)
Unit number	Unit generation	
4	No limit	–650 ~ 850
3	> 1550	–350 ~ 850
	< 1550	–350 ~ 550
2	> 650	–350 ~ 550
	< 650	–50 ~ 550

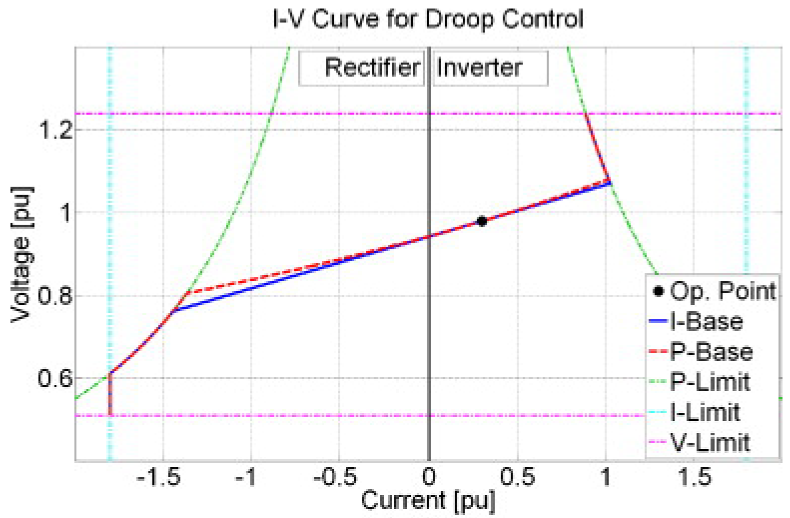
TCSC Forced Compensation and DC Emergency Power Transfer helps improve system stability

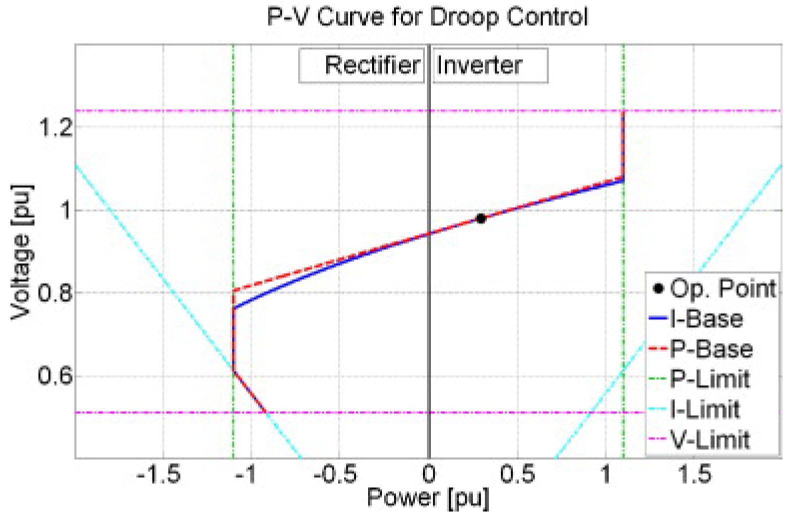


Power Balance Control

- DC Voltage serves as indication of power balance in HVDC. Hence, it bears a lot of similarities to the way AC frequency behaves in AC system. Currently there is no requirement on acceptable DC voltage range. Wider ranges could be considered following an outage (N – 1 operation).
- Power unbalance containment in contingency condition will probably require demand-side management or load curtailment. Note: System Collapse can be faster than the activation of UFLS scheme. Fast Communication-based demand response program could improve load shedding scheme.
- Hierarchical Control structure is needed to coordinate remote end converters in AC hub to perform Power Balance control during contingency condition, under adverse system interactions and disturbance ride-through. It is to ensure stability of AC hub.





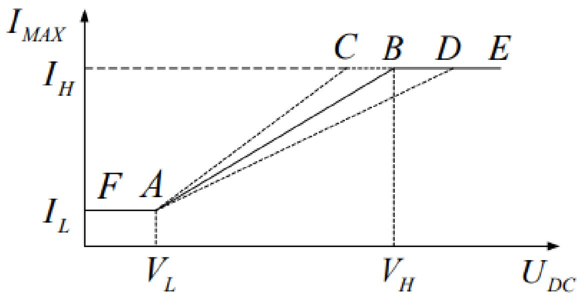


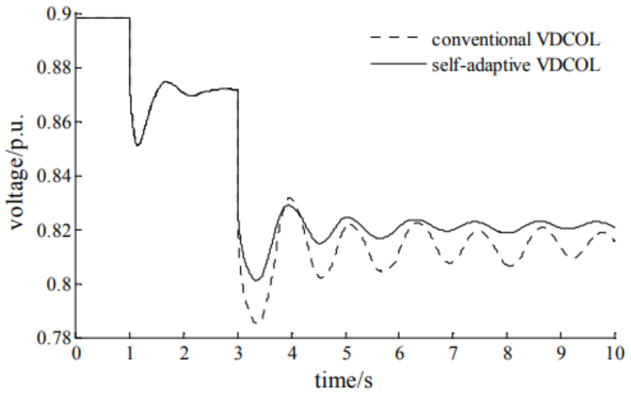
Emergency Power Control (EPC) under Continuous Commutation Failure

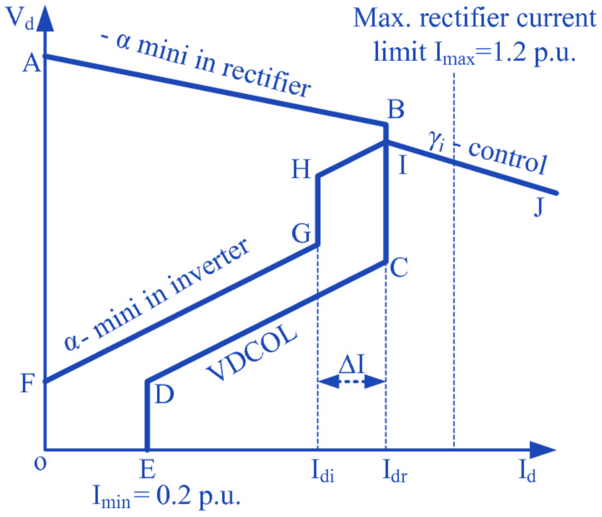
VDCOL Control

When DC Voltage drops obviously under large AC side disturbance, reactive power absorbed by the converter may increase if DC link still transmits rated power. Slow recovery or even voltage collapse may occur in AC/DC hybrid grid after fault if AC system is weak or reactive source is not enough.

VDCOL can restrain DC current when DC voltage or AC commutation voltage drops to specific value. It is beneficial to voltage stability for reduction of reactive power consumed during and after fault.

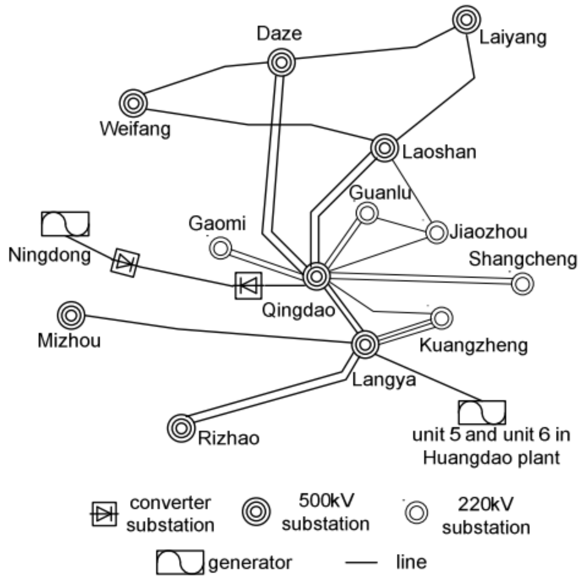






A dynamic self-adaptive VDCOL control is proposed.

1. In extreme cases, the setting value of VDCOL parameters are critical to AC voltage stability.
2. The modified VDCOL with dynamic self-adaptive control is based on inverter AC side voltage. It can restrict DC current rationally under various voltage levels and it contributes to voltage stability of receiving end power grid.
3. With AC voltage and DC voltage drop seriously for severe faults, dynamic self-adaptive VDCOL can restrain DC current more obviously w.r.t. VDCOL with fixed parameter.



Emergency Power Control (EPC) under Continuous Commutation Failure

Rotor motion equation of equivalent generators G1 and G2 is

$$\begin{cases} \frac{T_{J1}}{\omega_0}\frac{d^2\delta_{s1}}{dt^2} = P_{G1} - P_{DC} - P_{L1} - \frac{U_1U_2\sin(\theta_1-\theta_2)}{x_{12}} \\ \frac{T_{J2}}{\omega_0}\frac{d^2\delta_{s2}}{dt^2} = P_{G2} - P_{L2} + \frac{U_1U_2\sin(\theta_1-\theta_2)}{x_{12}} \end{cases}$$

The equivalent single machine rotor equation is

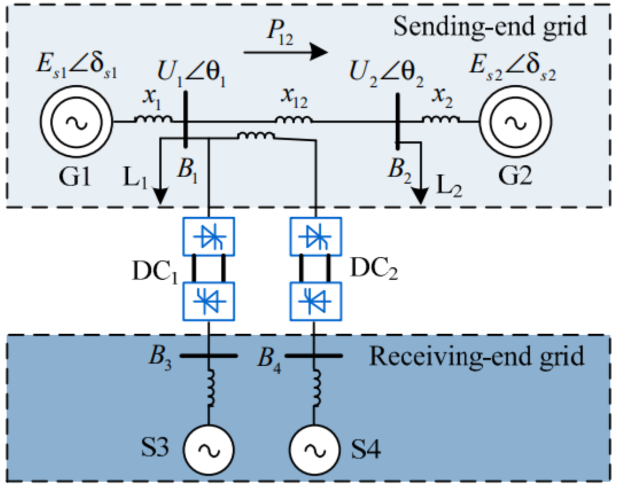
$$P_m = \left(\frac{P_{G1}}{M_1} - \frac{P_{G2}}{M_2}\right) - \left(\frac{P_{L1}}{M_1} - \frac{P_{L2}}{M_2}\right) \boxed{- \frac{P_{DC}}{M_1}}$$

$$\boxed{\frac{d\delta^2}{dt^2} = P_m - P_{e\max}\sin\delta}$$

$$P_{e\max} = \left(\frac{1}{M_1} + \frac{1}{M_2}\right)\frac{U_1U_2}{x_{12}}$$

$$\delta = \delta_{s1} - \delta_{s2}$$

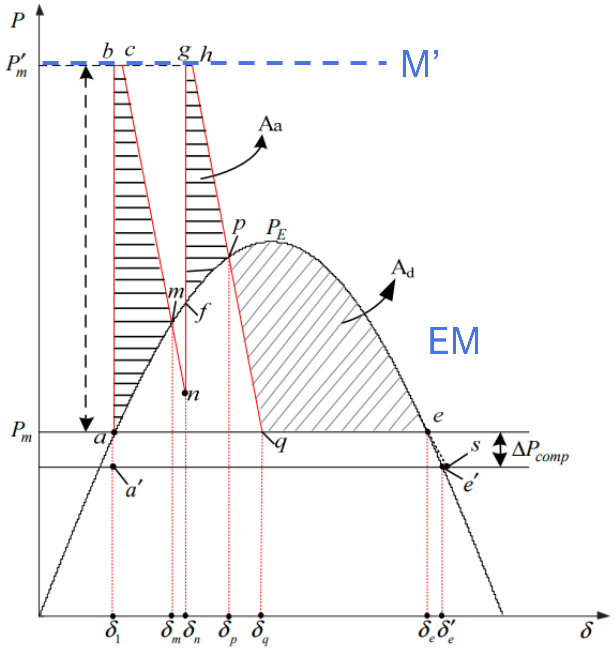
$$M_1 = T_{J1}/\omega_0, M_2 = T_{J2}/\omega_0.$$



Continuous CFs cause a continuous sag of the power transmitted by DC_1, thereby increasing the equivalent mechanical power P_m to P_m'. During the period when the equivalent mechanical power is greater than the electromagnetic power, the rotor accelerates and the rotor angle δ is gradually increased. Consequently, the operating point moves along the power curve from point a to point m, and the corresponding acceleration area is A_{abcm}. During CF recovery, the equivalent EM power becomes gradually higher than the equivalent mechanical power and the rotor starts to decelerate.

Consider the balance of acceleration area and deceleration area to generate the current setpoint.

$$A_{a\_j} = \sum_{i=1}^{m-1}\int_{\delta_i}^{\delta_{i+1}} (P'_{mi} - P_{e\max}\sin\delta)d\delta \qquad A_d = \int_{\delta_n}^{\delta_e} (P_{e\max}\sin\delta - P_m)d\delta$$



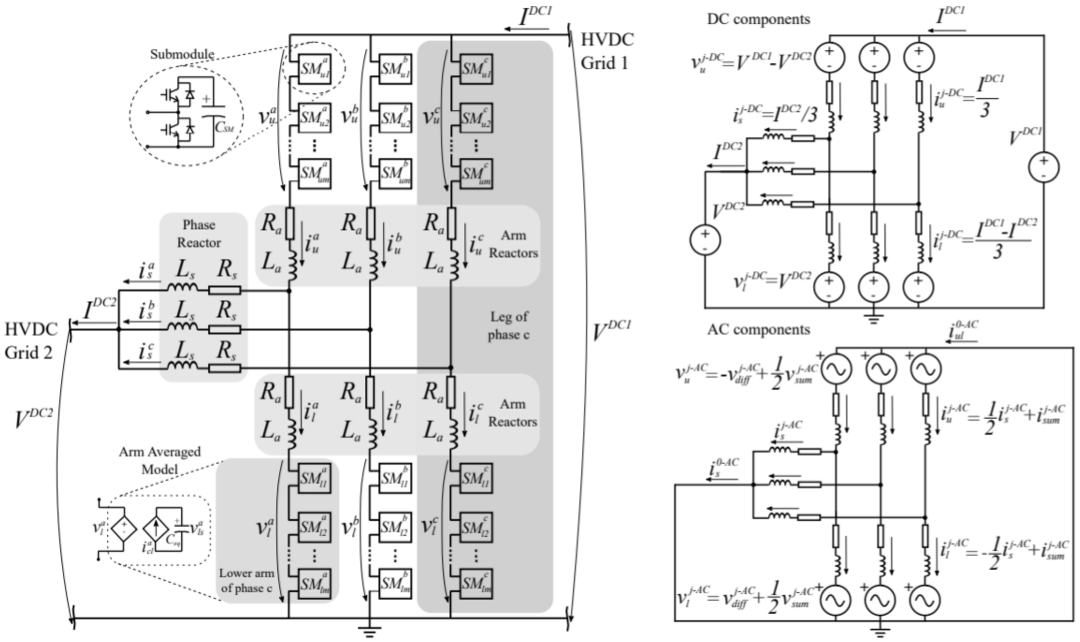
Converter Stability

Energy Components are derived from active power of upper and lower arms, which can be expressed in decoupled system. Assume a symmetrical three-phase system.

$$\begin{cases} v_{diff}^j = v_{diff}^{j-DC} + v_{diff}^{j-AC} = V_{diff}^{DC} + V_{diff}^{AC}\cos(\omega t + \phi_{diff}^j) \\ i_s^j = i_s^{j-DC} + i_s^{j-AC} = I_s^{DC} + I_s^{AC}\cos(\omega t + \phi_s^j) \\ v_{sum}^j = v_{sum}^{j-DC} + v_{sum}^{j-AC} = V_{sum}^{DC} + V_{sum}^{AC}\cos(\omega t + \phi_{vsum}^j) \\ i_{sum}^j = i_{sum}^{j-DC} + i_{sum}^{j-AC} = I_{sum}^{DC} + I_{sum}^{AC}\cos(\omega t + \phi_{isum}^j) \end{cases} \longrightarrow \begin{cases} P_u^j = (\frac{v_{sum}^j}{2} - v_{diff}^j)(\frac{i_s^j}{2} + i_{sum}^j) \\ \quad = P_u^{j-DC} + P_u^{j-AC} + P_u^{j-\omega} + P_u^{j-2\omega} \\ P_l^j = (\frac{v_{sum}^j}{2} + v_{diff}^j)(-\frac{i_s^j}{2} + i_{sum}^j) \\ \quad = P_l^{j-DC} + P_l^{j-AC} + P_l^{j-\omega} + P_l^{j-2\omega} \end{cases}$$

The converter stability is ensured when the **total energy is maintained constant** and there is **energy balance between upper and lower arms and between legs.**

- Energy difference between upper and lower arm:
  It is caused by active power exchange between upper and lower arm, which charges and discharges SM capacitors of the arm.
  (Due to voltage unbalance from AC source, impedance difference between arm such as burnt submodule, or common control with DC link voltage)
- Energy difference between legs:
  It is caused by active power exchange between legs, which increases or decreases the energy stored in each leg.
  (Due to low discharge resistance path or malfunction of leg balancing module)
- Total Energy:
  It represents the total energy stored in SM capacitors, which must be maintained to a specific constant value during converter operation.

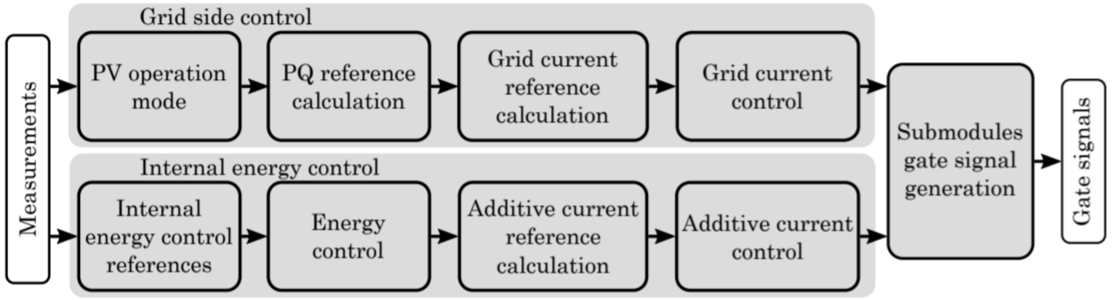


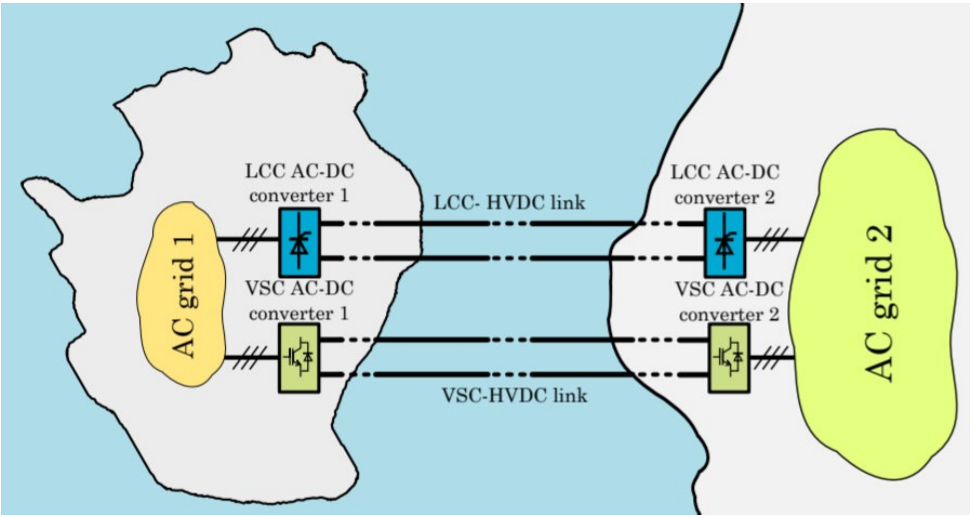
(a) General scheme (b) AC and DC components

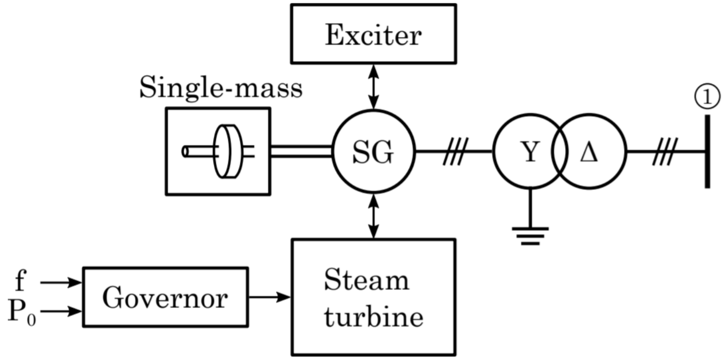
AC-DC Voltage and Current of DC-MMC in Steady State

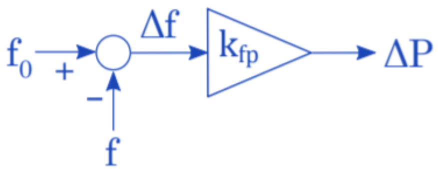
Frequency Response after Disturbance with HVDC support

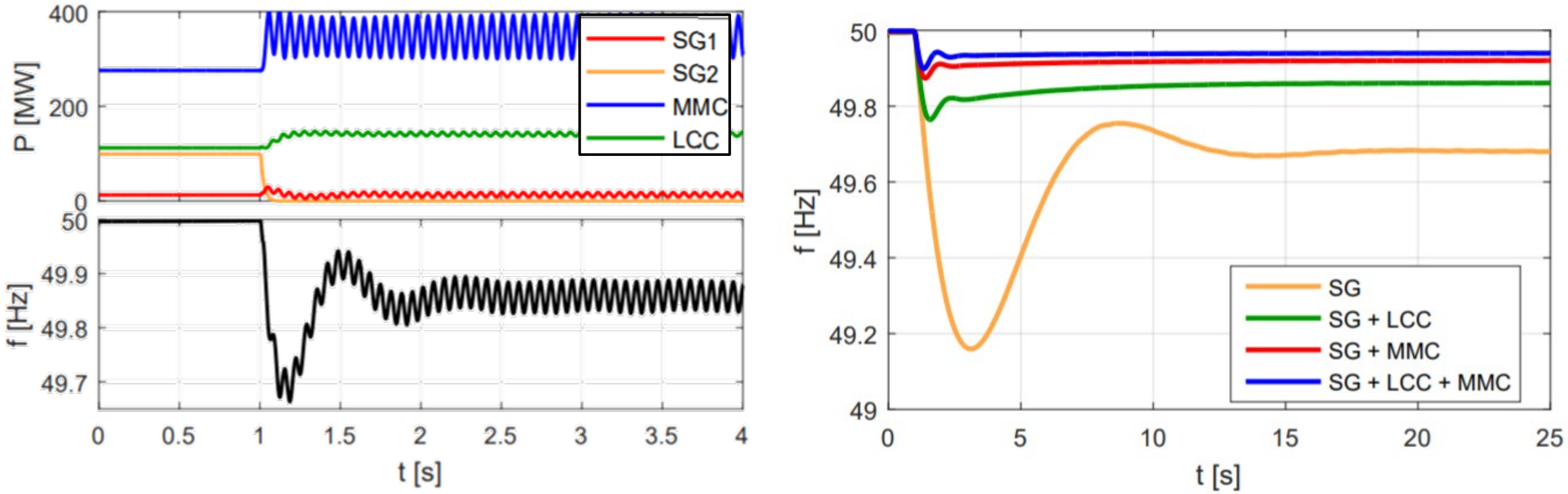
Converters are designed to mimic synchronous generators to provide frequency support with droop control. It is noted that without frequency support control, the reduced inertia among two groups can exhibit a large disturbance. It can cause severe oscillation in output power and frequency.











