New Converter Topologies for High-Voltage Dc Converters

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Outline

- Brief History of HVDC Transmission
- Conventional HVDC and its Problems
- Capacitor Commutated Type Converters
- Voltage Sourced Converter Based HVDC
  - PWM Based
  - Multi-level Modular
Originally HVDC was used for Distribution (Edison’s Dc Dynamo) (pre 1900)

Disadvantages: Complicated machinery (dc commutator), lack of voltage transformability

Ac overcame these disadvantages

However:
Long distance DC transmission is not adversely affected by Transmission Line or Cable inductance/capacitance
• Why not generate and consume ac but transmit dc?
• Thury (early 1900’s) in France: ~100 km Dc transmission
  – Disadvantage: Ac/Dc Converter – motor generator set
• Use of Power Electronic Devices (Mercury-Arc Valves) made for more efficient Ac/Dc Conversion
• First Scheme Based on Modern day concepts:
  – Gotland (Sweden Mainland-Island) 1954,. Used Grid Control Mercury Arc Rectifiers. Manufacturer ASEA 100 kV (Monopolar), 20 MW under-sea transmission spanning 96 km.

• First Canadian Scheme:
  – Vancouver - Vancouver Island, 1968, +/-130 kV , 312 MW, 41 km overheadline, 32 km underwater cable.

• Last Mercury Arc Scheme:
  – Nelson River Bipole 1 in Manitoba (1800 MW, +/-450 kV)
HVDC: Brief History…

• First Canadian Scheme:
  – Vancouver - Vancouver Island, 1968, +/-130 kV, 312 MW, 41 km overheadline, 32 km underwater cable

• First Use of Solid-State Thyristors:
  – Eel River (New Brunswick-Quebec, Canada) :1972, +/-80 kV, 350MW. Back to back connection between two utilities.

• Large HVDC Systems:
  – Itaipu (Brazil, Generation: Paraguay/Brazil) +/- 600 kV, 6000 MW, over850 km. Main reason for Dc: Paraguay is 50 Hz, Brazil is 60 Hz.
  – Volvograd Dunbas: USSR, 6000 MW?
  – Three Gorges, China (10,000 MW), +/- 600 kV
Manitoba:

– Nelson River Bipole-III (Henday-Riel)
– 1400 km? 2200 MW +/- 500 kV
Manitoba Hydro’s Nelson River HVDC Transmission System: 4 GW over 950 km (approx. 70% of total Manitoba installed generation)

Approx. 40% of MH revenues come from exports

Manitoba Dams are a reservoir that permits power cycling

Revenue generated includes power cycling (day/night)
Many technology revisions
Conventional HVDC Transmission - Advantages

- HVDC Offers many advantages over Ac Transmission
  - Lower Transmission losses
  - Smaller rights of way
  - Asynchronous Connection Between Ac Networks - improved stability limit
  - Possibility of Long-distance underground/underwater cable transmission
  - ..... etc
Basics of HVDC LCC Converter Operation

Dc Converter Building Block: Thyristor

Fig 2.1: Thyristor
Conventional HVDC: LCC Operation and Limitations:

- Converter Operation is significantly impacted by ac network
- Commutation voltage drop

Vd

Id
However there are some disadvantages:

- The terminating ac networks must provide the commutation voltage
- Require reactive power at the converter which must vary with loading (i.e. switched filter banks)
- Difficulty in operating into weak ac systems (Short Circuit ratios under 2)
- Generates Ad and Dc side Harmonics
New HVDC Converter Configurations

• New converter configurations have been developed to address these issues:
• Capacitor Commutated Configurations
  – CCC
  – CSCC
• Voltage Sourced Converter (VSC) based Configurations
  – PWM / SHPWM based Converters
  – Modular Multilevel Converters (MMC)
Capacitor Commutated Converter

- The CCC uses the voltage across its series capacitors to assist in the commutation process.
- It can operate into very weak ac networks.
- The reactive power absorbed by the converter is minimal.
- Can be operated even with leading power factor.
CCC Operation

(a) Ac Current

(I_d = 1 kA)

(b) Cap. Voltage

(V_{cap}(kV))

(c) Line-line voltages

(L-L Voltage (kV))
Reactive Power Requirement
Ac Filter Issues

- A low Mvar filter is also sharply tuned and hence subject to detuning with component variations.
- Solution:
  - Contune Filter (inductor can be tuned via bias dc current)
  - Active Ac Filter
CCC Steady State Operating Characteristics
CCC Configuration: Advantages

- The risk of commutation failure is minimized—can operate into very weak ac networks.
- The apparent extinction angle (measured w.r.t. converter bus) is small, even negative—hence power factor is near 1.0.
- Filter switching can be avoided.
- Although valves are more expensive, the converter transformer is cheaper and the valve short circuit current is smaller than for the LCC.
- The Series Capacitors do not cause ferroresonance, as they are out of the circuit when converter is blocked.
CCC Configuration: Disadvantages

- The converter cost is slightly larger
- The series capacitors must be protected against overvoltages resulting from overcharging
- The energy storage on the series capacitors negatively impacts the dynamic response in unbalanced conditions (i.e. recovery from I-g faults)
CCC Installations worldwide:

• Garabi Converter Station, Brazil/Argentina

• 2200 MW, +/- 70 kV back to back system connecting 50 Hz and 60 Hz networks

• CCC used because SCMVA can be as low as 2000

• CCC Avoids installation of Synch. Compensator

Courtesy: ABB
Garabi CCC HVDC: Major Components

Outdoor Valves

“Contune” Filters

Series Capacitors

All Pictures: Courtesy ABB
• Sixth in sequence of Back to Back HVDC Stations connecting the Eastern and Western North American Systems

• 200 MW, +/- 12.85 kV

• CCC selected to lower comm. Fail risk due to extremely weak ac networks.
Alternate Topology: CSCC

- Requires only LCC
- Behaviour very similar to CCC
- Series capacitors must be switched to avoid ferroresonance
- Capacitance level can be adjusted as per system conditions

- Simplifies capacitor arrangement in 12-pulse configurations
- For radial ac feeds, capacitors can be placed in each ac line for accurate control of power in each ac feeder

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New Approaches to LCC: The GPFC

- Filters are between transformer and converter
- Uses a *Conventional* Transformer
- Transformer at remote end can be eliminated
- Results in reduced cost
Cost Distribution for Converter Station

- Civil Works & Buildings: 14%
- Freight & Insurance: 5%
- Valves: 20%
- Other Equipment: 10%
- Installation & Commissioning: 8%
- Engineering: 10%
- Controls: 7%
- Ac Filters: 10%
- Converter Transformers: 16%

Source: Martin Marietta Energy Systems
Oak Ridge National Laboratories,
PO Box 2002, Oak Ridge,
TN 37831-6501, U.S.A.

Fig 2.24: Cost Distribution for a DC Converter Station
IEEE Southern Alberta Section, Sept. 12, 2011

GPFC-HVDC 12-pulse arrangement

Fig 5.19 Twelve Pulse GPFC Scheme
Voltage Sourced Converter (VSC) Based HVDC

- Thyristor Based Converters generally require an ac network to provide commutation voltage
- Hence they are significantly affected by ac system conditions, etc.
- The VSC uses switches that can be turned on as well as turned-off using externally generated commands
- Hence the impact of ac system conditions on performance can be minimized
VSC: Basic Operating Principle

VSC Switches are turned on and off on command.
Three Phase Arrangement
VSC Voltage Magnitude and Phase Control

- Pulse Width Modulation
- Fundamental freq. component of output follows the desired ‘signal’ reference waveform
- Harmonics are pushed to the high (easily filtered) range
- Disadvantage:
  - Difficult to extend single bridge to High Voltages
  - High Switching Losses
VSC: Real and Reactive Power Control

Id* controls the real power
Iq* controls the reactive power

Id* is the output of a dc bus capacitor voltage controller

Fig 2: PWM Waveforms
Decoupled Control ensures that an order change of id* does not cause a transient in iq (and vice versa)

# VSC versus LCC HVDC

<table>
<thead>
<tr>
<th>LCC HVDC</th>
<th>VSC HVDC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line-commutated</td>
<td>Gate-turnoff</td>
</tr>
<tr>
<td>Current Source</td>
<td>Voltage Sourced</td>
</tr>
<tr>
<td>Poorer performance with weak ac systems</td>
<td>Less affected by system strength</td>
</tr>
<tr>
<td>Cheaper for High Power</td>
<td>More expensive, but may be comparable when all aspects are considered</td>
</tr>
<tr>
<td>Lower Losses</td>
<td>Higher losses (improved by new topologies)</td>
</tr>
<tr>
<td>Power direction reversed by voltage reversal</td>
<td>Power direction changed by current reversal</td>
</tr>
<tr>
<td>Difficult to use in a dc grid</td>
<td>Well suited for dc grid</td>
</tr>
<tr>
<td>Ideal for dc transmission with overhead lines</td>
<td>Ideal for weak ac systems, cable transmission or dc grids</td>
</tr>
</tbody>
</table>

![Diagram](image)

**IEEE Southern Alberta Section, Sept. 12., 2011**
Example of VSC HVDC: Troll Link

- **Purpose:** To Run Compressor Motors for Offshore Gas Extraction
- **Gas Pressure from Wells decreases as gas is extracted, hence a compressor is needed to force gas through pipeline**
- **A conventional precompression project, with gas turbines, would have resulted in annual emissions of some 230,000 tons of CO2 and 230 tons of NOx.**
Location: Offshore Norway
One Half of Troll HVDC System
Troll VSC HVDC: Ratings

**Main data**
- Rated power: 2x40 MW
- DC voltage: ±60 kV
- AC system voltage: 132 kV
- AC motor voltage: 56 kV

**AC filters**
- Kollsnes: 39’th and 78’th harmonic
- Troll A: 33’th and 66’th harmonic

**IGBT valves**
- Valve type: Two level
- Cooling system: Water
- IGBT type: 2,5 kV/500 A

**Cable**
- Type: Triple extruded polymer
- Cross section: 300 mm²
- Length: 4 x 70 km

**Transformers (Kollsnes only)**
- Type: Three-phase, two winding
- Rated power: 52 MVA
Multilevel Modular Converter (MMC)

- PWM converters produce a waveform with high level of higher order harmonics
- Result: High Switching Losses, EMI, Stresses etc.
- With High Voltages, Device ratings become an issue

Simple Voltage Sourced Inverter
Basic unit of MMC scheme – Submodule

\[ T_x \] – IGBT
\[ D_x \] – Diode
\[ C \] – Storage Capacitor

\[ x = 1, 2 \]
Each submodule acts as a controllable voltage source.

Control States of a Sub-module

<table>
<thead>
<tr>
<th>Device ON</th>
<th>$V_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SW$_1$</td>
<td>$V_c$</td>
</tr>
<tr>
<td>SW$_2$</td>
<td>0</td>
</tr>
</tbody>
</table>
MMC Topology

**MMC basic scheme**

- $+V_d$
- $-V_d$

1. $T_1$, $D_1$, $T_2$, $D_2$, $C$
2. $SM_i$, $SM_j$, $SM_n$
3. $B$, $C$

**Equations:**

$$i + V_d - V_d = 0$$
Introduction – MMC Topology

**MMC basic scheme**

![Diagram showing MMC topology]

Phase Voltage

(n = 10)
MMC Controls

- Reference Waveform is quantized to determine switching instants
- Special algorithms for Capacitor voltage balancing and ensuring sharing of module duty
- Higher level controls identical to other VSC topologies (i.e. decoupled id/iq control etc.)
Trans-Bay HVDC Project

• **Purpose:**
  – Congestion Relief
  – Improvement of security of supply
  – Retirement of Generation in San Francisco Area

• **Customer** Trans Bay Cable, LLC

• **Location** Pittsburg, California, and San Francisco, California

• **Power Rating** 400 MW

• **Voltage levels** ± 200 kV DC, 230 kV /138 kV, 60 Hz

• **Type of plant** 85 km HVDC PLUS submarine cable

• **Type of Thyristor** IGBT
Transbay Cable (San Francisco-Oakland)

Trans Bay Cable Project – Submarine Cable Route

Courtesy: Siemens
Trans Bay Cable Project – Need Study Results: Plots Showing Greater Bay Area Power Flows – Jefferson-Martin ON, Hunters Point OFF, Potrero (or CCSF Peakers) ON, Trans Bay Cable OFF

Courtesy: Siemens
Trans Bay Cable Project – Need Study Results: Plots Showing Greater Bay Area Power Flows – Jefferson-Martin ON, Hunters Point OFF, Potrero (or CCSF Peakers) OFF, Trans Bay Cable ON

Courtesy: Siemens
HVDC Supergrids?

- VSC Converters enable construction of HVDC Grids
- Reduced Losses
- Increased power capacity per line/cable vs. AC
- Underground/Underwater or reduced rights of ways imply:
  - lesser right of way limitations,
  - lower visual impact and lower EM fields
- Stabilized AC & DC grid operation – AC networks can be asynchronous
- Applicable for Harnessing Multiple off-shore windfarms
Concluding Remarks

- HVDC Transmission Technology is evolving to adapt to the change in attitudes about energy

- The barriers on conventional LCC HVDC imposed by the ac system conditions are being overcome

- CCC Technology extends the range of thyristor based converters

- VSC technology is promising - less influenced by the ac network

- Recent innovations such as the MMC are reducing losses and making VSC technology very attractive

- The future is bright - radical changes in the power network, such as dc grids are on the horizon