HVDC Transmission Systems Based on Modular Multilevel Converters

Maryam Saeedifard
Georgia Institute of Technology
(maryam@ece.gatech.edu)
Presentation Outline

• Introduction to HVDC Transmission Systems

• Converter Requirements for HVDC Transmission Systems

• The Modular Multilevel Converter (MMC)
  - Features
  - Operational Challenges
  - Solutions

• Future Work
Introduction: AC Corridor’s Power Flow Control

- Boost or control ac voltage \( (V) \)
- Reduce line reactance \( (X) \)
- Regulate phase angle \( (\delta) \)

\[
P = \frac{V_1 V_2}{X_{12}} \sin (\delta_1 - \delta_2)
\]

Ref: ABB
Introduction: DC Corridor’s Power Flow Control

\[ P = V_{DC} \cdot I_{DC} \]

HVDC: High Voltage Direct Current Transmission
## Introduction: AC vs DC Transmission

<table>
<thead>
<tr>
<th>AC Transmission</th>
<th>DC Transmission</th>
</tr>
</thead>
<tbody>
<tr>
<td>✗ Loading a function of Z</td>
<td>✔ Power flow controlled</td>
</tr>
<tr>
<td>✗ Charging current a function of voltage level and cable capacitance</td>
<td>✔ No charging current effect or need for shunt compensation</td>
</tr>
<tr>
<td>✗ Distance limitation</td>
<td>✔ No distance limitation</td>
</tr>
<tr>
<td>✗ 3 cables</td>
<td>✔ 2 cables</td>
</tr>
</tbody>
</table>
Introduction: AC vs DC Transmission

- Due to reactive power charging, AC transfer capacity is dramatically reduced with distance
- DC transfer capacity is almost independent of distance

Ref: ABB
Introduction: Overhead Line Transmission

Investment vs Cost

Ref: ABB
Introduction: Types of HVDC Systems

- **Point-to-Point Systems**
  - Overhead lines
  - Subsea or underground cables

- **Back-to-Back Systems**
  - Interconnection of asynchronous AC grids
Introduction: Basics of HVDC Systems
HVDC Technology: Converter Requirements

Shortcomings:
- Harmonic distortion
- Switching frequency and power losses

Ref: ABB
HVDC Technology: Converter Requirements

- Staircase voltage waveform ==> Reduced harmonic distortion and filtering size
- Low switching frequency ==> High efficiency
The MMC

Features:

- ✓ Modular and scalable design
- ✓ Smooth and sinusoidal waveform
- ✓ Increased reliability and redundancy

Challenges:

- × SM capacitor voltage balancing
- × Circulating currents
Equivalent Circuit of an MMC

\[ i_{upj} = \frac{i_j}{2} + \frac{i_{dc}}{3} + i_{zj}, \]

\[ i_{lowj} = -\frac{i_j}{2} + \frac{i_{dc}}{3} + i_{zj}, \]

\[ i_j = i_{upj} - i_{lowj}. \]
SM Capacitor Voltage Balancing

\[ V_{SM} = \frac{1}{2} V_{dc} \]

Voltage level 1

\[ n_{p,j} = 0, \quad n_{n,j} = n \]
\[ n_{p,j} = 1, \quad n_{n,j} = n - 1 \]
\[ n_{p,j} = n - 1, \quad n_{n,j} = 1 \]
\[ n_{p,j} = n, \quad n_{n,j} = 0 \]
SM Capacitor Voltage Balancing

Example: Five-Level MMC
Circulating Current Control

High circulating current:
- Rating value/size of components
- SM capacitor voltage ripple
- Power losses

\[ i_j = i_{upj} - i_{lwj} \]
\[ i_{zj} = \frac{1}{2} (i_{upj} + i_{lwj}) - \frac{i_{dc}}{3}, \]
\[ \frac{V_{dc}}{2} - \frac{v_{lwj} + v_{upj}}{2} = l \frac{di_{zj}}{dt}. \]
Circulating Current Control

• Circulating current – contains 2\textsuperscript{nd} harmonic predominantly

• Controllers to eliminate circulating current:
  • Proportional Resonant (PR) Controller
  • Predictive Circulating Current Controller
Circulating Current Control: PR Controller

- Circulating current dynamics:

\[ L_o \frac{d i_{z,abc}}{dt} + R_o i_{z,abc} = v_{z,abc} \approx m_{z,abc} V_{dc} \]