(Reduced Inertia)

Frequency Response after Disturbance with HVDC support

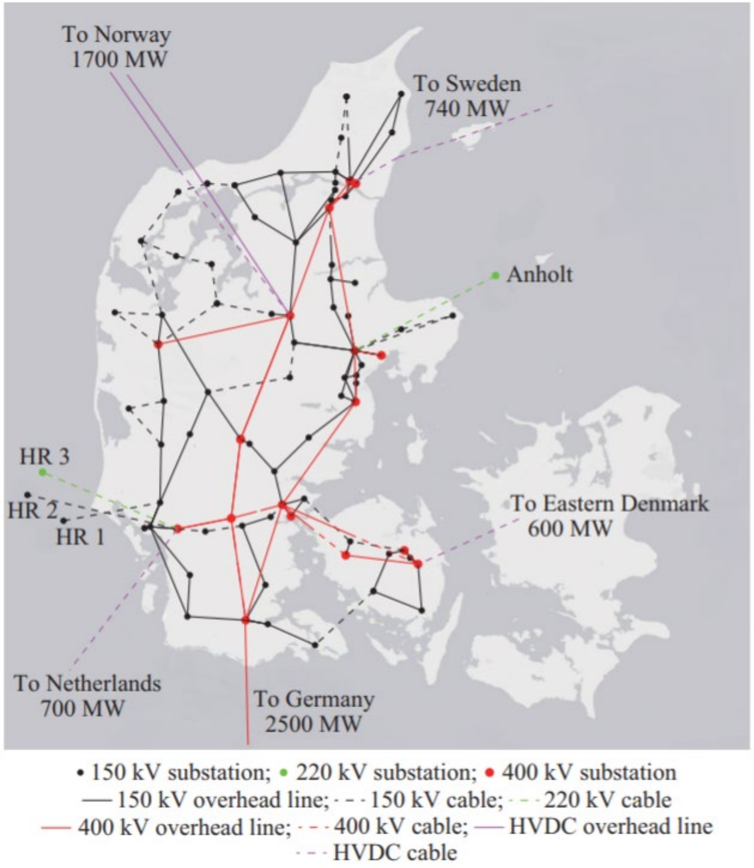
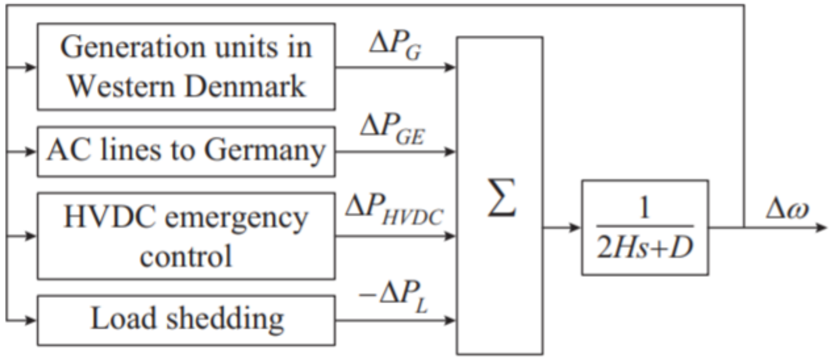
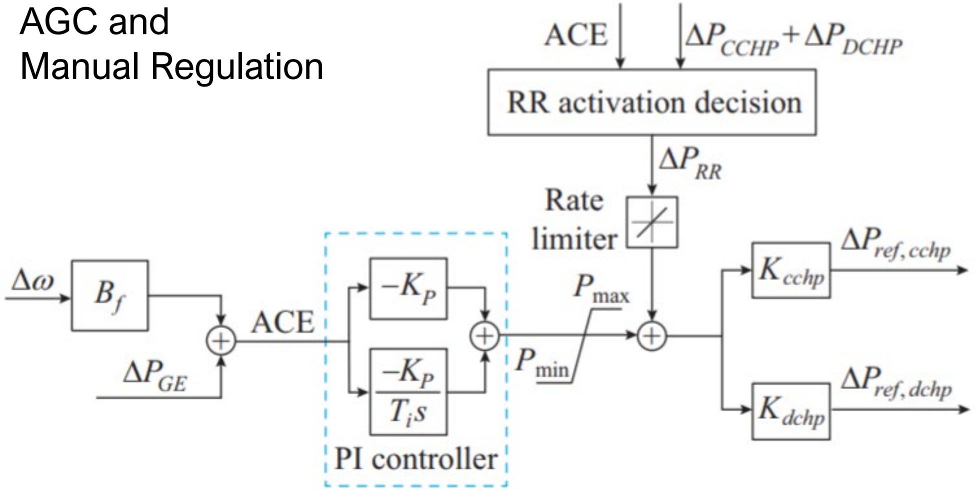
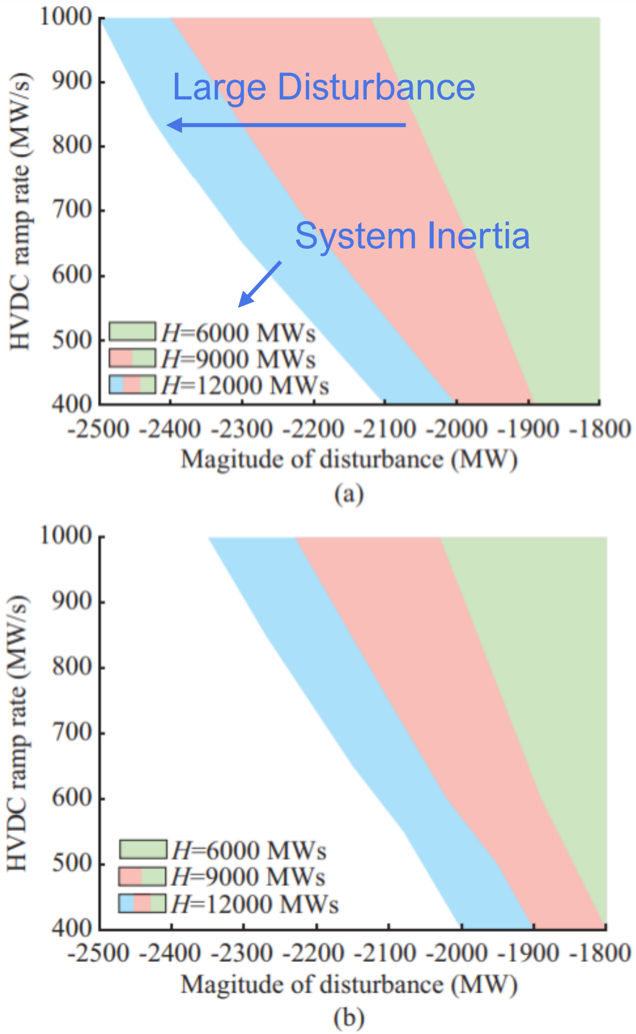


Fig. 1. Transmission and interconnection network of DK-W grid in 2020.



AGC and
Manual Regulation





Sensitivity Analysis in UF
(a) Higher (b) Lower Load Shedding Plan

Note:

- System Inertia mainly depends on online synchronous generations and load, and it is difficult to estimate inertia constant (H = ?? MWs) in **real time**.
- Inertia of an islanded system with large share of wind power is LOW.
- Following any power impedance, frequency containment reserve (FCR) is needed.

Synthetic Inertia

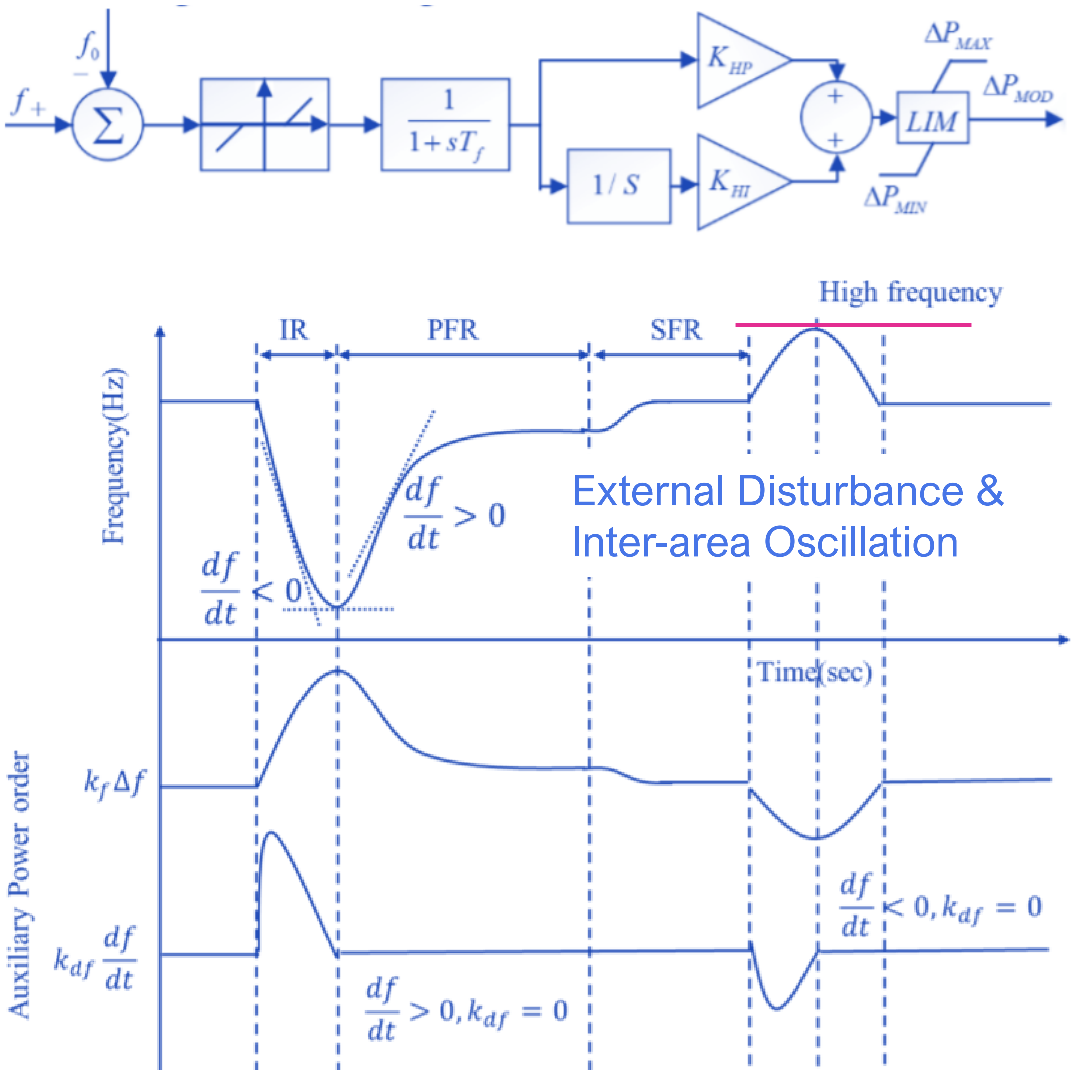
HVDC should be capable, if specified, of providing synthetic inertia in response to frequency changes to limit the rate of change of frequency (RoCoF).

Challenges of Synthetic Inertia:

- Limit RoCoF – df/dt: The RoCoF should not exceed the maximum withstand capability of demand and power generation units to ensure **control system robustness**, sensitivity of **islanding detector** and correct operation of **Loss of Main (LoM) protection**.
- Limit frequency – $f_{min} < f < f_{max}$: Fast activation of **operational reserves** is necessary to reduce df/dt and hence reduce the deviation, which could prevent the disconnection of demand and generation.

For operation reserves, the TSO should specify:

- Frequency and df/dt measurement criteria (time window, accuracy and total delay time)
- Function Characteristics (e.g. df/dt, Δf, dead band and droop)
- TSO input signal for activation and access to change setting.

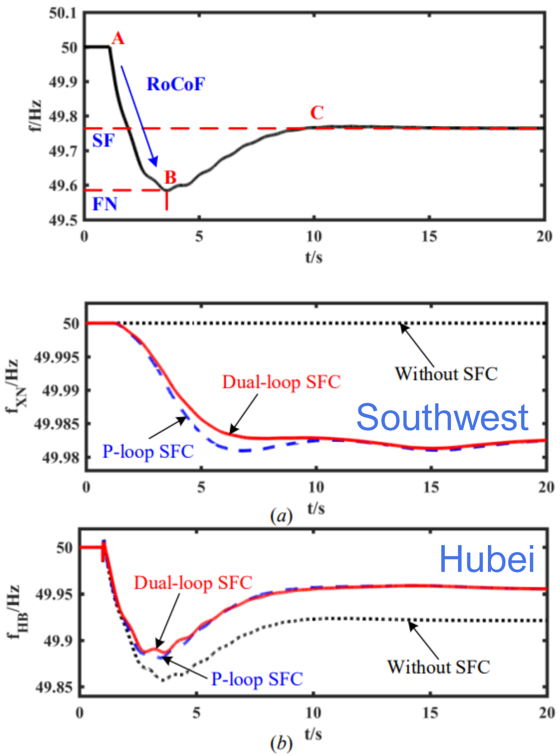


Frequency and Inertia Support in Chongqing – Hubei Link

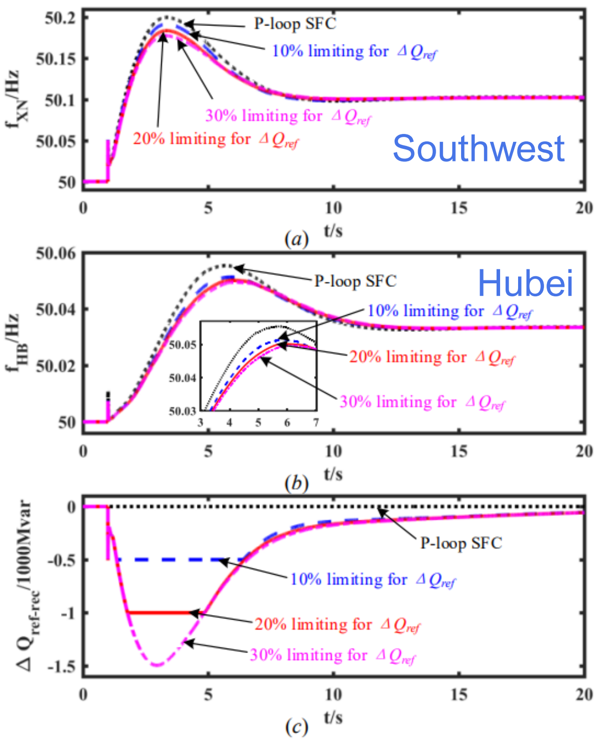
Dual Loop Supplementary Frequency Control

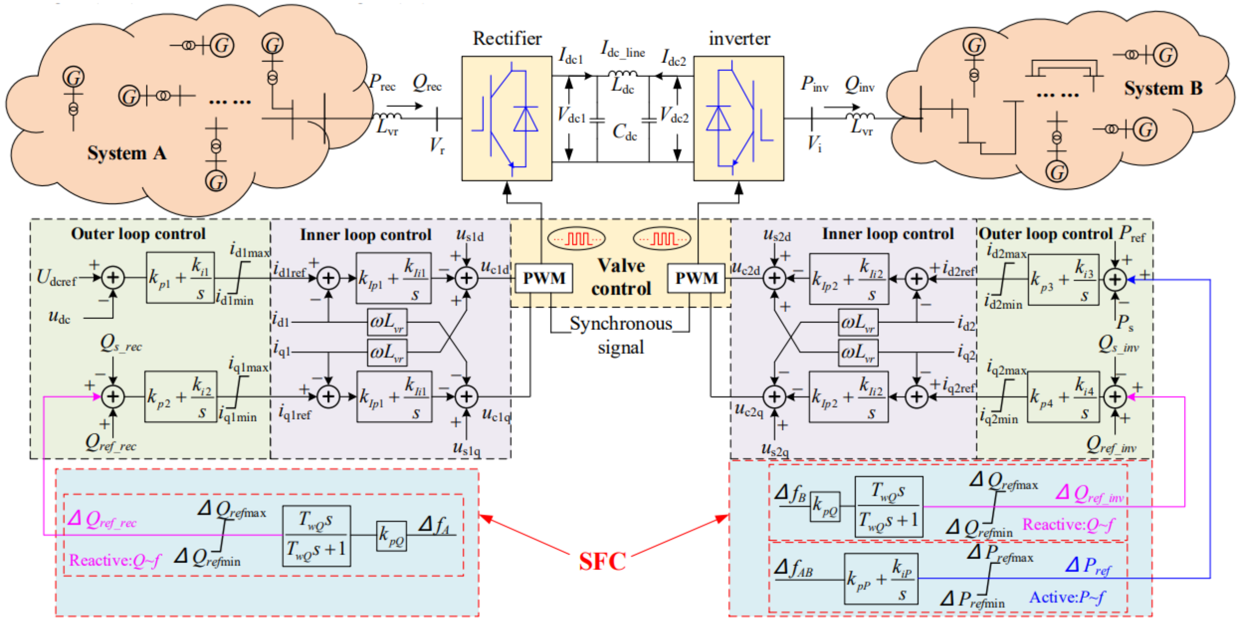
F-P droop + F- Q droop which respectively provide frequency support and virtual inertia support for the disturbed system to improve the characteristics of the frequency response.

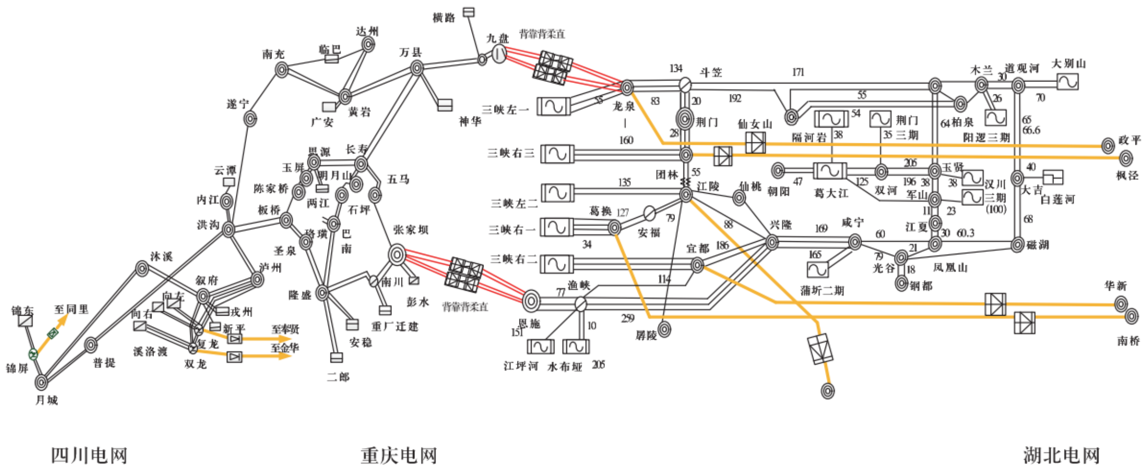
Load Disturbance



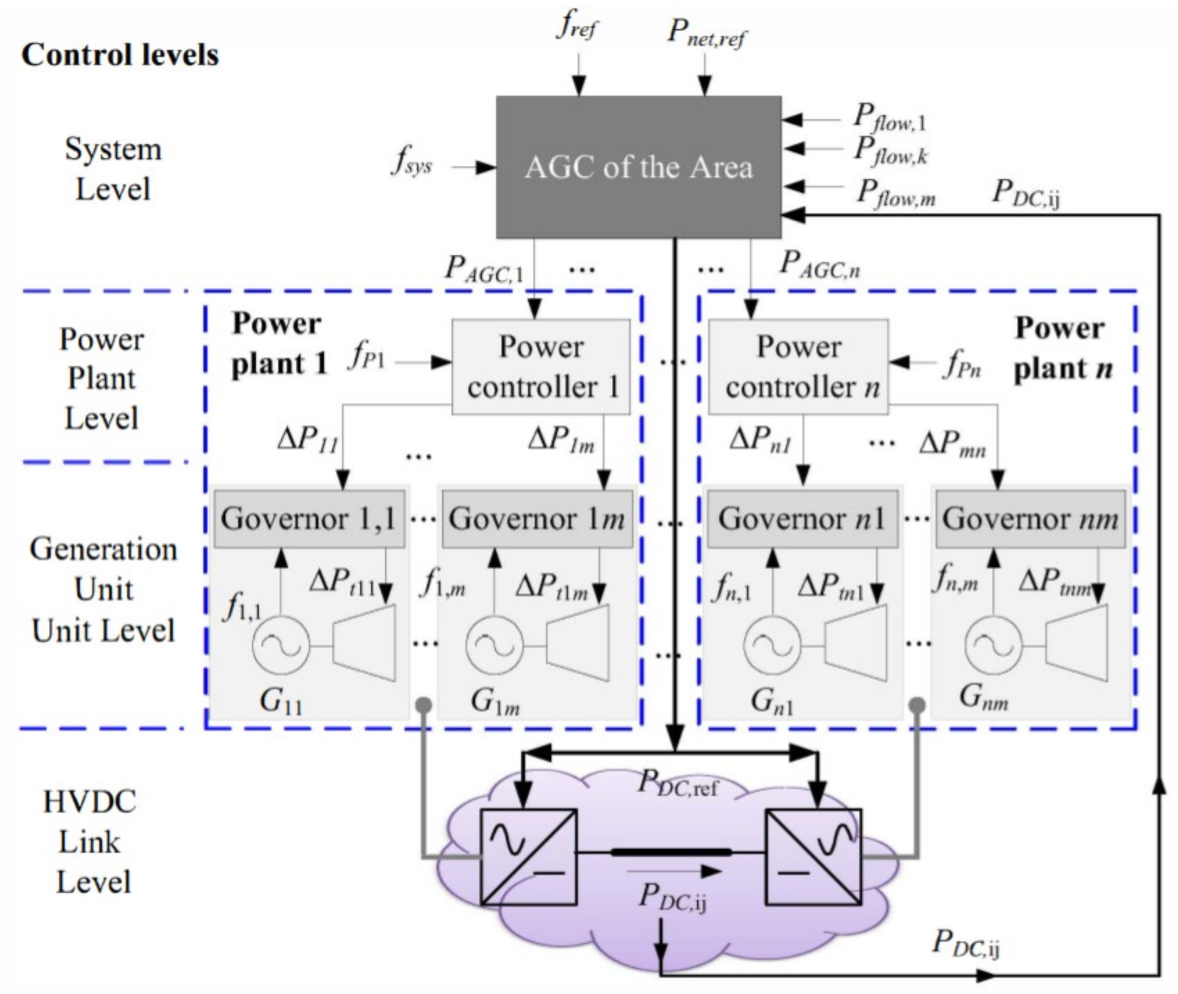
Reactive Injection



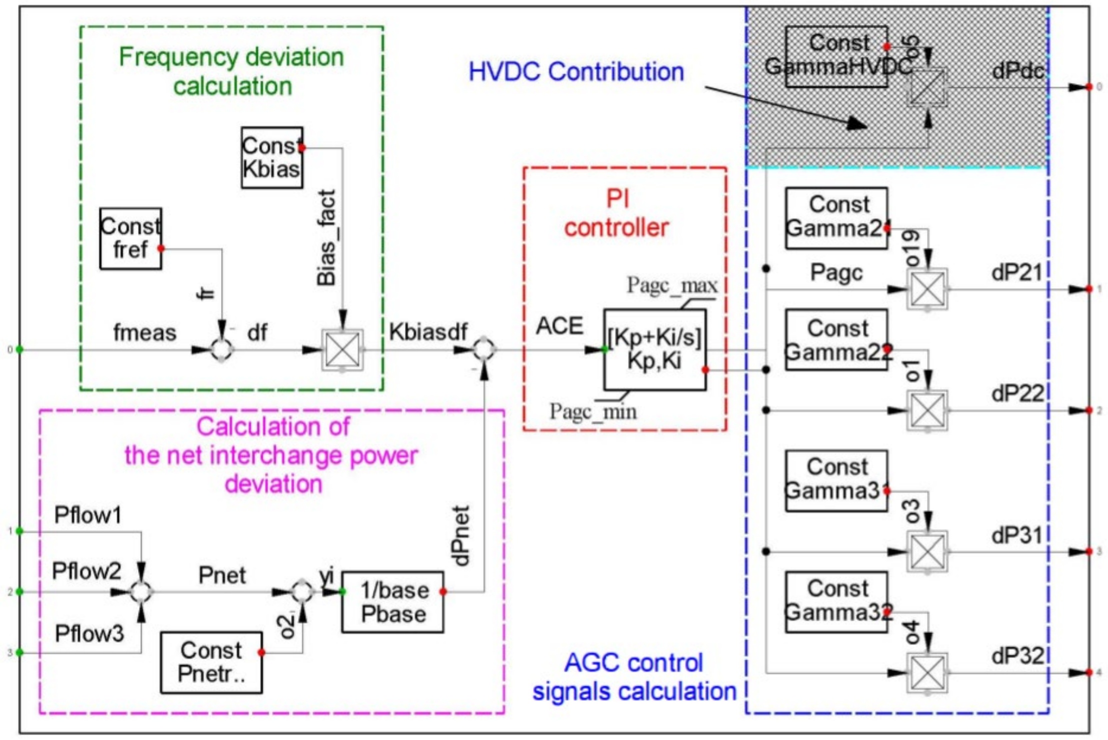




Simulation on Frequency Response with Hybrid HVAC – HVDC Grid



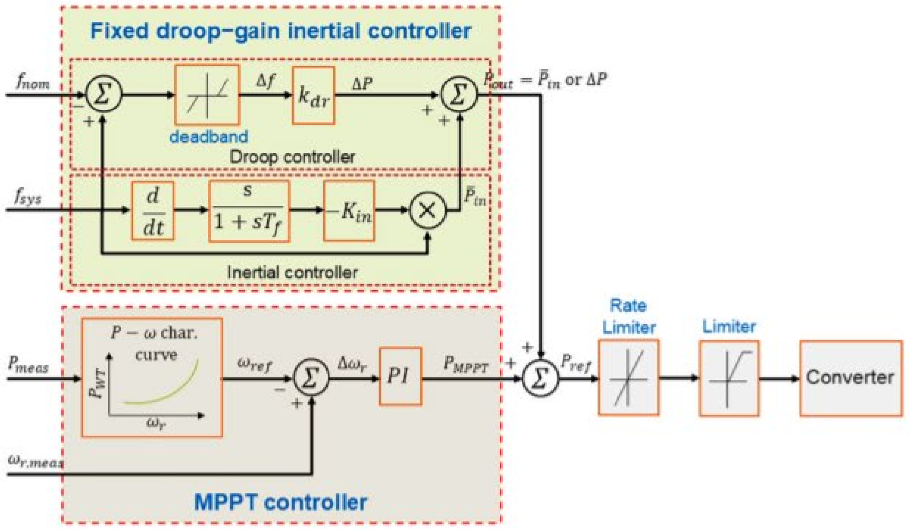
AGC AREA2 controller:



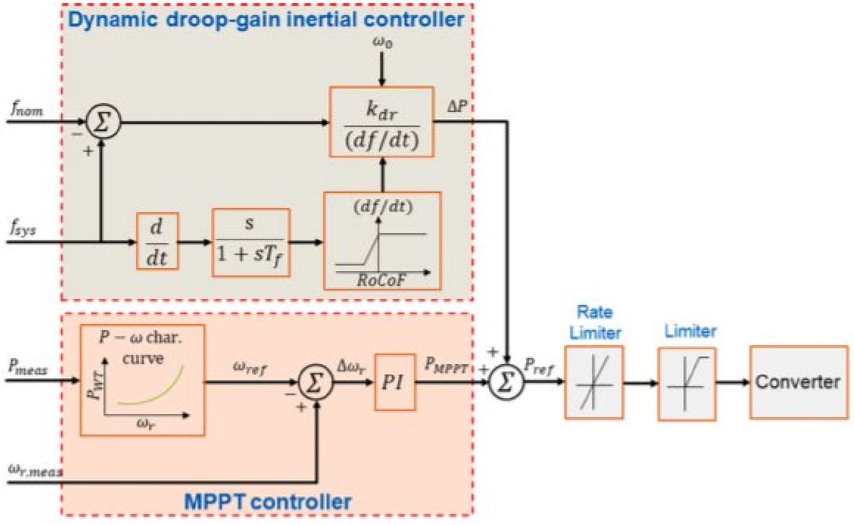
Note:

- HVDC Power Flow should be coordinated in whole AGC Response with **net interchange power**, **frequency deviation** and **HVDC contribution**.
- Frequency **inaccuracy** from frequency droop if AGC is not modelled in disturbance recovery.

