METE 3100U
Actuators and Power Electronics

Lecture 8

3-Phase Inverters

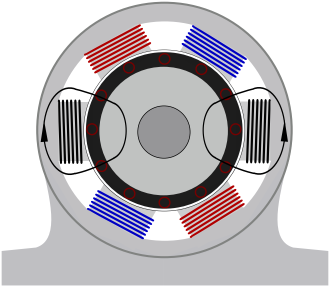
Outline of Lecture 8

By the end of today's lecture, you should be able to

- Understand the working principle of 3-phase inverters
- Control the voltage of a 3-phase inverter using PWM
- Develop a PWM controller for a 3-phase inverter

Applications

Brushless motors used in drones are typically powered by PWW inverters. The windings are commutated to produce a rotating magnetic field that drags the rotor around.



How can a 3-phase signal be generated from a DC supply?

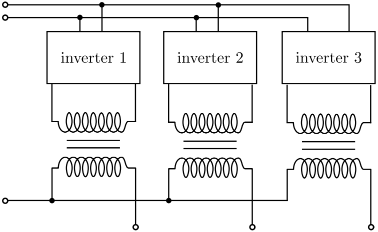
Applications

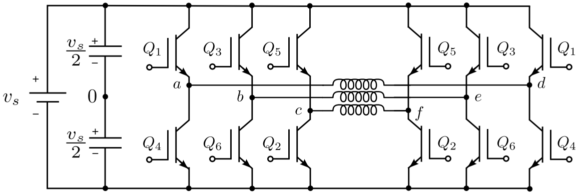
Three-phase electric power is a common method of alternating current electric power generation, transmission, and distribution.

DC current generated by solar farms needs to be converted into 3-phase AC for transmission.

3-phase inverters

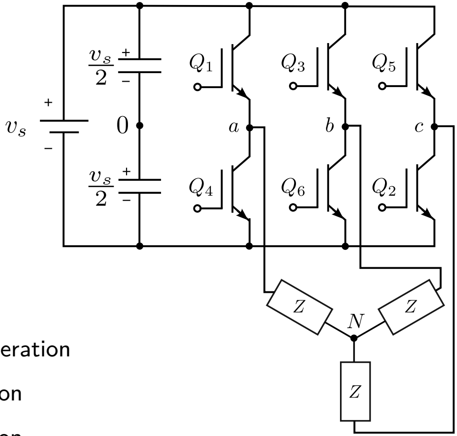
Three-single phase inverter are connected to form a 3-phase inverter





Half-bridge 3-phase inverter

The 3 arms are delayed by 120° to generate a three-phase AC supply.

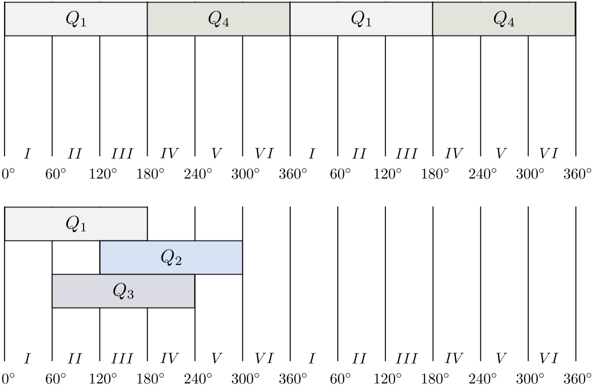


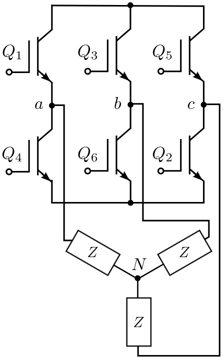
Two modes of operation

→ 180° conduction

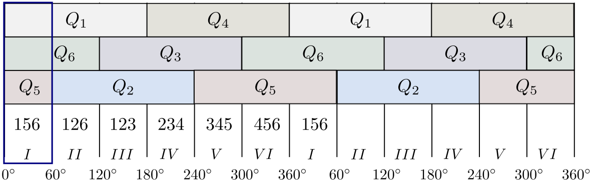
→ 120° conduction

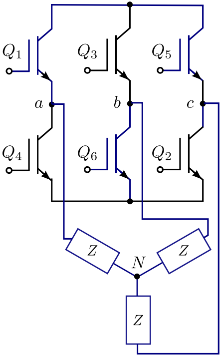
180° phase conduction





180° phase conduction



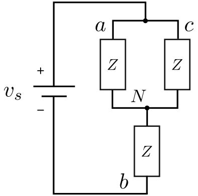


Transistors conducting in Phase I

→ Q_1, Q_5, and Q_6

The current is

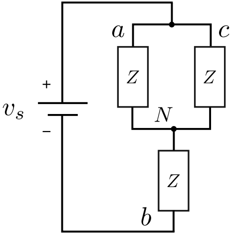
$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction

Transistors conducting in Phase I

→ Q_1, Q_5, and Q_6



The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

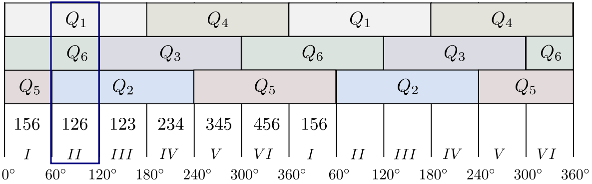
The voltage across the load is

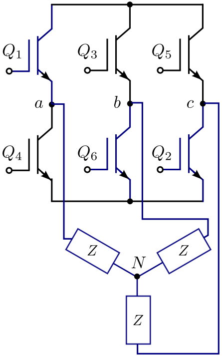
$$v_{aN} = \frac{i_1}{2}Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$

$$v_{bN} = i_1 Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right] Z = -\frac{2v_s}{3}$$

$$v_{cN} = \frac{i_1}{2}Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$

180° phase conduction



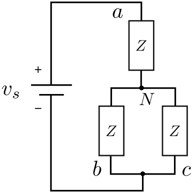


Transistors conducting in Phase II

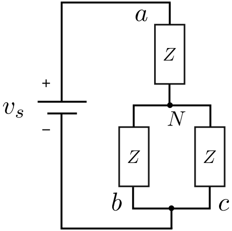
→ Q_1, Q_2, and Q_6

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction



Transistors conducting in Phase II

→ Q_1, Q_2, and Q_6

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

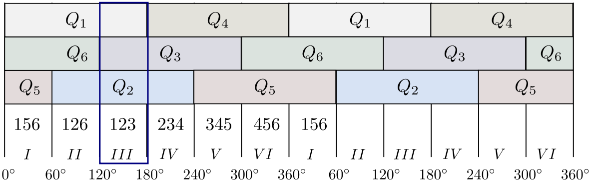
The voltage across the load is

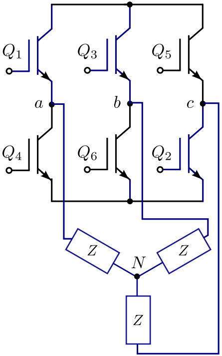
$$v_{aN} = i_1 Z = \left[\frac{2}{3}\frac{v_s}{Z}\right] Z = \frac{2v_s}{3}$$

$$v_{bN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

$$v_{cN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

180° phase conduction



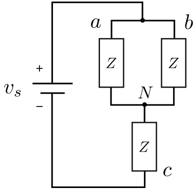


Transistors conducting in Phase III

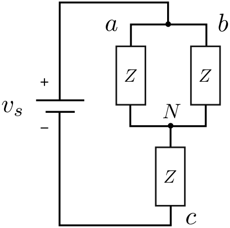
→ Q_1, Q_2, and Q_3

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction



Transistors conducting in Phase III

→ Q_1, Q_2, and Q_3

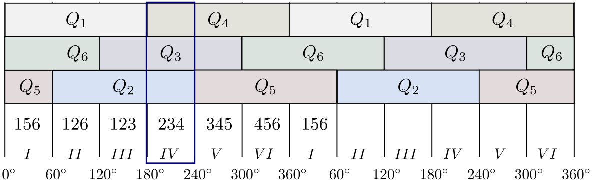
The current is

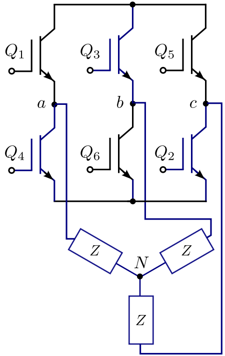
$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

