Power Electronics for Grid Applications

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Traditional Power Grid Equipment

- Sources – rotating synchronous generators etc.
- T&D – lines & cables, transformers, switchgear, series/shunt capacitor/reactor compensators etc.
- Loads – motors, lighting, thermal loads, etc.
- Limited power electronics
Power Transfer in Grid - From “AC vs DC” to “AC and DC”

\[
V_1/\delta_1 \quad \text{Powerflow} \quad P \quad V_2/\delta_2
\]

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

Shunt Compensation  Series Compensation  Phase Shifting Transformers  HVDC

ABB
Power Electronics for AC Transmission – Flexible AC Transmission Systems (FACTS)

- **Series connected compensators**
  - Thyristor-controlled series compensator (TCSC)
  - Interphase power controller (IPC)
  - Static synchronous compensator (STATCOM)

- **Shunt connected compensators**
  - Thyristor-switched capacitor (TSC)
  - Thyristor-switched reactor (TSC)
  - Static var compensator (SVC)
  - Static synchronous compensator (STATCOM)

- **Series and shunt connected compensators**
  - Thyristor-controlled phase shifting transformer (TCPST)
  - Unified power flow controller (UPFC)

Conventional FACTS mostly based on Si thyristor technology, with limited performance and capabilities.
Power Electronics for AC Distribution – Custom Power

- Power flow control and interruption
  - Solid-state transfer switch (SSTS)
  - Solid-state circuit breaker (SSCB)
  - Solid-state fault current limiter (SSFCL)

- Power system conditioning and compensation
  - Distribution static synchronous compensator (DSTATCOM)
  - Static var compensator (SVC)
  - Dynamic voltage restorer (DVR)
  - Thyristor-controlled voltage regulator (TCVR)

- Power quality enhancement
  - Active power filter (APF)
  - Unified power quality conditioner (UPQC)
Power Electronics for T&D – More Recent Development

Solid-state transformer

Controllable network transformer

Distributed static series compensator

Continuously variable series reactor (CVSR)
Grid Power Electronics – Sources and Loads

- Renewable energy source interface

- Energy storage systems

- Power electronic loads: data center, EV charging station, large motor drive
Microgrids

- Feature renewable and energy storage
- Reliability and resiliency
- Grid support
- AC synchronous, AC asynchronous, and DC
AC and DC Transmission Principles

Compared with AC, the main features of DC transmissions:
- Long distance
- Asynchronous interconnection
- Controllability

DC does require AC/DC converters and other associated equipment:
- Filters and var compensators
- Communications
- Special transformers
• There is a breakeven or critical distance beyond which the DC scheme will be more economical
• The breakeven distance depends on many factors. For overhead lines in the range of several hundred of miles (300 to 500); for cables, in the range of tens of miles (30 to 60 miles)
HVDC Converter – Principle of Load Commutated Converter (LCC)

Thyristor or SCR

Anode (A)  
Gate (G)  
Cathode (K)

Six Pulse LCC Converter Bridge and Its Operation
HVDC Converter – Principles of Voltage Source Converter (VSC)

Pulse Width Modulation (PWM) Control

VSC – Voltage Source Converter

IGBT

Collector

Emitter

Gate
HVDC Technology Development

- **Mercury Arc Valve HVDC (Phased out)**
  - Pros: Low losses
  - Cons: Reliability, Maintenance, Environment

- **Thyristor Valve HVDC Classic**
  - Pros: Reliable, Scalable
  - Cons: Footprint

- **IGBT (Transistor) HVDC Light (VSC HVDC)**
  - Pros: Controllability, DC Grids
  - Cons: Footprint, Losses

Year:
- 1954
- 1970
- 1980
- 2000
HVDC Technology Evolution: Voltage Source Converter (VSC) Topologies

- VSC based on switching devices (IGBT/IGCT), with better performance than thyristor based LCC, and significantly reduced converter station footprint and less right-of-way
- MMC latest generation of VSC topology: low loss, and no series devices
MMC VSC vs. Conventional VSC
Technology Evolution – VSC Efficiency

- Generations 1-3 adopt the two-level converter and 3-level converter.
- Generation 4 adopts MMC, and the converter efficiency is comparable to LCC HVDC.
HVDC more economical for long-distance transmission; HVDC can decouple dynamics of AC systems, benefiting system stability and protection.
Summary of HVDC Benefits

• Long distance bulk power transmission
• Asynchronous interconnections
• Lower cost for cable transmission (subsea, offshore)
• AC system support
  ➢ Controllability (including damping, f support, power flow and voltage control)
  ➢ Limitation of faults
  ➢ Low short-circuit current contribution
• Better use of right-of-way
• Environmental benefits (corona, noise, etc.)
Better Use of Right-of-Way

Several aspects on this point:

- For the same power transmitted, HVDC requires less right-of-way
- For the same right-of-the-way, HVDC can transfer more power
- With the same lines, HVDC can have lower loss

Based on information from ABB
Disadvantages and Issues with HVDC

• High cost and complex converters
• Converters generate harmonics
• LCC HVDC require large var compensation and filters
• Challenges on grounding electrodes and converter transformers
• Difficulty of breaking DC current (DC breaker)
VSC HVDC Protection – Challenge

- VSC is vulnerable to DC side short circuit fault, as the fault current can still flow through the diode after IGBT switches turned off
- DC current is difficult to clear without zero-crossing
VSC HVDC DC Fault Protection – Solution

- State of art solution: AC breaker + bypass thyristor (if necessary)
- 100 ms to clear the fault, and 2 s to restart the system
VSC HVDC DC Fault Protection – Solution

