Power Converter Systems

Graduate Course EE8407

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Ryerson Campus

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley - IEEE Press, 2006

Topic 7

Multilevel Neutral Point Clamped (NPC) Inverters

Three-Level NPC Inverter Based MV Drive

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley - IEEE Press, 2006

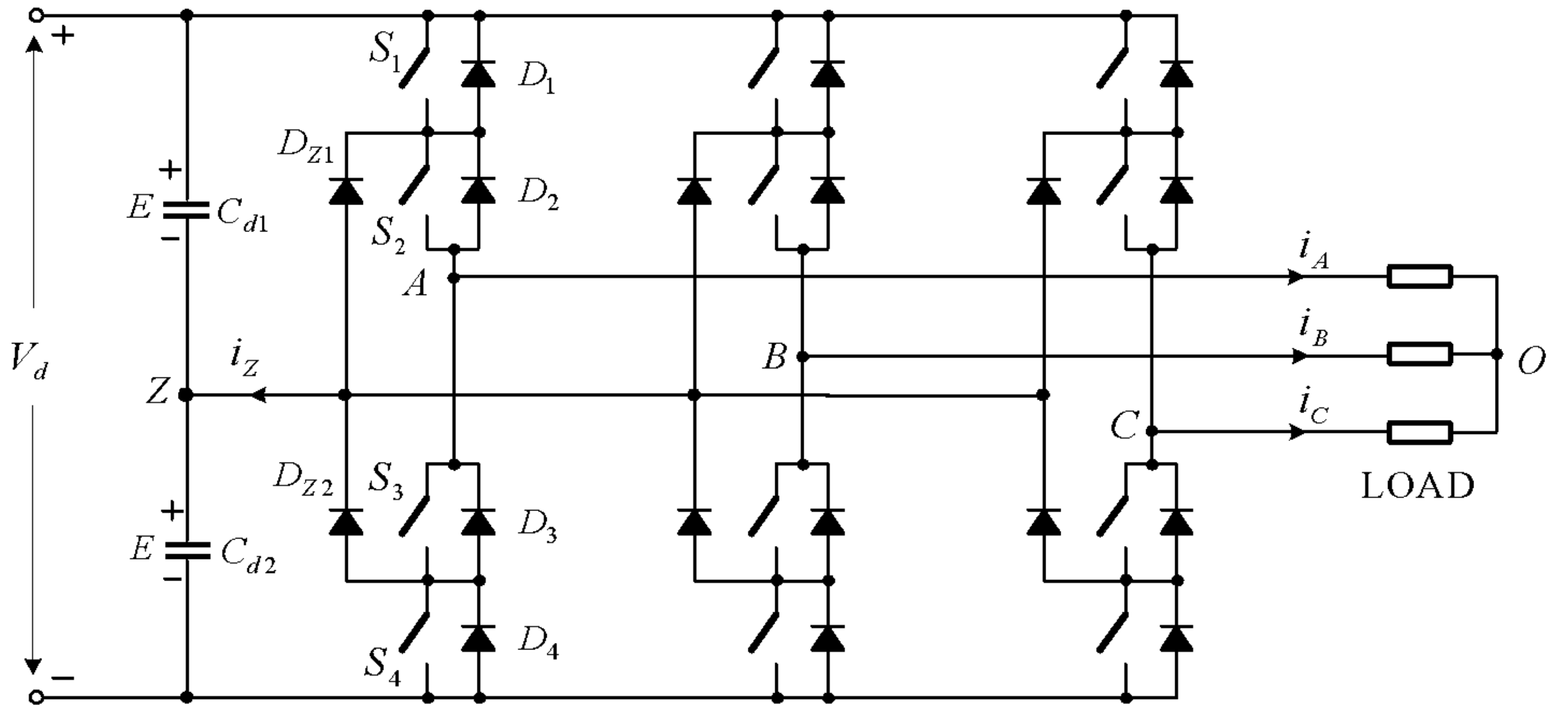
Multilevel NPC Inverters

Lecture Topics

- Three-level NPC Inverter
- Space Vector Modulation
- Neutral Point Voltage Control
- High-level NPC Inverters

Three-Level NPC Inverters

• Inverter Configuration



Clamping diodes: D_{Z1} and D_{Z2} (Phase A)

