POWER ELECTRONICS

DC-TO-AC INVERTERS

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Lecture # 11

DC-AC Inverters

Various applications of inverters are:

- The DC-to-AC converter, which is also termed an *inverter, converts DC power into* AC power at a desired output voltage and frequency.
- The term *inverter generally* refers to the voltage source rather than current source, that is, it converts energy from a battery or any other fixed DC voltage into AC form whose both magnitude and frequency can be controlled.
- Thyristor-based inverters are used only in high-power applications.
- For low- and medium-power applications, devices such as the power bipolar junction transistor (BJT), metal-oxide semiconductor field-effect transistor (MOSFET), insulated-gate bipolar transistor (IGBT), and gate turn-off (GTO) are used.

DC-AC inverters

Various applications of inverters are:

- Adjustable speed AC drive
- Uninterruptible power supplies (UPS)
- Induction heating
- High-voltage direct current (HVDC) transmission lines

Types of DC-AC Inverters

Inverters can be classified as:

1. **Line-Commutated Inverters:** Inverters that require an existing AC supply at output terminal for their commutation. Their output AC voltage level and frequency cannot be changed.

2. **Force-Commutated Inverter:** Inverters whose output AC voltage level and frequency can be changed as per requirement. These require forced commutation for their turn-off, for example, series inverter, auxiliary commutated inverter, parallel inverter, complementary-commutated inverter.

3. **Voltage Source Inverters (VSI):** Inverters in which the DC source has small impedance.

4. **Current Source Inverter (CSI):** Inverts in which the DC source has high impedance.

5. **Square Wave Inverters:** Such inverters produce a square-wave AC voltage of a constant magnitude. The output voltage of this type of inverter can only be varied by controlling the input DC voltage.

6. **Pulse-Width Modulation (PWM) Inverters:** In these, output has one or more pulses in each half cycle, and by varying the width of pulses, the output voltage is controlled.

PERFORMANCE PARAMETERS OF INVERTERS

Ideally, an inverter should give a sinusoidal voltage at its output. But the output of practical inverters is non-sinusoidal and contains harmonics. The quality of an inverter is evaluated in terms of the following performance parameters:

1. **Harmonic Factor of *nth Harmonic* (HFn):** A harmonic factor is a measure of the individual harmonic contribution in the output voltage of an inverter. It is defined as:

$$HF_n = \frac{V_n}{V_1}$$

where

V_n = root mean square (RMS) value of the nth harmonic component.

V_1 = RMS value of the fundamental component of the output voltage.

PERFORMANCE PARAMETERS OF INVERTERS

2. **Total Harmonic Distortion (THD):** A total harmonic distortion is a measure of closeness in shape between a waveform and its fundamental component. It is defined as the ratio of the RMS value of the total harmonic component of the output voltage and the RMS value of the fundamental component, that is,

$$\mathrm{THD} = \frac{\sqrt{\sum_{n=2,3\ldots}^{\infty} V_n^2}}{V_1} = \frac{\sqrt{V_{\mathrm{rms}}^2 - V_1^2}}{V_1}$$

where V_{rms} is the RMS value of output voltage.

PERFORMANCE PARAMETERS OF INVERTERS

3. **Distortion Factor (DF):** A DF indicates the amount of harmonics (or harmonic distortions) that remains in the output voltage waveform. It is a measure of effectiveness in reducing unwanted harmonics. It is defined as:

$$THD = \frac{\sqrt{\sum_{n=2,3...}^{\infty}\left(\frac{V_n}{n}\right)^2}}{V_1}$$

The DF of an individual (or *nth)* harmonic component is defined as:

$$DF_n = \frac{V_n}{V_1 n^2}$$

4. **Lowest-Order Harmonic (LOH):** The LOH is that harmonic component whose frequency is closest to the fundamental one, and its amplitude is greater than or equal to 3% of the fundamental component.