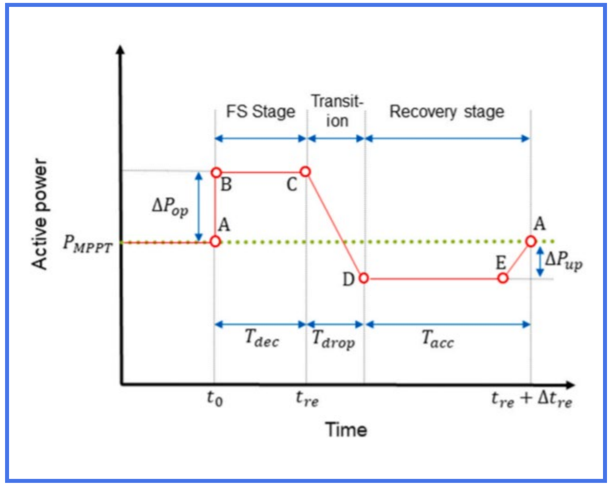
Active Power Injection during Fault and HVDC Controllers

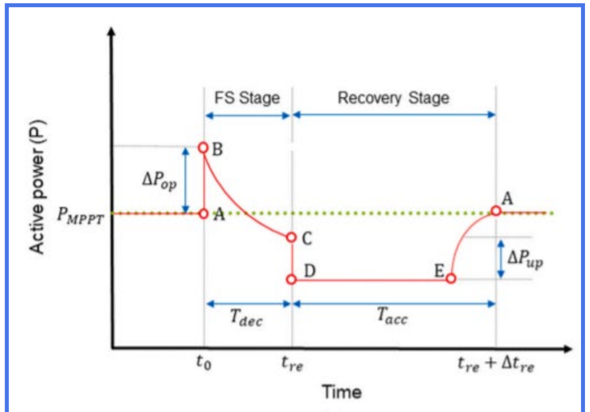


(a)

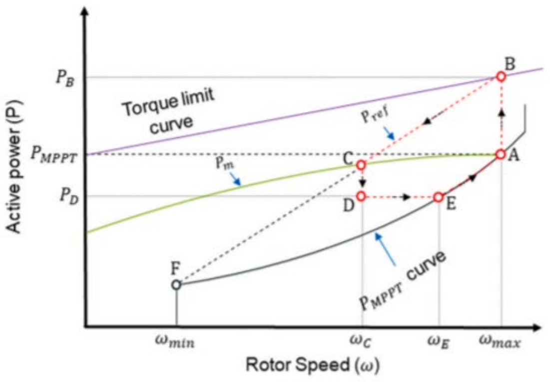


(b)





(a)



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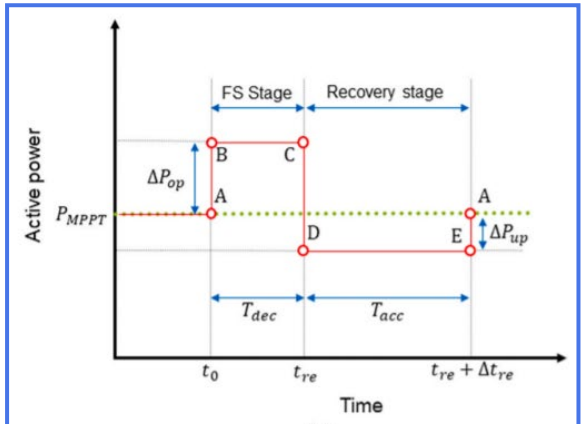
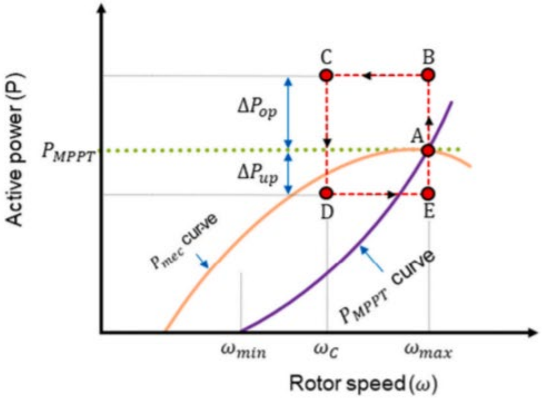


(a)



(b)

Voltage Instability Factors

Voltage Sensitivity Factor (VSF) is usually applied to analyze the voltage stability in power grids:

$$VSF_i = \Delta U_i / \Delta Q_i$$

i.e. sensitivity of voltage to reactive power injection at node i

Multi-Infeed Interaction Factor (MIIF) is an index for degree of interaction between DC converter buses i and j with reactive power change at converter j.

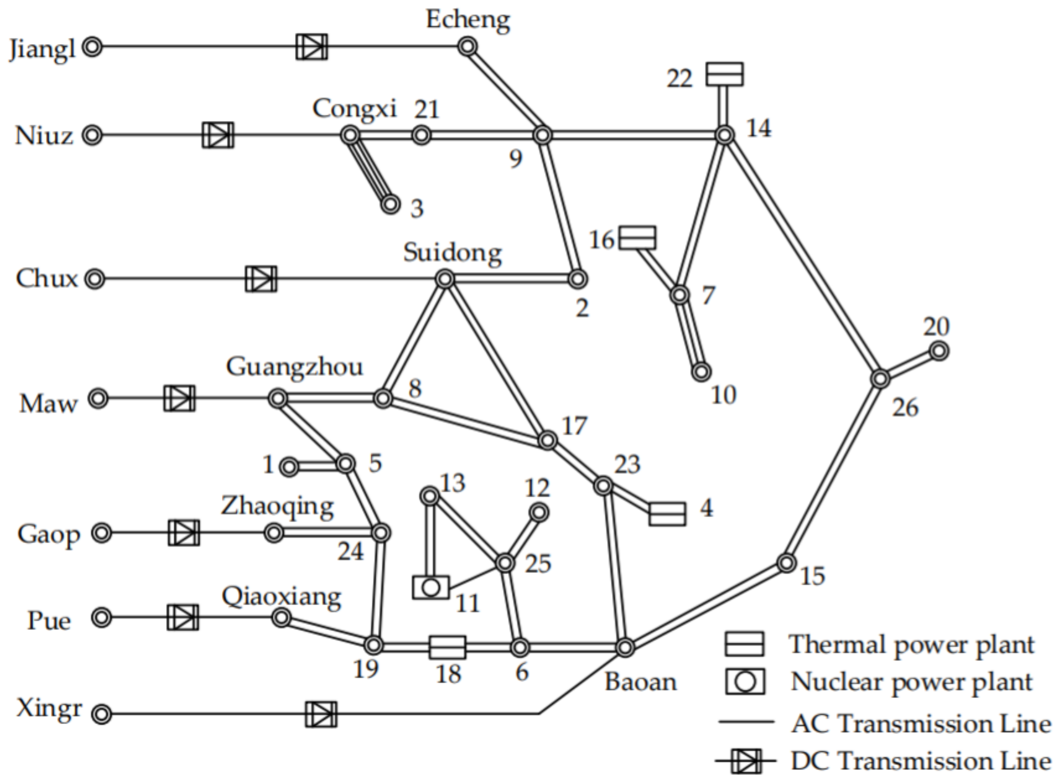
$$MIIF_{ij} = \Delta U_i / \Delta U_j$$

i.e. larger MIIF = stronger interaction between two.

Note:

$$\boxed{MIIF_{ij} = \frac{Z_{ij}}{Z_{jj}} \left(1 + Z_{ii}\frac{dQ_i}{dU_i} - \frac{Z_{ij}^2}{Z_{jj}}\frac{dQ_i}{dU_i}\right)^{-1}}$$

1. **Self Impedance Effect**: When $dQ_i/dU_i > 0$, MIIF increases with $1/Z_{ii}$; When $dQ_i/dU_i < 0$, MIIF decreases with $1/Z_{ii}$.
2. **Power Base Ratio Effect**: When $dQ_i/dU_i = -1.5$, MIIF increases with power base ratio (P_{dj} / P_{di})



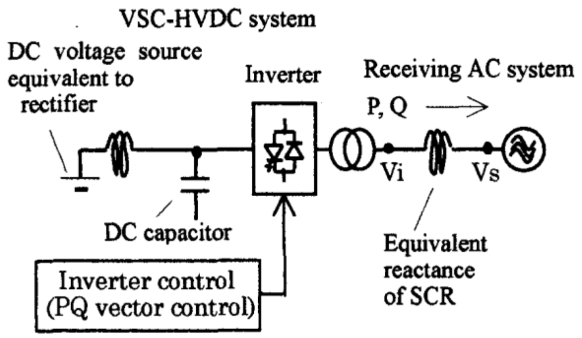
Note:

Generally, one side of HVDC controls DC voltage or extinction angle, and the other side controls DC current or DC power. CC – CEA, CP – CEA or CC – CDV (Constant Current/Power, Constant Extinction Angle/ DC Voltage) is often used.

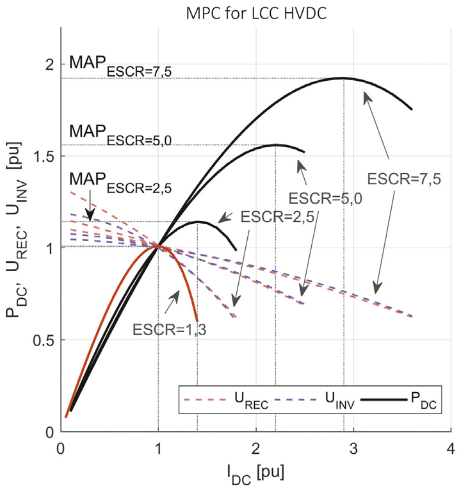
3. **Control Mode Effect:** CP – CEA tends to have large MIIF.

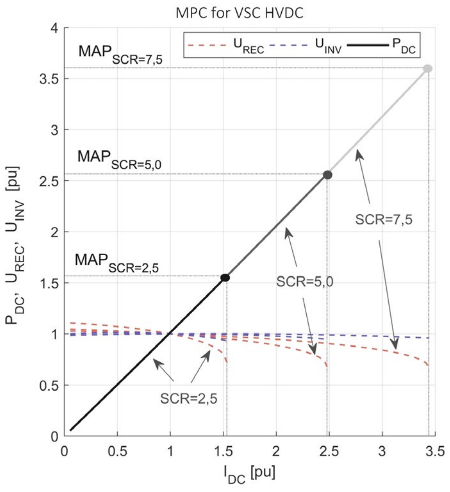
Factors of Voltage Stability in Multi-Terminal HVDC System

- Maximum Achievable Power (MAP)-based approach:
  Maximum DC power achieved by an inverter at a **constant extinction angle** (CEA) is taken as stability limit. **Maximum Power Curve** (MPC) is observed and **system strength** at the maximum point is said to be the critical strength.
- dP_{DC}/dI_{DC} is used as an index to assess stability. If $dP_{DC}/dI_{DC} > 0$, the system is stable.
- Voltage Stability Factor (VSF) is small and positive when the system is stable. Similarly, Power Flow Jacobian (and its eigenvalues) can also be observed with stability.
- VSC – HVDC System could operate where the AC system must be of larger capacity than VSC – HVDC system capacity. The stability limits were between 1-2 times of SCR. When the inverter of VSC – HVDC operates with leading reactive power, the stable operating limit can be increased with AC voltage stabilization.

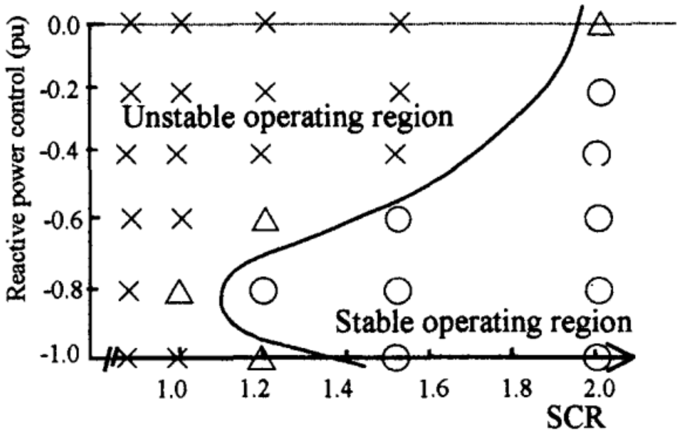


○ : stable operation, △: nearly stable operation,
×: unstable operation





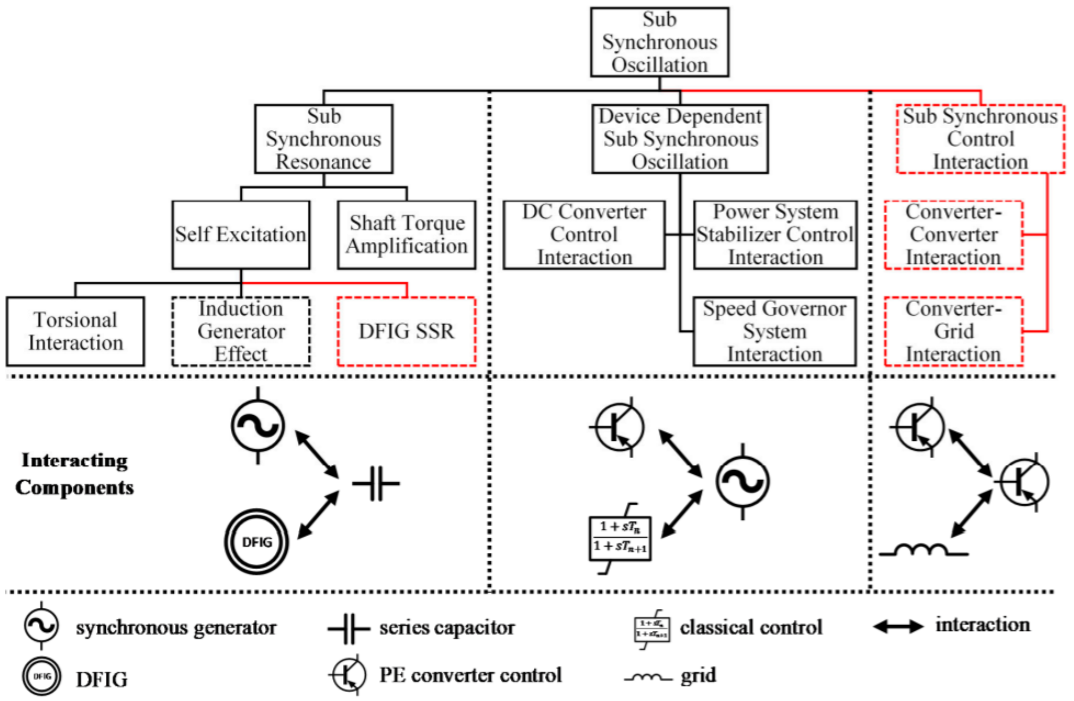
HVDC Capacity Limit from AC side system strength

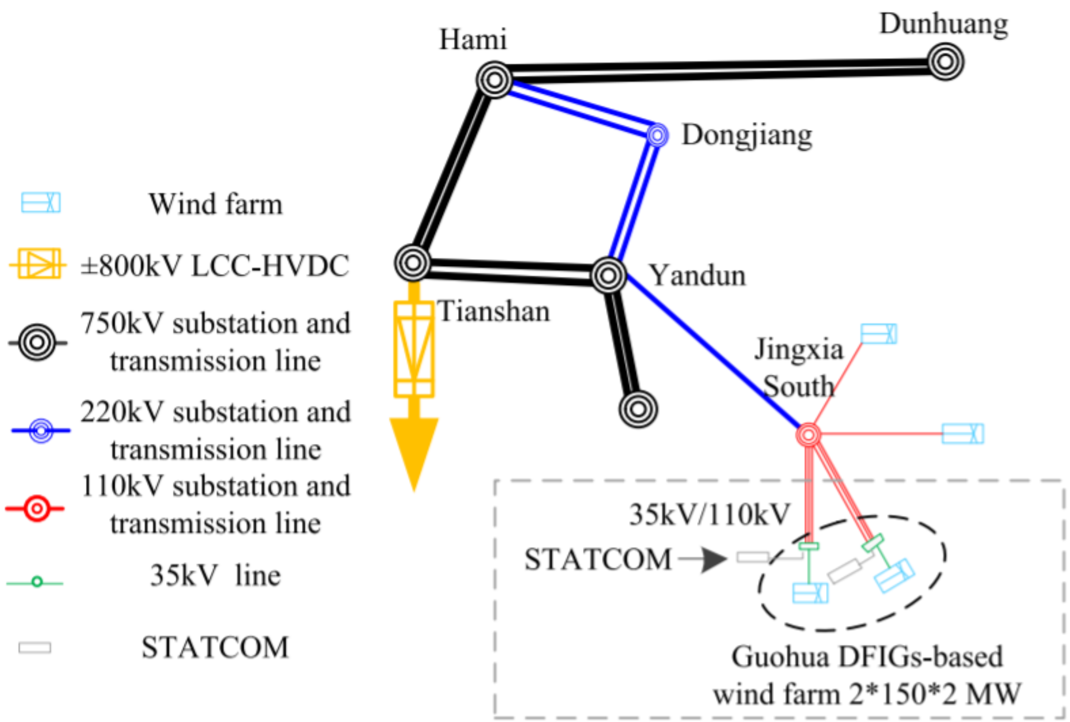


Sub-Synchronous Oscillation

Oscillation at the outlet of Guohua wind farm is observed.

- NOT caused by DFIG + series compensation.
- Caused by improper configuration of control parameter between DFIG and STATCOM
- Suggestion:
  Reduce **PI coefficient** of inner loop current control of DFIG or STATCOM or **increase Q output** of STATCOM.





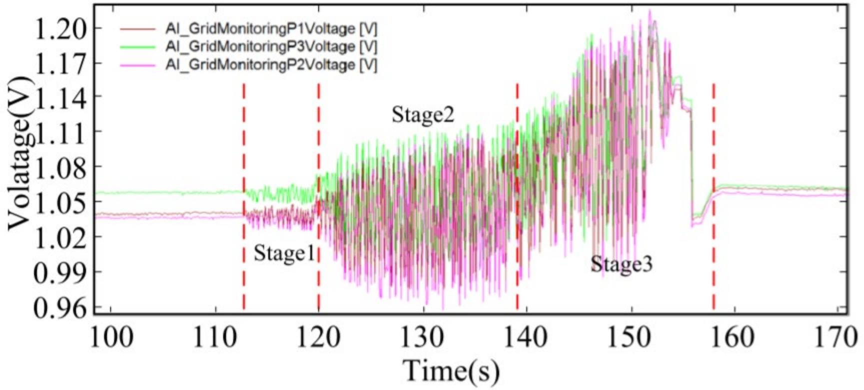
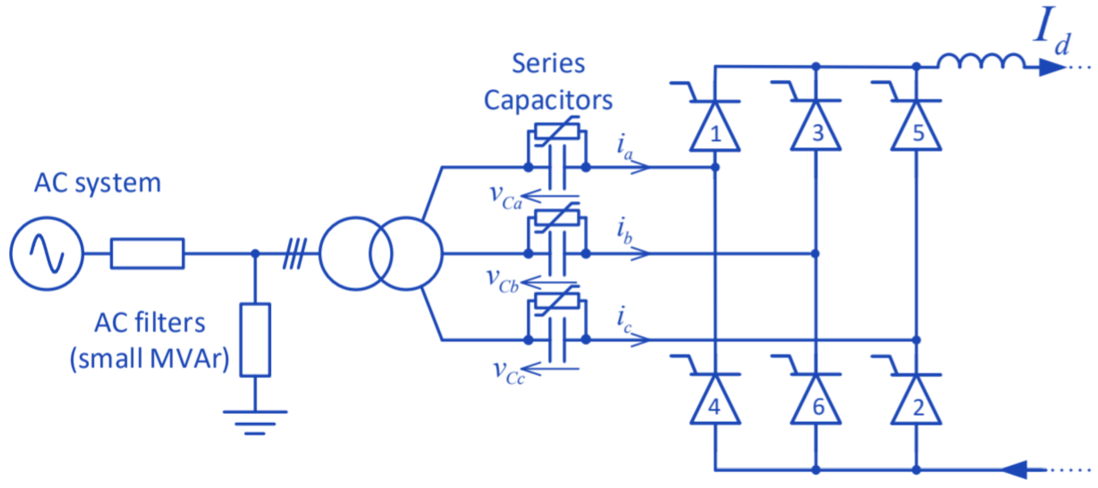


FIGURE 2. The voltage at the outlet of Guohua wind farm during SSO.

Capacitor Commutated Converter and Ferroresonance

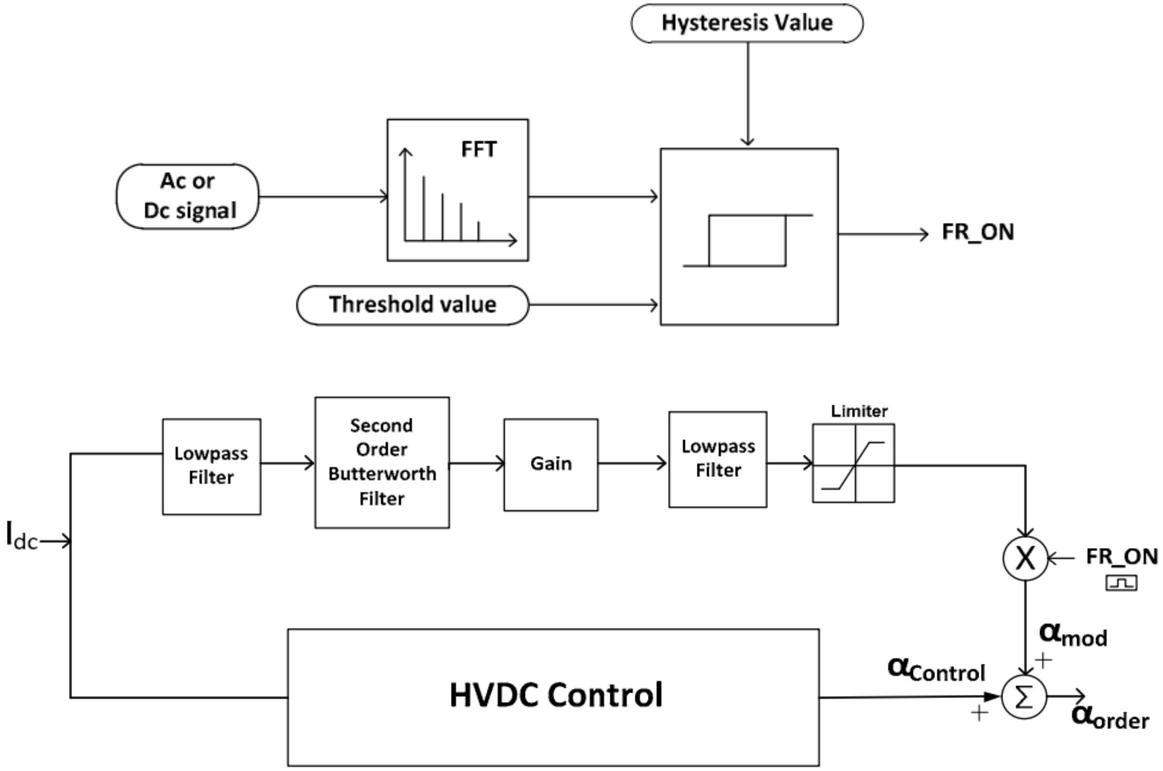


Placing a capacitor in series with the converter transformer can

- Lower commutating reactance
- Reduce Q demand and hence shunt compensation
- Increase immunity to commutation failure
- Increase stability at low SCR
- Smaller overvoltage at load rejection
- No AC side zero sequence current
- Improved control properties
- Reduced shunt bank switching and OLTC operation
- Reduce transformer rating (reduced Q) and remove the risk of Ferroresonance or Sub-synchronous Resonance

Ferroresonance can potentially establish itself as an **undamped exchange of energy** at sub-synchronous frequencies between the series capacitor and **saturating magnetic circuits** of the converter transformers.

