ECE 529
Utility Applications of Power Electronics
Session 36
An Overview of the Operation of HVDC Classic Transmission Systems (LCC)

ECE 529
Spring 2021

Steady-State HVDC Converter Representation

- Steady state equivalent circuit

- Have fast, direct control over $\alpha$ (firing delay angle)

- $V_{dc} = V_{do} \cdot \cos \alpha$ (firing delay angle) where $V_{do} = const \cdot |V_{LL}|$

- Some control of $|V_{ac}|$ with tap changing transformer

- DC current indirectly controlled by changing $\alpha$
Basic Six-Pulse Converter

- Based on line commutated, current source converter
- Thyristors used as devices
- Converter with stiff current source on dc side
- Stiff voltage source on ac side (turns off thyristors)
- Basic 6-pulse bridge:

Basic Six-Pulse Converter

1. Ideal ac sources,
2. Ideal switches,
3. $X_c = 0$
4. $L_s \to \infty$

- AC side of converter has an ideal voltage source, dc side of converter has an ideal current source

- Apply Kirchhoff's Current Law:
  - $i_1 + i_5 = I_{dc}$ (one switch always closed)
  - $i_2 + i_6 = I_{dc}$

- Apply Kirchhoff's Voltage Law:
  - $e_{an} + e_{bn} + e_{cn} = 0$ (balanced 3 phase set)

- Since $X_c = 0$, only one switch in (1,3,5) can be closed with a switch in (2,4,6)
Basic Six-Pulse Converter (cont.)

- Allowable combinations:
  1 with (2 or 6) (4 shorts dc bus)
  3 with (2 or 4)
  5 with (4 or 6)
  2 with (1 or 5)
  4 with (1 or 3)
  6 with (3 or 5)

- Need to determine a switching sequence
- Start from assumption of positive phase sequence

- Typical current waveforms:
  \[ i_a \quad \begin{array}{c} \text{at} \quad 50^\circ \\ \text{at} \quad 120^\circ \end{array} \]

Basic Six-Pulse Converter (cont.)

- Possible sequences:
  Top three switches: 1-3-5-1 or 1-5-3-1
  Bottom three switches: 4-6-2-4 or 4-2-6-4

- Assume: \( V_{dc} = V_{dc}^+ - V_{dc}^- \)

<table>
<thead>
<tr>
<th>Switch #</th>
<th>( V_{dc}^+ )</th>
<th>Switch #</th>
<th>( V_{dc}^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( e_{an}(t) )</td>
<td>4</td>
<td>( e_{an}(t) )</td>
</tr>
<tr>
<td>3</td>
<td>( e_{bn}(t) )</td>
<td>6</td>
<td>( e_{bn}(t) )</td>
</tr>
<tr>
<td>5</td>
<td>( e_{cn}(t) )</td>
<td>2</td>
<td>( e_{cn}(t) )</td>
</tr>
</tbody>
</table>

Pole to Pole voltage:
\[ V_{dc} = V_{dc}^+ - V_{dc}^- = R_a(t) - e_{bn(t)} \]

Pole to Neutral:
\[ V_{dc} = V_{dc}^+ - V_{dc}^- = V_{dc} \text{ during period both switched on.} \]
\[ V_{sc}^+ \]

\[ V_{dc}^+ - V_{dc}^- \]

\[ V_{ab} = V_{ca} \quad V_{bc} = V_{ab} + V_{sc} \]

360° - 1 cycle → 6 "peaks"

\[ \langle V_{dc} \rangle = \langle V_{dc}^+ \rangle - \langle V_{dc}^- \rangle \]

- Fourier series
  - DC component
    - 6th
    - 12th
    - 18th
  - h, 6
Basic Six-Pulse Converter (cont.)

- Positive sequence ($\alpha = 0$, 1-3-5-1 and 4-6-2-4)

- Negative sequence ($\alpha = 0$, 1-5-3-1 and 4-2-6-4)

- Phase currents:

<table>
<thead>
<tr>
<th>Switch Combination</th>
<th>$V_{dc} = V_{dc^+} - V_{dc^-}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - 6</td>
<td>$e_{ab} = e_{an} - e_{bn} = V_{dc}$</td>
</tr>
<tr>
<td>1 - 2</td>
<td>$e_{ac} = e_{an} - e_{cn}$</td>
</tr>
<tr>
<td>3 - 2</td>
<td>$e_{bc} = e_{bn} - e_{cn}$</td>
</tr>
<tr>
<td>3 - 4</td>
<td>$e_{ba} = e_{bn} - e_{an}$</td>
</tr>
<tr>
<td>5 - 4</td>
<td>$e_{ca} = e_{cn} - e_{an}$</td>
</tr>
<tr>
<td>5 - 6</td>
<td>$e_{cb} = e_{cn} - e_{bn}$</td>
</tr>
</tbody>
</table>

- If $\alpha = 0$, then $V_{dc} = \frac{3\sqrt{2}}{\pi} |V_{LL}| = 1.35 |V_{LL}|$ We define this as $V_{do}$
Controlled Firing of Thyristors

- Now add a firing delay ($\alpha$) for the thyristors. Same delay for all 6 switches.

\[
\begin{align*}
V_{dc}^+ & > \quad \alpha = 0 \\
V_{dc}^- & > \quad \alpha \neq 0 \\
\alpha & = 0 \\
\alpha & = 90^\circ
\end{align*}
\]

\[
V_{dc}^+ + -> = V_{dc}^- + -> = 0
\]

Controlled Firing of Thyristors

- \[V_{dc} = \frac{3}{\pi} \int_{\frac{\pi}{6} + \alpha}^{\frac{\pi}{2} + \alpha} \sqrt{2|V_{LL}| \cos(\theta)} d\theta = \frac{3\sqrt{2}}{\pi} |V_{LL}| \sin(\theta) \left| \frac{\pi}{6} + \alpha \right| \]

- Then \[V_{dc} = \frac{3\sqrt{2}}{\pi} |V_{LL}| \cos(\alpha)\]

- Define \[V_{do} = \frac{3\sqrt{2}}{\pi} |V_{LL}|\]

- Therefore \[V_{dc} = V_{do} \cos(\alpha)\]

- \[\alpha = 0 \rightarrow \text{diode bridge} \quad V_{dc} = V_{do}\]
  \[
  0 \leq \alpha < 90 \rightarrow \text{rectifier} \quad V_{dc} > 0
  \]
  \[
  \alpha = 90 \rightarrow P = 0 \quad V_{dc} = 0
  \]
  \[
  90 < \alpha \leq 180 \rightarrow \text{inverter} \quad V_{dc} < 0
  \]

- Current does not reverse

\[P_{dc} < 0\]

Power from ac to dc
Commutation Overlap

- Now add source inductance \( L_c \neq 0 \)

Current Transfer Between Switches

- Current does not fall to zero immediately in ac side inductance
- Temporarily create line to line short

\[ l_1 + l_3 + l_5 = I_{dc} \]