Three-Level NPC Inverters

- **Switching State**

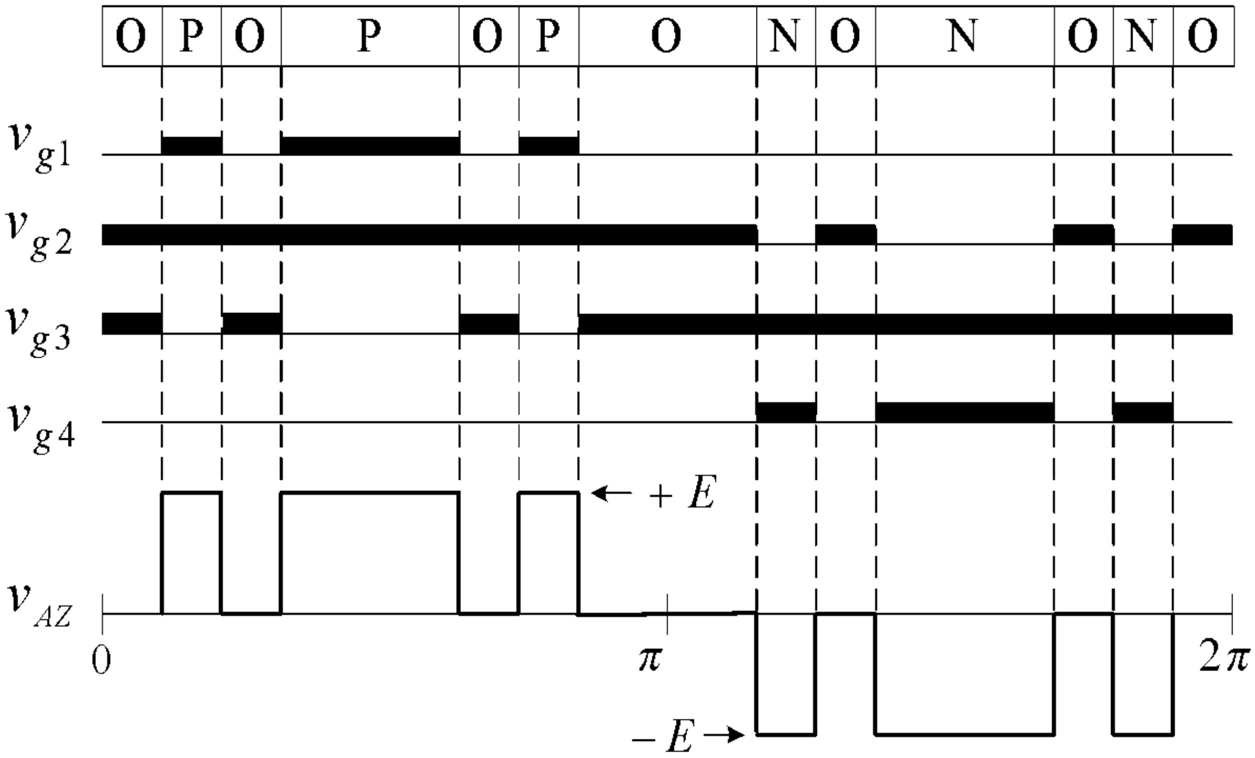
Switching State	Device Switching Status (Phase A)				Inverter Terminal Voltage V_{AZ}
	S_1	S_2	S_3	S_4	
P	On	On	Off	Off	E
O	Off	On	On	Off	0
N	Off	Off	On	On	$-E$

Complementary Switch pairs:

S_1 and S_3; S_2 and S_4;

