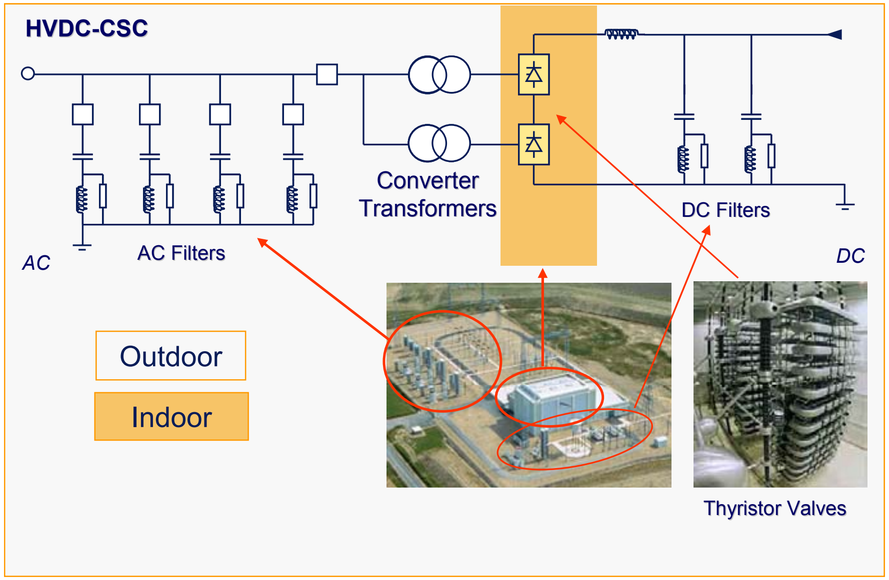
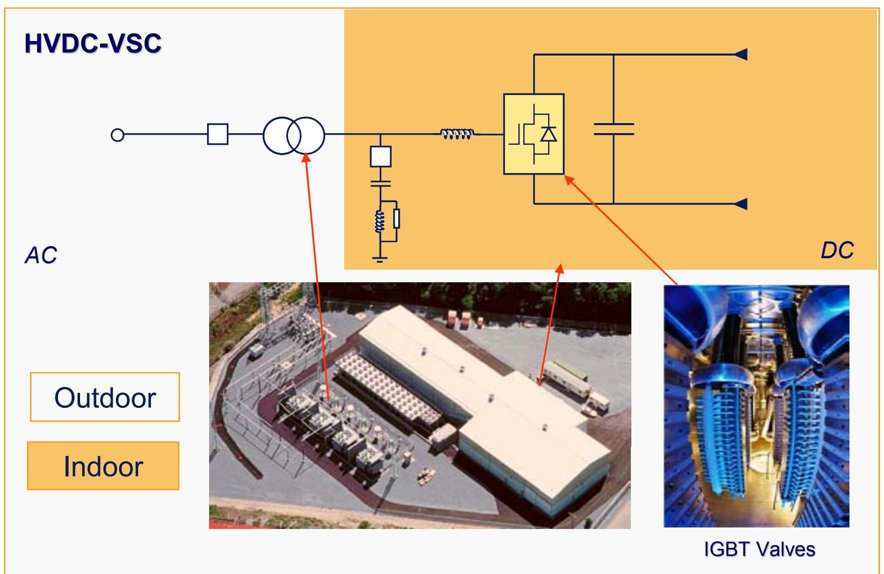
HVDC Development Topics

- Core HVDC Technologies
  - Conventional HVDC
  - VSC Based HVDC
- ± 800 kV HVDC
- Cost Comparison of AC & DC Transmission Alternatives
- HVDC Light
  - ± 320 kV, 1100 MW
  - Offshore
  - Multi-terminal & Overhead
- Project Examples

ABB

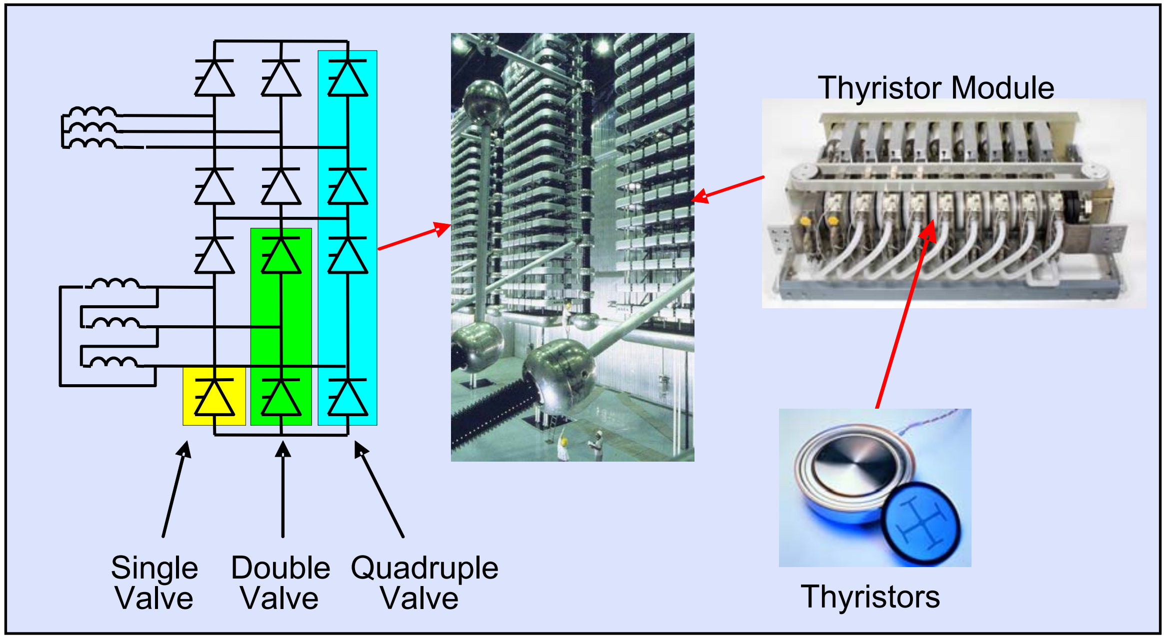
Core HVDC Technologies

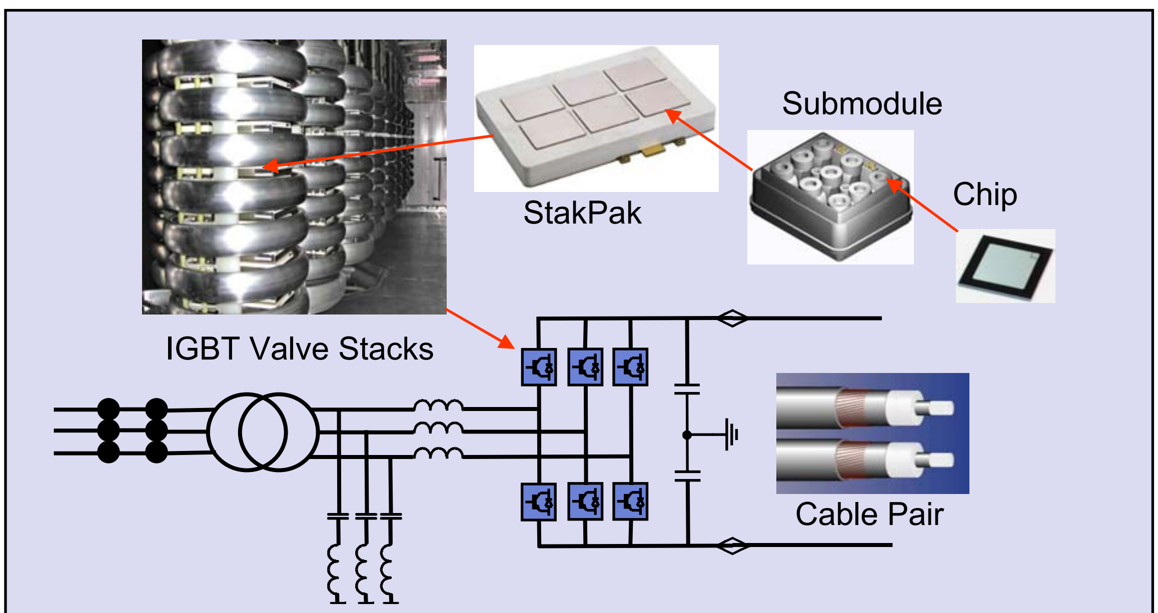




- HVDC Classic
  - Current source converters
  - Line-commutated thyristor valves
  - Requires 50% reactive compensation (35% HF)
  - Converter transformers
  - Minimum short circuit capacity > 2x converter rating
- HVDC Light
  - Voltage source converters
  - Self-commutated IGBT valves
  - Requires no reactive power compensation (15% HF)
  - Standard transformers
  - No minimum short circuit capacity, black start