The voltage across the load is

$$v_{aN} = \frac{i_1}{2}Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$
$$v_{bN} = \frac{i_1}{2}Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$
$$v_{cN} = i_1 Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right] Z = -\frac{2v_s}{3}$$

180° phase conduction



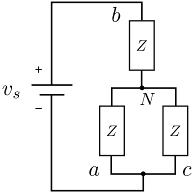


Transistors conducting in Phase IV

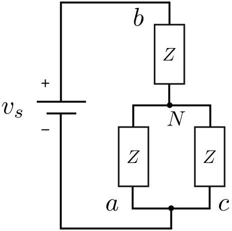
→ Q_2, Q_3, and Q_4

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction



Transistors conducting in Phase IV

→ Q_2, Q_3, and Q_4

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

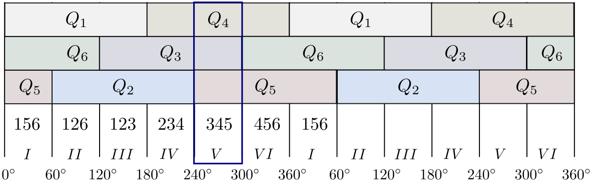
The voltage across the load is

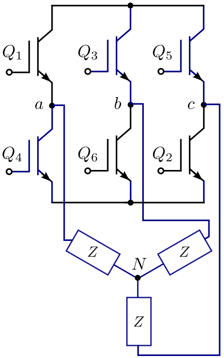
$$v_{aN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

$$v_{bN} = i_1 Z = \left[\frac{2}{3}\frac{v_s}{Z}\right] Z = \frac{2v_s}{3}$$

$$v_{cN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

180° phase conduction



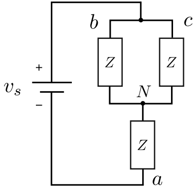


Transistors conducting in Phase V

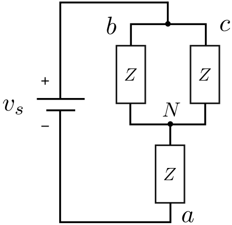
→ Q_3, Q_4, and Q_5

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction



Transistors conducting in Phase V

→ Q_3, Q_4, and Q_5

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

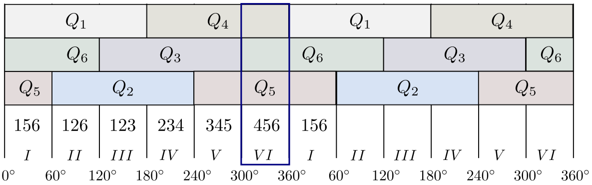
The voltage across the load is

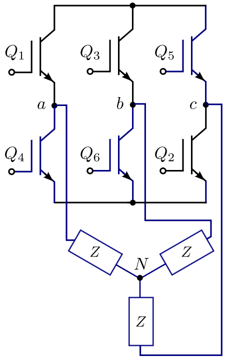
$$v_{aN} = i_1 Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right] Z = -\frac{2v_s}{3}$$

$$v_{bN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$

$$v_{cN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{v_s}{Z}\right]\frac{Z}{2} = \frac{v_s}{3}$$

