HVDC Transmission Systems

Past - Present - Future

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Valve hall at Longquan.

Acknowledgement

Photos and material: Courtesy of ABB and Siemens; Manitoba Hydro; Hydro-Quebec

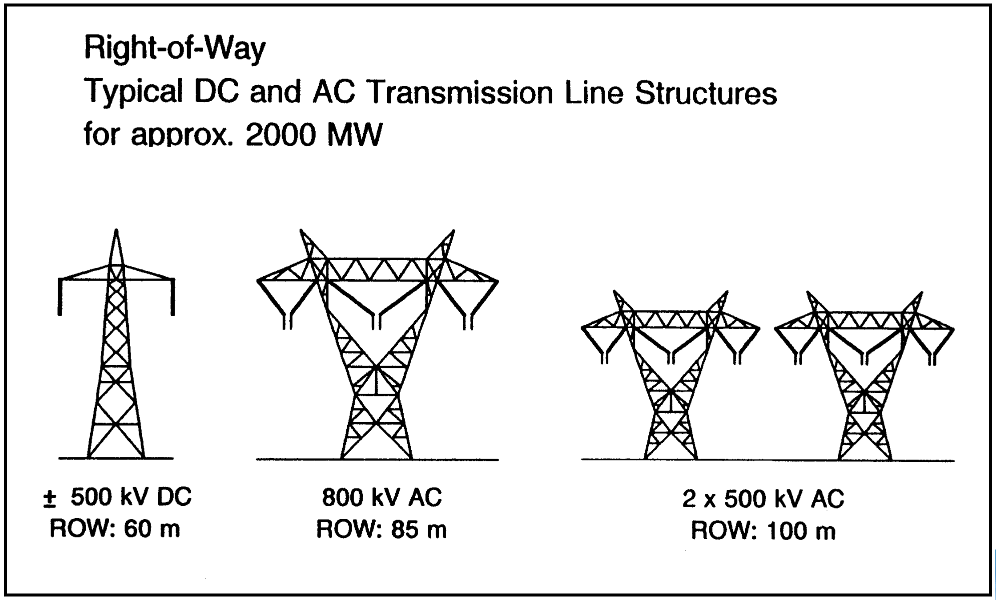
Outline of Presentation

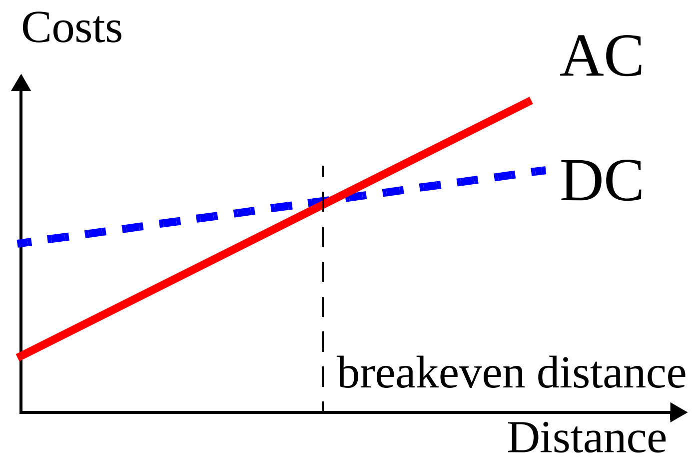
- Primer on HVDC Transmission
- Mercury-Arc Era - 1950-1975
- Thyristor Era - 1975+
- Transistor Era - 1995+
- Future Directions

Primer on HVDC Transmission

- In under-sea cable interconnections of Gotland (1954) and Sardinia (1967),
- In long distance transmission with the Pacific Intertie (1970) and Nelson River (1973) schemes using mercury-arc valves.
- In 1972 with the first Back to Back (BB) asynchronous interconnection at Eel River between Quebec and N. Brunswick; this installation also marked the introduction of thyristor valves to the technology and replaced the earlier mercury-arc valves.
- Traditional Current Source Converters with line commutation uptil 1990s
- Voltage Source Converters with forced commutation after about 1995
- Rapid growth of DC transmission in the past 50 years, it is first necessary to compare it to conventional AC transmission.

Comparison of AC-DC transmission





Evaluation of transmission costs

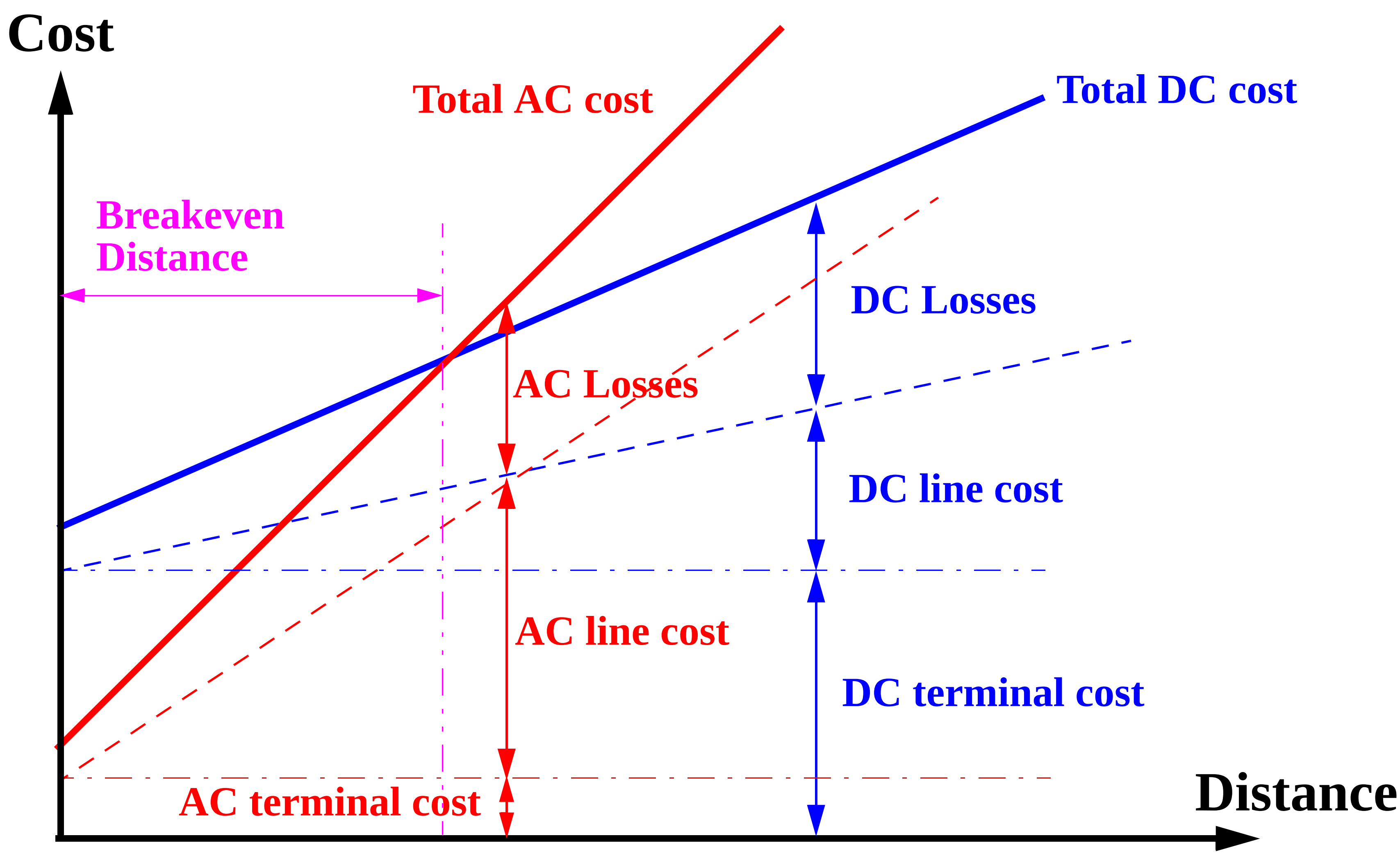
- Right of Way (ROW)
- 2 conductors v. 3 conductors

Comparison of AC-DC transmission

Evaluation of Technical Considerations:

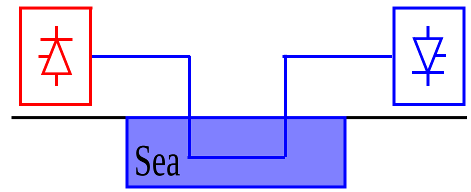
- Stability limits
- Voltage Control
- Line Compensation
- Problems of AC interconnection
- Ground Impedance
- Problems of DC transmission
- Evaluation of reliability and availability costs

Comparison of AC-DC transmission

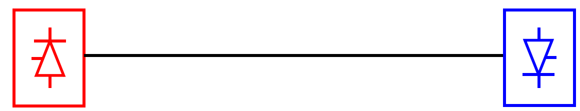


Applications of DC transmission

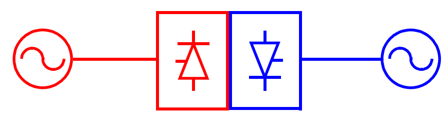
- Systems using underground or undersea cables



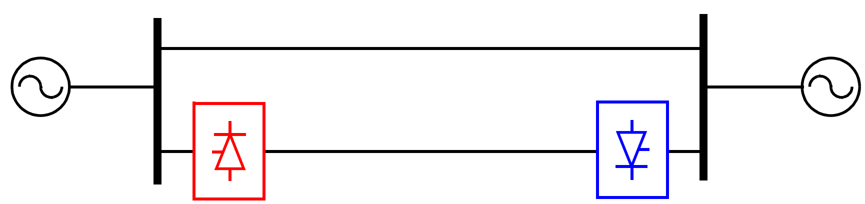
- Long distance bulk-power transmission system



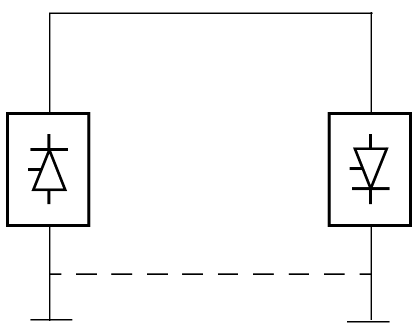
- Asynchronous BB interconnection of AC systems



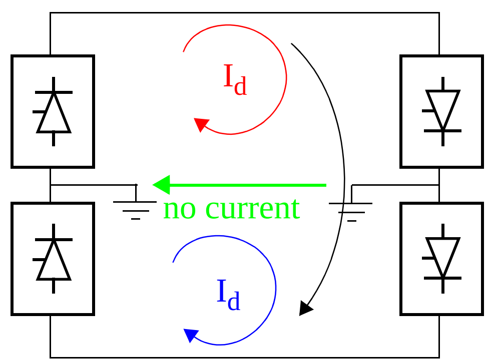
- Stabilization of power flows in an integrated power system



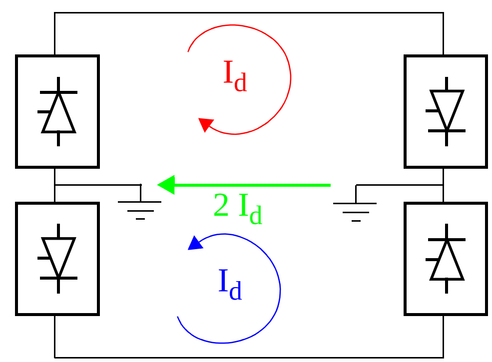
Types of HVDC systems



(a) Monopolar link

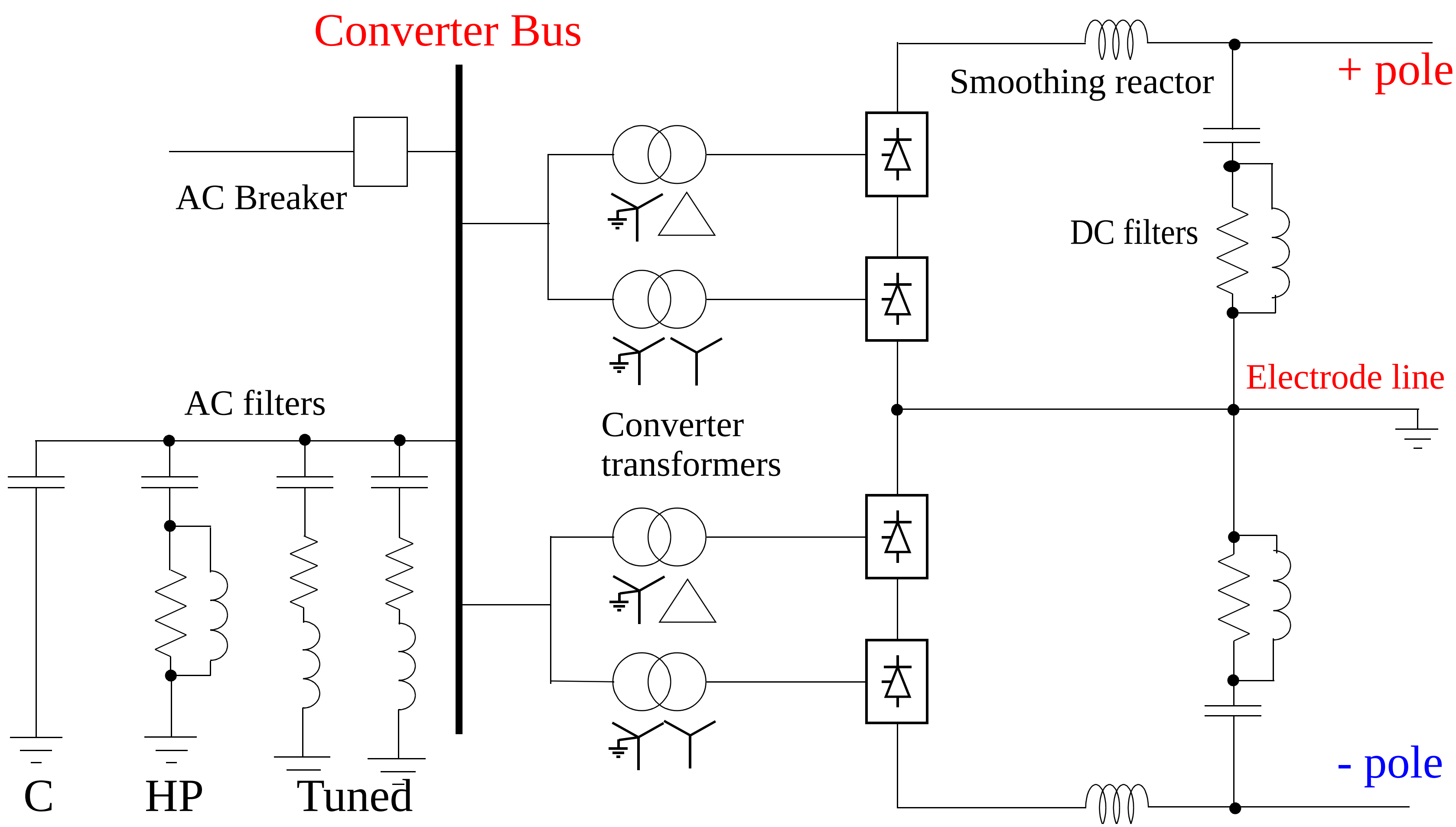


(b) Bipolar link

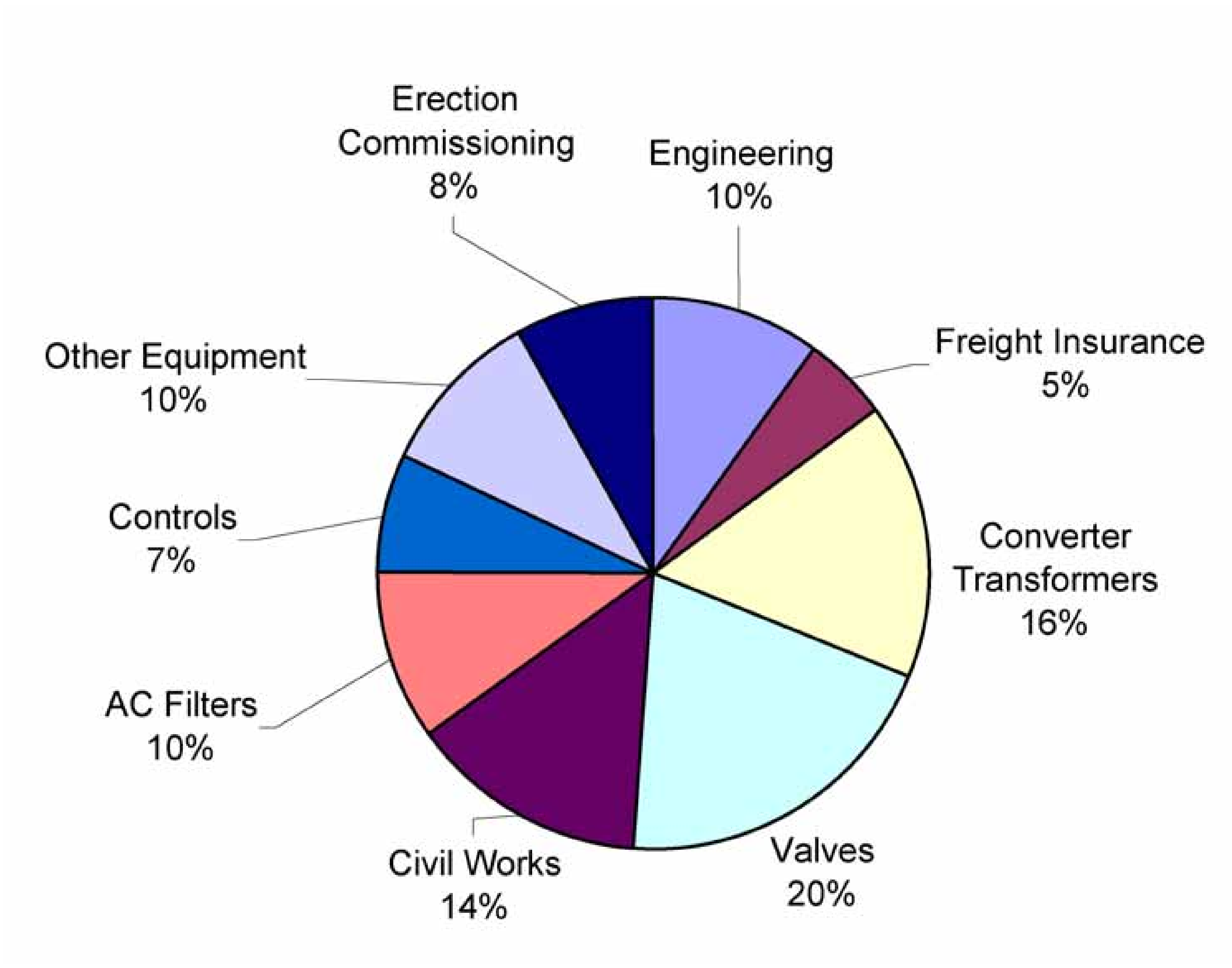


(c) Homopolar Link

Main components of HVDC station



HVDC Station Cost Breakdown



Reliability figures for 3GC Scheme in China

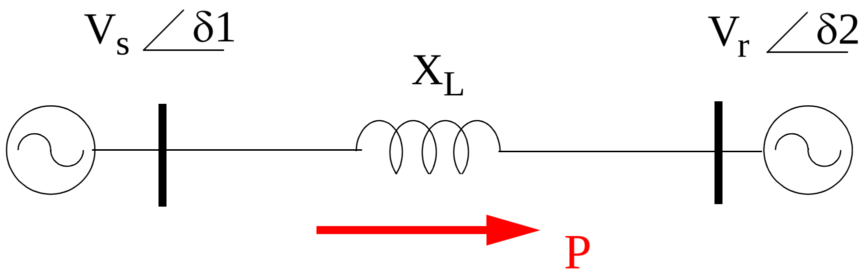
Equipment failure rates for 3GC and 3GG Schemes in China