Three-Level NPC Inverters

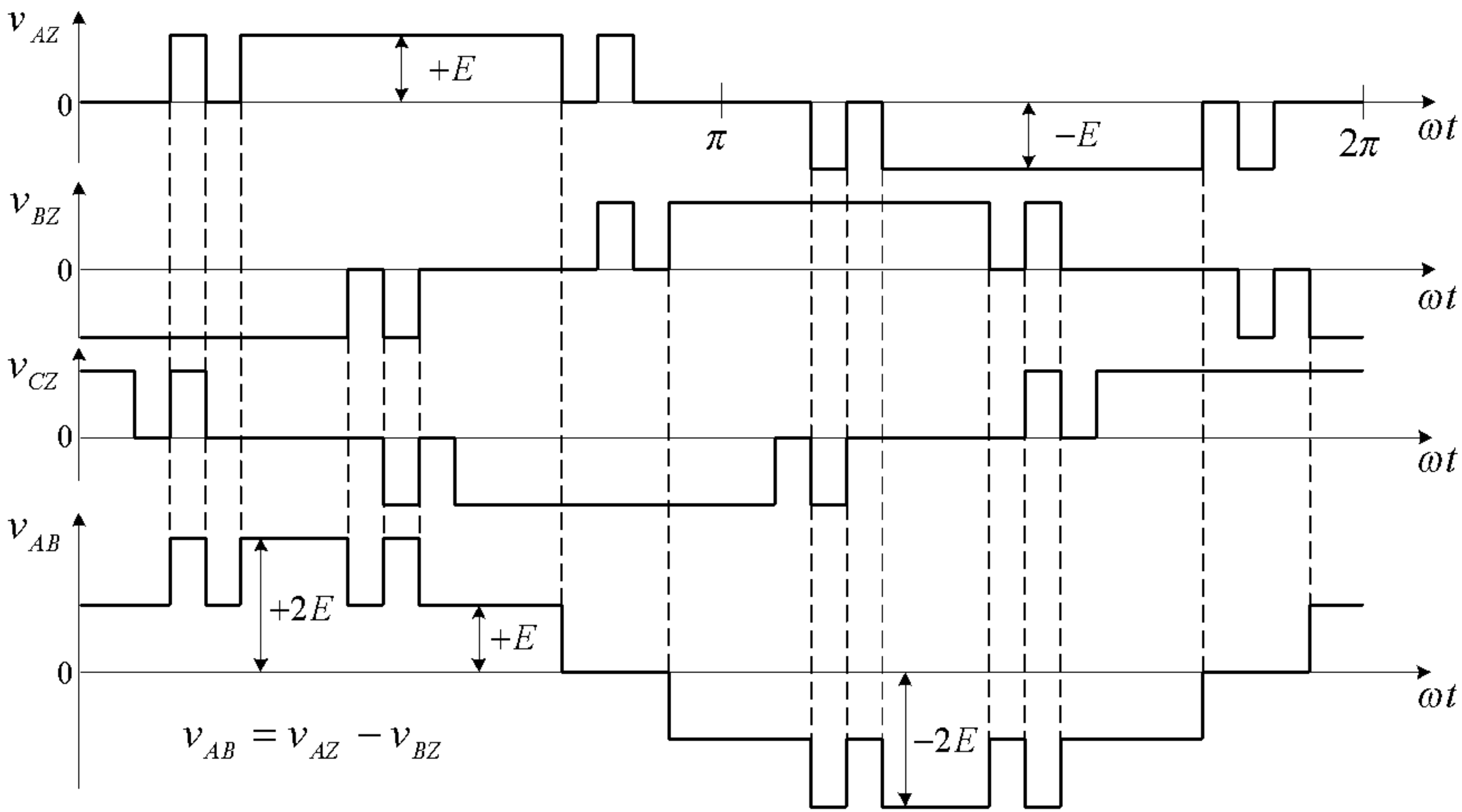
- **Gate Signal Arrangements**



Inverter phase voltage v_{AZ} has three levels: E, 0 and $-E$

Three-Level NPC Inverters

• Inverter Output Waveforms



Space Vector Modulation

- **Space Vectors**
  - **Three-phase voltages**

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

  - **Two-phase voltages**

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

  - **Space vector representation**

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

(2) → (3)

$$\vec{V}(t) = \frac{2}{3}\left[v_{AO}(t)\, e^{j0} + v_{BO}(t)\, e^{j2\pi/3} + v_{CO}(t)\, e^{j4\pi/3} \right] \qquad (4)$$

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

Textbook: Bin Wu, 'High-Power Converters and AC Drives', Wiley - IEEE Press, 2006

Space Vector Modulation

• Space Vectors (Example)

Switching state [POO] → on-state switches:
Phase A: upper two switches [P]
Phase B: middle two switches [O]
Phase C: middle two switches [O]
from which

$$v_{AO}(t) = \frac{1}{3}V_d, \; v_{BO}(t) = -\frac{1}{6}V_d \quad \text{and} \quad v_{CO}(t) = -\frac{1}{6}V_d \qquad (5)$$