VOLTAGE SOURCE INVERTERS

If thyristors are used in voltage source inverters (VSIs), then forced commutation is required. But, if GTOs, power MOSFETs, and power IGBTs are used, then self commutation with base or gate drive signals is used for their turn on/turn off.

1. SIngle-Phase Voltage Source Inverters

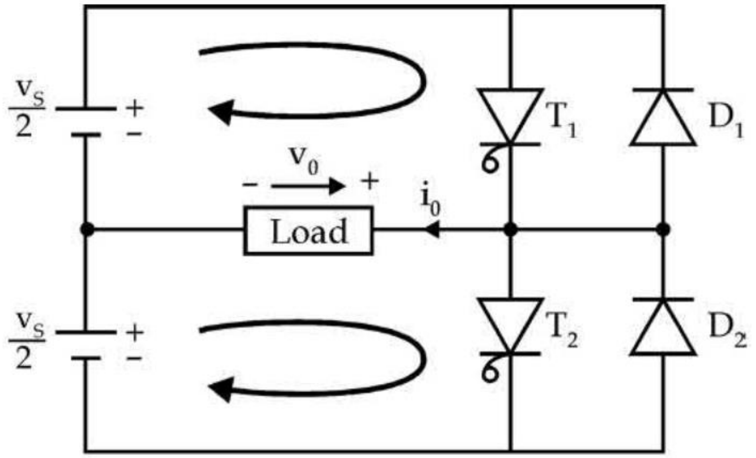
Single-phase bridge inverters have two configurations

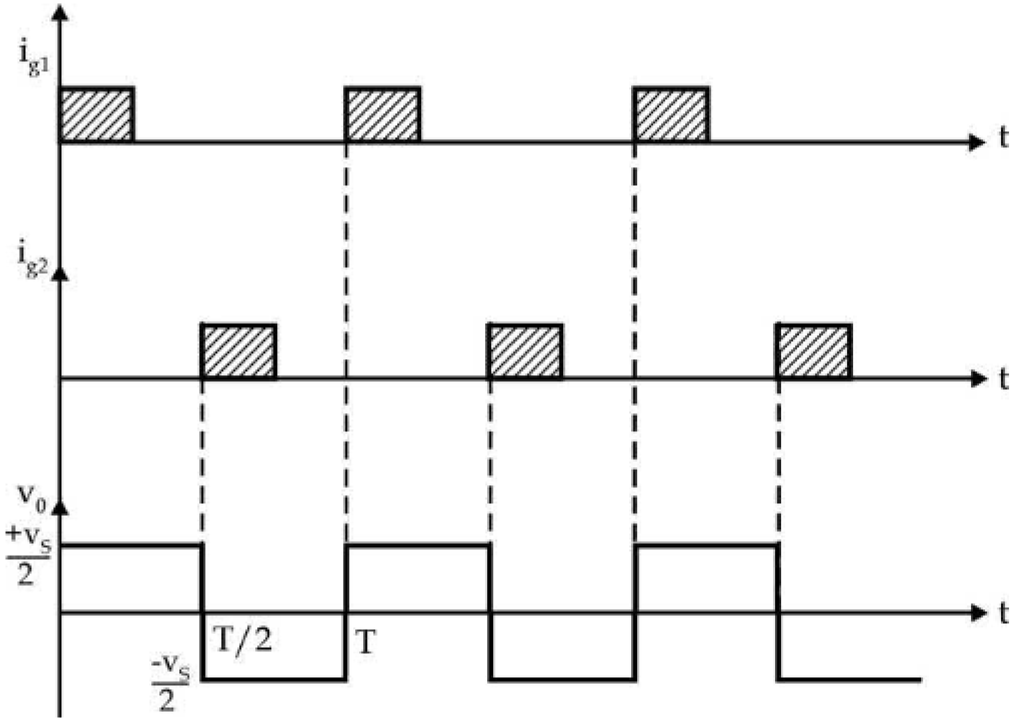
1) Single-phase half-bridge inverter.
2) Single-phase full-bridge inverter.

