特高压混合多端直流输电技术及应用

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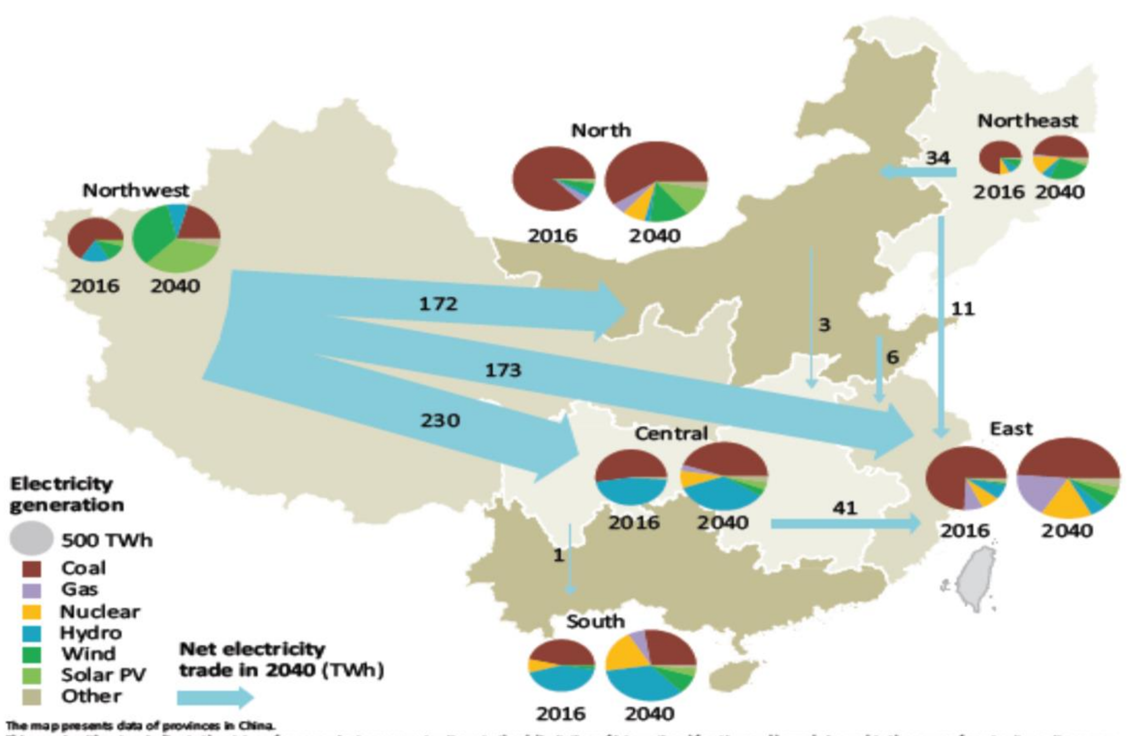
2019-11-14，北京，中国

目录




直流输电是远距离、大容量输电的客观需要

Figure 13.23 ▷ China electricity generation mix by region and net electricity trade flows in the New Policies Scenario



The map presents data of provinces in China.
This map is without prejudice to the status of or sovereignty over any territory, to the delimitation of international frontiers and boundaries and to the name of any territory, city or area.

The Northwest and Northeast regions become the major exporters of electricity, supplying a mix of renewables-based and fossil-fuelled generation to the East and Central regions

直流输电应用

- 远距离送电
- 不同步电网互联
- 提升电网运行可控性和灵活性
- 新能源并网

常规直流LCC和柔性直流VSC

- 基于晶闸管器件的常规直流LCC-HVDC历经70余年发展，技术成熟，容量持续增加
- 基于IGBT器件的柔性直流VSC-HVDC历经20年，近10年发展迅速，应用更加广泛

*参考World Energy Outlook 2018和网上资料

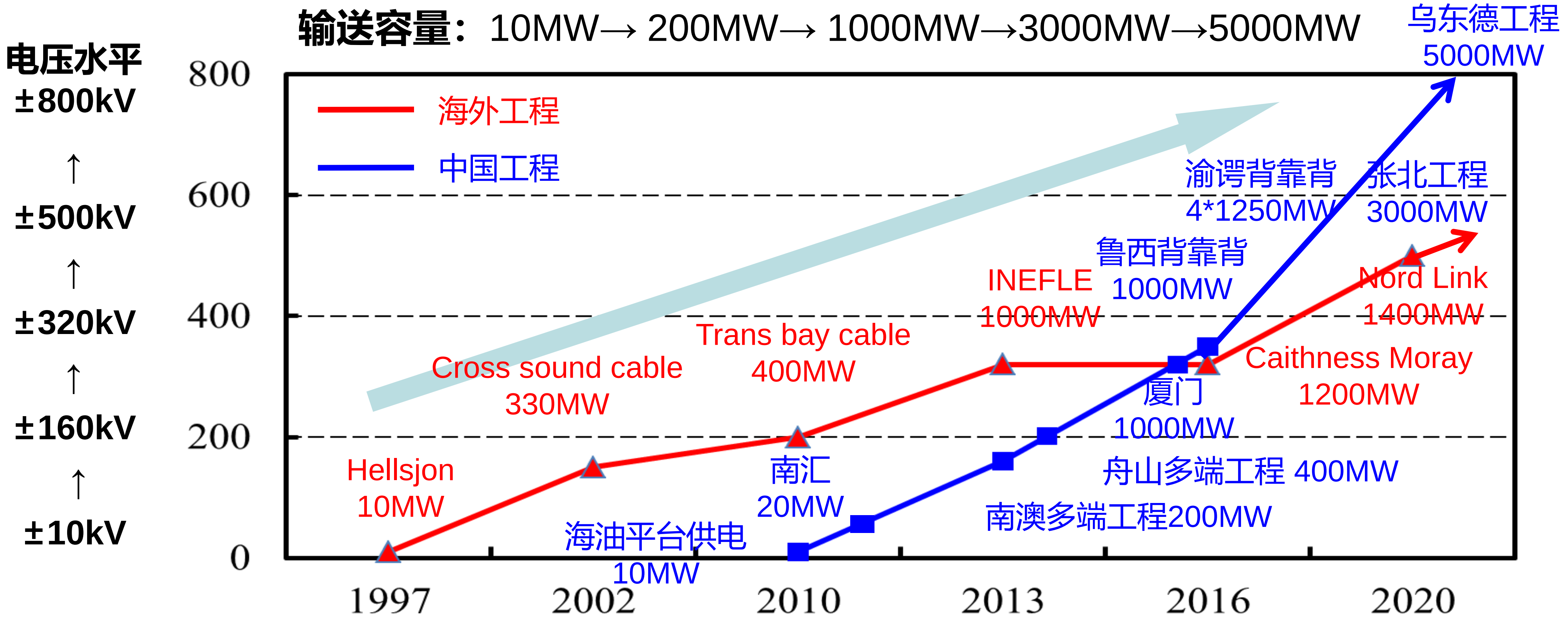
常规直流LCC-HVDC VS 柔性直流VSC-HVDC

技术路线	电源换相换流器(LCC)	电压源换流器 (VSC)
半导体器件	晶闸管(开通可控，关断不可控) 受端逆变侧存在换相失败	IGBT (开通和关断均可控) 自换相，不存在换相失败
额定容量	高电压、大容量 参数达±1100kV/12000MW	参数较低 目前可达±800kV/5000MW
功率控制	有功功率控制，需要无功补偿	有功功率和无功功率独立控制
交流滤波器	需要，50~60%	不需要（MMC）
最小短路容量要求	>2	0
黑启动功能	无	有
过负荷能力	较强过负荷能力	通常没有，除非特殊要求
占地	占地面积大，主要是交流滤波器场	较为紧凑
接线和结构	单极、双极系统，对称单极等	对称单极、单极、双极、多端等
应用	点对点送电，背靠背，多端系统	点对点送电，背靠背，多端系统，直流电网

*参考CIGRE B4资料

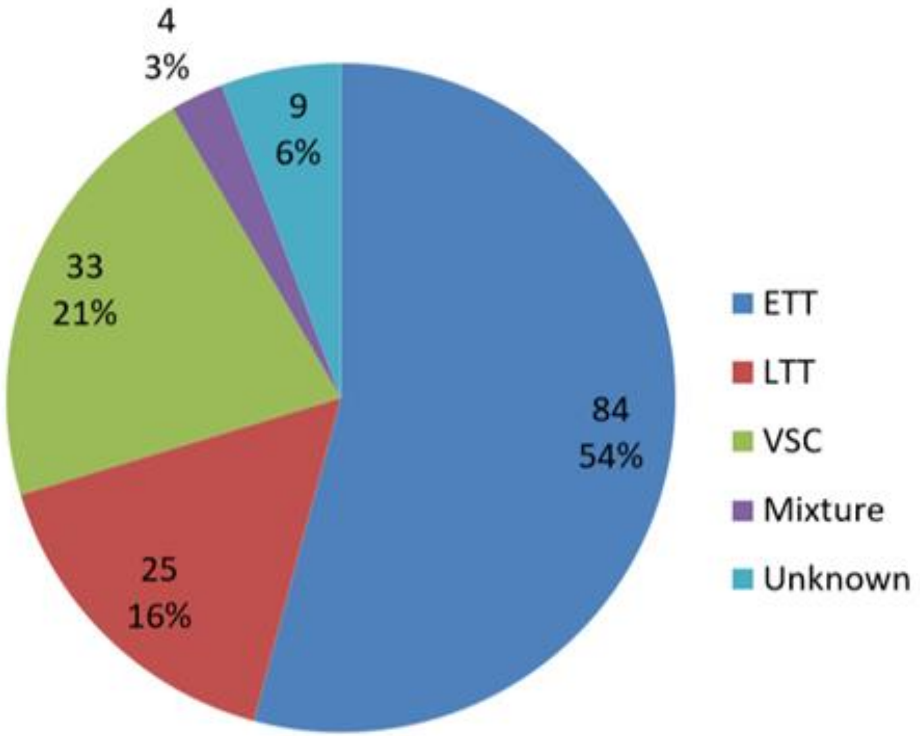
柔性直流VSC-HVDC已开始用于远距离大容量送电

- 随着换流器拓扑技术的发展和IGBT器件的技术进步，柔性直流近10年技术发展很快
- 其电压和容量已经能够满足大容量、远距离输电的应用需求，在电网的应用越加广泛

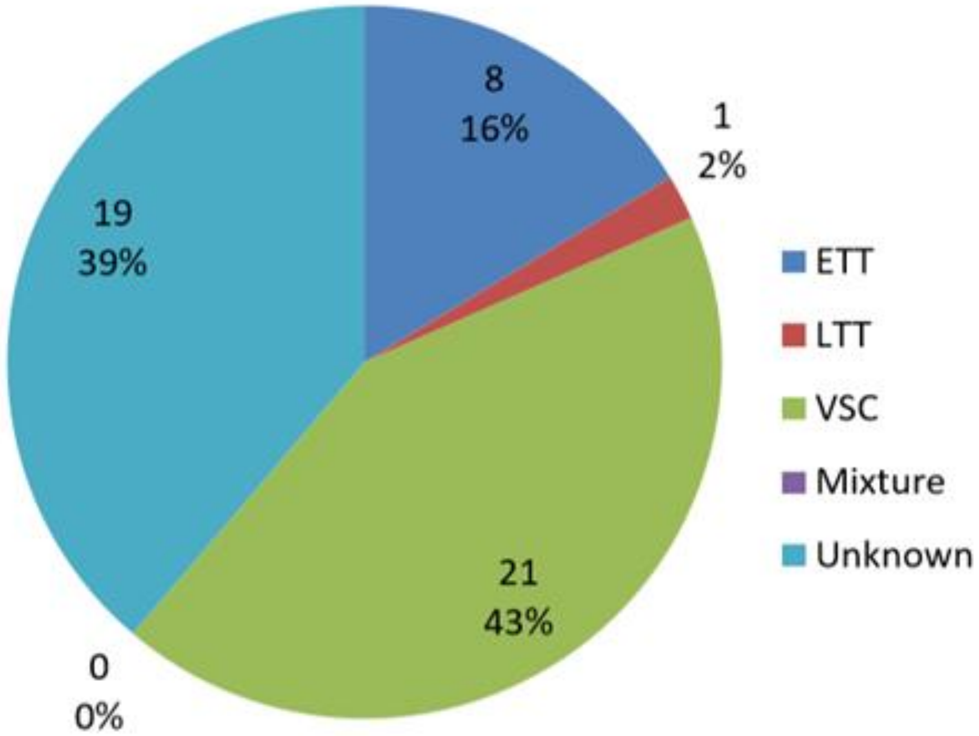


世界范围内直流输电工程数量

- 2018年底，全世界供155项工程在运行，其中LCC占70%，VSC占21%
- 在建工程49项，其中VSC占近一半



在运工程



在建工程

*参考CIGRE B4资料

已建成柔性直流工程

HVDC VSC Projects

System Operational	Name	Year Com-missioned	Power (MW)	Voltage DC (kV)	Voltage AC (kV)	Transmission Length (km)	Converter Manufacturer	Reference
1	Hällsjön - Sweden	1997	3	±10	10	10	ABB	http://r
2	Gotland, Sweden	1999	50	±80	80	70	ABB	htt
3	Direct Link /TerraNora, Aus.	2000	3x60	±80	132/110	59	ABB	http://
4	Tjaereborg, Den.	2000	7.2	±9	10.5	4.3	ABB	
5	Eagle Pass, USA	2000	36	±15.9	132	Back to Back	ABB	
6	Cross Sound, USA	2002	330	±150	345/138	40	ABB	htt
7	Murraylink, Australia	2002	220	±150	132/220	180	ABB	
8	Troll A, Norway	2005	2x44	±60	56/132	70	ABB	
9	Estlink, Finland	2006	350	±150	400/330	31 (underground) 74 (submarine)	ABB	
10	Caprivi Link, Namibia	2010	300	-350	330/400	950	ABB	
11	Trans Bay Cable, USA	2010	400	±200	230/138	85	Siemens	
12	Valhall, Norway	2011	78	150	300/11	292	ABB	
13	Nanhui	2011	18	±30	35/35	8.4 (underground)	C-EPRI	
14	EWIC: East-West Interconnector, Ireland-UK	2013	500	±200	400	75 (underground) 186 (submarine)	ABB	http://
15	Nan'ao Island	2013	200, 150, 50	±160	110	Multi-terminal	RXPE, XiDian, NR-Electric	htt
29	Luxi, Yunnan Province China	2016	1000	±350	/	Back-to-back	China Southern Grid, RXPE (Yunnan) XD Group/IEECAS (Guangxi)	http://english.iee.cas.cn/rh/rp/201609/t20160905_167435.html
30	NordBalt, Sweden	2016/17	700	±300	400/330	450	ABB	http://new.abb.com/systems/hvdc/references/nordbalt

