Electric Energy Conversion

7. DC/AC converters – part 1

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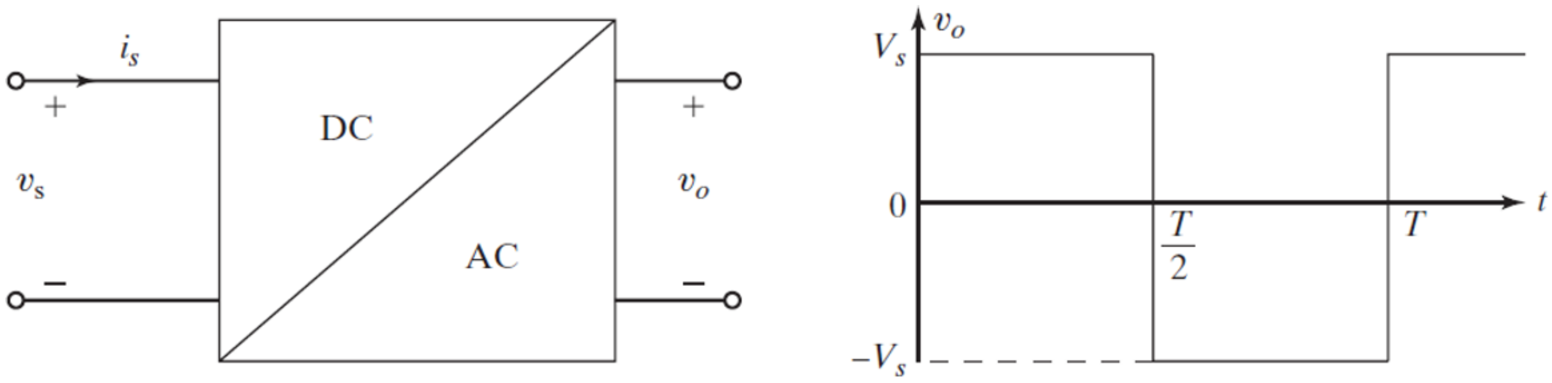
Outline

- Single-phase inverters
- Three-phase inverters
- Simulation

Introduction

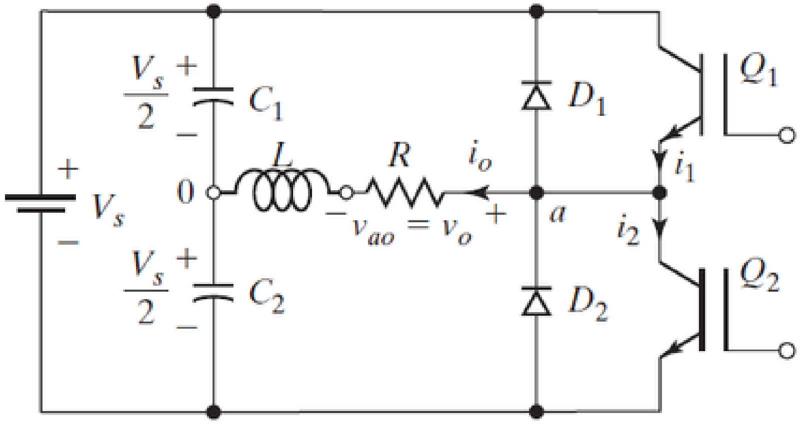
- DC/AC converters are also called **inverters** because they can synthesise AC waveforms from a DC source.
- The AC waveforms are created by switching ON and OFF the converter transistors.



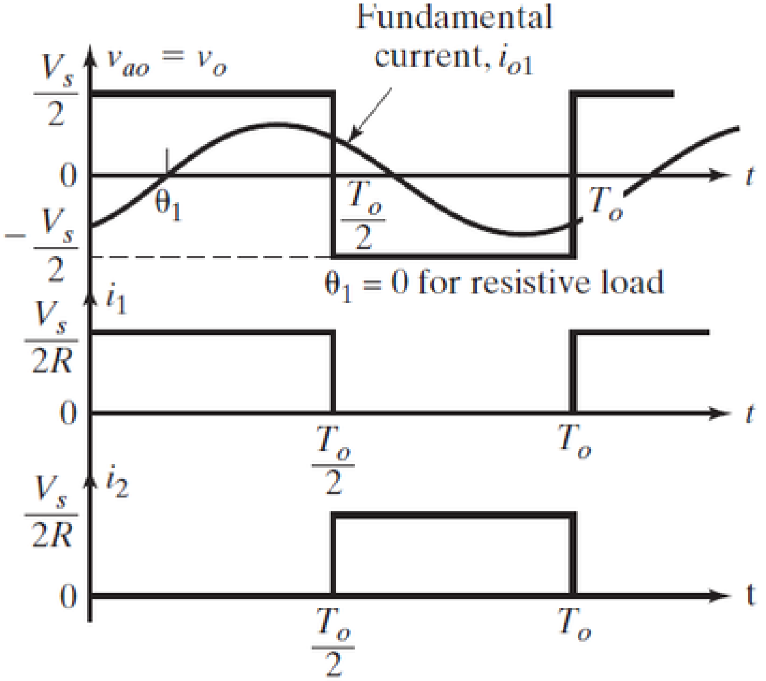
(a) Block diagram (b) Output voltage

Principle of operation – half-bridge

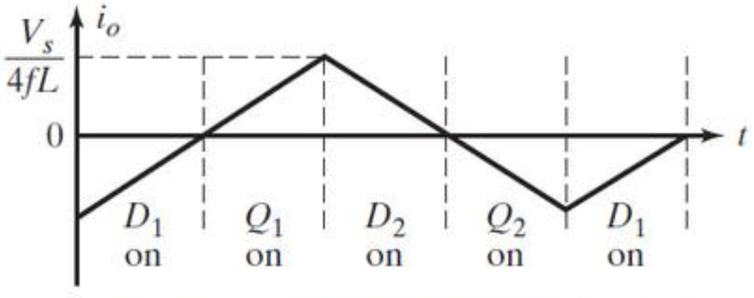
- The principle of operation of inverters can be illustrated by analysing a single phase-inverter.
- When Q_1 is ON (Q_2 OFF) the instantaneous voltage on the load is $V_s/2$.
- When Q_2 is ON (Q_1 OFF) for the instantaneous voltage on the load is $-V_s/2$.
- The commutation diodes D_1 and D_2 create a path for the current that cannot return through Q_1 and Q_2. So each pair Q_1/D_1 and Q_2/D_2 conducts for $T_0/2$.



