High Voltage Direct Current (HVDC) Power Transmission

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Conference of the Future of the Power system and Electromechanical Industry's Role.

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Outline

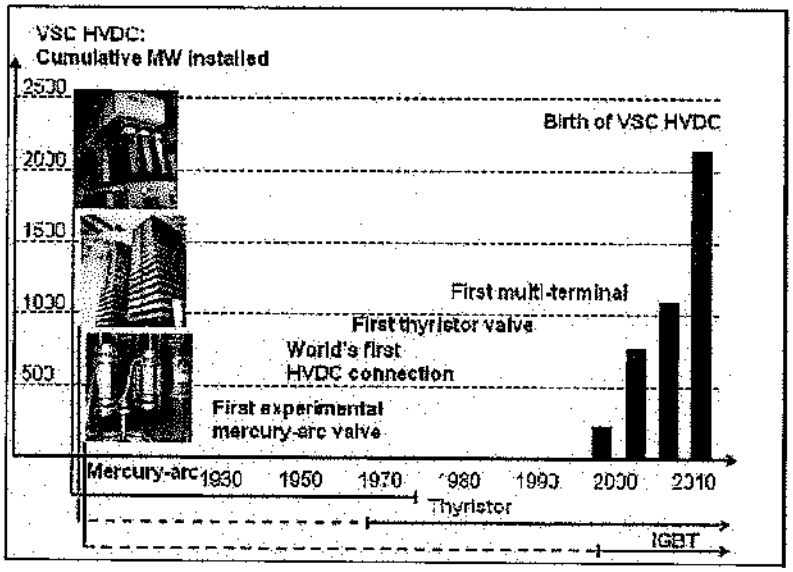
- History
- Comparison of AC and DC transmission
- The disadvantages of HVDC
- Cost of HVDC Transmission
- HVDC System Configurations and Components
- HVDC Transmission Configuration
- HVDC Transmission Working
- Researhes on HVDC Transmission

History

Important Milestones in the Development of HVDC technology

- Hewitt´s mercury-vapour rectifier, which appeared in 1901.
- Experiments with thyratrons in America 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 Voltage Source Converter for transmission in Gotland, Sweden ,1999

HVDC Transmission: History



Source: IEEE Magazine 2008

Comparison of AC and DC transmission

- Technical Comparison.
  - Stability limits,
  - Voltage Control,
  - Reactive Power Compensation in AC systems
- Transmission Costs Comparison.
  - Right-of-Way (RoW)

Reasons For AC Generation and Transmission

- Due to ease of transformation of voltage levels (simple transformer action).
- Alternating Current is universally utilized.—Both for GENERATION and LOADS and hence for Transmission.
- Generators are at remote places, away from the populated areas i.e. the load centers.

Limitations of HVAC Transmission

- Reactive Power Loses
- Stability
- Current Carrying Capability
- Skin Effect
- Ferranty Effect
- Difficulty on Power Flow Control

Advantages of HVDC Transmission

- No reactive power losses,
- No stability problem,
- No charging current,
- No skin & Ferranti Effect,
- Power control is possible,
- Requires less space compared to Ac same voltage rating and size,
- Less corona loss & radio inference.

Advantages of HVDC Transmission

- No technical limit to the length of a submarine cable connection.
- No requirement that the linked systems run in synchronism.
- No increase to the short circuit capacity imposed on AC switchgear.
- Immunity from impedance, phase angle, frequency or voltage fluctuations.
- Preserves independent management of frequency and generator control.
- Improves both the AC system's stability and, therefore, improves the internal power-carrying capacity, by modulation of power in response to frequency, power swing or line rating.

Advantages of HVDC Transmission

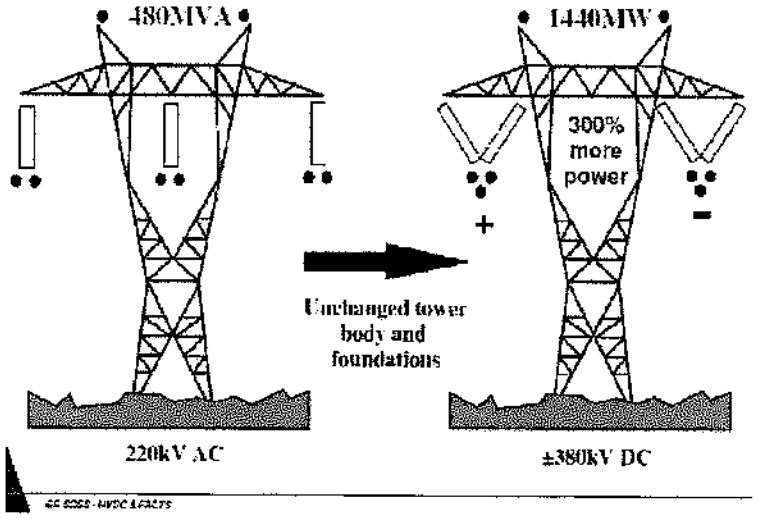
- Long power transmission without intermediate taps, for example, in remote areas.
- Power transmission and stabilization between unsynchronized AC distribution systems.
- Connecting a remote generating plant to the distribution grid.
- Undersea cables, where high capacitance causes additional AC losses.
- Facilitate power transmission between different countries that use AC at differing voltages and/or frequencies.
- Synchronize AC produced by renewable energy sources