Solution II: Add a Ferroresonance Suppress Controller



LCC – HVAC Response to AC Side Fault

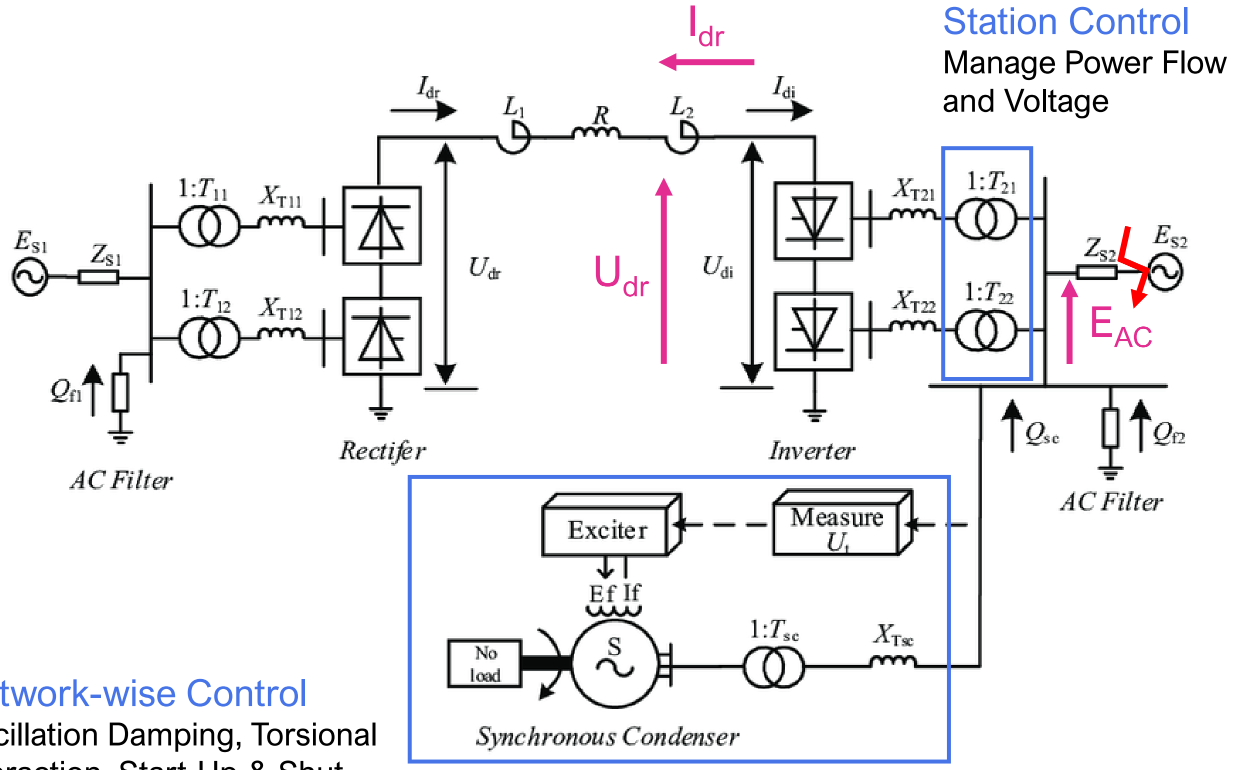
Consider a **three-phase end fault** in AC side.

- Rectifier Commutation Voltage E_{AC} drops slightly.
- Rectifier DC voltage V_{dr} drops and hence current I_{dr} drop (due to smaller voltage difference)
- Current Regulator tries to reset firing angle of the rectifier (reduce firing angle) to restore current I_{dr} by increasing voltage V_{dr}
- If the commutation voltage E_{ac} remains low after tap changing, the VDCOL controller will take over to regulate current and power transfer under low voltage.
- If low commutation voltage persist, shut down HVDC station might be possible.

Commutation failure refers to a **phenomenon where a valve that has just been turned off is subjected to negative voltage for a time (γ angle) insufficient** for it to regain blocking capability and the valve is reconducted when voltage applied across its two terminals becomes positive.

It takes time (0.1 – 0.5s) to recover the pre-fault power in DC system.

Station Control
Manage Power Flow and Voltage



Network-wise Control
Oscillation Damping, Torsional Interaction, Start-Up & Shut-down, Coordinate with other AC system

Pareto Optimal on Fault Level and Stability in HVAC / HVDC Hybrid Grid

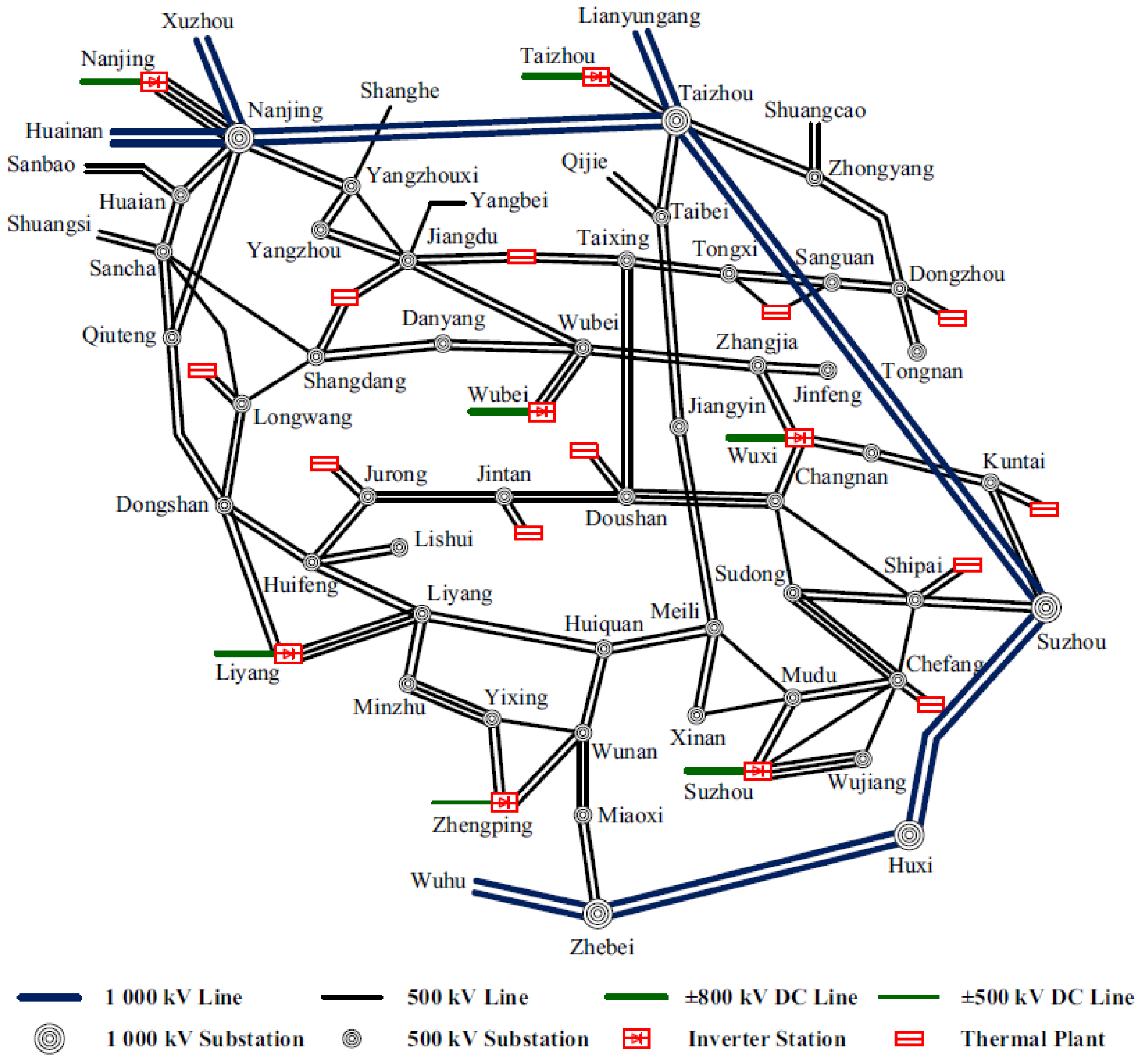
Controlling short circuit current (↑ electrical length) and increasing power system stability (↓ electrical length) is a contradiction.

A passive way is to **open a line** or install **fault current limiter**.

Objective function includes:

1. Economy of Current Limiting Measures
2. Tightness of Network Structure (SCR) – reflects anti-disturbance performance and connection strength
3. Impact on Current Limiting Measures on Multi-Infeed Short Circuit Ratio, i.e. Voltage Support Capability

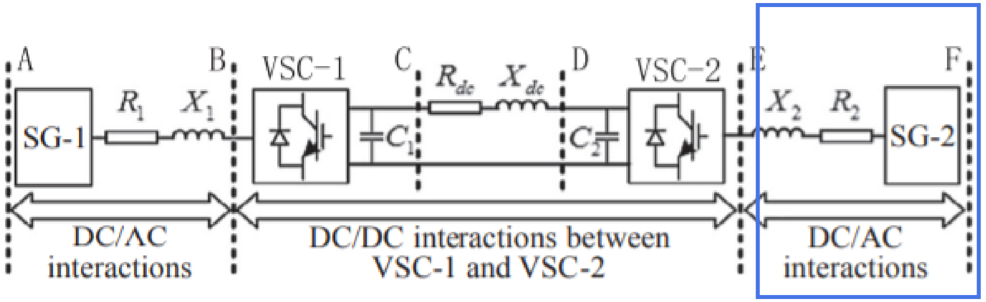
Scheme	Current limiting measure	
	Open the line	Install the current limiting reactor
1	Shipai-Changnan Changnan-Sudong Xinan-Mudu Meili-Mudu	None
2	Shipai-Changnan Doushan-Changnan I	Shipai-Suzhou I Line +9Ω Shipai-Suzhou II Line +10Ω
3	Shipai-Changnan Xinan-Mudu Meili-Mudu Shipai-Suzhou II	None
4	Shipai-Changnan Doushan-Changnan I Shipai-Suzhou I	Shipai-Suzhou II Line +2Ω



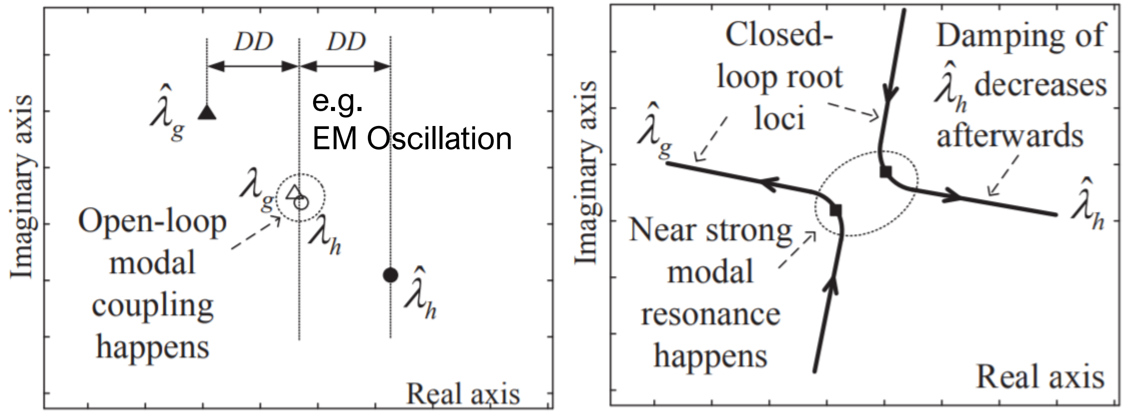
Dynamic Interaction in VSC System

Types of dynamic interactions	Frequency ranges
Dynamic interactions between the PLLs	10 Hz–100 Hz
Dynamic interactions between the PLL and VSC control outer loops	5 Hz–20 Hz
Dynamic interactions between the PLL and VSC control inner loops	40 Hz–100 Hz

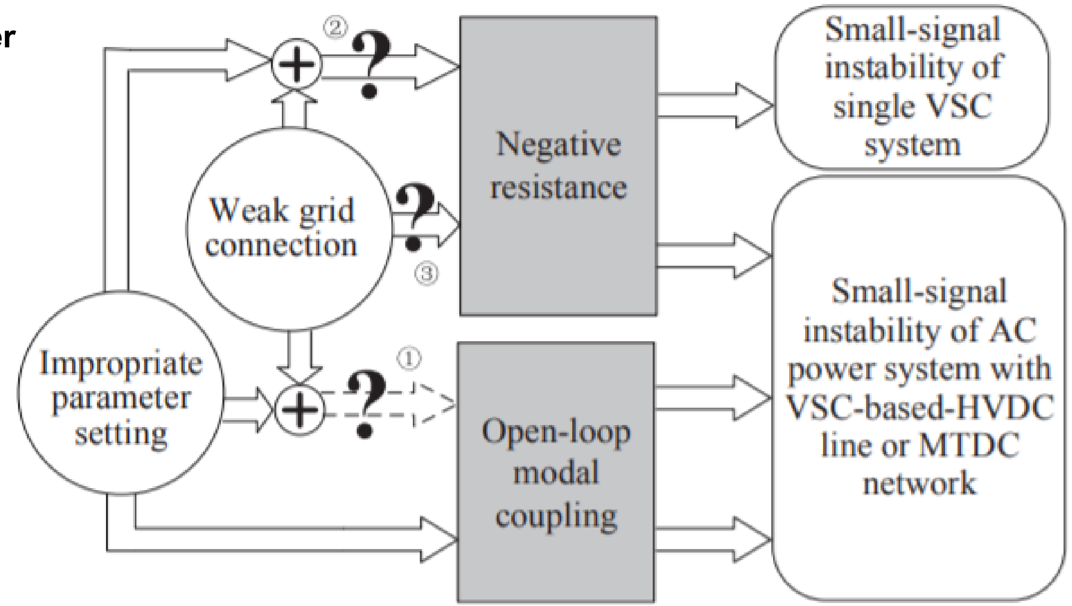
Types of dynamic interactions	Frequency ranges
AC/DC dynamic interactions – AC electromechanical oscillations	0.2 Hz–2 Hz
AC/DC dynamic interactions – the SSO of AC power systems	Below 50 Hz
Dynamic interactions between the VSCs	10 Hz–100 Hz
Dynamic interactions introduced by the VSC control	0.2 Hz–100 Hz



Constant Power Source cannot reflect dynamic interaction



(a) Open-loop modal coupling (b) Near strong modal resonance

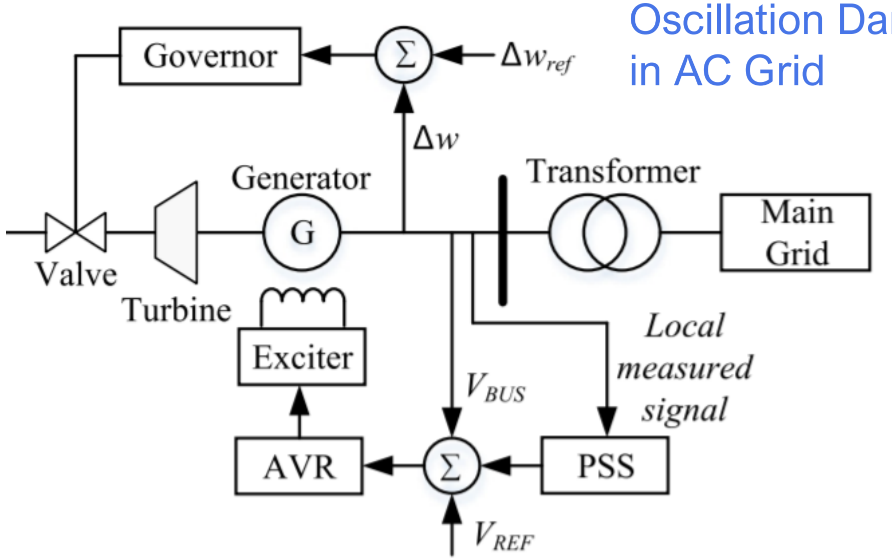


Improper Controller Setting & Weak Coupling between Grids

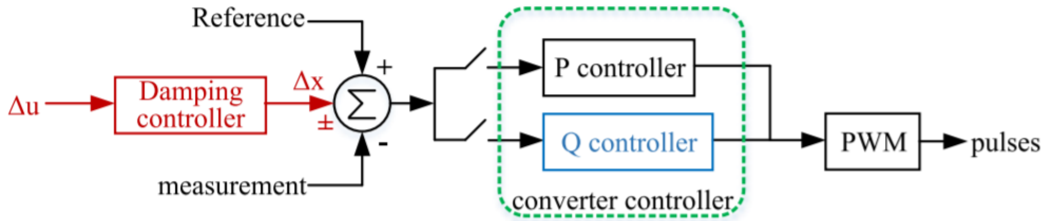
Research Gap on Damping with PSS Type Controller

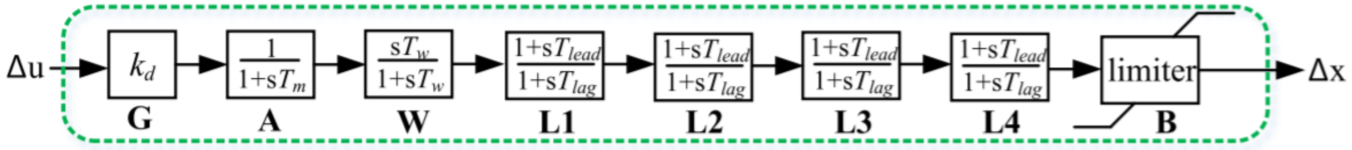
1. Coordination Control **between AC Generation and HVDC system** for effective control in damping multiple inter-area oscillation
2. **Damping Controller Design** for HVDC utilizing new converter topology
3. Real Time Digital Simulator (RTDS) based experimental studies to assess damping performance of robust wide-area HVDC damping controller in **real time**
4. Small signal/transient stability of large interconnected network with **multi-agent system** and **multi-terminal HVDC system** to cope with non-linearity, uncertainty and dynamic configuration change
5. Adaptive Wide-area HVDC damping controller to enhance overall stability considering **delayed** measurement signal transfer
6. Coordinated control of **DG and multi-terminal HVDC system** to cope with inter-area oscillation

Oscillation Damping in AC Grid

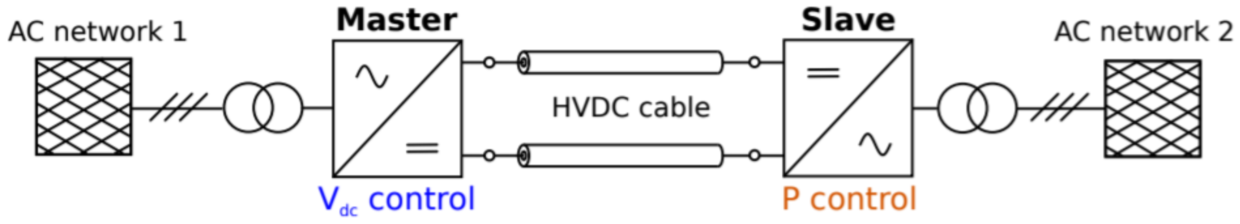


Damping Controller in HVDC Links



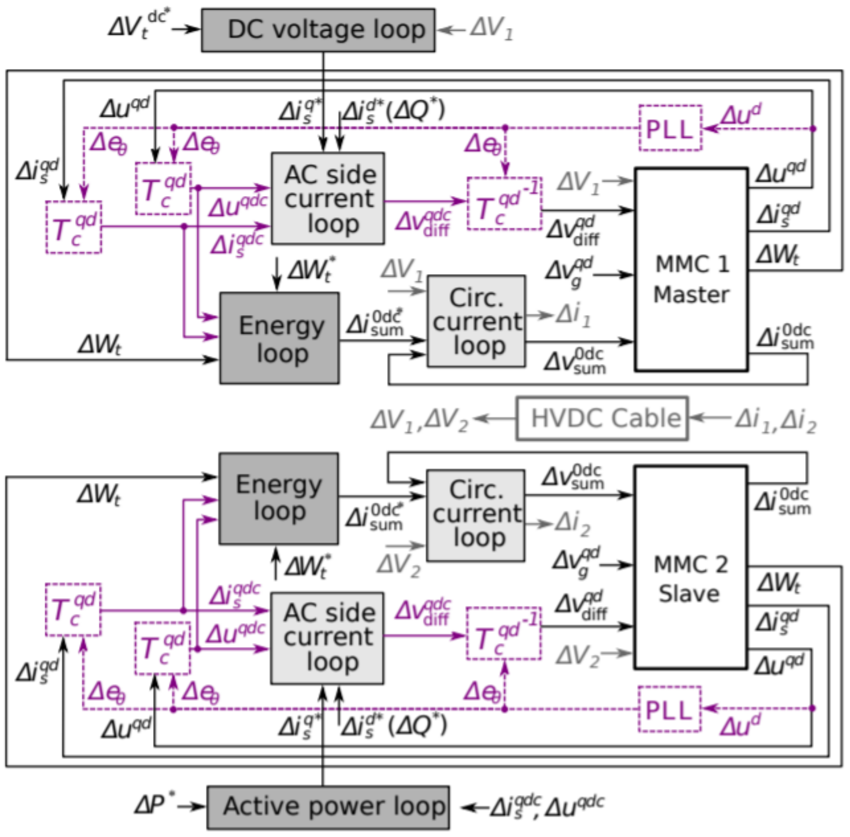


Modelling Interactions and Oscillation Behavior in HVDC System



Method:

- State Space Modelling based on dq-transformation
- State Space Modelling based on dynamic phasor (Harmonic Stability)
- Impedance-based modelling (Impedance Stability)



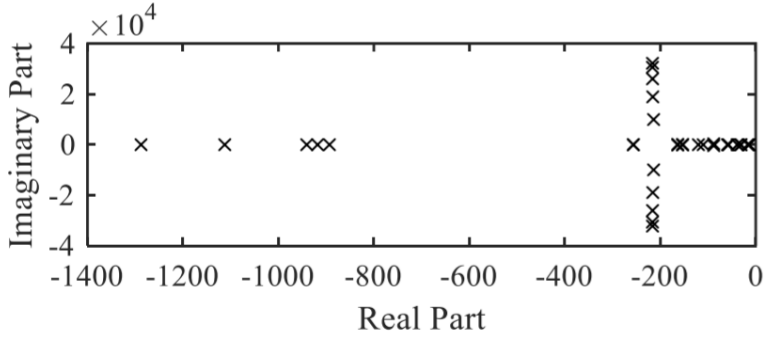
Note:

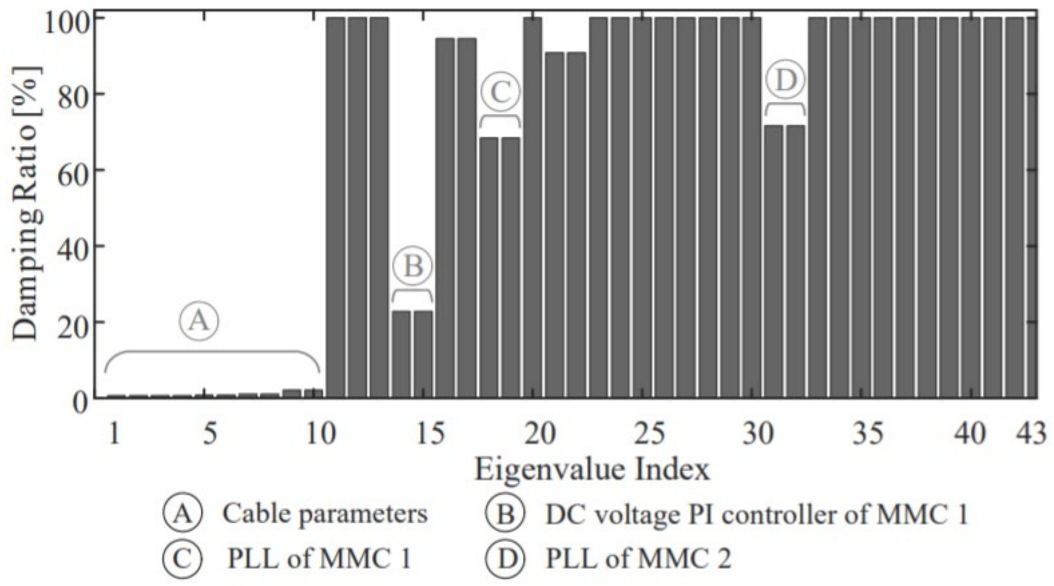
- Control system for both MMCs is based on energy-controlled approach.
- Grid side current controller tracks current references sent by outer control loop.
- Master MMC: DC Voltage Outer Control Loop provides **q-axis** reference.
- Slave MMC: Active Power Control Loop provides **q-axis** reference.
- d-axis current reference is given by Reactive Power Control Loop
- Energy Balancing and Total Energy Control sends the circulating current reference for inner current controller
- Phase Locked Loop (PLL) tracks AC voltage at PCC
- Output of both current control system (grid side and circulating) are used to generate six-arm voltage
- Modulation and Cell Balancing Algorithm are responsible for generating required voltage through communication with submodule switches.