HVDC Converter Arrangements





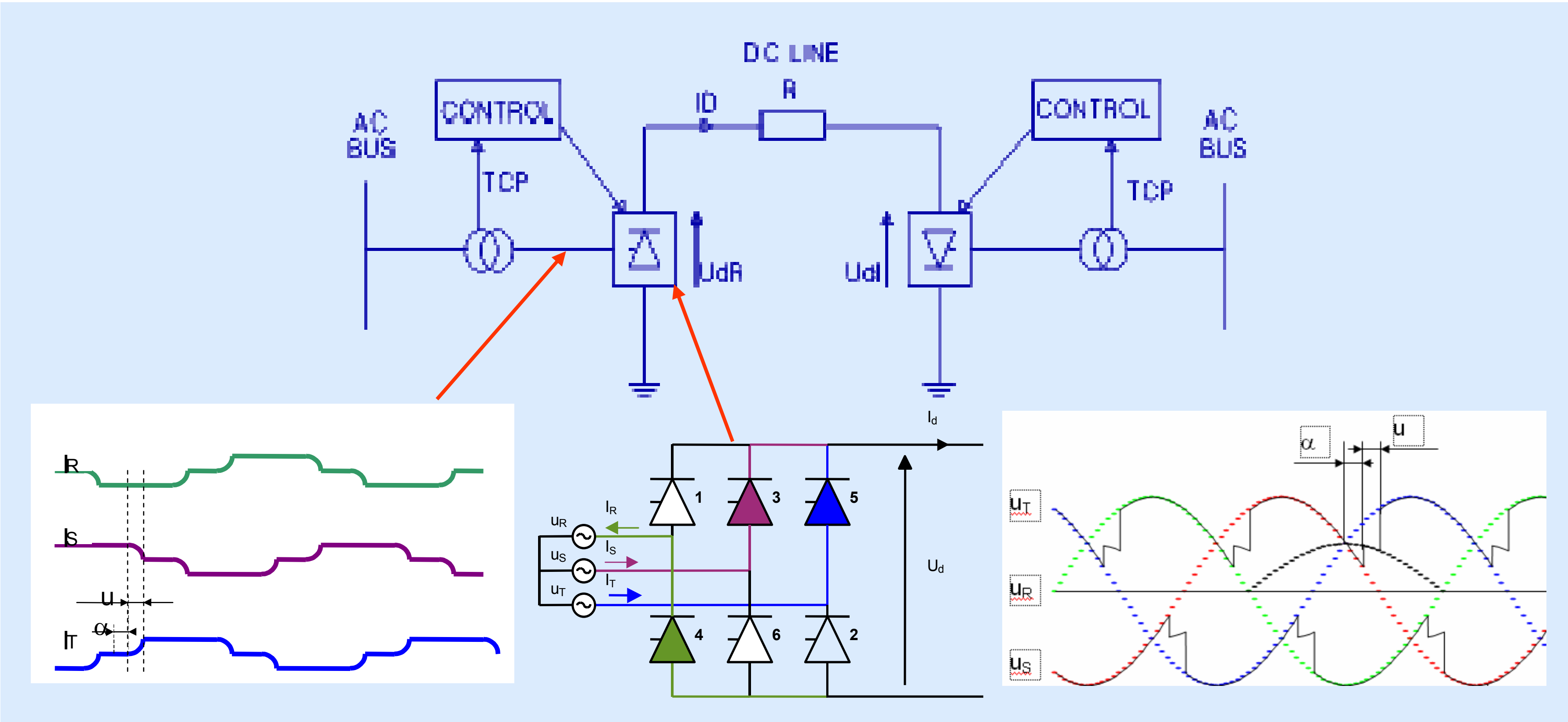
HVDC Classic

- Thyristor valves
- Thyristor modules
- Thyristors
- Line commutated

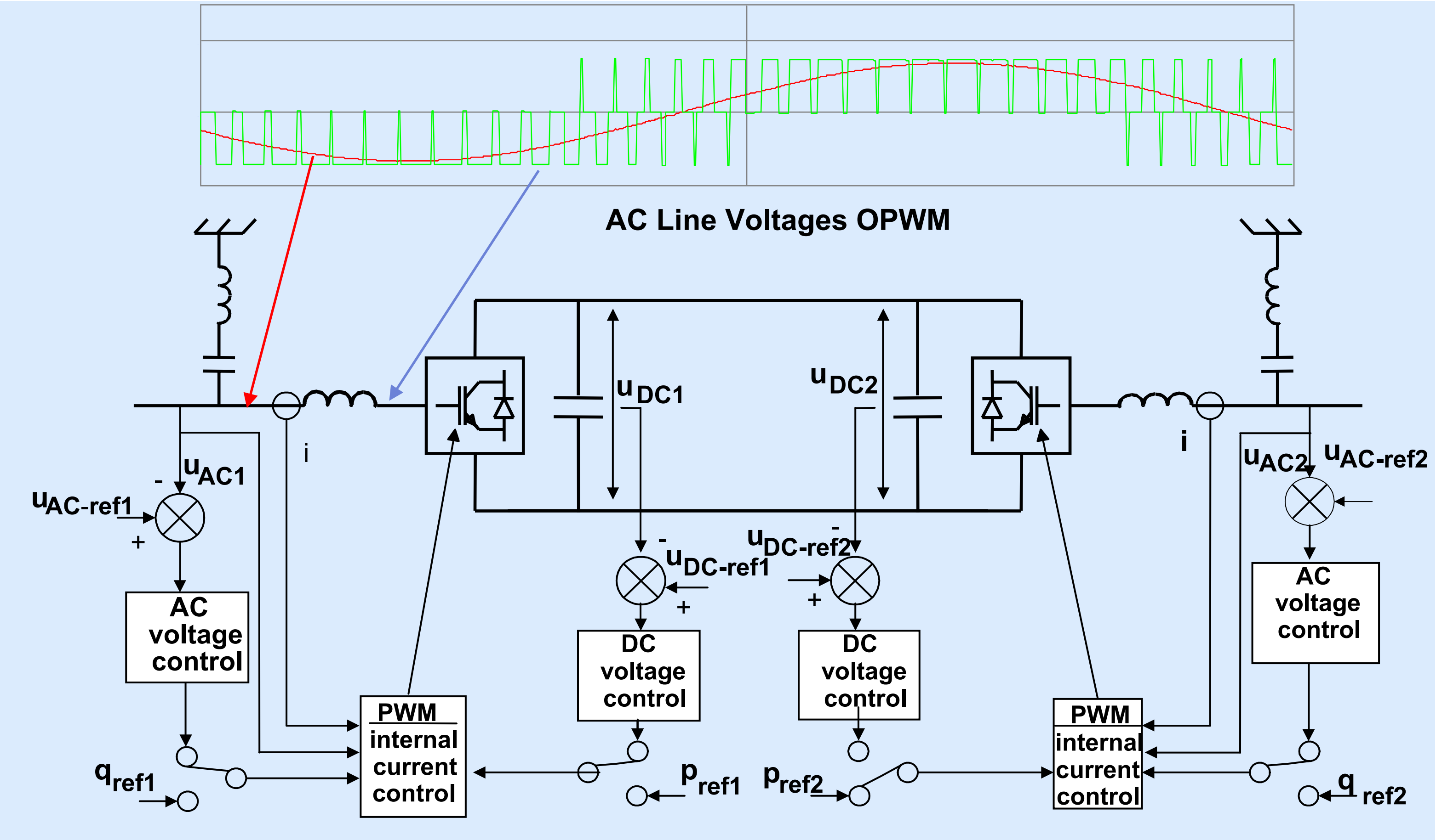
HVDC Light

- IGBT valves
- IGBT valve stacks
- StakPaks