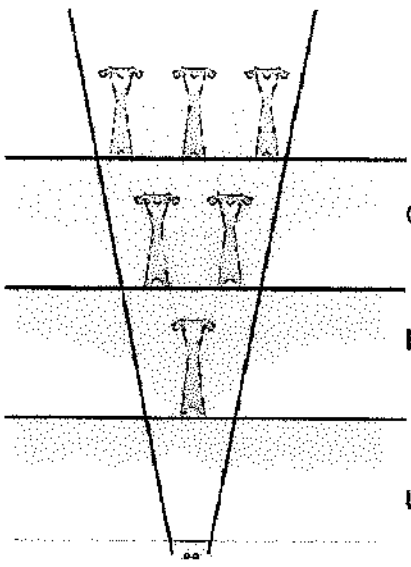
Advantages of HVDC Transmission

- **No reactive losses**
  - ✓Provision for high cable length
  - ✓Lower electrical losses
- **Accommodate Renewable Power**
  - ✓B2B connection
  - ✓Better Voltage Ride through Capability
- **The Power Flow on an HVDC link is Fully Controllable** (Fast and Accurate)
  - ✓The operator or automatic controller determines how much power flows via the link and in which direction Irrespective of the interconnected AC system conditions

Advantages of HVDC Transmission

- **An HVDC Link is asynchronous**
  - ✓The ac voltage and frequency in the two ac networks can be controlled independently of each other
  - ✓No need for common frequency control
- **The HVDC link can be used to improve the dynamic conditions in both of the interconnected ac networks (power system damping)**
  - ✓Can be controlled independently of AC system variations
- **HVDC links do not increase the Short Circuit Level of the connected systems**
- **Faults and oscillations don't transfer across HVDC interconnected systems**
  - ✓Firewall against cascading outages
  - ✓Faults in one ac systems will not effect the other ac system





RoW needed for
same power being transmitted

Traditional overhead line with HVAC

Overhead line improved with FACTS

HVDC Classic Overhead Line

Underground HVDC Cable

Substantially lower 1) Right of Way; 2) Losses

ABB

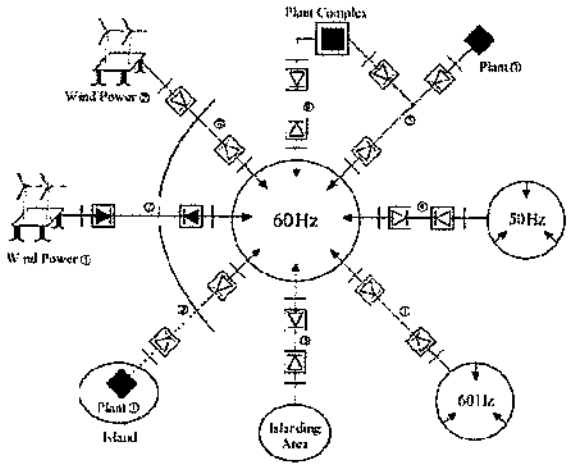


Figure 1.1 Various applications of an HVDC system.

Disadvantages of HVDC Transmission

The disadvantages of HVDC are in conversion, switching and control.

- Expensive cost of the equipment used for power conversion.
  - The dc converter stations are expensive,
  - Expensive inverters with limited overload capacity,
  - The cost of the inverters may not be offset by reductions in line construction cost and lower line loss.
- Higher losses in static inverters at smaller transmission distances
- High voltage DC circuit breakers are difficult to build because some mechanism must be included in the circuit breaker to force current to zero, otherwise arcing and contact wear would be too great to allow reliable switching.

Disadvantages of HVDC Transmission

- The converters generate harmonic voltages and currents on both ac and dc sides and therefore filters are needed
- Requirement of reactive power compensation for the converters.
- Control complexity.
- The DC lines might contribute to a voltage collapse during the swings that might come after a large disturbance followed by extreme reactive power consumption but using the active and reactive power modulation technique in the HVDC controller alleviates this problem.
- Operating a HVDC scheme requires many spare parts to be kept, often exclusively for one system, as HVDC systems are less standardized than AC systems and technology changes faster.

Table 1 Comparative costs of HVDC and EHV AC transmission alternatives

Alternative	DC Alternatives				AC Alternatives			Hybrid AC/DC Alternative		
	± 500 Kv Bipole	2 x ± 500 kV 2 bipoles	± 600 kV Bipole	±800 kV Bipole	500 kV 2 Single Ckt	500 kV Double Ckt	765 kV 2 Sngl Ckt	± 500 kV Bipole	500 kV Single Ckt	Total AC + DC
Capital Cost										
Rated Power (MW)	3000	4000	3000	3000	3000	3000	3000	3000	1500	4500
Station costs including reactive compensation (M$)	$420	$680	$465	$510	$542	$542	$630	$420	$302	$722
Transmission line cost (M$/mile)	$1.60	$1.60	$1.80	$1.95	$2.00	$1.20	$2.80	$1.60	$2.00	
Distance in miles	750	1,500	750	750	1,500	750	1,500	750	750	1,500
Transmission Line Cost (M$)	$1,200	$2,400	$1,350	$1,463	$3,000	$2,400	$4,200	$1,200	$1,500	$2,700
Total Cost (M$)	$1,620	$3,080	$1,815	$1,973	$3,542	$2,942	$4,830	$1,620	$1,802	$3,422
Annual Payment, 30 years @ 10%	$172	$327	$193	$209	$376	$312	$512	$172	$191	$363
Cost per kW-Yr	$57.28	$81.68	$64.18	$69.75	$125.34	$104.03	$170.77	$57.28	$127.48	$80.66
Cost per MWh @ 65% Utilization Factor	$7.69	$10.97	$8.62	$9.37	$16.82	$13.97	$22.91	$7.69	$17.13	$10.83
Losses @ full load	193	144	148	103	208	208	139	106	48	154
Losses at full load in %	6.44%	4.80%	4.93%	3.43%	6.93%	6.93%	4.62%	5.29%	4.79%	5.12%
Capitalized cost of losses @ $1500 kW (M$)	$246	$171	$188	$131	$265	$265	$177	$135	$61	$196
Parameters:										
Interest rate %	10%									
Capitalized cost of losses $/kW	$1,500									