Modelling Interactions and Oscillation Behavior in HVDC System

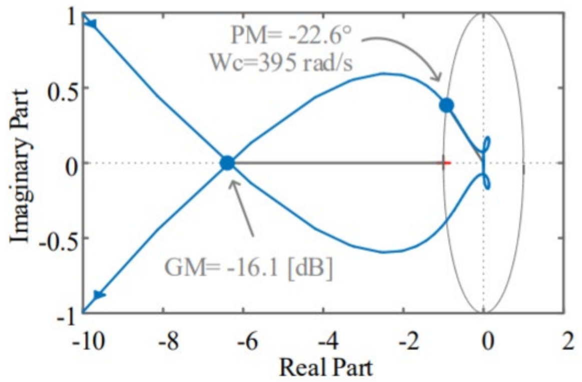
Eigenvalues of HVDC Link

(Eigenvalue Analysis from State Space Model of HVDC link
 - **Stability to each parameter**)



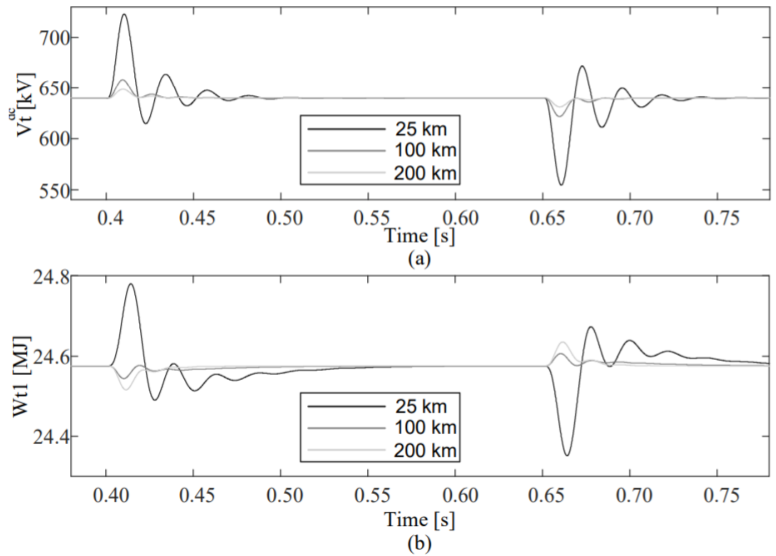


HVDC Link (L = 100km)
Stability Margin: PM = - 22.6^o and GM = -16.1 dB



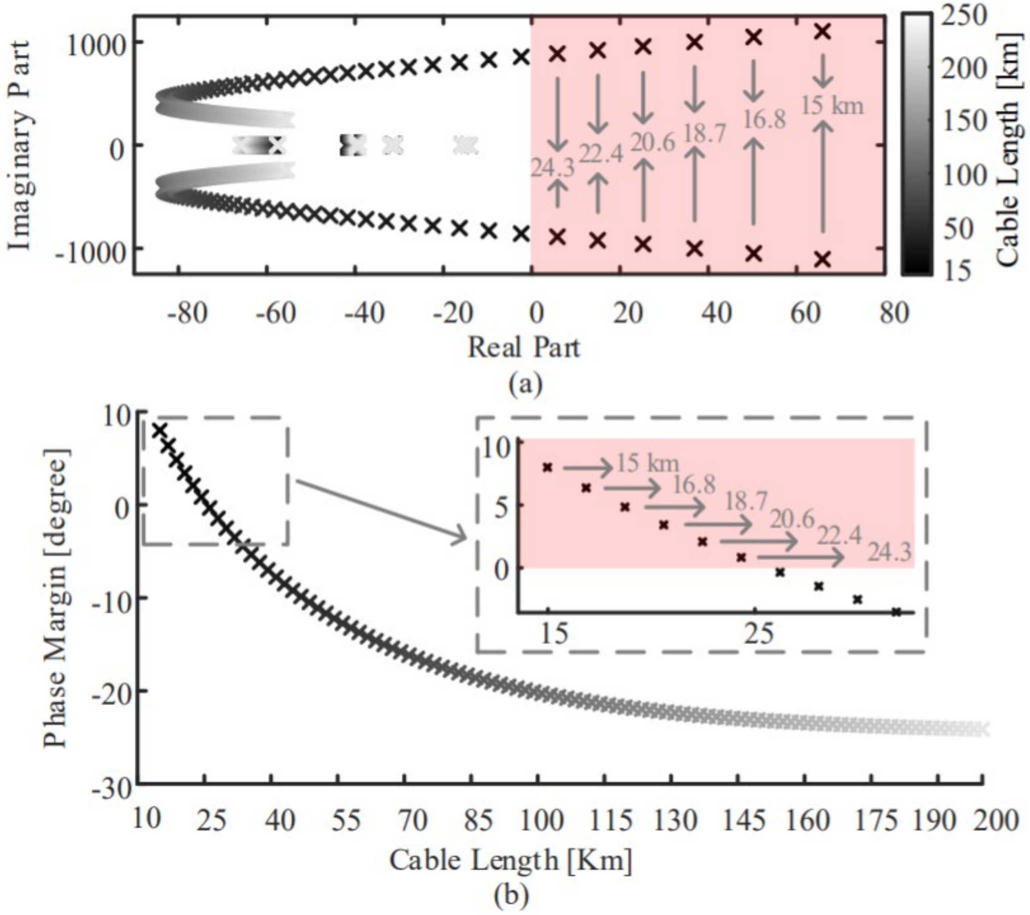
Nyquist Plot
- **How far from instability**

Shorter Cable Length = Higher Oscillation

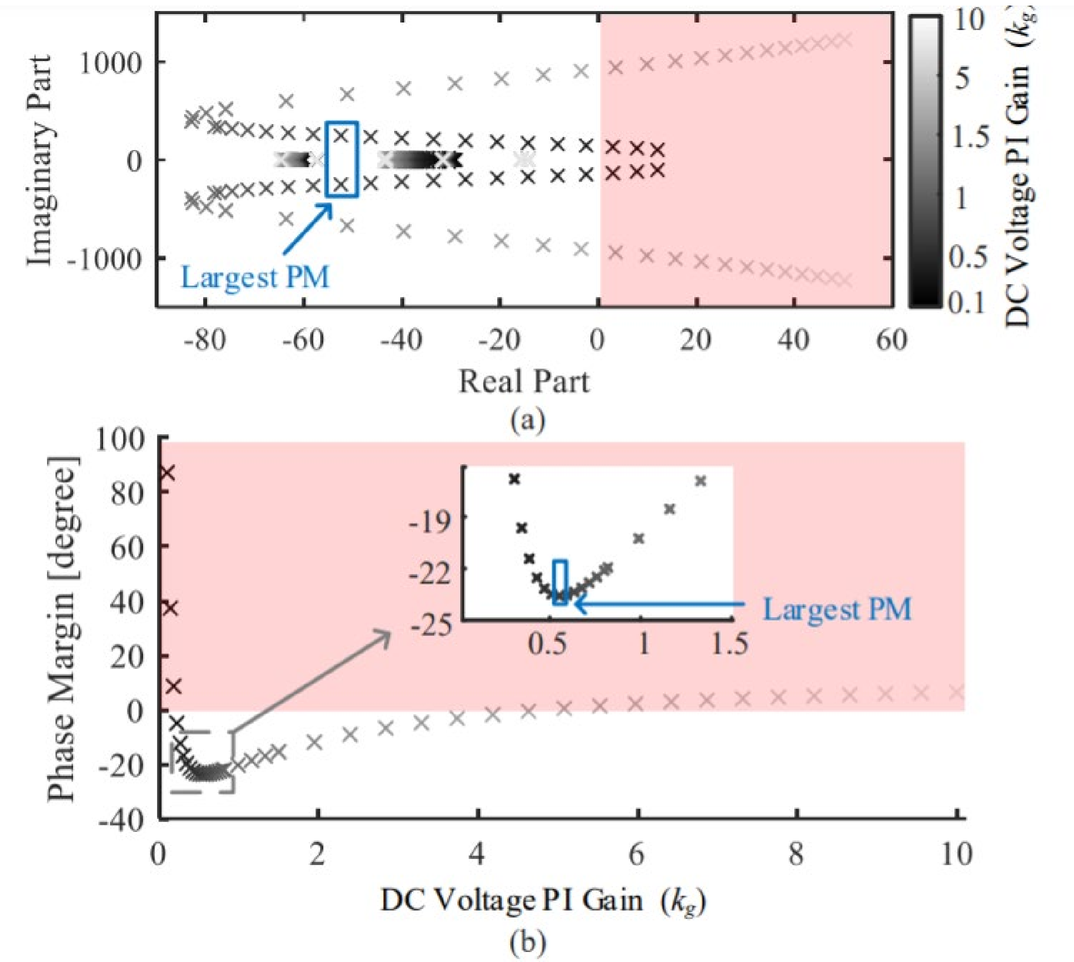


Modelling Interactions and Oscillation Behavior in HVDC System

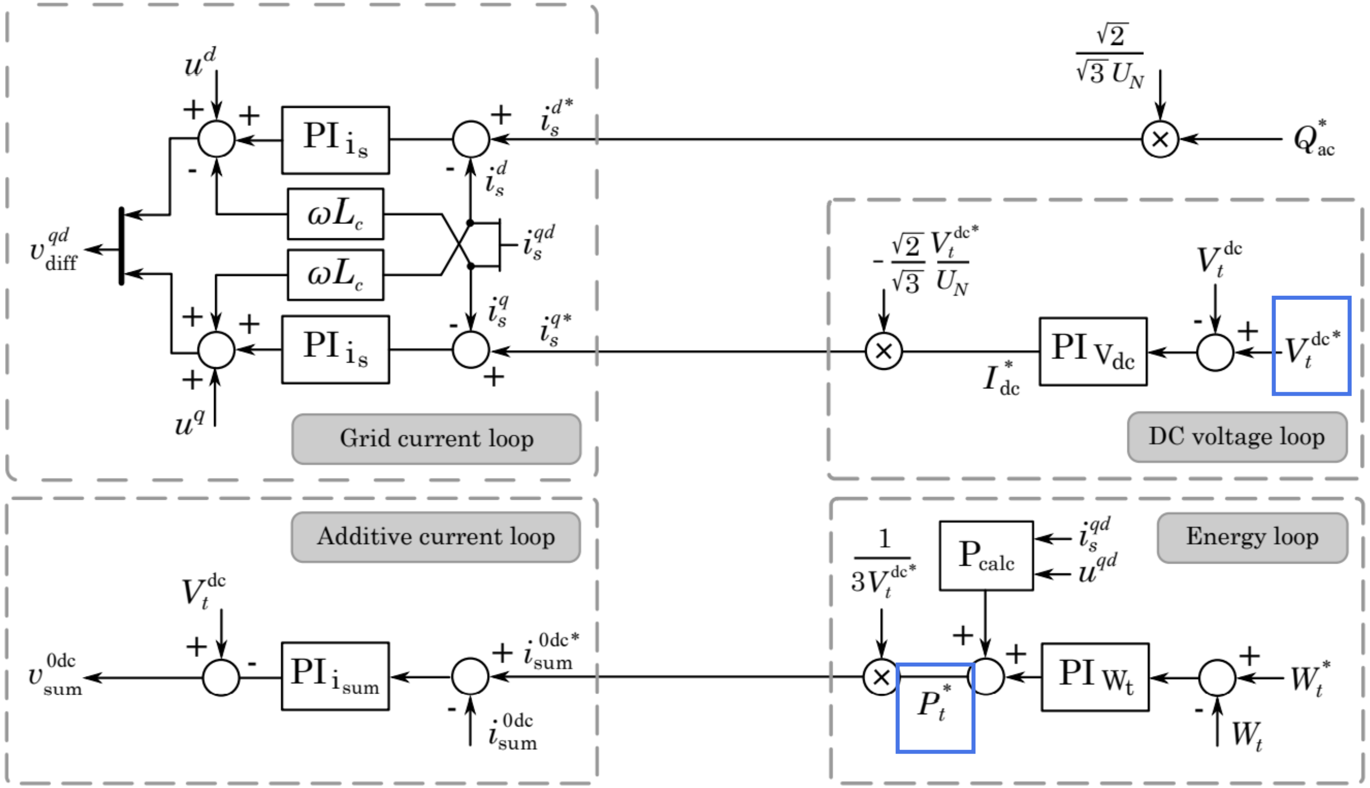
Effect of DC Cable Length



Effect of DC Voltage PI Gain

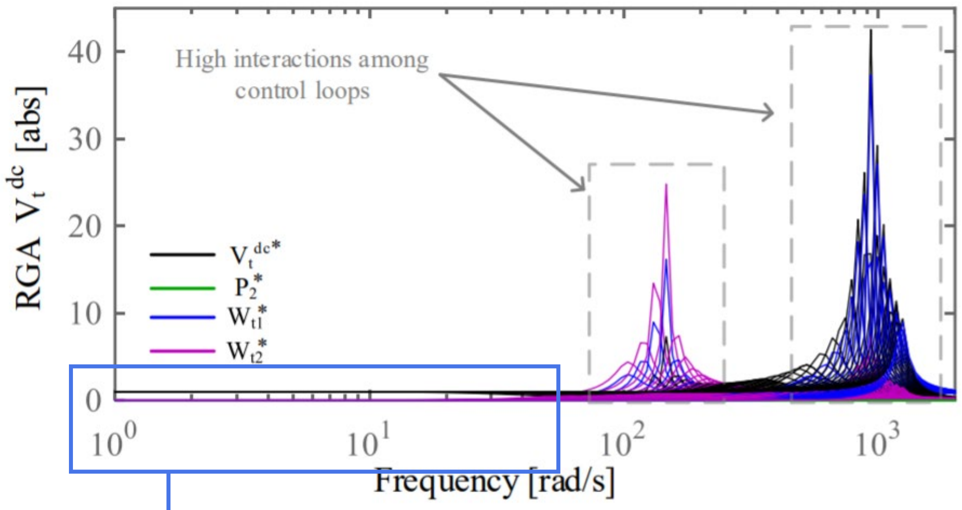


Modelling Interactions and Oscillation Behavior in HVDC System



Relative Gain Analysis (RGA)

- **Frequency Range for Control Loop Interaction**
  (system PM occurs near these frequency)

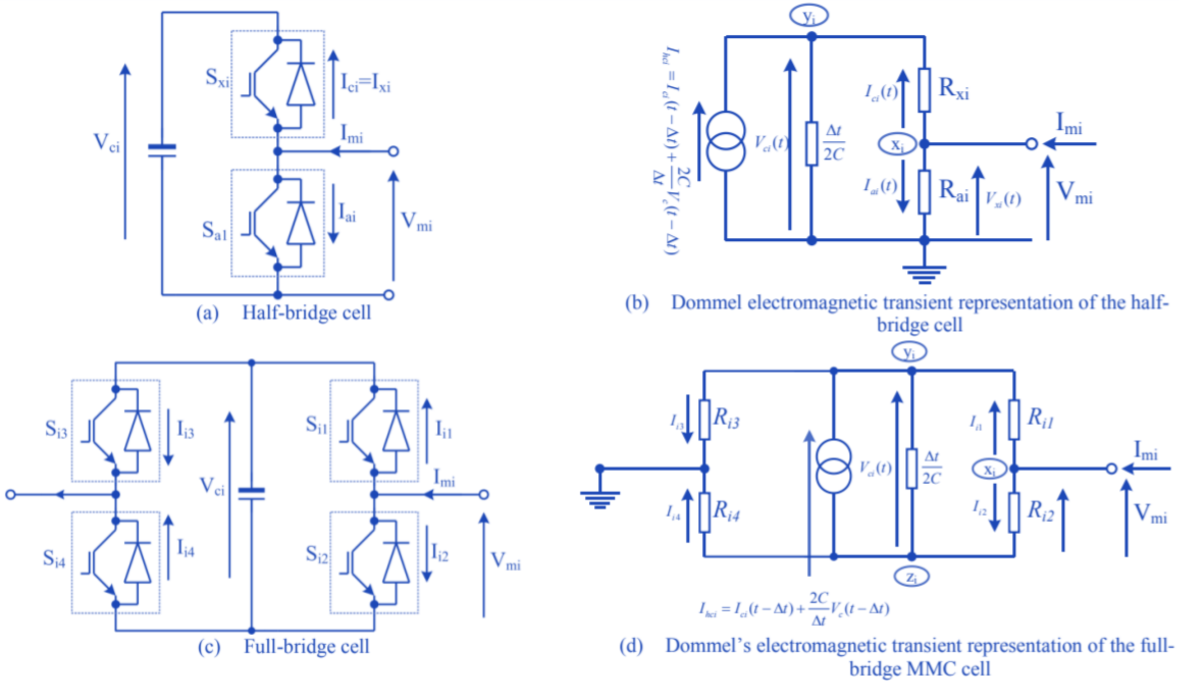


Note:

- At low frequency, all four control loops are strongly coupled with their own reference. Hence all four are well-designed for DC or low frequency.
- Active Power Control Loop P_2 does NOT interact with other three control loops, and it is coupled only with its own reference.
- At high frequency, control loops starts to interact.
- Reference values should be changed with a limited bandwidth lower than 400 rad/s to avoid interactions between loops.

Half-Bridge Submodule VS Full-Bridge Submodule

- Apply Full Bridge in series with Director Valves enable the MMC to provide a voltage that opposes and limits the flow of current into a network short circuit.
- It enables the converter to **remain connected** and ready to continue power transmission once the fault is removed (without disconnect it and waiting for discharge).
- Yet, it increases **converter loss**.
- A fast and cost-effective DC CB is needed to limit impact of DC side fault, particularly in **multi-terminal HVDC**. It only require isolating the faulted line **without complete shutdown**.
- FBSM has their **fault handling capacity,** and it is suitable for **OHL** HVDC transmission, while HBSM with fewer devices and hence **lower loss** are widely used in underground and submarine HVDC **cable** systems.
- Voltage balancing control ensure capacitor voltage to be constant across all SM. It requires instantaneous control to ensure **charging of depleting capacitor** and **discharging of charged capacitors**. Such voltage balancing techniques include circular transposition of carrier waves or calculated methods such as capacitor voltage rank-based method.

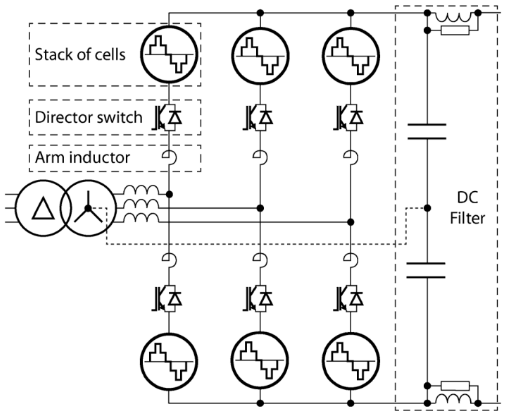


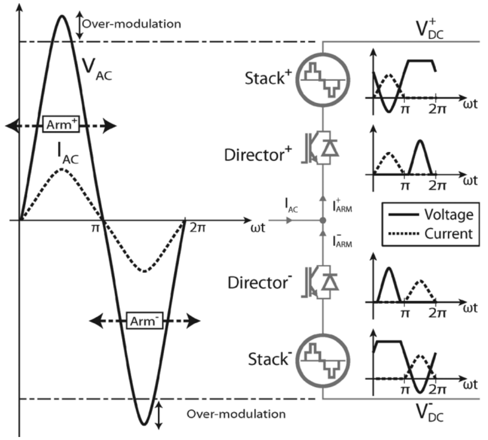
(a) Half-bridge cell

(b) Dommel electromagnetic transient representation of the half-bridge cell

(c) Full-bridge cell

(d) Dommel's electromagnetic transient representation of the full-bridge MMC cell



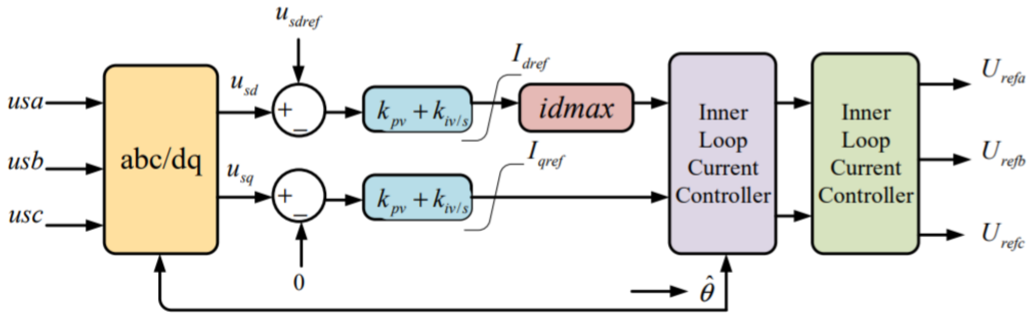


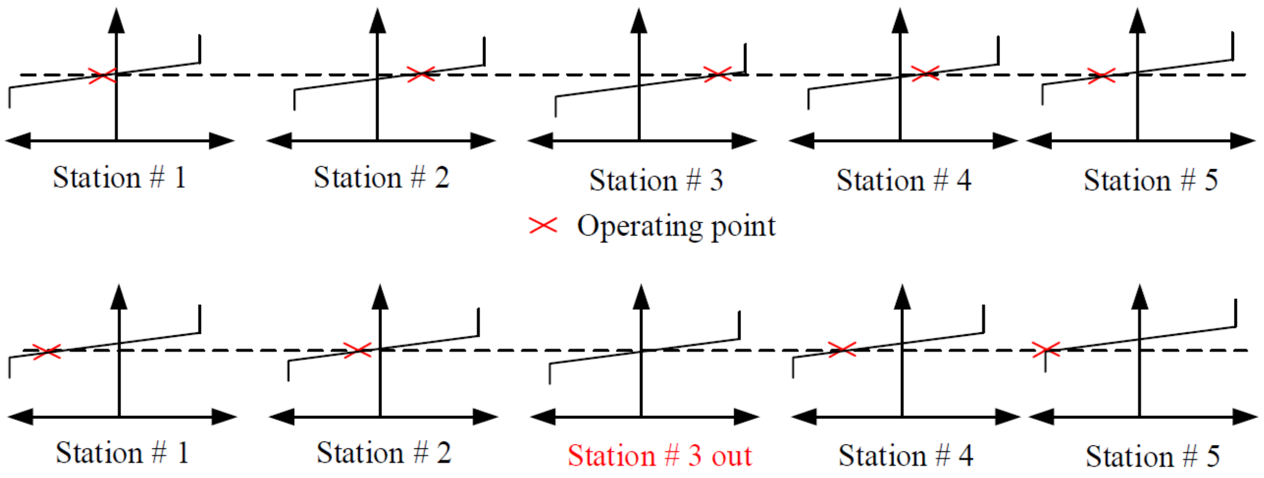
Control Strategies for Multi-Terminal HVDC

1. DC Voltage Control –
   Slip of dynamic load equivalent induction motor and **change ratio of OLTC switching affects voltage stability**.
   HVDC converter station needs about **reactive power** of 30 - 50% rated DC Power at rectifier side and 40 – 60% at inverter side.
   Inner and outer control loops with **VDCOL** is to avoid overtaking current for voltage collapse.

2. Power Flow –
   Power Flow and Sharing of multi-terminal system is controlled by DC voltage at each terminal. It is essential to consider the **stability region**, **limitation** and **optimal parameter** of voltage control to calculate load flow and sharing

3. Power Oscillation Damping –
   Further control function to develop system dynamic execution, such as **transient stability** and **fault recovery**, **oscillation damping** to avoid total area blackout is important and has remained a challenge for a long time.

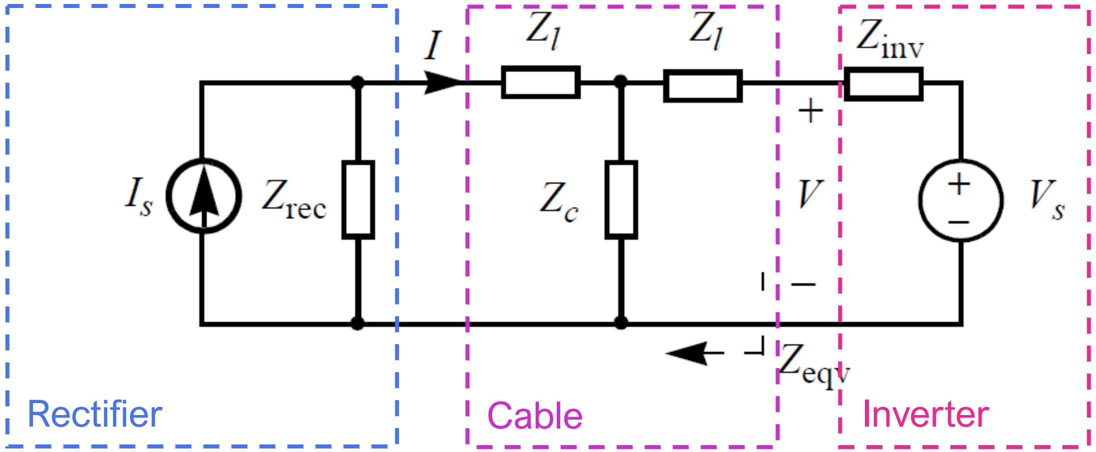




Harmonic Instability

Harmonic instability may occur in HVDC links due to **dynamic interactions** between HVDC terminals and the impedance of the dc lines or cables, possibly under unbalanced condition.

Inverter Stability can be determined from the ratio of the grid impedance to the inverter output impedance in both positive- and negative-sequence.

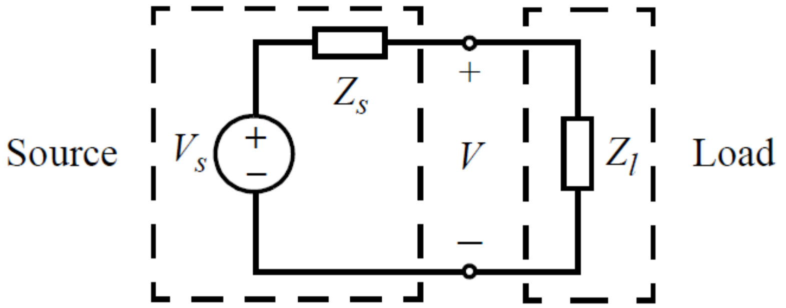


$$Z_{\text{dc}} = Z_l + \frac{Z_c Z_l}{Z_c + Z_l}$$

Given that

Case 1: Rectifier Current Control (Stable) e.g. $H(s) = 1.6 + 19.3/s$

Case 2: Fast Inverter DC Voltage Control (Unstable) e.g. $H(s) = 2 + 0.2/s$.

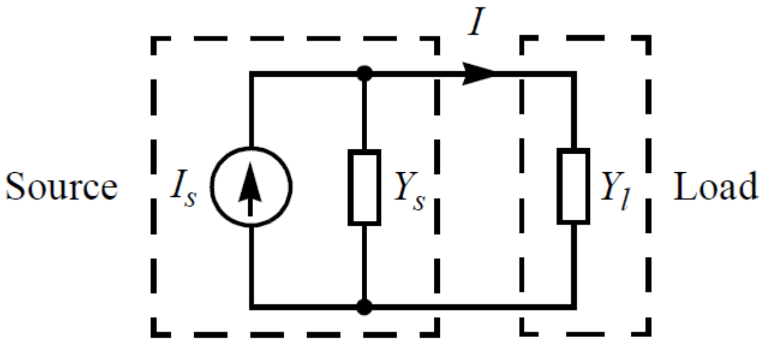


Voltage Source Stability:

$$Z_{eq} = \frac{Z_s}{Z_l}$$

Note:

Assumption – voltage source with stable voltage control in open circuit condition with NO load connected.

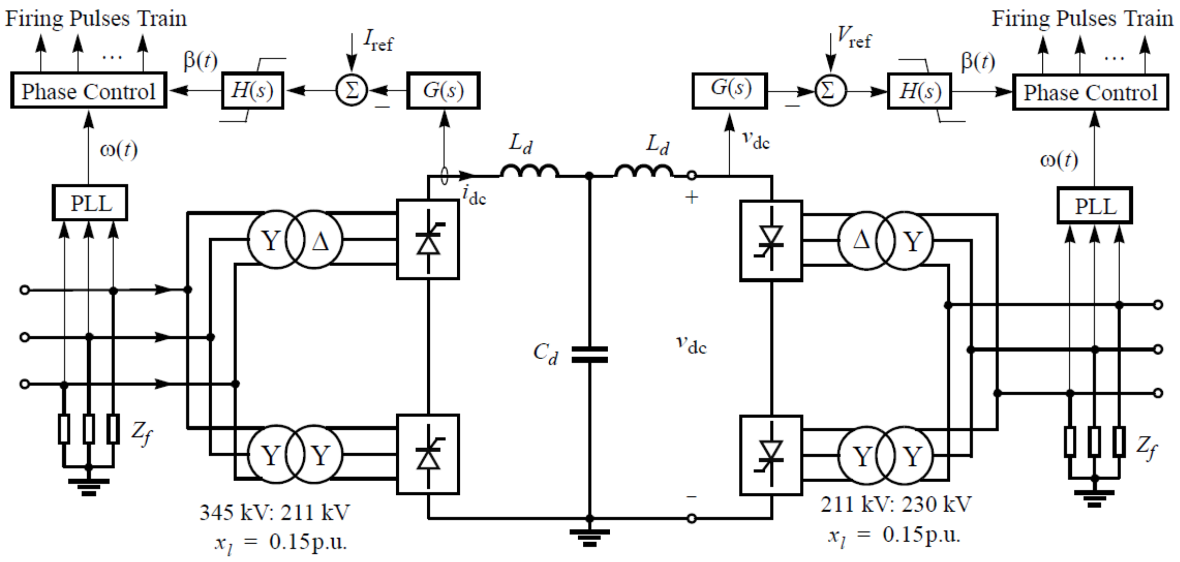


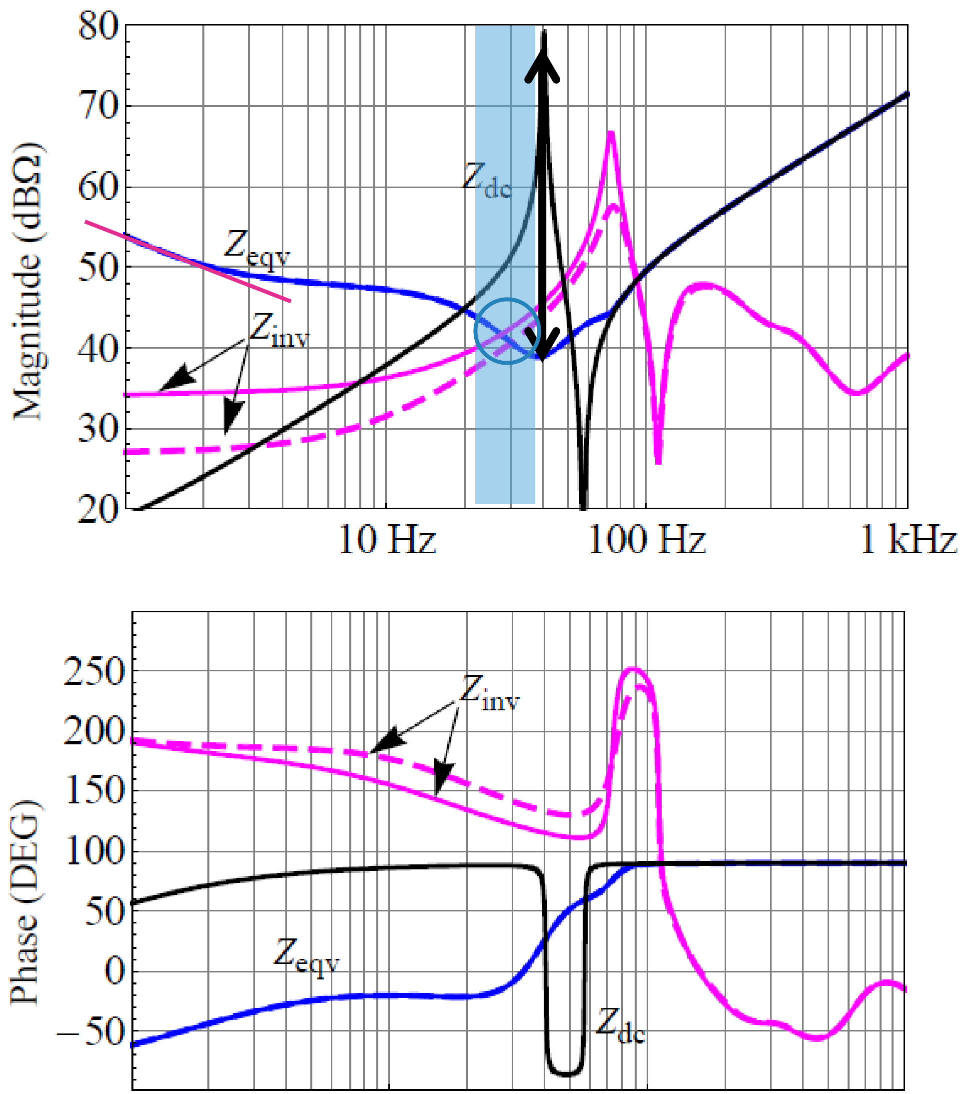
Current Source Stability:

$$Y_{eq} = \frac{Y_s}{Y_l}$$

Harmonic Instability

Consider the following system:

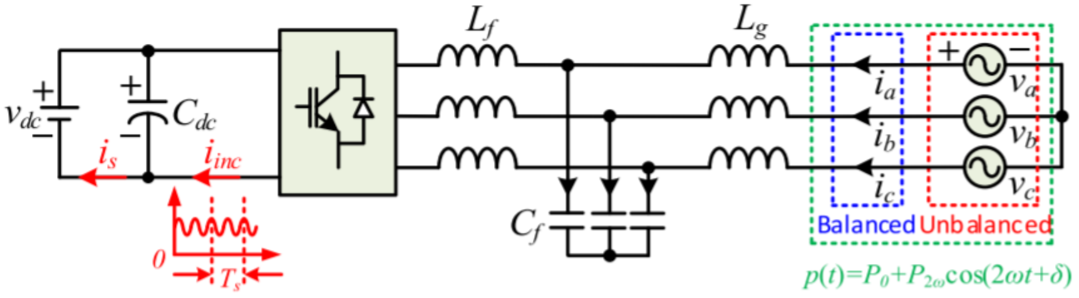




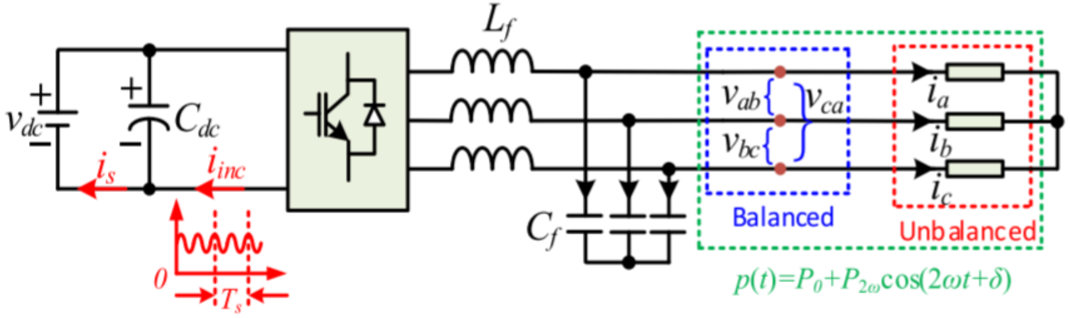
- Even rectifier DC impedance included large DC smoothing reactor, it looks capacitive at low frequencies. It is due to integral gain of current controller.
- Case 1: Z_{inv} and Z_{eqv} intersects at 28Hz with PM = 45°. (Stable)
  Case 2: Z_{inv} and Z_{eqv} intersects at 30Hz with PM = 25°.
- Simulation of Case 2 exhibits resonance at 30Hz.
- Rectifier Impedance Z_{REC} greatly changes Z_{DC} to Z_{eqv} as seen by inverter at the frequency where resonance occurs.

Second Harmonic Oscillation

- Balance grid current (or balanced load voltage) is expected to be provided by VSC.
- Under unbalanced condition, controlling the VSC to inject balanced current to the grid (or balanced voltage to the load) will lead to double frequency power ripple due to existence of negative-sequence grid voltage (load current component).



(a)



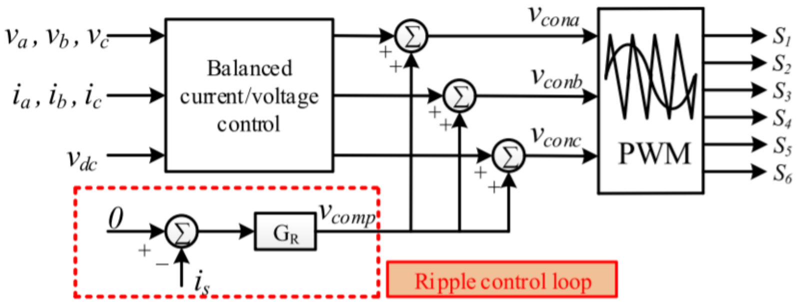
(b)

$$\begin{cases} v_a = \sqrt{2}V_a \sin(\omega t + \alpha_1) \\ v_b = \sqrt{2}V_b \sin(\omega t + \alpha_2) \\ v_c = \sqrt{2}V_c \sin(\omega t + \alpha_3) \end{cases}$$

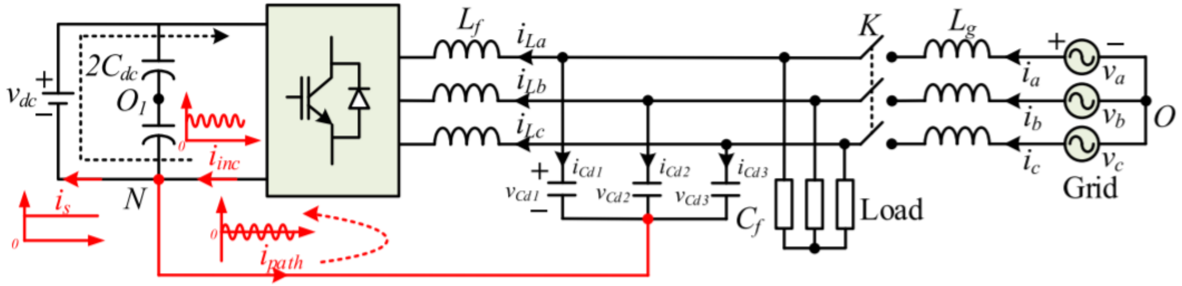
$$\begin{cases} i_a = \sqrt{2}I \sin(\omega t + \varphi) \\ i_b = \sqrt{2}I \sin(\omega t - 120^\circ + \varphi) \\ i_c = \sqrt{2}I \sin(\omega t + 120^\circ + \varphi) \end{cases} \longrightarrow$$

$$\begin{aligned} P_0 &= V_a I \cos(\alpha_1 - \varphi) + V_b I \cos(\alpha_2 - \varphi + 120^\circ) \\ &\quad + V_c I \cos(\alpha_3 - \varphi - 120^\circ) \\ P_{2\omega} \cos(2\omega t + \delta) & \\ &= -(V_a I \cos(2\omega t + \alpha_1 + \varphi) \\ &\quad + V_b I \cos(2\omega t + \alpha_2 + \varphi - 120^\circ) \\ &\quad + V_c I \cos(2\omega t + \alpha_3 + \varphi + 120^\circ)) \end{aligned}$$

- Common-Mode Path is added to reduce double-frequency component, leakage current and circulating current (parallel VSC).

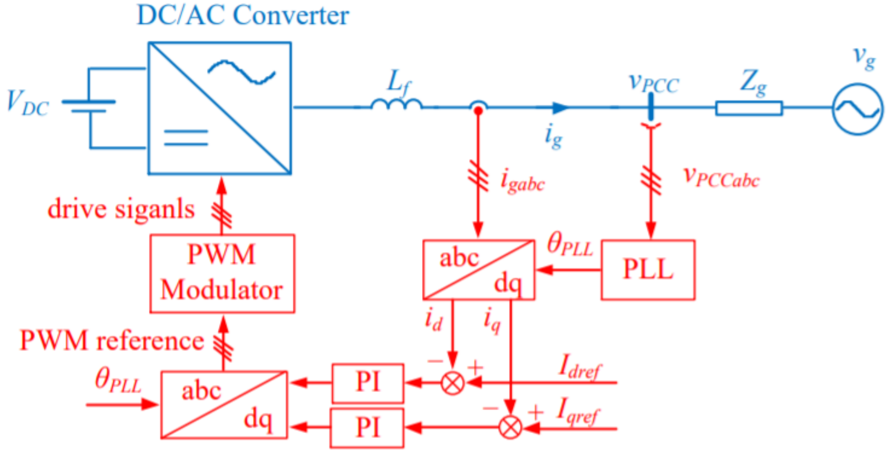


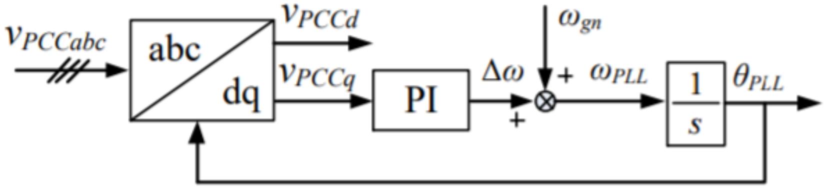
Suggestion:



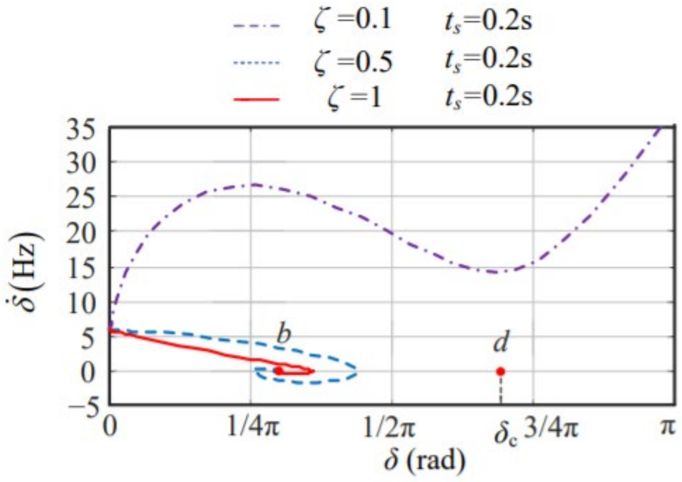
Phase Locked Loop Induced Instability

- Transient Stability of PLL is mainly affected by its damping ratio in resistive grid and settling time in inductive grid. Generally, **slow dynamics** and **large damping** are recommended for transient stability enhancement of PLL.
- Another suggestion is **synchro-converter** or **virtual inertia**.

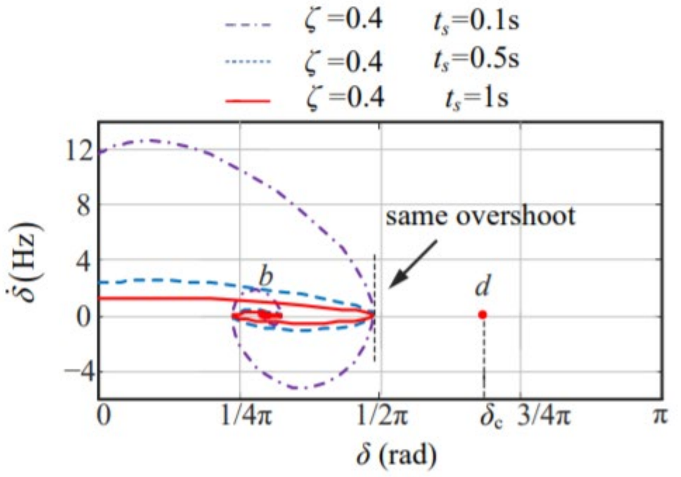




Resistive Grid

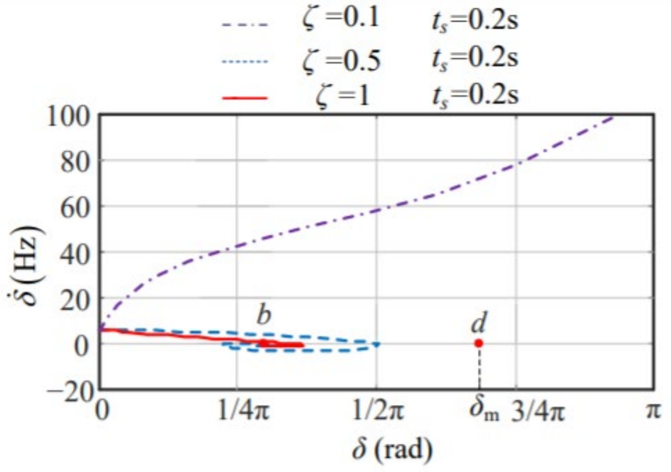


(a)

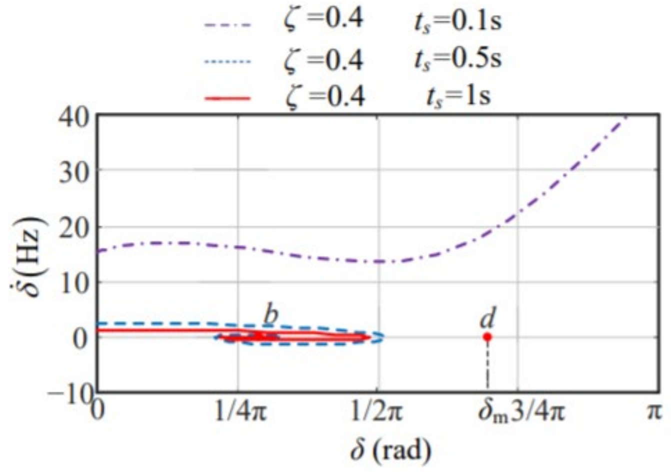


(b)

Inductive Grid



(a)



(b)

Instability in LCC – HVDC System

LCC – HVDC is more dependent on AC system. Synchronous Condensers are placed at inverter end if SCR is too small to avoid commutation failure.

Types of Instability for LCC:

1. Super-Synchronous Instability (Harmonic Instability)
2. Core-Saturation Instability (due to Conv. Tx saturation)
3. Sub-Synchronous Instability (5 – 40 Hz)
4. Power Control Instability

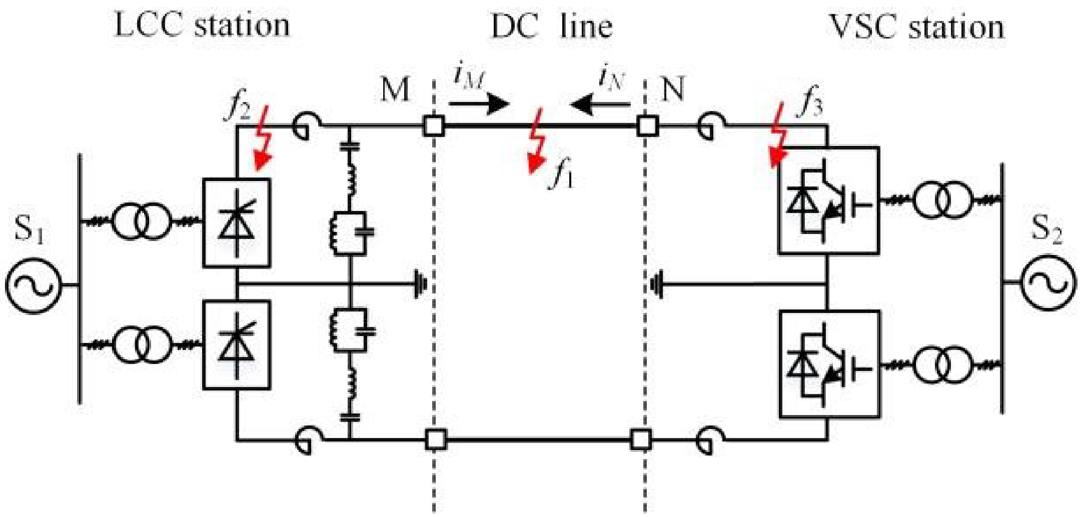
Typical Consideration for LCC – HVDC:

1. Load Injection Overvoltage
2. Temporary Overvoltage (TOV) after AC System Fault
3. Voltage Change on Reactive Switching
4. AC network frequency and stabilization / modulation control
5. Possible Sub-synchronous Torsional Interactions with nearby Turbine Generators.

Note:

- The response time of DC control is short as compared to other time constant of the network.
- Interaction between converter control for multi-terminal case should be considered even in single terminal HVDC link in planning stage.

Why Hybrid LCC/ VSC HVDC?



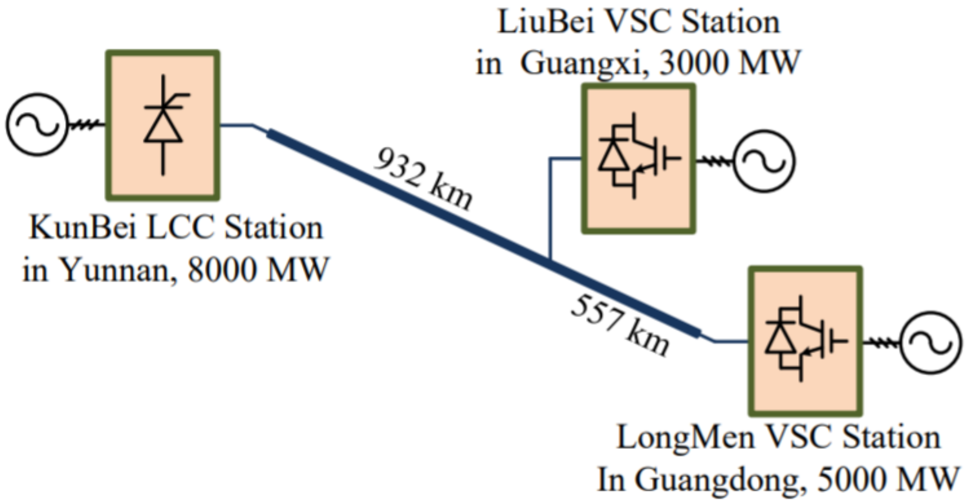
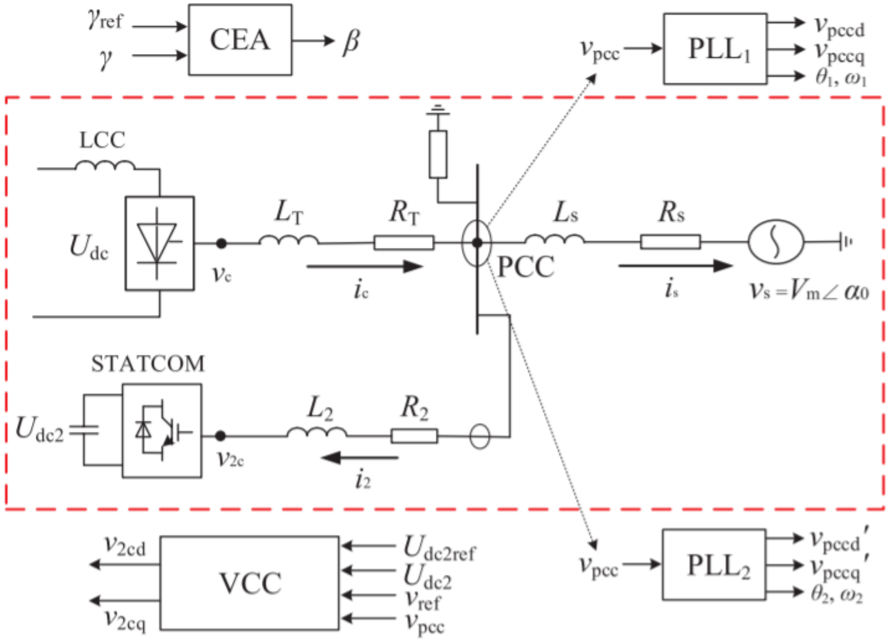
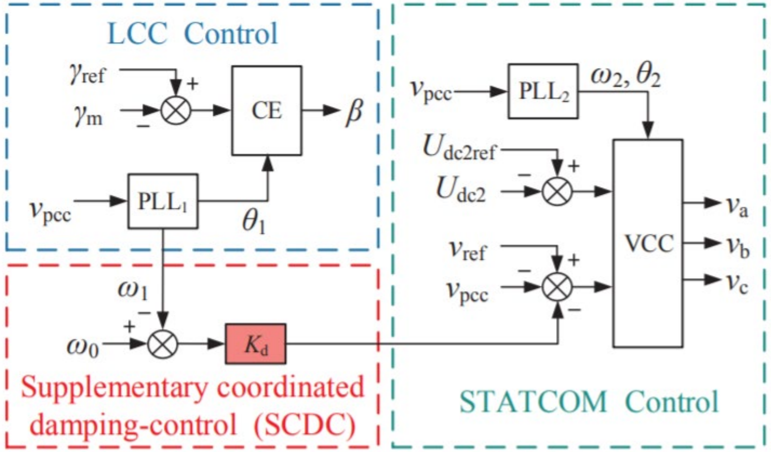


FIGURE 5. The Kun-Liu-Long hybrid multi-terminal UHVDC project.

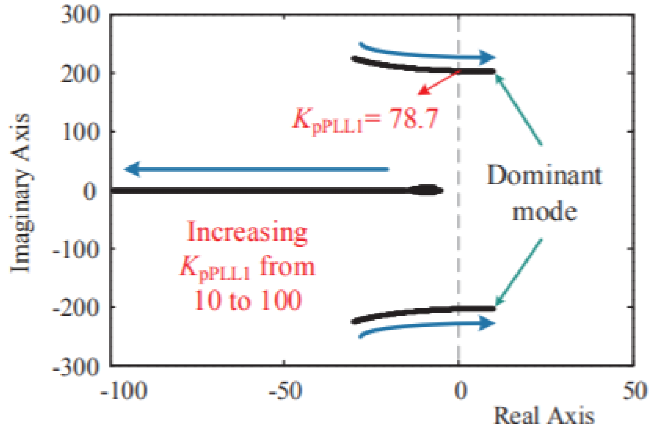
- **LCC as Rectifier side**: LCC has higher power rating, lower power losses, lower manufacturing cost and self-extinguishing capability for DC line faults.
- **VSC as Inverter side**: VSC eliminates the risk of commutation failure.
- VSC as Rectifier side: Limited space on offshore converter platform (absence of bulky AC filters), with black-start capability and decoupled P – Q control.
- Note: Pulse Firing Control for LCC leads to high harmonic distortion (hence needs filter) can lead to DC link series resonance, causing the operation of HVAC/DC more complex. VSC has synchronization issues when connected to weak AC system.

Oscillation Damping for LCC + STATCOM with SCDC

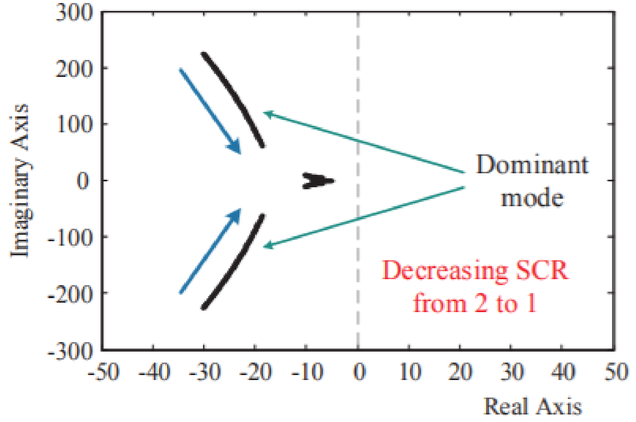




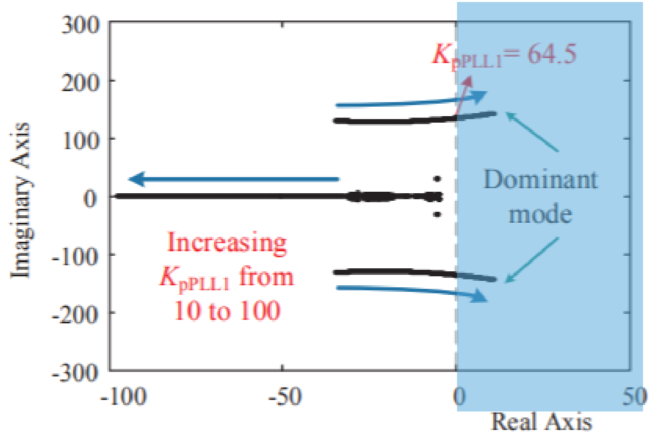
Worse with STATCOM support under weak grid
(better in strong grid)



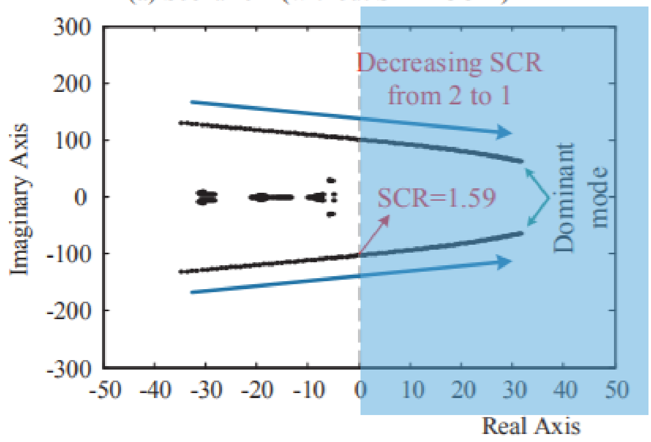
(a) Scenario 1 (without STATCOM)



(a) Scenario 1 (without STATCOM)



(b) Scenario 2 (with STATCOM)



(b) Scenario 2 (with STATCOM)

Weak system experience instability.

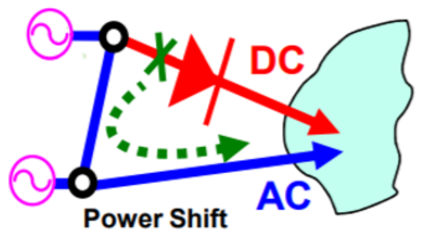
Challenges from China Experience in HVDC Application

Challenge 1: DC Power Shift

Bulk Power will shift from HVDC to HVAC during – HVDC Block, Line Fault or Power Reduction

Bulk Power Shift may lead to voltage drop, AC line overload, relay mal-operation, system instability, blackout

Solution: **Wide Area SPS** - It can initiate generation shedding, HVDC modulation, load shedding and run backup of HVDC with communication by FO channel. → **Energy Balance**

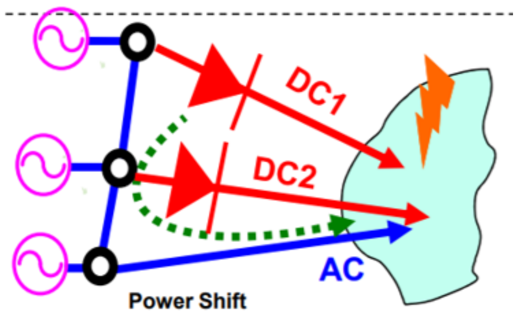


Challenge 2: Commutation Failure of Multi-Terminal HVDC

Concurrent Commutation Failure of 5 HVDC links will be caused by AC faults in 500kV S/S or 220kV S/S within GD area. It will lead to **sharp power reduction of HVDC** and **bulk power shift** to HVAC. If AC fault cannot be cleared fast, continuous commutation failure may lead to multi-terminal HVDC block and hence systems with over-generation and under-generation and blackout

Solution: **Coordination between AC and DC in Protection and Control** – AC Relay and DC Protection & Control should coordinate with SPS to **avoid HVDC block** during AC fault.

Solution: Optimization of HVDC Control Parameter (e.g. VDCOL)

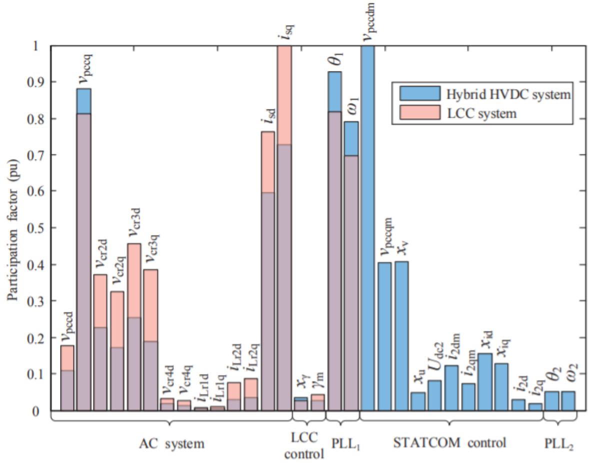


Challenge 3: Simulation of AC/DC Hybrid System

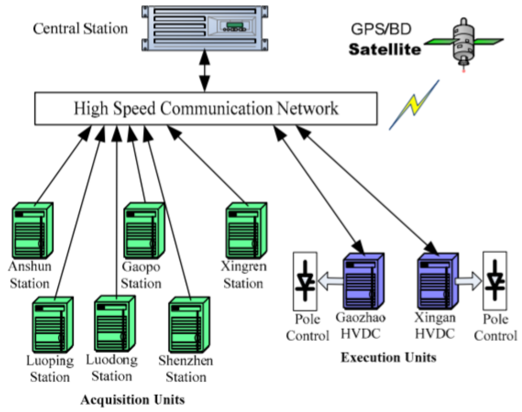
Traditional simulation tools developed for bulk power systems such as PSS/E or BPA cannot deal with interaction between AC and DC exactly. They are not able to simulation commutation failure in DC and consequent dynamic in AC system. EMTDC can only deal with small system.

Challenges from China Experience in HVDC Application

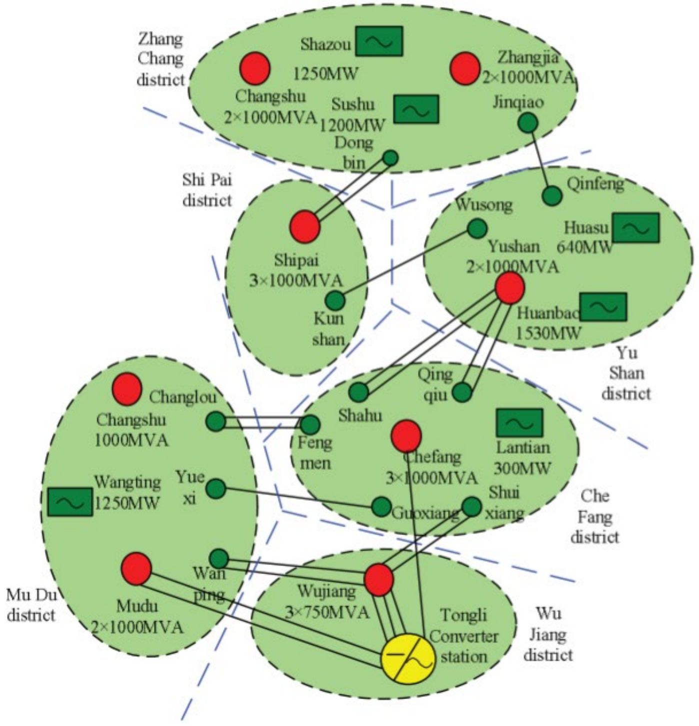
Interaction Analysis



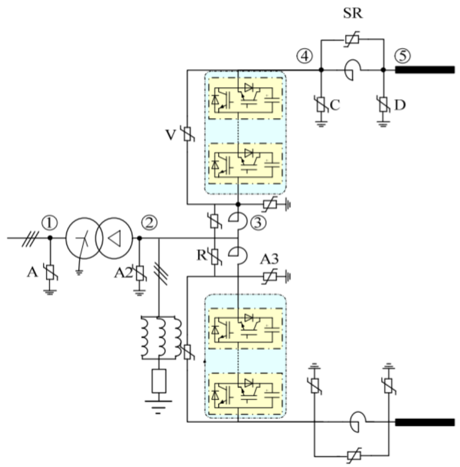
Wide Area Damping Control (WACS)



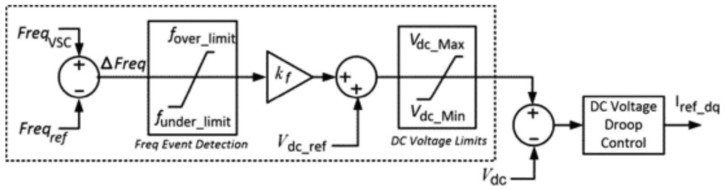
Grid Partitioning

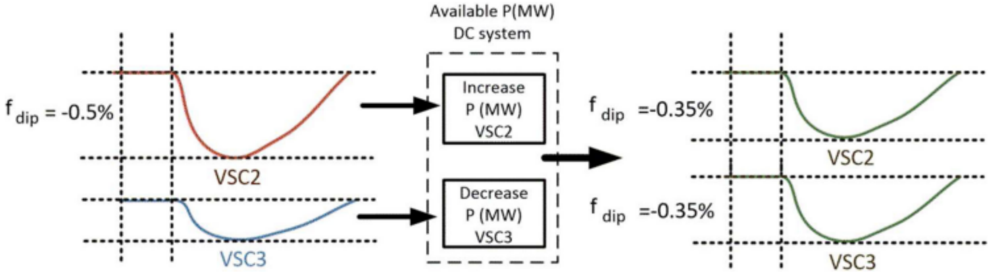


Overvoltage Control (Fast Tripping, Arrester, Ferro-Saturation)



Frequency Control





Note:
Sharing of Load Imbalance
After disturbance

Challenges from China Experience in HVDC Application

Grid Partitioning as Results of Optimization

- By using Complex Network Theory Used for Opening Parallel Loops

Edge Connectivity:

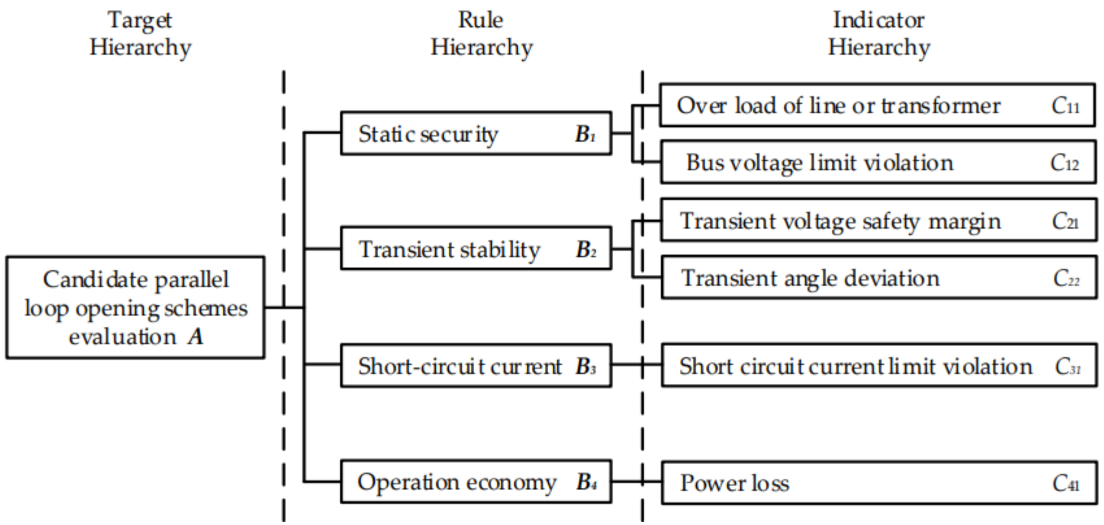
$$Q = \frac{1}{2m}\sum_{v=1}^{n}\sum_{w=1}^{n}\left(A_{vw} - \frac{k_v k_w}{2m}\right)\delta(c_v, c_w),$$

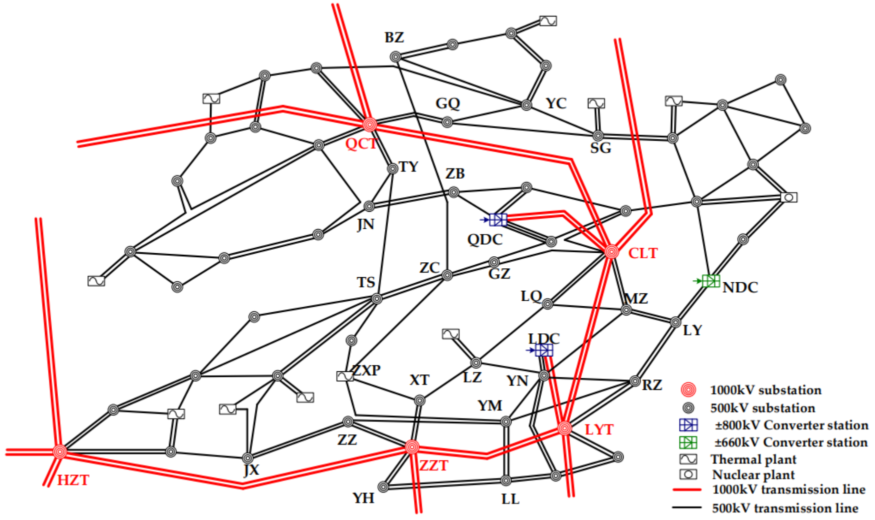
$$A_{vw} = \begin{cases} 1, & \text{node } v \text{ is connected with node } w \\ 0, & \text{node } v \text{ is not connected with node } w \end{cases}$$

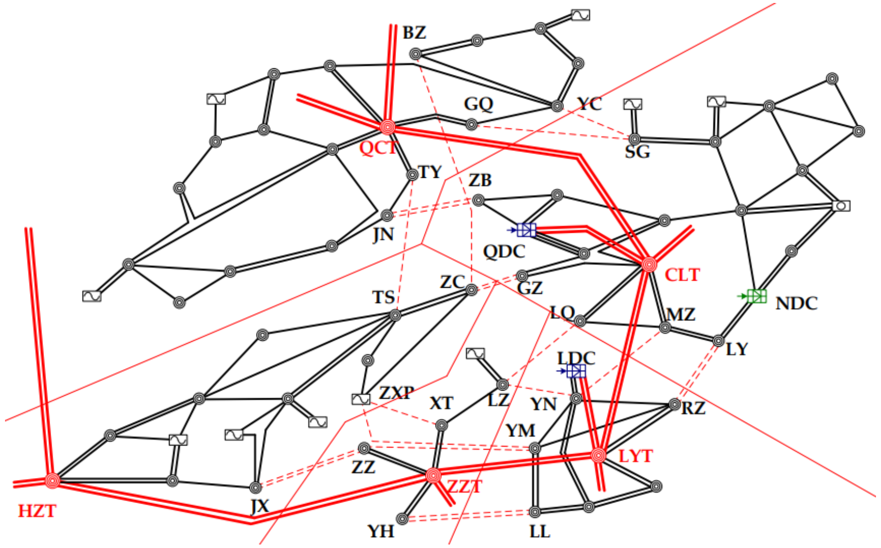
$$\delta(c_v, c_w) = \begin{cases} 1, & \text{node } v \text{ and } w \text{ are in the same community} \\ 0, & \text{node } v \text{ and } w \text{ are in different communities} \end{cases}$$

Multi-Infeed SCR:

$$MISCR_i = \frac{U_{aci}^2 / |Z_{eqii}|}{P_{di} + \sum_{j=1, j\neq i}^{n} |Z_{eqij}/Z_{eqii}| P_{dj}}$$



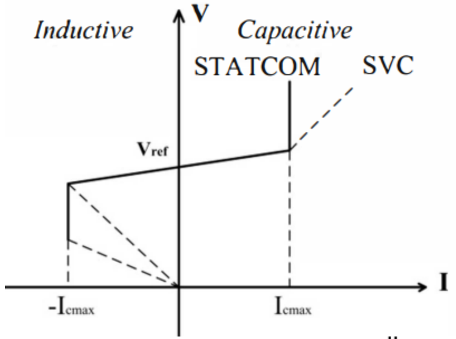


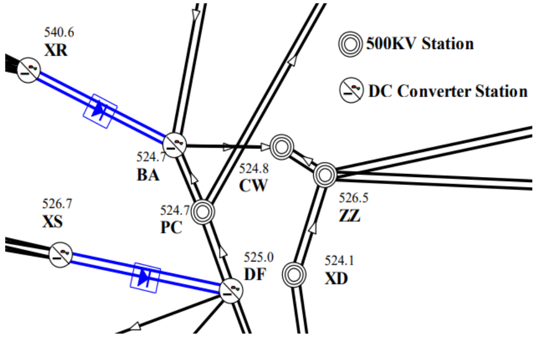


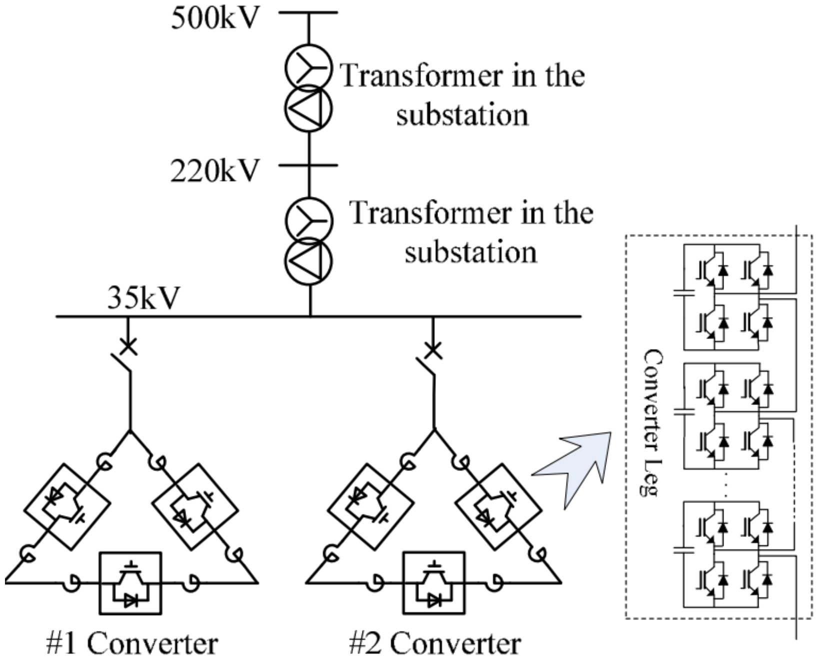
Challenges from China Experience in HVDC Application

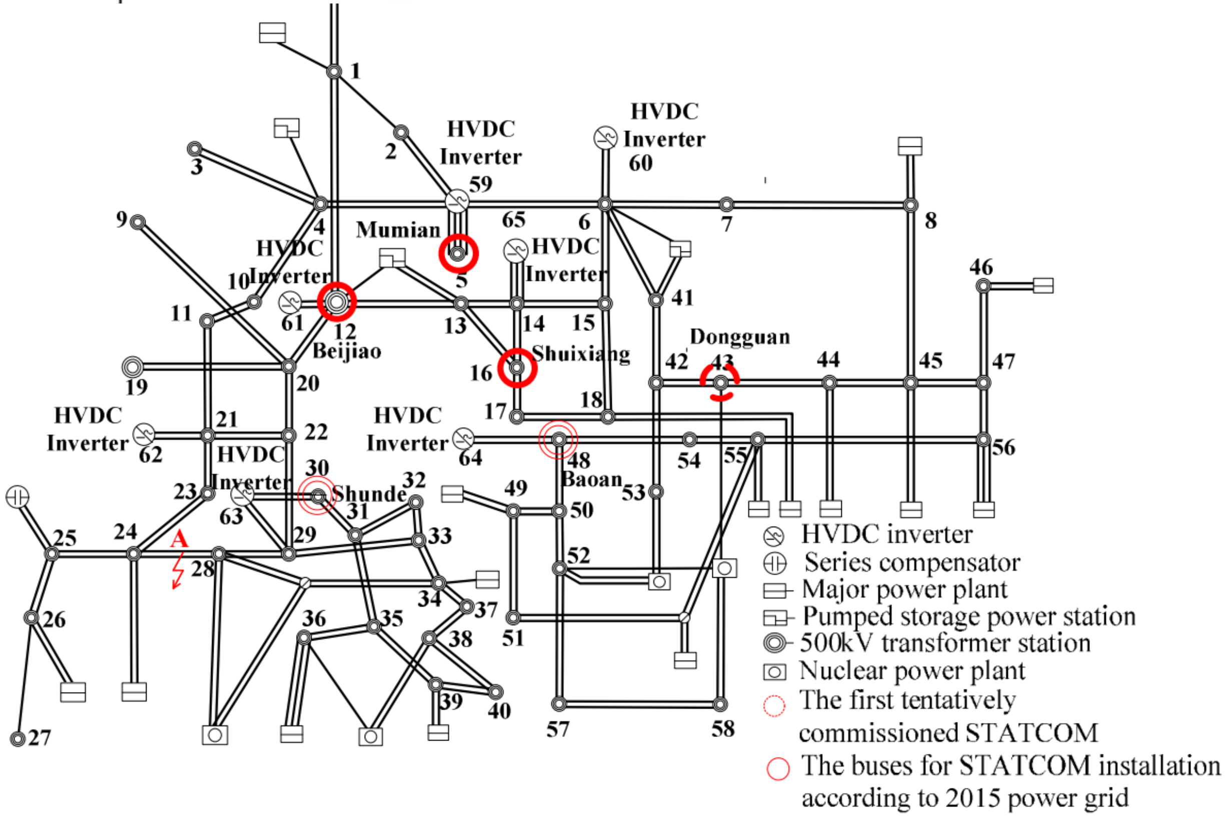
To ensure fast recovery after AC fault without blocking HVDC channel,

1. Installation with STATCOM (200MVAr)
2. Fast Capacitor Switching within 200ms
3. Optimization of Generator Excitation Parameter









Challenges from China Experience in HVDC Application

Earthing Electrode

- HVDC Link can operate in **Ground Return Mode** (GRM) during debugging stage or pole outage.
- During GRM, the ground return current are injected into HVDC grounding electrode, leading to **Ground Potential Rises** (GPR) of neutral-grounded transformers.
- If large enough, GRC > 30V can lead **to saturation of transformer core** and hence **vibration and overheating** of AC transformer.