(a) Circuit



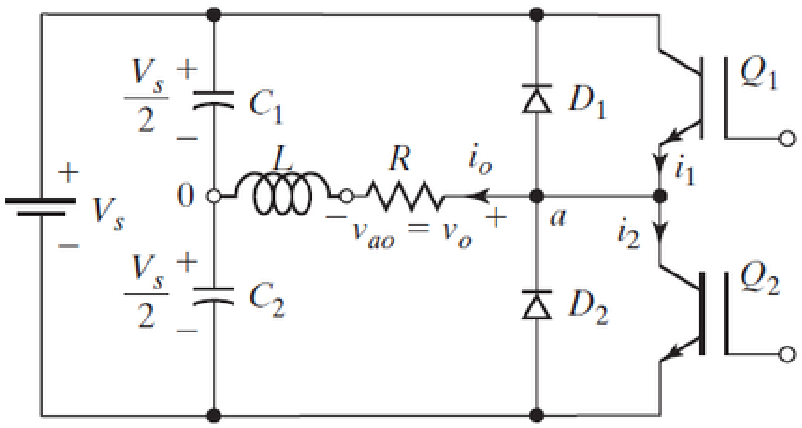
(b) Waveforms with resistive load



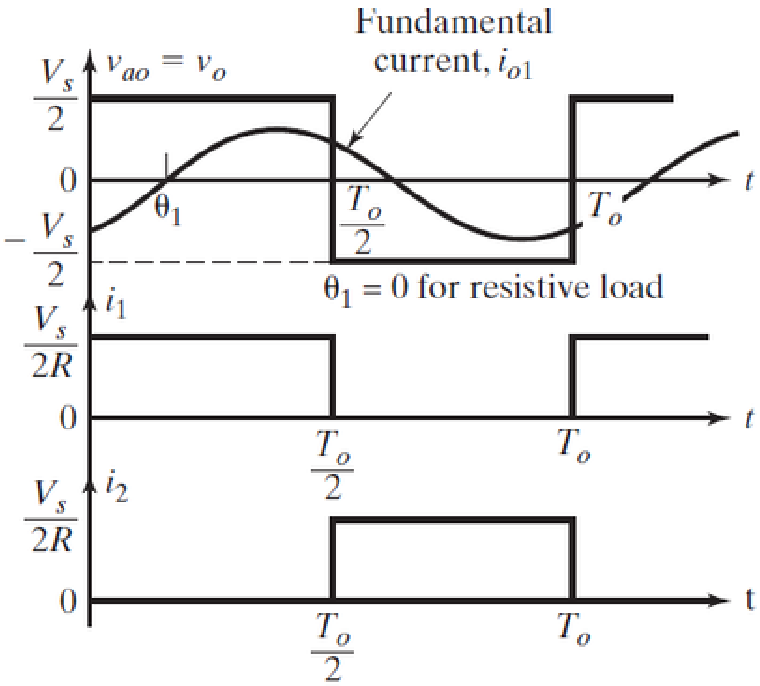
(c) Load current with highly inductive load

Principle of operation – half-bridge

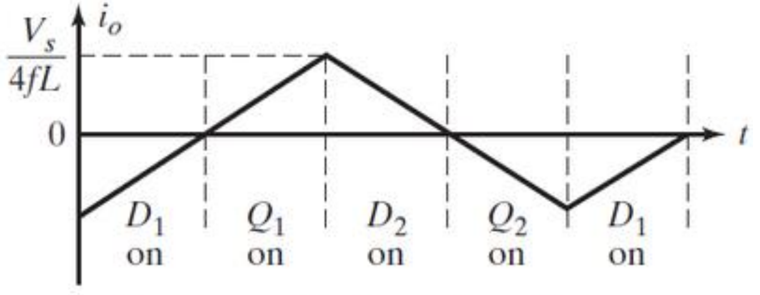
- The output voltage is a square wave with amplitude $V_s/2$.
- The RMS voltage is $V_o = \sqrt{\frac{2}{T_0}\int_0^{T_0/2}\left(\frac{V_s}{2}\right)^2 dt} = V_s/2$
- The Fourier series of the instantaneous output voltage gives $v_o = \sum_{n=1,3,5,\ldots}^{\infty} 2V_s/(n\pi)\ \sin n\omega t$
- The greater the angle between voltage and current, the more the diodes D_1 and D_2 conduct (from 0 to 90°)



(a) Circuit



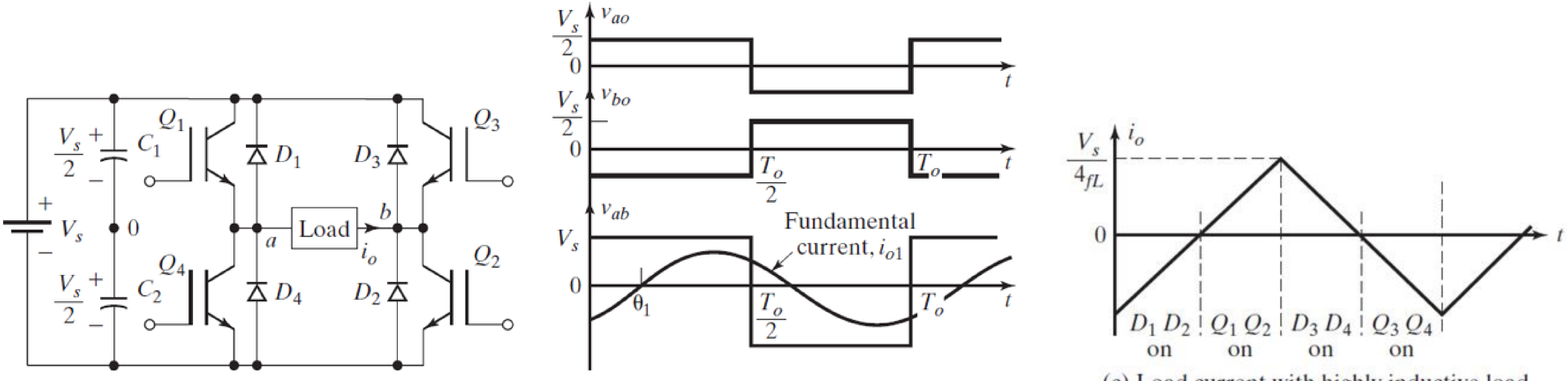
(b) Waveforms with resistive load



(c) Load current with highly inductive load

Principle of operation – full bridge

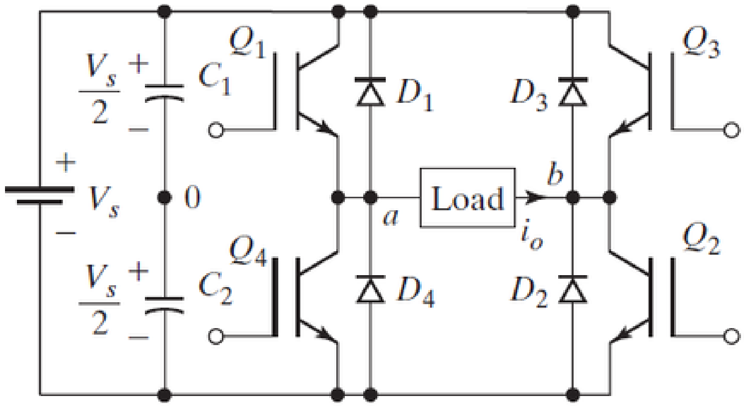
- A full-bridge inverter is built with 4 transistors.
- When $Q_1$and Q_2 are ON for $T_o/2$ the instantaneous voltage on the load is V_s.
- When $Q_3$and Q_4 are ON for $T_o/2$ the instantaneous voltage on the load is $-V_s$.
- The full-bridge can apply the full voltage to the load and also apply zero voltage, creating a third voltage level.



