Chapter 10

MMC-HVDC Transmission Technology and MTDC Networks
Outline (1)

- Introduction
- 10.2 LCC-HVDC Transmission Technology
- 10.3 Two-Level VSC-HVDC Transmission Technology
- 10.3.1 Comparison of VSC-HVDC vs. LCC-HVDC Technology
- 10.4 Modular Multilevel HVDC Transmission Technology
- 10.4.1 Monopolar Asymmetric MMC-HVDC Scheme Configuration
- 10.4.2 Symmetrical Monopole MMC-HVDC Scheme Configuration
- 10.4.3 Bipolar HVDC Scheme Configuration
- 10.4.4 Homopolar HVDC Scheme Configuration
- 10.4.5 Back-to-Back HVDC Scheme Configuration
- 10.5.1 The North Sea Countries Offshore Grid Initiative (NSCOGI)
- 10.5.2 Large Integration of Offshore Wind Farms and Creation of the Offshore DC Grid
- 10.6 Multi-Terminal HVDC Configurations
- 10.6.1 Series-Connected MTDC Network
10.6.2 Parallel-Connected MTDC Network 346
10.6.3 Meshed MTDC Networks 347
10.7 DC Load Flow Control in MTDC Networks 348
10.8 DC Grid Control Strategies
10.8.1 Dynamic Voltage Control and Power Balancing in MTDC Networks
10.8.2 Power and Voltage Droop Control Strategy
10.8.3 Voltage Margin Control Method
10.8.4 Dead-Band Droop Control
10.8.5 Centralized and Distributed Voltage Control Strategies
10.9 DC Fault Detection and Protection in MTDC Networks
10.10 10.11 DC Circuit Breaker Technologies
10.12 Fault-Current Limiters
10.12.3 10.13 The Influence of Grounding Strategy on Fault Currents
10.14 DC Supergrids of the Future
Introduction

- LCC HVDC transmission technology is widely recognized as being advantageous for bulk power transmission over long distances, asynchronous interconnections of AC power systems and interconnectors with long submarine cable. In addition the LCC-HVDC technology is utilized as firewall in back-to-back configurations.

- New Modular Multilevel converter designs have broadened the potential range of HVDC transmission to include application of HVDC schemes in weak AC networks e.g. integration of remote offshore wind power plants to the onshore AC networks. MMC-HVDC technology is foreseen as the most suitable technology for development of Multi Terminal DC (MTDC) networks.
Short History of HVDC technology

- 1957 - First commercial installation in Sweden
  100kV, DC, 20 MW - Mercury value
- 1970 - First installation with Thyristor values
- 1997 - First VSC HVDC installation (Gotland)
- 2004 - First offshore VSC-HVDC installation
  Troll oil and gas platform (Norway)
- 2014 - First MMC-HVDC offshore installation for export of wind energy to shore, BorWin2
LCC HVDC transmission technology

• The converter typically consists of two six-pulse Thyristor bridges, called Graetz bridges, which are series connected on the DC side, and parallel connected on the AC side. By using a YY converter transformer for one bridge and a YD converter transformer for the other bridge, the 6-pulse harmonics are theoretically cancelled, both on the AC and the DC side, which reduces the filtering requirements. AC filters are required to limit the impact of the remaining low order harmonics on the AC network and on the DC side. LCC HVDC systems require connection to a strong AC network in order to ensure the commutation and to avoid operation instability of the converters.
VSC-HVDC transmission technology

• Voltage Source Converter consisting of IGBTs and large DC capacitors;
• Converter reactors;
• DC smoothing reactor;
• AC filters;
• Interface transformer;
• VSC control and protection systems;
• Auxiliary systems (e.g. cooling systems, auxiliary power, fire protection system, etc.)
Comparison of VSC-HVDC vs. LCC-HVDC technology

- VSC-HVDC transmission technology has 40 – 60% smaller footprint compared with the LCC-HVDC technology.
- 2-level VSC-HVDC has higher converter loses and costs compared with the LCC technology.
- XLPE cables with polyethylene cross-linked insulation can be utilized to link the VSC-HVDC terminals as power reversal does not require voltage polarity reversal.
Monopolar MMC-HVDC scheme configurations

(a) Symmetrical Monopole

(b) Symmetrical Monopole With metallic return

(c) Symmetrical Monopole With ground electrode return
Bipolar HVDC scheme configuration

With metallic return

With ground return
Homopolar HVDC scheme configuration

With metallic return

With ground return

\[ I_{dc} \]

\[ V_{dc} \]

\[ 2I_{dc} \]
Typical configuration of offshore wind farm with HVDC export link to shore

