Thyristor Converters

EE 442-642
Thyristor Converters

- Two-quadrant conversion
Simple half-wave circuits with thyristors

(a) 

(b) 

(c)
Thyristor Triggering

\[ \alpha^o = 180^o \frac{V_{\text{control}}}{\hat{V}_{st}} \]

- ICs available
Case of Pure Resistive Load
Full-Bridge Thyristor Converters – Constant DC Current

(a) $\alpha = 0$

(b) $\alpha = \text{finite}$
Average DC voltage: 

\[ V_{d\alpha} = V_{do} \cos \alpha \]

where

\[ V_{do} = 0.9V_s \]
AC-Side Current

RSM value of source current
\[ I_s = I_d \]

RMS value of fundamental current
\[ I_{s1} = (2\sqrt{2} / \pi)I_d \approx 0.9I_d \]

RMS value of harmonic current
\[ I_{sh} = I_{s1} / h, \quad h = 3, 5, 7, \ldots \]

Current THD
\[ THD = 100\sqrt{(\pi^2 / 8)} - 1 = 48.43\% \]

Displacement Power Factor
\[ DPF = \cos \alpha \]

Power Factor
\[ PF = 0.9 \cos \alpha \]
Effect of Source Inductance

Commutation angle:
\[ \cos(\alpha + \mu) = \cos \alpha - \frac{2\omega L_s I_d}{\sqrt{2V_s}} \]

Average of DC-side voltage:
\[ V_d = 0.9V_s \cos \alpha - \frac{2\omega L_s I_d}{\pi} \]

Displacement Power Factor
\[ DPF \approx \cos(\alpha + 0.5\mu) \]

RMS fundamental current
\[ I_{s1} = \frac{V_d I_d}{V_s DPF} \approx \frac{0.9V_s I_d \cos \alpha - (2/\pi)\omega L_s I_d^2}{V_s \cos(\alpha + 0.5\mu)} \]
Thyristor Converter with DC Source

Continuous current conduction mode

Discontinuous current conduction mode
AC-Side Current Waveform
(continuous conduction mode)

PSpice-based simulation example: $V_s = 240 \, \text{V}$, $f = 60 \, \text{Hz}$, $L_s = 1.4 \, \text{mH}$, $\alpha = 45 \, \text{deg.}$, $L_d = 9 \, \text{mH}$, $E_d = 145 \, \text{V}$.

Solution: $I_s = 60.1 \, \text{A}$, $I_{s1} = 59.7 \, \text{A}$, $\text{DPF} = 0.576$, $\text{PF} = 0.572$, $\text{THD} = 12.3\%$
DC Voltage versus Load Current

![Graph showing the relationship between DC voltage and load current with different angles.]
Inverter Mode ($\alpha > 90^\circ$)
• For a large value of $L_d$, $i_d$ can be assumed constant ($= I_d$), then

$$E_d = V_d = 0.9V_s \cos \alpha - \frac{2}{\pi} \omega L_s I_d$$
Inverter Mode: Extinction Angle

Importance of extinction angle in inverter mode: The extinction time interval should be greater than the thyristor turn-off time:

\[ \gamma = 180^\circ - (\alpha + \mu) \]

\[ t_\gamma = \frac{\gamma}{\omega} > t_q \]
3-Phase Thyristor Converters: Simplified Case
DC-side voltage waveforms assuming zero ac-side inductance

\[ V_d = V_{do} \cos \alpha \]

\[ = \frac{3}{\pi} \sqrt{2V_{LL}} \cos \alpha \]

\[ = 1.35V_{LL} \cos \alpha \]
Input Line-Current Waveform

\[ \omega t = 0 \]

\[ \phi_1 = \alpha \]

(a)

(b)

\[ \frac{I_{sh}}{I_{s1}} \]

\[ 0.2 \quad \frac{1}{7} \quad \frac{1}{11} \quad \frac{1}{13} \]

\[ 1 \quad 5 \quad 7 \quad 11 \quad 13 \quad 17 \quad 19 \quad 23 \quad 25 \]

\( h \)
Input line-current waveforms assuming zero ac-side inductance

\( I_s = \sqrt{2/3} I_d = 0.816 I_d \)

\( I_{s1} = (\sqrt{6/\pi}) I_d \approx 0.78 I_d \)

\( I_{sh} = I_{s1} / h, \quad h = 3, 5, 7, \ldots \)

