Chapter 8
Switch-Mode DC-AC Inverters

- converters for ac motor drives and uninterruptible power supplies
Switch-Mode DC-AC Inverter

Figure 8-1  Switch-mode inverter in ac motor drive.

- Block diagram of a motor drive where the power flow is unidirectional
Switch-Mode DC-AC Inverter

Figure 8-2  Switch-mode converters for motoring and regenerative braking in ac motor drive.

- Block diagram of a motor drive where the power flow can be bi-directional
Switch-Mode DC-AC Inverter

- Four quadrants of operation

Figure 8-3 Single-phase switch-mode inverter.
One Leg of a Switch-Mode DC-AC Inverter

Figure 8-4 One-leg switch-mode inverter.

- The mid-point shown is fictitious.
Synthesis of a Sinusoidal Output by PWM

Figure 8-5  Pulse-width modulation.
Details of a Switching Time Period

- Control voltage can be assumed constant during a switching time-period.

Figure 8-6  Sinusoidal PWM.

\[ V_{Ao} = \frac{v_{control}}{v_{tri}} \cdot \frac{V_d}{2} \]
Harmonics in the DC-AC Inverter Output Voltage

Table 8-1 Generalized Harmonics of $v_{Ao}$ for a Large $m_f$.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.2</td>
<td>0.4</td>
<td>0.6</td>
<td>0.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$m_f$</th>
<th>1.242</th>
<th>1.15</th>
<th>1.006</th>
<th>0.818</th>
<th>0.601</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_f$ ± 2</td>
<td>0.016</td>
<td>0.061</td>
<td>0.131</td>
<td>0.220</td>
<td>0.318</td>
</tr>
<tr>
<td>$m_f$ ± 4</td>
<td></td>
<td></td>
<td></td>
<td>0.018</td>
<td></td>
</tr>
<tr>
<td>$2m_f$ ± 1</td>
<td>0.190</td>
<td>0.326</td>
<td>0.370</td>
<td>0.314</td>
<td>0.181</td>
</tr>
<tr>
<td>$2m_f$ ± 3</td>
<td></td>
<td>0.024</td>
<td>0.071</td>
<td>0.139</td>
<td>0.212</td>
</tr>
<tr>
<td>$2m_f$ ± 5</td>
<td></td>
<td></td>
<td>0.013</td>
<td>0.033</td>
<td></td>
</tr>
<tr>
<td>$3m_f$</td>
<td>0.335</td>
<td>0.123</td>
<td>0.083</td>
<td>0.171</td>
<td>0.113</td>
</tr>
<tr>
<td>$3m_f$ ± 2</td>
<td>0.044</td>
<td>0.139</td>
<td>0.203</td>
<td>0.176</td>
<td>0.062</td>
</tr>
<tr>
<td>$3m_f$ ± 4</td>
<td>0.012</td>
<td>0.047</td>
<td>0.104</td>
<td>0.157</td>
<td></td>
</tr>
<tr>
<td>$3m_f$ ± 6</td>
<td></td>
<td>0.016</td>
<td>0.044</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4m_f$ ± 1</td>
<td>0.163</td>
<td>0.157</td>
<td>0.008</td>
<td>0.105</td>
<td>0.068</td>
</tr>
<tr>
<td>$4m_f$ ± 3</td>
<td>0.012</td>
<td>0.070</td>
<td>0.132</td>
<td>0.115</td>
<td>0.009</td>
</tr>
<tr>
<td>$4m_f$ ± 5</td>
<td>0.034</td>
<td>0.084</td>
<td>0.119</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$4m_f$ ± 7</td>
<td></td>
<td>0.017</td>
<td>0.050</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: $(\tilde{v}_{Ao})_{h/2} V_d$ [$= (\tilde{v}_{AN})_{h/2} V_d$] is tabulated as a function of $m_a$.