- Submodules
- Self commutated

HVDC Classic Control

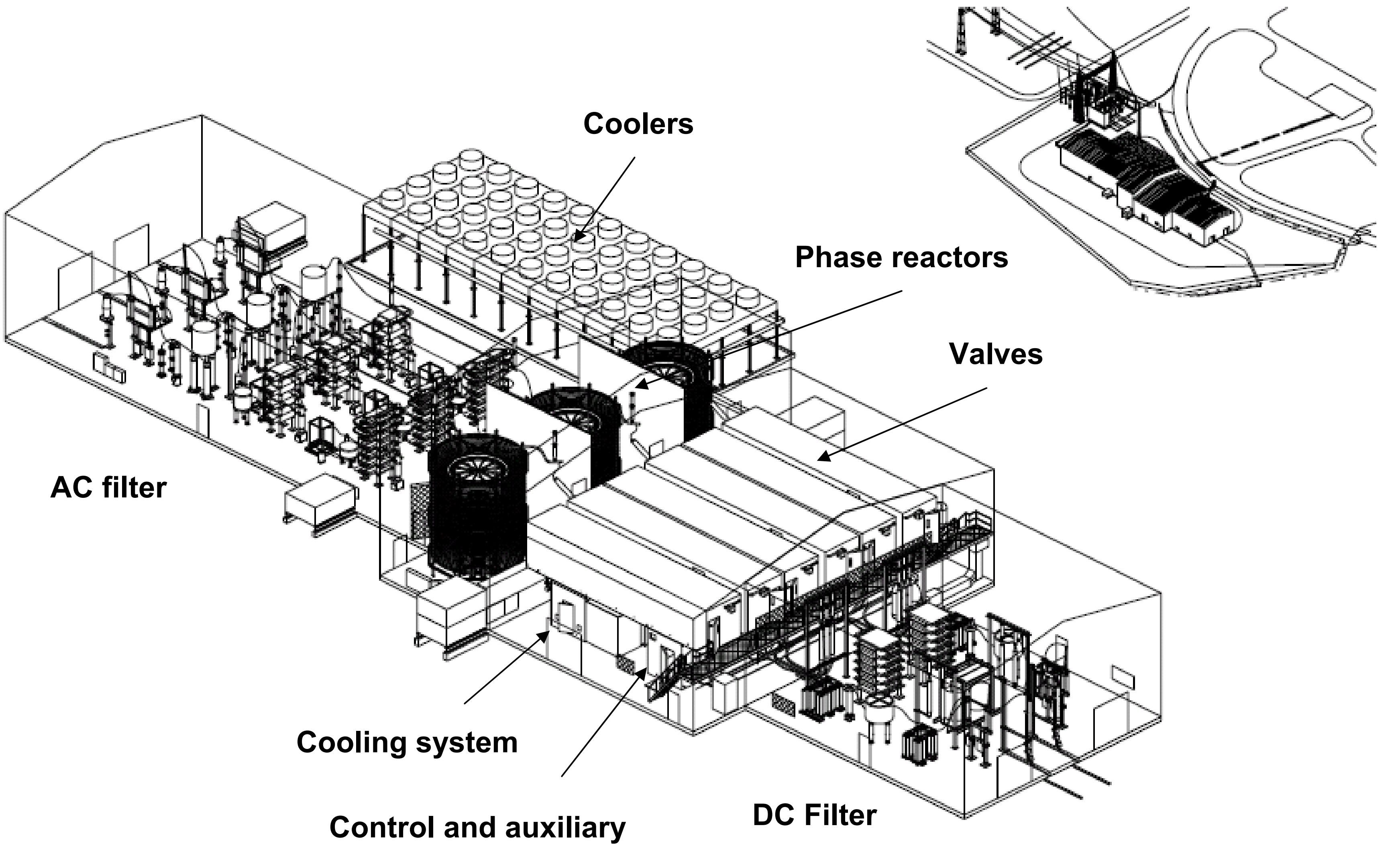


Control of VSC Based HVDC Transmission



Principle control of HVDC-Light

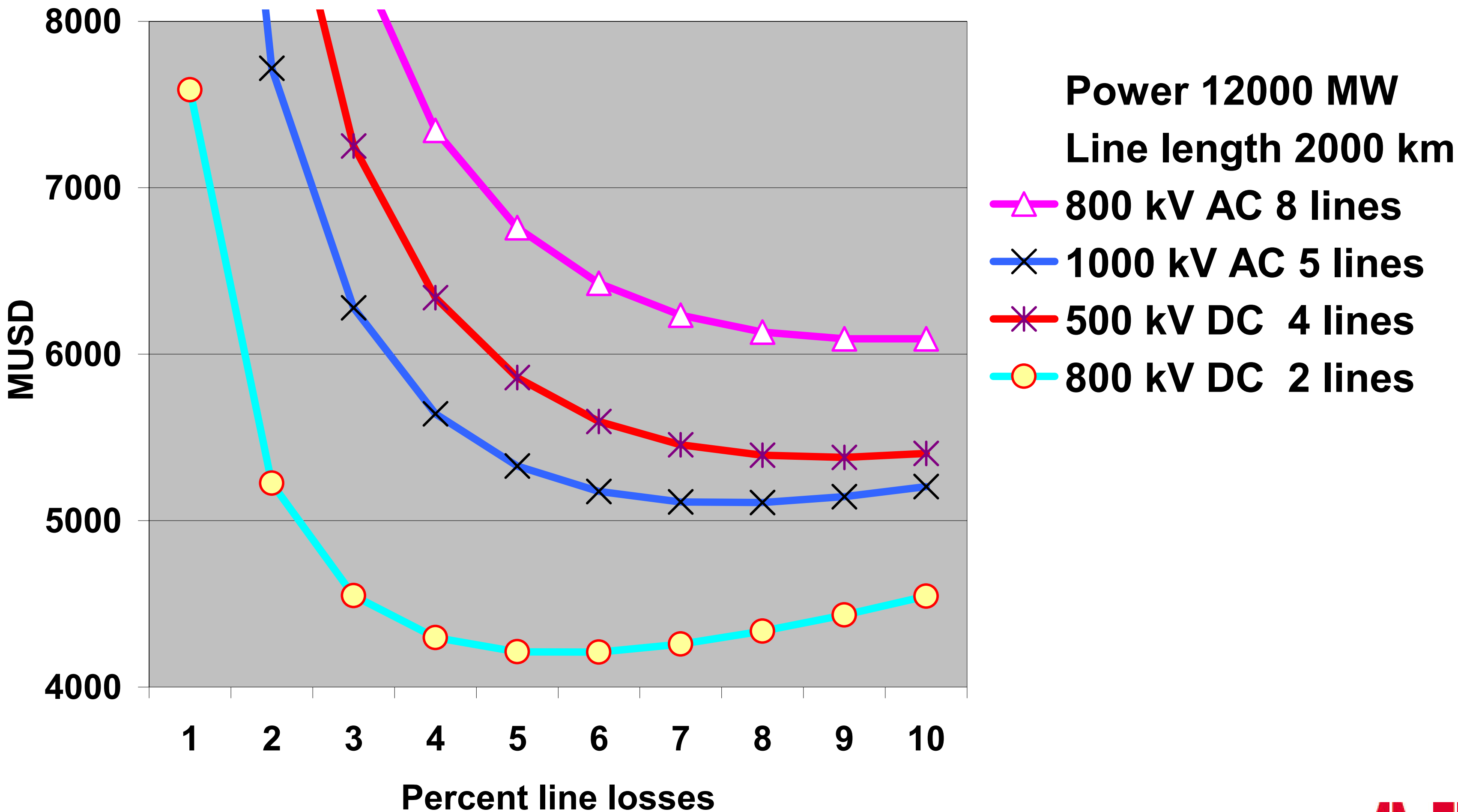
HVDC Light Plant Layout, ±150 kV, 175- 555 MW