VOLTAGE SOURCE INVERTERS

1- Single-phase half-bridge inverter:

Power circuit and various waveforms for single-phase half-bridge configuration are shown in the figure. The output voltage is an alternating voltage waveform of amplitude $V_S/2$ and frequency $1/T$ Hz. Frequency of inverter output AC voltage can be changed by varying the periodic time T.





Demerits (Drawbacks) of half-bridge configuration:

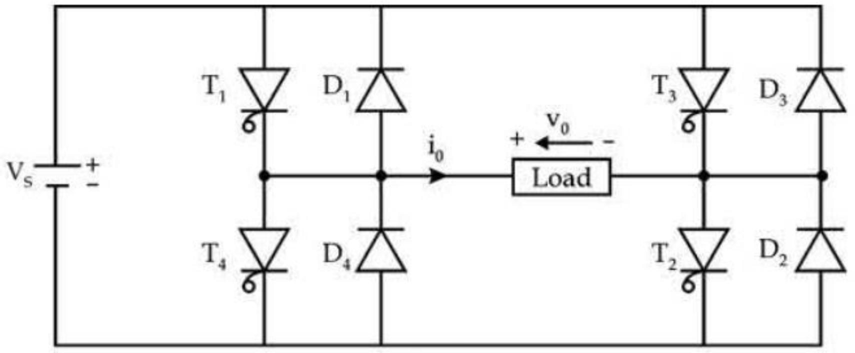
a. It requires a three-wire DC supply.

b. Output voltage magnitude is $V_S/2$ only.

VOLTAGE SOURCE INVERTERS

2- Single-phase full-bridge inverter:

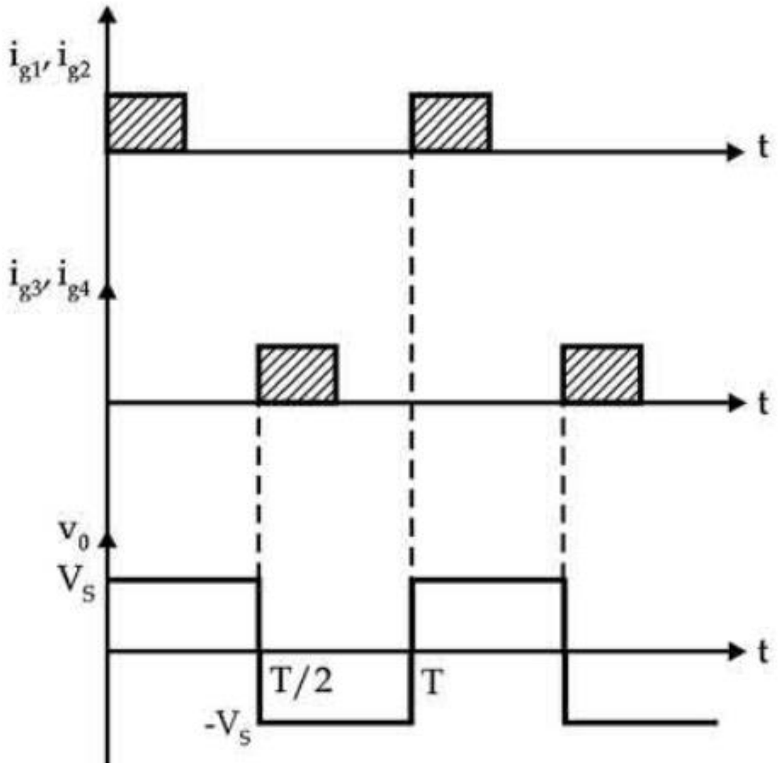
Single-phase full-bridge inverter: Power circuit diagram of full-bridge configuration with various waveforms are shown in the figure.