Notes
AC current assumes 94% pf
Full load converter station losses = 0.75% per station
Total substation losses (transformers, reactors) assumed = 0.5% of rated power

Source: IEEE Magazine 2008

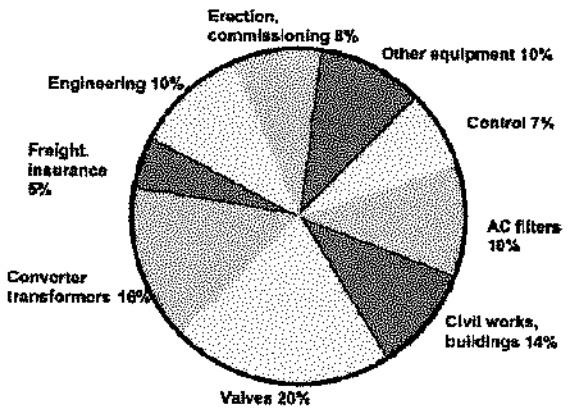
Cost of HVDC Transmission

The cost of an HVDC transmission system depends on many factors, such as:

- Power capacity to be transmitted,
- Type of transmission medium,
- Environmental conditions and
- Other safety, regulatory requirements etc
- Even when these are available, the options available for optimal design (different commutation techniques, variety of filters, transformers etc.) render it is difficult to give a cost figure for an HVDC system.

Cost of HVDC Transmission

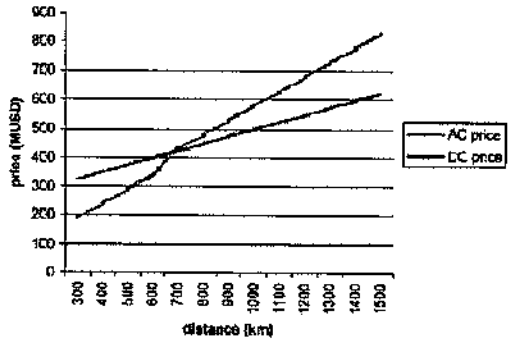
A typical cost structure for the converter stations could be as follows:



Cost structure of HVDC

Cost of HVDC Transmission

- As a guidance, an example showing the price variation for an AC transmission compared with an**HVDC transmission for 2000 MW** is presented below.



Price variation of HVDC and HVAC

Assumptions made in the price calculations

For the AC transmission a double circuit is assumed with a price per km of 250 kUSD/km(each), AC substations and series compensation (above 600 km) are estimated to 80 MUSD.

For the HVDC transmission a bipolar OH line was assumed with a price per km of 250 kUSD/km, converter stations are estimated to 250 MUSD.

Cost of HVDC Transmission

The cost of an HVDC transmission system depends on many factors, such as:

- Power capacity to be transmitted,
- Type of transmission medium,
- Environmental conditions and
- Other safety, regulatory requirements etc
- Even when these are available, the options available for optimal design (different commutation techniques, variety of filters, transformers etc.) render it is difficult to give a cost figure for an HVDC system.

Cost of HVDC Transmission

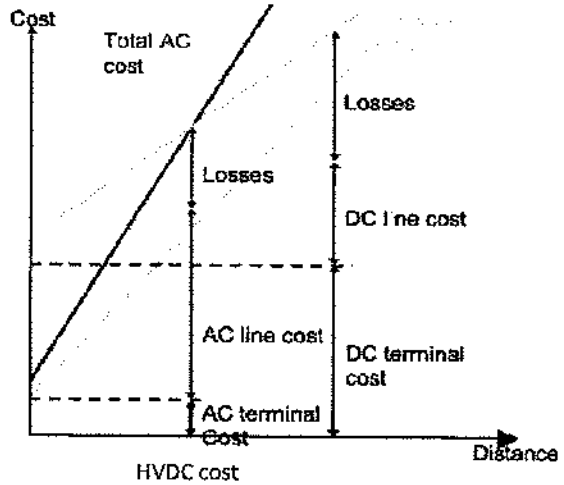
Two different comparisons are needed to highlight the cost comparison between high voltage AC and HVDC systems:

- One is between thyristor based HVDC systems and a high voltage AC transmission system; AND
- The other between a VSC based HVDC system; an AC system and a local generation source.

Cost of HVDC Transmission

- The investment costs for HVDC converter stations are higher than for high voltage AC substations.
- On the other hand, the costs of transmission medium, land acquisition/right-of-way costs are lower in the HVDC case.
- Moreover, the **operation and maintenance costs** are lower in the HVDC case.
- Initial loss levels are higher in the HVDC system, but they do not vary with distance.
- In contrast, loss levels increase with distance in a high voltage AC system.