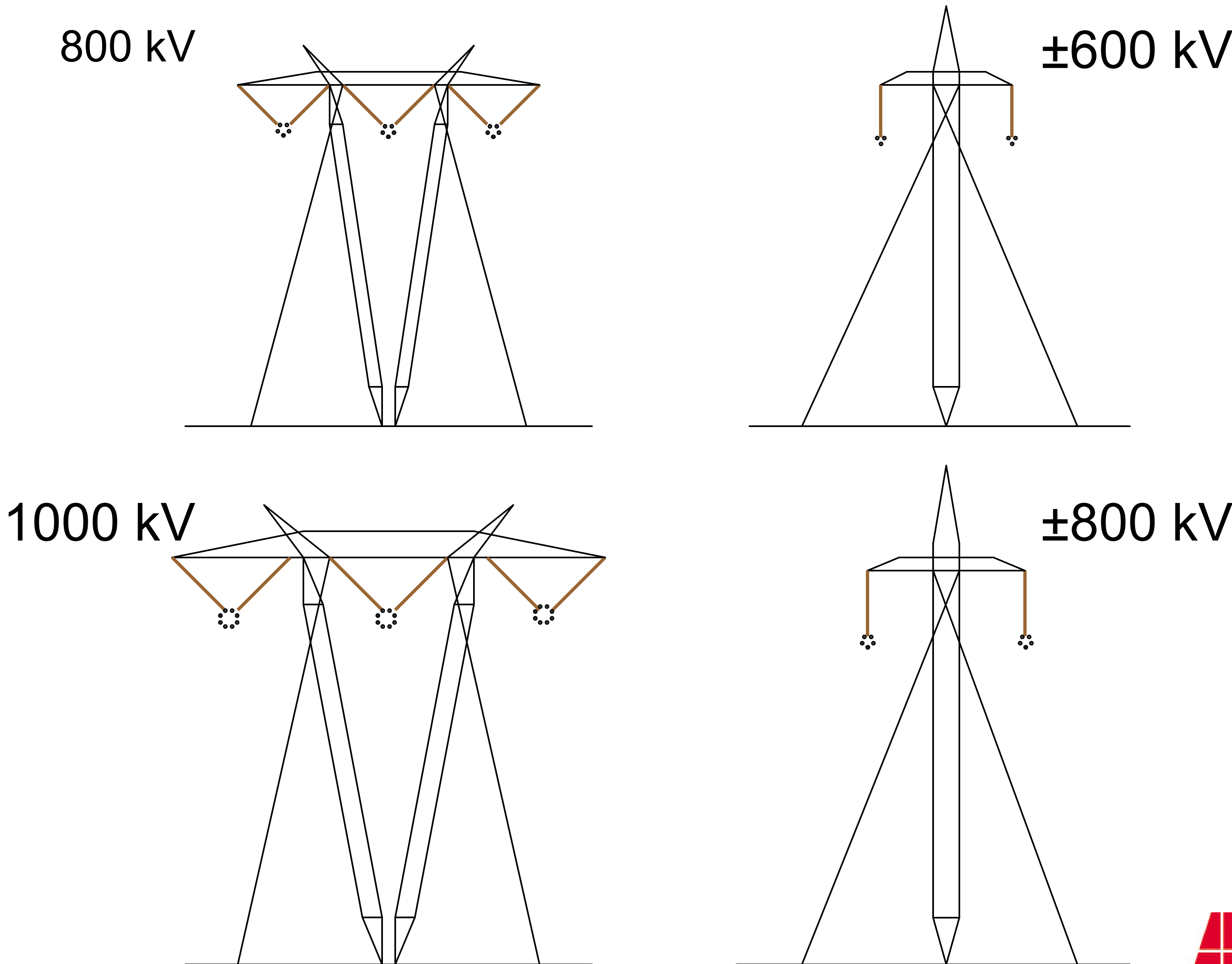
Cost Comparison of Transmission Alternatives

Alternative			500 kV AC Two Single Circuits	± 500 kV HVDC Bipole	± 600 kV HVDC Bipole	± 800 kV HVDC Bipole	500 kV AC Double Circuit	765 kV AC Single Circuit
Capital Cost								
Line voltage (kV)			525	500	600	800	525	765
Rated Power (MW)			3000	3000	3000	3000	3000	3000
No. of ac line segments			6				6	3
No. of series capacitors per line segment			2				2	0
Total No. Series Capacitors			12				12	0
Total No. AC or DC Substations			4	2	2	2	4	4
No. Shunt Reactors per ac line segment			2				2	4
Total No. Shunt Reactors			12				12	12
Total No. Transformers			2				2	4
No. of SVC's			3	2	2	2	3	3
No. Shunt Capacitors			0				0	0
HVDC stations & AC substations incl reactive comp			$366,000,000	$560,000,000	$600,000,000	$625,000,000	$366,000,000	$404,000,000
Transmission Line (cost/mile)			$1,700,000	$1,400,000	$1,456,000	$1,582,000	$2,720,000	$3,600,000
Transmission Line R/W (cost/mile)			$500,000	$300,000	$400,000	$500,000	$500,000	$900,000
Total line distance in miles			1,500	750	750	750	750	750
Transmission Line Cost			$3,300,000,000	$1,275,000,000	$1,392,000,000	$1,561,500,000	$2,415,000,000	$3,375,000,000
Total Transmission Cost + 10% contingency			**$4,032,600,000**	**$2,018,500,000**	**$2,191,200,000**	**$2,405,150,000**	**$3,059,100,000**	**$4,156,900,000**
Annual Payment, 30 years @ rate of		10%	$427,775,177	$214,120,963	$232,440,849	$255,136,504	$324,507,028	$440,960,827
Cost per kW-Yr			$142.59	$71.37	$77.48	$85.05	$108.17	$146.99
Cost per MWh @ Utilization Factor of		65%	$25.04	$12.53	$13.61	$14.94	$19.00	$25.81
No of conductors/pole/phase			2	3	3	3	2	2
Conductor (ohms/mile) ac or dc @ temp of:		50	0.0420	0.0364	0.0364	0.0364	0.0420	0.0420
Line/Pole Current (Amps)			1755	3000	2500	1875	1755	1204
Conductor current density (A/mm^2)			0.610	0.695	0.579	0.435	0.610	0.419
Losses @ full load			291	209	159	109	291	137
Losses at full load in %			9.69%	6.96%	5.29%	3.63%	9.69%	4.56%
Cost of losses @ UF & $/kW of:	65%	$1,500	$283,503,864	$203,705,153	$154,868,162	$106,308,654	$283,503,864	$133,522,581

Cost of transmitting 12000 MW 2000 km



Comparison of overall line design



Itaipu 600 kV HVDC Line Performance

	Bipole 1						Bipole 2					
	P1 -			P2 +			P3 -			P4 +		
	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm	Trans	Red.V	Perm
1993	0	1	0	8	1	2	2	0	3	2	0	0
1994	3	0	3	3	0	1	1	2	3	3	0	1
1995	4	0	0	3	0	1	0	0	0	3	1	0
1996	3	0	0	5	0	0	0	0	0	5	0	0
1997	5	2	5	0	0	1	0	0	1*	2	0	1*
1998	2	1	0	4	2	2	0	0	1*	1	0	1*
1999	2	0	0	3	0	0	2	0	1	2	0	1
2000	5	0	1	7	0	1	2	0	0	3	0	0
8 year	24	4	9	33	3	8	7	2	7	21	1	2
Ave.	3	0,5	1,13	4,13	0,38	1	0,88	0,25	0,88	2,63	0,13	0,25

Trans = 0,659 pole faults / 100km / year
RedV = 0,078 pole faults / 100km / year
Perm = 0,202 pole faults / 100km / year

*Line Tower Failures total two events

Isokeraunic Level 90 (Foz) to 50 (SP)

Trans = Successful restart at full voltage
RedV = Successful restart at reduced voltage (450 kV)
Perm = Permanent, excluding tower failures

Itaipu 765 kV AC Line Performance

	765 kVac Transmission Lines								
	Line 1			Line 2			Line 3		
	Trans	Perm	Length	Trans	Perm	Length	Trans	Perm	Length
1995	0	4	891	1	11	891	-	-	0
1996	1	13	891	0	7	891	-	-	0
1997	0	6	891	2	13	891	-	-	0
1998	0	10	891	2	16	891	-	-	0
1999	1	27	891	1	10	891	-	-	0
2000	3	15	891	3	14	891	2	9	602
2001	2	4	891	4	8	891	2	5	915
2002	4	12	891	1	7	891	4	16	915
8 year	11	91	7128	14	86	7128	8	30	2432

Trans = 0,198 faults / 100km / year
Perm = 1,240 faults / 100km / year

Trans = Successful reclose, one attempt
Perm = Permanent, excluding tower failures

Isokeraunic Level 90 (Foz) to 50 (SP)