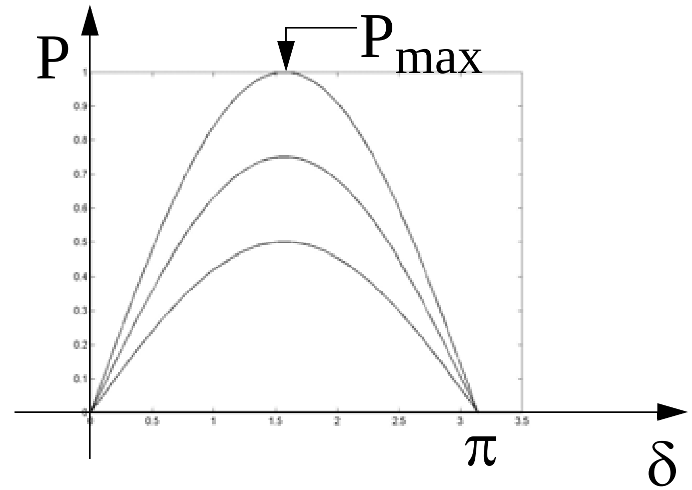
Equipment	Annual Failure Rate
Thyristors	0.2%
AC-DC Filter Capacitors	0.2%
Circuit Boards, per pole and station	4

Reliability and availability targets for 3GC

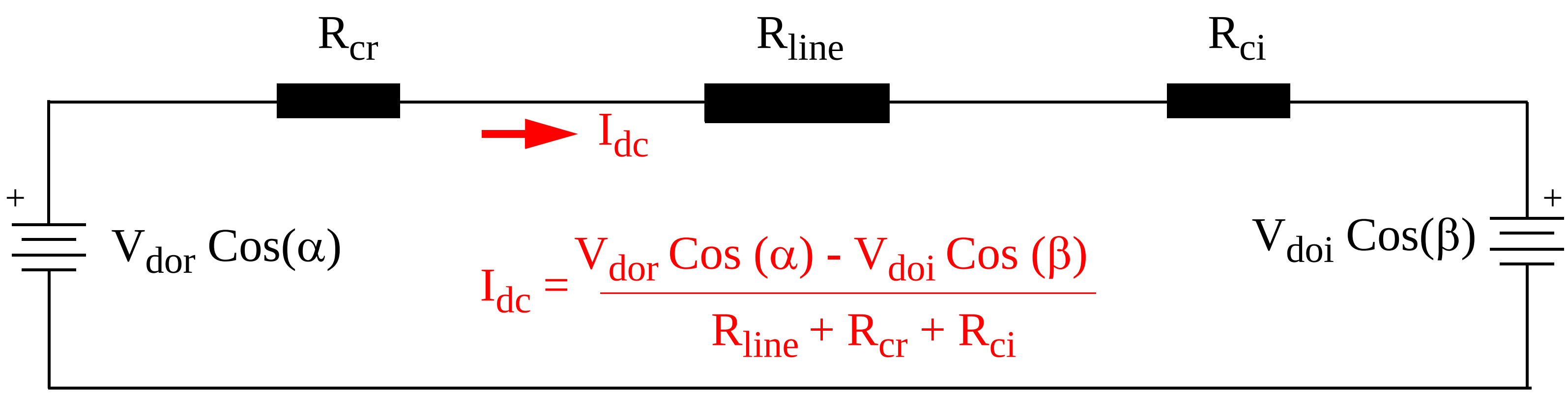
Index/Parameter	Target Value
Forced Energy Unavailability (FEU)	0.5 % or less
Schedule Energy Unavailability (SEU)	1.0 % or less
Single Pole Forced Outage Rate	6 per year or less
Bipole Forced Outage Rate	0.1 per year or less

Control Techniques: AC vs. DC Transmission





$$P = (V_s . V_r / X_L). \text{Sin} (\delta_1 - \delta_2)$$



$$I_{dc} = \frac{V_{dor} \text{Cos} (\alpha) - V_{doi} \text{Cos} (\beta)}{R_{line} + R_{cr} + R_{ci}}$$

HVDC Milestones

- Hewitt's mercury-vapour rectifier, which appeared in 1901.
- Experiments with thyratrons in USA and mercury arc valves in Europe before 1940.
- First commercial HVDC transmission, Gotland 1 in Sweden in 1954.
- First solid-state semiconductor valves in 1970.
- First microcomputer based control equipment for HVDC in 1979.
- Highest DC transmission voltage (+/- 600 kV) in Itaipú, Brazil, 1984.
- First active DC filters for outstanding filtering performance in 1994.
- First Capacitor Commutated Converter (CCC) in Argentina-Brazil interconnection, 1998
- First VSC for transmission in Gotland, Sweden,1999

Mercury arc era

Thyristor Era

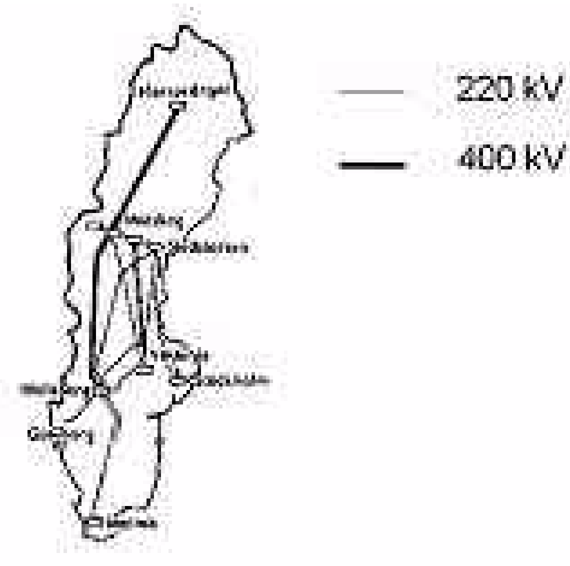
Transistor (Other)

Mercury Arc Era

1950-1975

- Sweden in the 1950's was fertile ground for transmission development. Electric energy consumption doubled each decade, with major hydro reserves in the north, some 1000 kms from load centers in the south.

- The choice was between going from 230 to 400 kV AC or introduce a completely new technology, High Voltage Direct Current, HVDC. When the decision had to be made in the late forties the HVDC alternative was not yet ripe for such a major backbone transmission case.



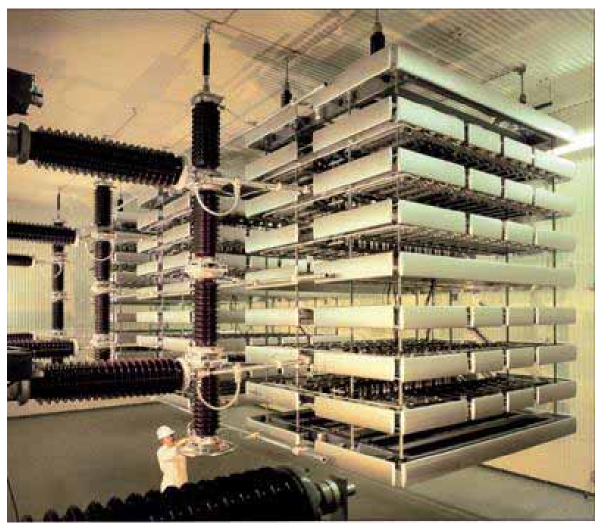
- Thus, in 1952 the World's first 400 kV AC transmission was commissioned.

- Gotland was the only part of Sweden, which completely lacked hydro resources, and it was too far out in the Baltic Sea to have an AC connection to the Swedish mainland. The island was supplied by a single steam power plant and the electricity rates were considerably higher than on the mainland.

- But even for this size, some 20 MW, major development was required, i.e. on system layout and design, a high-voltage converter valve, other main circuit components, control systems and a 100 kV submarine cable.

- In 1954, the first commercial HVDC plant was commissioned in Gotland

1954 Stage I: 20 MW, 100 kV



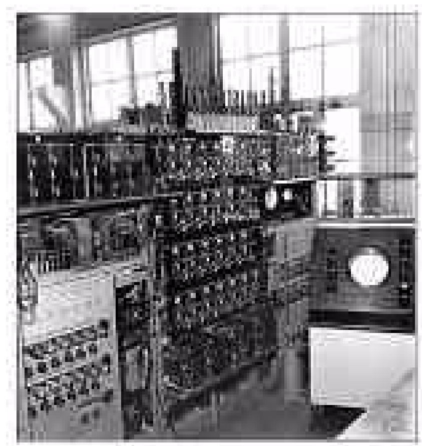
- In 1929, ASEA in Ludvika, Sweden decided to manufacture mercury arc rectifier valves, a product used by many industrial customers.

- The first valve did not work properly - it suffered so-called arc-backs - and a young engineer fresh from university and military service, **Uno Lamm**, was asked to study it. This proved to be his fate. When he retired in 1969, the problem was still not completely solved but in the process Lamm had become "the Father of HVDC".

- And what about the arc-backs? Well, it proved possible to reduce the frequency drastically and design the system so it could live with an occasional arc-back. From the very beginning it was obvious that high voltage was a major challenge.

- ASEA fairly soon could market rectifiers for industrial plants,i.e for a few kV, but not for transmission over any appreciable distance.

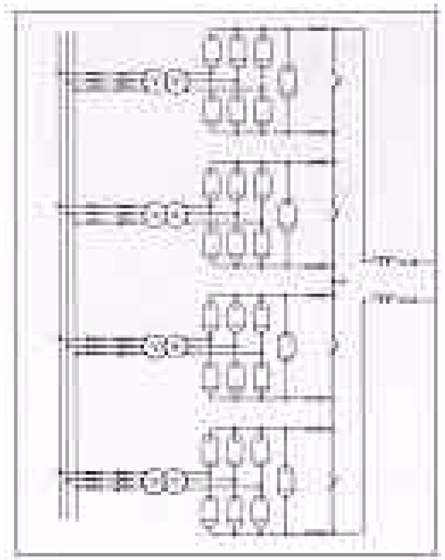
Dr. Uno Lamm



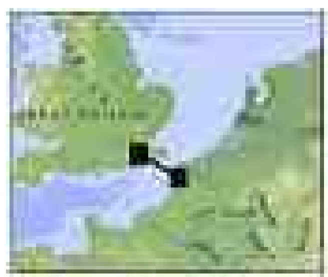
The first DC Simulator in Ludvika.

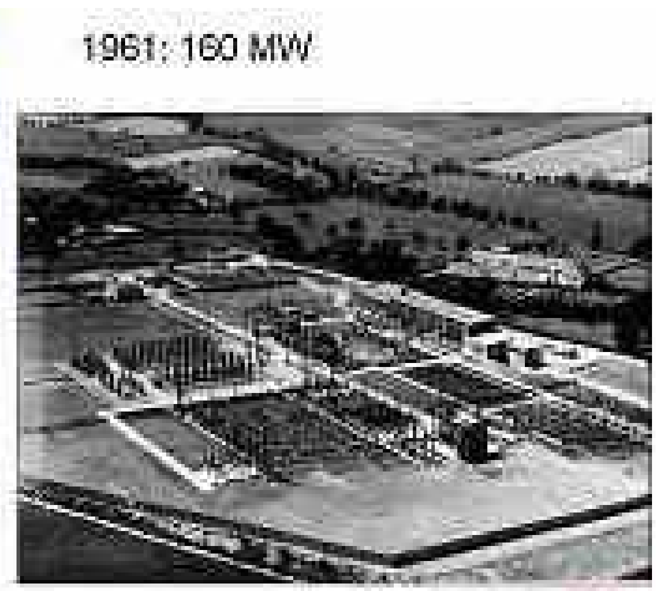
- Back to Uno Lamm: He had seen the problem and already in 1929 got a patent on a “device to prohibit arc-backs in metal vapor rectifiers”. From then on, the development towards really high voltages built on his idea of a number of intermediate electrodes connected to an external voltage divider.

- Many design problems remained to be solved, such as shape of the electrodes, choice of materials, processing techniques etc. It gradually became obvious that this was an empirical science, valve behavior had to be tested in long-term, full scale testing.

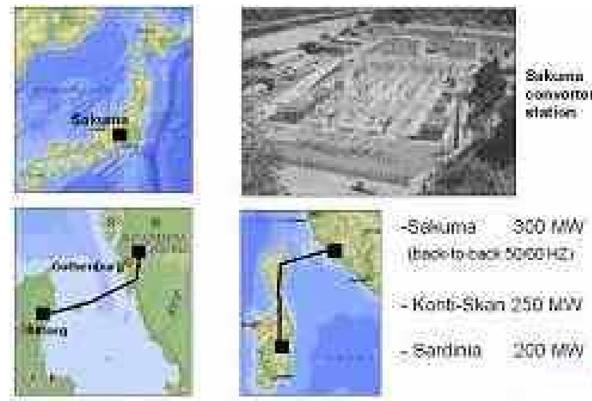


- It took quite some time before the next contract was placed, for an HVDC cable transmission under the English Channel. Power rating was 160 MW and cable voltage 100 kV. The scheme was justified by the difference in time for the daily power peaks in the English and French networks respectively.





Then came, in the 1960's, the commercial break-through for HVDC, with work on 4 schemes:



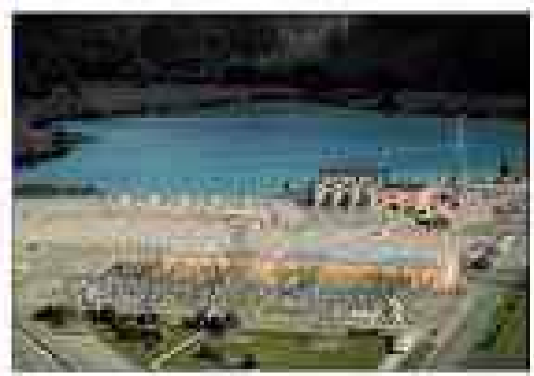
- Konti-Skan linked the Nordic system with Western Europe primarily to sell surplus hydro energy to Denmark and Germany and to provide peak support to the Nordic system when needed.

- Sardinia-Italy utilized coal resources on Sardinia and delivered energy to the Italian mainland.

- Sakuma, Japan, the first HVDC frequency converter, connected the 50 and 60 Hz systems in Japan, to some extent for energy exchange but primarily to provide emergency support at disturbances in either network.

and

- In New Zealand, a 600 MW transmission was built from new hydro developments on the Southern island to Haywards close to Wellington on the Northern island. The scheme boasted several new features: the first long (580 km) HVDC overhead line, combined with cables under Cook Strait (known for its strong currents), ground return with both sea and land electrodes, measures to reduce impact from earthquake stresses, etc.



New Zealand HVDC - the inter-island link
1965: 600 MW
(later extended to 1240 MW)

The final step in ratings for the mercury arc valves was in North America:

- 150 kV bridge voltage and 2000 A in Nelson River, Manitoba, Canada, and
- 133 kV/1800 A in the Pacific Northwest-Southwest HVDC Intertie in the U.S. At 1300 km, the Pacific Intertie was then the longest power transmission in the World. (A final rating of 3100 MW at +/- 500 kV. But these upgrades belong to the thyristor era.)

In 1972, thyristors became competitive with the mercury arc valve. Thus, further development of the mercury arc was ceased.