Frequency of the inverter output AC voltage can be changed by varying the periodic time *T*.
Therefore,

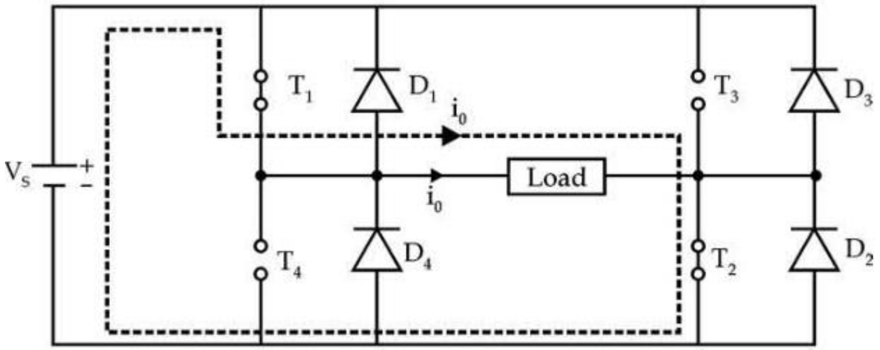
$$v_0 = +V_S \text{ and } i_0 = +I_0 \quad \text{for} \quad 0 < t < T/2$$

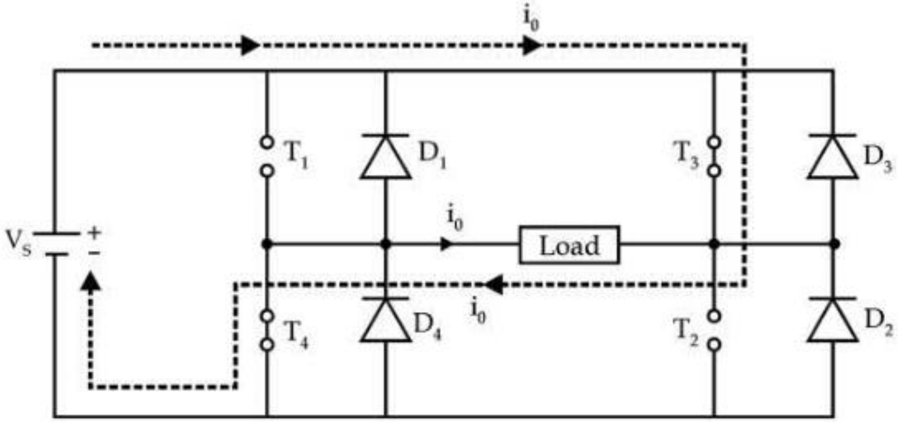
$$v_0 = -V_S \text{ and } i_0 = -I_0 \quad \text{for} \quad T/2 < t < T$$



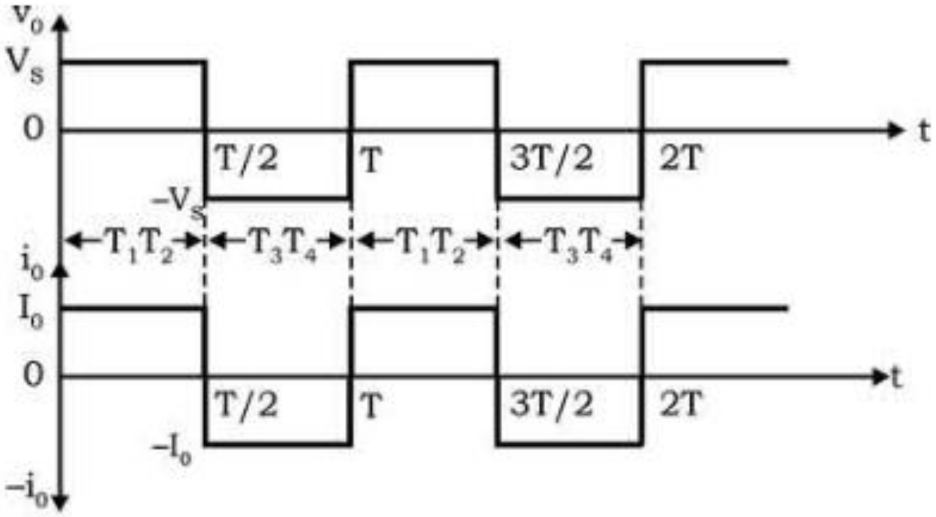
VOLTAGE SOURCE INVERTERS

It should be noted that in VSIs, the load voltage waveforms do not depend on the nature of load, but the load current depends on the nature of load.