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	Name	Year Com-missioned	Power (MW)	Voltage DC (kV)	Voltage AC (kV)	Transmission Length (km)	Converter Manufacturer	Reference
31	DolWin2, Germany	2017	916	±320	155/380	45 (underground) 90 (submarine)	ABB	http://new.abb.com/systems/hvdc/references/dolwin2
32	Maritime Link	2018	500	±200	230/345	187 OHL, 170 submarine, bipole	ABB	http://new.abb.com/systems/hvdc/references/maritime-link
33	Caithness-Moray	2018	800 (1200)	±320	275/400	113 (submarine) + overhead lines	ABB	http://new.abb.com/systems/hvdc/references/caithness-moray-hvdc-link
34	NEMO GB-Belgium	2019	1000	±400	400/380	140	Siemens	http://www.nemo-link.com/the-project/overview/
35	Hokkaido-Honshu, Japan	2019	250kV	+250	275	98 (overhead line) 24 (cable)	Toshiba	https://www.cigre2019.jp/_img/program/The%20New%20Hokkaido-Honshu%20HVDC%20Link.pdf
36	Yu'E	2018/9	1250x 4	±420		Back-to-back, 2 parallel pairs	RXPE, XuJi Electric and C-EPRI	https://www.rxhk.co.uk/corporate/news/yue-hvdc-commissioning-complete/
37	BorWin3	2019	900	±320	150/400	30 (underground) 130 (submarine)	Siemens	http://www.energy.siemens.com/hq/en/power-transmission/hvdc/references.htm
38	Cobra Cable, Neth.-Denmark	2019	700	±320	400	325	Siemens	http://www.cobracable.eu/
39	Johan Sverdrup Phase 1	2019	100	+/-80	300/33	100	ABB	http://new.abb.com/systems/hvdc/references/johan-sverdrup

*参考网上资料

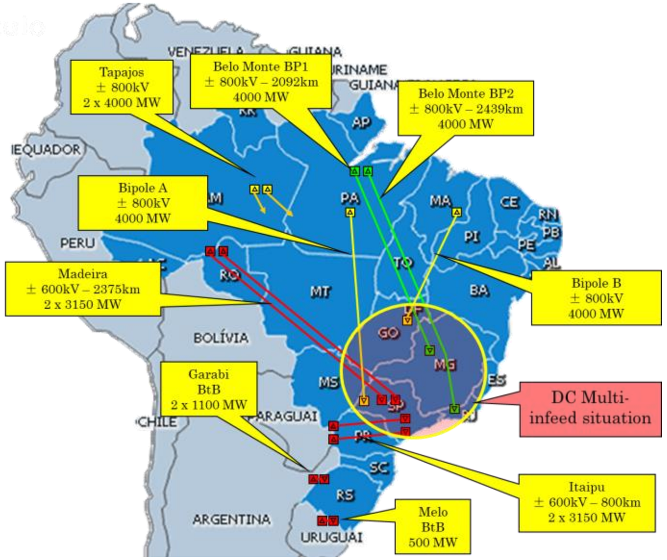
在建柔性直流工程

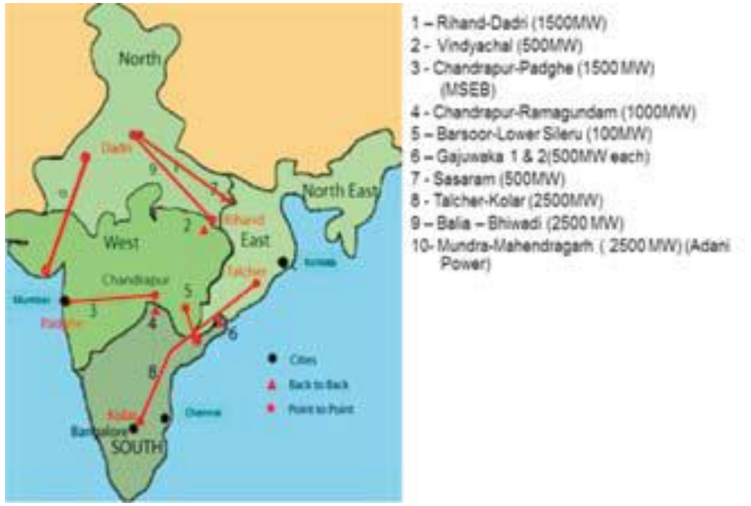
Future Projects (details subject to change)								
	Name	Year to be Commissioned	Power (MW)	Voltage DC (kV)	Voltage AC (kV)	Transmission Length (km)	Converter Manufacturer	Reference
1	DolWin3, Germany	2018/9	900	±320		80 (underground) 80 (submarine)	GE	http://www.gegridsolutions.com/AlstomEnergy/grid/cleangrid/environmental-benefits-for-the-electrical-grid/super-grid-solutions/index.html http://www.tennet.eu/our-grid/offshore-projects-germany/dolwin3/
2	Zhangbei phase 1	2019	3000x2, 1500x2	±500			NR Electric, XuJi Electric, C-EPRI and ABB SiFang	https://new.abb.com/systems/hvdc/references/zhangbei
3	Savoie-Piemont, Italy-France	2019	2x600					
4	Krigers-Flak Combined Solution	2019	410					
5	ElecLink, UK-France	2019	1000					
6	SW Link, Sweden (SydVästlänken)	2019	2x600 (2x720)					
7	IFA2 , UK-France	2020	1000					
8	Nordlink, Germany-Norway	2020	1400					
9	ALEGrO	2020	1000					
10	Trichur-Kerala, India (PK2000)	2020	1000					
11	AWC, USA	2020/21	1000					
12	KunLiuLong / Wudongde CSG China	2020/21	8000,500 , 3000					
13	Borwin4	2020+	900					
14	Zhangbei phase 2	2021	/					
15	Ultranet, Germany	2021	2000					
16	North Sea Link, Norway-UK	2021	1400					

	Name	Year to be Commissioned	Power (MW)	Voltage DC (kV)	Voltage AC (kV)	Transmission Length (km)	Converter Manufacturer	Reference
39	Higashi-Shimizu	2027	600	/	/	/	ABB (Hitachi)	https://new.abb.com/news/detail/19701/abb-wins-600-mw-hvdc-order-to-reinforce-japanese-power-supply-through-hvdc-jv-with-hitachi
40	Nautilus	2028	1400					https://www.nationalgrid.com/group/about-us/what-we-do/interconnectors-connecting-cleaner-future
41	Eurolink	2030	1400					https://www.nationalgrid.com/group/about-us/what-we-do/interconnectors-connecting-cleaner-future
42	Icelink	2030 - Under consideration	1000			1000		https://www.nationalgrid.com/group/about-us/what-we-do/interconnectors-connecting-cleaner-future
43	Shetland	Early planning / possibly VSC	600	/	/	267	/	https://www.ssen-transmission.co.uk/projects/shetland/
44	Jeju island, Korea	Unknown	200			100	ABB	https://new.abb.com/news/detail/25354/abb-to-support-south-koreas-greener-future/
45	BorWin 5	Submitting for approval	900	/	/	/	/	http://www.4coffshore.com/windfarms/hvdc-converter-borwin5-converter-cid96.html
46	SylWin 2	Submitting for approval	900	/	/	/	/	http://www.4coffshore.com/windfarms/hvdc-converter-sylwin2-converter-cid13.html
47	Eastern link, UK	Under consideration	2000	/	/	/	/	https://www.ssepd.co.uk/EasternHVDClink/
48	SENER-BC, Mexico	Pre-tender	1500	+/-500		700 (bipolar)	/	http://www.nortonrosefulbright.com/knowledge/publications/163291/mexicos-first-public-bid-for-electric-transmission-lines
49	Suedlink	Under consideration	/	/	/	/	/	https://www.transnetbw.de/de/suedlink

*参考网上资料

直流输电在主要国家应用：落点密集、通道紧张

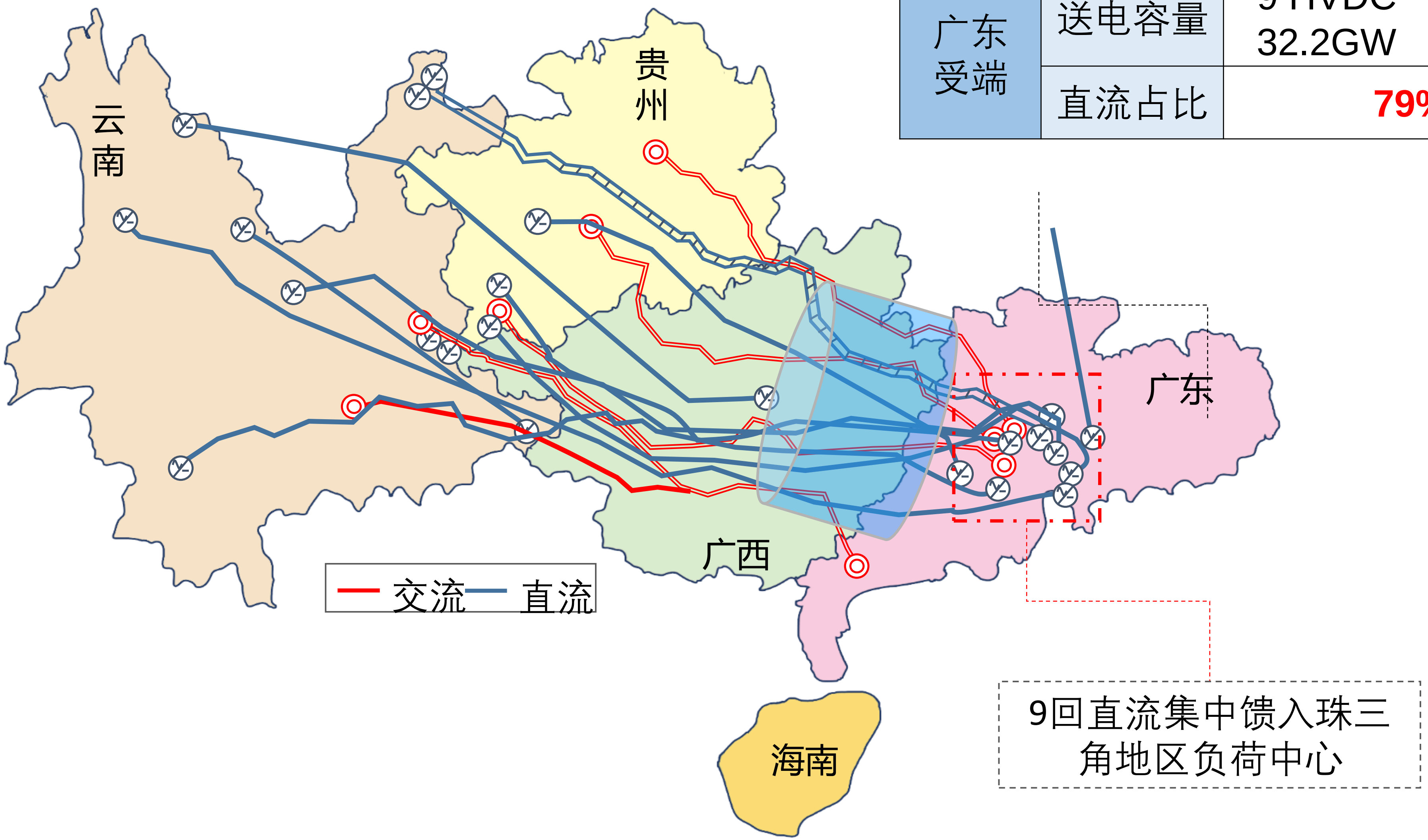




*参考CIGRE B4资料

截至2018年底，南方电网形成9回直流西电东送电网格局

广东受端	送电容量	9 HVDC 32.2GW	8 HVAC 8.3GW
	直流占比	79%	



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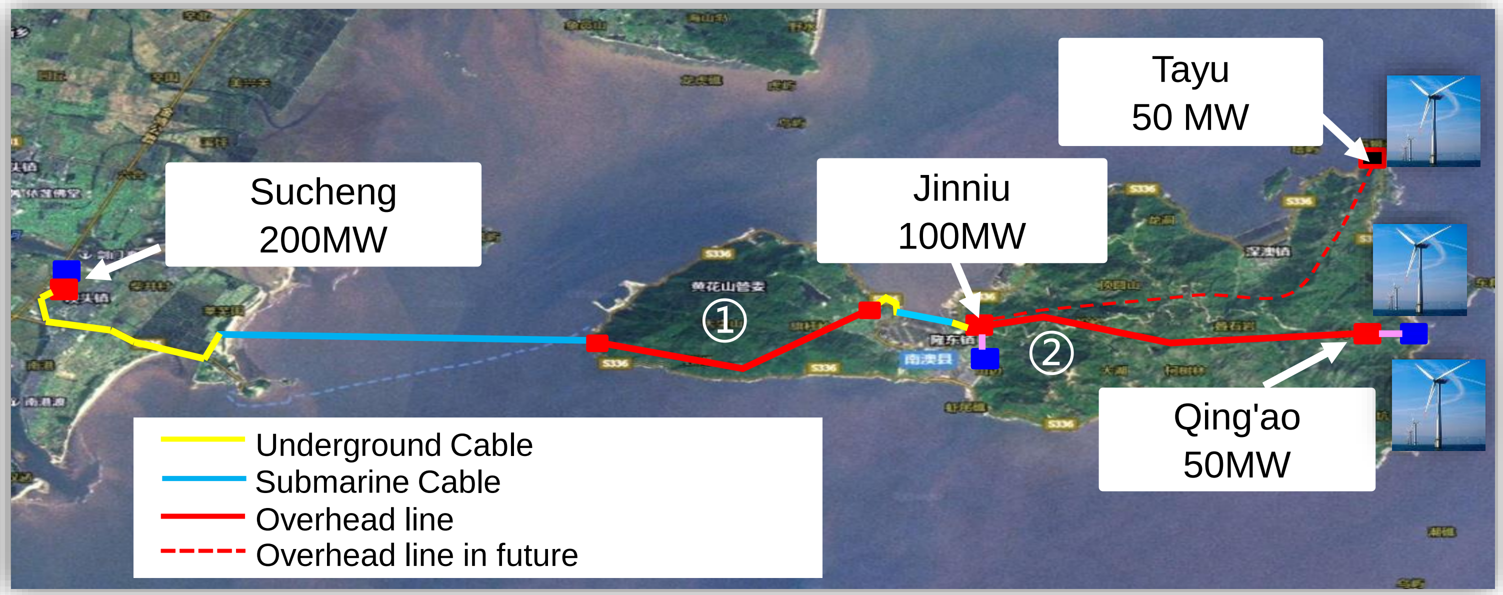
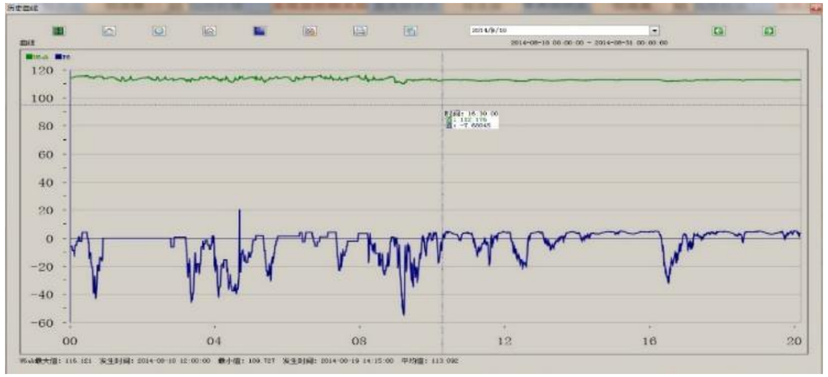
世界上首个VSC-MTDC：南澳多端柔性直流工程

