Power Electronics

INVERTERS

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Inverter Classification

Classification of inverters based on wave shape

- Square wave
- Quasi square wave
- Sine wave

Classification of inverters based on Input

- Voltage source
- Current source
Half bridge inverter

- Switches S1 and S2 used are gate commutated devices such as BJT, MOSFET, IGBT, GTO etc.
- S1 and S2 are turned on alternately to produce an ac voltage across the load.
- Each switch is ON for half time period (T/2) of the desired frequency.
Full bridge inverter

- S1 and S2 turned on in the first half cycle (T/2)
- S3 and S4 turned on in the second half cycle (T/2)
Two modes of operation:
Mode 1:
S1 and S2 are ON
Mode 2
S3 and S4 are ON
Full bridge inverter – RL load

Four modes of operation:

Mode 1: S1 and S2 are ON, Output +ve
Mode 2: D3, D4 conducts, Output -ve
Mode 3: S3 and S4 are ON, Output –ve
Mode 4: D1, D2 conducts, Output +ve
Full Bridge Inverter – Transistor Ratings

\[ V_{CE(0)} \geq E_{DC} \]

\[ I_{T(ave)} = \frac{E_{DC}}{2R} \]

\[ I_{T(peak)} = \frac{E_{DC}}{R} \]
Fourier series for symmetrical square wave, \( e(t) = \sum_{n=1,3,5,\ldots}^{\infty} \frac{4E_{DC}}{n\pi} \sin(n \omega t) \)
Harmonics

Fourier Series, \( e = \sum_{n=1,3,5,...}^{\infty} \frac{4E_{DC}}{n\pi} \sin(n \omega t) \)

Fundamental output voltage, \( E_1 = \frac{2\sqrt{2}}{\pi} E_{DC} \)

\( \text{ie.} \quad E_1 = 0.9 \ E_{DC} \)

\( n^{th} \) order output voltage, \( E_n = \frac{E_1}{n} \)

RMS value, \( E_{(rms)} = \sqrt{E_1^2 + E_3^2 + E_5^2 + \ldots} \)

Harmonic voltage, \( E_h = \left( \sum_{n=3,5,\ldots}^{\infty} E_n^2 \right)^{\frac{1}{2}} = \left( E^2 - E_1^2 \right)^{\frac{1}{2}} = 0.4352 \ E_{DC} \)
Harmonic Parameters

Harmonic factor for $n^{th}$ harmonic measures the individual harmonic contribution

$$\text{Harmonic Factor, } HF_n = \frac{E_n}{E_1}$$

Total harmonic distortion is a measures of how different is the actual waveform from its fundamental component

$$\text{Total Harmonic Distortion, } THD = \frac{1}{E_1} \left( \sum_{n=3,5,..}^{\infty} E_n^2 \right)^{1/2} = \frac{E_h}{E_1}$$

Harmonic factor is a measures of effectiveness in reducing unwanted harmonics using filters

$$\text{Distortion Factor, } DF = \frac{1}{E_1} \left( \sum_{n=3,5,..}^{\infty} \left( \frac{E_n}{n^2} \right)^2 \right)^{1/2}$$
Comparison of parameters in Half Bridge and Full Bridge Inverters

<table>
<thead>
<tr>
<th></th>
<th>Full Bridge</th>
<th>Half Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output voltage</td>
<td>$E_O = E_{DC}$</td>
<td>$E_O = \frac{E_{DC}}{2}$</td>
</tr>
<tr>
<td>Fundamental output voltage</td>
<td>$E_1 = \frac{2\sqrt{2}}{\pi} E_{DC} = 0.9 E_{DC}$</td>
<td>$E_1 = \frac{2\sqrt{2}}{\pi} \frac{E_{DC}}{2} = 0.45 E_{DC}$</td>
</tr>
<tr>
<td>Harmonic output voltage</td>
<td>$E_h = 0.4352 E_{DC}$</td>
<td>$E_h = 0.2176 E_{DC}$</td>
</tr>
<tr>
<td>Peak breaking voltage of switches</td>
<td>$E_{BR} = E_{DC}$</td>
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</table>
Example

A single phase full bridge inverter is operated from 48 V battery and supplying power to a 24 ohm load. Determine output power THD of output and transistor ratings.

Solution:

RMS Power, \( P = \frac{E^2}{R} = \frac{48^2}{24} = 96 \text{ W} \)

\[ E_1 = 0.9 \ E_{DC} = 0.9 \times 48 = 43.2 \text{ V} \]

\[ E_h = 0.4352 \ E_{DC} = 0.4352 \times 48 = 20.89 \text{ V} \]

\[ \text{THD} = \frac{E_h}{E_1} = \frac{20.89}{43.2} = 48.36\% \]

\( V_{CE} \geq 48 \text{ V} \)

\[ I_{T(peak)} = \frac{E_{DC}}{R} \]

\[ = \frac{48}{24} = 2 \text{ A} \]
Cross Conduction or Shoot Through Fault

- Normally the switches in the bridge switch on in pairs – S1-S2 turn on first and after they are off, S3-S4 turn on.
- Therefore the switches in the same leg (say S1 and S4) may not turn on at the same time.
- Due to turn off delay, incoming device and outgoing device of the same leg in the bridge conduct at the same instant and short circuits the DC source.
- This fault damages both the devices.
Cross Conduction or Shoot Through Fault

A solution for cross conduction fault is to introduce a dead band or delay between the trailing edge of the gate input of outgoing device and the leading edge of the gate input of incoming device.