(a) Circuit (b) Waveforms (c) Load current with highly inductive load

Principle of operation – full bridge

- Switch states: 1 if an upper switch is ON and 0 if a lower switch is OFF.

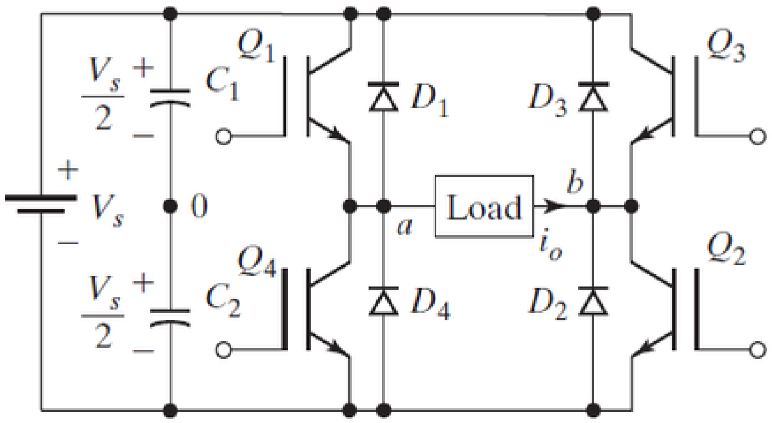


State	State No.	Switch State*	v_{ao}	v_{bo}	v_o	Components Conducting
S_1 and S_2 are on and S_4 and S_3 are off	1	10	$V_S/2$	$-V_S/2$	V_S	S_1 and S_2 if $i_o > 0$ D_1 and D_2 if $i_o < 0$
S_4 and S_3 are on and S_1 and S_2 are off	2	01	$-V_S/2$	$V_S/2$	$-V_S$	D_4 and D_3 if $i_o > 0$ S_4 and S_3 if $i_o < 0$
S_1 and S_3 are on and S_4 and S_2 are off	3	11	$V_S/2$	$V_S/2$	0	S_1 and D_3 if $i_o > 0$ D_1 and S_3 if $i_o < 0$
S_4 and S_2 are on and S_1 and S_3 are off	4	00	$-V_S/2$	$-V_S/2$	0	D_4 and S_2 if $i_o > 0$ S_4 and D_2 if $i_o < 0$
S_1, S_2, S_3, and S_4 are all off	5	off	$-V_S/2$ $V_S/2$	$V_S/2$ $-V_S/2$	$-V_S$ V_S	D_4 and D_3 if $i_o > 0$ D_1 and D_2 if $i_o < 0$

- The RMS voltage is $V_o = \sqrt{\frac{2}{T_0}\int_0^{T_0/2} V_s^2\,dt} = V_s$
- The Fourier series of the instantaneous output voltage gives $v_o = \sum_{n=1,3,5,\ldots}^{\infty} 4V_s/(n\pi)\ \sin n\omega t$

Exercise

- The full-bridge inverter of the figure is connected to an RLC load with $R = 10\ \Omega$, $L = 31.5$ mH and $C\ =\ 112\ \mu F$. The fundamental AC frequency is 60 Hz.



a) Express the instantaneous current up to the ninth harmonic.

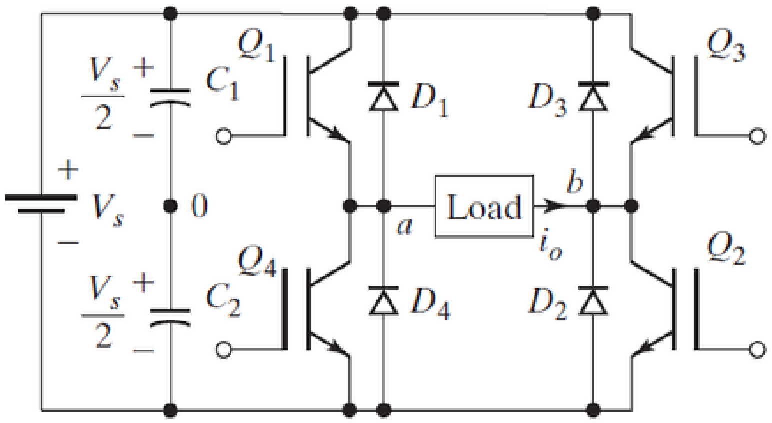
b) Calculate the RMS load current at the fundamental frequency.

- Key equations

The RMS voltage is $V_o = \sqrt{\frac{2}{T_0}\int_0^{T_0/2} V_s^2 dt} = V_s$

The Fourier series of the instantaneous output voltage is $v_o = \sum_{n=1,3,5,\ldots}^{\infty} 4V_s/(n\pi)\ \sin n\omega t$

Exercise



- The load impedance is:

$$X_L = j_n\omega L = j2n\pi \times 60 \times 31.5 \times 10^{-3} = j11.87n\ \Omega$$

$$X_c = \frac{j}{n\omega C} = -\frac{j10^6}{2n\pi \times 60 \times 112} = \frac{-j23.68}{n}\ \Omega$$

$$Z_n = R + j(11.87n\ - 23.68/n)$$

- The output voltage is: $v_o(t) = \sum_{n=1,3,5,\ldots}^{\infty} 4V_s/(n\pi)\ \sin n\omega t$

$$= 280.1\sin(\omega t) + 93.4\sin(3\omega t) + 56\sin(5\omega t) + 40\sin(7\omega t) + 31.1\sin(9\omega t)$$

- The output current is obtainted by dividing each voltage harmonic by its impedance:

$$i_o(t) = 18.1\sin(\omega t + 49.7°) + 3.2\sin(3\omega t - 70.2°) + \sin(5\omega t - 79.6°) + 0.5\sin(7\omega t - 82.9°) + 0.3\sin(9\omega t - 84.5°)$$