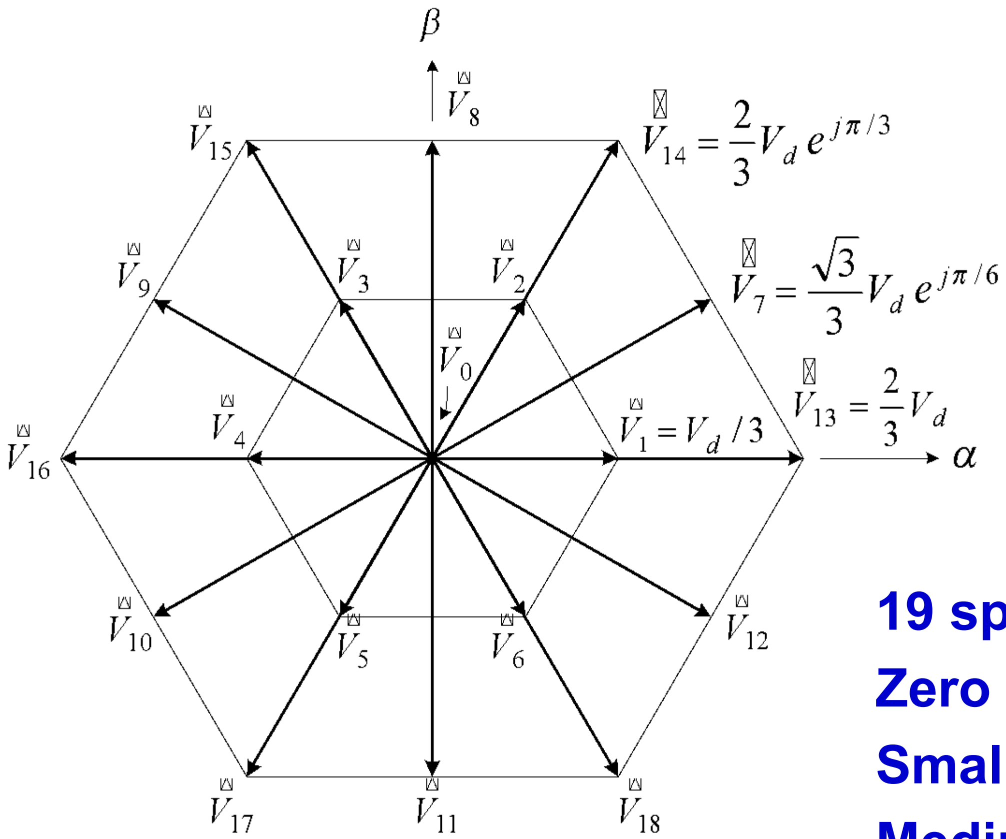
Substituting (5) to (4) gives a space vector

$$\vec{V}_1 = \frac{1}{3}V_d\, e^{j0} \qquad (6)$$

Total switching states: 27
Total space vectors: 19

Space Vector Modulation

• Space Vectors Diagram



19 space vectors:

Zero vector: V_0

Small vectors: $V_1 - V_6$

Medium vectors: $V_7 - V_{12}$

Large vectors: $V_{13} - V_{18}$

Space Vector Modulation

• Switching States and Space Vectors

Space Vector		Switching State		Vector Classification	Vector Magnitude
$\vec{V}_0$		[PPP][OOO] [NNN]		Zero Vector (ZV)	0
		P-type	N-type		
$\vec{V}_1$	$\vec{V}_{1P}$	[POO]		Small Vector (SV) P-type Small Vector (PSV) N-type Small Vector (NSV)	$\frac{1}{3}V_d$
	$\vec{V}_{1N}$		[ONN]		
$\vec{V}_2$	$\vec{V}_{2P}$	[PPO]			
	$\vec{V}_{2N}$		[OON]		
$\vec{V}_3$	$\vec{V}_{3P}$	[OPO]			
	$\vec{V}_{3N}$		[NON]		
$\vec{V}_4$	$\vec{V}_{4P}$	[OPP]			
	$\vec{V}_{4N}$		[NOO]		
$\vec{V}_5$	$\vec{V}_{5P}$	[OOP]			
	$\vec{V}_{5N}$		[NNO]		
$\vec{V}_6$	$\vec{V}_{6P}$	[POP]			
	$\vec{V}_{6N}$		[ONO]		

Redundancy: Zero vector – three switching states
Small vectors – two states per vector