Dead band should be longer than the turn off time of the inverter.
3-Phase Inverter

Load configurations
3-Phase Inverter
180° conduction

Connection during first interval
3-Phase Inverter
180° conduction

Connection during second interval
3-Phase Inverter

180° conduction

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<tr>
<th>Interval</th>
<th>Incoming Device</th>
<th>Conducting Devices</th>
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<td>1</td>
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<td>5,6,1</td>
</tr>
<tr>
<td>2</td>
<td>S1</td>
<td>6,1,2</td>
</tr>
<tr>
<td>3</td>
<td>S3</td>
<td>1,2,3</td>
</tr>
<tr>
<td>4</td>
<td>S4</td>
<td>2,3,4</td>
</tr>
<tr>
<td>5</td>
<td>S5</td>
<td>3,4,5</td>
</tr>
<tr>
<td>6</td>
<td>S6</td>
<td>4,5,6</td>
</tr>
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Features of 180 degree conduction

- Conduction period for each switch is 180°
- Three switches conduct at a time
- There is possibility of cross conduction if a dead band delay is not deliberately introduced.
- Phase voltages are six step waves
- Line voltages are quasi square waves
3-Phase Inverter

120° conduction

Connection during first interval
3-Phase Inverter
120° conduction

Connection during second interval
3-Phase Inverter
120° conduction

Connection during third interval
3-Phase Inverter
120° conduction

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<td>S5</td>
<td>4,5</td>
</tr>
<tr>
<td>6</td>
<td>S6</td>
<td>5,6</td>
</tr>
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</table>
Features of 120 degree conduction

- Conduction period for each switch is only 120°
- Only two switches conduct at a time
- Two switches in the same leg of bridge have inherent dead band of 60° and there is no possibility of cross conduction
- Phase voltages are quasi square waves
- Line voltages are six step waves
Parallel Inverter

- SCRs can be used as switch, simple forced commutation is possible.
- When T1 is turned on, the transformer is energised in one direction and the capacitor C is charged with a voltage of $2E_{DC}$.
- When T2 is turned on, capacitor voltage is applied to T1 in reverse direction and commutates it; the capacitor C is charged with a voltage of $-2E_{DC}$.
- T1 is turned on again forcing T2 to turn off and the cycle repeats.
- Higher output voltage is possible by suitable transformer turns ratio.
Voltage Control with Pulse Width Modulation

- **Single Pulse width Modulation**
  - Consists of a pulse with variable width in each half cycle
  - width varies from 0 to $\pi$

- **Multiple Pulse Width Modulation**
  - Is an extension of single PWM and uses several equidistant pulses in each half cycle

- **Sinusoidal Pulse Width Modulation**
  - Pulse width is a sinusoidal function of angular position of the pulse in a cycle
Single Pulse PWM

Reference wave  Carrier wave

Carrier Wave

Square Wave

Comparator
Single Pulse PWM

RMS value of output voltage, \( V = V_{DC} \left[ \frac{2d}{\pi} \right]^{\frac{1}{2}} \)

Peak value of nth harmonic, \( V_{onm} = \frac{4 V_{DC}}{n\pi} \sin nd \)

When pulsewidth is 120°, \( d = 60° \)

Then peak value of 3rd harmonic, \( V_{o3m} = \frac{4 V_{DC}}{3\pi} \sin 3 \times 60 = 0 \)

This implies, when the pulse width is 120°, third harmonics will be eliminated
Multiple Pulse PWM

\[ V = V_{DC} \left[ \frac{N_p \times P}{\pi} \right]^{\frac{1}{2}} \]

\( N_p \) = number of pulses in a half cycle

\( P \) = pulse width

RMS value of output voltage, \( V = V_{DC} \left[ \frac{N_p \times P}{\pi} \right]^{\frac{1}{2}} \)
Sine PWM

Modulation Index, \( MI = \frac{V_r}{V_c} \)

where \( V_r \) is the peak of reference wave and \( V_c \) is the peak of carrier wave

There will be low order harmonics when \( MI \) is greater than 1
Typical MOSFETS

IRFP250N
HEXFET® Power MOSFET

- $V_{DSS} = 200\text{V}$
- $R_{DS(on)} = 0.075\Omega$
- $I_D = 30\text{A}$

TO-247AC

VMO 650-01F

- $V_{DSS} = 100\text{V}$
- $I_{D25} = 690\text{A}$
- $R_{DS(on)} = 1.8\text{mΩ}$

Maximum Ratings

<table>
<thead>
<tr>
<th></th>
<th>100</th>
<th>100</th>
<th>±20</th>
<th>±30</th>
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</thead>
<tbody>
<tr>
<td>$V$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$I_D$</td>
<td></td>
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</table>

D = Drain
KS = Kelvin Source
S = Source
G = Gate

Utilize advanced processing per silicon area. This benefit, along with the small device design that provides the designer with a wide variety of applications.

Industrial applications where device sizes are very critical. The TO-247 is similar to its isolated mounting hole.
Typical IGBTs