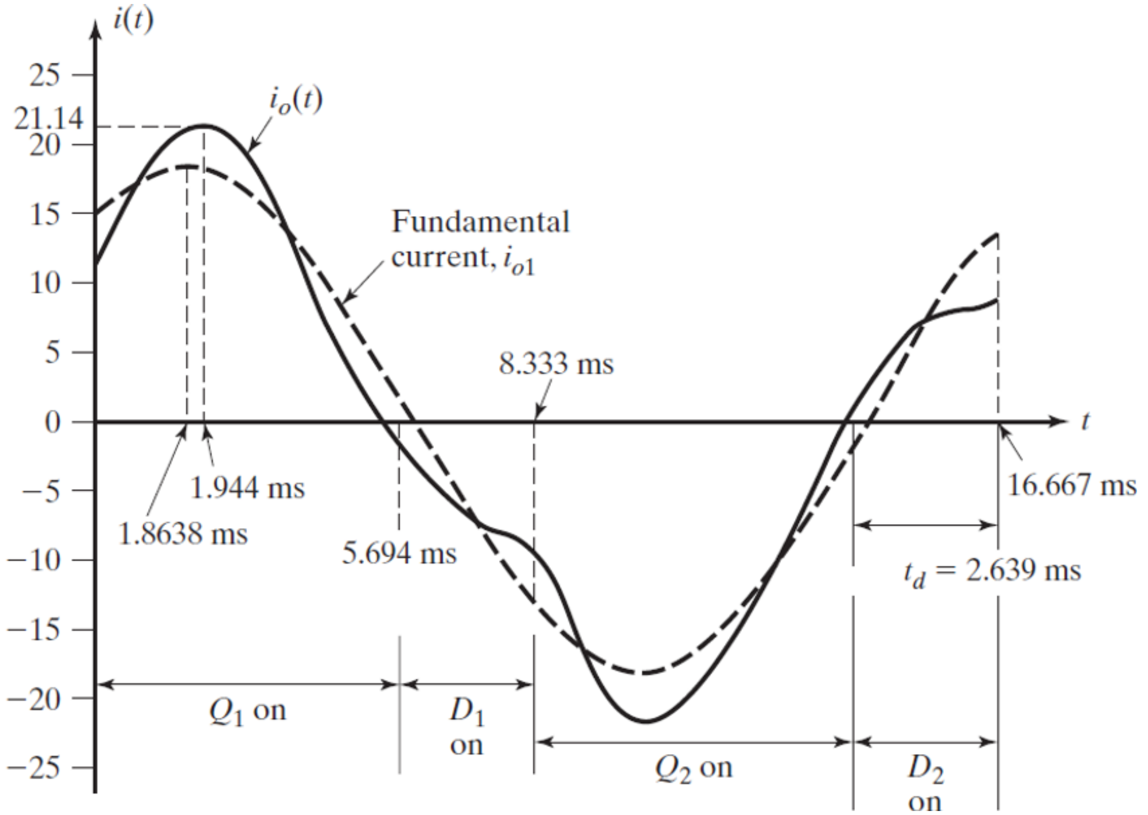
- The the RMS laod current at fundamental frequency is:

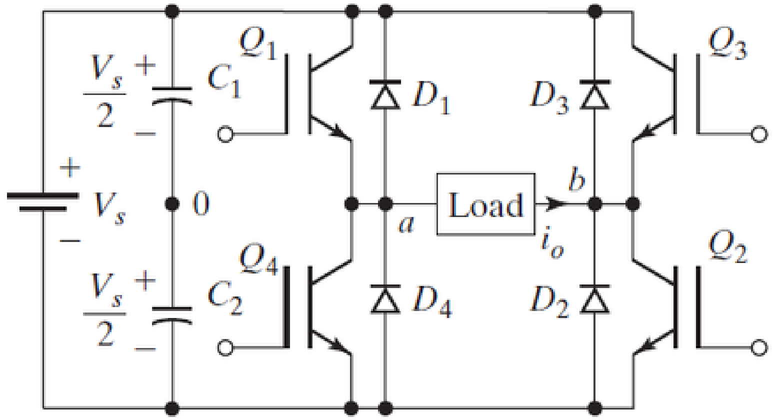
$$I_{o1} = \frac{18.1}{\sqrt{2}} = 12.8\text{ A}$$

Exercise

- The current waveform is shown below

$$i_o(t) = 18.1\sin(\omega t + 49.7°) + 3.2\sin(3\omega t - 70.2°) + \sin(5\omega t - 79.6°) + 0.5\sin(7\omega t - 82.9°) + 0.3\sin(9\omega t - 84.5°)$$