Space Vector Modulation

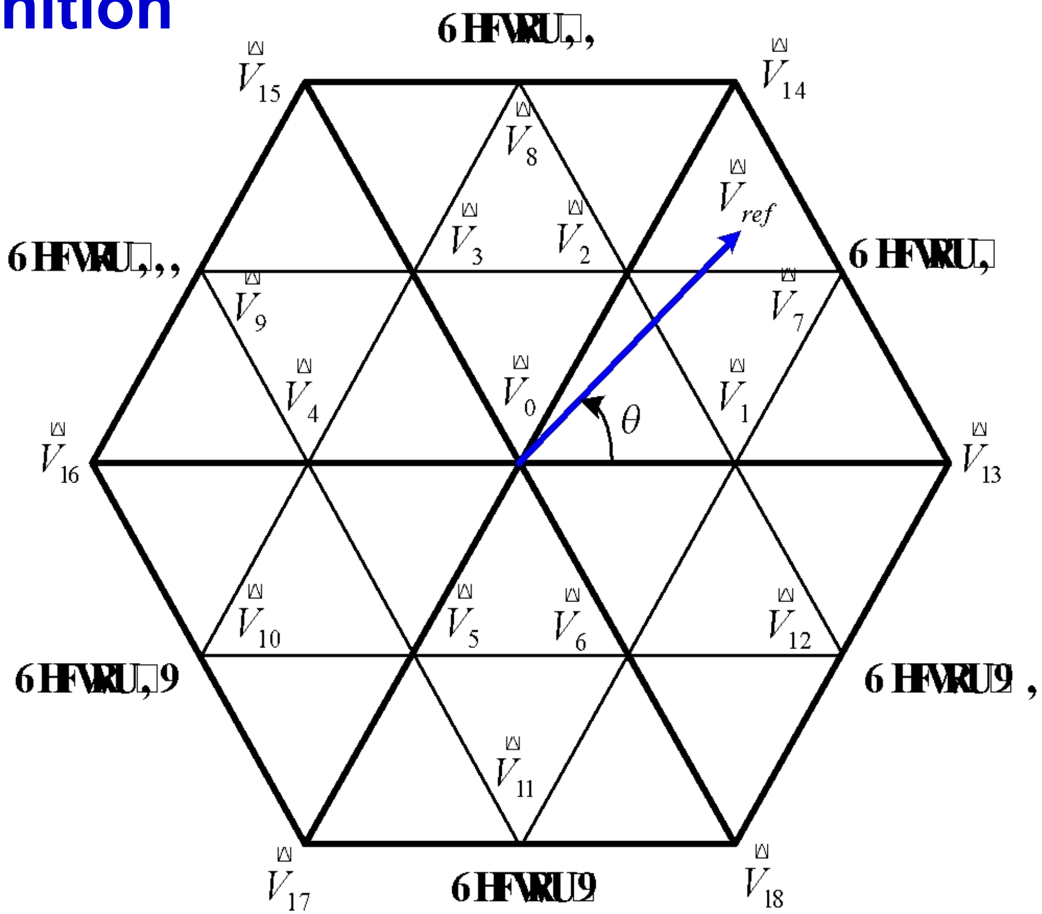
• Switching States and Space Vectors

Space Vector	Switching State	Vector Classification	Vector Magnitude
$\vec{V}_7$	[PON]	Medium Vector (MV)	$\frac{\sqrt{3}}{3}V_d$
$\vec{V}_8$	[OPN]		
$\vec{V}_9$	[NPO]		
$\vec{V}_{10}$	[NOP]		
$\vec{V}_{11}$	[ONP]		
$\vec{V}_{12}$	[PNO]		
$\vec{V}_{13}$	[PNN]	Large Vector (LV)	$\frac{2}{3}V_d$
$\vec{V}_{14}$	[PPN]		
$\vec{V}_{15}$	[NPN]		
$\vec{V}_{16}$	[NPP]		
$\vec{V}_{17}$	[NNP]		
$\vec{V}_{18}$	[PNP]		

No redundant switching states for medium or large vectors

Space Vector Modulation

- **Sector Definition**



V_{ref} : Reference vector, rotating in space at a certain speed; All other vectors are stationary.

Space Vector Modulation

- **SVM Principle**

  - For a given length and position in space, V_{ref} can be approximated by three nearby stationary vectors;
  - Based on the chosen stationary vectors, switching states are selected and gate signals are generated;
  - When V_{ref} passes through sectors one by one, different sets of switches are turned on or off;
  - When V_{ref} rotates one revolution in space, the inverter output voltage varies one cycle over time;
  - The inverter output frequency corresponds to the rotating speed of V_{ref} ;
  - The inverter output voltage can be adjusted by the magnitude of V_{ref}.