直流电压	±160 kV
输送功率	200/100/50/50MW
输送距离	架空线 ① 8.1 km，架空线 ② 12.5 km，地下电缆 9.5 km，海缆 10.7 km
换流站	南澳岛，汕头，广东
投运时间	2013年12月
主要特点	VSC技术，世界上首个多端柔性直流输电工程。用于南澳岛多个风电场并网。设计交直流并联运行和孤岛运行方式，风电场低压黑启动功能，换流站设备全户内设计。2017年增加直流断路器，提升运行灵活性。

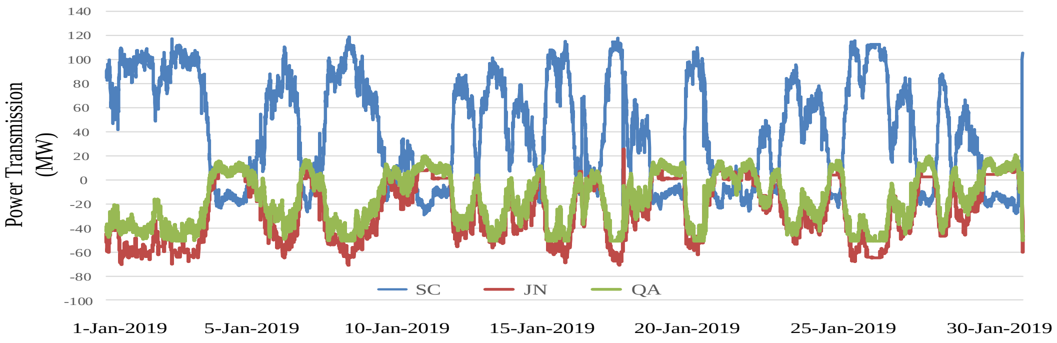


南澳多端柔性直流工程运行和特点

改善风电并网电能质量，高效友好并网



快速功率反转，潮流控制灵活

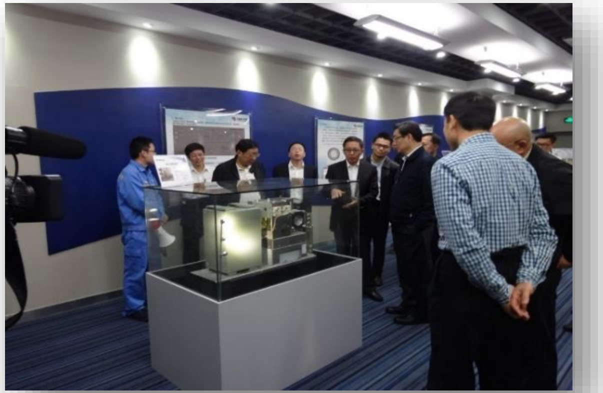


运行稳定，和LCC技术同样可靠

		SC	JN	QA	MTDC system
2016	Energy availability	88.18	91.10	93.63	89.79
	Scheduled energy unavailability	10.70	8.30	5.70	9.30
	Forced energy unavailability	1.11	0.60	0.66	0.90
2017	Energy availability	95.94	94.50	95.94	95.52
	Scheduled energy unavailability	3.36	3.36	3.36	3.36
	Forced energy unavailability	0.70	2.15	0.70	1.11
2018	Energy availability	92.76	92.97	92.38	92.77
	Scheduled energy unavailability	7.15	6.94	6.94	7.06
	Forced energy unavailability	0.09	0.09	0.68	0.17
Q1 2019	Energy availability	99.61	99.61	99.61	99.61
	Scheduled energy unavailability	0	0	0	0
	Forced energy unavailability	0.39	0.39	0.39	0.39

南澳多端柔性直流受到世界同行广泛关注

法电集团EDF总裁科学顾问



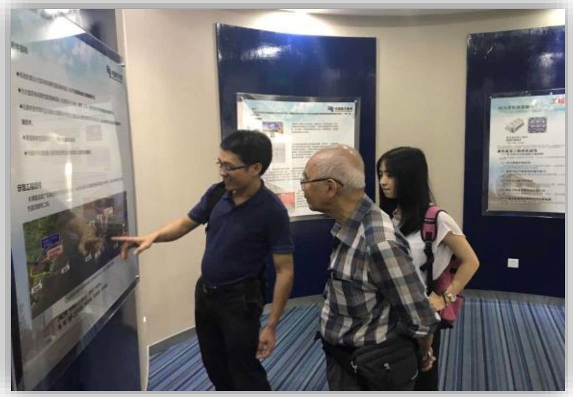
国家能源局到现场调研

CIGRE大会专门介绍南澳工程

CIGRE B4主席访问南澳工程

荷兰风电协会访问南澳

国家科技部组织行业专家考察

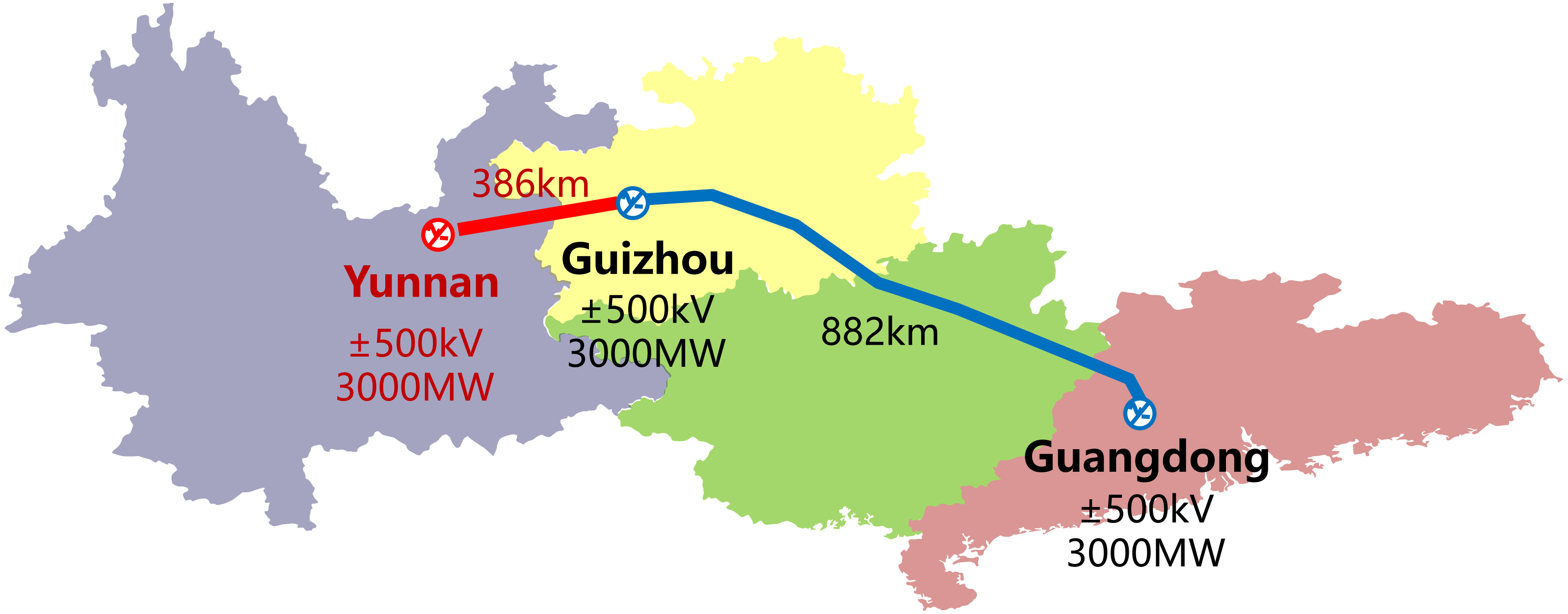


加拿大Ooi教授访问南澳工程

CIGRE意大利主席访问南澳工程

多端常规直流：利用原有通道，升级两端直流为三端直流

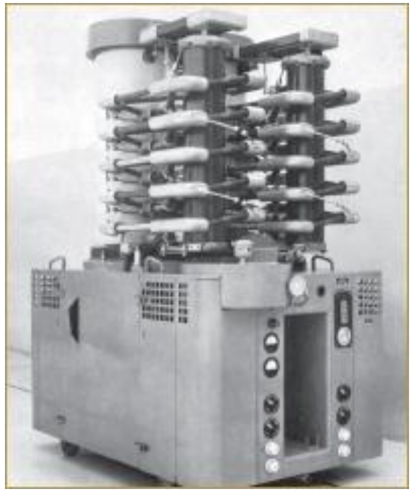
- 将原来两端直流升级成三端直流，增加通道利用率，输送云南水电



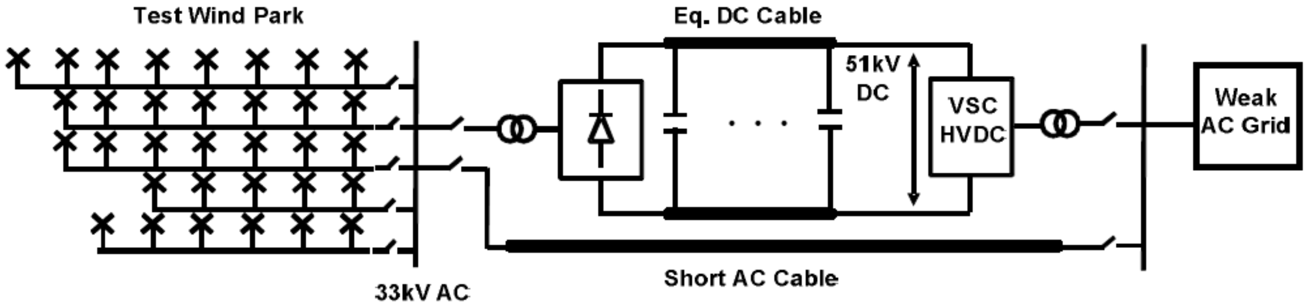
混合直流输电技术

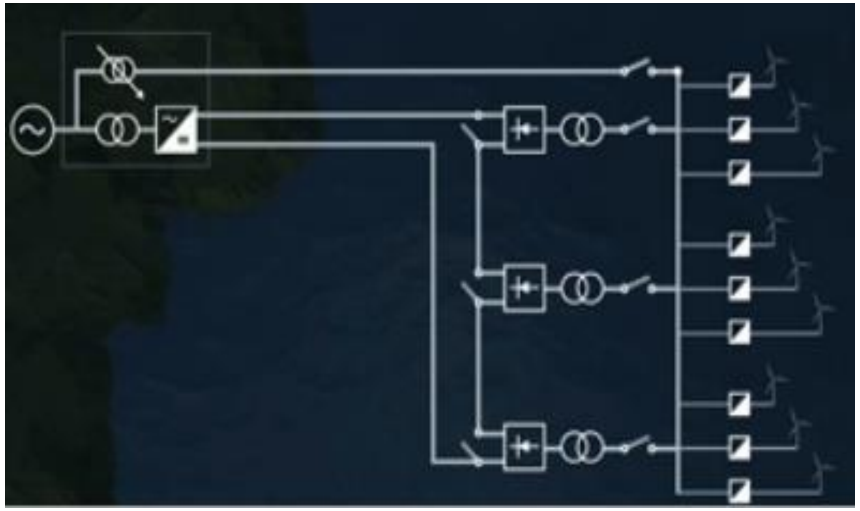
■ 汞弧阀+晶闸管的串联

The Gotland scheme became a test bed for many HVDC innovations and in 1970 became the first application of the new thyristor valve technology. The original mercury-arc valves were operated alongside the new thyristor valve technology, becoming the first hybrid HVDC scheme, but the advent of the thyristor marked the end of the mercury-arc valve HVDC converter scheme. There are many texts available with more detail of the pioneering work between 1902 and 1954 if you are interested in reading more about the mercury-arc valve.

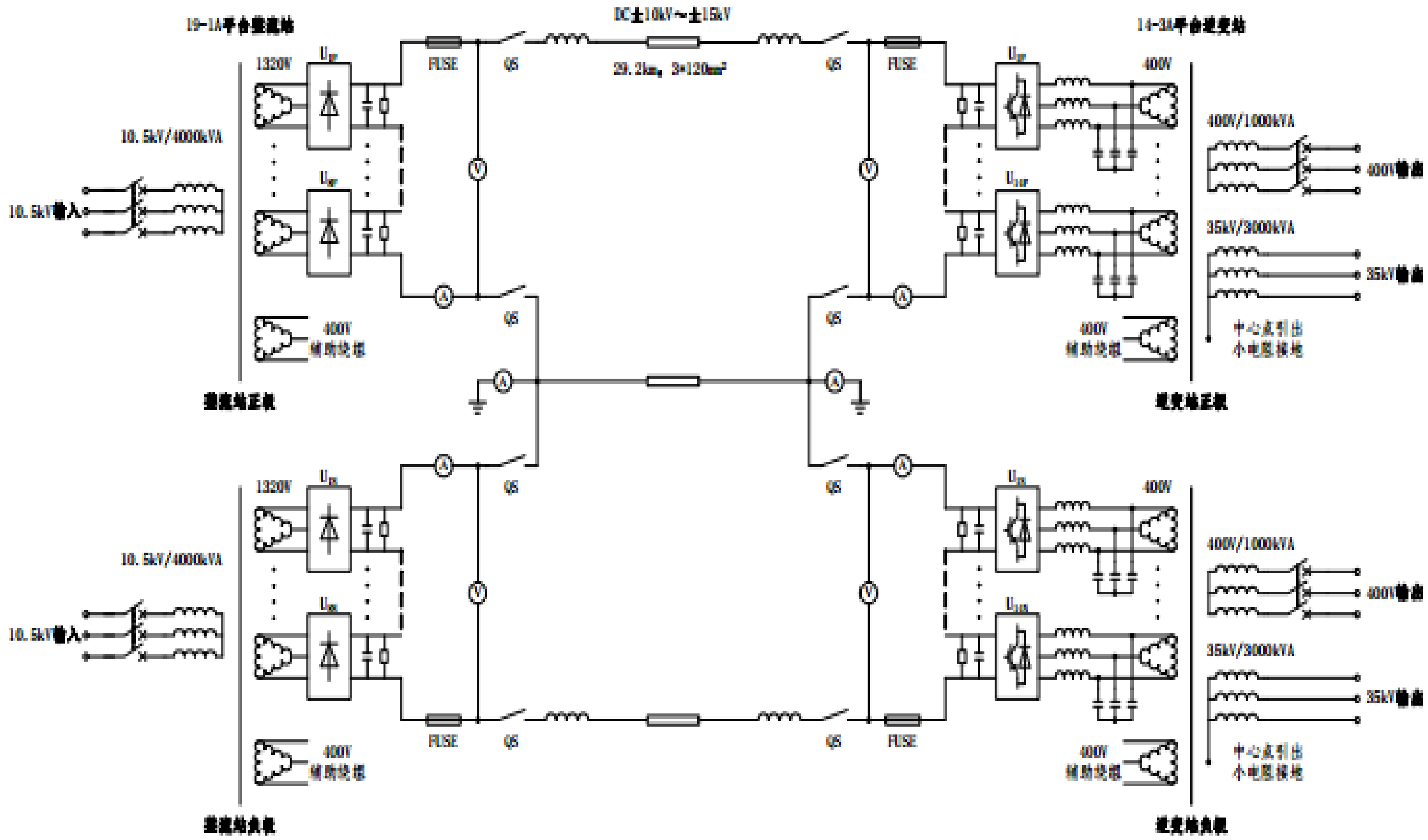


■ 送端二极管+受端MMC直流系统



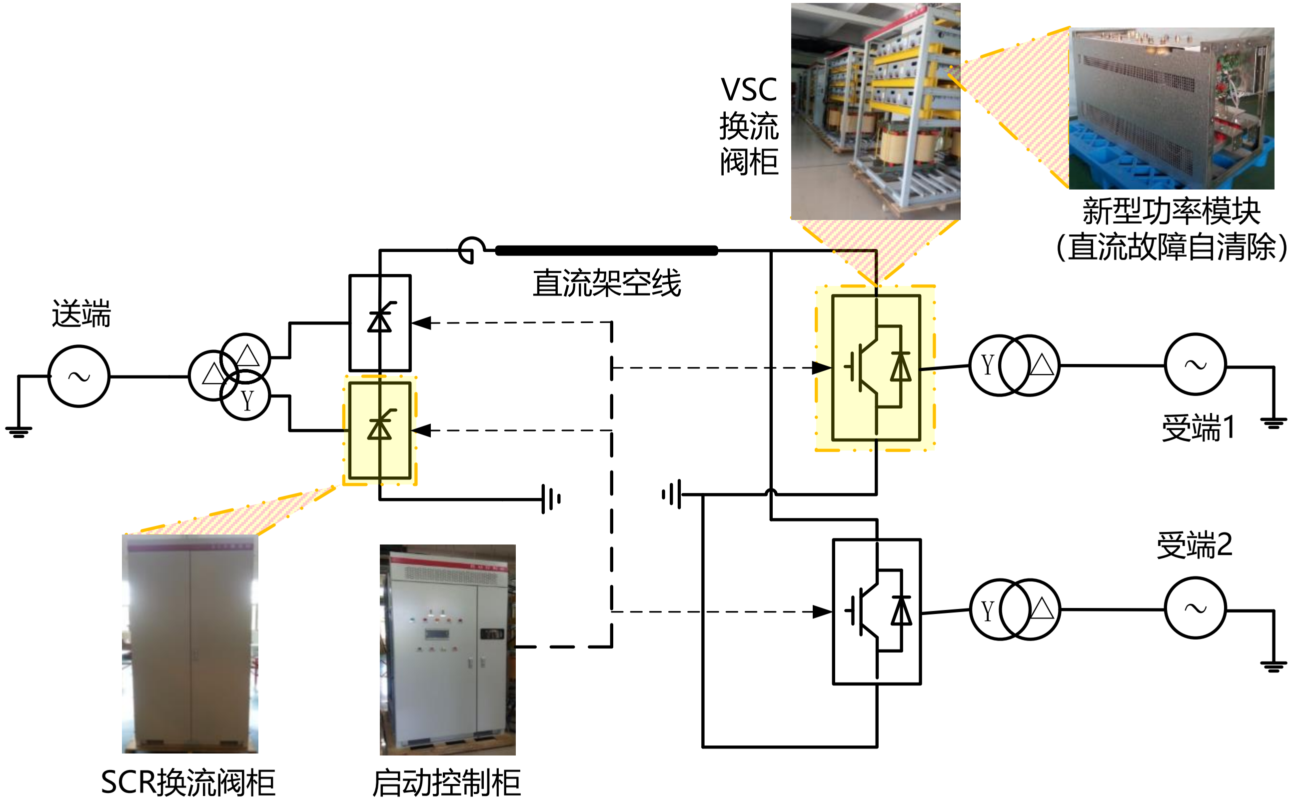


中海油海上平台±10kV/8MW混合直流输电送电

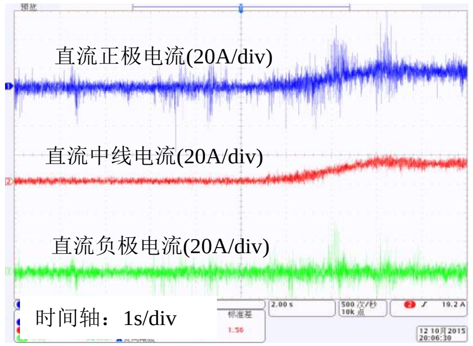


南方电网设立重点项目研究高压大容量柔性直流和混合直流输电技术

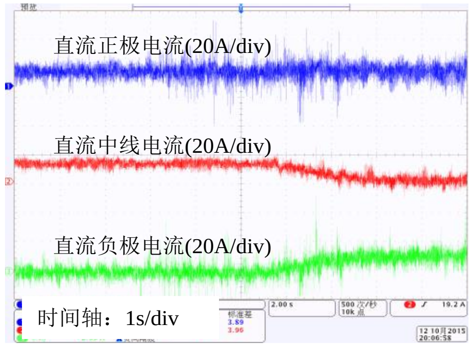
- 研究±500kV/3000MW级以上柔性直流关键技术
- 研究LCC+VSC混合直流关键技术
- 研究3000A等级IGBT应用



10kV/4MW混合直流物理样机



(a)



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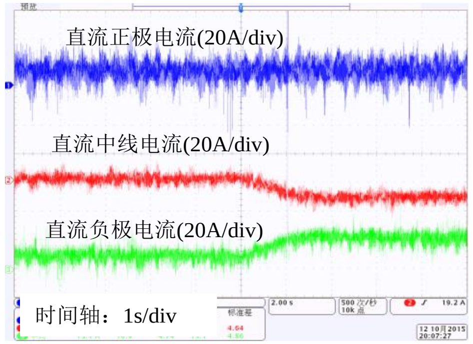
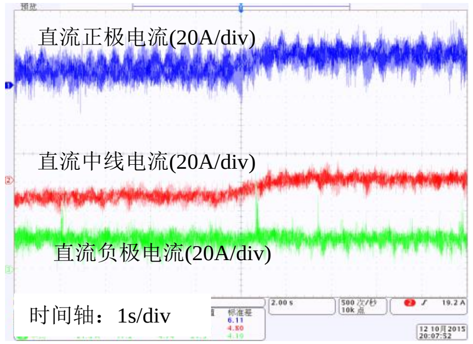
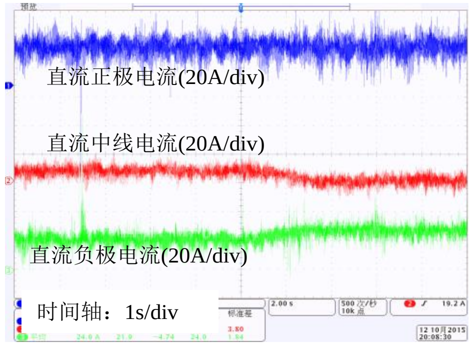


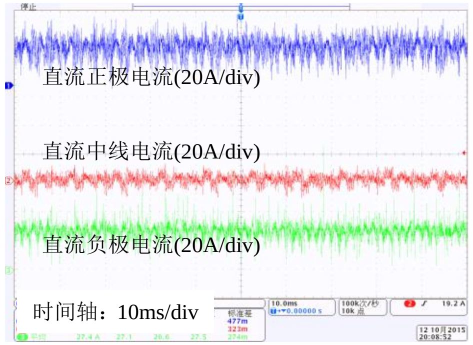
(c)



(d)



(e)



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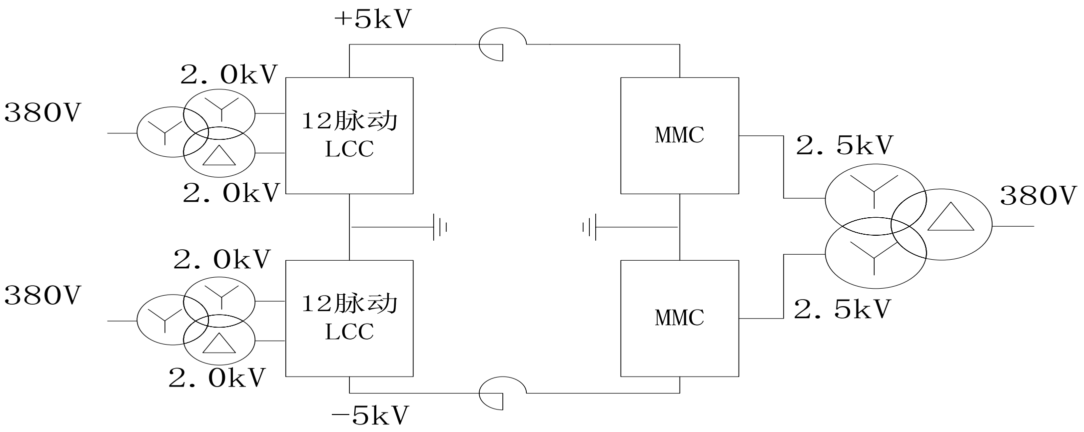
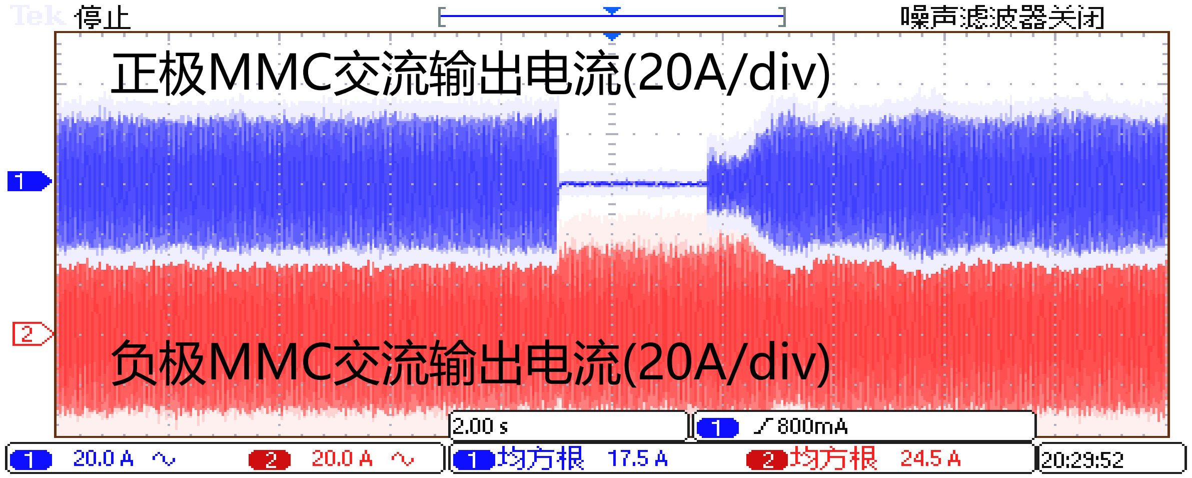
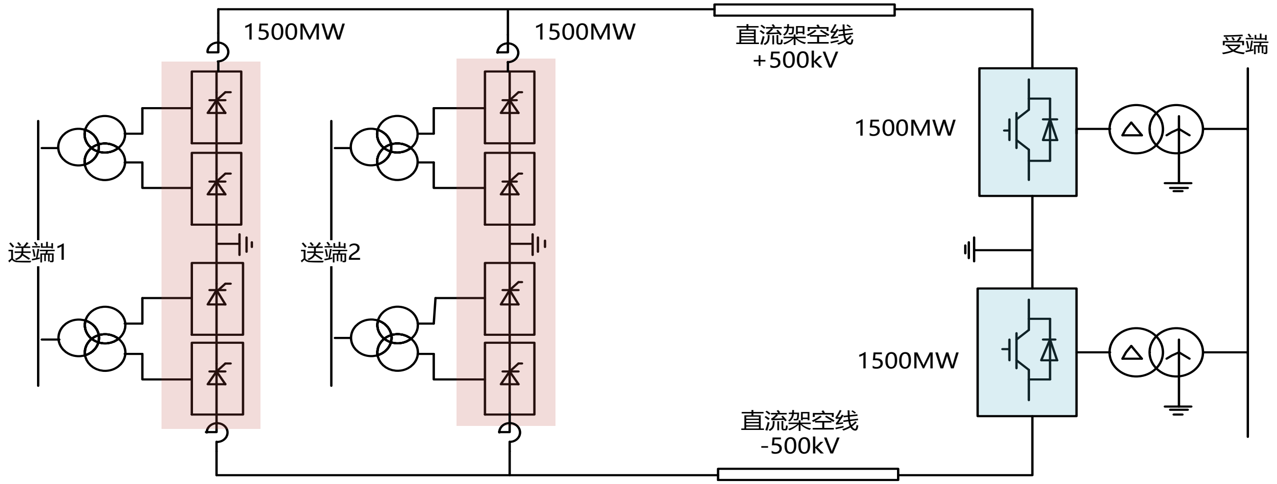