180° phase conduction



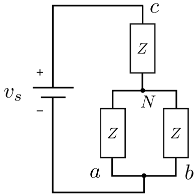


Transistors conducting in Phase VI

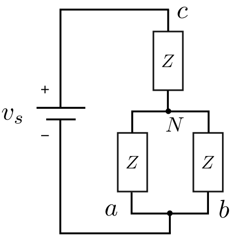
→ Q_4, Q_5, and Q_6

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$



180° phase conduction



Transistors conducting in Phase VI

→ Q_4, Q_5, and Q_6

The current is

$$i_1 = \frac{v_s}{Z + \frac{Z}{2}} = \frac{2}{3}\frac{v_s}{Z}$$

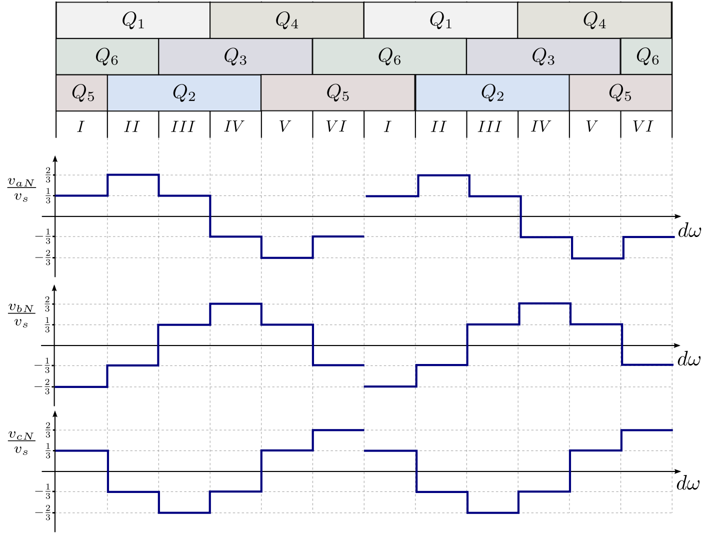
The voltage across the load is

$$v_{aN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

$$v_{bN} = \frac{i_1}{2} Z = \left[\frac{2}{3}\frac{(-v_s)}{Z}\right]\frac{Z}{2} = -\frac{v_s}{3}$$

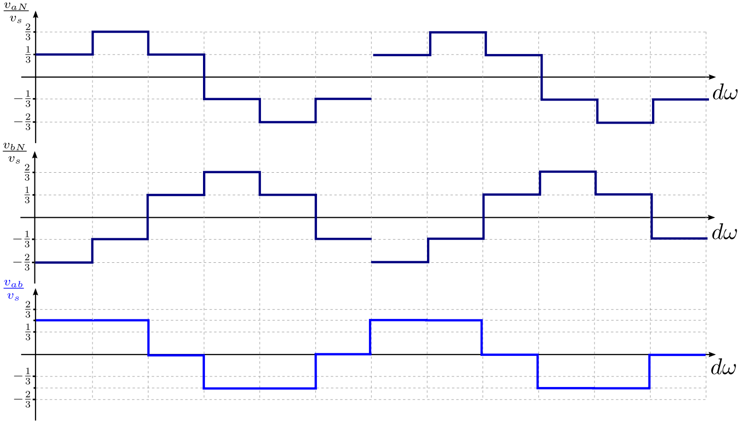
$$v_{cN} = i_1 Z = \left[\frac{2}{3}\frac{v_s}{Z}\right] Z = \frac{2v_s}{3}$$

Line to neutral waveforms



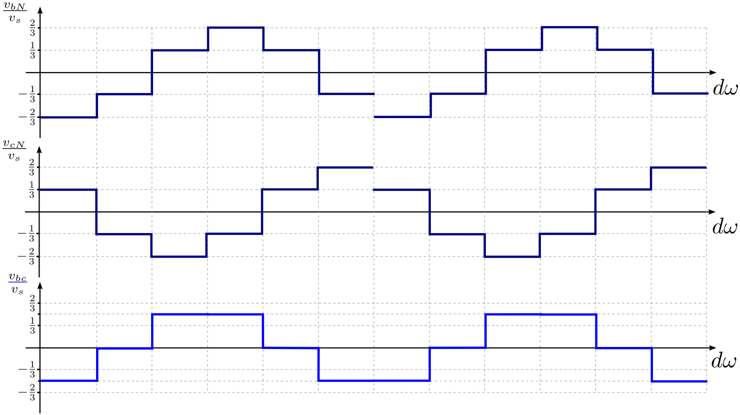
Line to line waveforms

$$V_{ab} = V_{aN} - V_{bN}$$



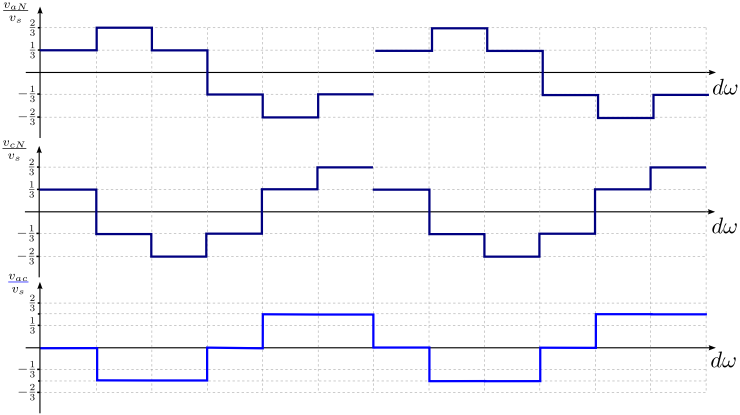
Line to line waveforms

$$V_{bc} = V_{bN} - V_{cN}$$



Line to line waveforms

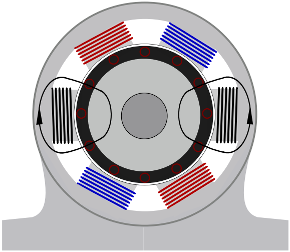
$$V_{ac} = V_{aN} - V_{cN}$$



Line to neutral and line to line voltages are shifted by 60°.