- Harmonics appear around the carrier frequency and its multiples
Harmonics due to Over-modulation

Figure 8-7 Harmonics due to overmodulation; drawn for $m_a = 2.5$ and $m_f = 15$.

- These are harmonics of the fundamental frequency
Output voltage Fundamental as a Function of the Modulation Index

\[
\frac{\left(\hat{V}_{do}\right)}{\left(V_{d}\right)} = \frac{4}{\pi} \approx 1.278
\]

- Shows the linear and the over-modulation regions; square-wave operation in the limit

**Figure 8-8** Voltage control by varying \(m_a\).

(for \(m_f = 15\))
Square-Wave Mode of Operation

- Harmonics are of the fundamental frequency

Figure 8-9  Square-wave switching.
Half-Bridge Inverter

- Capacitors provide the mid-point

Figure 8-10  Half-bridge inverter.
Single-Phase Full-Bridge DC-AC Inverter

Figure 8-11 Single-phase full-bridge inverter.

• Consists of two inverter legs
PWM to Synthesize Sinusoidal Output

- The dotted curve is the desired output; also the fundamental frequency

Figure 8-12  PWM with bipolar voltage switching.
Analysis assuming Fictitious Filters

Figure 8-13 Inverter with “fictitious” filters.

• Small fictitious filters eliminate the switching-frequency related ripple
DC-Side Current

Figure 8-14 The dc-side current in a single-phase inverter with PWM bipolar voltage switching.

- Bi-Polar Voltage switching
Output Waveforms: Uni-polar Voltage Switching

- Harmonic components around the switching frequency are absent.
DC-Side Current in a Single-Phase Inverter

Figure 8-16 The dc-side current in a single-phase inverter with PWM unipolar voltage switching.

- Uni-polar voltage switching
Sinusoidal Synthesis by Voltage Shift

- Phase shift allows voltage cancellation to synthesize a 1-Phase sinusoidal output

Figure 8-17  Full-bridge, single-phase inverter control by voltage cancellation: (a) power circuit; (b) waveforms; (c) normalized fundamental and harmonic voltage output and total harmonic distortion as a function of $\alpha$.
Single-Phase Inverter

Figure 8-18 Single-phase inverter: (a) circuit; (b) fundamental-frequency components; (c) ripple frequency components; (d) fundamental-frequency phasor diagram.

• Analysis at the fundamental frequency
Square-Wave and PWM Operation

- PWM results in much smaller ripple current
Push-Pull Inverter

- Low Voltage to higher output using square-wave operation

Figure 8-20 Push–pull inverter (single phase).
Figure 8-21 Three-phase inverter.

- Three inverter legs; capacitor mid-point is fictitious
Three-Phase PWM Waveforms

Figure 8-22  Three-phase PWM waveforms and harmonic spectrum.
## Three-Phase Inverter Harmonics

Table 8-2 Generalized Harmonics of $v_{LL}$ for a Large and Odd $m_f$ That Is a Multiple of 3.

<table>
<thead>
<tr>
<th>$m_a$</th>
<th>0.2</th>
<th>0.4</th>
<th>0.6</th>
<th>0.8</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i$</td>
<td>0.122</td>
<td>0.245</td>
<td>0.367</td>
<td>0.490</td>
<td>0.612</td>
</tr>
<tr>
<td>$m_f \pm 2$</td>
<td>0.010</td>
<td>0.037</td>
<td>0.080</td>
<td>0.135</td>
<td>0.195</td>
</tr>
<tr>
<td>$m_f \pm 4$</td>
<td></td>
<td>0.005</td>
<td>0.011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$2m_f \pm 1$</td>
<td>0.116</td>
<td>0.200</td>
<td>0.227</td>
<td>0.192</td>
<td>0.111</td>
</tr>
<tr>
<td>$2m_f \pm 5$</td>
<td></td>
<td></td>
<td>0.008</td>
<td>0.020</td>
<td></td>
</tr>
<tr>
<td>$3m_f \pm 2$</td>
<td>0.027</td>
<td>0.085</td>
<td>0.124</td>
<td>0.108</td>
<td>0.038</td>
</tr>
<tr>
<td>$3m_f \pm 4$</td>
<td></td>
<td>0.007</td>
<td>0.029</td>
<td>0.064</td>
<td>0.096</td>
</tr>
<tr>
<td>$4m_f \pm 1$</td>
<td>0.100</td>
<td>0.096</td>
<td>0.005</td>
<td>0.064</td>
<td>0.042</td>
</tr>
<tr>
<td>$4m_f \pm 5$</td>
<td></td>
<td></td>
<td>0.021</td>
<td>0.051</td>
<td>0.073</td>
</tr>
<tr>
<td>$4m_f \pm 7$</td>
<td></td>
<td></td>
<td></td>
<td>0.010</td>
<td>0.030</td>
</tr>
</tbody>
</table>