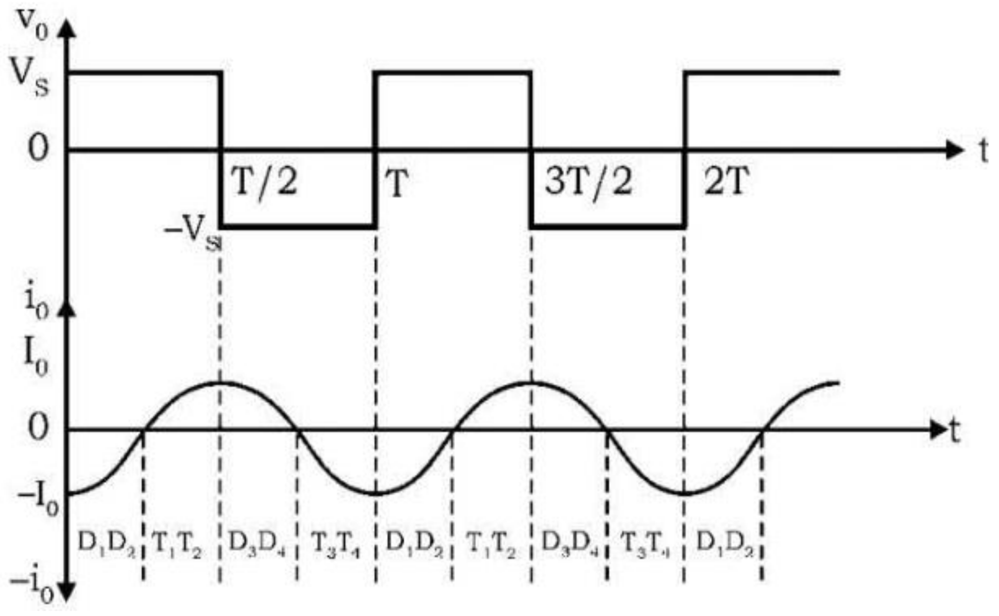
With R load: For resistive load R, load current i_0 is identical with load voltage waveform v_0 and diodes D_1–D_4 connected in antiparallel with thyristors (called feedback diodes) are not required



VOLTAGE SOURCE INVERTERS

With RL and RLC Overdamped Loads

For inductive loads, load current will not be in phase with voltage v_o, and therefore, feedback diodes D_1–D_4 are required to allow the current to flow when the main thyristors are turned off. The load current waveforms for RL and RLC overdamped loads are shown in the Figures. Before $T = 0$, *thyristors* T_3 , T_4 are conducting, and therefore load current i_0 was $-I_0$.