- Fast fault clearance solution (<5 ms)
  - Siemens method: MMC with fault blocking sub-module
VSC HVDC DC Fault Protection – Solution

• Fast fault clearance solution (<5 ms)
  ▶ GE/Alstom method: hybrid MMC

Diagram of VSC HVDC DC Fault Protection solution.
VSC HVDC DC Fault Protection – Solution

• Fast fault clearance solution (<5 ms)
  - Hitachi/ABB method: Hybrid DC breaker
Objective: Upgrade existing AC lines to hybrid AC and DC lines, to expand the power transmission capability
Basic Concept of Hybrid AC/DC System

System topology:

DC injection link: zigzag transformer
Benefits and Issues

Benefits:
• A lower cost solution for increased power transfer and improved stability

Issues:
• Zigzag transformer may be saturated with unbalanced AC line resistance, due to the uncanceled DC flux within zigzag windings.
• Neutral point of zigzag transformer needs extra insulation to withstand dc bias voltage
Method 1: Design Tolerance Margin

Method 1: DC tolerance design

- Can tolerate a certain unbalance range ($\pm \beta$)
- To tolerate more unbalance will cause more power loss and/or VAR loss
- Effective AC flux density is reduced, lead to higher cost

\[ \Phi_{DC} \]

\[ F_{AC} + F_{DC} \]

\[ B_{ac_{max}} \]

\[ B_{max} \]

\[ I_{DC} \]

\[ \text{Exciting current Im} \]
Method 2: Adjust Transformer Turns

Method 2: DC flux cancelation design by adjusting turns

- Less power or VAR loss compared to method1 for the same rating
- Cost closest to normal AC transformer.
- Introduces a certain extra voltage unbalance
- Sensitive to real-time unbalance

\[ N_{z1}I_{a\_DC} - N_{z2}I_{b\_DC} = 0 \]

\[ \frac{N_{z1}}{N_{z2}} = \frac{I_{b\_DC}}{I_{a\_DC}} \]

For a general design: use tap changers for each winding

Impacts on method 2

Voltage unbalance
Method 3: Active Unbalance Mitigation

Method 3: Hybrid line balance control

- Immunity to unbalance
- Low voltage rating, no insulation issue
- Active impedance with low loss
- With extra converter cost, but low compared to main HVDC converters

Hybrid line impedance conditioner:

\[
\Delta R = \frac{V_{AC/DC}}{I_{AC/DC}} \approx \frac{\Delta V_{DC}}{I_{DC}} / 3
\]

Adjust the line resistance by phase.

Can be enabled or bypassed

Bidirectional Active Hybrid Line Impedance Conditioners
(Two conditioners are active, at the most)
Method 3: Impedance Conditioner Design and Simulation

**System Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Line Length</td>
<td>650km</td>
</tr>
<tr>
<td>Impedance</td>
<td>0.035 Ohm/km + 0.9337 mH/km</td>
</tr>
<tr>
<td>Unbalance</td>
<td>5%</td>
</tr>
<tr>
<td>Line voltage (phase)</td>
<td>AC: 115 kV; DC 180 kV</td>
</tr>
<tr>
<td>Line current</td>
<td>AC: 612A, DC: 1000A</td>
</tr>
<tr>
<td>Transmission Power</td>
<td>729 MW (189 AC and 540 DC)</td>
</tr>
<tr>
<td>Inverter AC voltage</td>
<td>3.183 kV (peak)</td>
</tr>
<tr>
<td>DC link voltage</td>
<td>3.617 kV</td>
</tr>
<tr>
<td>DC link Capacitance</td>
<td>3300 uF</td>
</tr>
<tr>
<td>Rectifier AC voltage</td>
<td>3.183 kV (peak)</td>
</tr>
<tr>
<td>Zigzag transformer windings</td>
<td>balance design + conditioner winding (170/138/138/3)</td>
</tr>
</tbody>
</table>

Conditioner enabled at 0.6s. Control reference goes from zero to the desired impedance.
Scaled Hybrid AC/DC System Prototype

Prototype:

\[ L_x = 0.5 \text{mH} \]
\[ R = 20 \Omega \]
Scaled Hybrid AC/DC System Experiments

Before DC injection:

- $v_{AB}$ (100V/div)
- $i_a$ (2A/div)
- $i_{a_zig2}$ (2A/div)
- $v_{an}$ (250V/div)

After DC injection:

- $v_{AB}$ (100V/div)
- $i_a$ (2A/div)
- $i_{a_zig2}$ (500mA/div)
- $v_{an}$ (250V/div)

BTB AC grid voltage: 80V
Rectifier: $V_{DC\_ref} = 150V$, $Q_{ref} = 0\text{var}$

AC line voltage: 104V
Inverter: $I_{DC} = 12A$, $Q_{ref} = 0\text{var}$
• Emulate various grid scenarios with interconnected clusters of scaled-down generators, loads, and energy storage.
Four-area WECC system including multi-terminal HVDC, high penetration of renewables
**Multi-Terminal HVDC Testbed**

**Objective:** Build a hardware platform for MT-HVDC system operation/control/protection development and demonstration

**System Structure**

- **Onshore I**
  - Wind emulator I
  - Offshore I
  - Offshore II
- **Onshore II**
  - Offshore II
  - Wind emulator II
- **MTDC Testbed Hardware**

**Testbed Capability on Scenario Emulation:**

- System start-up
- Station online re-commission
- Wind farm power variation
- Station outage
- Transmission line trip
- Station online mode transition
Acknowledgements

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Thank You!