- Offshore AC collector hub
- Offshore AC subsea cable
- Onshore substation
- AC Grid
Multi-terminal HVDC configurations

Meshed MTDC networks

Series connected MTDC network

Parallel connected MTDC network

Offshore wind generation
Offshore Oil & Gas Consumer
Hydro generation
Solar PV generation
Onshore grid HVDC Terminal
Load flow control in a DC grid
MTDC grid control system hierarchy

- Voltage optimizer
- Master DC grid controller
  - Outer current control
  - Inner current control
  - MMC-HVDC converter 1
  - Outer current control
  - Inner current control
  - MMC-HVDC converter 2
  - Outer current control
  - Inner current control
  - MMC-HVDC converter 3
Dynamic voltage control and power balancing in MTDC networks

- A multi-terminal HVDC system has to operate with unplanned contingencies, such as power exchange variations, loss of a transmission link or a terminal trip. Therefore converter stations injecting active power into the DC grid should limit the possible overvoltage by reducing power import and terminals exporting power should limit the under-voltage by reducing its power export. The chosen control strategy must be able to keep the interconnected system at a stable operating point e.g. stay within the predefined voltage limits. Because of long distances between substations and the risk of communication failure, local control method seems to be a better solution for such a primary control as it is the case with primary control in AC systems.
Power and voltage droop control strategy

- **Current-Voltage control:** The current-voltage (I-V) relationship characteristic is used to control the DC voltage in a current-based control strategy. The main advantage of a current-voltage control characteristic is that it reflects the linear control behaviour in the sense that a voltage deviation will result in an equivalent current deviation. As the voltage is linked with charging or discharging the capacitors in the DC system, the control is linear and it is the same for all voltage deviations from any reference value.

- **Voltage – power control:** In the power based control strategy the DC voltage control is expressed in terms of active power. The power-voltage (P-V) relation is assumed to be linear. The voltage droop control strategy for MTDC networks is similar to the voltage droop control traditionally implemented in AC power system.
Droop control voltage and current characteristics
Voltage margin control method

![Diagram showing voltage margin control method with graphs for Rectifier and Inverter showing current and voltage relationship with reference point and droop characteristics.](image-url)
Centralized and decentralized voltage control strategies

- In a centralized control strategy one converter controls the DC voltage to a constant value of the converter’s DC bus voltage, and acts as a DC slack bus. While the other converters control their current/power.

- In a decentralized voltage control strategy, not all converters take part in the control of the DC voltage similar to AC grids, where some power stations take part in the primary frequency control while others do not. In a distributed control strategy for large multi-terminal DC networks, each DC-voltage-controlling HVDC terminal is assigned to a specific direct voltage set-point control. In distributed control strategy, no single converter is left alone with the responsibility of balancing the power inside the DC network, i.e. the control of the DC system voltage is distributed between several nodes inside the MTDC network.
DC fault detection and protection in MTDC networks (1)

- **Selectivity:** The protection system should only operate after a fault (not during normal operation), and only if the fault is in its protection zone.
- **Speed:** The protection system should be fast enough to interrupt faults before they reach the unacceptable high values which may cause permanent damage to the DC grid components.
- **Reliability:** A good protection system is reliable and has a backup system in case the primary protection system fails.
- **Robustness:** The protection system should have the ability to detect faults in normal mode as in degraded mode, and to discriminate faults from any other operation occurring (e.g. setpoint changes, normal switching operations,)
- **Seamless:** After the fault clearance, the remaining part of the system should continue operating in a secure state
Once the fault is detected the location of the fault must be identified and the fault current must be interrupted, and finally the faulty equipment or line must be isolated.

In a DC system this can be achieved in three distinct ways:

- Utilizing DC Circuit Breakers (DCB), interrupting the DC fault current and isolating the faulty section.
- Fast converter control action (e.g. converters with inherent fault blocking capabilities).
- Activating the AC breakers of all HVDC converters and isolating the DC grid from the connecting AC networks.
DC fault current

It is essential to detect, limit or interrupt the fault current before reaching critical values in few ms.