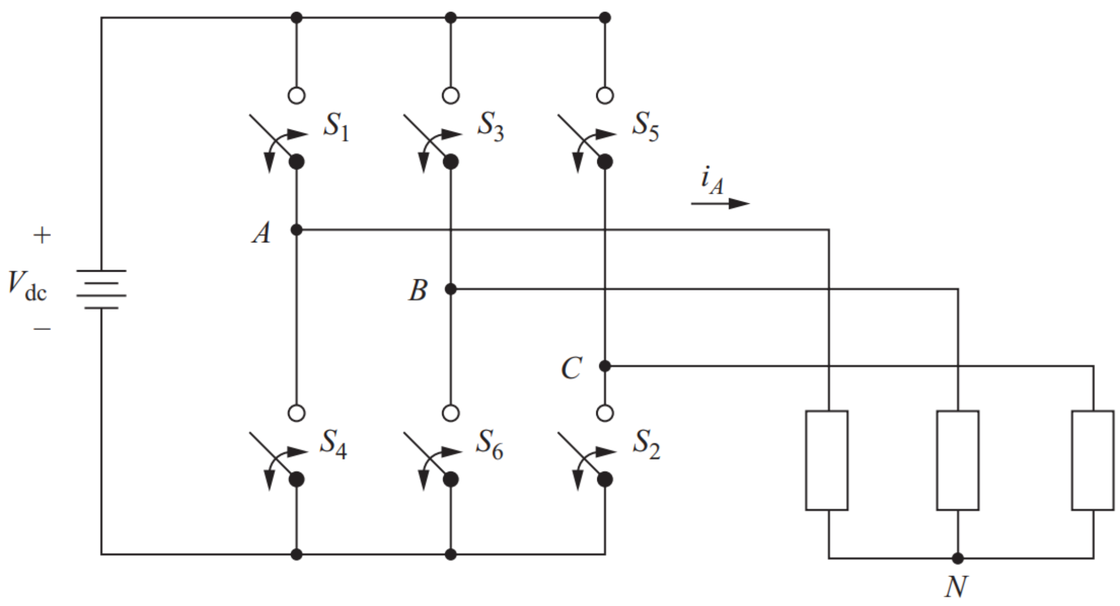


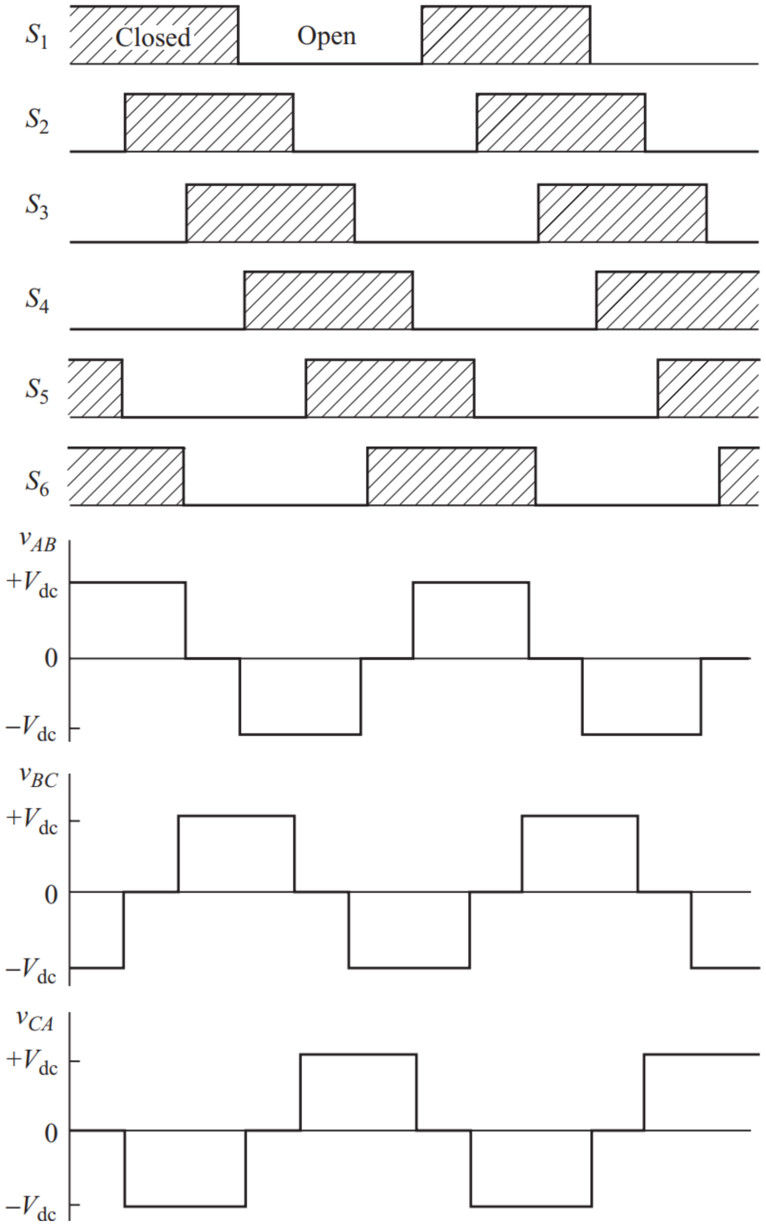
Outline

- Single-phase inverters
- Three-phase inverters
- Simulation

Three-phase inverters

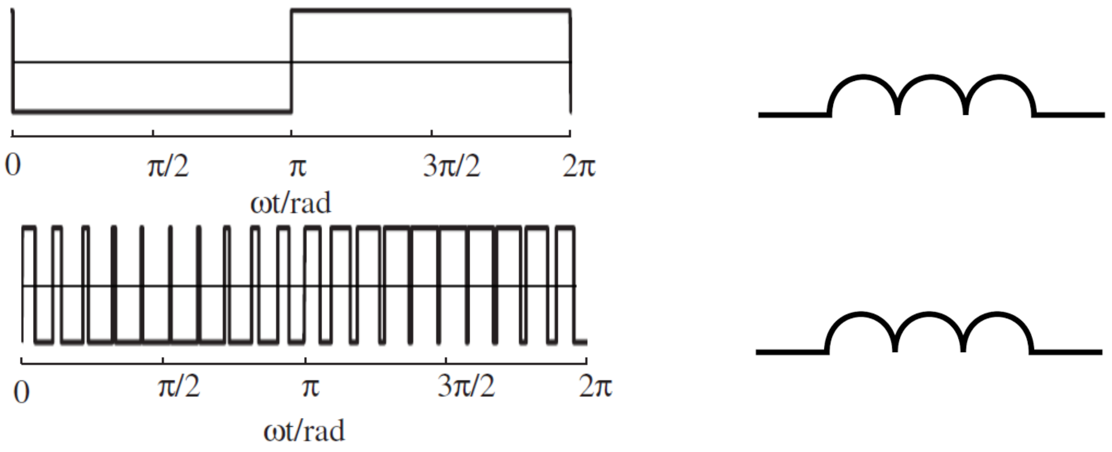
- The simplest operation of a three-phase inverter is the 180º conduction method.
- The switches (S_1, S_4),(S_2, S_5),(S_3, S_6) are opposed to each other.
- A switching action occurs every $T/6$ time interval or every 60º
- For a Y-connected load: $V_{n,\,L-L} = \left|\frac{4V_{dc}}{n\pi}\cos\left(n\frac{\pi}{6}\right)\right| \quad n = 1, 5, 7, 11, 13, \ldots$





Three-phase inverters

Which type of switching will produce a better sinusoidal current?