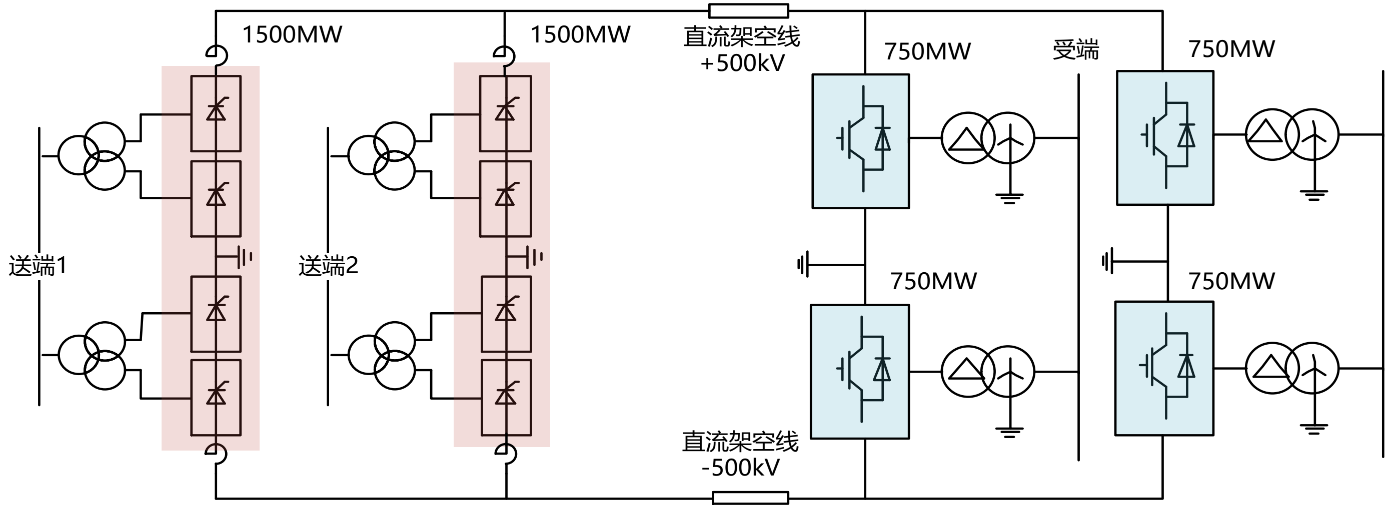


正极直流极线短路试验

±500kV/3000MW常规直流改造

- ±500kV/3000MW
- 送端LCC
- 受端VSC





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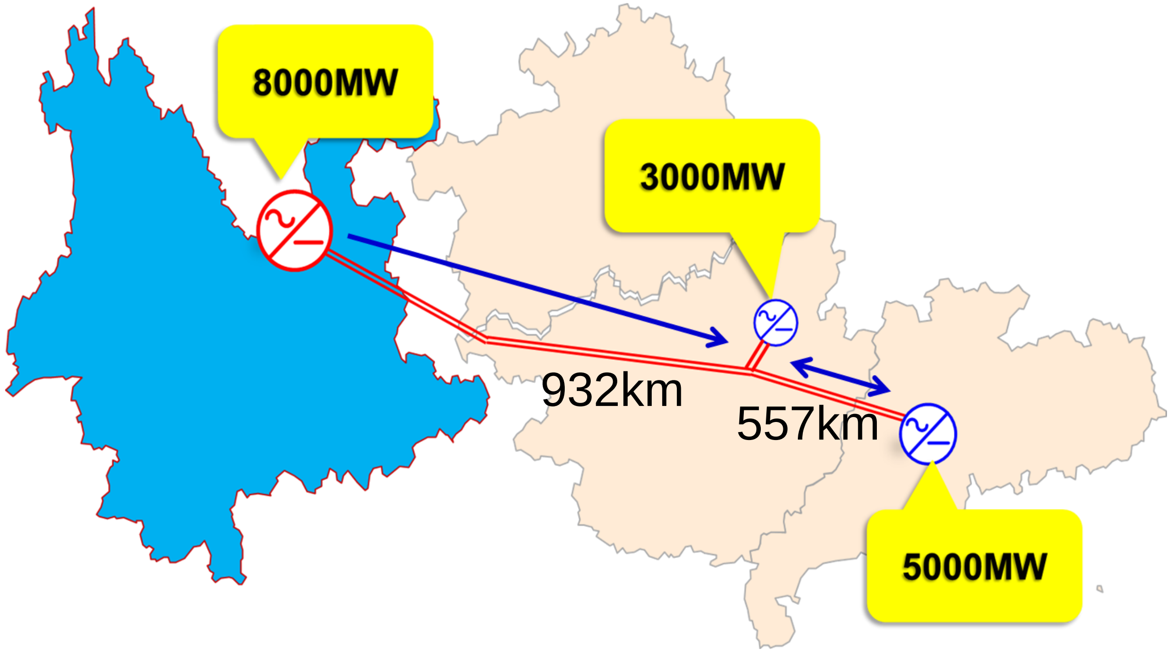
乌东德直流概况

■ 乌东德直流是西电东送落点珠三角地区的第10回高压直流，输送西部清洁水电到珠三角负荷中心

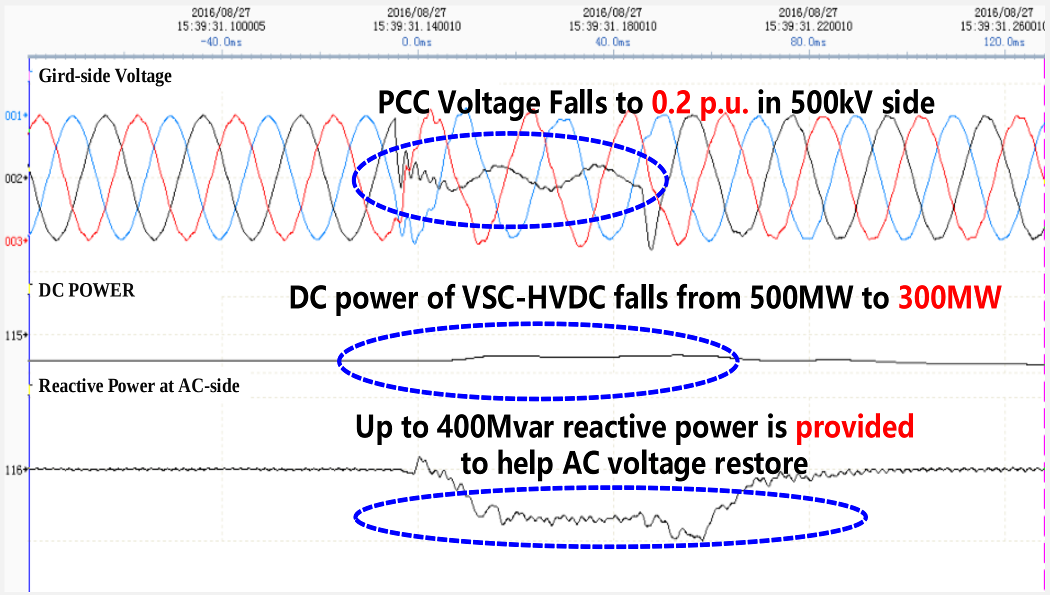
- 额定直流电压：±800 kV
- 系统接线：三端直流系统
- 送端功率：8000MW
- 广西受端：3000MW
- 广东受端：5000MW
- 架空线路：1489km
- 计划调试：2020



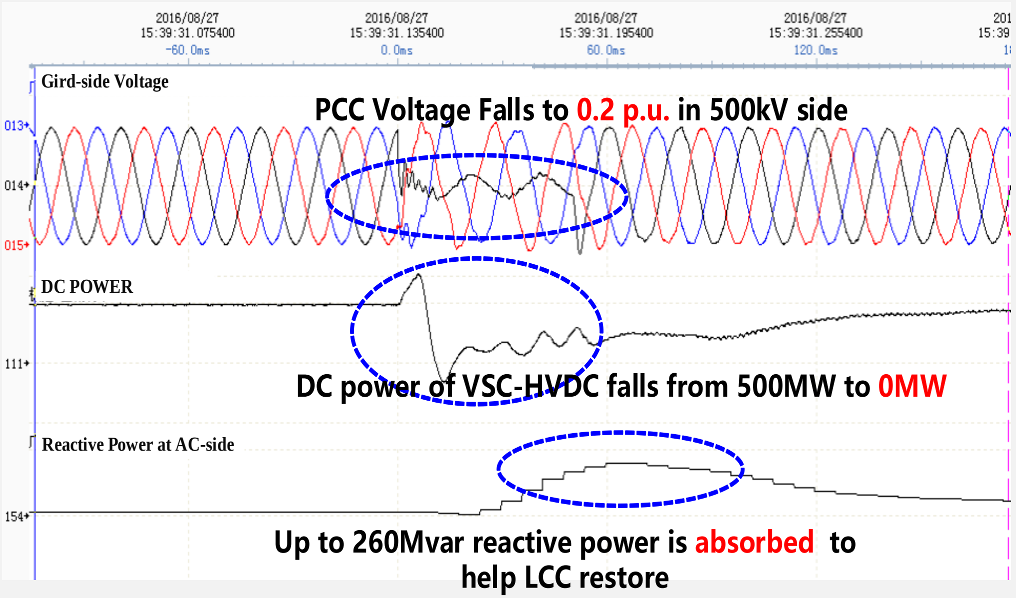
■ 技术方案设计考虑?