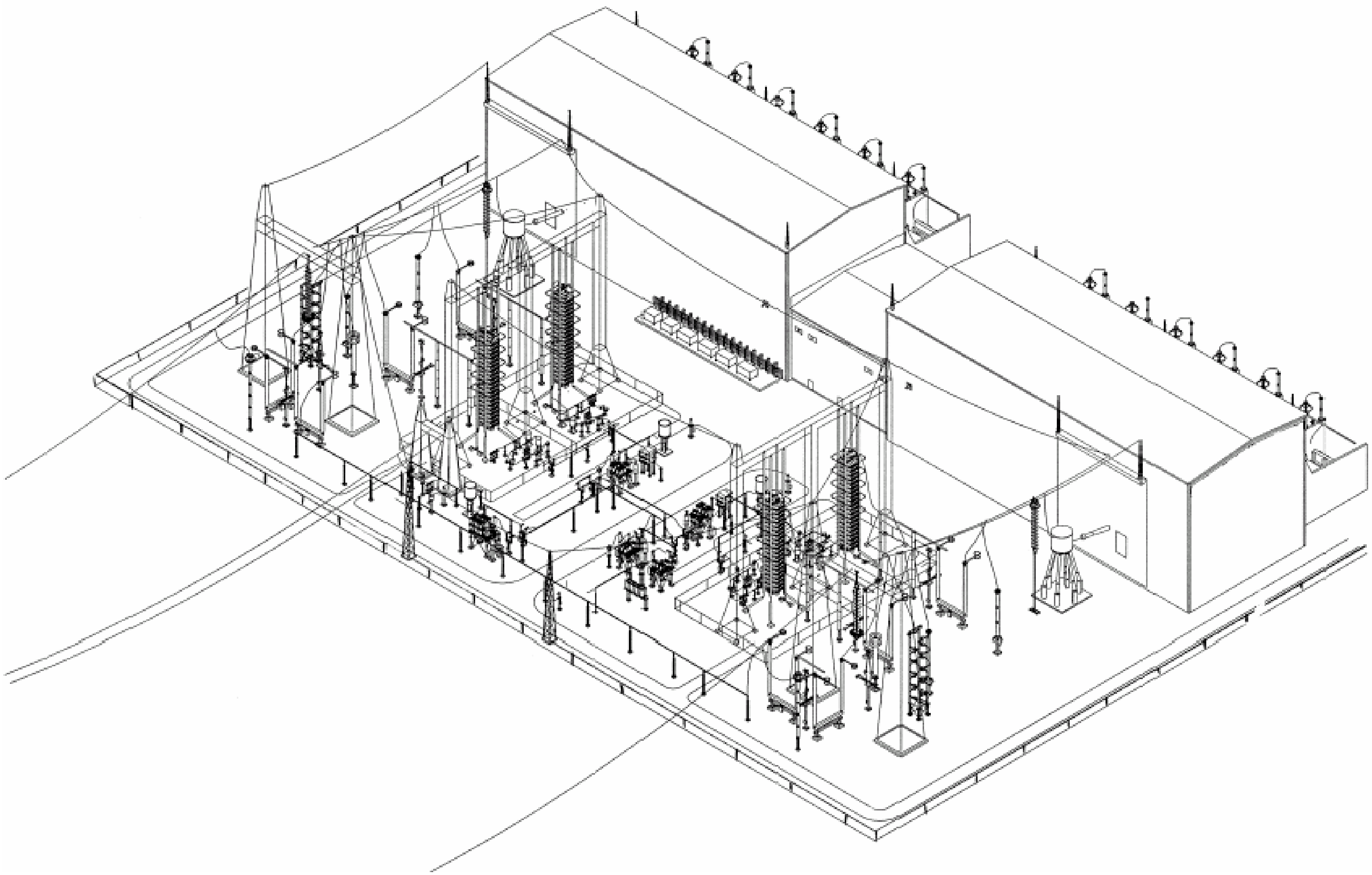
Tower Failures due to wind:

1994 3 both circuits*
1997 2 both circuits*
1998 2 both circuits*
*total of 3 events