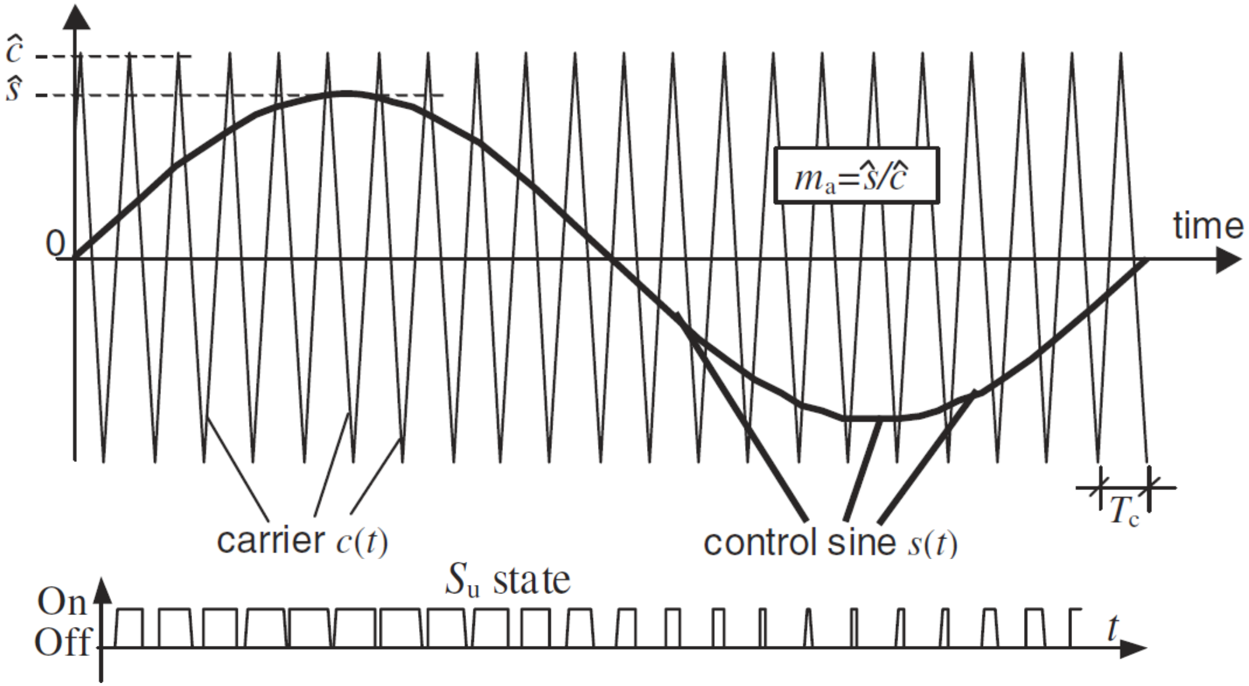


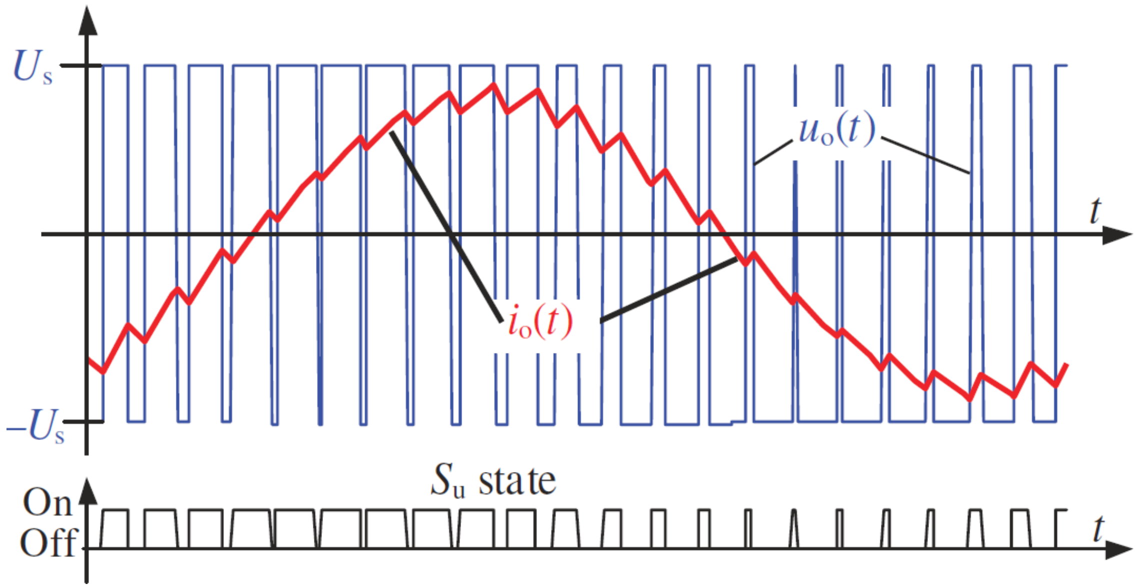
- To have good quality on the waveforms, high switching frequency is needed. Losses increase with switching frequency → Trade-off between power quality and losses.

Source: David Campos-Gaona

Three-phase inverters

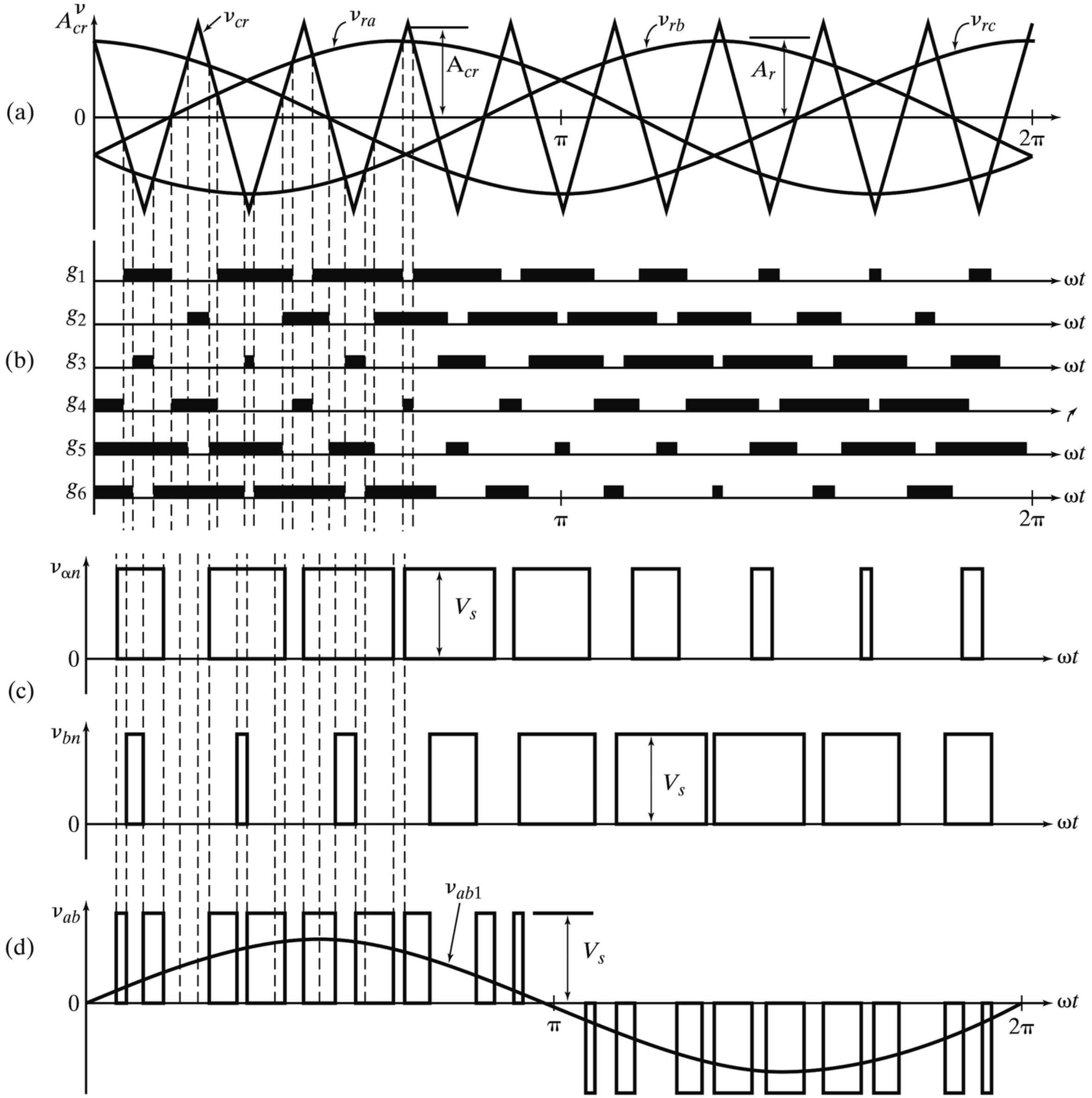
- The previous method generates an AC voltage of fixed amplitude and high harmonic content.
- **Pulse-Width Modulation (PWM)** is used to allow control of AC voltage amplitude and reduce filtering requirements. Among several methods, the sinusoidal PWM (SPWM) is widely used in industry.
- In this method, the gates of each switch are generated by comparing a sinusoidal **reference wave** with a **triangular carrier wave**. The switches are turned ON when they are greater than the carrier.