- Technologies to limit the DC fault current e.g. fault current limiters and utilize AC breakers
- MMC topologies with inherent fault blocking capability e.g. Full-bridge topology
- Interrupt the fault current with DC breakers.
DC fault current development under pole-to-pole short circuit condition

![Graph showing current development over time](image)

- **Prospective Fault Current**
- **Interrupted Fault Current**

Current [kA] vs. Time [ms]
DC fault detection methods in MTDC

- Fault detection and location methods
  - Direct based measurement methods
    - Differential protection
    - Distance protection
    - Overcurrent protection
  - Signal Processing based methods
    - Neural network based protection
    - Wavelets based protection
    - Travelling wave based protection
    - Derivative based protection
Example: Mesh HVDC configuration and the dc fault current

In a meshed grid the fault currents in the branches are much higher due to summation of individual contributions.
DC breaker technologies

Different HVDC breaker technologies:

- Solid state breaker (fast but expensive and high losses)
- Hybrid breaker (combination power electronics and fast disconnector switch)
- Mechanical breaker (making use of auxiliary resonance circuit, slow, not applicable in DC grids)
The direct current in the grid can only be extinguished by inserting a counter-emf that exceeds the driving source $U_{\text{drive}}$, which is typically the DC system voltage.

- Example:
  DC grid voltage = 500kV
  Fault current 10kA

  The counter emf of 1.5 times nominal voltage, which is 750kV must be inserted to extinguish the DC fault current.
DC breaker

- Fault inception → rise of the current
- Rise of magnetic energy in the network
- Circuit-breaker inserts an opposite voltage and energy absorber
- Energy transferred to surge arresters and network capacitors

Insert a surge arrester in series
Hybrid DC breaker

1. The power electronic switch in the low-impedance branch is turned off so that the current must flow through the (low-voltage) varistor;

2. The first thyristor switch in the auxiliary branch is triggered and the current in the low-impedance branch commutates into the uncharged capacitor, thereby eliminating the current through the ultra-fast disconnector. The mechanical switch opens and establishes the required voltage withstand capability;

3. The current is commutated through a number of similar branches with varistors with increasing voltage. When a new branch is turned on, the preceding one turns off as the current initially commutates into the uncharged newly inserted capacitor;

4. The last capacitor in the auxiliary branch conducts the current until the voltage reaches the level when the metal-oxide extinguishing branch starts to conduct; and

5. The metal-oxide varistor inserts a counter-voltage that makes the current drop to zero. The thyristor turns off when the voltage across the varistor drops.
DC Circuit Breaker requirement

A DC circuit breaker has to fulfil the following requirements:

• The DC breaker must function and interrupt the fault current in a few milliseconds.
• It must create an artificial current zero
• The breaker must be able to absorb and dissipate large amounts of energy stored in the DC system
DC breaker technologies

- Resonant DC breakers with serial or parallel resonance circuits
- Solid state DC breakers
- Hybrid DC breakers

DC breaker energy absorbers inserted in series or in shunt.
DC breaker operation stages

1. The power electronic switch in the low-impedance branch is turned off so that the current must flow through the (low-voltage) varistor;

2. The first thyristor switch in the auxiliary branch is triggered and the current in the low-impedance branch commutates into the uncharged capacitor, thereby eliminating the current through the ultra-fast disconnector. The mechanical switch opens and establishes the required voltage withstand capability;

3. The current is commutated through a number of similar branches with varistors with increasing voltage. When a new branch is turned on, the preceding one turns off as the current initially commutates into the uncharged newly inserted capacitor;

4. The last capacitor in the auxiliary branch conducts the current until the voltage reaches the level when the metal-oxide extinguishing branch starts to conduct;

5. The metal-oxide varistor inserts a counter-voltage that makes the current drop to zero. The thyristor turns off when the voltage across the varistor drops.
Hybrid dc breakers with MOVs in series
DC breaker with MOV in parallel

- The counter-emf can alternatively be inserted in shunt
Influence grounding strategy on fault currents

1. Faults across high impedance ground = High voltage

2. Fault across the converter = High current
Influence of grounding strategy on fault currents

- HVDC schemes and converters can be designed with solid grounding, resistive grounding, or high- or low-impedance grounding. The scheme configuration and the grounding strategy influence the dc fault dynamics and behavior.

- High impedance grounding results in significant voltage stresses during ac and dc fault conditions. In the event of low impedance grounding, the system will experience significant current stresses. During earth faults in a high-impedance-grounded HVDC scheme, the fault currents are effectively limited. However, the converters will be subjected to large over-voltages, up to twice the normal operating voltage. For a symmetrical bi-pole configuration with an isolated grounding, very high short-circuit currents will flow through the system during a solid pole-to-pole fault. In the event of a single pole-to-ground fault, the system will experience lower short-circuit currents determined by the grounding impedance. Symmetrical MMC-HVDC configurations are designed with high-resistive-grounding configurations. The single pole-to-ground faults will result in a dc voltage imbalance between the poles, and cause the un-faulted pole to be charged by up to 2 p.u. of the normal operating voltage.