Space vector modulation

In brushless motor, the windings are commutated to produce a rotating magnetic field that drags the rotor around.



Can it be powered by a 3-phase inverter?

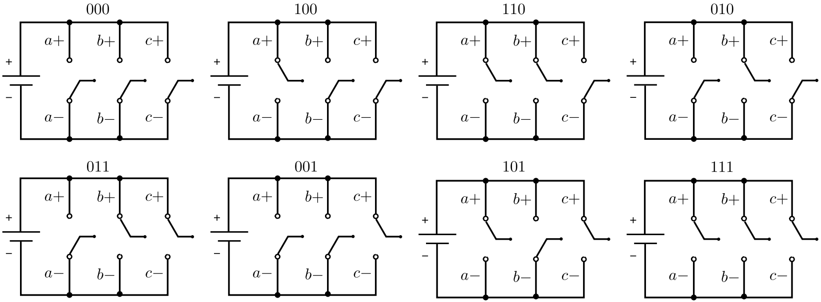
→ There are only six different voltage angles available.

→ To rotate a motor, a smoothly rotating voltage vector is required.

Space vector modulation

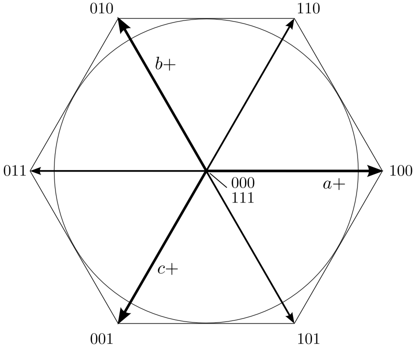
→ Transistor in the same leg cannot be activated at the same time

→ There are 8 possible combinations



Space vector modulation

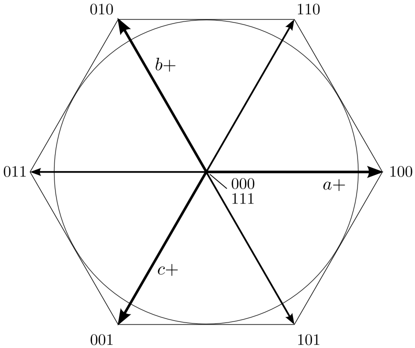
Possible switching vectors for a 3-phase inverter using space vector modulation



000	100	110	010	011	001	101	111
zero	$+a$	$-c$	$+b$	$-a$	$+c$	$-b$	zero

Synthesizing output voltage

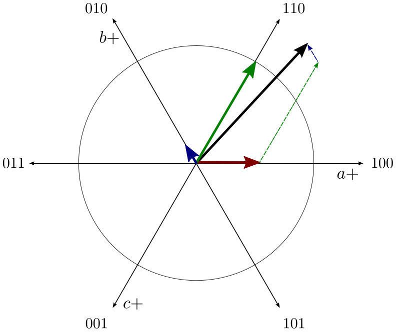
Possible switching vectors for a 3-phase inverter using space vector modulation

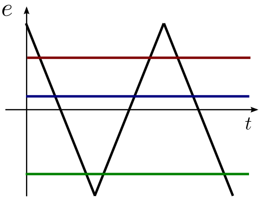


000	100	110	010	011	001	101	111
zero	$+a$	$-c$	$+b$	$-a$	$+c$	$-b$	zero

Synthesizing output voltage

Objective: Follow a reference vector signal using 3 different voltages and angles