直流受端采用LCC和VSC的对比

- 相同交流故障下，LCC和VSC影响性能对比
- VSC具有明显的穿越交流系统故障能力（FRT）



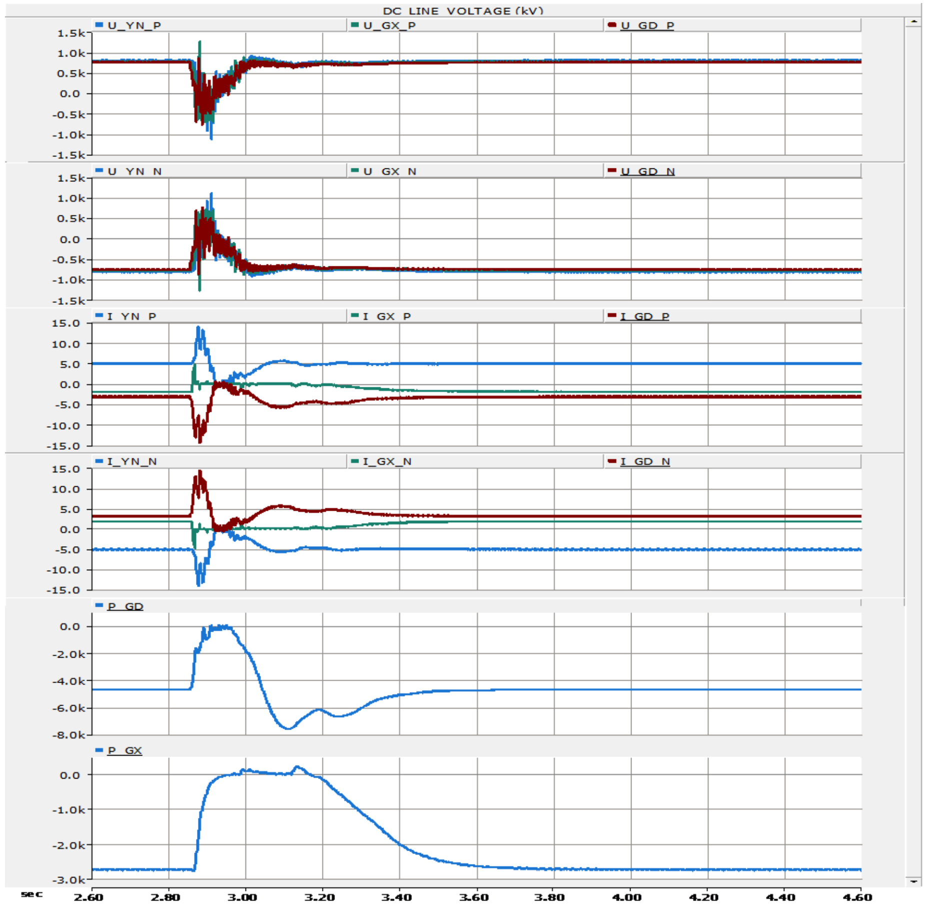
柔性直流有功无功响应情况

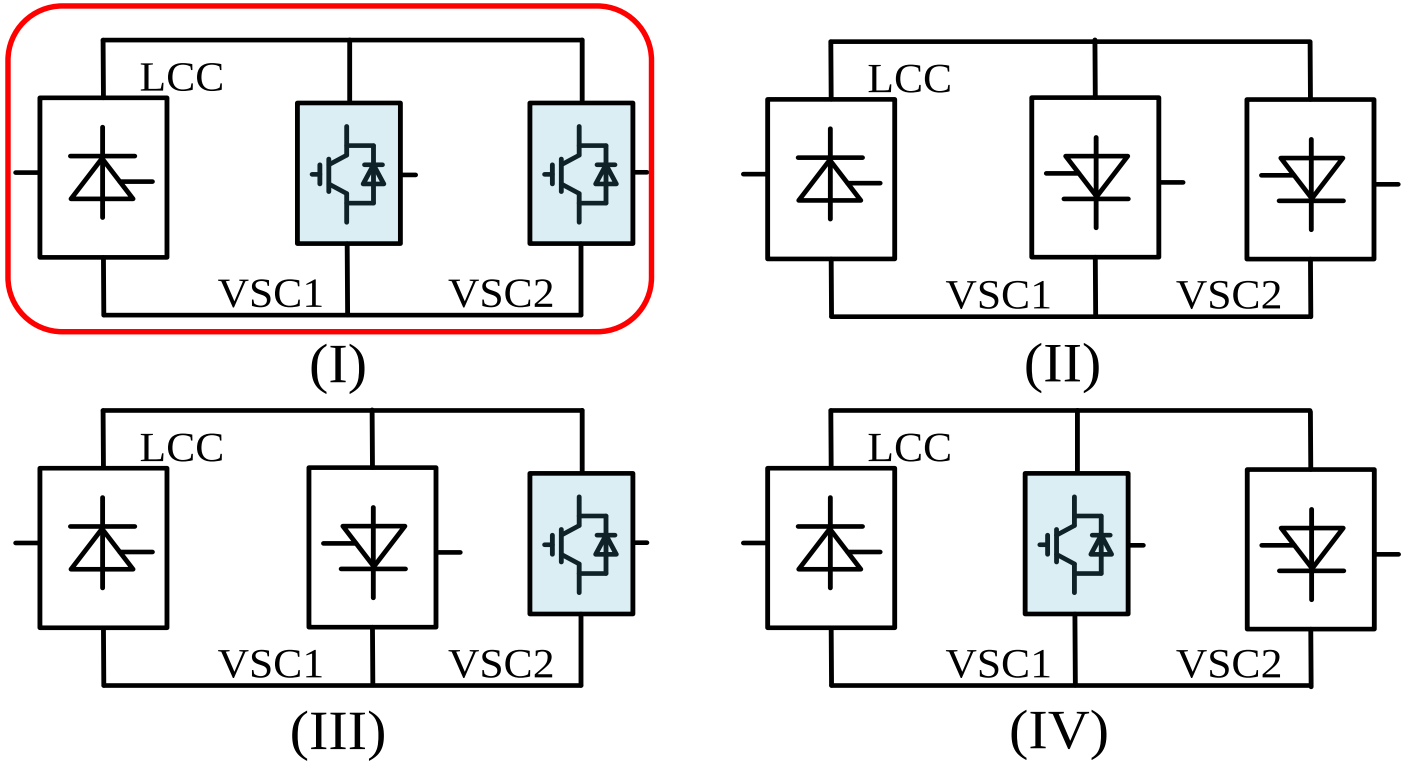


常规直流有功无功响应情况

两个直流受端适合均采用VSC技术

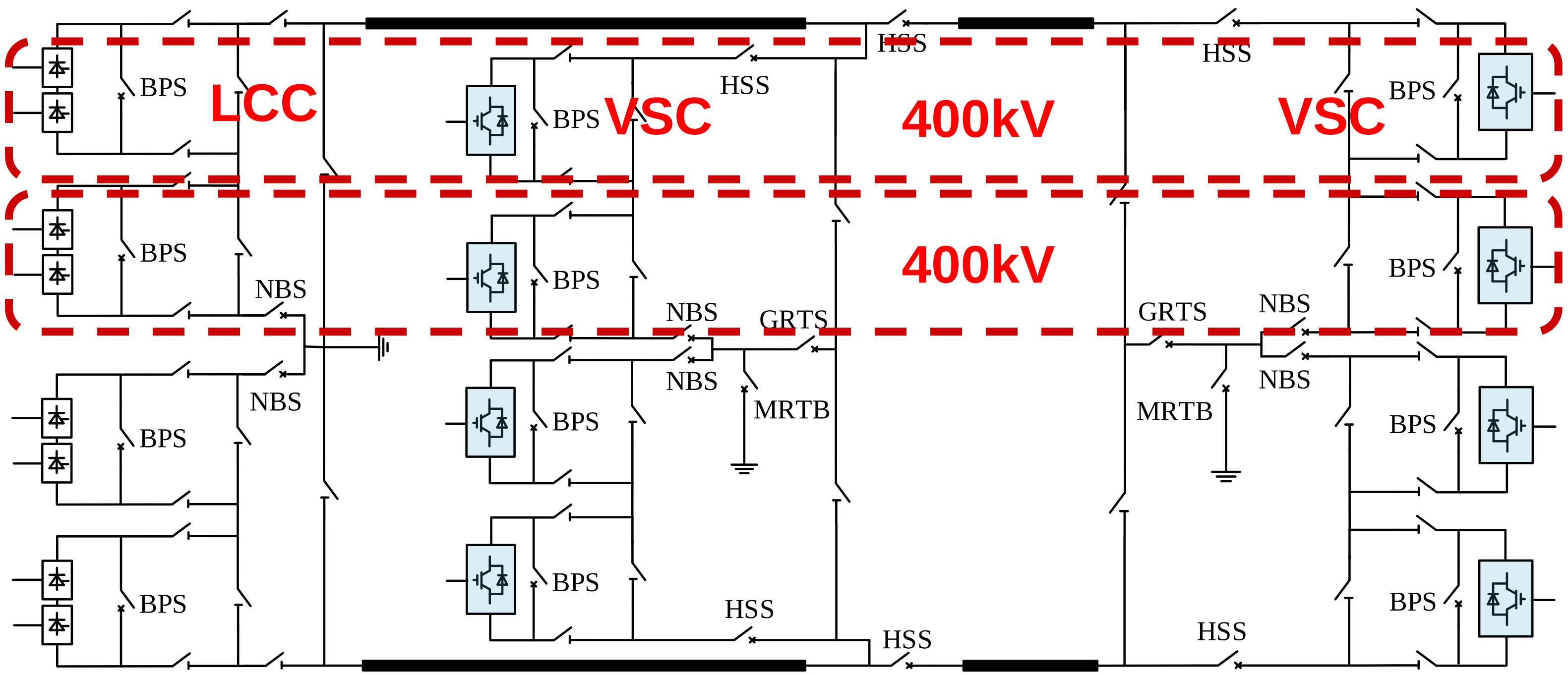
- 两个受端一旦有一个采用LCC，则交流故障下，LCC换相失败会导致直流电压跌落至0，直流电压无法维持，另一端即使采用VSC也无法保持正常运行





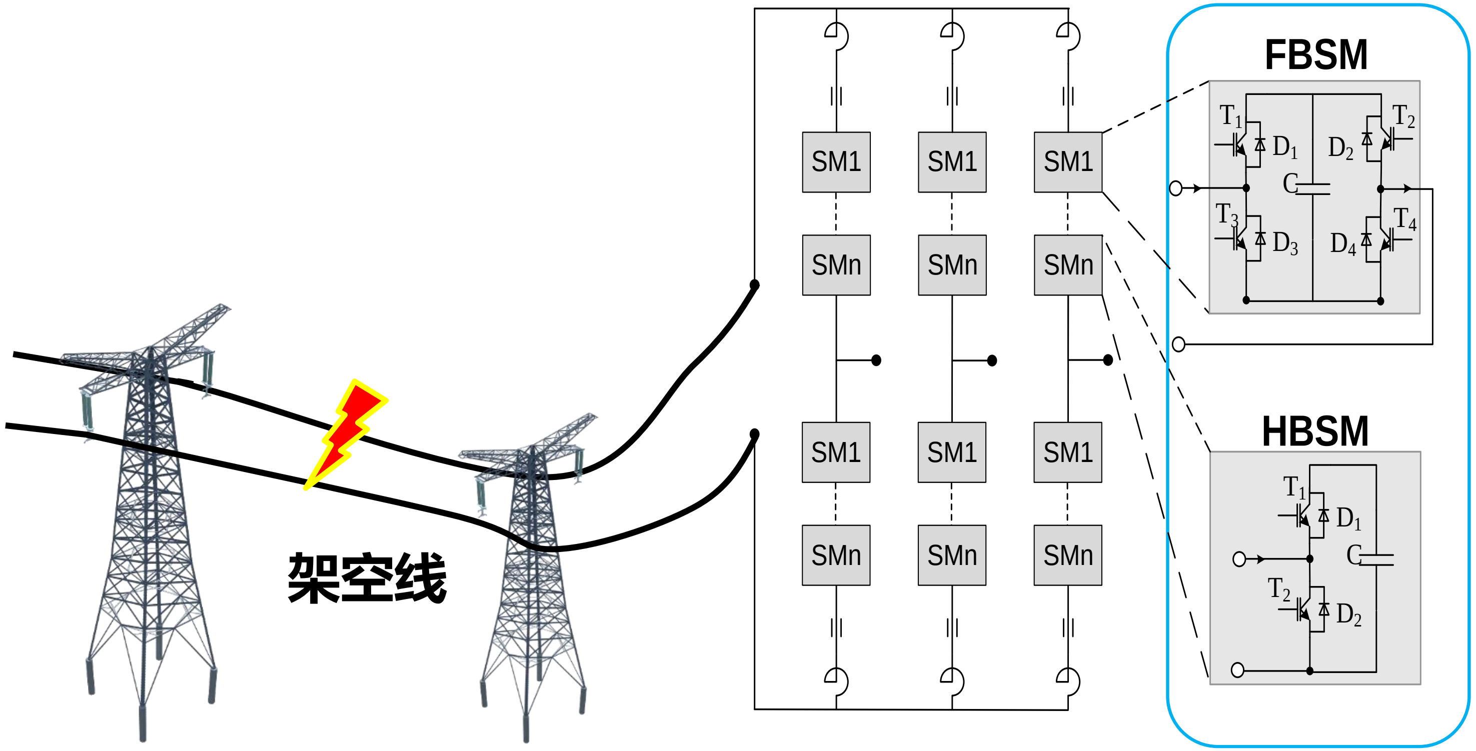
特高压多端混合直流主回路接线

- 送端采用LCC，两个受端均采用VSC
  - 对于送端LCC，设计成为经典的两个400kV、12脉动阀组串联
  - 对于受端VSC，设计成为两个400kV换流器串联
  - 送端和受端相互匹配



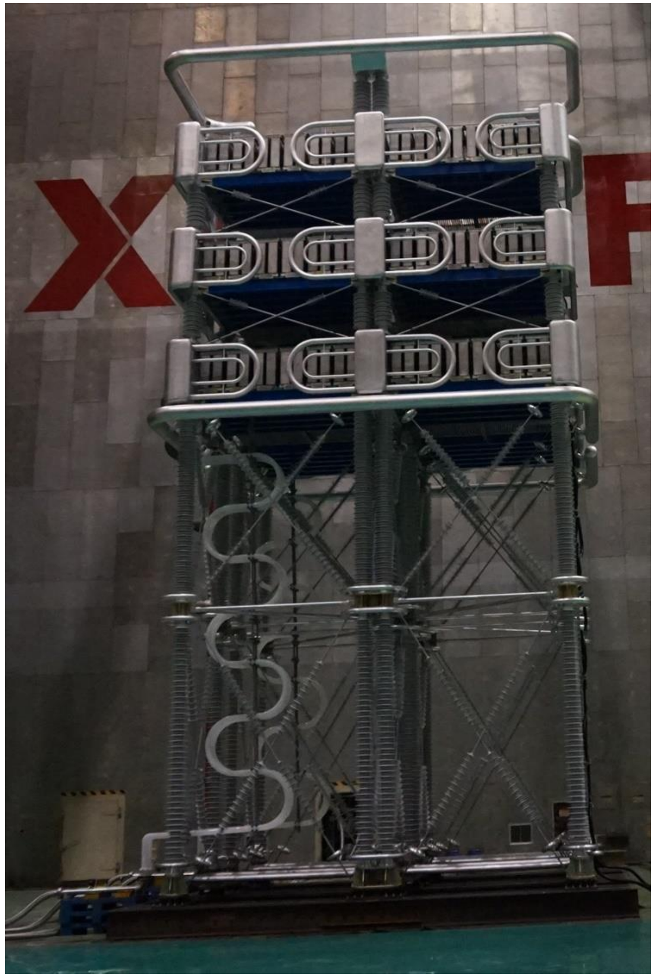
受端VSC首次采用“全桥+半桥”混合拓扑，实现直流故障清除和重启

- VSC换流器能够很好应对交流故障
- 以往两电平、三电平和半桥型MMC由于反并联二极管的存在，无法清除直流故障
- 全桥拓扑能够阻止交流电流馈入直流故障点，并且直流电压能够调节，能够清除直流故障
- 为了进一步降低元件数量和损耗，设计了部分半桥替代全桥的混合拓扑方案