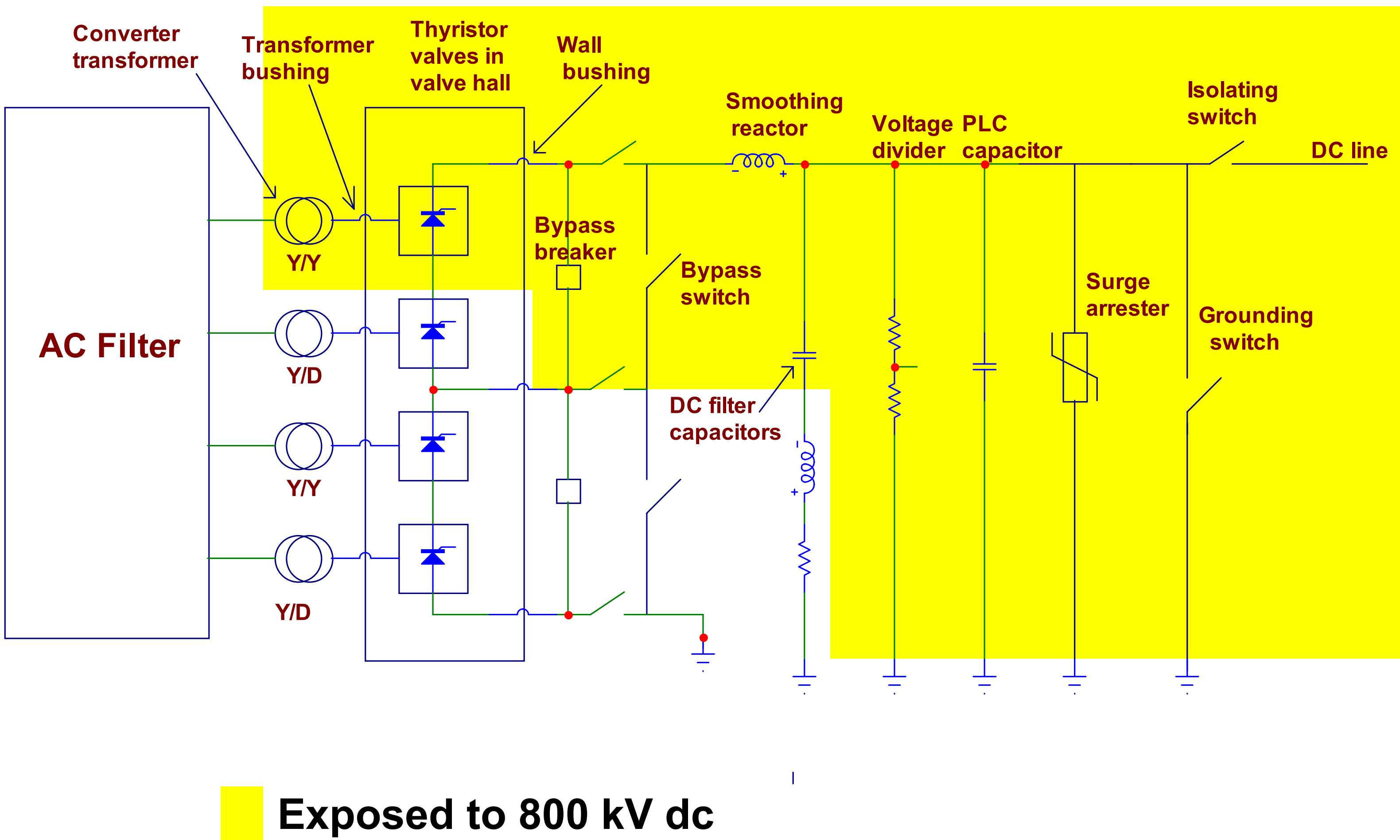
Three Gorges China 3000 MW

The thyristor valve hall

±800 kV, 3600 MW Converter Station



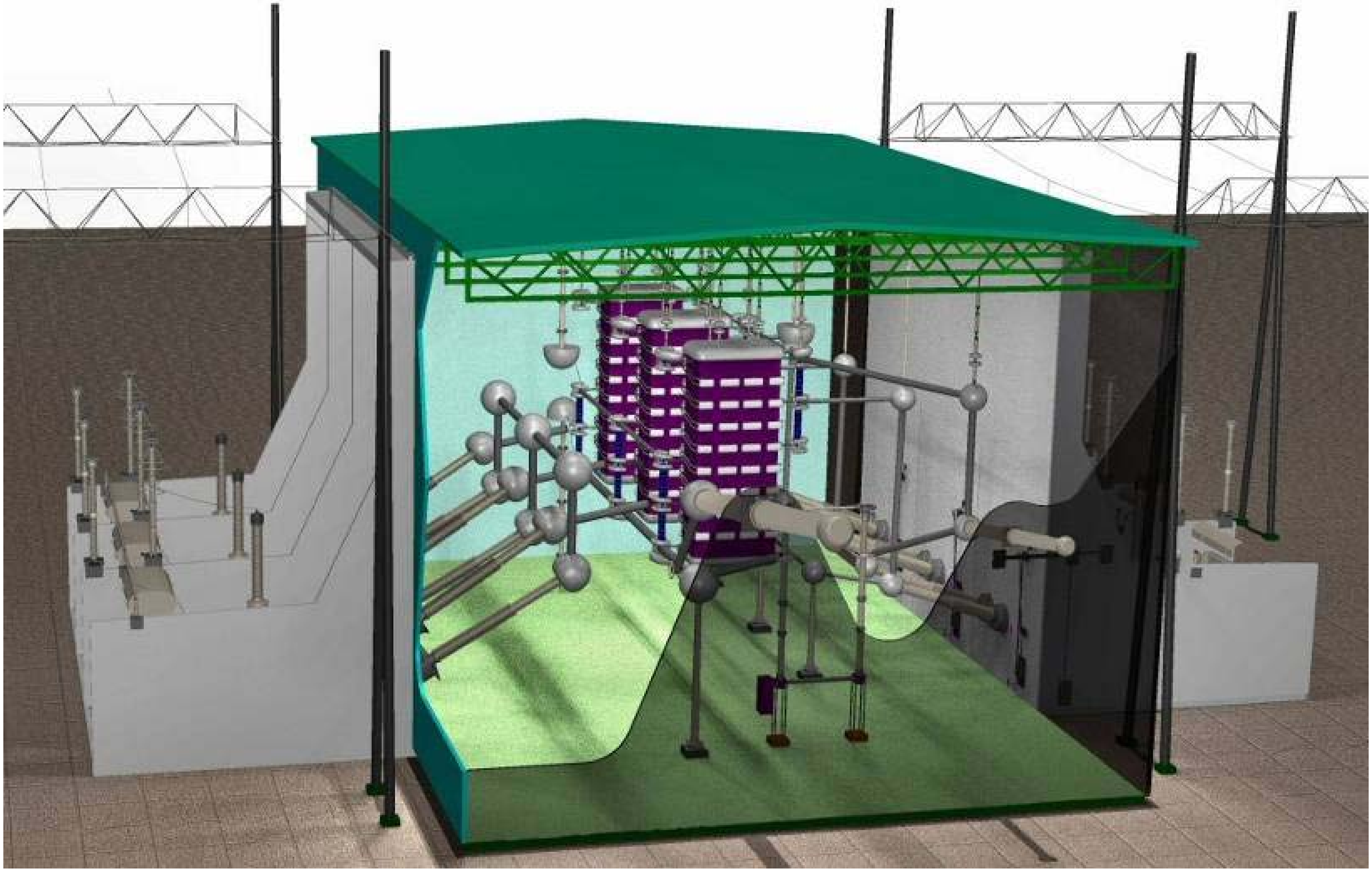
800 kV HVDC- one pole



Long term test circuit for 800 kV HVDC

Testing for valve hall clearances

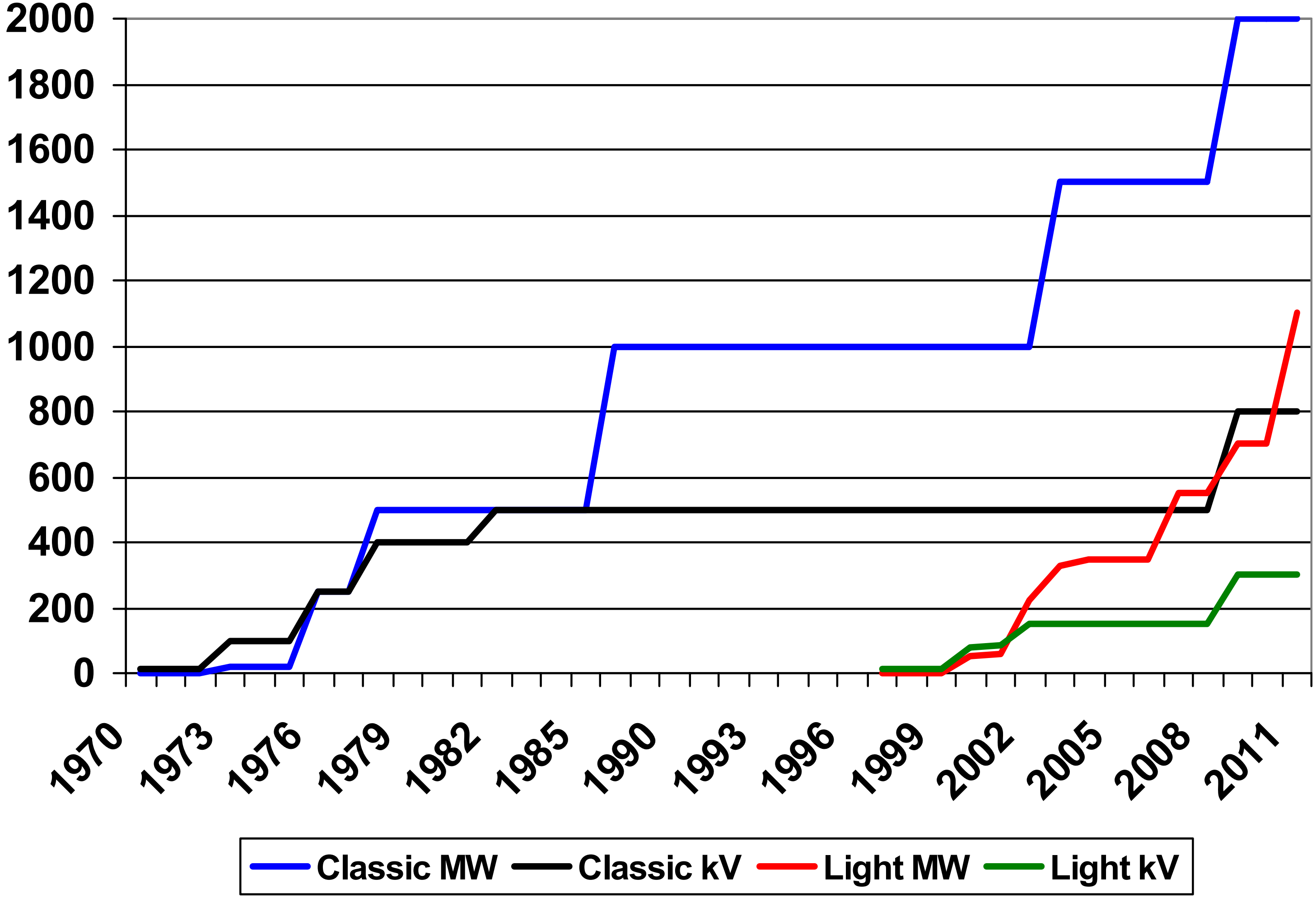
Valve Hall 800 KV HVDC



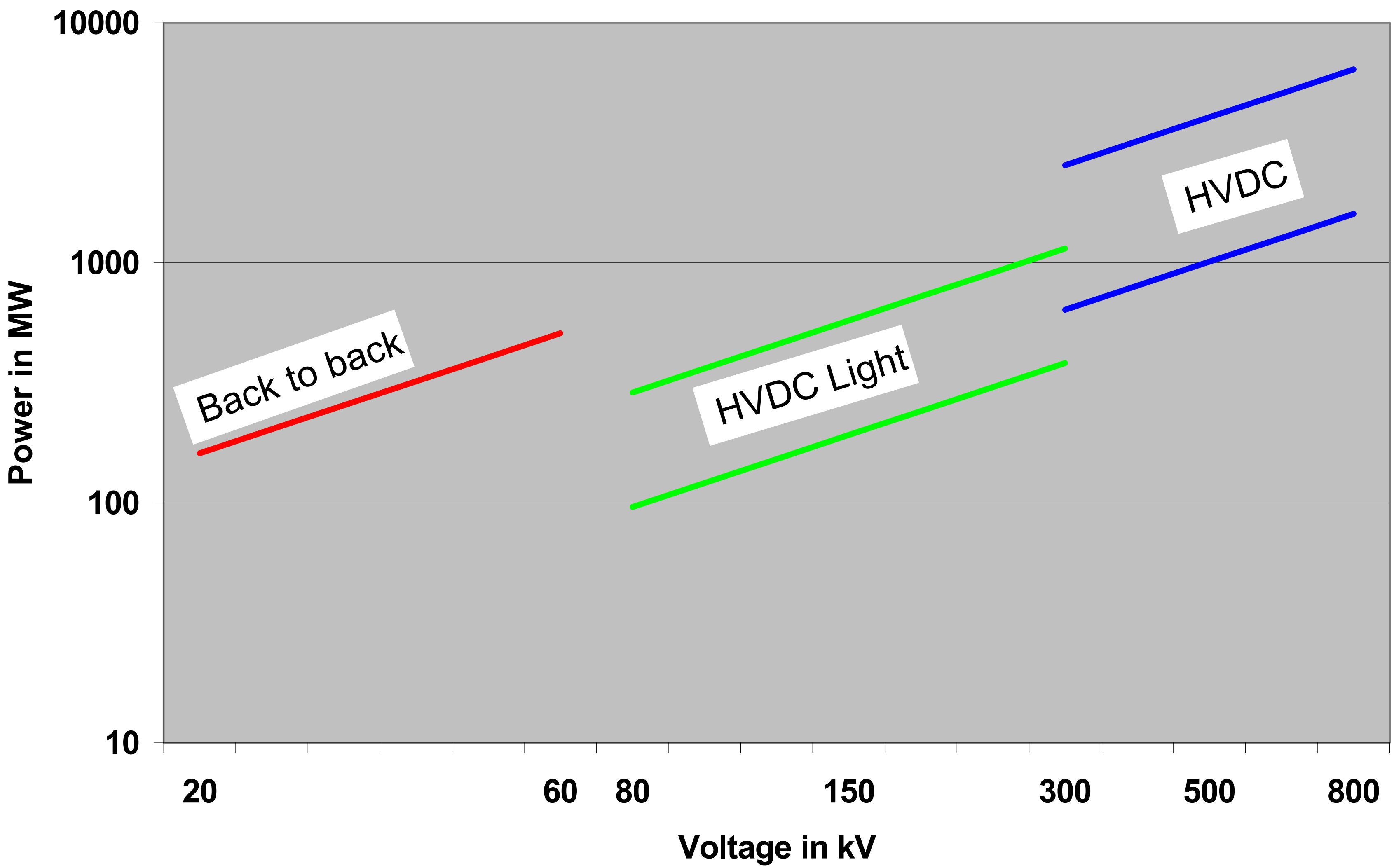
HVDC Light rating increase to 1100 MW

- Elements common to existing systems
  - IGBT chip
  - IGBT submodule
  - IGBT StakPak
  - IGBT module or stack
  - Control system
  - Cooling system
  - DC capacitor
- Increased dc current – six submodules per StakPak rather than four
- Increased dc voltage (150 kV to 320 kV)
  - Valve stacks comprised of IGBT modules with 26 positions arranged horizontally
  - Modules connected in series at site to reach rated voltage – elimination of valve enclosures used for the lower voltages
  - DC voltage still lower than that commonly used for conventional HVDC
- Higher ac voltage on ac filter bus – 400 kV
- Development parallels that for conventional HVDC thyristor valves
- Cable and cable accessories type tested to 320 kV, accelerated life tests to be completed this year

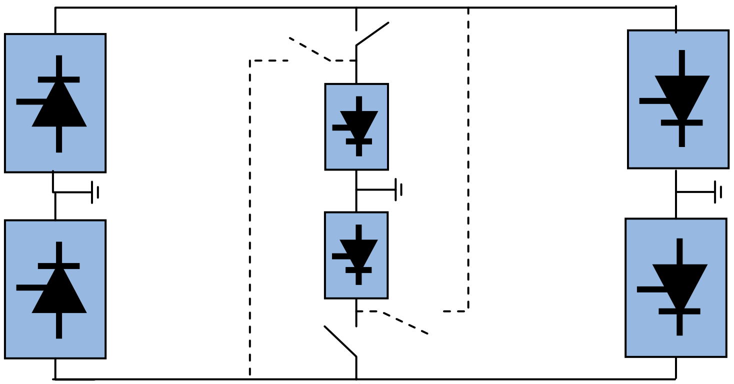
HVDC Converter Development



Power Ranges HVDC-Classic and HVDC-Light

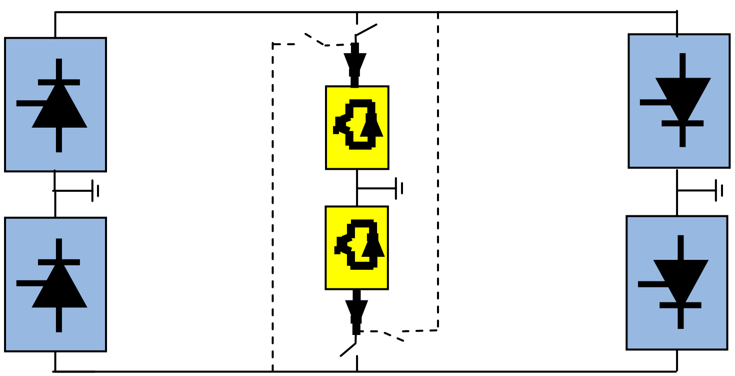


Tapping OVHD HVDC with Large VSC Converters



HVDC Tap

- Reverse power by polarity reversal
- Electronic clearing of dc line faults
- Fast isolation of faulty converters
- Reactive power constraints
- Momentary interruption due to CF at tap
- Limitations on tap rating, location and recovery rate due to stability