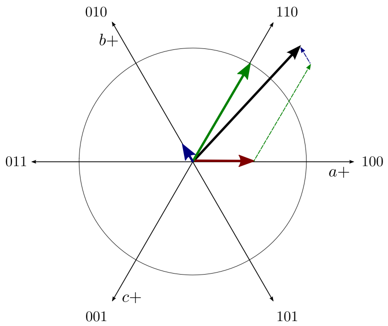


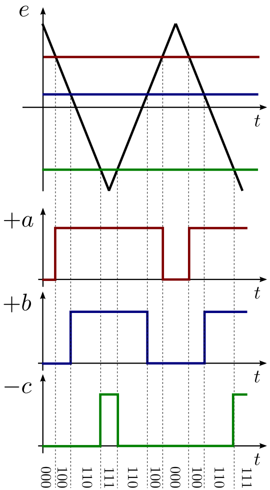
000	100	110	010	011	001	101	111
zero	$+a$	$-c$	$+b$	$-a$	$+c$	$-b$	zero

Vectors will have to be switched between $a+$, $c-$, and $b+$

Synthesizing output voltage

PWM is used to create the desired voltage vector



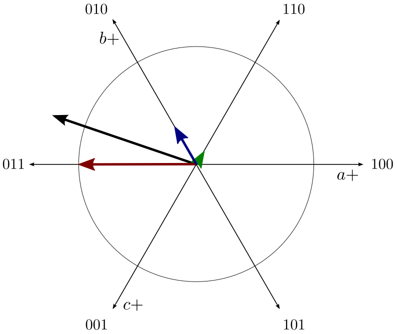


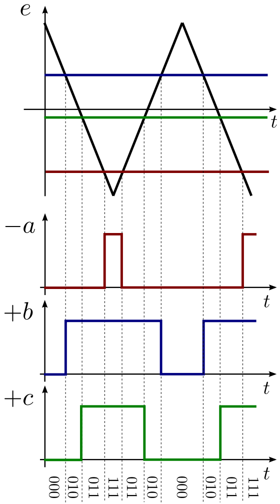
The sequence of activation is
000 100 110 111 110 100 000

`https://youtu.be/X1cqUuKqOH8`

Synthesizing output voltage

Example 2





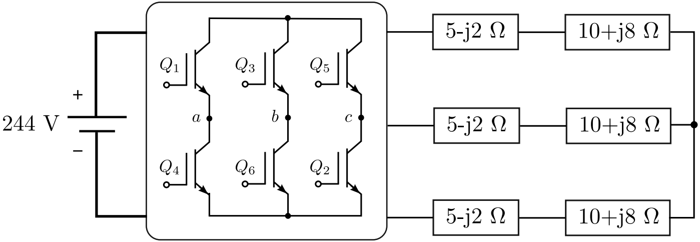
The sequence of activation is

000 010 011 111 011 010 000

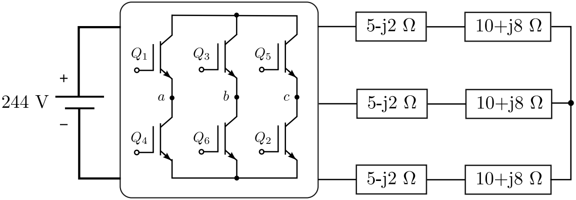
Note: the pulse width varies

Exercise 33

The sinusoidal **phase-to-neutral** voltage of the 3-phase inverter are shifted by 120°. Calculate the line currents in the load due to the fundamental component of the output voltage.



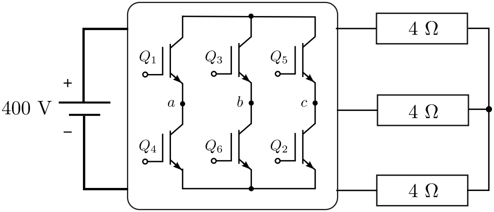
Exercise 33 - continued



Exercise 33 - continued

Exercise 34

The DC input voltage of the 3-phase inverter is 400 V and the load is $Z = 4\ \Omega$.

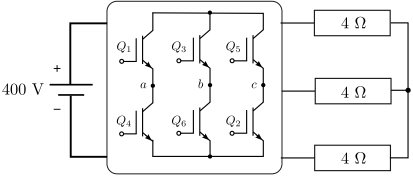


Calculate:

→ The instantaneous voltage levels of the line to-neutral-voltage

→ The peak current in each transistor

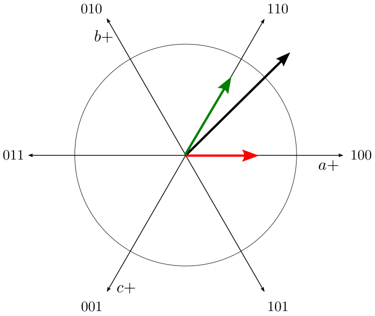
Exercise 34 - continued

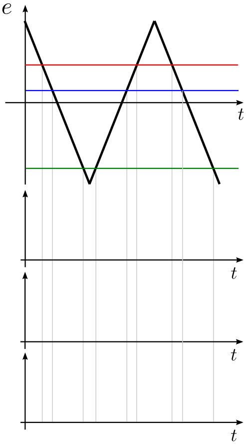


Exercise 34 - continued

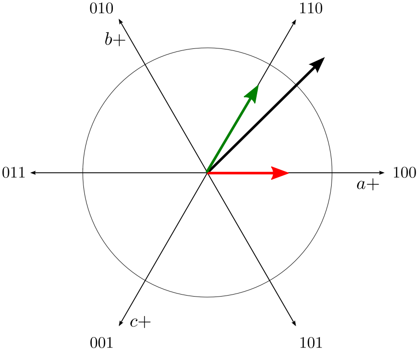
Exercise 35

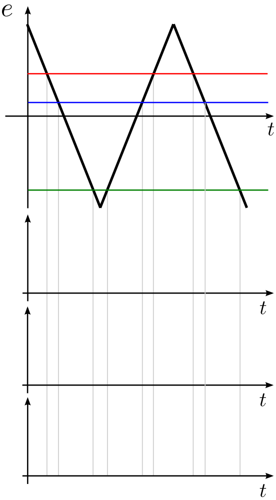
Determine the transition sequence of the state vector that are required to modulate the reference voltage vector shown.





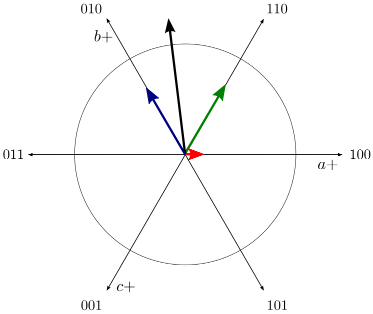
Exercise 35 - continued

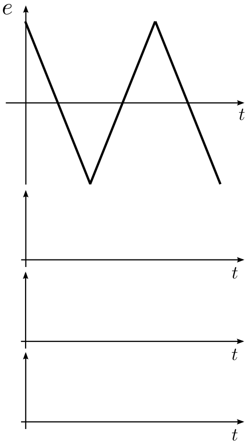




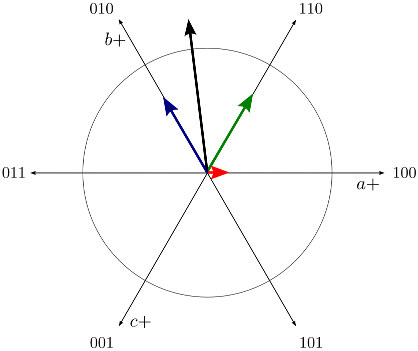
Exercise 36

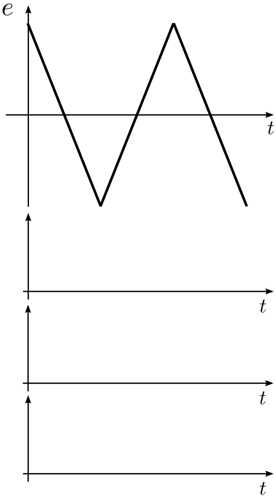
Determine the transition sequence of the state vector that are required to modulate the reference voltage vector shown.





Exercise 36 - continued





Exercise 37

(a) What is an inverter ?

(b) What is the principle of operation of an inverter?

(c) What are the performance parameters of inverter?

(d) What is space vector modulation?

(e) What is a boost-inverter (step up)?

(f) What is the voltage gain of a boost inverter ?

(g) What are the reason for adding a filter on an inverter output?

(h) What is the phase shift in a 180° conduction 3-phase inverter?

(i) What is sinusoidal PWM?

(j) What is the difference between unipolar and bipolar PWM?

Next class...

- Electromagnetic energy conversion

Additional supporting materials for Lecture 8:

Space vector modulation: `https://bit.ly/2C5QAfu`

120° conduction: `https://youtu.be/w6BIs3MZhUM`