1970: 1440 MW
(later extended to 3100 MW)

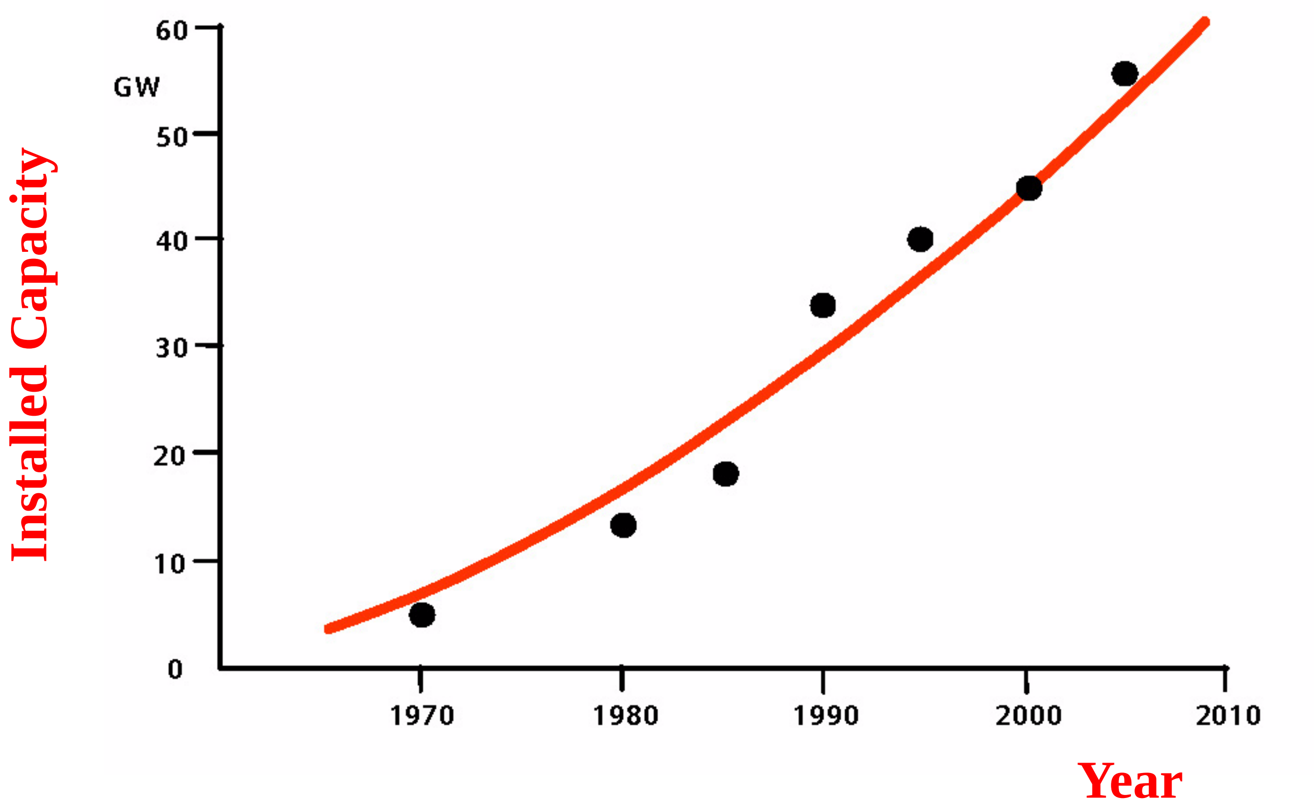
Mercury arc installations (11 in all, + 2 never used)

Name	Converter Station 1	Converter Station 2	Cable Length	Overhead line	Voltage	Power	Year	Remarks
Elbe-Project	Dessau, Germany	Berlin-Marien-felde, Germany	100 km		+/-200kV	60 MW	1945	Never placed in service, dismantled
Moscow-Kash-ira	Moscow, Russia	Kashira, Russia	100 km		200kV	30 MW	1951	Built of parts of HVDC Elbe-Project, shut down
Gotland 1	Vaestervik, Sweden	Ygne, Sweden	98 km		200kV	20 MW	1954	Shut down in February 1986
Cross-Channel	Echingen, France	Lydd, UK	64 km		+/-100kV	160 MW	1961	Shut down in 1984
Konti-Skan 1	Vester Hassing, Denmark	Stenkullen, Sweden	87 km	89 km	250kV	250 MW	1964	
Volgograd-Don-bass	Volzhskaya, Russia	Mikhailovskay a, Russia	475 km		+/-400kV	750 MW	1964	
Inter-Island, New Zealand	Benmore Dam, NZ	Haywards, NZ	40 km	570 km	+/-250kV	600 MW	1965	
BB Sakuma	Sakuma, Japan	Sakuma, Japan			+/-125kV	300 MW	1965	
SACOI 1 Suvereto, Italia	Lucciana, Corse	Codrongianos, Sardinia	304 km	118 km	200kV	200 MW	1965	Multiterminal scheme
Vancouver Island 1	Delta, BC	North Cow-ichan, BC	42 km	33 km	260kV	312 MW	1968	
Pacific Intertie	Celilo, Oregon	Sylmar, Cali-fornia		1362 km	+/-500kV	3100 MW	1970	Transmission voltage until 1984 +-400kV, maximum transmission power until 1982 1440 MW, from 1982 to 1984 1600 MW, from 1984 to 1989 2000 MW
Nelson River Bipole 1	Gillam, Canada	Rosser, Mani-toba		895 km	+/-450kV	1620 MW	1971	Largest mercury arc rectifiers ever built. Converted to thyristors in 1993, 2004
Kingsnorth, UK	London-Bedding-ton, UK	London-Willes-den, UK		85 km	+/-266kV	640 MW	1975	Shut down

Thyristor Era

- Eel River was the first HVDC system equipped with thyristors.
- System is a back-to-back HVDC station at Eel River, New Brunswick, Canada.
- Commissioned in 1972 and transmits 320 MW at a symmetrical voltage of 80 kV DC

Growth of HVDC installed capacity



First link (between Gotland & Swedish mainland) was a 20 MW, 150 kV link.

Today HVDC transmission is installed around the world in more than 100 projects.

See References Table in Book

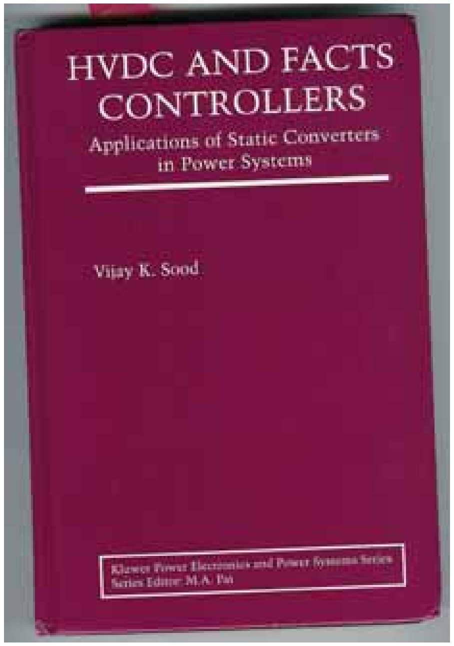
Name Converter Station 1 Converter Station 2 Length of Cable Length of overhead line Voltage Transmission power Inauguration Remarks
HVDC back-to-back station Eel River New Brunswick, Canada New Brunswick, Canada - - 80kV 320 MW 1972
Cross-Skagerak 1 + 2 Tjele, Denmark Kristiansand, Norway 130 km 100 km +-250kV 1000 MW 1977
HVDC Vancouver Island 2 Delta, British Columbia North Cowichan, British Columbia 33 km 42 km 280kV 370 MW 1977
Square Butte Center, North Dakota Arrowhead, Minnesota - 749 km +-250kV 500 MW 1977
HVDC back-to-back station Shin Shinano Shin Shinano, Japan Shin Shinano, Japan - - +-125kV 600 MW 1977
CU Coal Creek, North Dakota Dickinson, Minnesota - 710 km +-400kV 1000 MW 1979
HVDC Hokkaido-Honshu Hakodate, Japan Kamikita, Japan 44 km 149 km 250kV 300 MW 1979
Cabora Bassa Songo, Mozambique Apollo, South Africa - 1420 km +-533kV 1920 MW 1979
Inga-Shaba Kolwezi, Zaire Inga, Zaire - 1700 km +-500kV 560 MW 1964
HVDC back-to-back station Acaray Acaray, Paraguay Acaray, Paraguay - - 25,6 kV 50 MW 1981
HVDC back-to-back station Vyborg Vyborg, Russia Vyborg, Russia - - +-85 kV 1065 MW 1982
HVDC back-to-back station Dürnrohr Dürnrohr, Austria Dürnrohr, Austria - - 145 kV 550 MW 1983 shut down in October 1996
HVDC Gotland 2 Västervik, Sweden Yigne, Sweden 92.9 km 6.6 km 150 kV 130 MW 1983
HVDC back-to-back station Artesia, New Mexico Artesia, New Mexico Artesia, New Mexico - - 82 kV 200 MW 1983
HVDC back-to-back station Chateauguay Châteauguay — Saint-Constant Châteauguay — Saint-Constant - - 140 kV 1000 MW 1984
HVDC Itaipu 1 Foz do Iguaçu, Paraná São Roque, São Paulo - 785 km +-600 kV 3150 MW 1984
HVDC Itaipu 2 Foz do Iguaçu, Paraná São Roque, São Paulo - 805 km +-600 kV 3150 MW 1984
HVDC back-to-back station Oklaunion Oklaunion Oklaunion - - 82 kV 200 MW 1984
HVDC back-to-back station Blackwater, New Mexico Blackwater, New Mexico Blackwater, New Mexico - - 57 kV 200 MW 1984
HVDC back-to-back station Highgate, Vermont Highgate, Vermont Highgate, Vermont - - 56 kV 200 MW 1985
HVDC back-to-back station Madawaska Madawaska Madawaska - - 140 kV 350 MW 1985
HVDC back-to-back station Miles City Miles City Miles City - - +-82 kV 200 MW 1985
Nelson River Bipole 2 Sundance, Canada Rosser, Canada - 937 km +-500 kV 1800 MW 1985
HVDC Cross-Channel (new) Les Mandarins, France Sellindge, UK 72 km - +-270 kV 2000 MW 1986 2 bipolar systems
HVDC back-to-back station Broken Hill Broken Hill Broken Hill - - +-8.33 kV 40 MW 1986
Intermountain Intermountain, Utah Adelanto, California - 785 km +-500 kV 1920 MW 1986
HVDC back-to-back station Uruguaiana Uruguaiana, Brazil Uruguaiana, Brazil - - +-17.9 kV 53.9 MW 1986
HVDC Gotland 3 Västervik, Sweden Yigne, Sweden 98 km - 150 kV 130 MW 1987
HVDC back-to-back station Virginia Smith Sidney, Nebraska Sidney, Nebraska - - 55.5 kV 200 MW 1988
Konti-Skan 2 Vester Hassing, Denmark Stenkullen, Sweden 87 km 60 km 285 kV 300 MW 1988

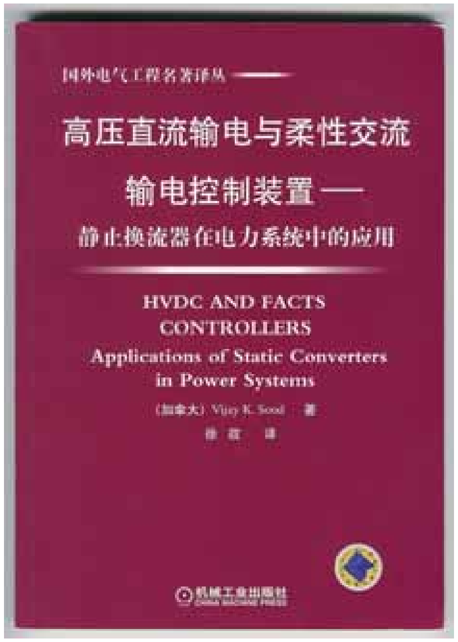
HVDC back-to-back station Mc Neill Mc Neill, Canada Mc Neill, Canada - - 42 kV 150 MW 1989
HVDC back-to-back station Vindhyachal Vindhyachal, India Vindhyachal, India - - 176 kV 500 MW 1989
HVDC Sileru-Barsoor Sileru, India Barsoor, India - 196 km +-200 kV 400 MW 1989
Fenno-Skan Dannebo, Sweden Rauma, Finland 200 km 33 km 400 kV 500 MW 1989
HVDC Gezhouba - Shanghai Gezhouba, China Nan Qiao, China - 1046 km +-500 kV 1200 MW 1989
Quebec - New England Transmission Radisson, Quebec Nicolet, Quebec; Des Cantons, Quebec; Comerford, New Hampshire; James Bay, Massachusetts - 1100 km +-450 kV 2000 MW 1991 multiterminal scheme
HVDC Rihand-Delhi Rihand, India Dadri, India - 814 km +-500 kV 1500 MW 1992
SACOI 2 Suvereto, Italia Lucciana, France; Codrongianos, Italy 118 km 304 km 200 kV 300 MW 1992 multiterminal scheme
HVDC Inter-Island 2 Benmore Dam, New Zealand Haywards, New Zealand 40 km 570 km 350 kV 640 MW 1992
Cross-Skagerak 3 Tjele, Denmark Kristiansand, Norway 130 km 100 km 350kV 500 MW 1993
Baltic-Cable Lübeck-Herrenwyk, Germany Kruseberg, Sweden 250 km 12 km 450 kV 600 MW 1993
HVDC back-to-back station Etzenricht Etzenricht, Germany Etzenricht, Germany - - 160 kV 600 MW 1993 shut down in October 1995
HVDC back-to-back station Vienna-Southeast Vienna, Austria Vienna, Austria - - 142 kV 600 MW 1993 shut down in October 1996
HVDC Haenam-Cheju Haenam, South Korea Jeju, South Korea 101 km - 180 kV 300 MW 1996
Kontek Bentwisch, Germany Bjaeverskov, Denmark 170 km - 400 kV 600 MW 1996
HVDC Hellsjön-Grängesberg Hellsjoen, Sweden Graengesberg, Sweden - 10 km 180 kV 3 MW 1997 experimental HVDC
HVDC back-to-back station Welch-Monticello Welch-Monticello, Texas Welch-Monticello, Texas - - 162 kV 600 MW 1998
HVDC Leyte - Luzon Orno, Leyton Ormoc, Luzon 21 km 430 km 350 kV 440 MW 1998
HVDC Visby-Nas Nas, Sweden Visby, Sweden 70 km - 80 kV 50 MW 1999
Swepol Starnö, Sweden Slupsk, Poland 245 km - 450 kV 600 MW 2000
HVDC Italy-Greece Galatina, Italy Arachthos, Greece 200 km 110 km 400 kV 500 MW 2001
Kii Channel HVDC system Anan, Japan Kihoku, Japan 50 km 50 km +-500 kV 1400 MW 2000
HVDC Moyle Auchencrosh, UK Ballycronan More, UK 63.5 km - 250 kV 250 MW 2001
HVDC Thailand-Malaysia Khlong Ngae, Thailand Gurun, Malaysia - 110 km 300 kV 300 MW 2002
HVDC back-to-back station Minami-Fukumitsu Minami-Fukumitsu, Japan Minami-Fukumitsu, Japan - - 125 kV 300 MW 1999
HVDC Three Gorges-Changzhou Longquan, China Zhengping, China - 890 km +-500 kV 3000 MW 2003
HVDC Three Gorges-Guangdong Jingzhou, China Huizhou, China - 940 km +-500 kV 3000 MW 2003
Basslink Loy Yang, Australia George Town, Australia 298.3 km 71.8 km 400 kV 600 MW 2005
Imera Power HVDC Wales-Ireland, East West Interconnector Leinster, Ireland Anglesea, Wales 130 km - +-400 kV 500 MW 2008
NorNed Feda, Norway Eemshaven, Netherlands 580 km - +-450 kV 700 MW 2010
HVDC back-to-back station at Vishakapatinam Vishakapatinam, India Vishakapatinam, India - -

Commercial Break!

See Tables in BOOK:

- V.K.Sood, “HVDC and FACTS Controllers - Applications of Static Converters in Power Systems”, April 2004, ISBN 1-4020-7890-0, Published by Kluwer Academic Publishers, 300 pages. Available also in Chinese, and soon in Russian.





Russian version soon

Past Decade Version

Driving forces were increased performance, increased reliability, reduced losses, higher overload capacity and better filtering with lower audible noise requirements. All of these requirements led to increased costs. The industry matured and was characterized by the following features:

- **Valves:** Typical valve was ±500 kV water-cooled for indoor utilization, having a 12-pulse, suspended 3 quadri-valve configuration,
- **Converter Transformers:** These were three 1-phase winding transformers which were mounted close to the valve-hall with protruding bushings,
- **AC Filters:** conventional, passive double-tuned and high-pass filters type with internal fused capacitors and air-cored reactors,
- **DC Filters:** passive type with either air or oil cooled reactors. The DCCTs were of the zero-flux type, and
- **DC Controls:** mainly digital, but with some analog parts for the protection and firing units.

