An Overview of the Operation of HVDC Classic Transmission Systems

ECE 529
Spring 2017

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 $\alpha$
System Impedance Limit Current

Power System

Phase to Phase Fault on

(o (4,6) (6,2) (6,2) Combinations
o (1,3) (1,5) (3,5) Combinations

IT
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:

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Basic Six-Pulse Converter

- Initially assume: 1) Ideal ac sources, 2) ideal switches, 3) $X_c = 0$, and 4) $L_s \rightarrow \infty$ source
- AC side of converter has an ideal voltage source, dc side of converter has an ideal current source
- Apply Kirchhoff's Current Law:
  - $i_1 + i_3 + i_5 = I_{dc}$ (one switch always closed)
  - $i_2 + i_4 + i_6 = I_{dc}$
- 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 $(2,4,6)$. We can have $(1,4)$ or $(3,6)$ or $(5,2)$ together $\Rightarrow$ bypass mode (no AC current)
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:

- Look at the line voltages:

- 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

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

- Then $V_{dc} = \frac{3\sqrt{2}}{\pi} |V_{LL}| \cos \alpha$
- Define $V_{do} = \frac{3\sqrt{2}}{\pi} |V_{LL}|$
- Therefore $V_{dc} - V_{do} \cos \alpha$
- $\alpha = 0 \rightarrow$ diode bridge $V_{dc} = V_{do}$
  - $0 \leq \alpha < 90$ → rectifier $V_{dc} > 0$
  - $\alpha = 90 \rightarrow P = 0$ $V_{dc} = 0$
  - $90 < \alpha \leq 180$ → inverter $V_{dc} < 0$
- Current does not reverse
Commutation Overlap

- Now add source inductance ($L_s \neq 0$)

![Diagram of a circuit showing commutation overlap]

Current Transfer Between Switches

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

![Diagram of current transfer between switches]

$\Delta t$ commutation overlap

$L_1(t) + L_2(t) = I_{dc}$ at all times
Current Transfer Between Switches (cont.)

- What happens if $\alpha$ gets to big (i.e. $\alpha \rightarrow 180^\circ$)?

\[ I_{dc} \]

This is called a commutation failure

- Thyristor 3 fails to turn on and thyristor 1 fails to turn off

- This is more common if $L_c$ is large, which is the case looking into a "weaker" ac system

- Normally corrects during next interval, although often have a second failure when thyristor 5 turns on, "double commutation failure"

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Output Voltage During Commutation

- Switch 1 contribution: $V_{dc1}^+ = e_{an} - L_c \frac{di_1}{dt}$

- Switch 3 contribution: $V_{dc3}^+ = e_{bn} - L_c \frac{di_3}{dt}$

- During overlap we see the average between $V_{dc1}^+ & V_{dc3}^+$

So $V_{dc}^+ = \frac{V_{dc1}^+ + V_{dc3}^+}{2} = \frac{e_{an} + e_{bn}}{2} - L_c \left( \frac{di_1}{dt} + \frac{di_3}{dt} \right)$

- $i_1 + i_3 = I_{dc}$, so $\frac{di_1 + di_3}{dt} = 0$

But since its a linear network: $\frac{di_1 + di_3}{dt} = \left( \frac{di_1}{dt} + \frac{di_3}{dt} \right) = 0$

- So: $V_{dc} = V_{dc}^+ - e_{cn} = \frac{e_{an} + e_{bn}}{2} - e_{cn} = \frac{e_{ac} + e_{bc}}{2}$
Average DC Voltage with Overlap

- Recall: \( V_{dc} = \frac{3\sqrt{3}}{\pi} |V_{LL}| = \frac{3\sqrt{6}}{\pi} |V_{\phi}| = \frac{3\sqrt{3}}{\pi} |E_m| \)
  where \( E_m \) is peak line to neutral voltage

- Then we find:
  \[
  V_{dc} = \frac{3}{\pi} \left[ \int_{-\alpha}^{\alpha+\mu} \frac{3}{2} E_m \cos \theta d\theta + \int_{\alpha+\mu}^{\alpha+\mu+\pi/3} \sqrt{3} E_m \cos (\theta - \frac{\pi}{6}) d\theta \right]
  \]

- Leading to: \( V_{dc} = \frac{3\sqrt{3}}{2\pi} E_m [\cos \alpha + \cos (\alpha + \mu)] \)

- Or \( V_{dc} = \frac{V_{pu}}{2} [\cos \alpha + \cos (\alpha + \mu)] \)

Average DC Current

- Start out with \( L_c = 0 \) and \( \alpha = 0 \) for now

- Firing delay simply adds a phase shift to the current (always lagging), and \( \cos \alpha = \cos \phi \)

- Fundamental Component
  \[
  i_{1pk} = \frac{2}{\pi} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} i_a \cos (\theta) d\theta = \frac{2}{\pi} I_{dc} \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \cos (\theta) d\theta = \frac{2\sqrt{3}}{\pi} I_{dc}
  \]

- \( |I_{1 RMS}| = \frac{\sqrt{6}}{\pi} I_{dc} \)
Average DC Current

- Then \( i_1(t) = 2\sqrt{3} \frac{I_{dc}}{\pi} \cos(\omega t - \alpha) \)
- Also: \( P = 3I_{1RMS}V_P \cos\phi = V_{dc}I_{dc} \)
  So: \( 3I_{1RMS}V_P \cos\phi = 3\sqrt{3} \frac{I_{dc}}{\pi} V_P \cos\alpha I_{dc} \)
- So: \( |i_{a1RMS}| = \frac{\sqrt{6}}{\pi} I_{dc} \) as expected
- During overlap: \( I_{dc} = I_c = \sqrt{\frac{3E_m}{2\omega L_c}} = \frac{V_{dc}}{2X_c} \)
- \( i_3(t) = I_c(\cos\alpha - \cos\omega t) \) with \( \alpha \leq \omega t \leq \alpha + \mu \) where \( \omega t = \alpha + \mu \) at the end of the commutation interval
- So average current is \( I_{dc} = I_c (\cos\alpha - \cos(\alpha + \mu)) \)
- Also: \( I_c = \sqrt{\frac{3E_m}{2\omega L_c}} = \sqrt{\frac{3|V_P|}{2X_c}} = \frac{|V_{dc}|}{\sqrt{2X_c}} \)

Average DC Circuit Equations

- We have the following equations:
  \[
  V_{dc} = \frac{V_{do}}{2} [\cos\alpha + \cos(\alpha + \mu)]
  
  I_{dc} = I_c (\cos\alpha - \cos(\alpha + \mu))
  
  V_{do} = \frac{3\sqrt{2}}{\pi} |V_{LL}|
  
  I_c = \frac{|V_{LL}|}{\sqrt{2X_c}} = \frac{\pi V_{do}}{6X_c}
  \]
- Substitute for the \( \cos(\alpha + \mu) \) in the \( V_{dc} \) equation
- Then \( V_{dc} = V_{do} \cos\alpha - \frac{V_{do}}{2I_c} I_{dc} \)
- Where \( \frac{V_{do}}{2I_c} = \frac{V_{do}}{\frac{dV_{dc}}{d\alpha}} = \frac{3}{2\pi} X_c = R_c \) (called the commutating "resistance"")
- So \( V_{dc} = V_{do} \cos\alpha - I_{dc} R_c \)