Cost of HVDC Transmission

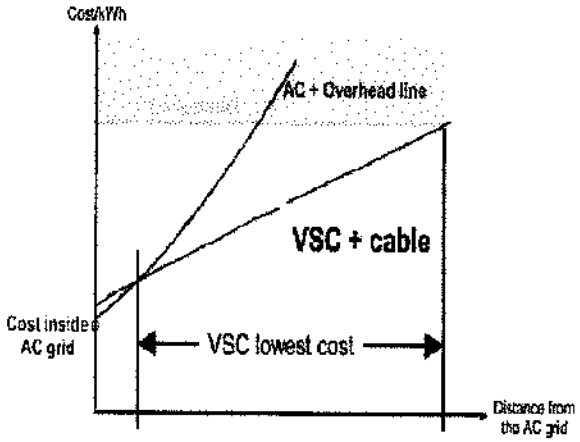


HVDC cost breakdown

The breakeven distance depends on several factors, as transmission medium , different local aspects.

When comparing high voltage AC with HVDC transmission, **it is important to compare a bipolar HVDC transmission to a double-circuit high voltage AC transmission**, especially when availability and reliability is considered

Cost of HVDC Transmission



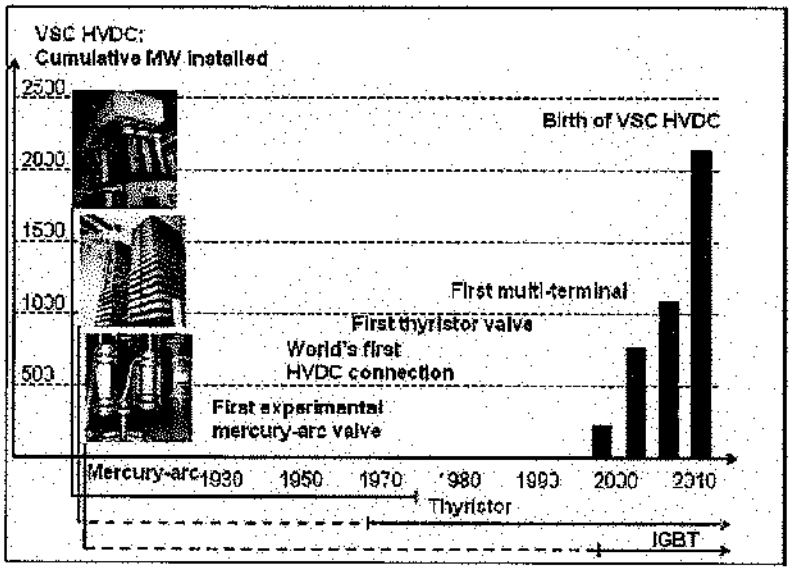
HVDCcost breakdown

VSC based HVDC system versus an AC system or a local generation source

VSC based HVDC systems cater to the small power applications (up to 200MW) and relatively shorter distances (hundred of km) segment of the power transmission spectrum.

The graph below shows that, the **VSC based HVDC system is the better alternative economically** when compared to either an high voltage AC system or a generation source local to the load centre (e.g., diesel generator).

HVDC Transmission: Concept



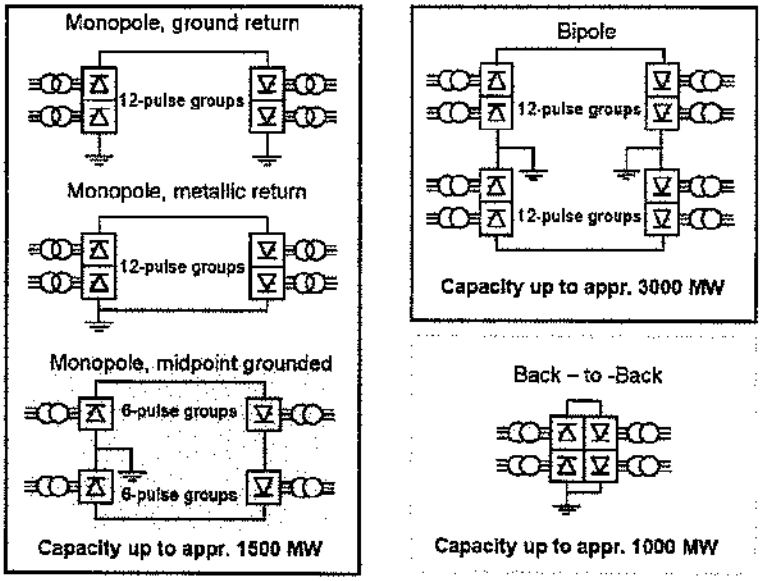
Source: IEEE Magazine 2008

HVDC System Configurations and Components

HVDC links can be broadly classified into:

- Monopolar links
- Bipolar links
- Homopolar links
- Back-to-back links
- Multiterminal links

HVDC System Configurations and Components [ABB]



Monopolar links

- It uses one conductor
- The return path is provided by ground or water
- Use of this system is mainly due to cost considerations
- A metallic return may be used where earth resistivity is too high
- This configuration type is the first step towards a bipolar link