Note: $(V_{LL})_h/V_d$ are tabulated as a function of $m_a$ where $(V_{LL})_h$ are the rms values of the harmonic voltages.
Three-Phase Inverter Output

\[ \frac{V_{LL_1} \text{(rms)}}{V_d} \]

- Square-wave
- Linear
- Overmodulation
- Square-wave

\[ \frac{\sqrt{6}}{\pi} = 0.78 \]
\[ \frac{\sqrt{3}}{2\sqrt{2}} = 0.612 \]

\[ V_{LL_1} \text{(rms)}/V_d \text{ as a function of } m_a. \]

- Linear and over-modulation ranges

Figure 8-23 Three-phase inverter; \( V_{LL_1} \text{(rms)}/V_d \) as a function of \( m_a \).
Three-Phase Inverter: Square-Wave Mode

Figure 8-24 Square-wave inverter (three phase).

- Harmonics are of the fundamental frequency
Three-Phase Inverter: Fundamental Frequency

Figure 8-25 Three-phase inverter: (a) circuit diagram; (b) phasor diagram (fundamental frequency).

- Analysis at the fundamental frequency can be done using phasors
Square-Wave and PWM Operation

- PWM results in much smaller ripple current
DC-Side Current in a Three-Phase Inverter

Figure 8-27  Input dc current in a three-phase inverter.

- The current consists of a dc component and the switching-frequency related harmonics.
Square-Wave Operation

- devices conducting are indicated

Figure 8-28 Square-wave inverter: phase A waveforms.
PWM Operation

- devices conducting are indicated

Figure 8-29  PWM inverter waveforms: load power factor angle = 30° (lag).
Short-Circuit States in PWM Operation

Figure 8-30  Short-circuit states in a three-phase PWM inverter.

- top group or the bottom group results in short circuiting three terminals
Effect of Blanking Time

- Results in nonlinearity

Figure 8-31  Effect of blanking time $t_a$. 
Effect of Blanking Time

Figure 8-32 Effect of $t_\Delta$ on $V_o$, where $\Delta V_o$ is defined as a voltage drop if positive.

- Voltage jump when the current reverses direction
Effect of Blanking Time

**Figure 8-33** Effect of $t_\Delta$ on the sinusoidal output.

- Effect on the output voltage
Programmed Harmonic Elimination

- Angles based on the desired output

Figure 8-34  Programmed harmonic elimination of fifth and seventh harmonics.
Tolerance-Band Current Control

- Results in a variable frequency operation

Figure 8-35  Tolerance band current control.
Fixed-Frequency Operation

- Better control is possible using $dq$ analysis

Figure 8-36  Fixed-frequency current control.
Transition from Inverter to Rectifier Mode

- Can analyze based on the fundamental-frequency components
Summary of DC-AC Inverters

- Functional representation in a block-diagram form

**Figure 8-38** Summary of inverter output voltages: (a) PWM operation ($m_a \leq 1$); (b) square-wave operation.