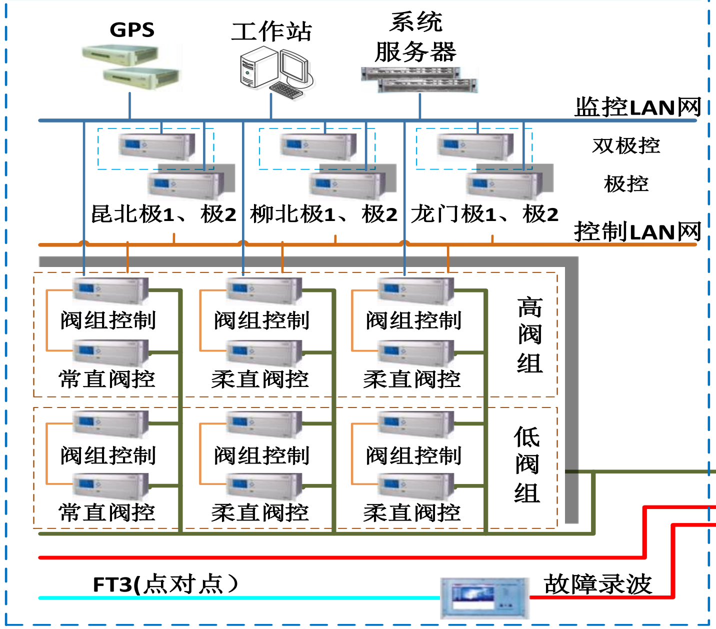
研制出满足系统设计要求的800kV-5000MW换流阀

- 采用4500V/3000A IGBT器件，通过IEC标准试验

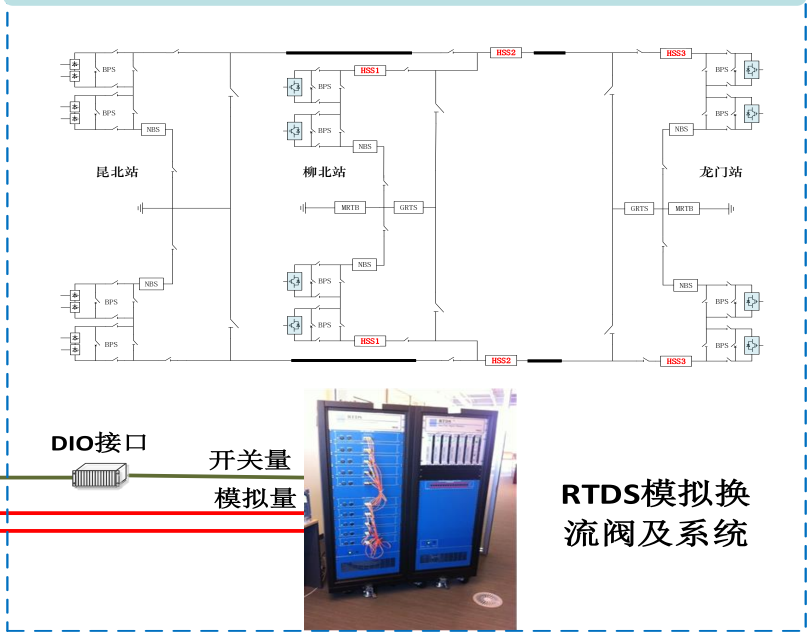


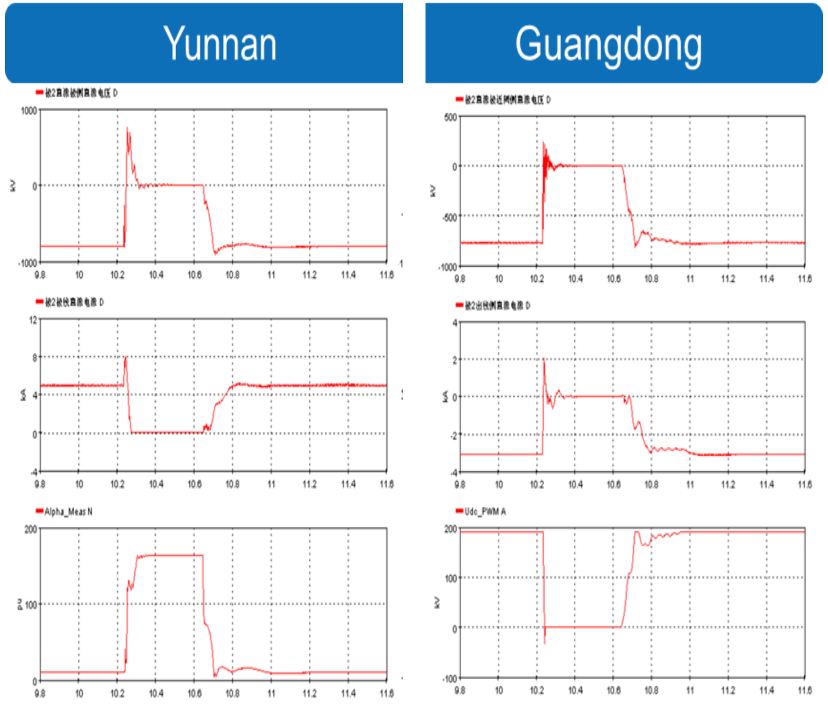
研制出满足系统设计要求的多端控制保护系统和测试平台

控制保护系统



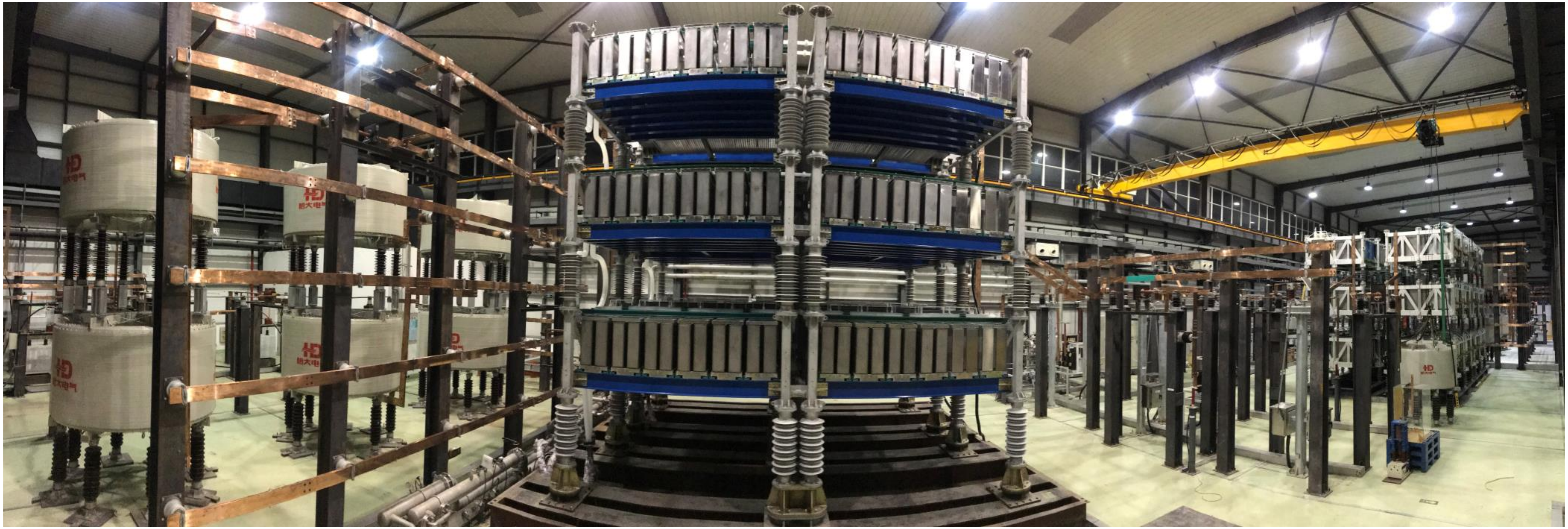
多端混合系统模型



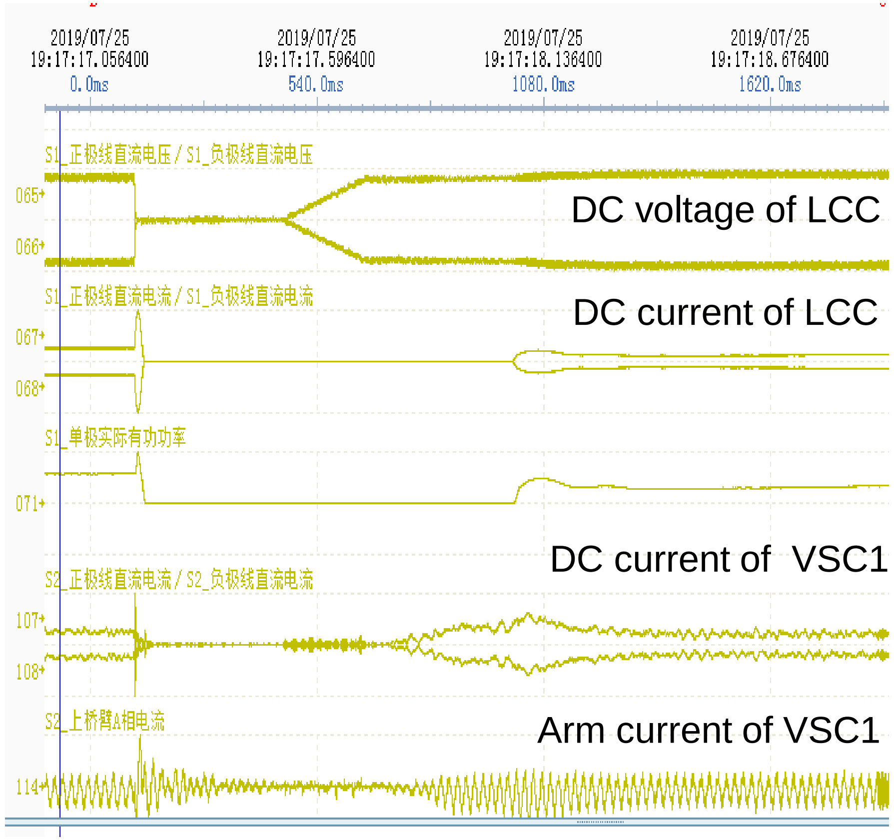


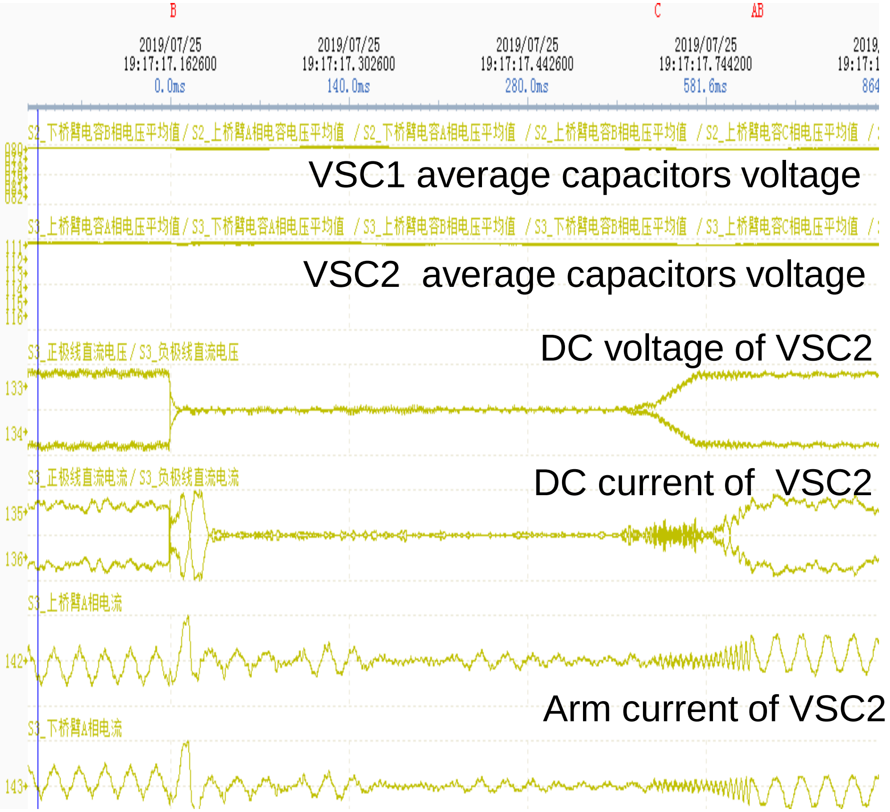
物理试验平台：三端系统，±10.5kV、LCC 21MW、2*VSC 66MW

◆ 三端混合系统，直流电压±10.5kV，送端LCC 21MW，两个受端VSC 66MW，VSC均采用4500V/3000A的IGBT器件，全桥+半桥结构



物理试验平台：直流故障试验

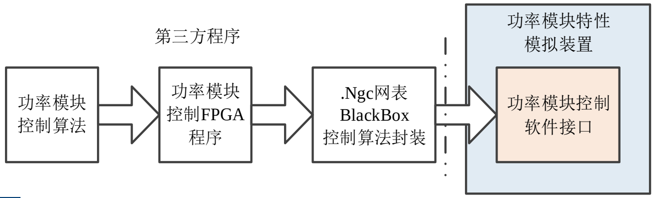




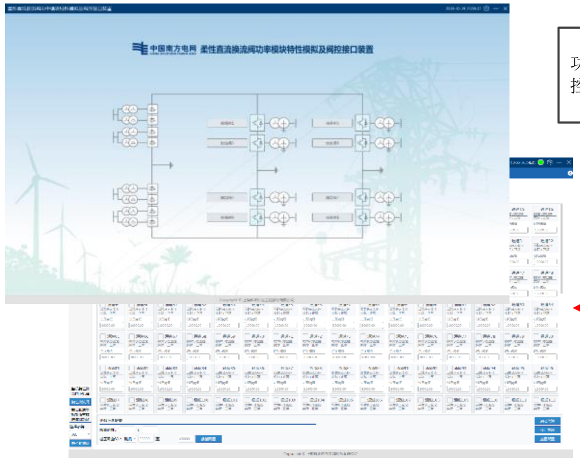
三端运行条件下直流故障试验

阀控测试系统：计及“功率模块+光纤系统+阀控”

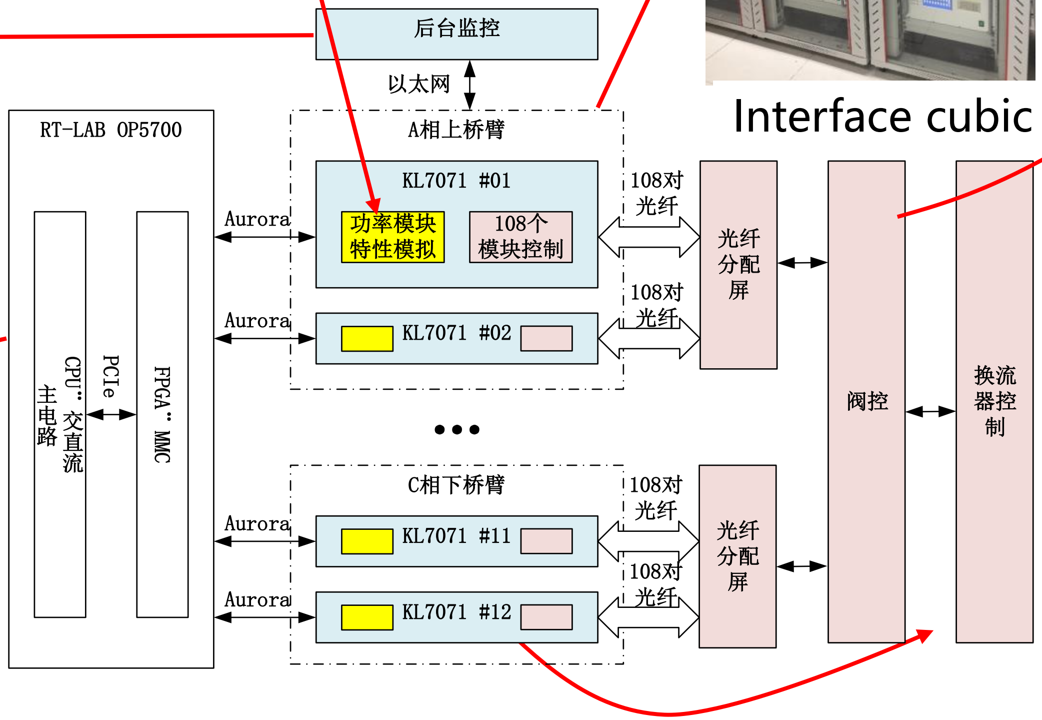
◆ 实时仿真系统，测试“阀控+光纤系统+功率模块”功能



Sub-model control function



HMI



simulator

Interface cubic

Valve control

Sub-model fibers

目录




南方电网与世界同行分享混合直流技术和经验

■ 依托直流技术发起成立具有影响力的工作组，与世界同行分享直流输电技术成果

- B4.79 - Hybrid LCC/VSC HVDC systems

CIGRE Study Committee B4

PROPOSAL FOR THE CREATION OF A NEW WORKING GROUP[1]

WG N° B4.79	**Name of Convenor:** Hong Rao (CHINA) **E-mail address**: raohong@csg.cn
Strategic Directions #[2]: 1	**Technical Issues #[3]: 1**
The WG applies to distribution networks[4]: No	
Potential Benefit of WG work #[6]: 3	
Title of the Group: Hybrid LCC/VSC HVDC Systems	

Scope, deliverables and proposed time schedule of the Group:

Background:

Line commutated converter (LCC) and voltage sourced converter (VSC) are the two technologies utilized in High Voltage Direct Current transmission systems (HVDC). Over the past 60 years more than 100 LCC-HVDC systems have been put into operation, with the transmission voltage reaching ±800kV and transmission power capacity of up to 10GW. Meanwhile, more than 30 VSC-HVDC systems have been put into operation, of which the transmission voltage is up to ±320kV and the transmission capacity is up to 1GW. VSC-HVDCs with higher transmission voltage (±500~800kV) and larger capacity (3~5GW) are expected to go into operation in the next few years.

LCC-HVDC offers the advantages of larger transmission capacity, but generally has a large footprint which means large site area. The inverter station must be supported by an AC system with sufficient short circuit capacity as defined in broad terms by the short circuit ratio (SCR) to ensure reliable operation and satisfactory performance. The disturbances caused by commutation failure due to AC and DC disturbances, as well as the reactive power requirements of an LCC converter certainly have an impact on the connected AC system. On the other-hand VSC-HVDC does not suffer commutation failures, and the active power and reactive power can be controlled independently. These technical advantages enable the VSC-HVDC to ride through AC system faults and to control the reactive power to the connected AC system. To this end each have been utilized on a standalone basis.

The concept of combining the LCC and the VSC technologies in one HVDC link seems to be gaining popularity. It combines the LCC and VSC technology within one HVDC system. For example, in the SK4 project the LCC and VSC are used in different poles in a bipolar system, in the Luxi back-to-back project the LCC and VSC converters are connected in parallel, in the application of power supply to offshore drilling platform and integration of offshore wind power the LCC and VSC can be installed at the rectifier and inverter respectively and in application of overhead line transmission (OHL) the LCC and VSC can be connected in series in one station. There are many other scenarios that need investigation. The hybrid HVDC system offers great technical value and application prospects, since it combines the lower cost of LCC and the absence of commutation failure and the flexible control of VSC.

At present, there are no systematic discussion on hybrid HVDC. The purpose of this working group is to comprehensively discuss the definition and configuration of hybrid HVDC systems, as well as the necessary equipment, control, applications and prospects. It will also highlight any issues related to implementation.