Bipolar links

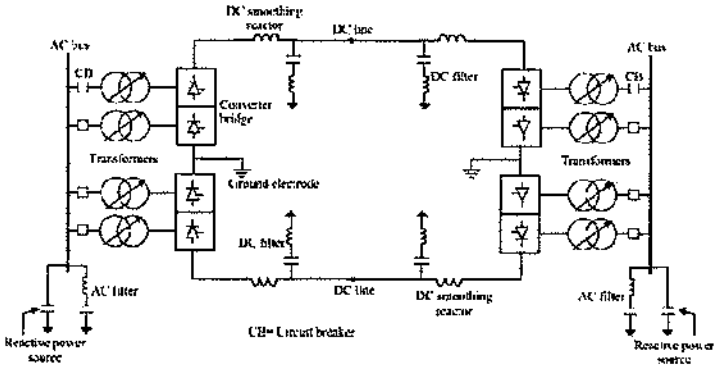
- It uses two conductors, one positive and the other negative
- Each terminal has two converters of equal rated voltage, connected in series on the DC side
- The junctions between the converters is grounded
- Currents in the two poles are equal and there is no ground current
- If one pole is isolated due to fault, the other pole can operate with ground and carry half the rated load (or more using overload capabilities of its converter line)

Homopolar links

- It has two or more conductors all having the same polarity, usually negative
- Since the corona effect in DC transmission lines is less for negative polarity, homopolar link is usually operated with negative polarity
- The return path for such a system is through ground

Components of HVDC Transmission Systems

1. Converters
2. Smoothing reactors
3. Harmonic filters
4. Reactive power supplies
5. Electrodes
6. DC lines
7. AC circuit breakers



A Schematic of bipolar HVDC system identifying main components [ ]

Components of HVDC Transmission Systems

Converters

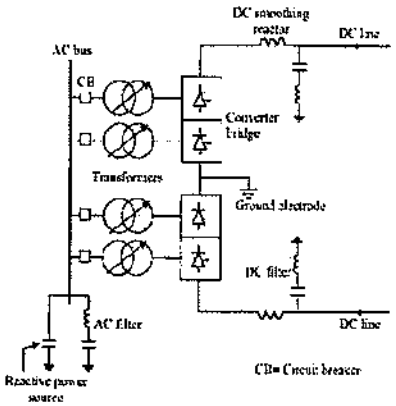
- They perform AC/DC and DC/AC conversion
- They consist of valve bridges and transformers
- Valve bridge consists of high voltage valves connected in a 6-pulse or 12-pulse arrangement
- The transformers are ungrounded such that the DC system will be able to establish its own reference to ground

Smoothing reactors

- They are high reactors with inductance as high as 1 H in series with each pole
- They serve the following:
  - They decrease harmonics in voltages and currents in DC lines
  - They prevent commutation failures in inverters
  - Prevent current from being discontinuous for light loads

Harmonic filters

- Converters generate harmonics in voltages and currents. These harmonics may cause overheating of capacitors and nearby generators and interference with telecommunication systems
- Harmonic filters are used to mitigate these harmonics



Components of HVDC Transmission Systems

Reactive power supplies

- Under steady state condition conditions, the reactive power consumed by the converter is about 50% of the active power transferred
- Under transient conditions it could be much higher
- Reactive power is, therefore, provided near the converters
- For a strong AC power system, this reactive power is provided by a shunt capacitor

Electrodes

- Electrodes are conductors that provide connection to the earth for neutral. They have large surface to minimize current densities and surface voltage gradients

DC lines

- They may be overhead lines or cables
- DC lines are very similar to AC lines

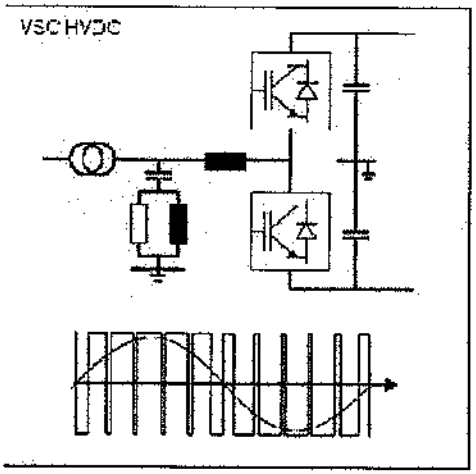
AC circuit breakers

- They used to clear faults in the transformer and for taking the DC link out of service
- They are not used for clearing DC faults
- DC faults are cleared by converter control more rapidly

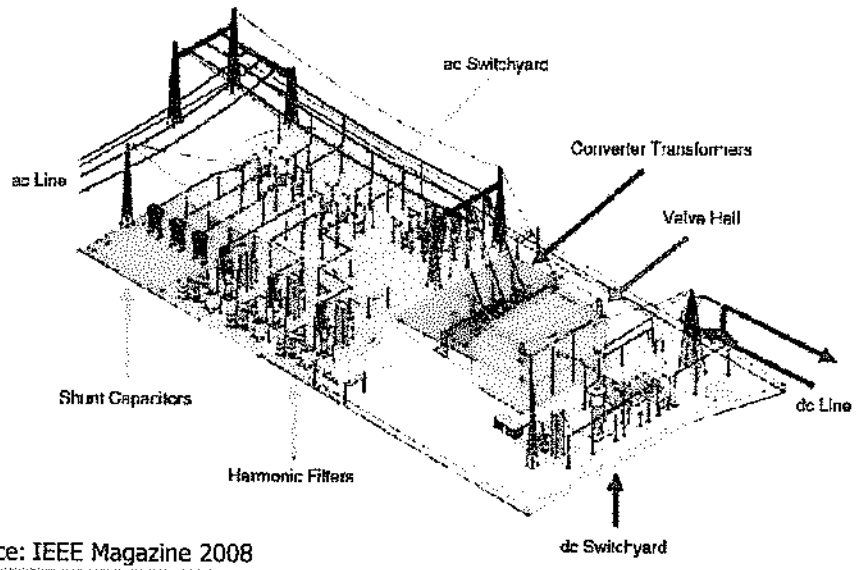
HVDC Transmission: Concept

VSC Based HVDC

- Natural Commutation Based HVDC
- IGBT valves
- P and Q (or U) control
- Can feed in passive networks
- Smaller footprint
- Less filters needed