Space Vector Modulation

• Dwell Time Calculation

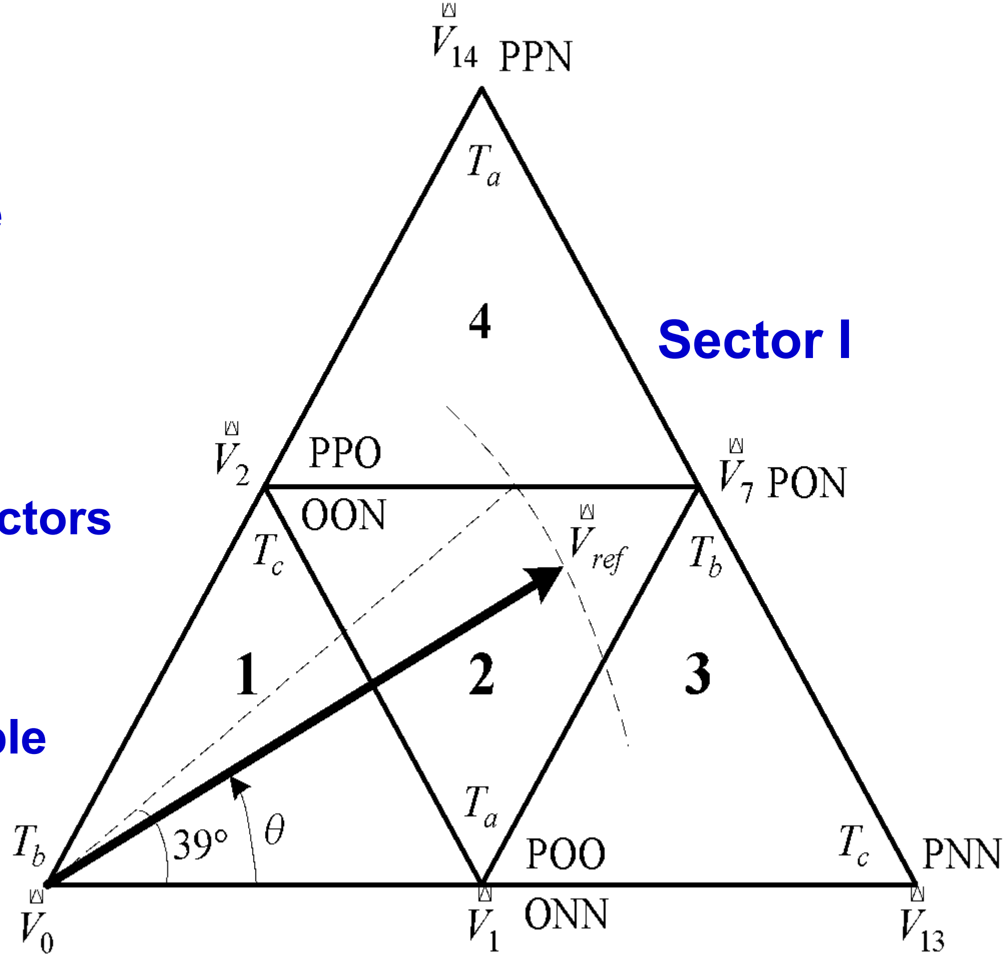
Dwell time is the duty-cycle time of selected switches during the sampling period T_s.

- **Select three nearest stationary vectors**

$\vec{V}_1, \vec{V}_2$ and $\vec{V}_7$

- **Use volt-second balancing principle**

$$\begin{cases} \vec{V}_1 T_a + \vec{V}_7 T_b + \vec{V}_2 T_c = \vec{V}_{ref}\, T_s \\ T_a + T_b + T_c = T_s \end{cases} \qquad \textbf{(a)}$$



Four Regions

Space Vector Modulation

• Dwell Time Calculation

From equation (a)

$$\begin{cases} T_a = T_s[1 - 2m_a \sin\theta] \\ T_b = T_s[2m_a \sin(\frac{\pi}{3} + \theta) - 1] \\ T_c = T_s[1 - 2m_a \sin(\frac{\pi}{3} - \theta)] \end{cases}$$

T_a , T_b and T_c – dwell times for V_1 , V_7 and V_2

$m_a = \sqrt{3}\frac{V_{ref}}{V_d}$ – modulation index

Space Vector Modulation

• Switching Sequence (Seven-segment)

General Design Requirements

a) The transition from one switching state to the next involves only two switches in the same inverter leg, one being turned on and the other turned off; and

b) The transition for V_{ref} moving from one sector (or one region) to the next requires no or minimum number of switchings.

Note:

The switching sequence design is not unique, but the above requirements should be satisfied for switching frequency minimization.