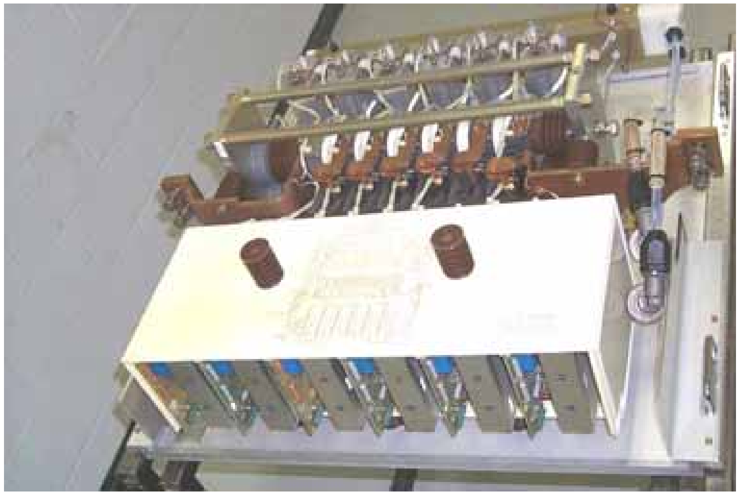
AC Side Bushings in Valve Hall

Top: DC Side Bushing in Valve Hall

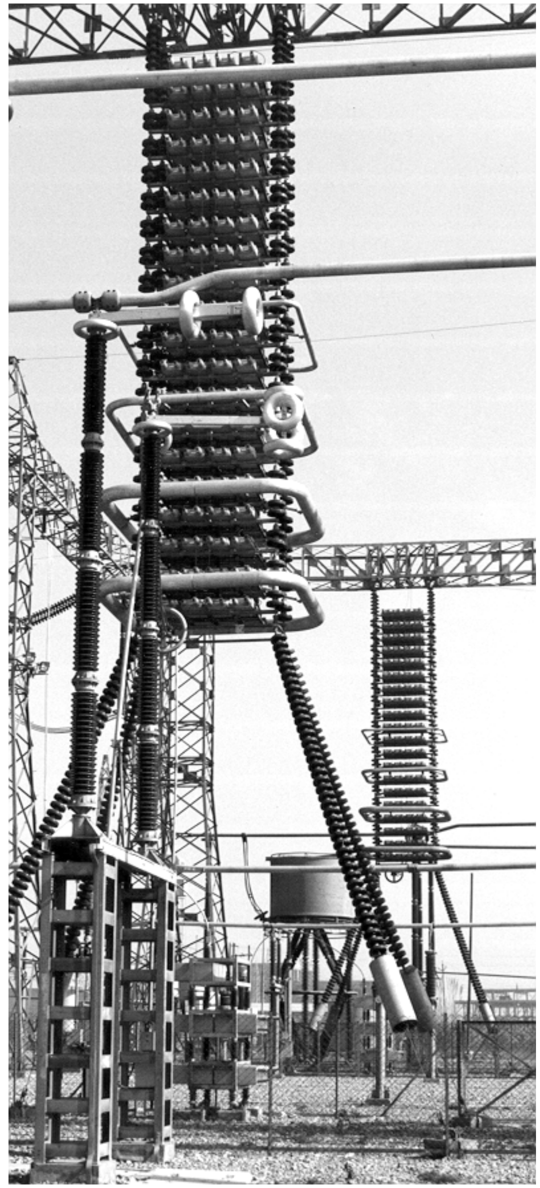
Converter transformer

Inside of Valve Hall and Quadri-Valves

Below: View of Valve Modules



Older style oil-coiled smoothing reactor in tank



Damped Filters

New style air-cored smoothing reactor

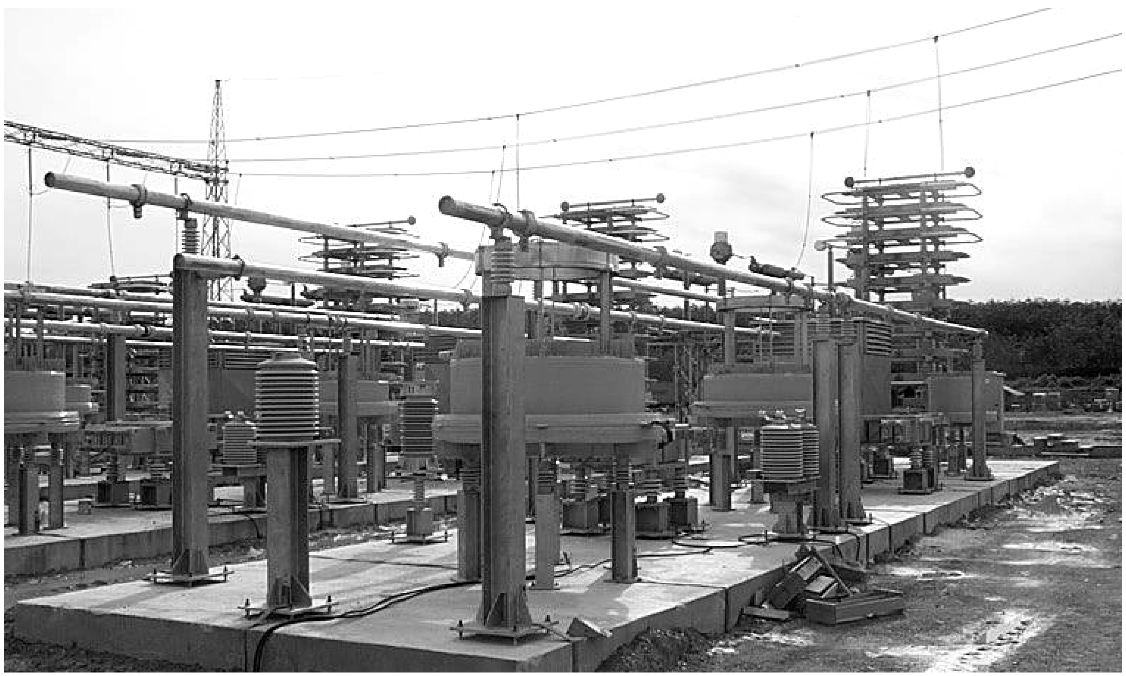
AC High pass filter. Being a HP filter no seasonal tuning is necessary. However the filter has a resistor in parallel with the reactor (the rectangular tower on the right)

DC side Voltage Divider

High speed bypass breaker across the converter on the dc side.

Spare Converter Transformer in switchyard (Dadri, India)

Air cored smoothing reactor

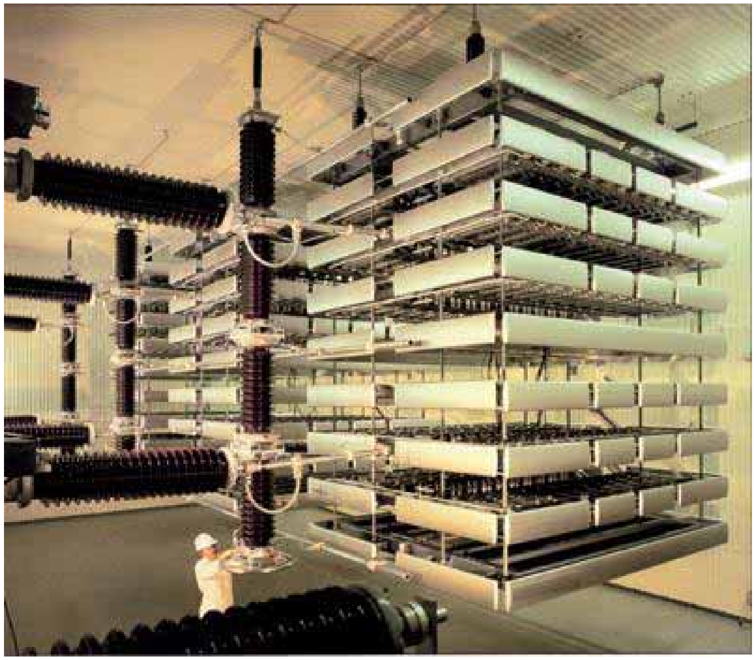


Triple-tuned AC Filter (Gurun, Malaysia)

Present Decade Version

New trends in the present decade are being led by a commitment to reduce costs so that DC transmission can become competitive with AC transmission. These cost reductions are coming about due to:

- Modular, standardized and re-usable designs are being employed,
- Developments of the past decade in the areas of digital electronics, and
- Power switches.

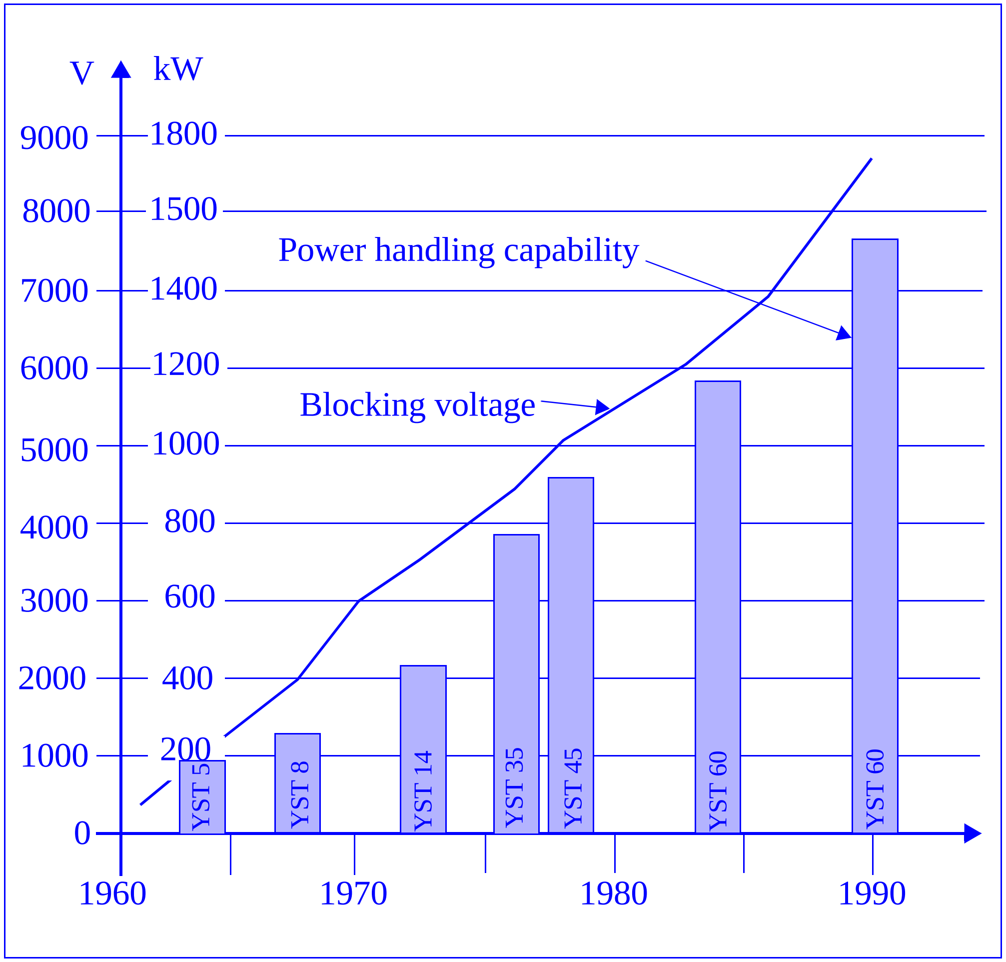


Thyristor Valves

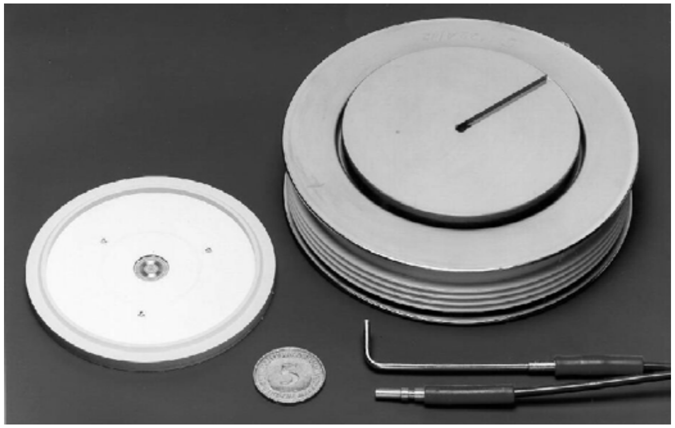
- Today, thyristor ratings of 9.5+ kV and 1500 kW on silicon wafers of 150 mm diameter are commercially feasible. This has led to a dramatic decrease in the number of series connected thyristor elements comprising a valve, thus simplifying the design and reducing the power losses,
- The thyristors can be either light or electrically triggered. Light-Triggered Thyristors (LTT) will offer performance and cost advantages in the future by eliminating the high number of components in the electronic firing unit. Monitoring and protection features are also incorporated in these devices,
- The valves are now of the air-insulated type and can be housed in outdoor units or modules with one valve per module,
- An important development in the usage of outdoor valves is a composite insulator which is used as a communications channel for the fibre optics, cooling water and ventilation air between the valve unit and ground,
- An outdoor valve of this type has been in operation at the Konti-Skan I station since 1992 for 275 kV DC voltage.

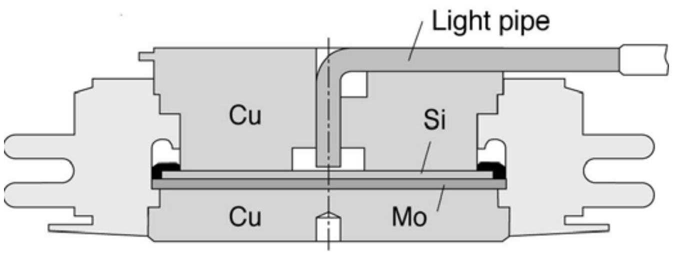
Benefits of LTT-Thyristor Technology and View on the Thyristor Stack (right side)

Thyristor Capabilities



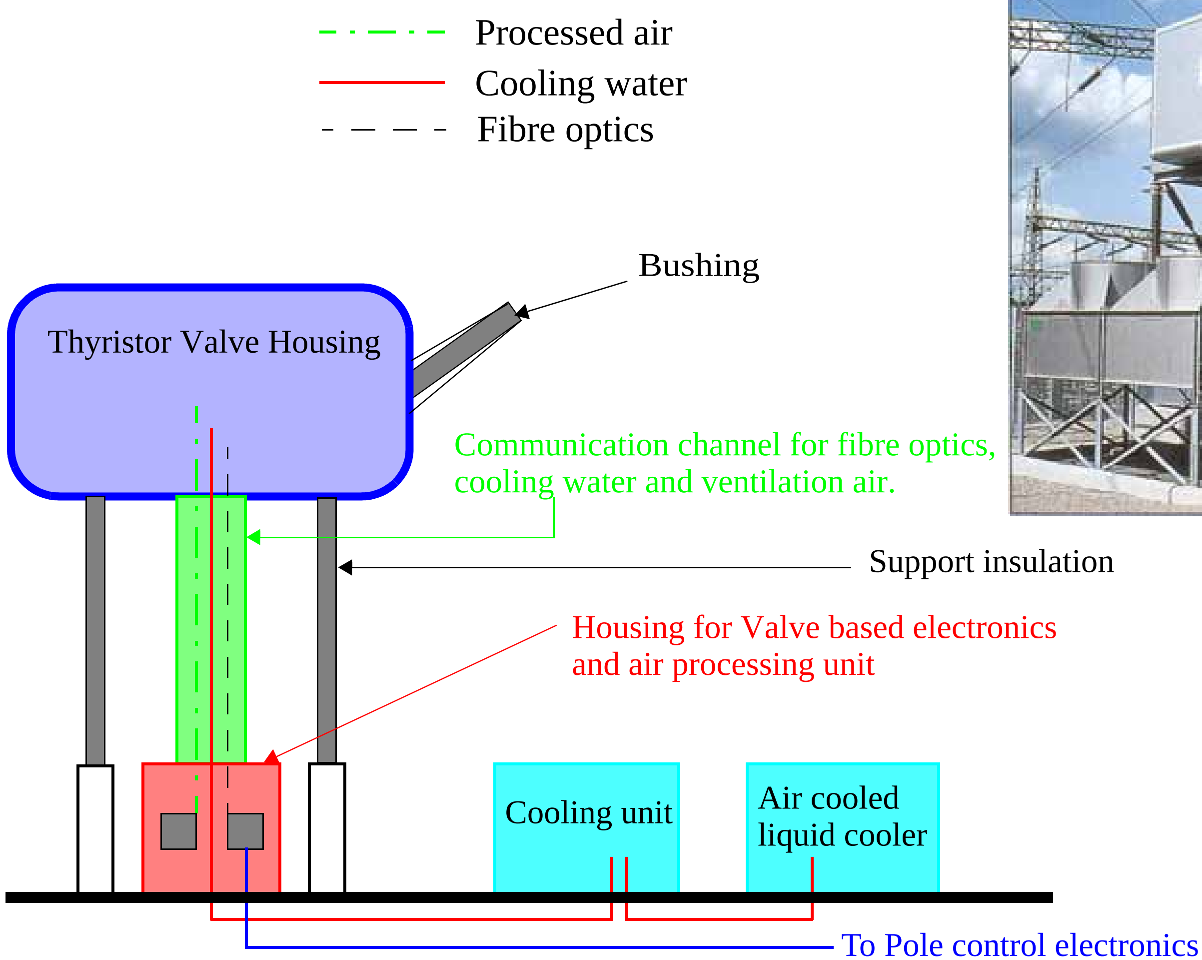
Development of blocking voltage and power handling capacity for HVDC thyristors





Silicon wafer and construction of the LTT. The light guides appear in the bottom right hand corner.