- PR Controller:

\[ K_{p1} + \frac{K_{i1} s}{s^2 + \omega_{n1}^2} + \frac{K_{i2} s}{s^2 + \omega_{n2}^2} \]

- \( \omega_{n1} \) and \( \omega_{n2} \) are tuned to 2\(^{nd}\) and 4\(^{th}\) harmonic.
Circulating Current Control: PR Controller

Ac-side current controller

Circulating current controller

SM Capacitor Voltage Balancing

Software

Hardware

Upper-arm switching signals

Lower-arm switching signals

Measured upper-arm SM Capacitor Voltages

Measured lower-arm SM Capacitor Voltages

Measured arm currents

i-th Sub-module

SM Capacitor Voltage Balancing

PWM Generator-1

PWM Generator-2

Phase-c

Phase-b

Phase-a

SM1

SM2

SMn
Circulating Current Control: PR Controller
Circulating Current Control: Predictive Current Controller

From KVL:

\[
\frac{V_{dc}}{2} - v_{upa} = l \frac{di_{upa}}{dt} + Ri_a + L \frac{di_a}{dt} + v_{sa},
\]
\[
\frac{V_{dc}}{2} - v_{lowa} = l \frac{di_{lowa}}{dt} - Ri_a - L \frac{di_a}{dt} - v_{sa}
\]

Discrete model of the ac-side phase current:

\[
i_a(k+1) = \frac{1}{K'} \left( \frac{v_{lowa}(k+1) - v_{upa}(k+1) - v_{sa}(k+1)}{2} + \frac{L'}{T_s} i_a(k) \right) \frac{V_{dc}}{2} \]

\[
L' = \frac{l}{2} + L \hspace{1cm} K' = \frac{L'}{T_s} + R
\]

Discrete model for circulating current and SM capacitor voltages:

\[
i_z(k+1) = \frac{T_s}{2l} \left( V_{dc} - v_{lowa}(k+1) - v_{upa}(k+1) \right) + i_z(k)
\]
\[
V_{cij}(k+1) = V_{cij}(k) + \frac{i_l(k)}{C} T_s
\]
Prediction based on cost function minimization:

\[ J = \lambda \left( \sum_i \left| V_{cij} - \frac{V_{dc}}{n} \right| \right) + \lambda_z \left| i_{zj} \right| \]
Closed-Loop Control of MMC-HVDC
Predictive Control of MMC-HVDC
DC-Side Fault in MMC-HVDC Systems
SM Technologies: Normal Operation

Full-Bridge SM

- SM Insertion: S1, S4 ON; S2, S3 OFF
- SM Bypass: S1, S3 OFF, S2, S4 ON
- SM Bypass: S1, S3 ON, S2, S4 OFF

Clamp-Double SM

- SM1 Insertion: S1 ON, S2 OFF
- SM1 Bypass: S1 OFF, S2 ON
- SM2 Insertion: S4 ON, S3 OFF
- SM2 Bypass: S4 OFF, S3 ON
SM Technologies: DC-side Short-Circuit Fault Operation

Full-Bridge SM

Clamp-Double SM
DC-side Short-Circuit Fault Operation of Full-Bridge MMC
DC-Side Fault in MMC-HVDC Systems: Full-Bridge MMC Case
Power Losses for Various SM Circuits

Power Losses of Single SM-type MMCs Normalized with Respect to Half-Bridge MMC
Hybrid Design of MMC-HVDC Systems

\[ N_f \geq \frac{V_{\text{amp-LL}}}{2V_{\text{cap_ref}}} \]
DC-Side Fault in MMC-HVDC Systems: Hybrid MMC Case
Power Losses for Various Hybrid MMCs

Power Losses of Hybrid MMCs Normalized with Respect to Half-Bridge MMC

![Chart showing power losses for Hybrid MMCs normalized to Half-Bridge MMC. The chart compares Half-bridge + full-bridge and Half-bridge + clamp-double.]
Future Work

• Control and protection of multi-terminal HVDC systems based on the MMC

• Accurate and efficient modeling and simulation tools for MMC-HVDC systems

• Operation of the MMC-HVDC systems under fault conditions
Acknowledgement

• This presentation contains data and graphs from ABB publications/presentations available on the public domain including: