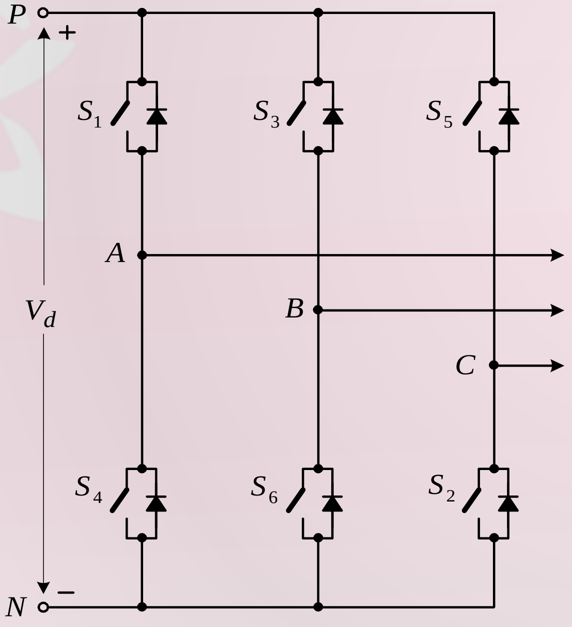
Space Vector PWM

Space Vector Modulation

Switching States (Three-Phase)

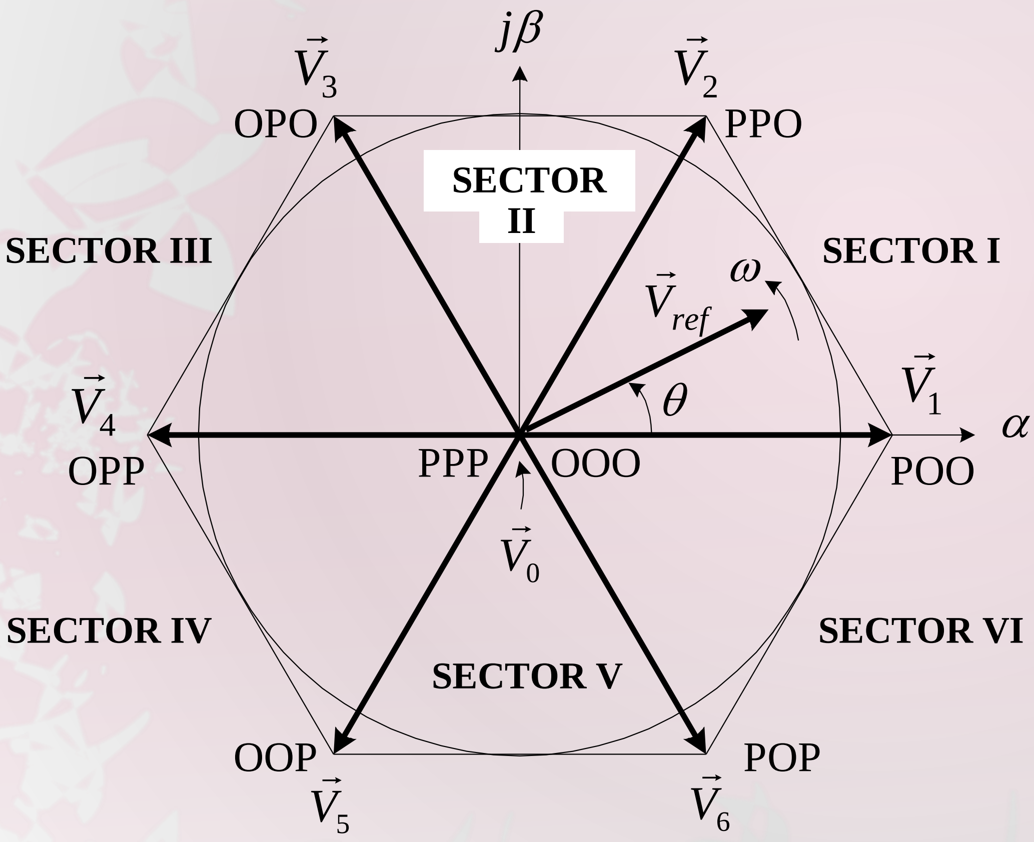


Switching State (Three Phases)	On-state Switch
[PPP]	S_1, S_3, S_5
[OOO]	S_4, S_6, S_2
[POO]	S_1, S_6, S_2
[PPO]	S_1, S_3, S_2
[OPO]	S_4, S_3, S_2
[OPP]	S_4, S_3, S_5
[OOP]	S_4, S_6, S_5
[POP]	S_1, S_6, S_5

Eight switching states

Space Vector Modulation

Space Vector Diagram



Active vectors: $\vec{V}_1$ **to** $\vec{V}_6$
(stationary, not rotating)

Zero vector: $\vec{V}_0$

Six sectors: ***I*** **to** ***VI***

Space Vector Modulation

Space Vectors

Three-phase voltages

$$v_{AO}(t) + v_{BO}(t) + v_{CO}(t) = 0 \qquad \textbf{(1)}$$

Two-phase voltages

$$\begin{bmatrix} v_\alpha(t) \\ v_\beta(t) \end{bmatrix} = \begin{bmatrix} \cos 0 & \cos\frac{2\pi}{3} & \cos\frac{4\pi}{3} \\ \sin 0 & \sin\frac{2\pi}{3} & \sin\frac{4\pi}{3} \end{bmatrix} \begin{bmatrix} v_{AO}(t) \\ v_{BO}(t) \\ v_{CO}(t) \end{bmatrix} \qquad \textbf{(2)}$$

Space vector representation

$$\vec{V}(t) = v_\alpha(t) + j\, v_\beta(t) \qquad \textbf{(3)}$$

(2) → (3)

$$\vec{V}(t) = \left[v_{AO}(t)\, e^{j0} + v_{BO}(t)\, e^{j2\pi/3} + v_{CO}(t)\, e^{j4\pi/3} \right] \qquad \textbf{(4)}$$

where $e^{jx} = \cos x + j \sin x$

Space Vector Modulation

Space Vectors (Example)

Switching state [POO] → S_1, S_6 and S_2 ON

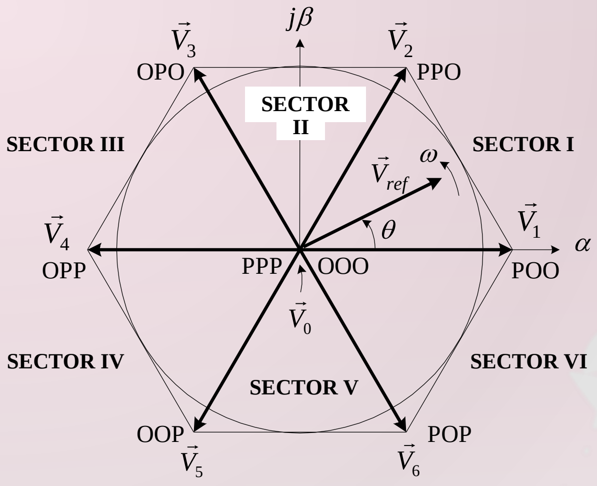
$$v_{AO}(t) = V_d, \quad v_{BO}(t) = -\frac{1}{2}V_d, v_{CO}(t) = -\frac{1}{2}V_d$$

(5) → (4)

$$\vec{V}_1 = V_d \, e^{j0}$$

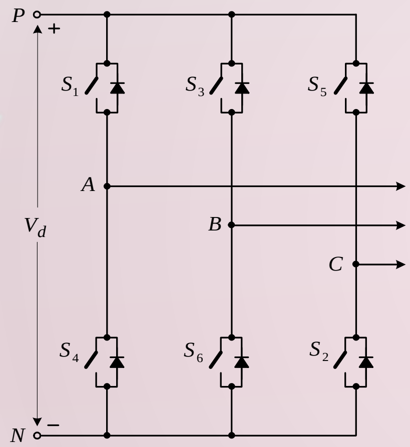
$$\vec{V}_k = V_d \, e^{j(k-1)\frac{\pi}{3}}$$

$$k = 1, 2, ..., 6.$$



Space Vector Modulation

Active and Zero Vectors



Active Vector: 6

Zero Vector: 1

Redundant switching states: [PPP] and [OOO]

Space Vector		Switching State (Three Phases)	On-state Switch	Vector Definition
Zero Vector	$\vec{V}_0$	[PPP]	S_1, S_3, S_5	$\vec{V}_0 = 0$
		[OOO]	S_4, S_6, S_2	
Active Vector	$\vec{V}_1$	[POO]	S_1, S_6, S_2	$\vec{V}_1 = V_d\, e^{j0}$
	$\vec{V}_2$	[PPO]	S_1, S_3, S_2	$\vec{V}_2 = V_d\, e^{j\frac{\pi}{3}}$
	$\vec{V}_3$	[OPO]	S_4, S_3, S_2	$\vec{V}_3 = V_d\, e^{j\frac{2\pi}{3}}$
	$\vec{V}_4$	[OPP]	S_4, S_3, S_5	$\vec{V}_4 = V_d\, e^{j\frac{3\pi}{3}}$
	$\vec{V}_5$	[OOP]	S_4, S_6, S_5	$\vec{V}_5 = V_d\, e^{j\frac{4\pi}{3}}$
	$\vec{V}_6$	[POP]	S_1, S_6, S_5	$\vec{V}_6 = V_d\, e^{j\frac{5\pi}{3}}$

Space Vector Modulation

Reference Vector V_{ref}

Definition

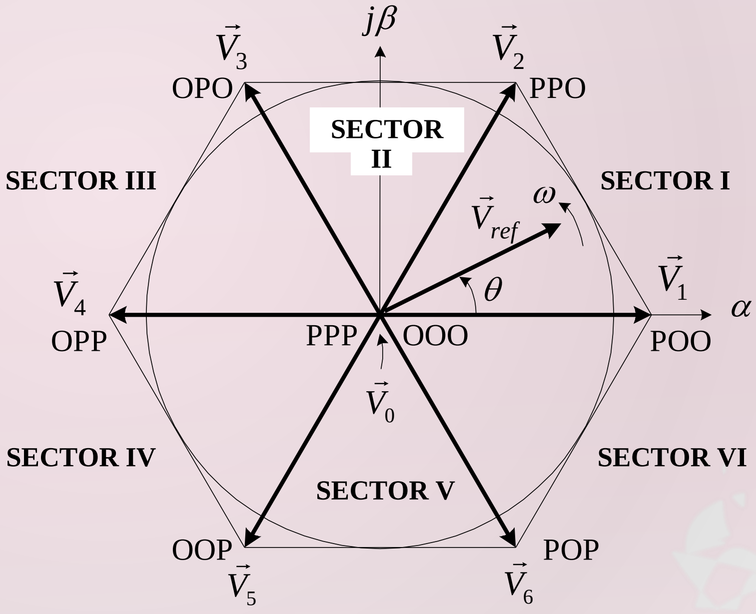
$$\vec{V}_{ref} = V_{ref}\, e^{j\theta}$$

Rotating in space at ω

$$\omega = 2\pi f \qquad \textbf{(8)}$$

Angular displacement

$$\theta(t) = \int_0^t \omega\, dt \qquad \textbf{(9)}$$



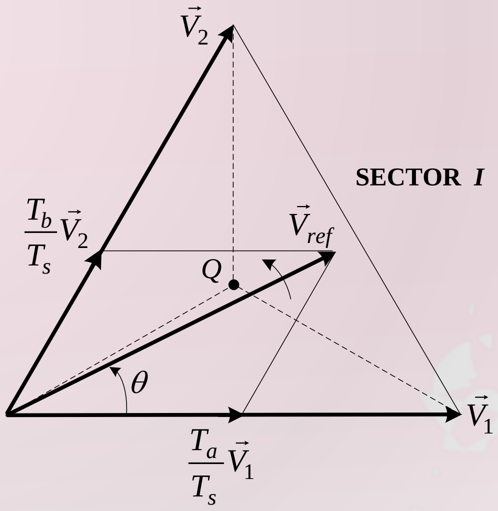
Space Vector Modulation

Relationship Between V_{ref} and V_{AB}

V_{ref} is approximated by two active and zero vectors

V_{ref} rotates one revolution, V_{AB} completes one cycle

Length of V_{ref} corresponds to magnitude of V_{AB}

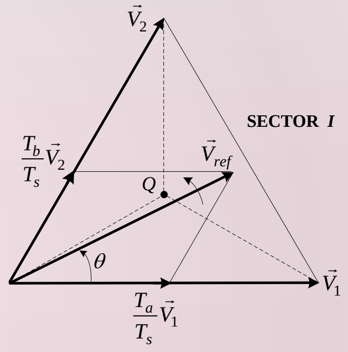


Space Vector Modulation

Dwell Time Calculation

Volt-Second Balancing

$$\begin{cases} \vec{V}_{ref}\, T_s = \vec{V}_1\, T_a + \vec{V}_2\, T_b + \vec{V}_0\, T_0 \\ T_s \;=\; T_a + T_b + T_0 \end{cases} \quad \textbf{(10)}$$



T_a, T_b and T_0 – dwell times for $\vec{V}_1, \vec{V}_2$ and $\vec{V}_0$

T_s – sampling period

Space vectors

$$\vec{V}_{ref} = V_{ref}\, e^{j\theta},\ \vec{V}_1 = V_d\ , \vec{V}_2 = V_d\, e^{j\frac{\pi}{3}} \ \text{ and } \vec{V}_0 = 0 \qquad \textbf{(11)}$$

(11) → (10)

$$\begin{cases} \textbf{Re:}\quad V_{ref}(\cos\theta)\,T_s \;=\; V_d\, T_a + \frac{1}{2}V_d\, T_b \\ \textbf{Im:}\quad V_{ref}(\sin\theta)\,T_s \;=\; \frac{\sqrt{3}}{2}V_d\, T_b \end{cases} \qquad \textbf{(12)}$$

Space Vector Modulation

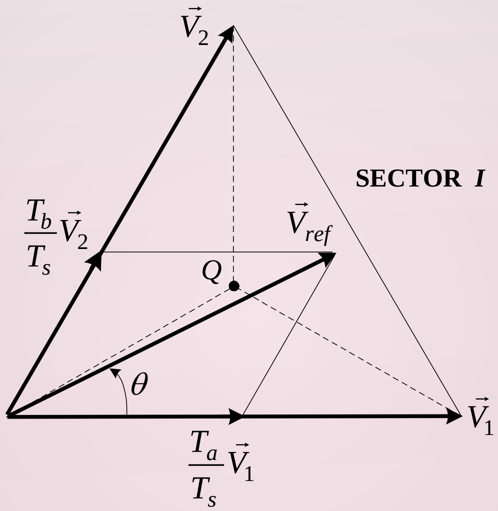
Dwell Times

Solve (12)

$$\begin{cases} T_a = \dfrac{2T_s V_{ref}}{\sqrt{3}\, V_d} \sin\left(\dfrac{\pi}{3} - \theta\right) \\ T_b = \dfrac{2T_s V_{ref}}{\sqrt{3}\, V_d} \sin\theta \\ T_0 = T_s - T_a - T_b \end{cases} \qquad 0 \le \theta < \pi/3 \qquad \textbf{(13)}$$

Space Vector Modulation

V_{ref} Location versus Dwell Times



$\vec{V}_{ref}$ **Location**	$\theta = 0$	$0 < \theta < \frac{\pi}{6}$	$\theta = \frac{\pi}{6}$	$\frac{\pi}{6} < \theta < \frac{\pi}{3}$	$\theta = \frac{\pi}{3}$
Dwell Times	$T_a > 0$ $T_b = 0$	$T_a > T_b$	$T_a = T_b$	$T_a < T_b$	$T_a = 0$ $T_b > 0$

Space Vector Modulation

Modulation Index

$$\begin{cases} T_a = T_s m_a \sin\left(\frac{\pi}{3} - \theta\right) \\ T_b = T_s m_a \sin\theta \\ T_0 = T_s - T_b - T_c \end{cases} \quad \textbf{(15)}$$

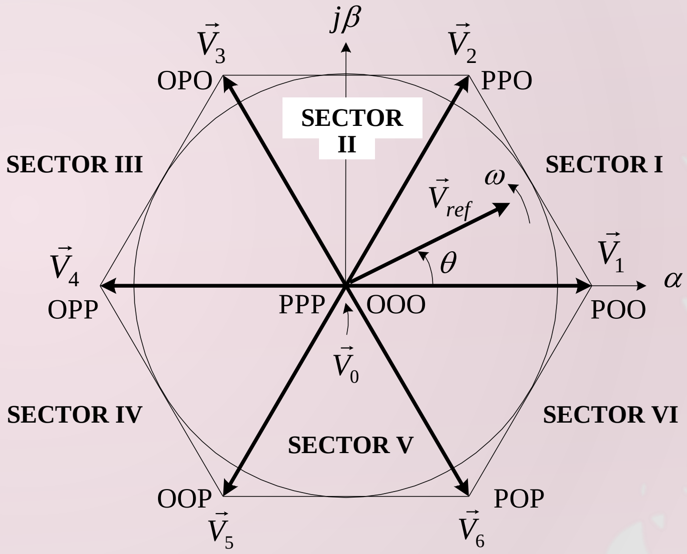
$$m_a = \frac{2V_{ref}}{\sqrt{3}V_d} \quad \textbf{(16)}$$

Space Vector Modulation

Modulation Range

$V_{ref,max}$

$$V_{ref,\max} = V_d \times \frac{\sqrt{3}}{2} = \frac{\sqrt{3}V_d}{2} \qquad \textbf{(17)}$$



(17) → (16)

$m_{a,max} = 1 \quad \rightarrow$

Modulation range: $0 \leq m_a \leq 1$ **(18)**

Space Vector Modulation

Switching Sequence Design

- **Basic Requirement:**

  Minimize the number of switchings per sampling period T_s

- **Implementation:**

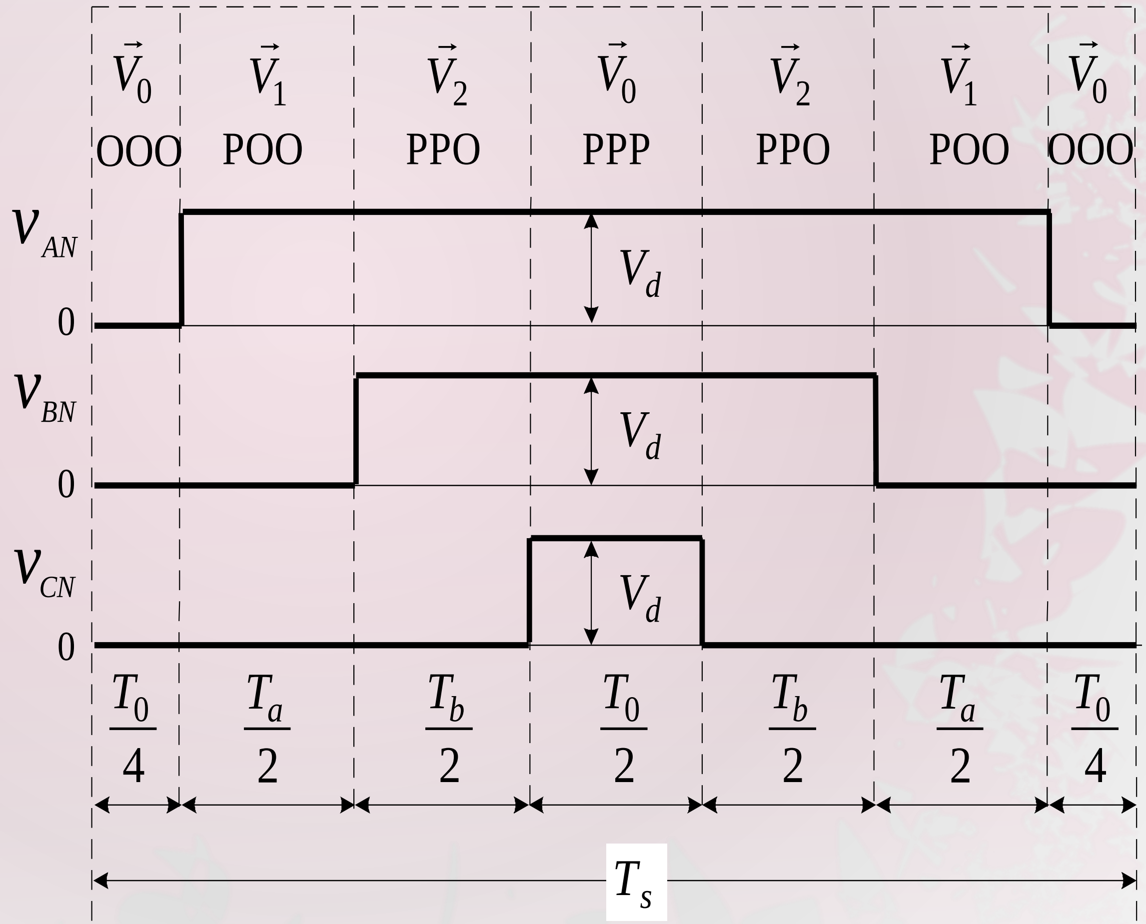
  Transition from one switching state to the next involves only two switches in the same inverter leg.

Space Vector Modulation

Seven-segment Switching Sequence

Selected vectors:
V_0, V_1 and V_2

Dwell times:
$T_s = T_0 + T_a + T_b$

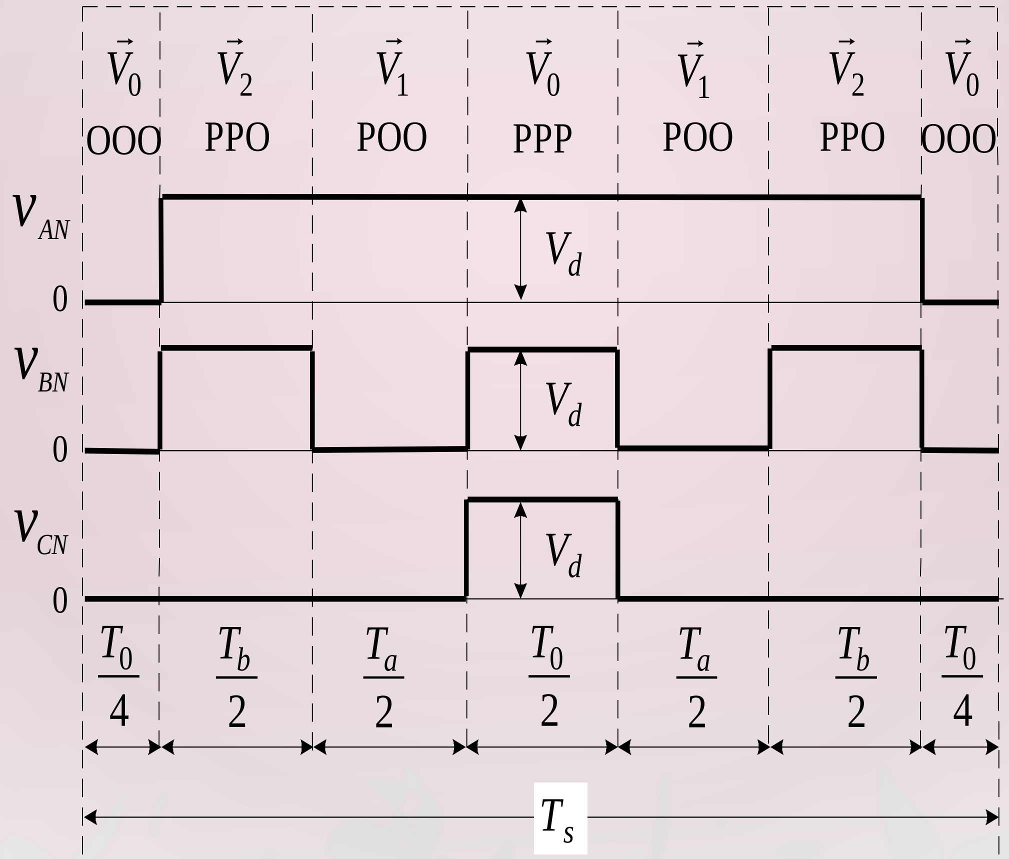


Total number of switchings: 6

Space Vector Modulation

Undesirable Switching Sequence

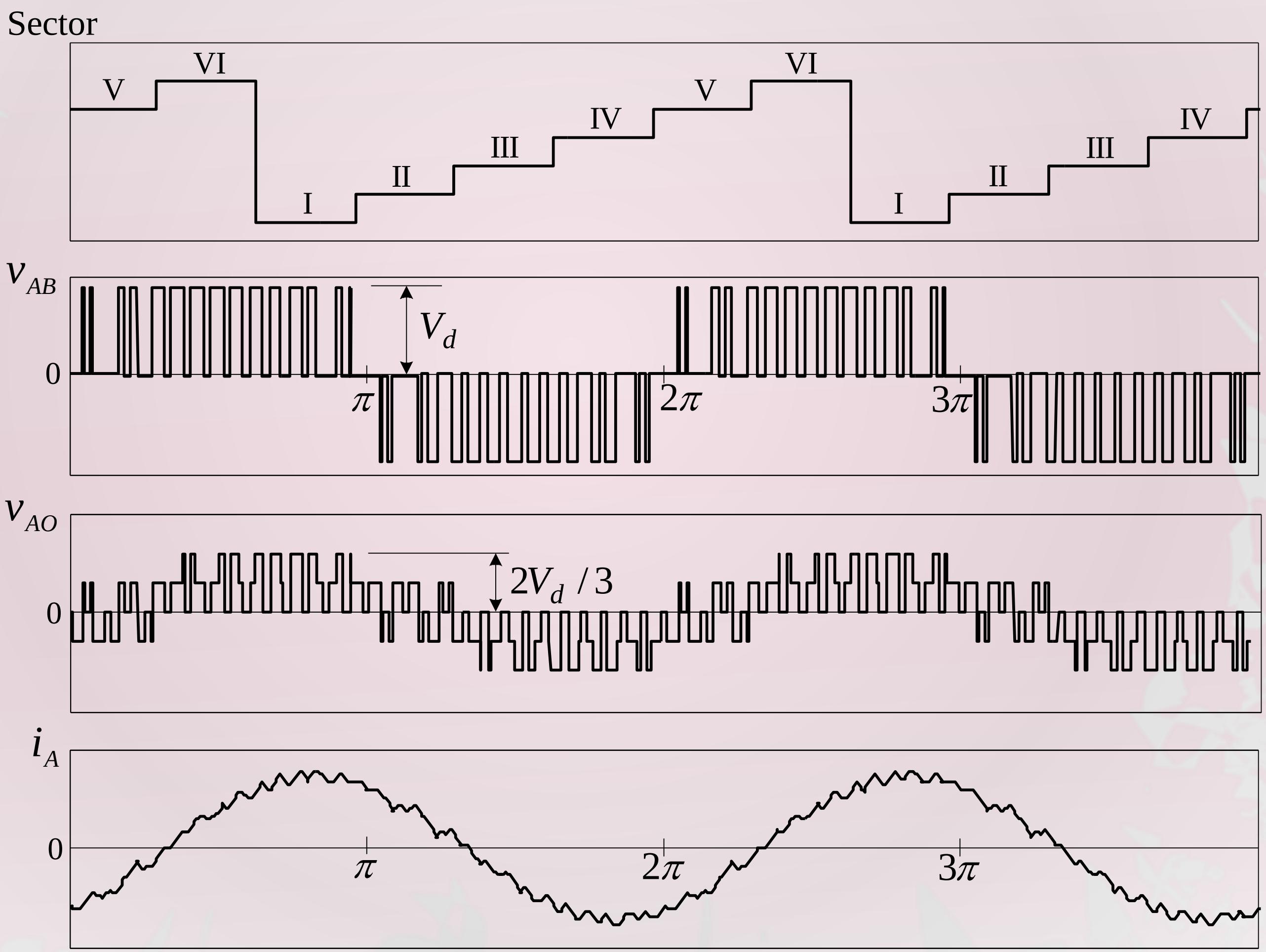
Vectors V_1 and V_2 swapped



Total number of switchings: 10

Space Vector Modulation

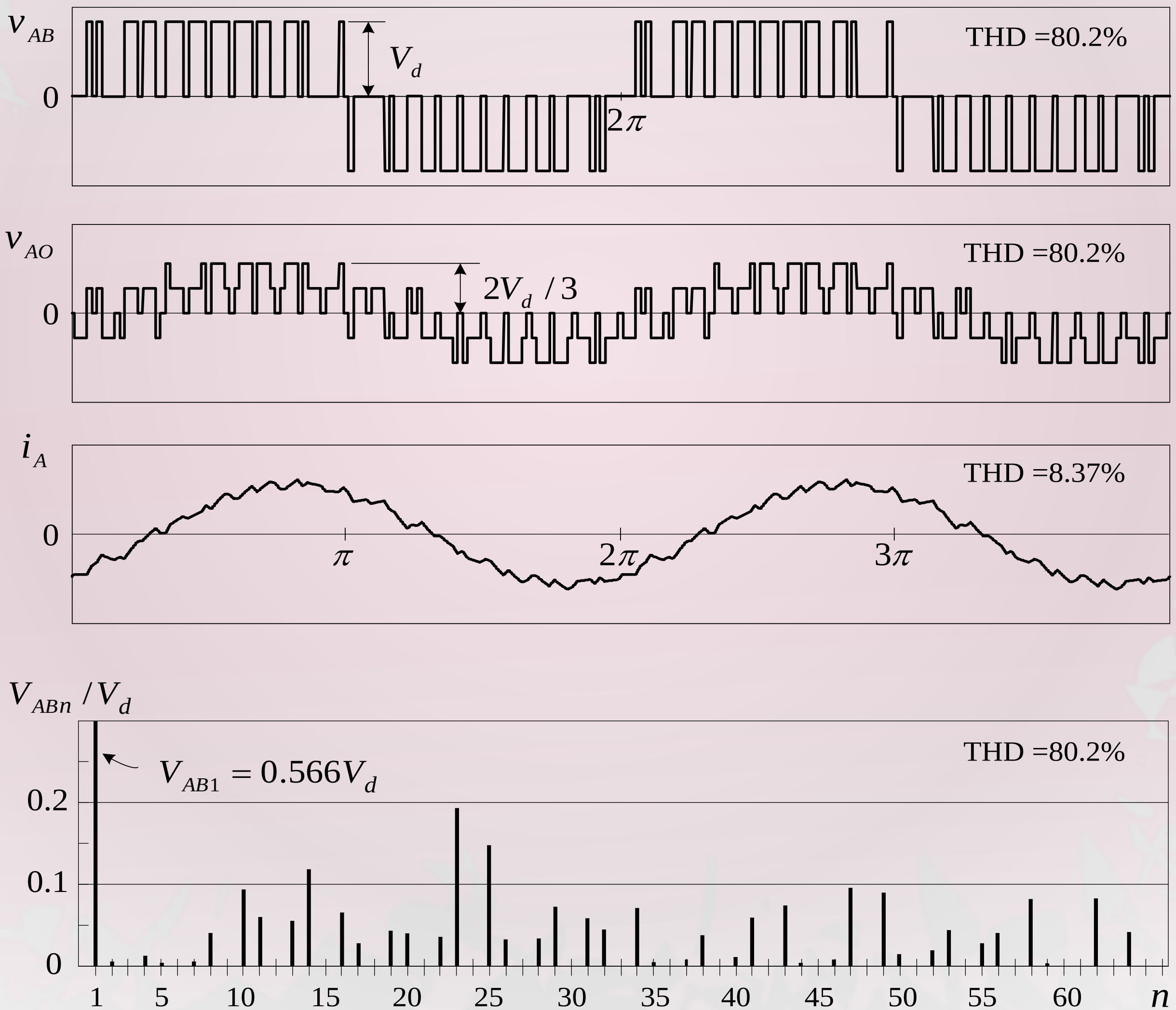
Simulated Waveforms



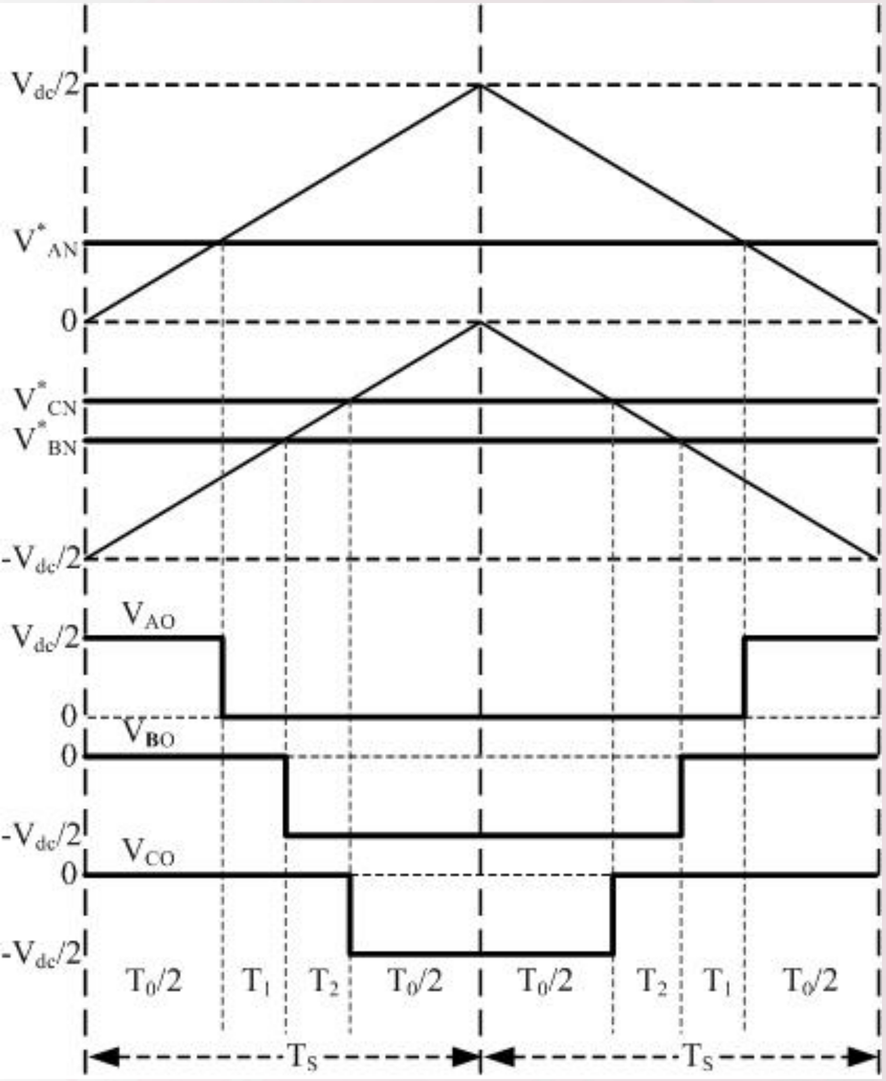
f_1 = 60Hz, f_{sw} = 900Hz, m_a = 0.696, T_s = 1.1ms

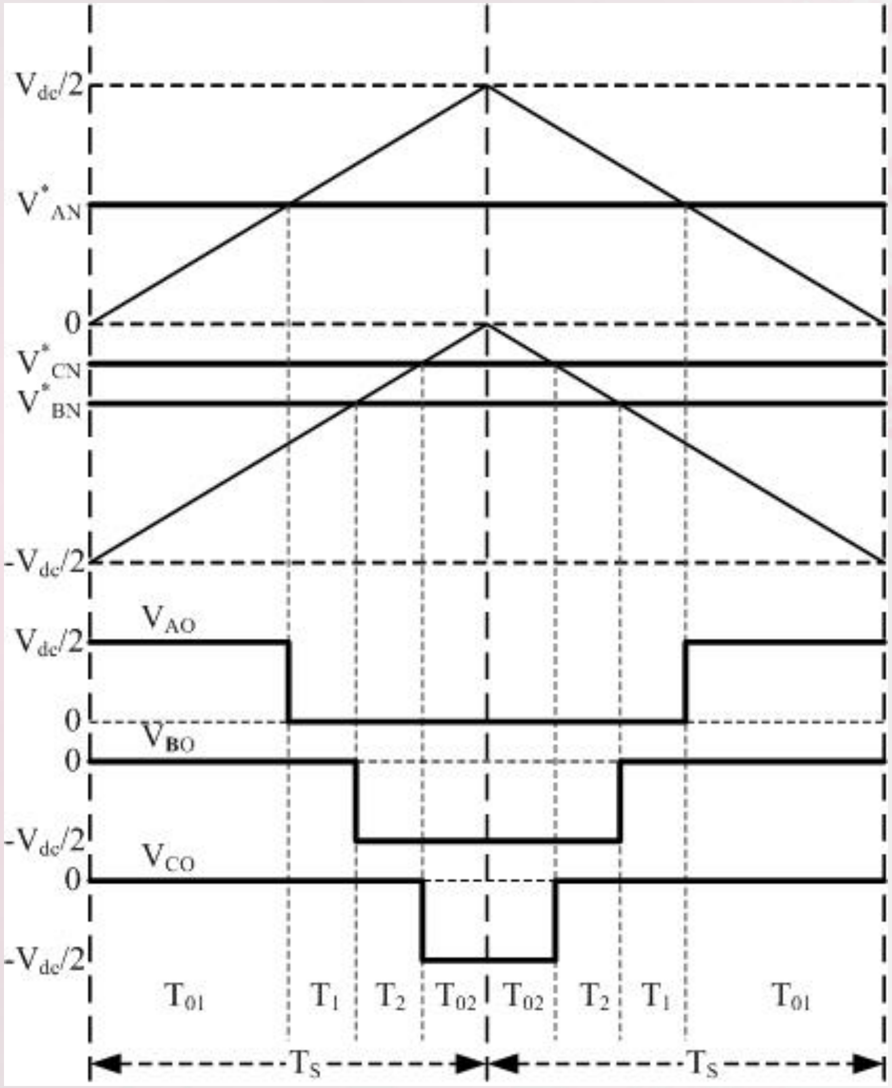
Space Vector Modulation

Waveforms and FFT



SVPWM – Modified SinePWM





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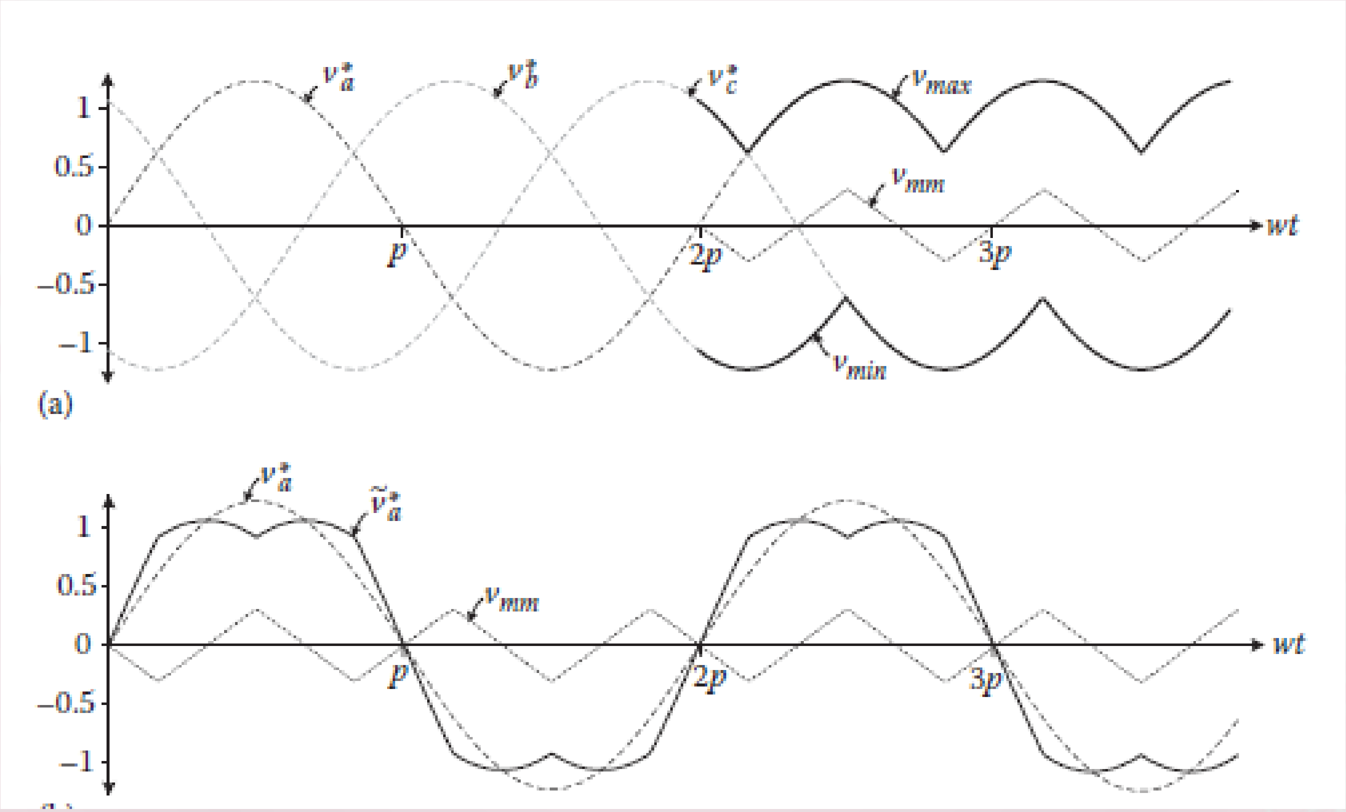

SVPWM – Modified SinePWM