HVDC Light Tap

- Polarity reversal if main link is bidirectional
- Cannot extinguish dc line fault current contribution without special provision, e.g., diode coupling for inverter
- No interruption to main power transfer due to CF at tap
- Less limitations on tap rating and location
- Cascade VSC connection for lower tap rating
- No reactive power constraints
- Improved voltage stability

ABB

Offshore Applications of HVDC Light

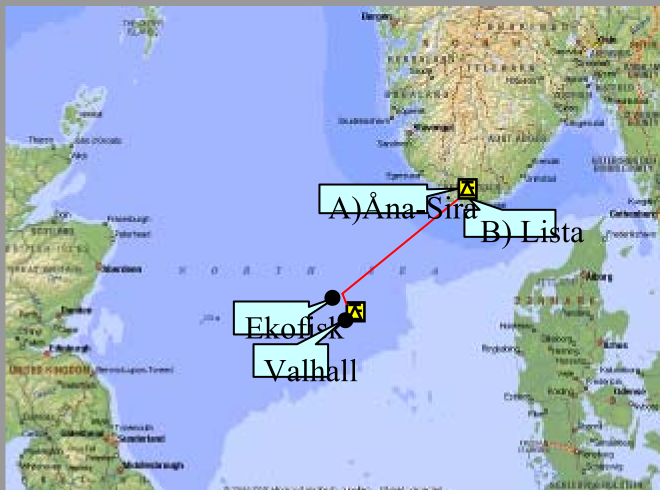
Offshore Wind Farms

- Long cable transmission to shore
- Voltage regulation
- Wind generator excitation power
- Black start

Oil and Gas Production

- Long cable transmission from shore
- Feed platform load
- Variable speed compressor drives
- Voltage regulation
- Reduced weight and volume
- Reduced emissions
- Greater efficiency
- Troll – no outages since 2005!

Valhall, BP



Nyckeldata

- Valhall är BP:s största plattform I Nordsjön
- Under byggnad
- HVDC Light-systemen ska sköta all kraftmatning till plattformen
- Ger betydande miljöfördelar och minskar behovet av personal på plattformen
- 1 x 78 MW, 290 km sjökabel
- Troll: I drift sedan 2005, inga fel!

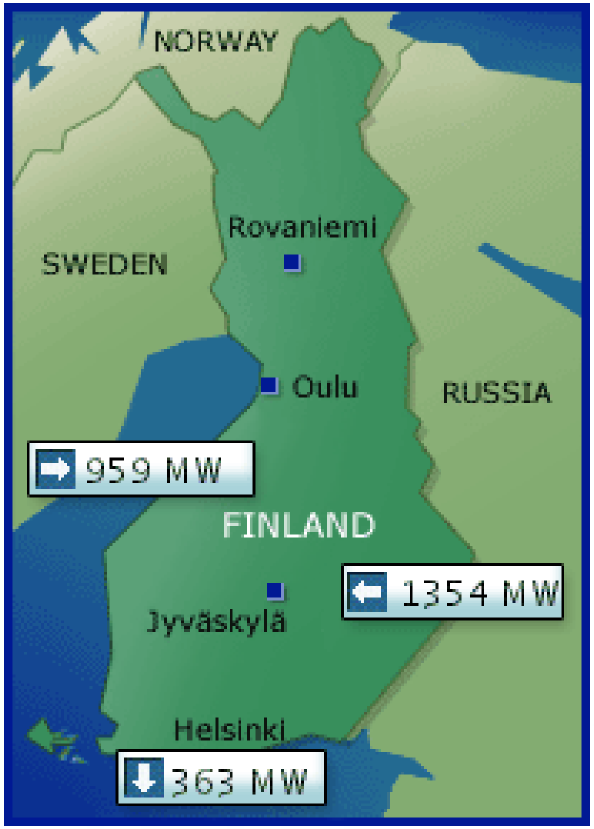
Estlink – HVDC Light between Estonia & Finland

Client:	Nordic Energy Link, Estonia
Contract signed:	April 2005
In service:	November 2006
Project duration:	19 months
Capacity:	350 MW, 365 MW low ambient
AC voltage:	330 kV at Harku
	400 kV at Espoo
DC voltage:	±150 kV
DC cable length:	2 x 105 km (31 km land)
Converters:	2 level, OPWM
Special features:	Black start Estonia, no diesel
Rationale:	Electricity trade
	Asynchronous Tie
	Long cable crossing
	Dynamic voltage support
	Black start