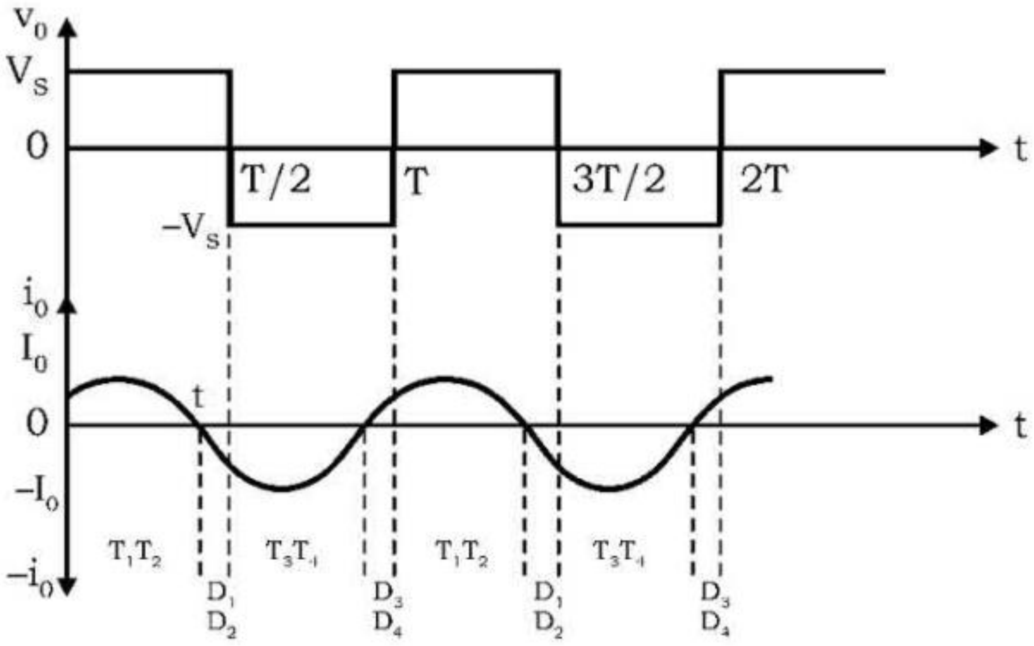


RLC overdamped load

VOLTAGE SOURCE INVERTERS

With RLC Underdamped Loads

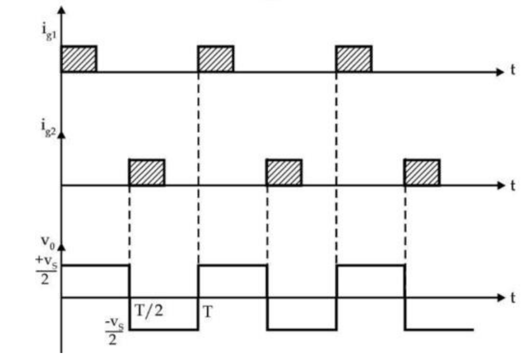
The load current i_0 for RLC underdamped load is shown in the Figure. After $t = 0$, load current flows through T_1, T_2. Because i_0 through T_1, T_2 reduces to zero at t_1, these SCRs are turned off before T_3, T_4, are triggered. As T_1, T_2 stop conducting, current through the load reverses and is now carried by diodes D_1, D_2 because T_3, T_4 are not yet gated. The diodes D_1, D_2 are connected in antiparallel to T_1, T_2 so voltage drop across these diodes appears as reverse biased across T_1, T_2.



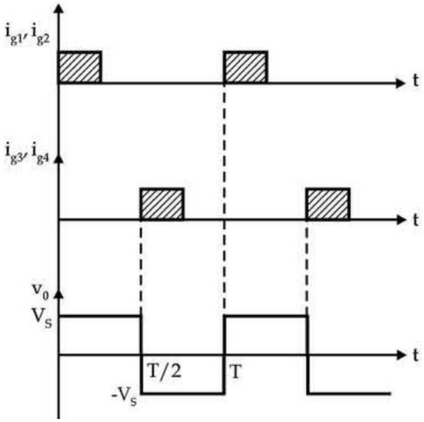
RLC underdamped load

Fourier Analysis of Single-Phase Inverter Output Voltage

The output or load voltage waveforms of the voltage source inverter do not depend on the nature of load. Voltage waveforms of the Figures can be resolved in Fourier series as



$$v_0 = \sum_{n=1,3,5...}^{\infty} \frac{2V_S}{n\pi} \sin n\,\omega t \ldots \text{ for } 1-\phi \text{ half bridge inverter}$$



$$v_0 = \sum_{n=1,3,5...}^{\infty} \frac{4V_S}{n\pi} \sin n\omega t \ \ldots \text{ for } 1-\phi \text{ full bridge inverter}$$