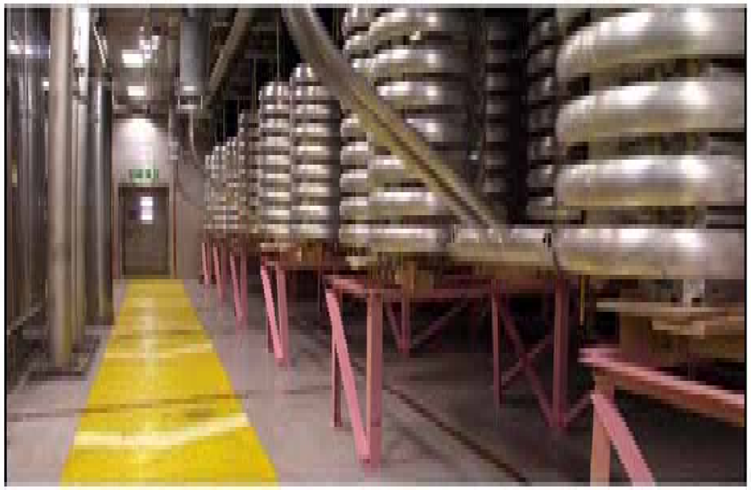
Basic elements of an outdoor valve



Transistor Era

IGBTs (HVDC Light) installations

Name	Converter Station 1	Converter Station 2	Cable Length	Voltage	Power	Year	Remarks
HVDC Tjæreborg	Tjæreborg, Denmark	Tjæreborg, Denmark	4.3 km	+-9 kV	7,2 MW	2000	interconnection to wind power generating stations
Directlink	Mullumbimby, Australia	Bungalora, Australia	59 km	+-80 kV	180 MW	2000	land cable
Cross Sound Cable	New Haven, Connecticut	Shoreham, Long Island	40 km	+-150 kV	330 MW	2002	buried underwater cable
Murraylink	Berri, Australia	Red Cliffs, Australia	177 km	+-150 kV	220 MW	2002	land cable
HVDC Troll	Kollsnes, Norway	Offshore platform Troll A	70 km	+-60 kV	84 MW	2005	power supply for offshore gas compressor
Estlink	Espoo, Finland	Harku, Estonia	105 km	+-150kV	350 MW	2006	



Self-commutated Valves

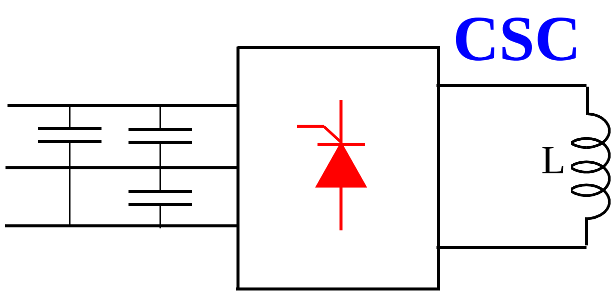
Increased interest in VSCs has been due to development of self-commutated switches at increased power ratings. These switches now permit the use of sophisticated algorithms for deriving sinusoidal output waveforms for controlling active-reactive power and the generation-absorption of harmonics.

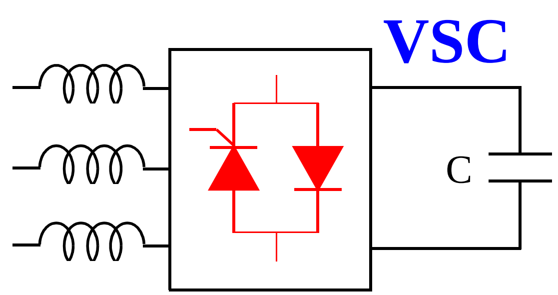
Comparison of power semi-conductor devices

	Thyristor	GTO	IGBT	SI	MCT	MOSFET
Max. Voltage rating (V)	9500	6000	1700	2500	3000	1000
Max. Current rating (A)	4000	6000	800	800	400	100
Voltage blocking	symmetric/ asymmetric	symmetric/ asymmetric	asymmetric	asymmetric	symmetric/ asymmetric	asymmetric
Gating	pulse	current	voltage	current	voltage	voltage
Conduction drop (V)	1.2	2.5	3	4	1.2	resistive
Switching frequency (kHz)	1	5	20	20	20	100
Development target max. voltage rating (V)	10,000	10,000	3,500	5000	5,000	2000
Development target max. current rating (A)	8,000	8,000	2,000	2,000	2,000	200

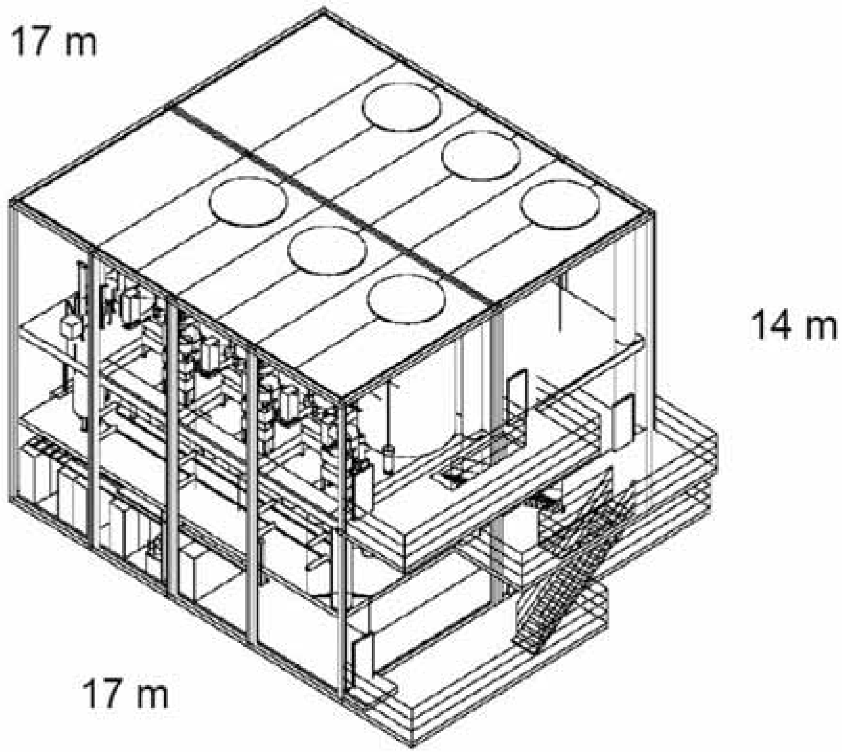
Comparison of CSC versus VSC

Current source converters	Voltage source converters
Uses inductor L for dc side energy storage	Uses capacitor C for dc side energy storage
Constant current	Constant voltage
Fast accurate control	Slower control
Higher losses	More efficient
Larger and more expensive	Smaller and less expensive
More fault tolerant and more reliable	Less fault tolerant and less reliable
Simpler controls	Complexity of control system is increased
Not easily expandable in series	Easily expanded in parallel for increased rating





Offshore Platform Supplies

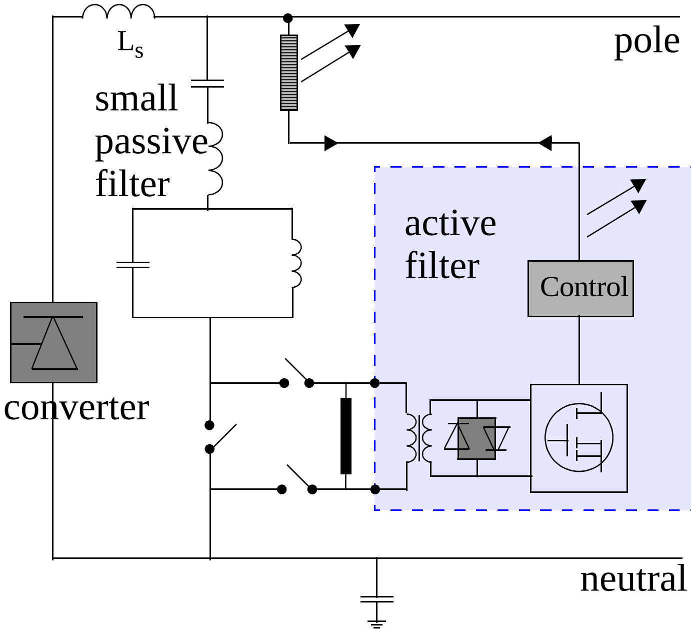


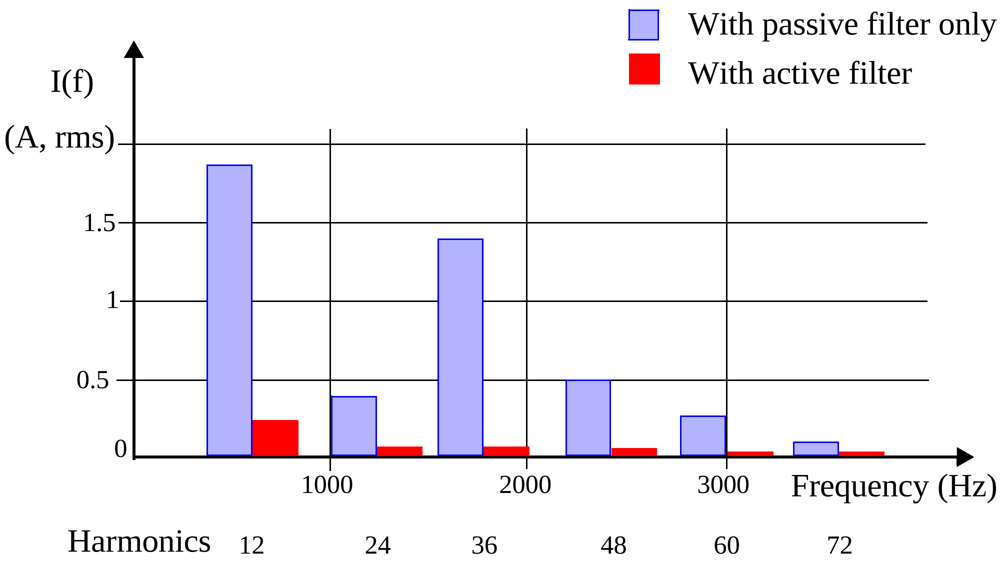
- 2 x 40 MW converter stations excluding transformer
- Equipment on three levels
- Weight: ~ 750 tons
- Footprint: ~ 350 m^2

Active Filters

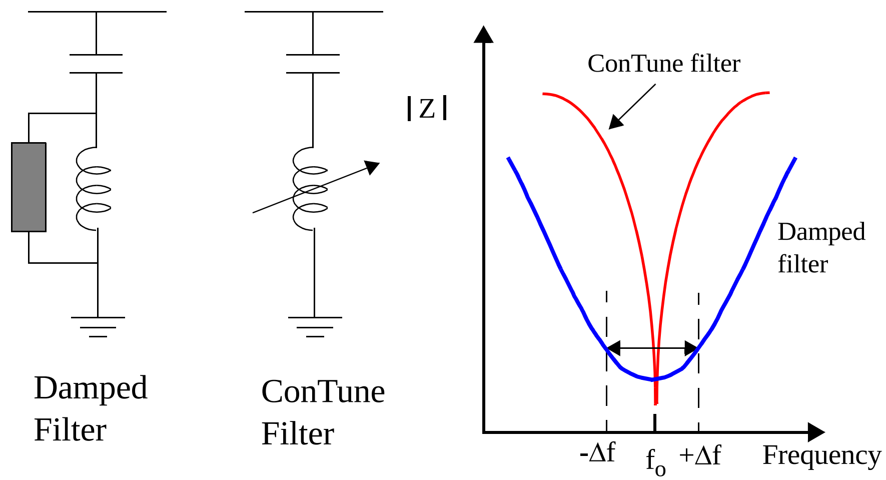
These devices become prominent due to the following:

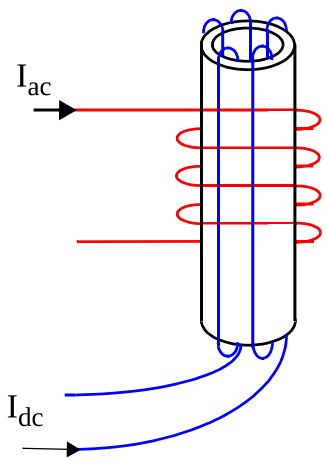
- Stringent requirements from the utilities for filtering harmonics,
- Availability of PWM VSC converters at high power and low losses..



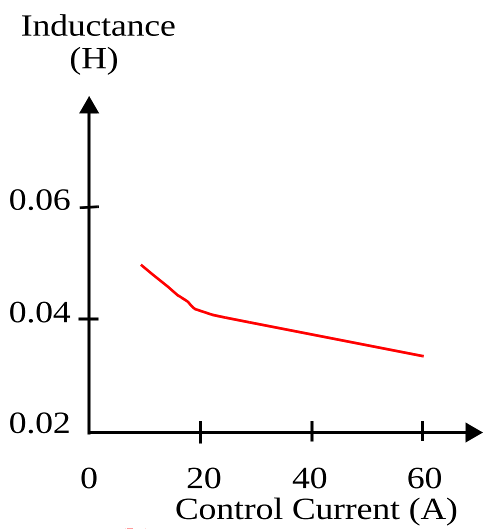


Tunable AC Filters





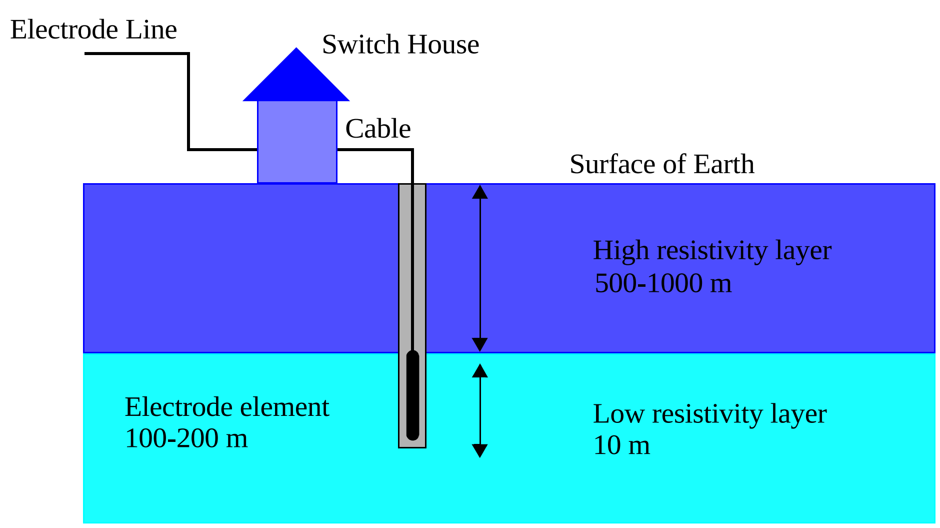
(a)



(b)

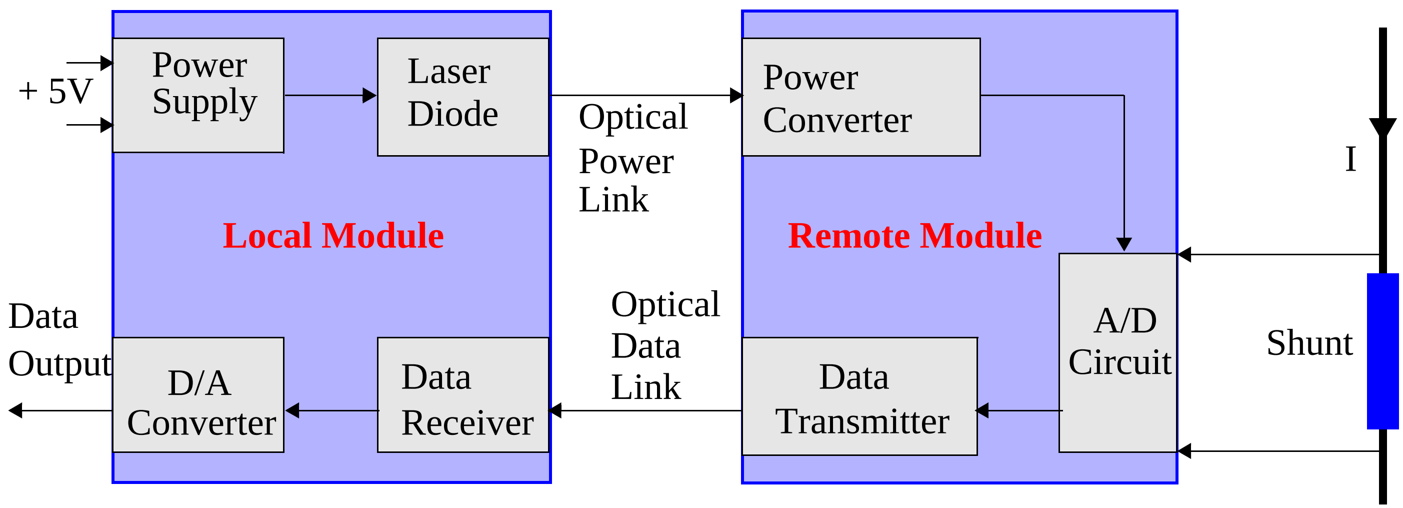
Deep Hole Ground Electrode

- Allows the electrode to be closer to the converter station,
- Usage of a shorter line with reduced power loss,
- Reduced interference and reduced risk of lightning strikes,
- Easier to find a suitable electrode site, and
- Enhanced possibilities to operate the DC link in mono-polar mode.