\( THD = 100[\sqrt{(\pi^2/9)} - 1] = 31\% \)

\( DPF = \cos \alpha \)

\( PF = \frac{3}{\pi} \cos \alpha = 0.955 \cos \alpha \)
3-Phase Thyristor Converter with AC-side Inductance

\[
\cos(\alpha + \mu) = \cos \alpha - \frac{2\omega L_s I_d}{\sqrt{2}V_{LL}}
\]

\[
V_d = 1.35V_{LL} \cos \alpha - \frac{3\omega L_s I_d}{\pi}
\]

\[
DPF \approx \cos(\alpha + 0.5\mu)
\]
Input Line-Current Harmonics

\[ \frac{I_h}{I_1} (\%) \]

(a) \( h = 5 \)
\[ \alpha = 0^\circ, 5^\circ, 15^\circ, 30^\circ-90^\circ \]

(b) \( h = 7 \)
\[ \alpha = 0^\circ, 5^\circ, 15^\circ, 30^\circ-90^\circ \]

(c) \( h = 11 \)
\[ \alpha = 0^\circ, 5^\circ, 15^\circ, 30^\circ-90^\circ \]

(d) \( h = 13 \)
\[ \alpha = 0^\circ, 5^\circ, 15^\circ, 60^\circ \]
## Input Line-Current Harmonics

<table>
<thead>
<tr>
<th>h</th>
<th>5</th>
<th>7</th>
<th>11</th>
<th>13</th>
<th>17</th>
<th>19</th>
<th>23</th>
<th>25</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical $I_h/I_1$</td>
<td>0.17</td>
<td>0.10</td>
<td>0.04</td>
<td>0.03</td>
<td>0.02</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
</tr>
<tr>
<td>Idealized $I_h/I_1$</td>
<td>0.20</td>
<td>0.14</td>
<td>0.09</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
</tbody>
</table>

Typical Passive Filter Block (for each phase)

![Typical Passive Filter Block](image)

### TABLE 12.1 Harmonic current limits in percent of fundamental

<table>
<thead>
<tr>
<th>Short circuit current (pu)</th>
<th>h &lt; 11</th>
<th>11 &lt; h &lt; 17</th>
<th>17 &lt; h &lt; 23</th>
<th>23 &lt; h &lt; 35</th>
<th>35 &lt; h</th>
<th>THD</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20–50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50–100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100–1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>
12-Pluse Phase Controlled Rectifier

Harmonic Order: 1, 11, 13, 23, 25, …
Continuous conduction
Mode

Discontinuous conduction
mode
3-Phase Thyristor Inverter – Constant Current
Thyristor Inverter – Constant Voltage & Current

Diagram (a) shows a thyristor inverter circuit with components labeled. Diagram (b) illustrates the voltage and current relationship with different angles of operation: $\alpha_0$, $\alpha_1$, $\alpha_2$, $\alpha_3 = 90^\circ$, $\alpha_4$, and $\alpha_5$. The diagram explains how the voltage $V_d$ and current $I_d$ vary with different angles of operation for both rectifier and inverter modes.
Thyristor Inverter Operation: Extinction Angle
Thyristor Converters: Voltage Notching

\[ L_{s1} = L_s \]
\[ L_{s2} = 0 \]

Depth: \( V_n = \sqrt{2} V_{LL} \sin \alpha \)

Area: \( A_n = 2\omega L_s I_d \)

Width: \( \mu \approx \frac{2\omega L_s I_d}{\sqrt{2} V_{LL} \sin \alpha} \)
Limits on Notching and Distortion

In practice, the notch depth at PCC depends on $L_{s1}$ relative to $L_{s2}$. Let depth factor be defined by

$$\rho = \frac{L_{s1}}{L_{s1} + L_{s2}}$$

Given $L_{s1}$, a higher value of $L_{s2}$ results in a smaller notch.

<table>
<thead>
<tr>
<th>Class</th>
<th>Line Notch Depth $\rho$ (%)</th>
<th>Line Notch Area $(V\cdot \mu s)$</th>
<th>Voltage Total Harmonic Distortion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Special applications</td>
<td>10</td>
<td>16,400</td>
<td>3</td>
</tr>
<tr>
<td>General system</td>
<td>20</td>
<td>22,800</td>
<td>5</td>
</tr>
<tr>
<td>Dedicated system</td>
<td>50</td>
<td>36,500</td>
<td>10</td>
</tr>
</tbody>
</table>