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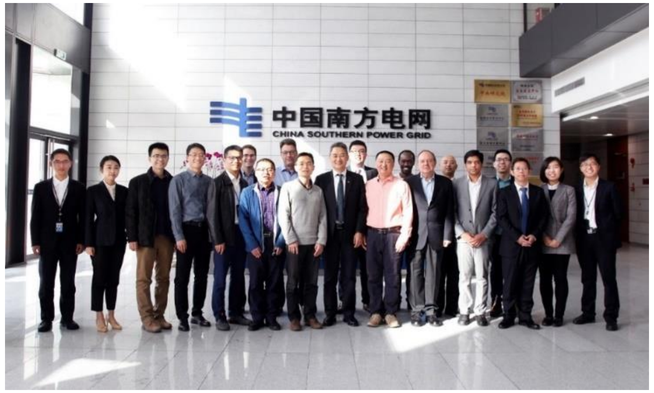
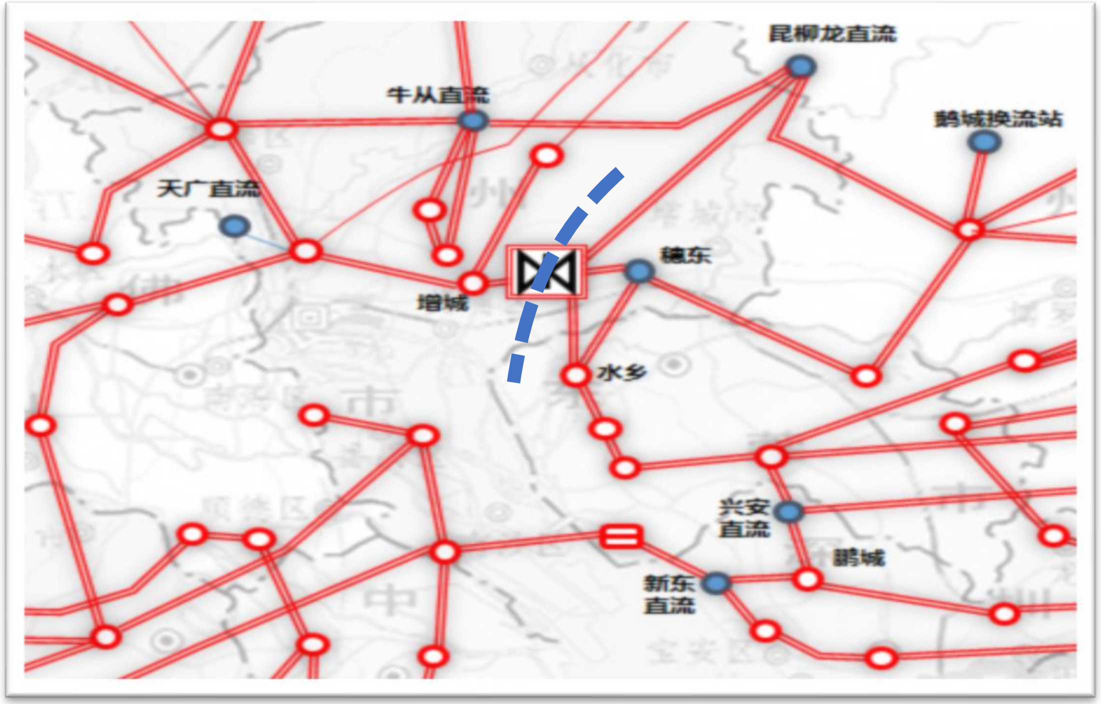
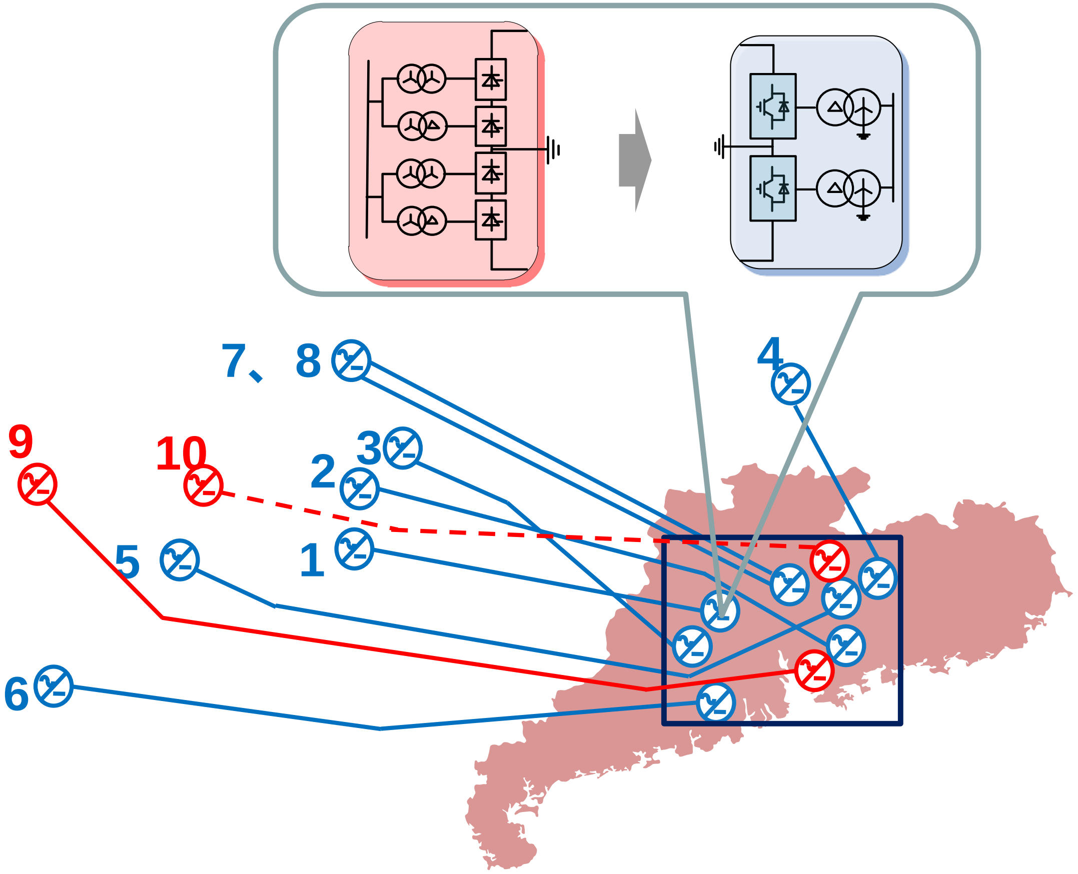
WG form 2017-V5



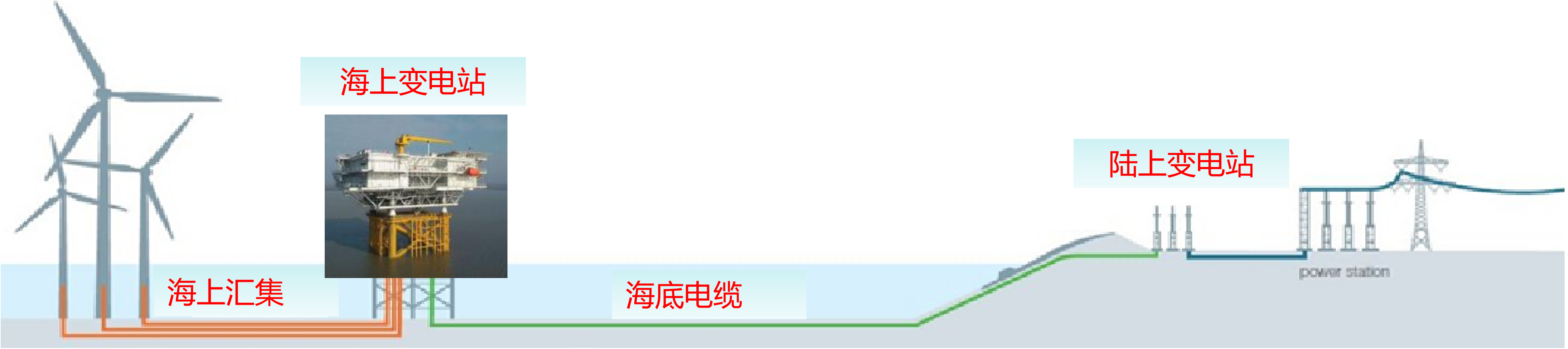
多直流馈入系统常规直流受端改造

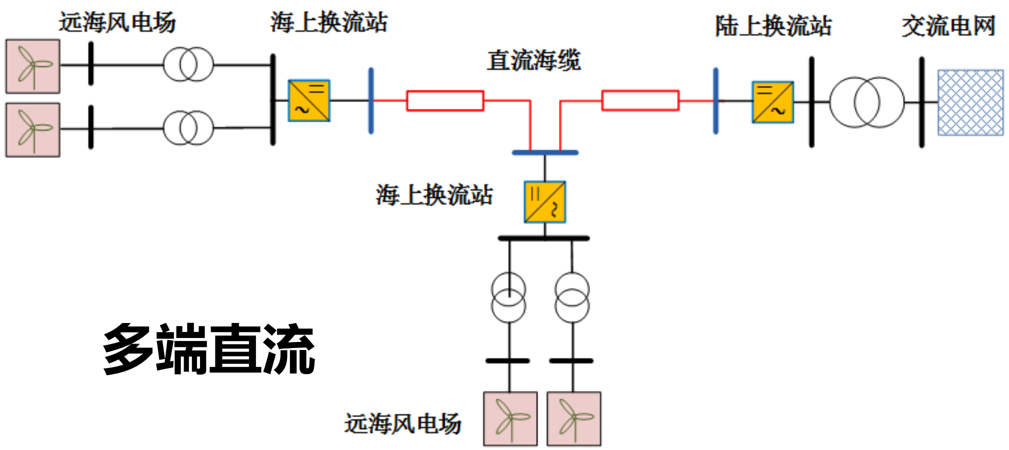




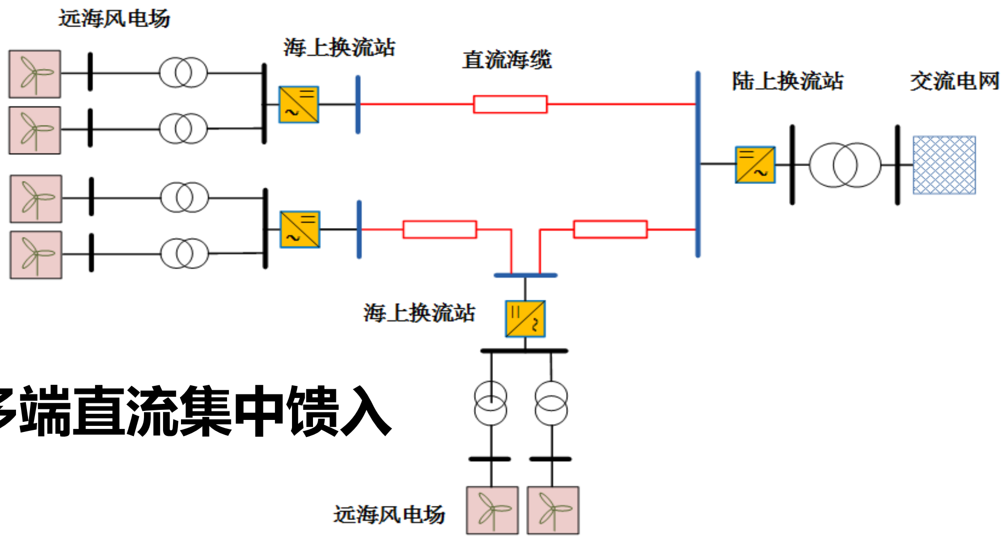
多端和混合直流应用于大规模海上风电并网

- 近海深水区海上风电采用柔直送出：海上将多个小容量风电场汇集为百万级柔直后送出，登陆后将多个柔直汇集为大容量直流后接入电网。



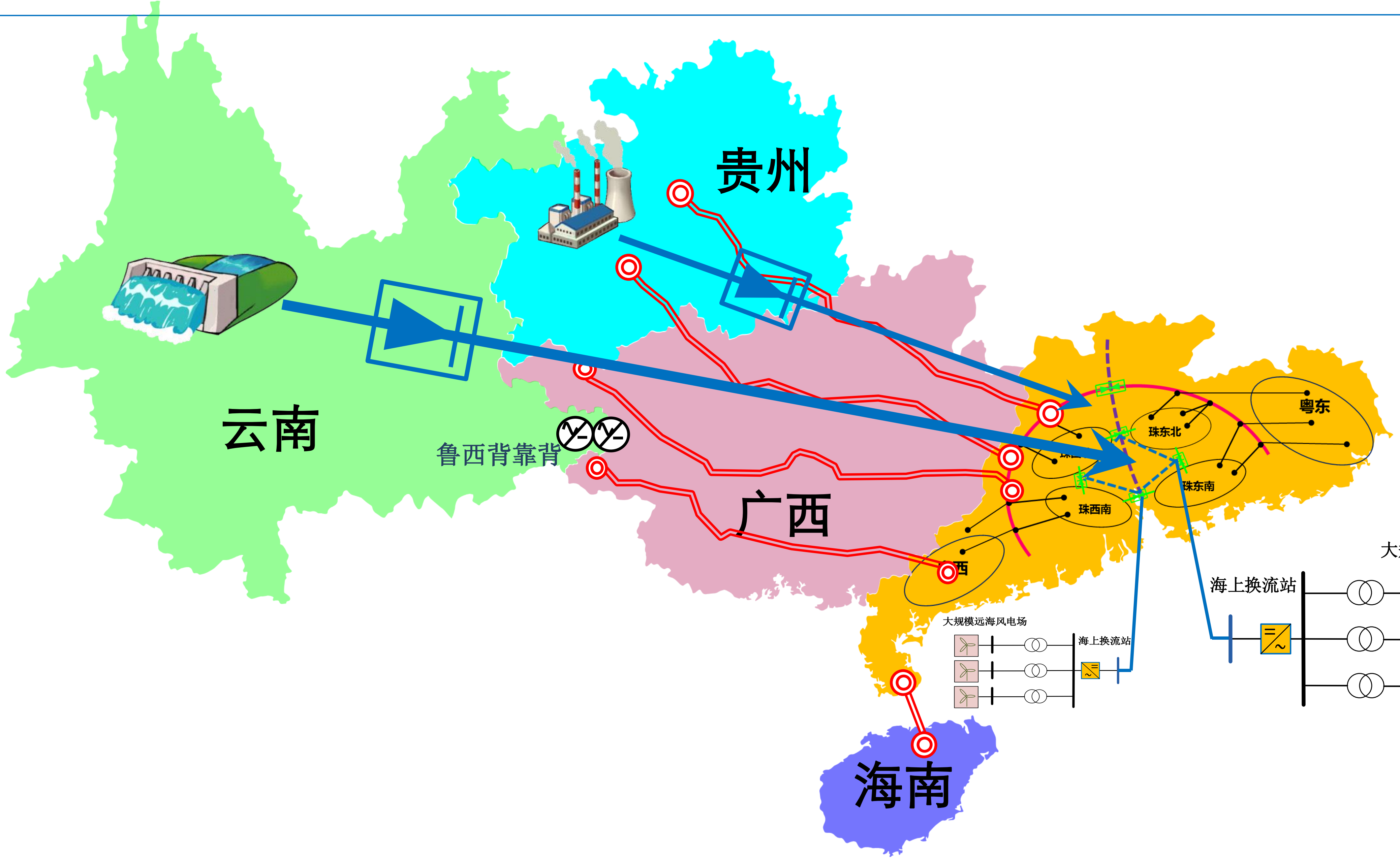


多端直流



多端直流集中馈入

直流可用于优化主网电网结构，支撑电网技术变革



直流应用：从高电压到中低压，构建用户定制的供用电系统

2018年CIGRE SC B4更名：

HVDC and power electronics ->

DC systems and power electronics

关注的技术领域：

- Direct Current equipment and systems including converter technology and semi-conductor devices.
  直流设备和系统，包括换流器拓扑和半导体器件
- Power electronics for AC systems and power quality improvement, advanced power electronics and applications.
  面向交流系统和电能质量改善的电力电子技术，先进电力电子技术及应用

请批评指正！

SKL

直流输电技术国家重点实验室

State Key Laboratory of HVDC