Mitigation Measure:

- Installation of DC Blocking Devices
- Control Operating Current under Metal Ground Return Mode

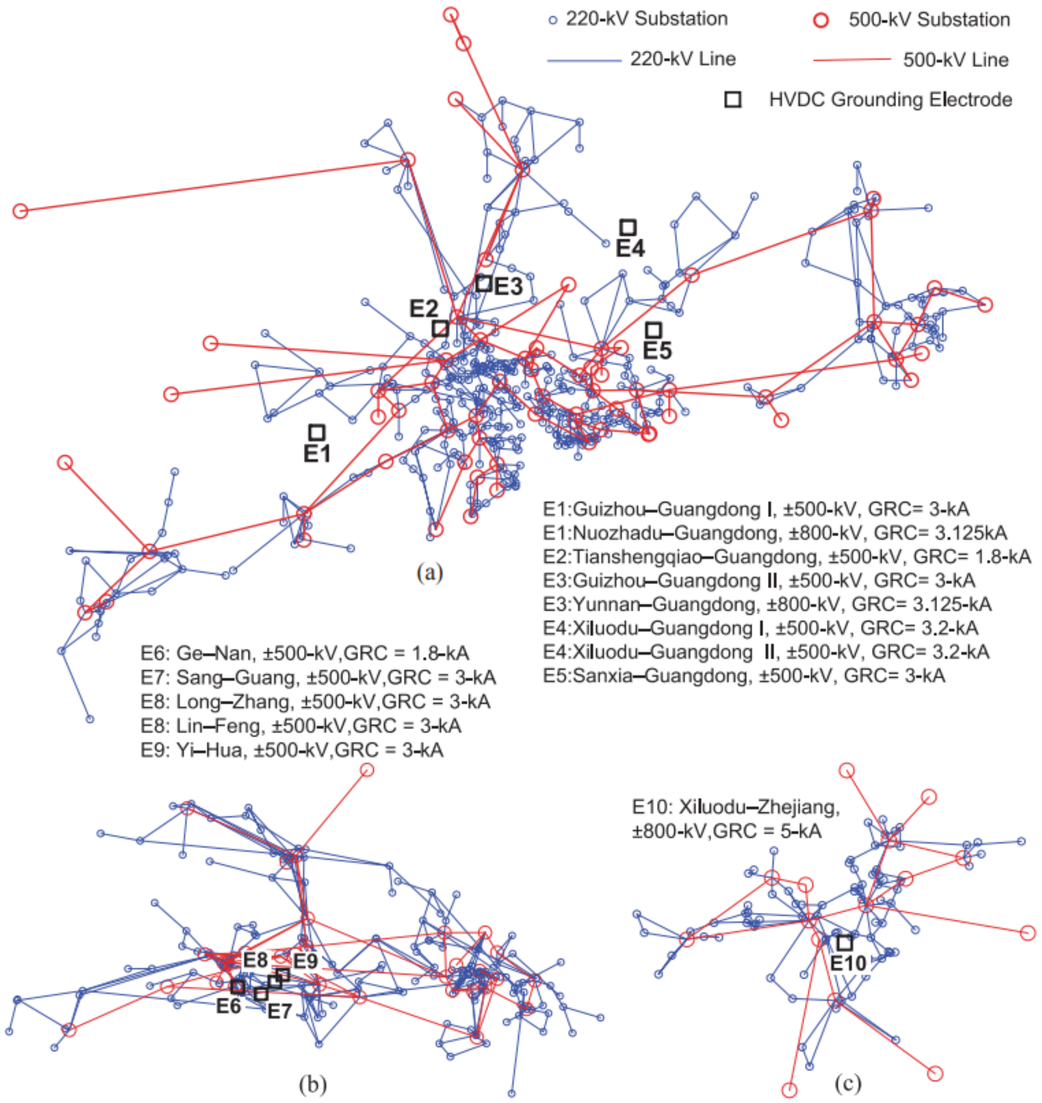


Fig. 4. Geographical diagram of the AC systems. (a) Guangdong; (b) Hubei; (c) Zhejiang.

Challenges from China Experience in HVDC Application

Mode Interaction

1. Sending side 3 machine group system has two coupled stability modes (cannot be decoupled using analytical method)
2. After Commutation Failure, Coupling Effect between two stability mode of sending side increases acceleration area.
3. Larger Inertia at fault side, and smaller inertia at other machine group can have better stability.

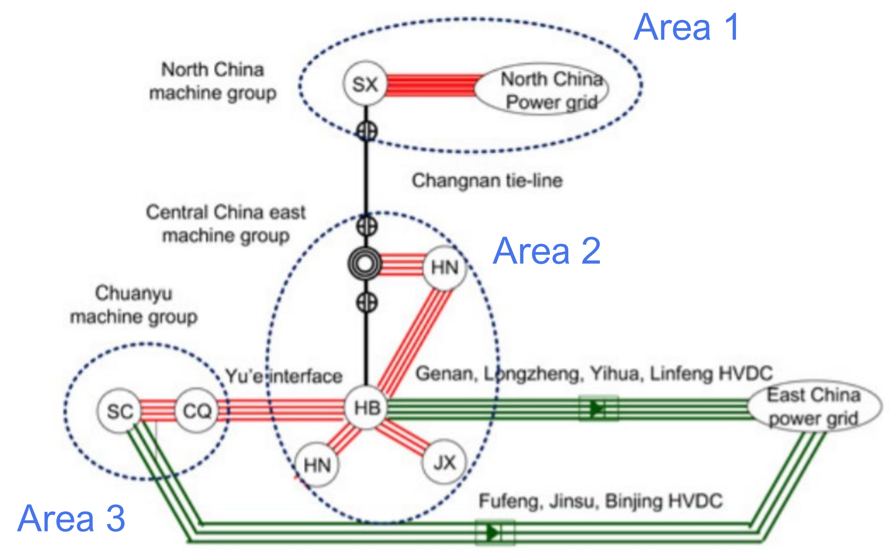


Table 1 Stability limit results of the Changnan tie-line and the Yu'e interface

No	Scenario	Contingency	Stability limit
1	Yu'e interface 0 power (no reserve)	Sichuan HVDCs two times of commutation failure	Changnan tie-line 2500 MW
2	Changnan tie-line 0 power (no reserve)	Sichuan HVDCs two times of commutation failure	Yu'e interface 1500 MW
3	Yu'e interface 0 power (increase Central China reserve)	Sichuan HVDCs two times of commutation failure	Changnan tie-line 2800 MW
4	Changnan tie-line 0 power (increase Central China reserve)	Sichuan HVDCs two times of commutation failure	Yu'e interface 900 MW

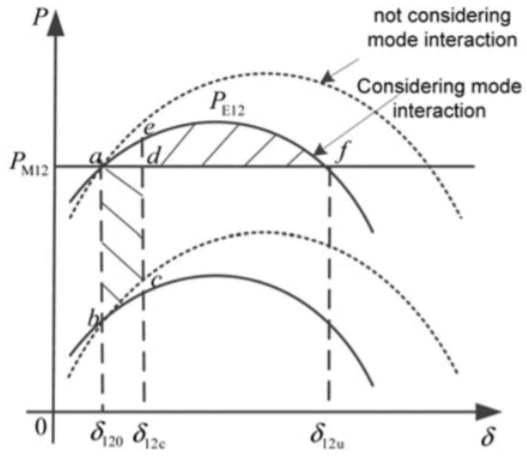


Fig. 4 *Power characteristic curve of the area 1-2 mode*

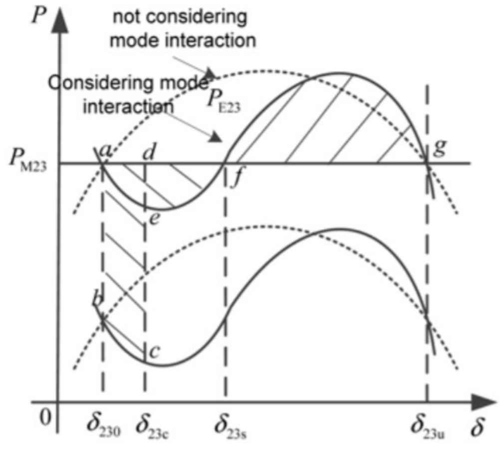


Fig. 5 *Power characteristic curve of the area 2-3 mode*

Challenges from China Experience in HVDC Application

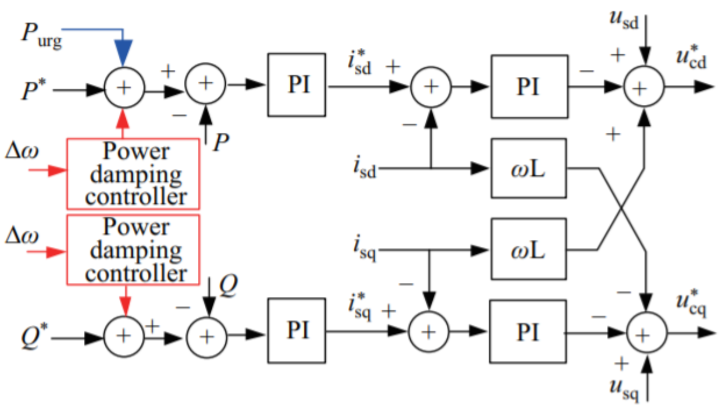
Sub-Synchronous Oscillation Suppression

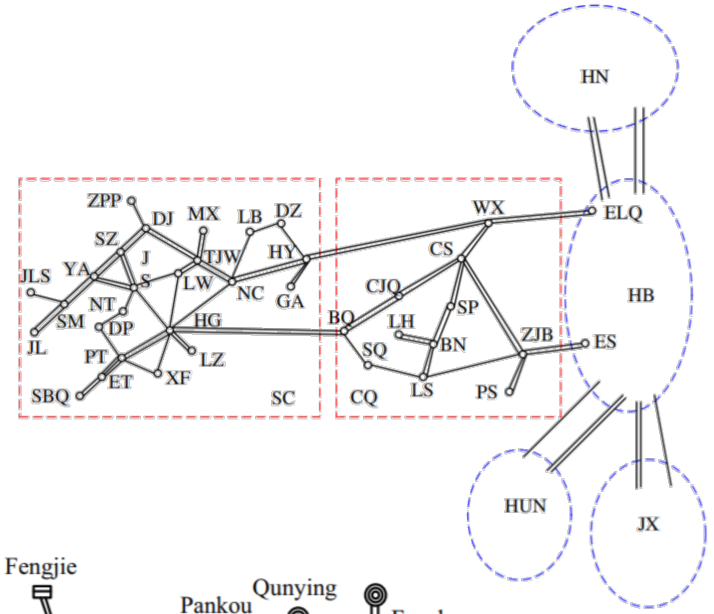
1. Hybrid damping control to suppress SSO is configured separately for the constant reactive power and active power regulation of VSC.
2. After employment of damping controller, overall electrical damping coefficient is further improved (positive damping).
3. Risk of series compensation to SSO is reduced.
4. SSTI (torsional vibration) can also be minimized with damping controller.

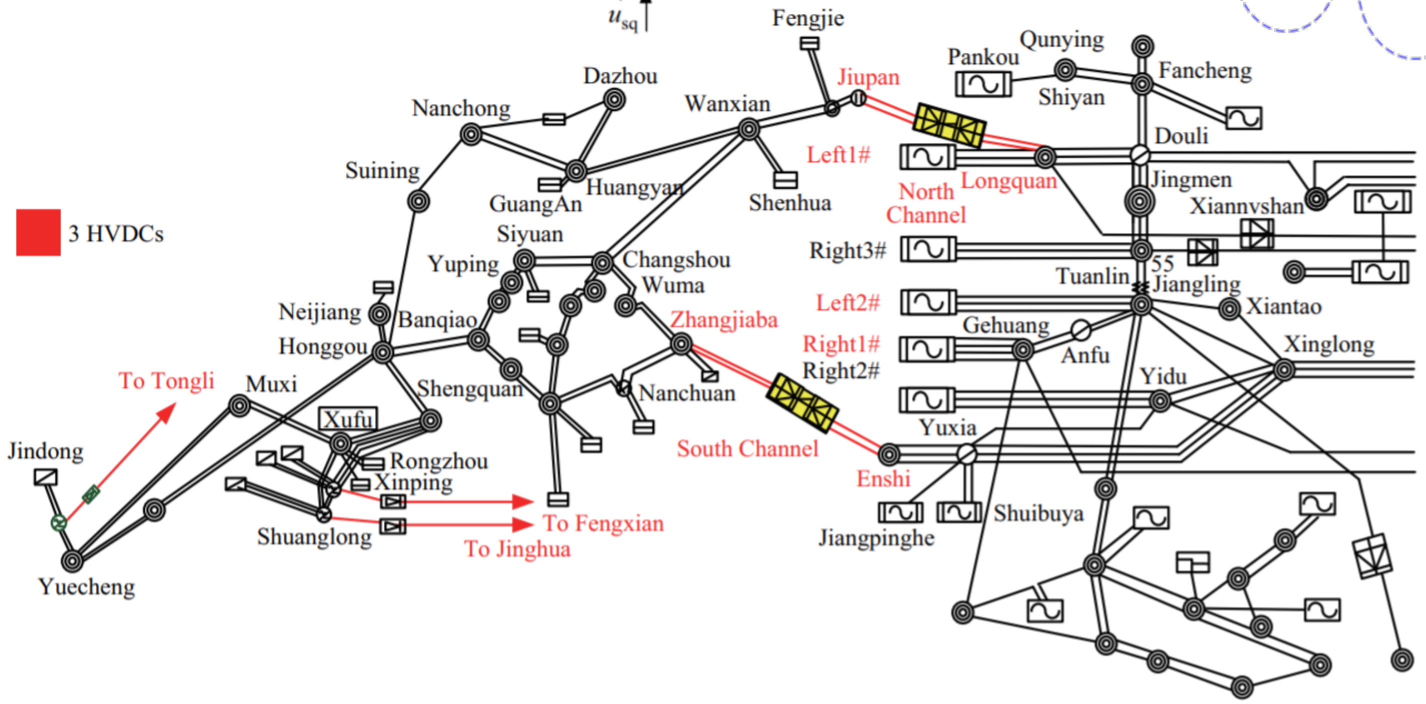
SHORT-CIRCUIT CURRENT OF 500 KV SYSTEM IN CHONGQING PROVINCE (UNIT: KA)

500 kV busbar	Original synchronous interconnection	VSC-HVDC asynchronous interconnection	Change value	Absolute value of the percentage
Jiupan	23.48	12.51	−10.97	46.72%
Wanxian	30.09	24.89	−5.2	17.28%
Huangyan	27.32	26.62	−0.7	2.56%
Changshou	40.15	37.36	−2.79	6.95%
Siyuan	33.95	32.84	−1.11	3.27%
Ba'nan	35.70	34.06	−1.64	4.59%
Banqiao	37.98	37.26	−0.72	1.90%
Zhangjiaba	32.28	25.44	−6.84	21.19%

Yu (Chongqing) and E (Hubei) in China



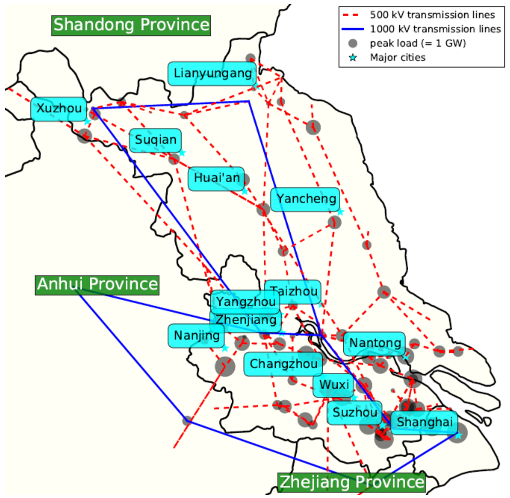


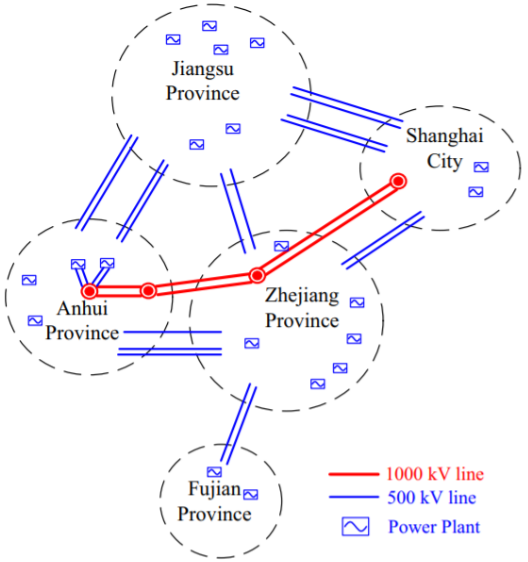


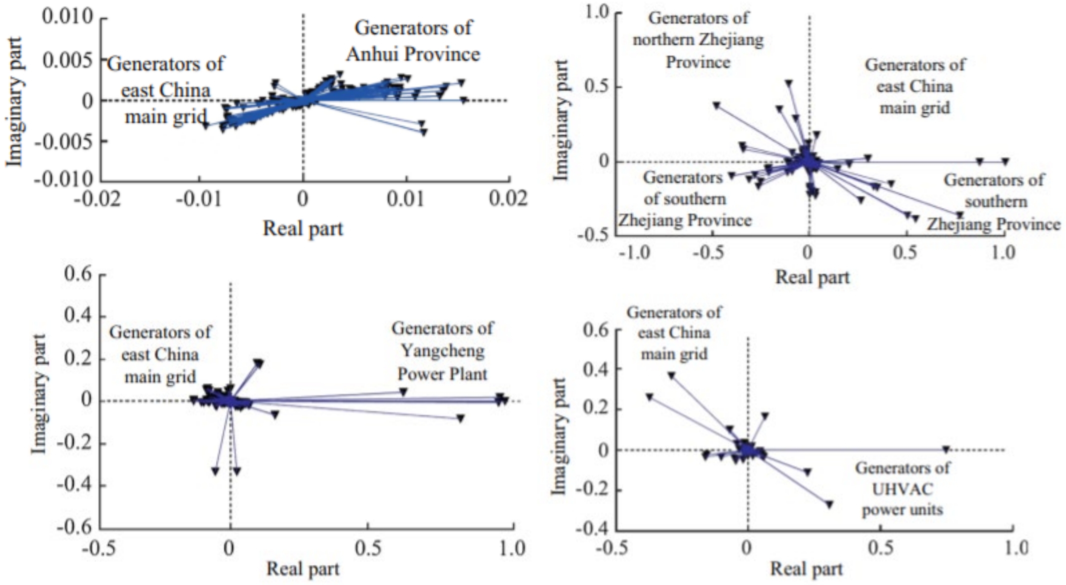
Challenges from China Experience in HVDC Application

Low Frequency Oscillation due to Weak Coupling

1. As the demand of long-distance power transmission from Southern Zhejiang Province drops, the oscillation mode between Zhejiang Province and East China Power Grid, which used to be a weakly damped mode, is improved.
2. A new oscillation mode between UHV units and East China appears. It is very important to ensure the PSS with continuously optimized parameter of UHV units to be in service.
3. Maintenance in regional area will not have great influence on power grid stability. With weaker grid structure, risk of poorly-damped low frequency oscillation may increase.
4. Influence of governing system on low frequency oscillation is researched with time-domain and frequency domain simulation. Governing system has some influence on low frequency oscillation characteristic, but not as large as the excitation system (PSS). Their responding frequency bands are quite different. With larger power system, oscillations with very low frequencies makes the effect of governing system more obvious and non-ignorable.



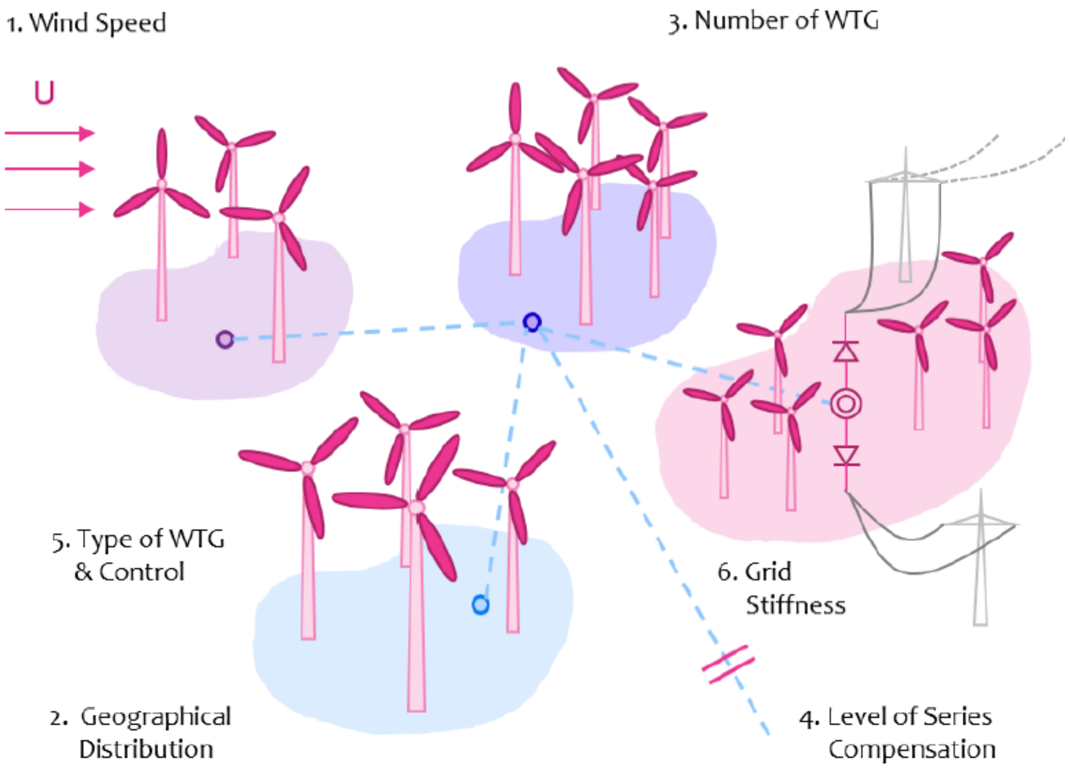




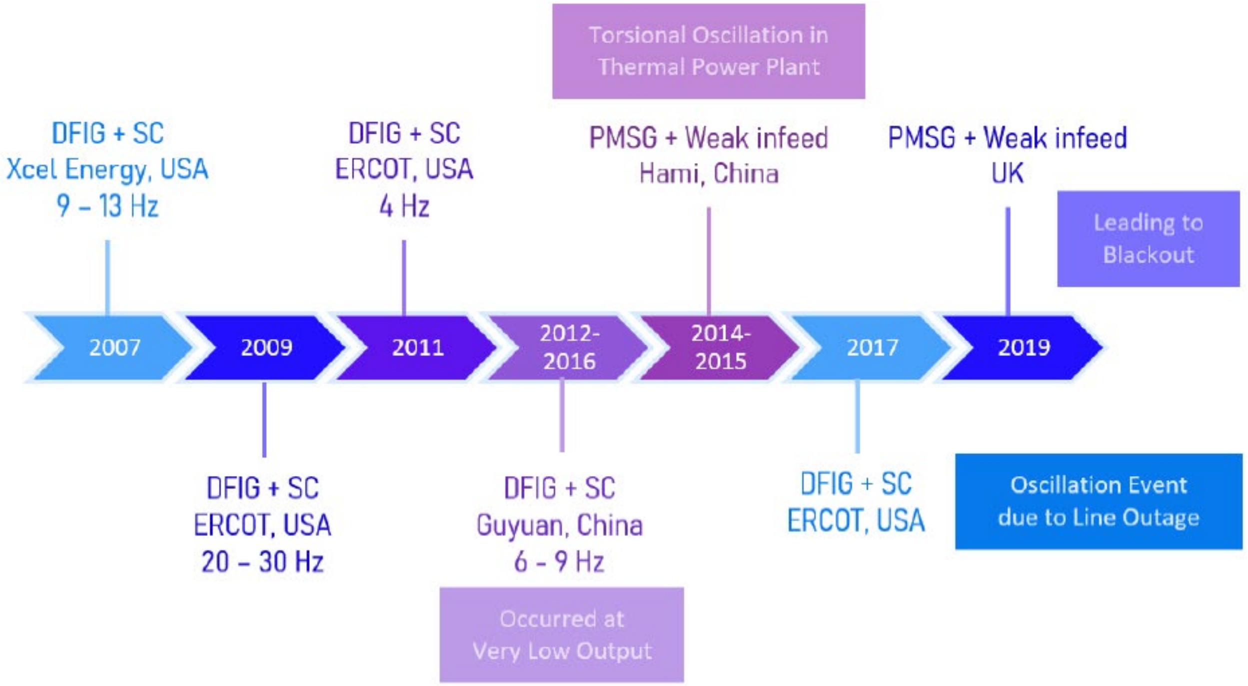
Challenges from China Experience in HVDC Application

Grid Stability Analysis

Factors Affecting Accuracy of Stability Analysis



Recorded Sub-Synchronous Oscillation due to WTG



Conclusion

1. LCCs are vulnerable to grid side unbalance and disturbance, and it leads to commutation failure and pole block. Yet, it has a DC smoothing reactor and by thyristor firing, DC fault current can be limited. VSCs are vulnerable to synchronization with high harmonics and disturbance and submodule capacitor discharging current. Yet, it provides flexibility in decoupled P – Q control. Some proposed LCC rectifier and VSC inverter as hybrid HVDC system.
2. Unlike AC system, in which instability are clearly classified (rotor angle, voltage, small signal and frequency instability), DC system can have instability problems in converter, between converter control, between converter and grid topology (e.g. SCR and DC cable length) or even between converter and distributed energy (e.g. wind power P(t)). Stability analysis can be performed with eigenvalue analysis (identify what makes unstable), Nyquist Plot (how far from unstable), Impedance analysis (before and after adding component) and relative gain analysis (interaction analysis). It is noted that the **assumption** may blind up the stability issue behind (e.g. without modelling PSS or surrounding equipment (IM, OLTC, STATCOM).
3. FBSM has their fault handling capacity, and it is suitable for OHL HVDC transmission, while HBSM with fewer devices and hence lower loss are widely used in underground and submarine HVDC cable systems.
4. Major controller requirements are voltage control, energy control, oscillation damping control and synchronization (start-up and shut-down). The major issue is how they respond to abnormal condition, such as black start, AC fault and consecutive commutation failure. Another consideration is on how to avoid complete shutdown of HVDC link and hence cascade tripping and blackout in AC system.