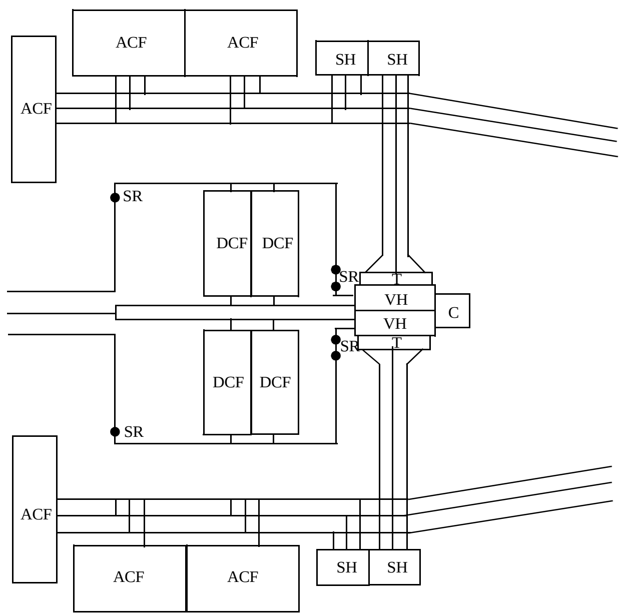


AC-DC Measurements

Optical Current Transducer



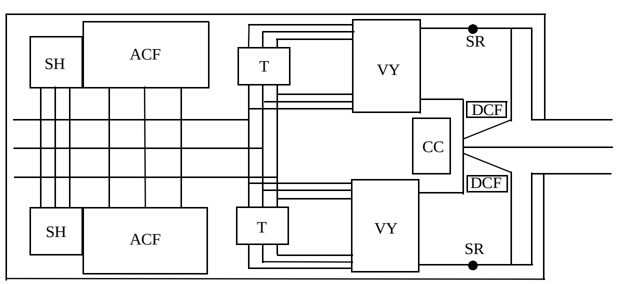
Comparison of a 2000 MW HVDC station layout of the 1990s with a modern design



ACF - AC Filter
DCF - DC Filter
VH - Valve Hall
VY - Valve Yard
SH - Shunt Capacitor
SR - Smoothing Reactor
C - Control Building
CC - Control & Auxi. Modules
T - Transformers

OLD DESIGN

circa 1990



ACF - AC Filter
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SR - Smoothing Reactor
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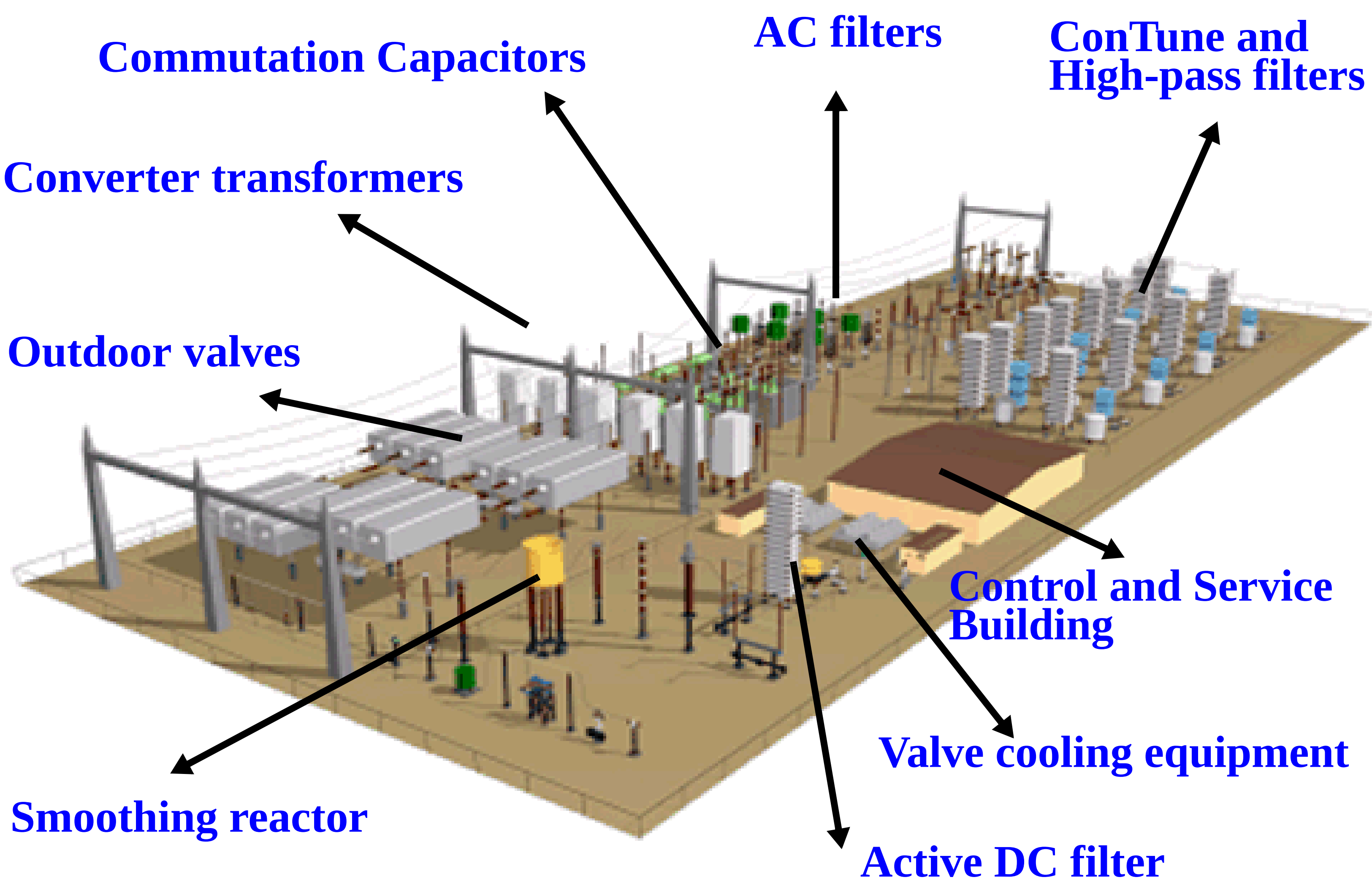
CC - Control & Auxi. Modules
T - Transformers

NEW DESIGN

circa 2005

Artist’s view of next generation Converter Station



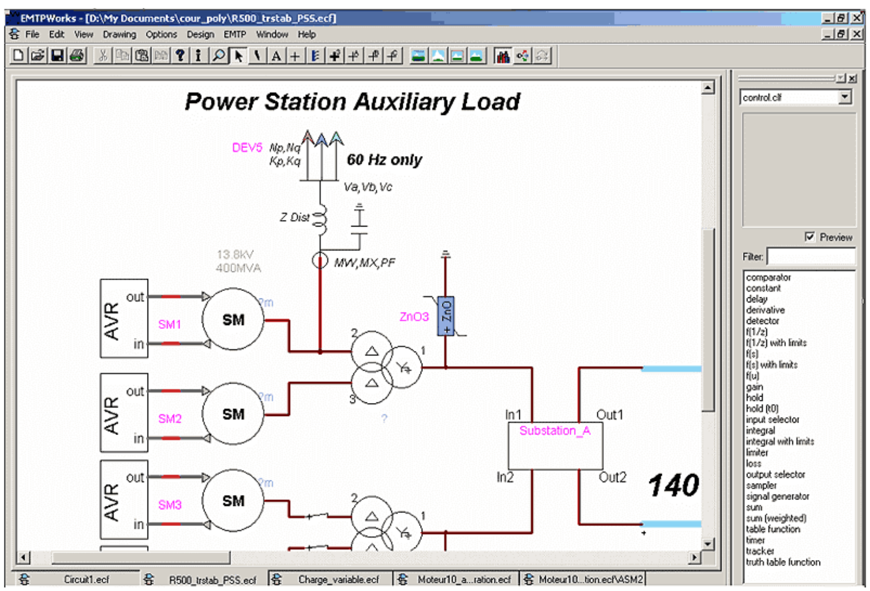
Aerial view of CCC at Garabi

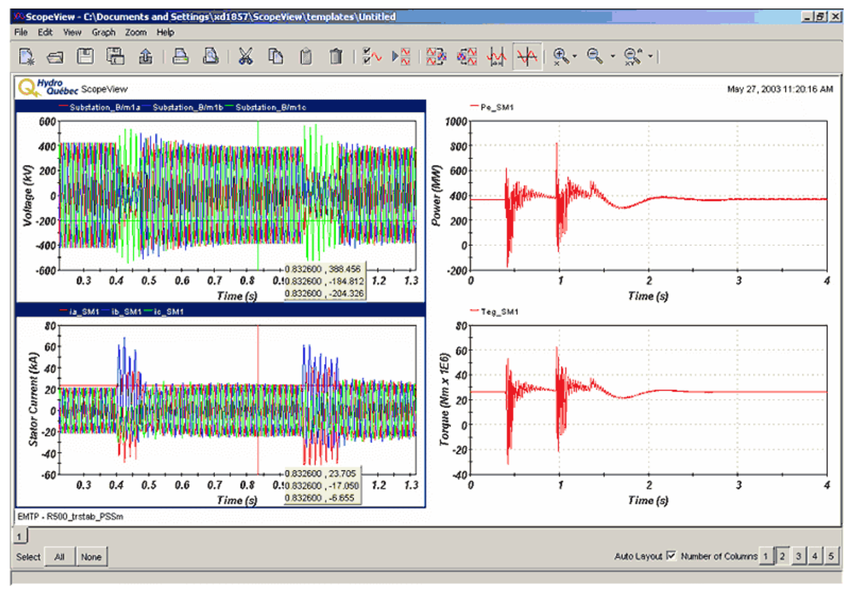
Modeling and Simulation

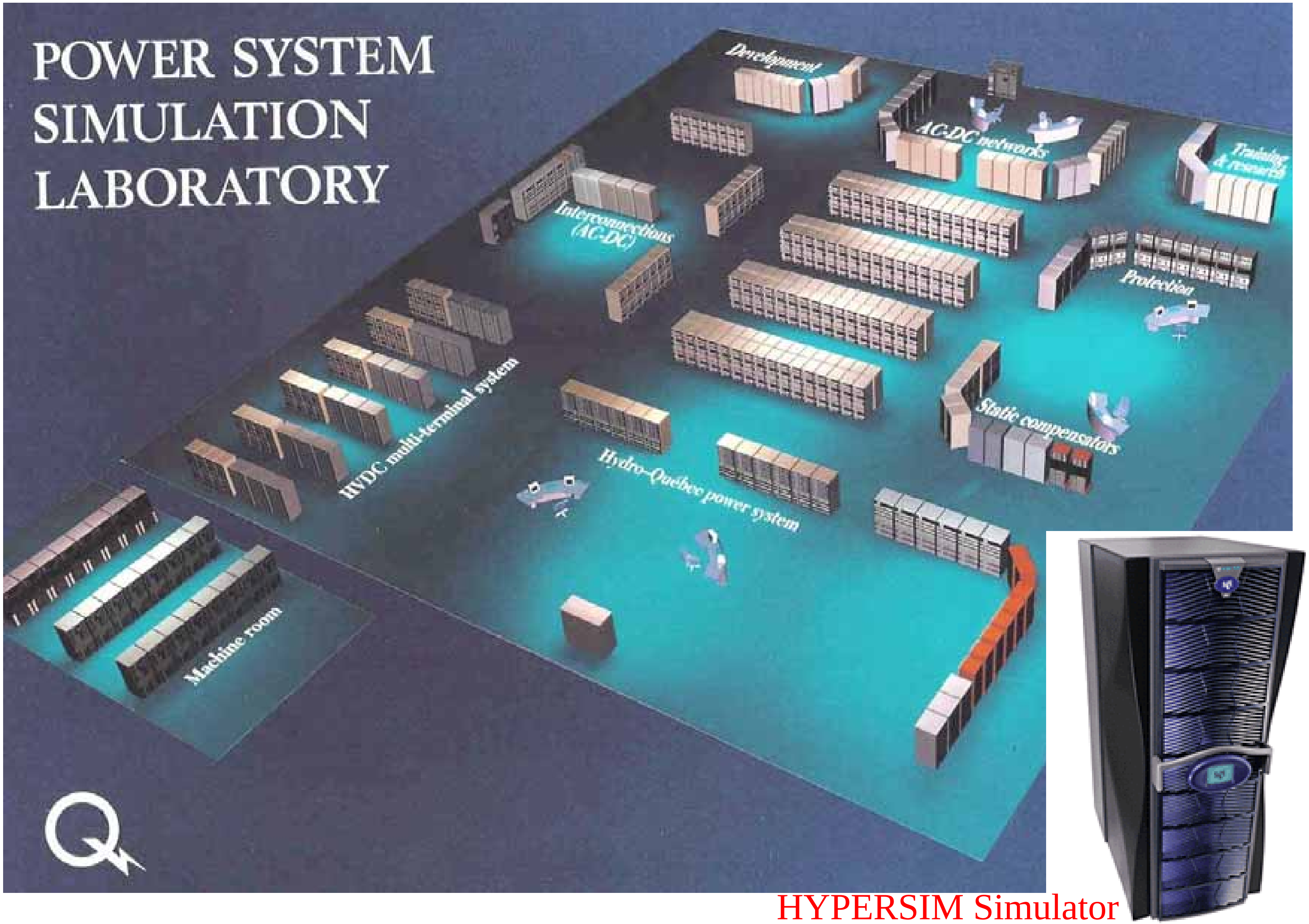
- Real-time Digital Simulators (ex. HYPERSIM, RTDS, OPAL RT)
- Off-line Digital Simulation packages (ex. EMTP RV, EMTDC etc)

EMTP-RV Package includes:

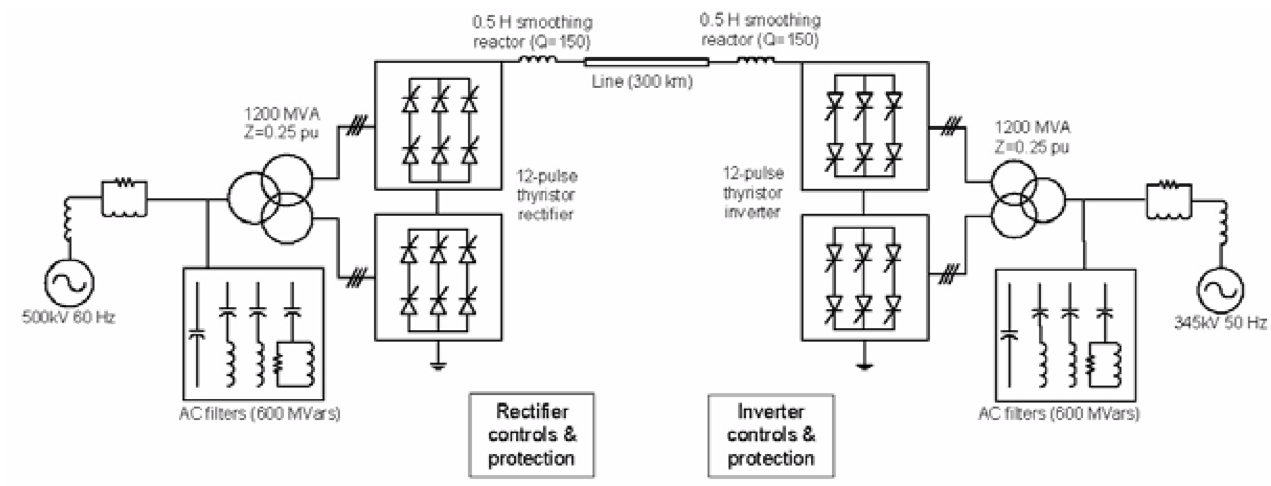
- EMTP-RV, the Engine;
- EMTPWorks, the GUI;
- ScopeView, the Output Processor.







HYPERSIM Simulator



Key Features

Pentium M with up to 3 VIRTEX II Pro FPGA
RT-LAB, SIMULINK, RTW, XILINX SG compatible
Compact and robust aluminum case15'' x 12'' x 5''
PC and IO sections can be used separately

Computer Section

Two slot PCI – one free for optional PCI IO boar
Pentium M, Mini-ITX, 2Ghz
One OP5110 XILINX FPGA board for IO management
Ethernet 10/100 4-port Hub (optional)

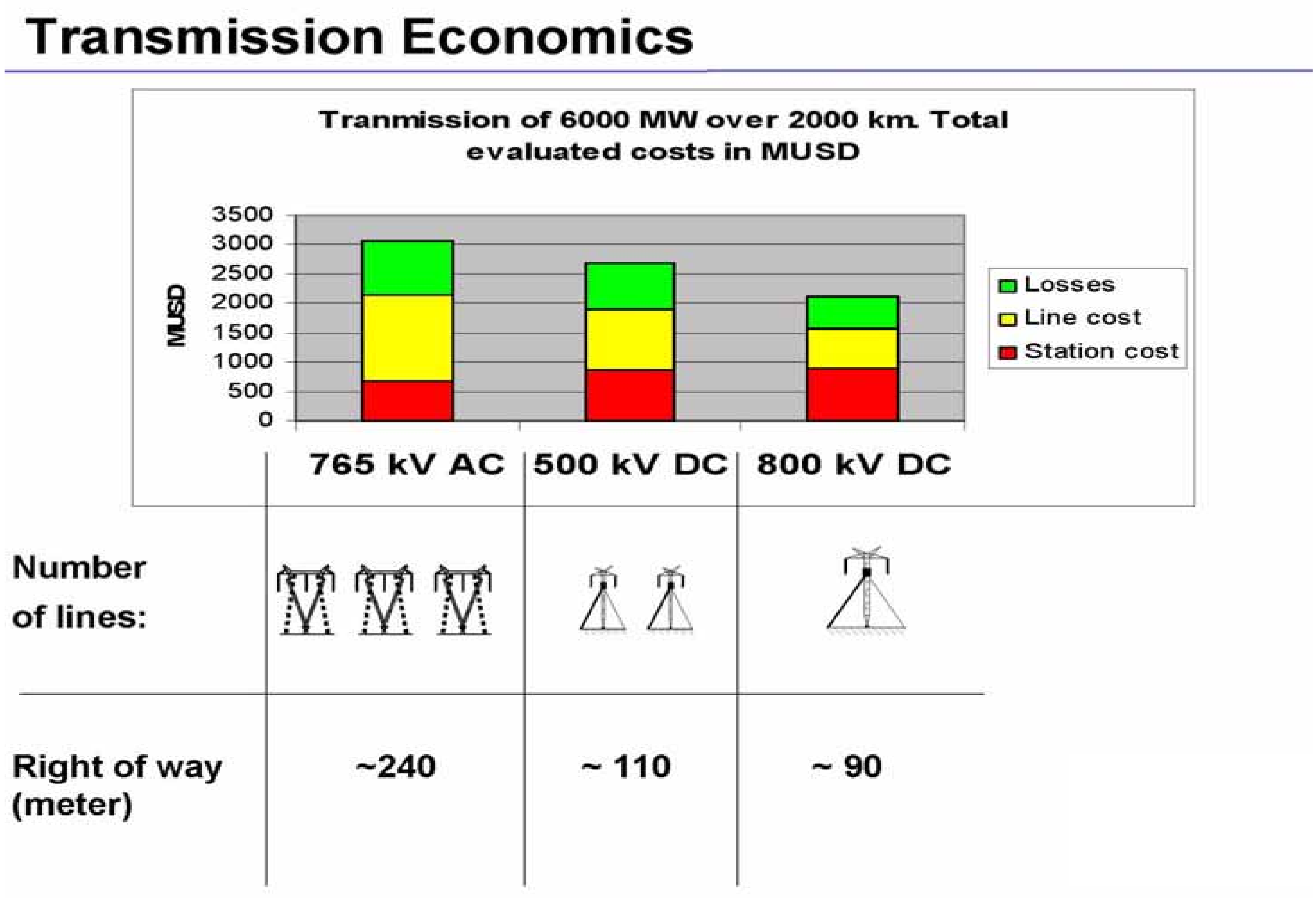
IO Section

Capacity of 4 IO carriers to create IO configurations using 16-channel high-speed IO modules:

Up to 128ch of opto-isolated DIO
Up to 128ch of DAC(5ma) or ADC
16-ch. A/D modules,16-bit 2-us total sampling time
16-ch. D/A modules, 16-bit, 1us update time.
Optional additional OP5130 FPGA boards for fast model execution and control prototyping.
32 Leds display controllable by the model
Linear IO power supply with Led indicator

Real-time Digital Simulator for Hardware-in-Loop testing of Controllers (from OPAL RT)

800 kV and beyond



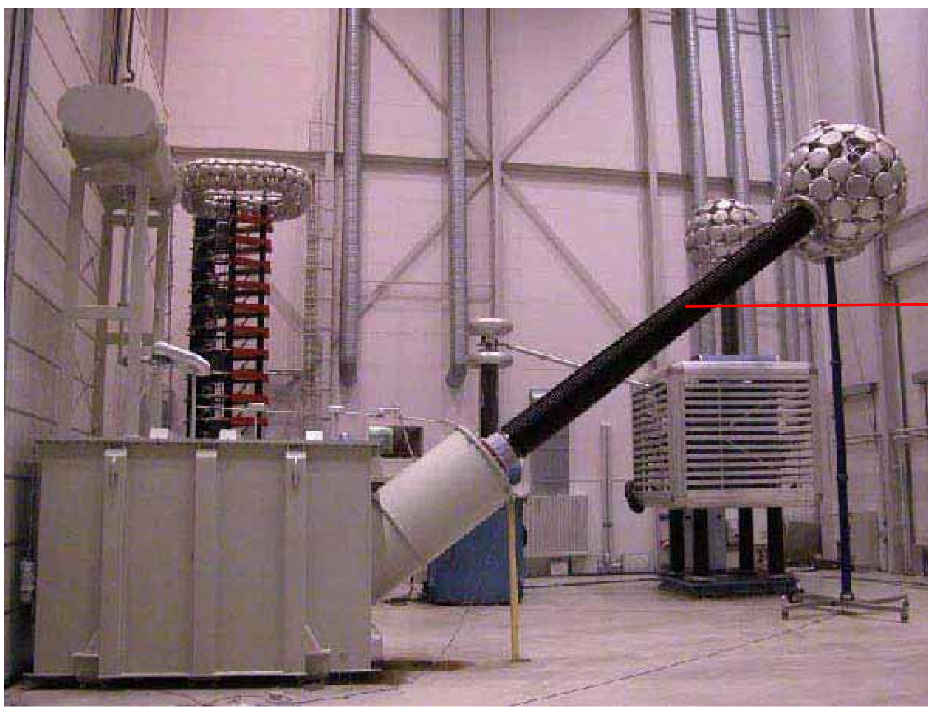
Number of lines in parallel required to transmit 8 – 12 GW

		Cond. diam.	Thermal limit (line)	Thermal limit (s/s)	SIL	1.5 x SIL	Required no. of lines	
	kV	mm	GW	GW	GW	GW	8 GW	12 GW
EHVAC	800	5 x 35	7.5	5.5	2.5	3.8	4	5
	1000	8 x 35	15.0	6.9	4.3	6.5	3	3
HVDC	±600	3 x 50	8.0	5.8	NA	NA	2	3
	±800	5 x 50	17.7	5.8	NA	NA	2	3

800 kV Equipment

Wall Bushing for 800 kV

800 kV Converter transformer



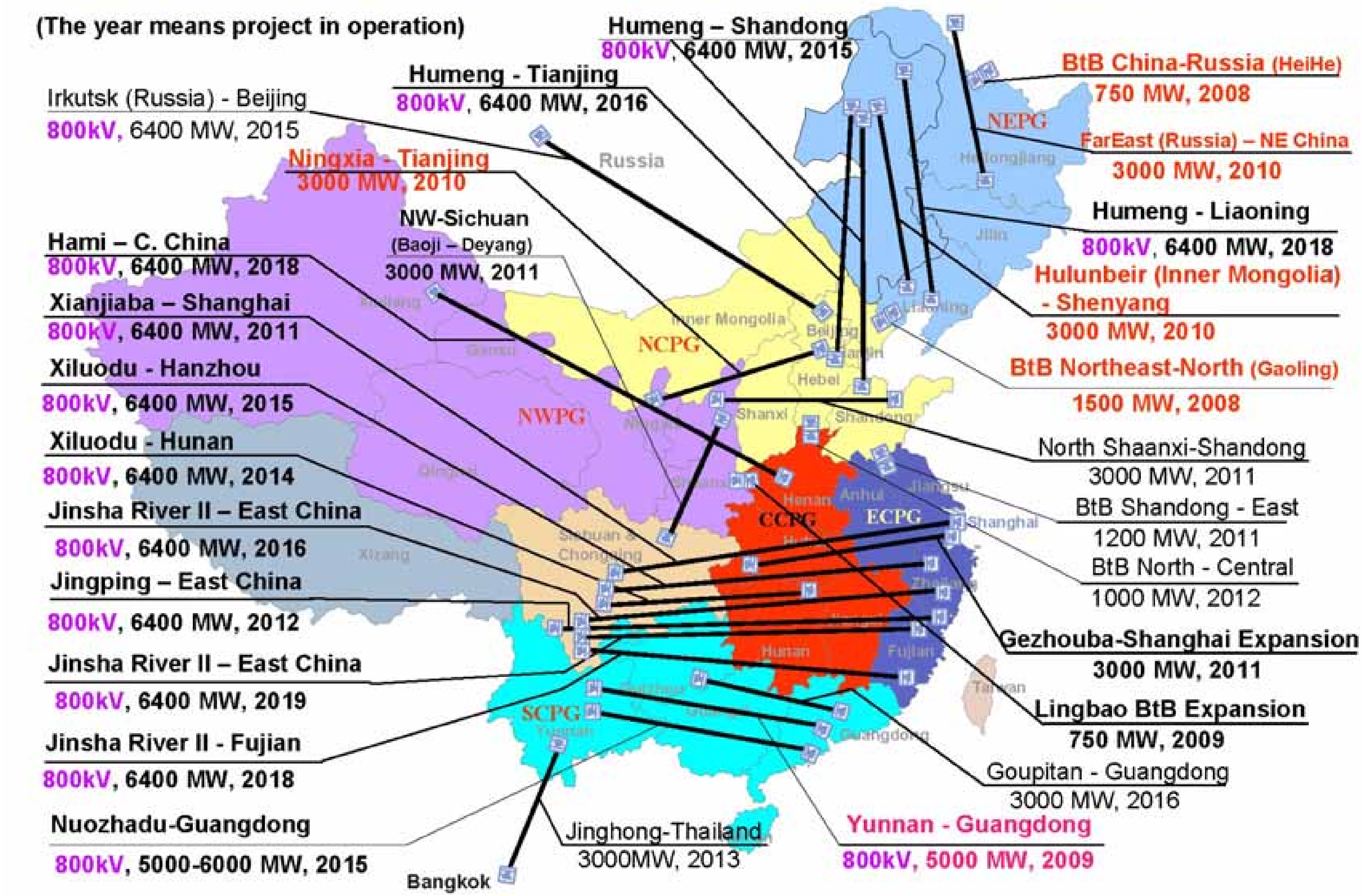
Transformer Bushing for 800 kV

Based on proven design used in 3G projects in China

- Hollow core composite insulator
- Silicon rubber sheds with proven profile
- SF_6 enhanced insulation
- "Explosion safe" – no porcelain

HVDC Projects in China

Planned Future HVDC Projects by 2020 in China



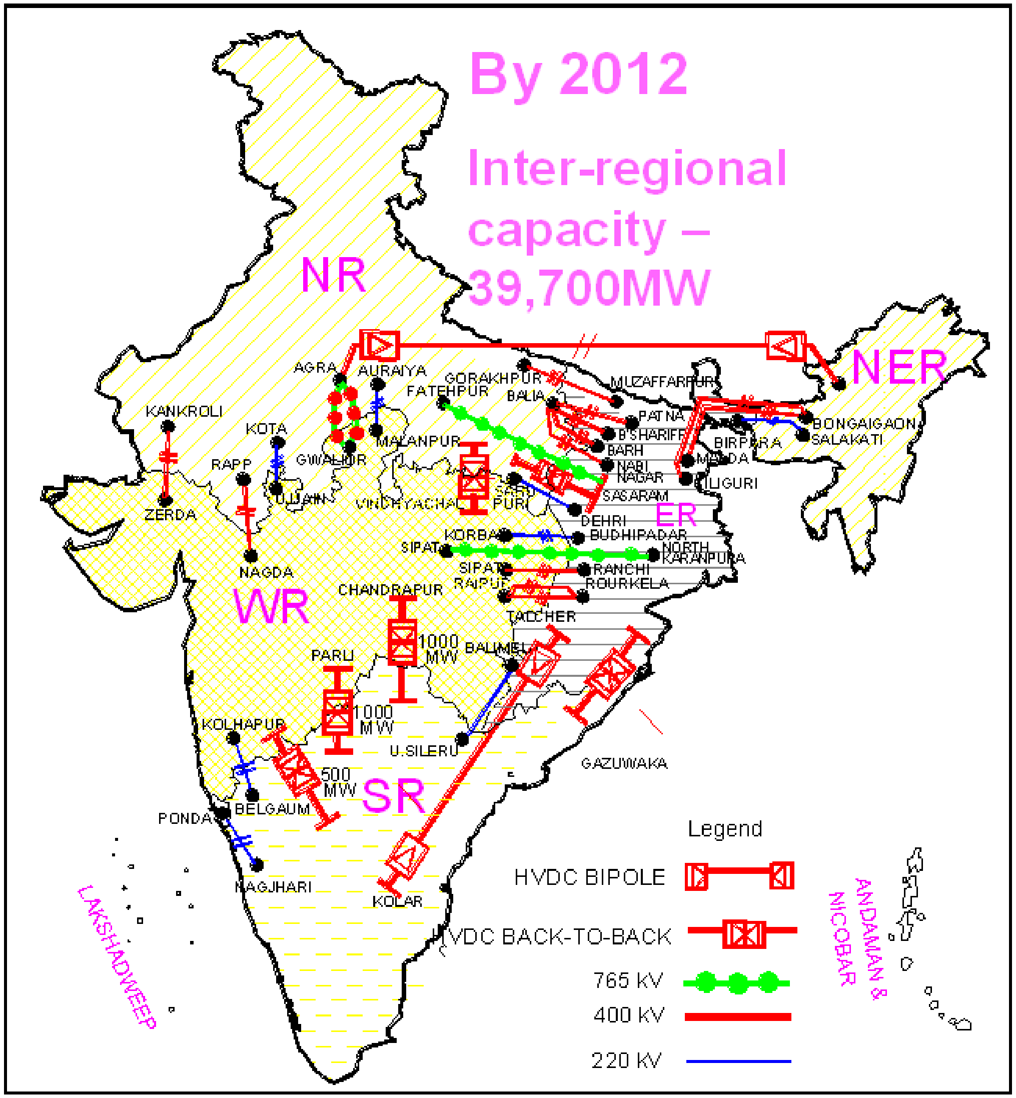
HVDC Projects in India

Existing Multi-infeed HVDC Scheme

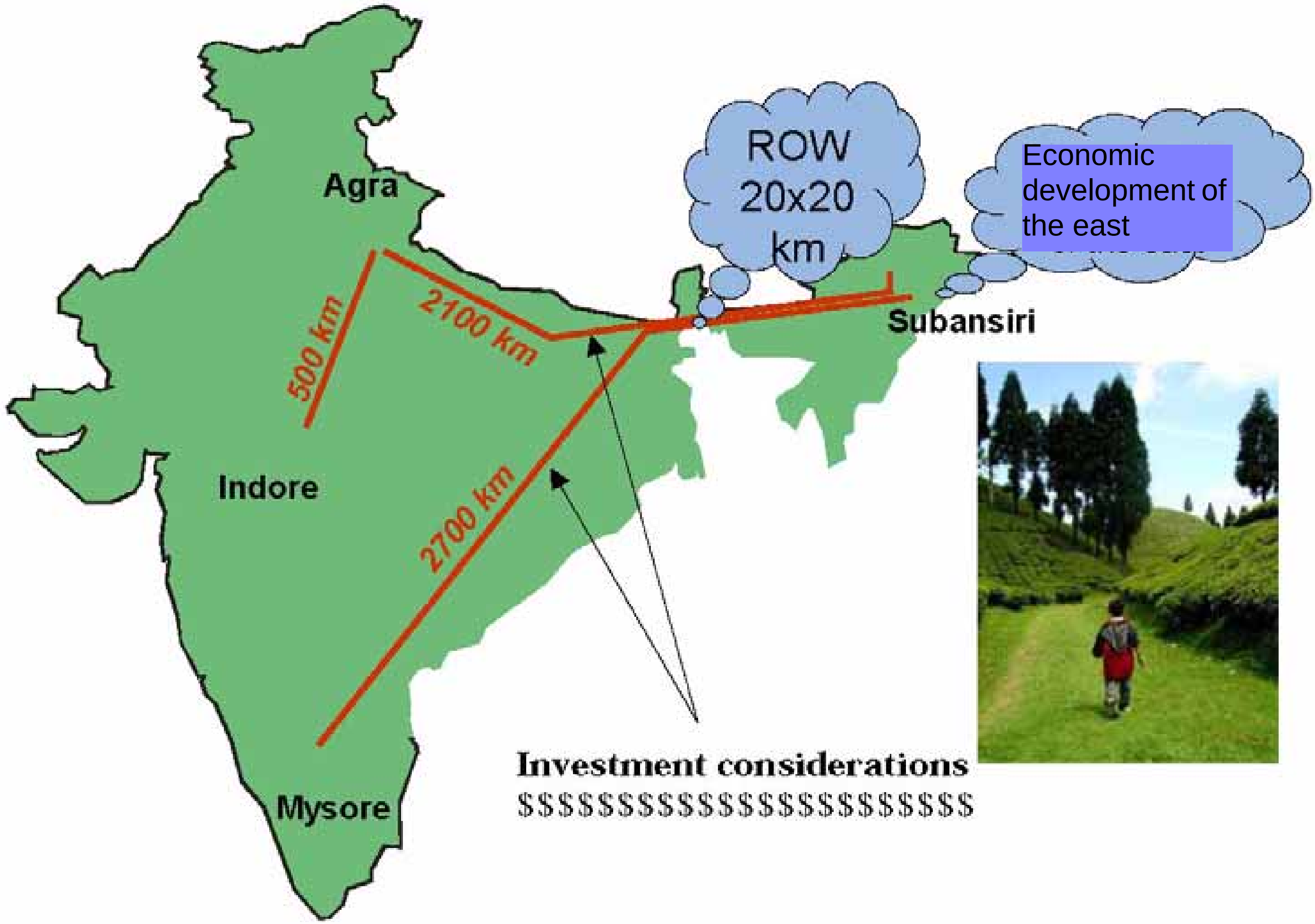
- At Chandrapur in Maharashtra, 1000 MW BB link and 1500 MW Rectifier end of Chandrapur – Padghe Bipole are linked through 19 km, 400 kV AC Line.