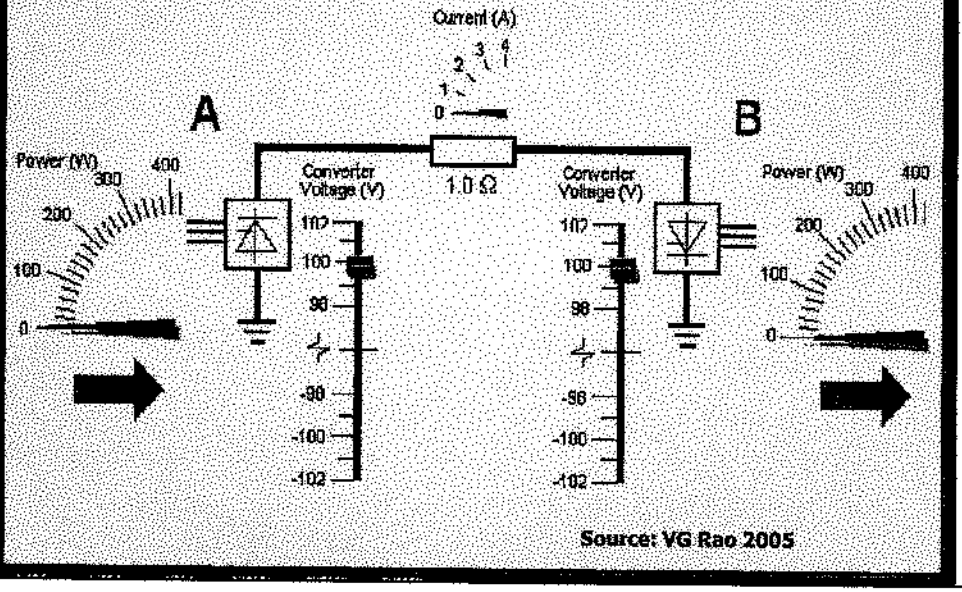


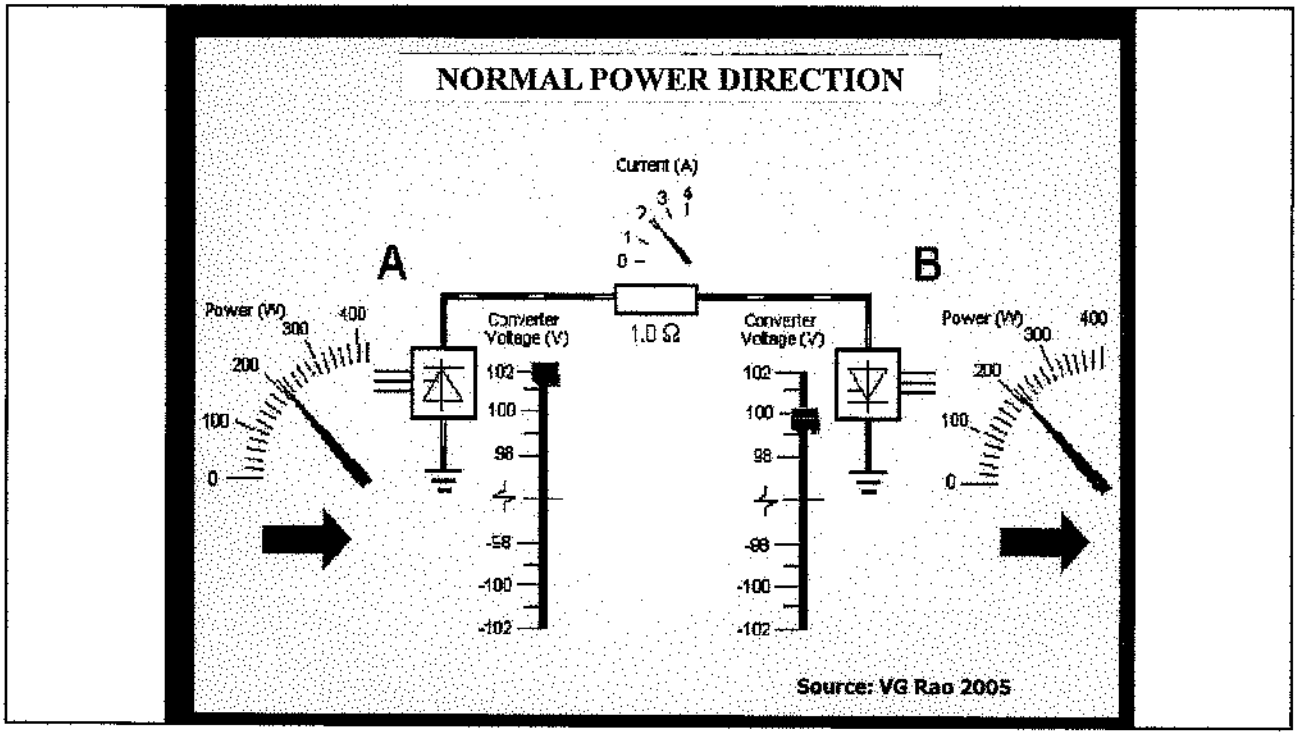
HVDC Transmission: Configuration