Space Vector Modulation

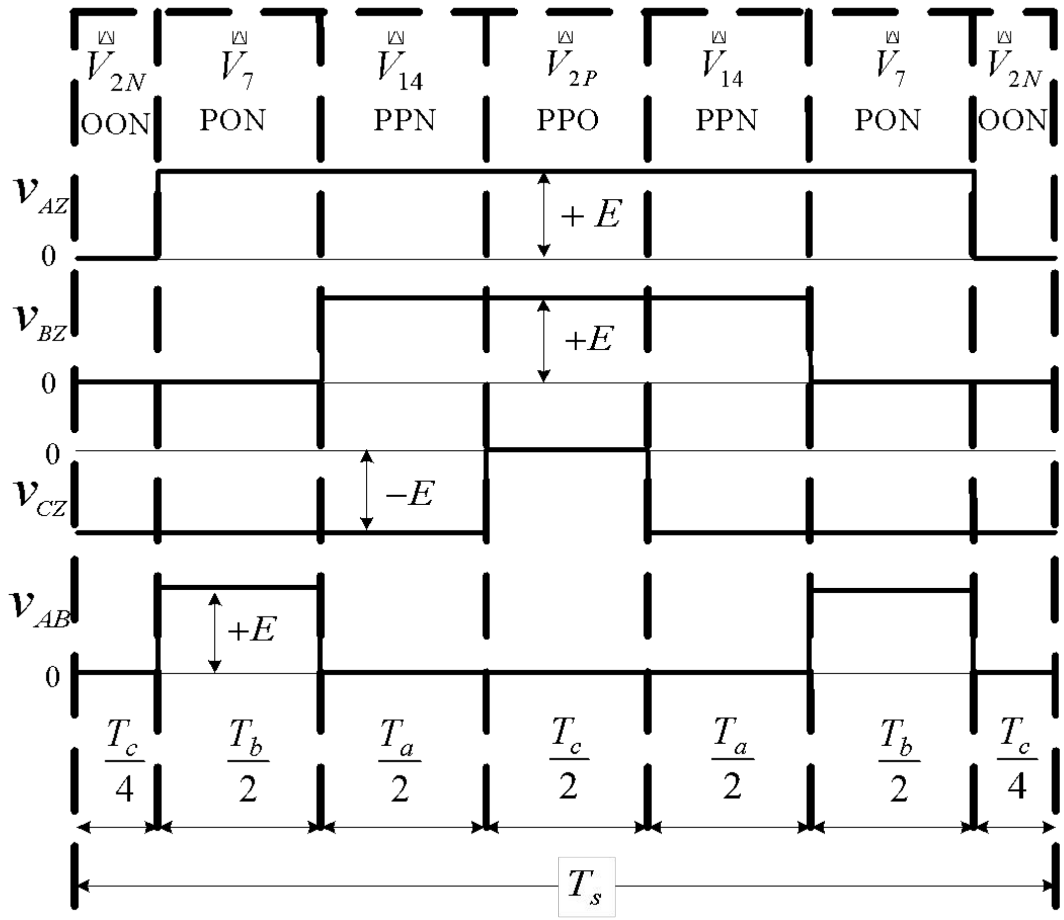
- **Switching Sequence** (Seven-segment)

Assuming V_{ref} is in Region 4 of Sector I, three vectors are selected: V_2, V_7 and V_{14}

Voltage Vector		$\vec{V}_{2N}$	$\vec{V}_7$	$\vec{V}_{14}$	$\vec{V}_{2P}$	$\vec{V}_{14}$	$\vec{V}_7$	$\vec{V}_{2N}$
Dwell Time		$\frac{T_c}{4}$	$\frac{T_b}{2}$	$\frac{T_a}{2}$	$\frac{T_c}{2}$	$\frac{T_a}{2}$	$\frac{T_b}{2}$	$\frac{T_c}{4}$
Switching State	Phase A	O	P	P	P	P	P	O
	Phase B	O	O	P	P	P	O	O
	Phase C	N	N	N	O	N	N	N
$[\mathrm{P}] = E$, $[\mathrm{O}] = 0$, $[\mathrm{N}] = -E$.								

Space Vector Modulation

- **Switching Sequence (Seven-segment)**



Switching sequence requirement *a*) is satisfied.