Where:
***n* = order of harmonics**
***ω* = frequency of output voltage in rad/s**

Fourier Analysis of Single-Phase Inverter Output Voltage

The load current i_0 for full-bridge inverter can be expressed as:

$$i_0 = \sum_{n=1,3,5\ldots}^{\infty} \frac{4V_S}{n\pi \cdot Z_n} \sin\left(n\omega t - \varphi_n\right)$$

where

z_n = load impedance at frequency nf $= \left[R^2 + \left(n\omega L - \frac{1}{n\omega C}\right)^2\right]^{\frac{1}{2}}$

$$\phi_n = \text{phase angle} = \tan^{-1} \frac{\left(n\omega L - \frac{1}{n\omega C}\right)}{R}$$

The fundamental load power $P_{01} = I_{01}^2 \ R = V_{01} I_{01} \cos \varphi_1$

At time of commutation:

If load current $I_0 > 0$, forced commutation is required.

If load current $I_0 < 0$, no forced commutation is required.

Example

A single-phase, half-bridge inverter feeds a resistive load, R = 10 Ohms.
If the source voltage is 240 V, determine
(a) the RMS value of fundamental component of output voltage,
(b) the output power,
(c) the peak off-state voltage across each semiconductor switch,
(d) the lowest-order harmonic and the corresponding harmonic factor, and
(e) the RMS and average values of currents through semiconductor switches.

Solution

The magnitude of square-wave output voltage for the half-bridge inverter,

$$V_L = \frac{240}{2} = 120\ V$$

Example

The output voltage may be expressed in Fourier series, using Equation:

$$v_0(t) = \sum_{n=1,3,5\ldots}^{\infty} \frac{2V_S}{n\pi}\sin(n\omega t)$$

$$= \frac{2\times 240}{\pi}\sum_{n=1,3,5\ldots}^{\infty} \frac{\sin(n\omega t)}{n}$$

$$= 152.87\left[\sin(\omega t) + \frac{\sin(3\omega t)}{3} + \frac{\sin(5\omega t)}{5} + \ldots\right]$$

Now, we get the following:

(a) The RMS value of fundamental component of the output voltage, $V_1 = 152.79/\sqrt{2} = 108.04\ \text{V}$

(b) The output power is given by $P_0 = V_0^2/R$
where V_0 is the RMS value of the output voltage. For the square-wave output, $V_0 = V_L = 120$ V. Therefore, $P_0 = 120^2/10 = 1440$ W

(c) The peak voltage that appears across each semiconductor switch is

$$2V_L = 2\times 120 = 240\ \text{V}$$

Example

(d) The lowest-order harmonic is the third harmonic, which has an RMS value equal to $V_3 = 152.79/\left(3\sqrt{2}\right) = 36.01\,\text{V}$. The corresponding harmonic factor is

$$HF_3 = \frac{V_3}{V_1} = \frac{36.01}{108.04} = 0.333$$

(e) The output current has a square-wave shape with magnitude 120/10 = 12 A. In the positive half cycle, the load current flows through the switch S_1, and in the negative half cycle, the switch S_2 carries the load current. The average switch current may be obtained as

$$I_{s(\text{avg})} = \frac{1}{T}\int_0^{T/2} 12dt = \frac{12(T/2)}{T} = 6\,\text{A}$$

The RMS switch current is given by

$$I_{s(\text{rms})} = \left[\frac{1}{T}\int_0^{T/2}(12)^2 dt\right]^{\frac{1}{2}} = \left[\frac{1}{T}\times(12)^2\times\frac{T}{2}\right]^{\frac{1}{2}} = \frac{12}{\sqrt{2}} = 8.48\,\text{A}$$

End of lecture # 11