Source: M. Ceraolo and D. Poli (2014), Fundamentals of Electric Power Engineering: From Electromagnetics to Power Systems, IET, John Wiley & Sons

Three-phase sinusoidal PWM



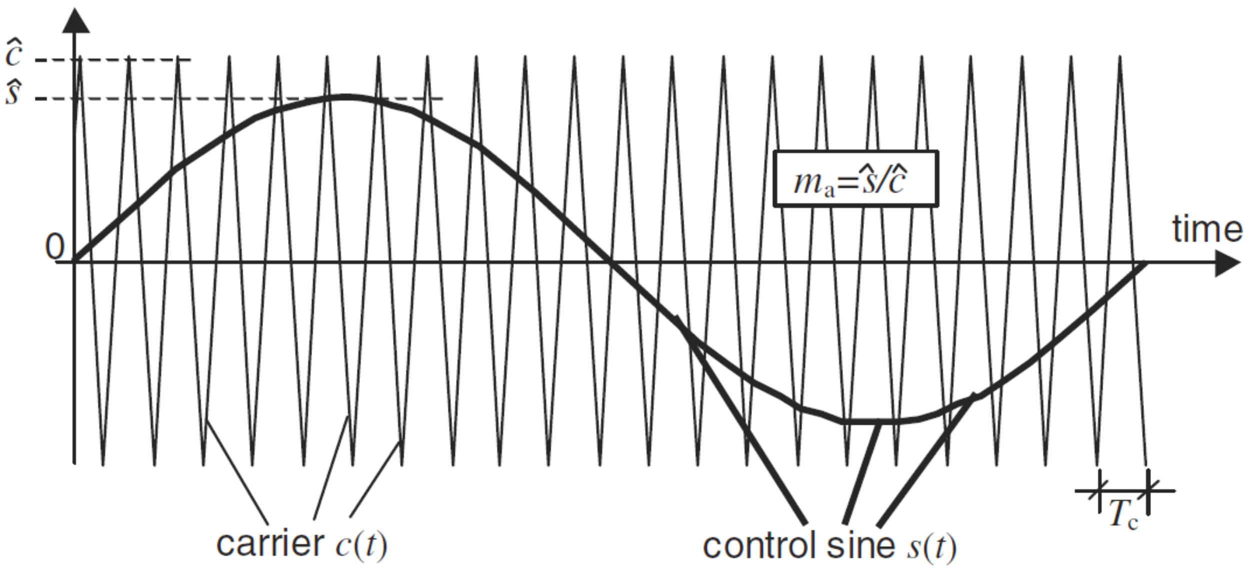
Three-phase sinusoidal PWM

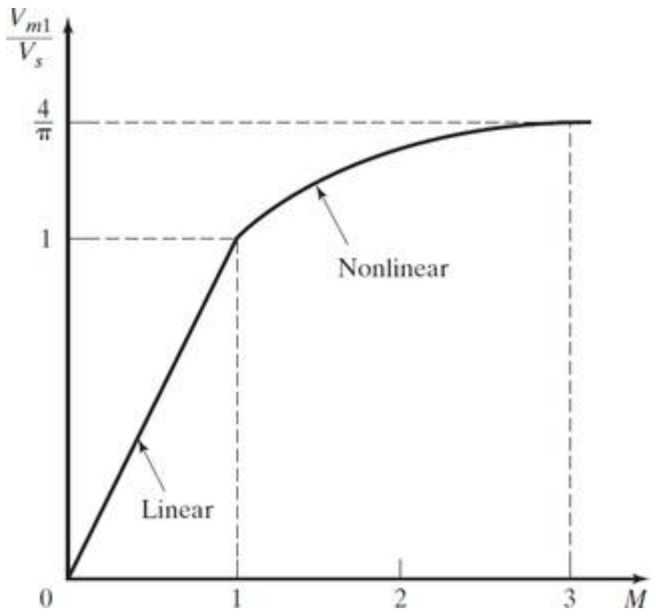
- The relation between line-to-line AC voltage and DC voltage is

$$\hat{v}_{ab1} = M\sqrt{3}\frac{V_s}{2} \quad \text{for } 0 < M \leq 1$$

- The AC voltage grows linearly with the modulation. But if M > 1 the relationship becomes nonlinear due to **overmodulation**.

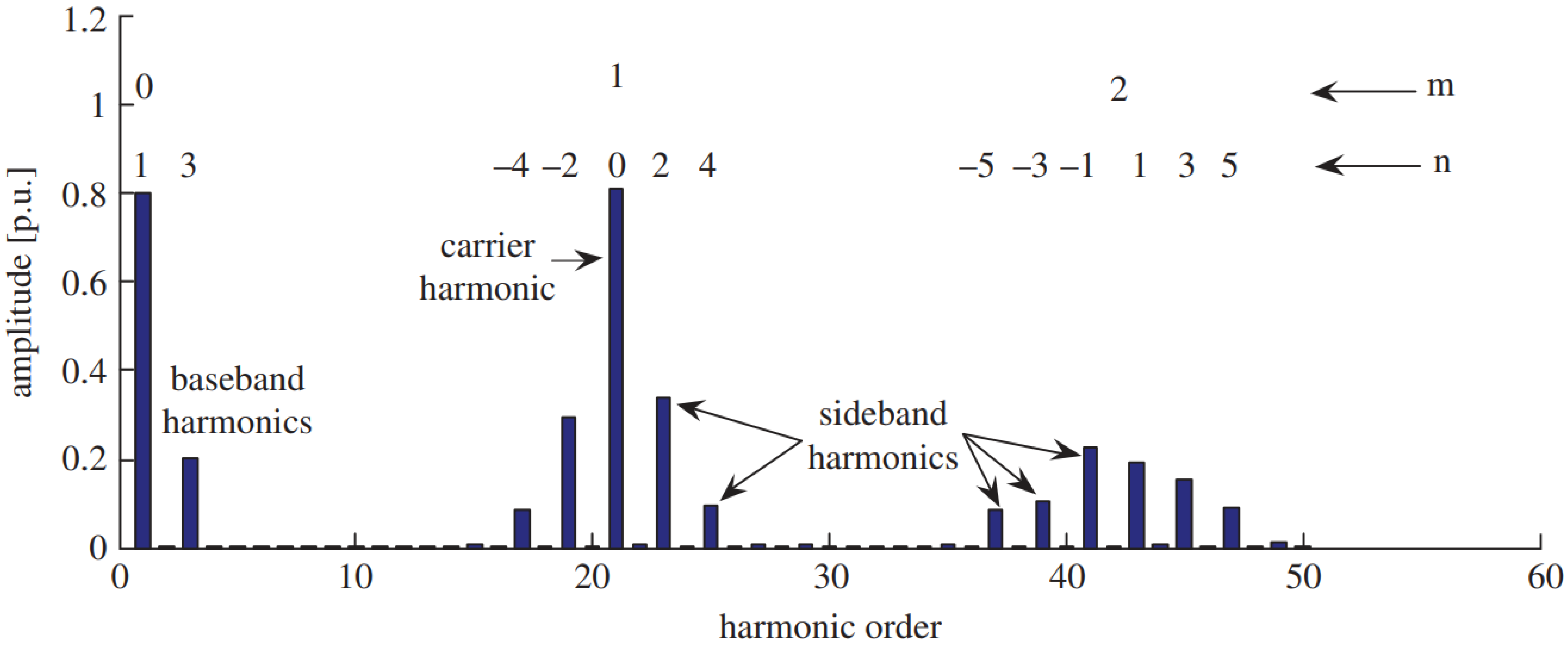
- It is important to define the correct DC and AC voltage magnitudes to avoid overmodulation.