ABB

Estlink – full power after 19 months

Last updated: 29 Nov 2006 15:18



Consumption and production in Finland

Consumption	11433 MW
Production	9483 MW
– hydro power	1484 MW
– nuclear power	2715 MW
– condensing power	881 MW
– district heat back pressure	2391 MW
– industry back pressure	1949 MW
– other production (estimate)	63 MW
Net import/export	1950 MW

Electricity price in Finland

Elspot price area Finland	41.65 e/MWh

Power balance

Production deficit/surplus in Finland	-393 MW
Surplus/deficit, cumulative	-90 MWh
Instantaneous freq. measurement	49.98 Hz
Time deviation	6.93 s

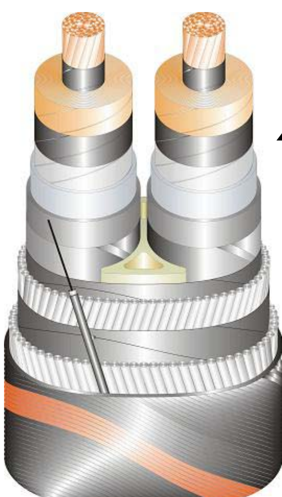
Temperatures in Finland: Helsinki +6°C, Jyväskylä +7°C, Oulu +6°C, Rovaniemi +4°C

NorNed Cable HVDC Project

The longest underwater high-voltage cable in the world.

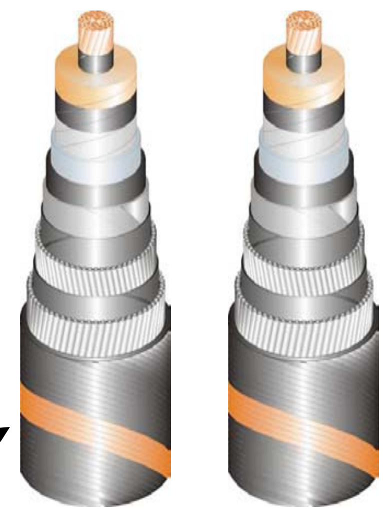
Clients: Statnett and TenneT

Transmission capacity:	700 MW
DC Voltage:	± 450 kV
Length of DC cable:	2*580 km
Water depths:	Up to 410 m
Project start:	January 2005
Completion time:	Approx. three years

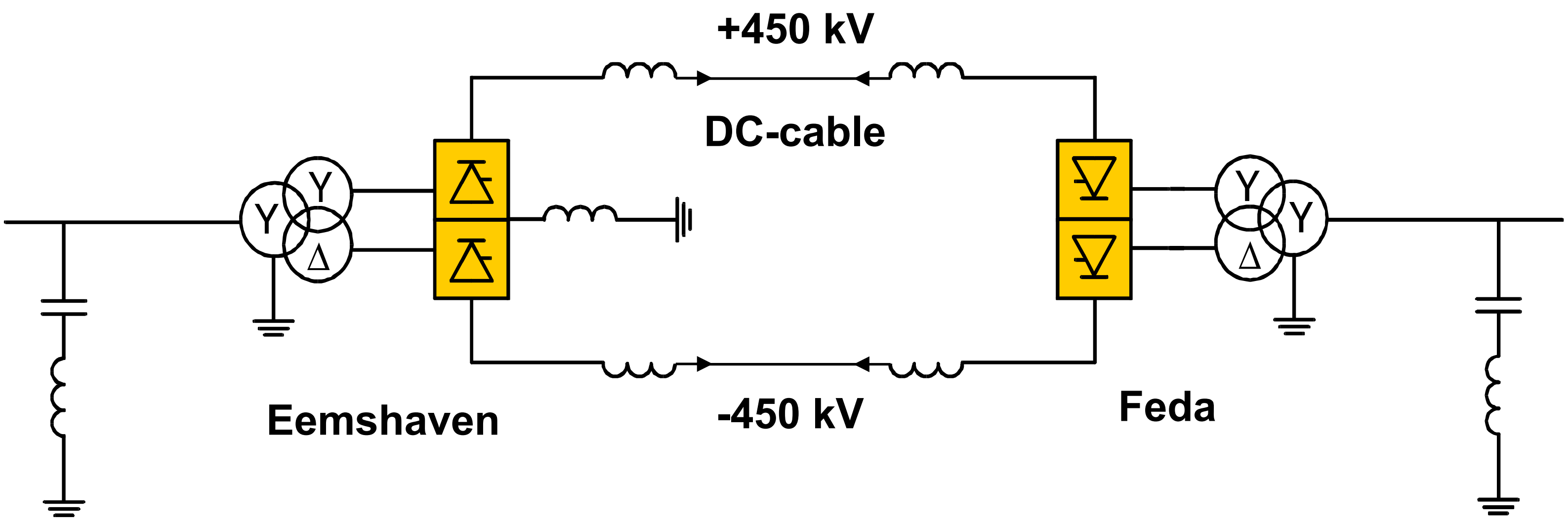


Flat Mass-Impregnated submarine cable
Copper profile wires, 790 mm^2

Mass Impregnated submarine cables
Copper profile wires, 700 mm^2



NorNed Cable HVDC Project *Symetric monopole*



- Rating 600 MW ± 450 kV
- Low losses 3.7 %
- Continuous 700 MW
- Cable length 580 km
- No sea electrode

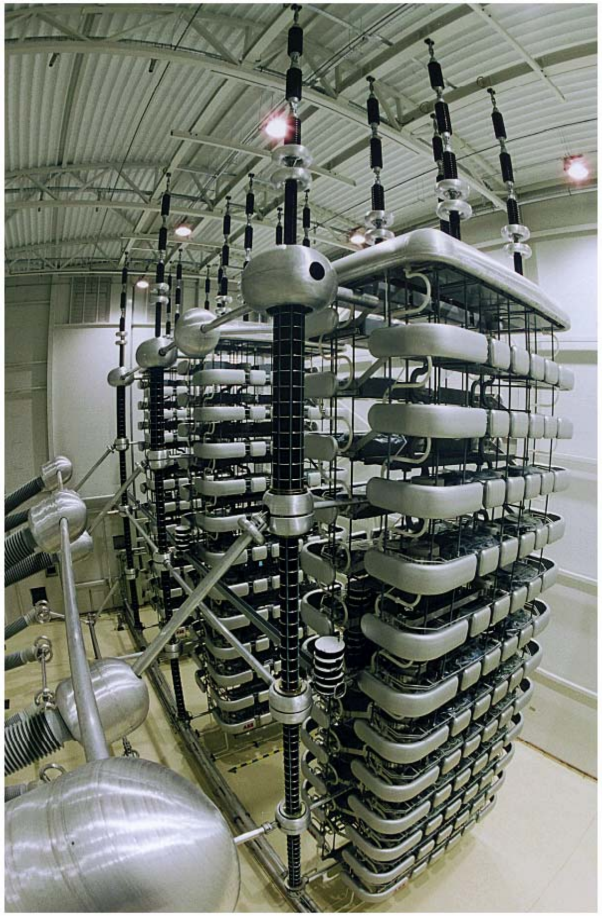
ABB

NorNed Cable HVDC Project

Converter valves ± 450 kV, 700 MW

120 thyristors per single valve

Totally 2880 thyristors



NorNed kabel HVDC Project

FMI Cable, 2 x 790 mm^2

+/- 450 kV, 700 MW

20 mm insulation

90 kilo/meter

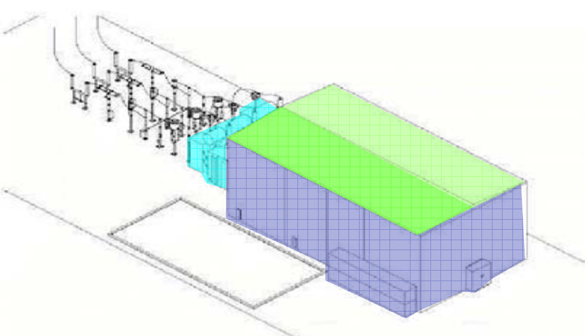
70 km/loading

8 joints 7-10 days/joint

24 hours/day production

2 months after order

Southlink, Swedish National Grid Company



Customer need

- Improved security of the electricity supply in South and Central Sweden
- Distance 250 miles

Alternatives

- 400 kV overhead transmission line
- Turnkey 500 – 700 MW ±300 kV underground HVDC Light system

Customer benefits with HVDC

- Shorter project time due to easier permitting (2 – 3 years)
- Increased power transfer existing a.c. lines (approx 200 MW)
- Voltage and reactive power control

Project status

- Final evaluation ongoing. Decision 2007

ABB