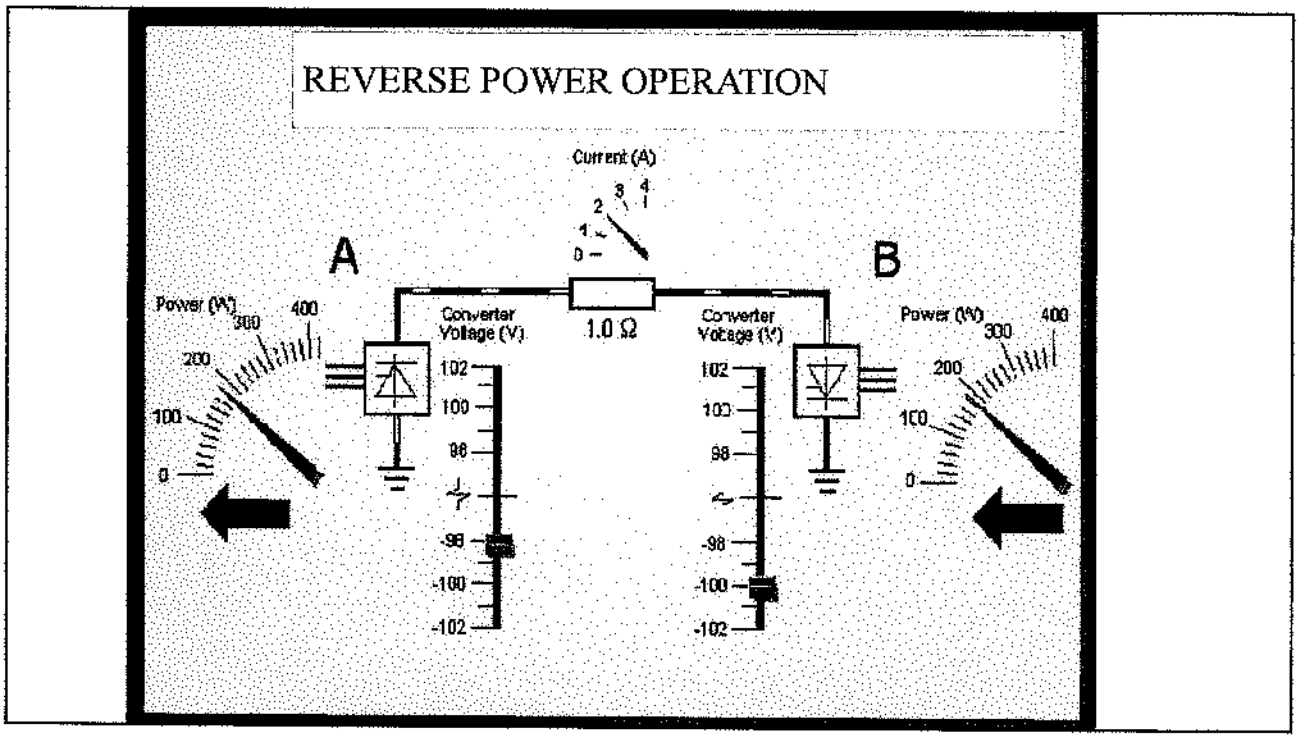


Source: IEEE Magazine 2008

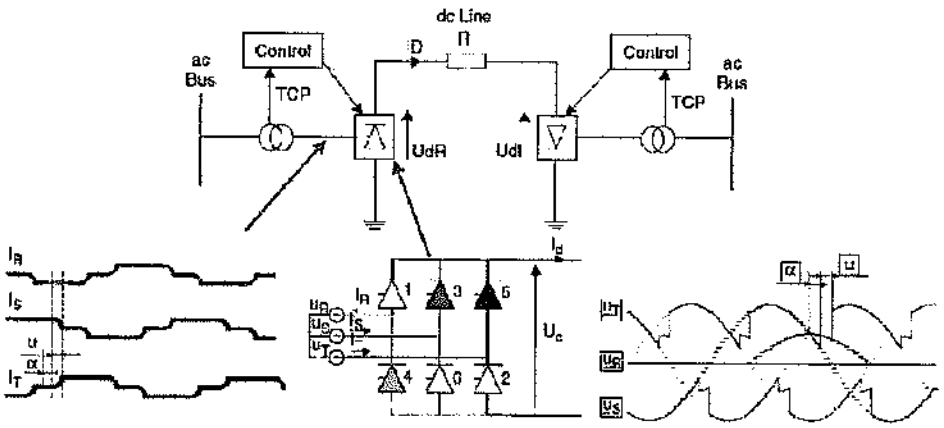
How does HVDC work?