Future Multi-infeed HVDC Schemes

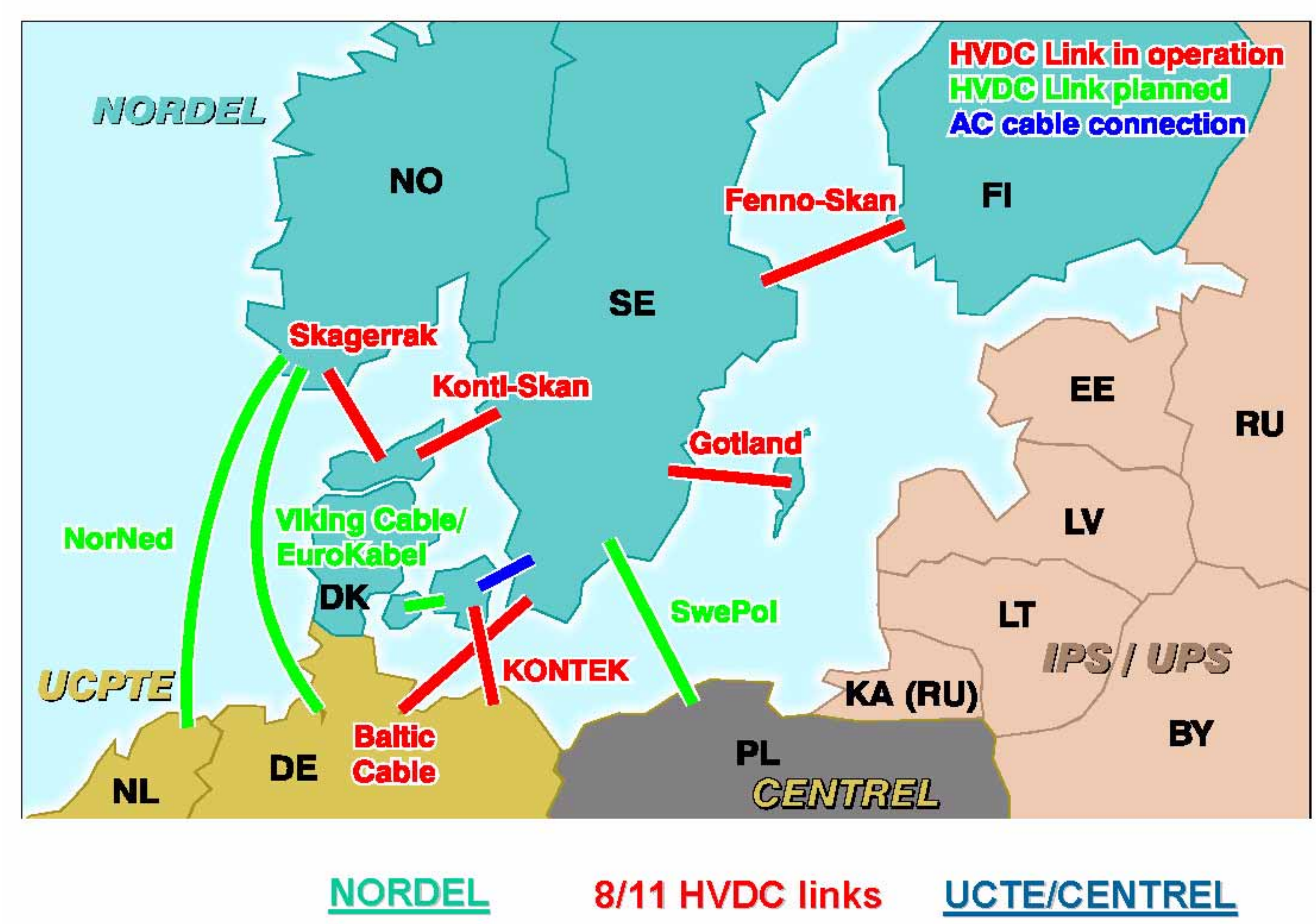
- Rihand - Dadri 1500 MW Bipole - In operation since 1991
- Ballia - Bhiwadi 2500 MW Bipole- To be commissioned by 2009.
- NER-Agra 3000 MW Bipole – Likely to commissioned by 2011.
- The Inverters of all three Bipole schemes are terminated in same network and are closely linked.



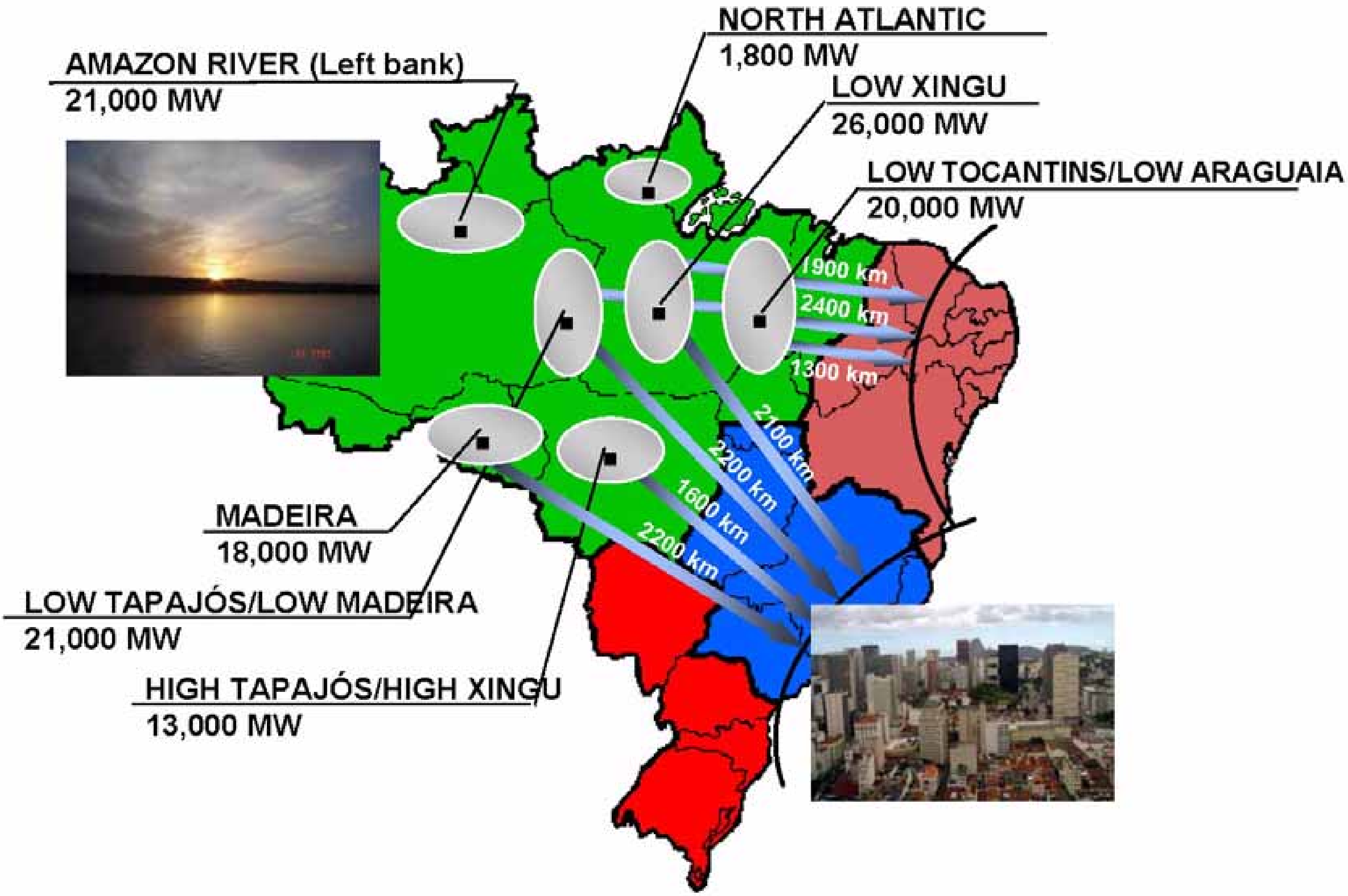
Brahmaputra River Hydro Power Development



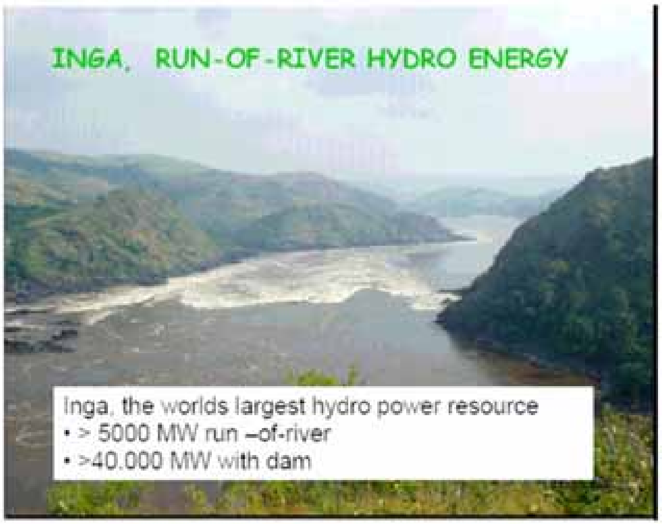
HVDC Projects in Scandinavia

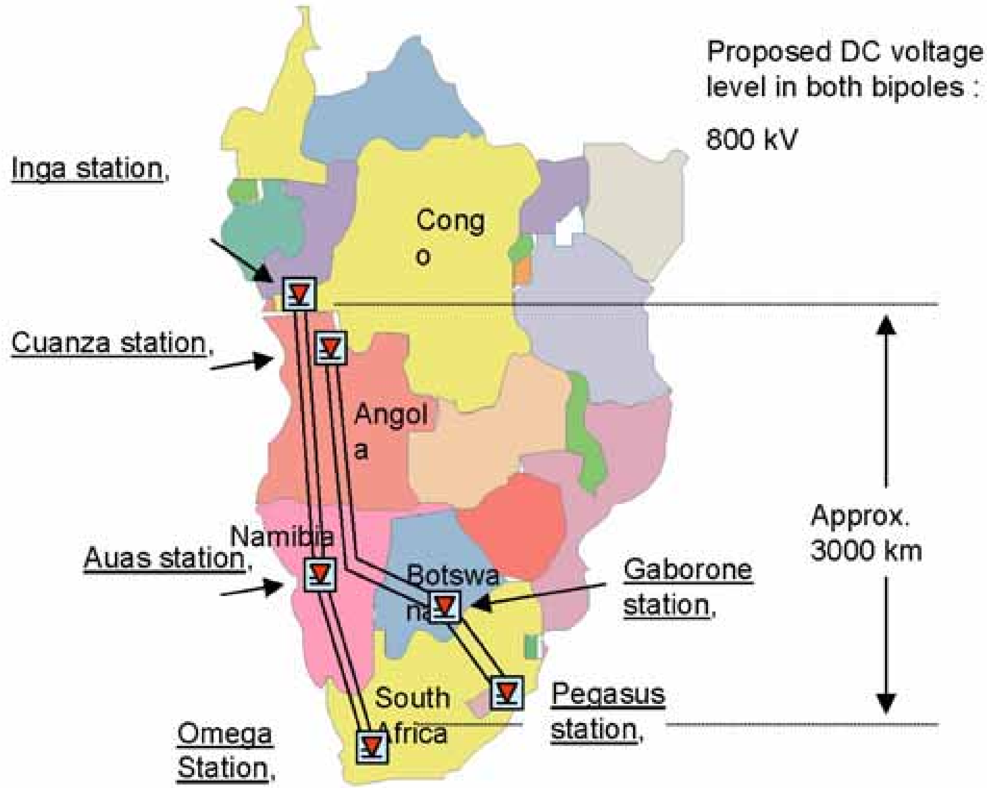


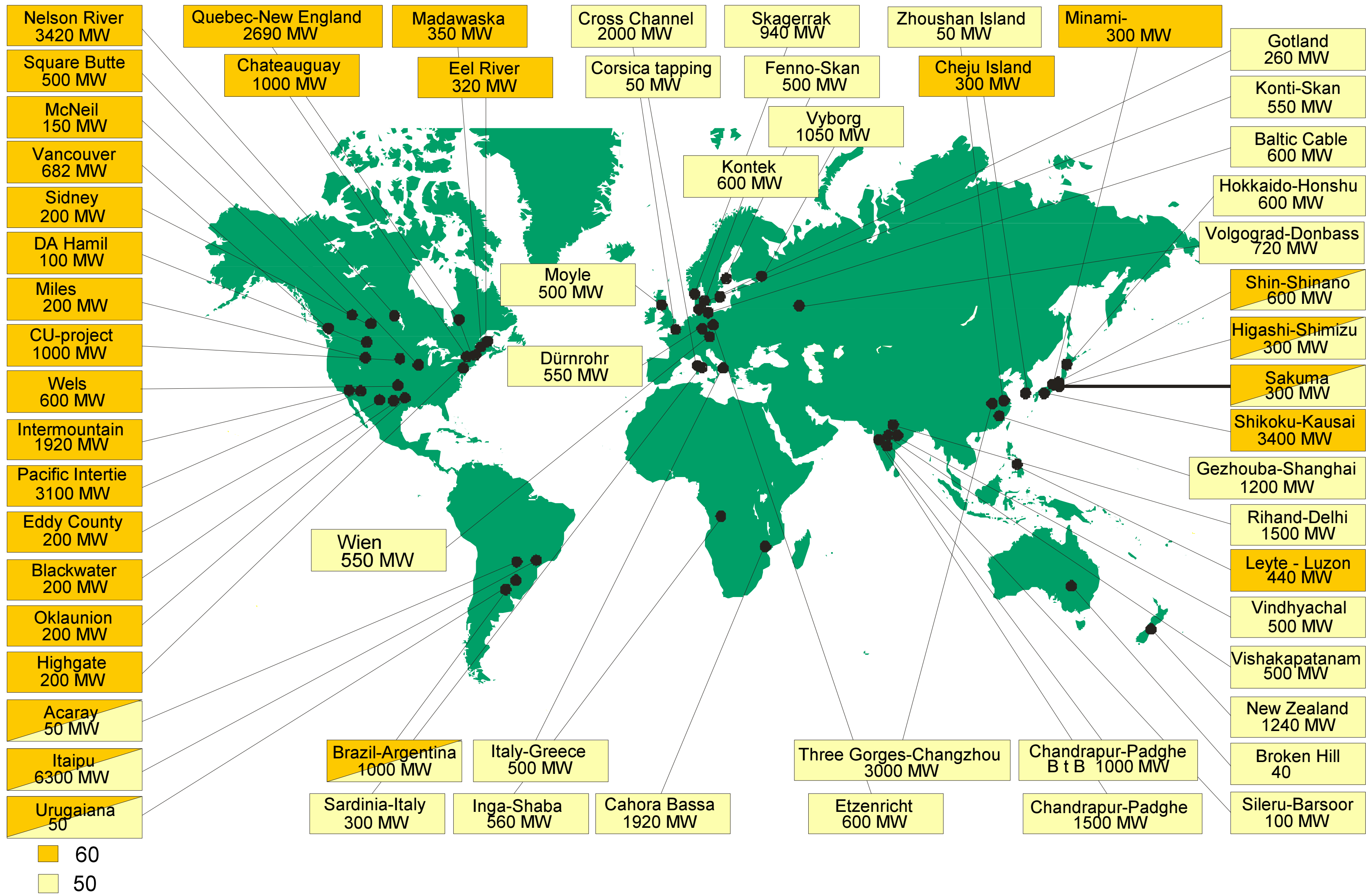
Brazil: Potential Amazonas River Projects



South Africa: West Cor Line







Nelson River 3420 MW
Square Butte 500 MW
McNeil 150 MW
Vancouver 682 MW
Sidney 200 MW
DA Hamil 100 MW
Miles 200 MW
CU-project 1000 MW
Wels 600 MW
Intermountain 1920 MW
Pacific Intertie 3100 MW
Eddy County 200 MW
Blackwater 200 MW
Oklaunion 200 MW
Highgate 200 MW
Acaray 50 MW
Itaipu 6300 MW
Urugaiana 50
Quebec-New England 2690 MW
Chateauguay 1000 MW
Madawaska 350 MW
Eel River 320 MW
Cross Channel 2000 MW
Corsica tapping 50 MW
Skagerrak 940 MW
Fenno-Skan 500 MW
Vyborg 1050 MW
Kontek 600 MW
Zhoushan Island 50 MW
Cheju Island 300 MW
Minami- 300 MW
Moyle 500 MW
Dürnrohr 550 MW
Wien 550 MW
Gotland 260 MW
Konti-Skan 550 MW
Baltic Cable 600 MW
Hokkaido-Honshu 600 MW
Volgograd-Donbass 720 MW
Shin-Shinano 600 MW
Higashi-Shimizu 300 MW
Sakuma 300 MW
Shikoku-Kausai 3400 MW
Gezhouba-Shanghai 1200 MW
Rihand-Delhi 1500 MW
Leyte - Luzon 440 MW
Vindhyachal 500 MW
Vishakapatanam 500 MW
New Zealand 1240 MW
Broken Hill 40
Sileru-Barsoor 100 MW
Brazil-Argentina 1000 MW
Italy-Greece 500 MW
Sardinia-Italy 300 MW
Inga-Shaba 560 MW
Cahora Bassa 1920 MW
Three Gorges-Changzhou 3000 MW
Etzenricht 600 MW
Chandrapur-Padghe B t B 1000 MW
Chandrapur-Padghe 1500 MW
60
50

Closing Comments

- 50+ years old HVDC technology is now mature, reliable and accepted globally. From its modest beginning, the technology has advanced considerably and maintained its leading edge image. Costs will continue to come down.

- The first 25 years were sustained by Mercury arc converters. The second 25 years where sustained by Thyristor technology. The next 25 years will be the era of the Transistor technology.

- There is no question of replacing AC transmission. However, AC-DC technology will work in a closely integrated fashion. The encroaching technology of FACTS has learned and gained from the enhancements made initially by HVDC systems. FACTS technology may challenge some of the traditional roles for HVDC applications as deregulation of the utility business will open up the market for increased interconnection of networks.

- HVDC transmission has unique characteristics which will provide it with new opportunities. Although the traditional applications of HVDC transmission will be maintained for bulk power transmission in places like China, India, S.America and Africa, the increasing desire for the exploitation of renewable resources will provide an opportunity for innovative solutions in the following applications:

- Connection of small dispersed generators to the grid,
- Alternatives to local generation, and
- Feeding to urban city centers (i.e. Super conducting cables).

- Further research/development will occur in the following areas:
  - Active harmonic filtering and reactive/active power support,
  - Multi-infeed converters,
  - Compensation of non-linear loads, and
  - Transient performance of the controller.