Three-phase sinusoidal PWM

- The SPWM shifts the harmonics towards the high-frequency spectrum, facilitating the filtering of the AC voltages and currents.



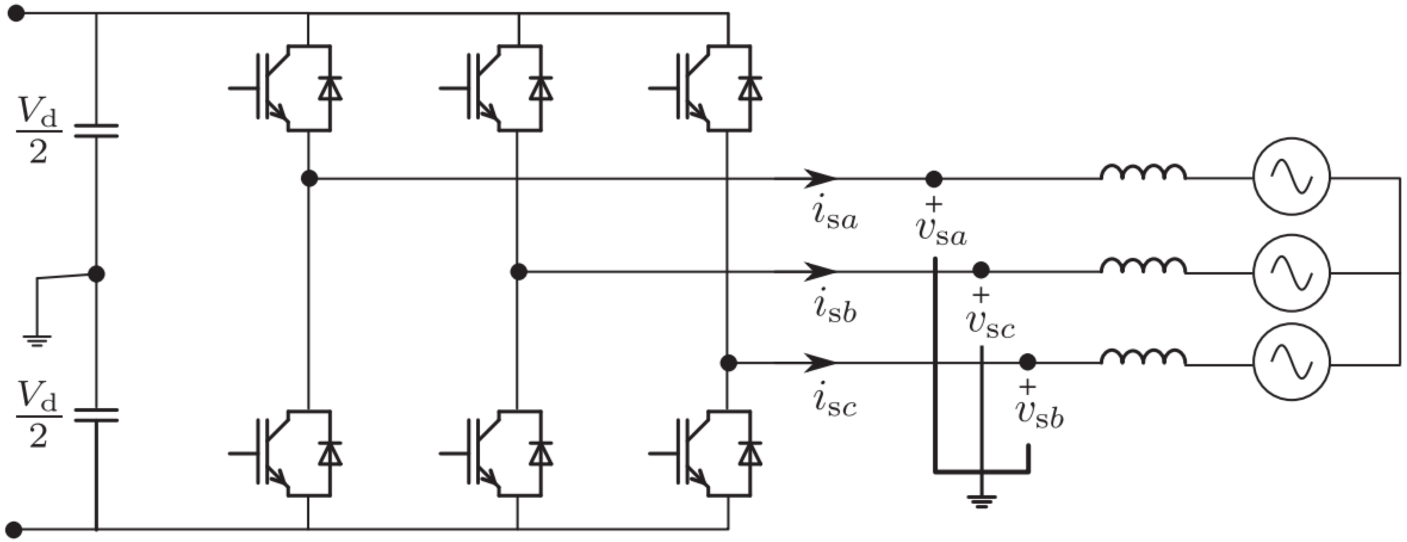
Source: Sharifabadi, K., Harnefors, L., Nee, H. P., Norrga, S., & Teodorescu, R. (2016). Design, control, and application of modular multilevel converters for HVDC transmission systems. John Wiley & Sons.

Three-phase sinusoidal PWM

- When a three-phase inverter is connected to the grid or load, the power imported or exported will depend on the voltage difference with respect to the grid.
- Neglecting losses, the power exported to the AC side is equal to the power imported from the DC side:

$$\frac{3}{2}\hat{v}_{\mathrm{s}}\hat{i}_{\mathrm{s}}\cos(\varphi) = V_{\mathrm{d}}I_{\mathrm{d}}$$

- The AC voltage is function of the reference voltage: $\hat{v}_{\mathrm{s}} = m_{\mathrm{a}}\frac{V_{\mathrm{d}}}{2} \longrightarrow 3m_{\mathrm{a}}\hat{i}_{\mathrm{s}}\cos(\varphi) = 2I_{\mathrm{d}}$



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- Single-phase inverters
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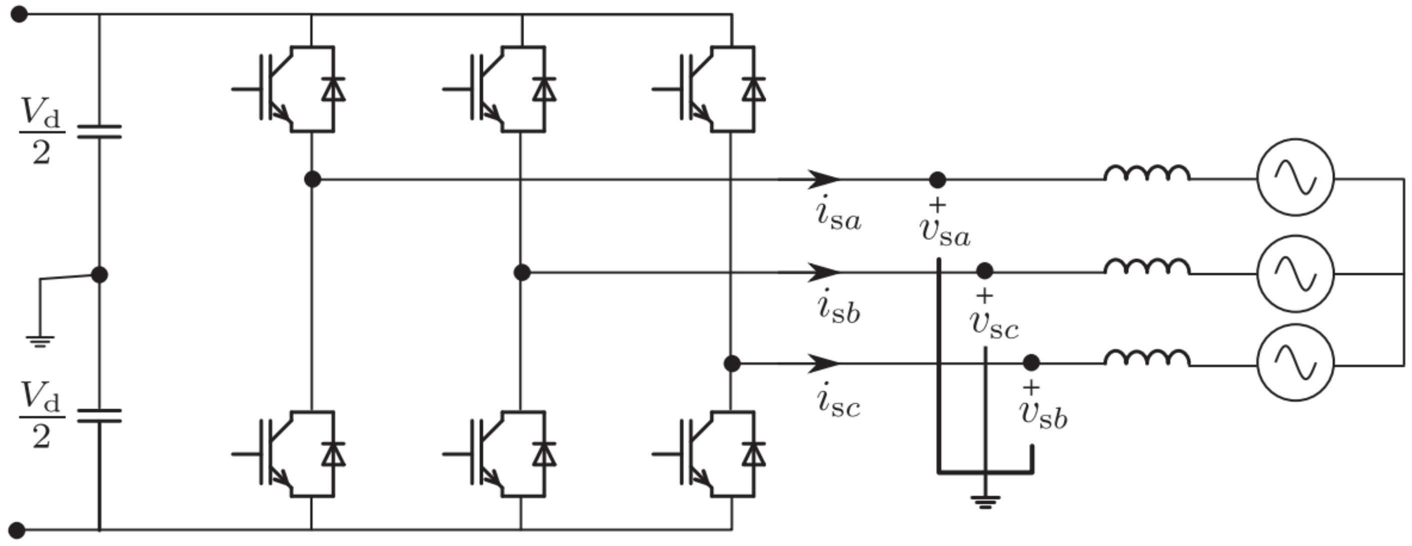
Simulation

- Simulate a three-phase DC/AC converter.

Data:

- Vdc = 1000 V
- L = 10 mH (R=X/30)
- Vgrid = XXXX RMS
- Carrier freq = 33*50 Hz



a) Define a carrier amplitude to generate YY V in the output

b) Define the angle to export XXX MW to the grid

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