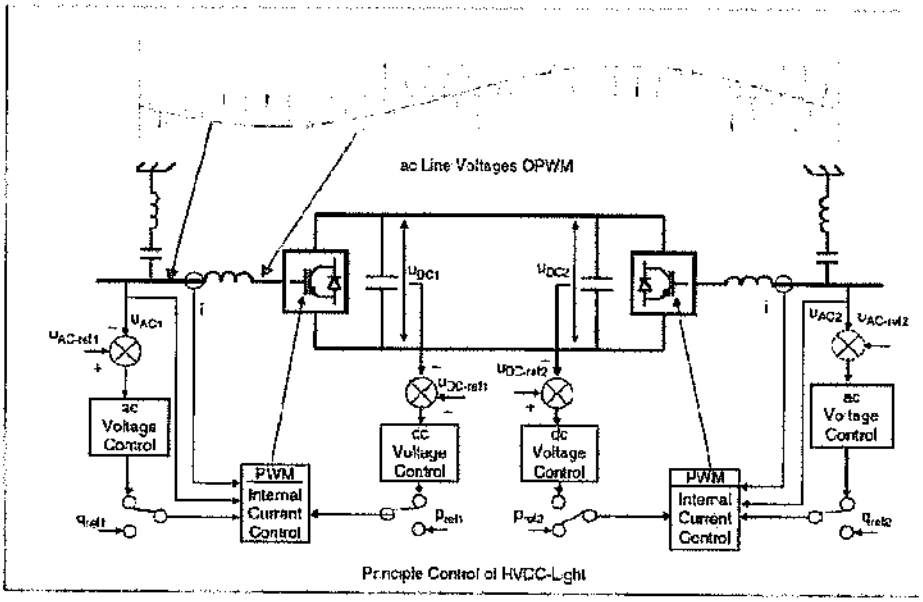

NORMAL POWER DIRECTION
Current (A)
A
B
Power (W)
Converter Voltage (V)
1.0 Ω
Converter Voltage (V)
Power (W)
Source: VG Rao 2005


REVERSE POWER OPERATION
Current (A)
A
B
Power (W)
Converter Voltage (V)
1.0 Ω
Converter Voltage (V)
Power (W)

HVDC Transmission: Working



HVDC Transmission: Working (HVDC – Light)



Overview of HVDC Applications

Overview of HVDC Applications

	Long distance transmission over land	Long distance transmission over sea	Interconnections of asynchronous networks	Windmill connection to network	Feed of small isolated loads
Natural commutated HVDC with OH lines	X		X		
Natural commutated HVDC with sea cables		X	X		
VSC Converters in Back-to-Back			X	X	
VSC Converters with Land or Sea Cables	X	X	X	X	X

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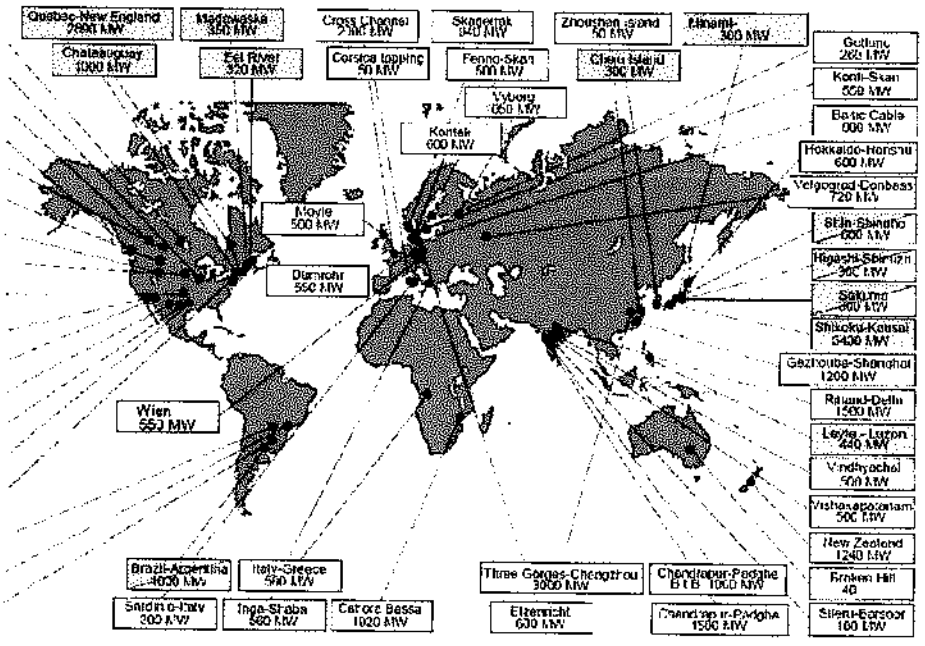
HVDC TRANSMISSION: WORLD PICTURE



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- HVDC transmission has number of benefits for bulk power transmission; namely efficiency, resilience, interoperability etc.
- In short distance, B2B HVDC provides smart link for frequency conversion and renewable power integration.
- For cross-border transmission link, HVDC is a good candidate.
- Combining with FACTS technology, HVDC provides a infrastructure of the future Smart Transmission Grid.

Researhes on HVDC Transmission

It will therefore be necessary to rank and prioritize the projects based on the on-going needs.

- The broad HVDC research themes include:
- Long distance transmission and the provision of telecommunications
- External insulation
- Corona and field effects
- Performance of lines and systems in Southern Africa
- Exploitation of VSC and HVDC cable technology
- Innovation

Reseahes on HVDC Transmission

Based on these research themes, the broad HVDC research projects may include:
(i.) Long distance Undersea HVDC cables and VSC technology in the Southern Africa.
(ii.) Long distance transmission and the provision of telecommunications over HVDC lines.
(iii.) External insulation, insulating materials
(iv.) Corona, partial discharge and field effects