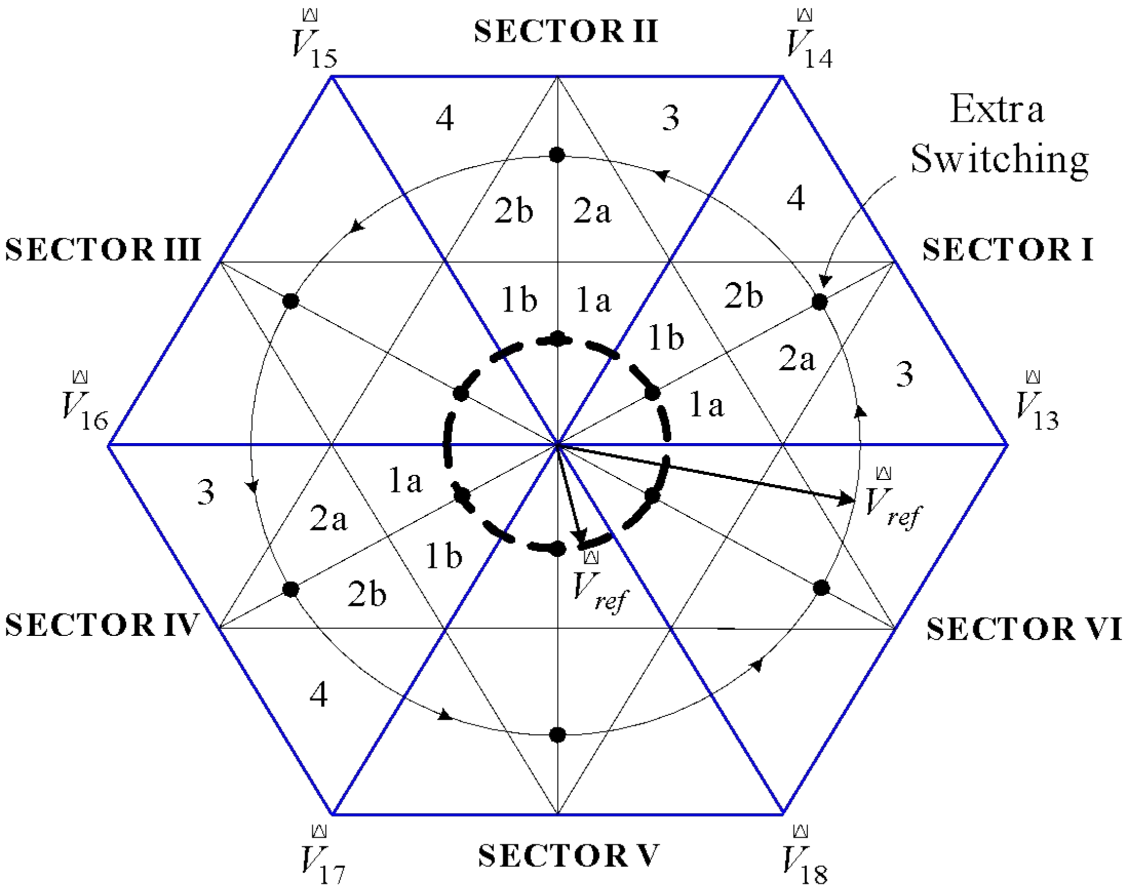
Space Vector Modulation

- **Switching Sequence** (Seven-segment)

Sector I												
Sgmt	**1a**		**1b**		**2a**		**2b**		**3**		**4**	
1^{st}	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]
2^{nd}	$\vec{V}_{2N}$	[OON]	$\vec{V}_0$	[OOO]	$\vec{V}_{2N}$	[OON]	$\vec{V}_7$	[PON]	$\vec{V}_{13}$	[PNN]	$\vec{V}_7$	[PON]
3^{rd}	$\vec{V}_0$	[OOO]	$\vec{V}_{1P}$	[POO]	$\vec{V}_7$	[PON]	$\vec{V}_{1P}$	[POO]	$\vec{V}_7$	[PON]	$\vec{V}_{14}$	[PPN]
4^{th}	$\vec{V}_{1P}$	[POO]	$\vec{V}_{2P}$	[PPO]	$\vec{V}_{1P}$	[POO]	$\vec{V}_{2P}$	[PPO]	$\vec{V}_{1P}$	[POO]	$\vec{V}_{2P}$	[PPO]
5^{th}	$\vec{V}_0$	[OOO]	$\vec{V}_{1P}$	[POO]	$\vec{V}_7$	[PON]	$\vec{V}_{1P}$	[POO]	$\vec{V}_7$	[PON]	$\vec{V}_{14}$	[PPN]
6^{th}	$\vec{V}_{2N}$	[OON]	$\vec{V}_0$	[OOO]	$\vec{V}_{2N}$	[OON]	$\vec{V}_7$	[PON]	$\vec{V}_{13}$	[PNN]	$\vec{V}_7$	[PON]
7^{th}	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]	$\vec{V}_{1N}$	[ONN]	$\vec{V}_{2N}$	[OON]

Space Vector Modulation

- **Switching Sequence** (Seven-segment)



Device switching frequency:

$$f_{sw,dev} = f_{sp} / 2 + f_1 / 2$$

Sampling frequency:

$$f_{sp} = 1 / T_s$$

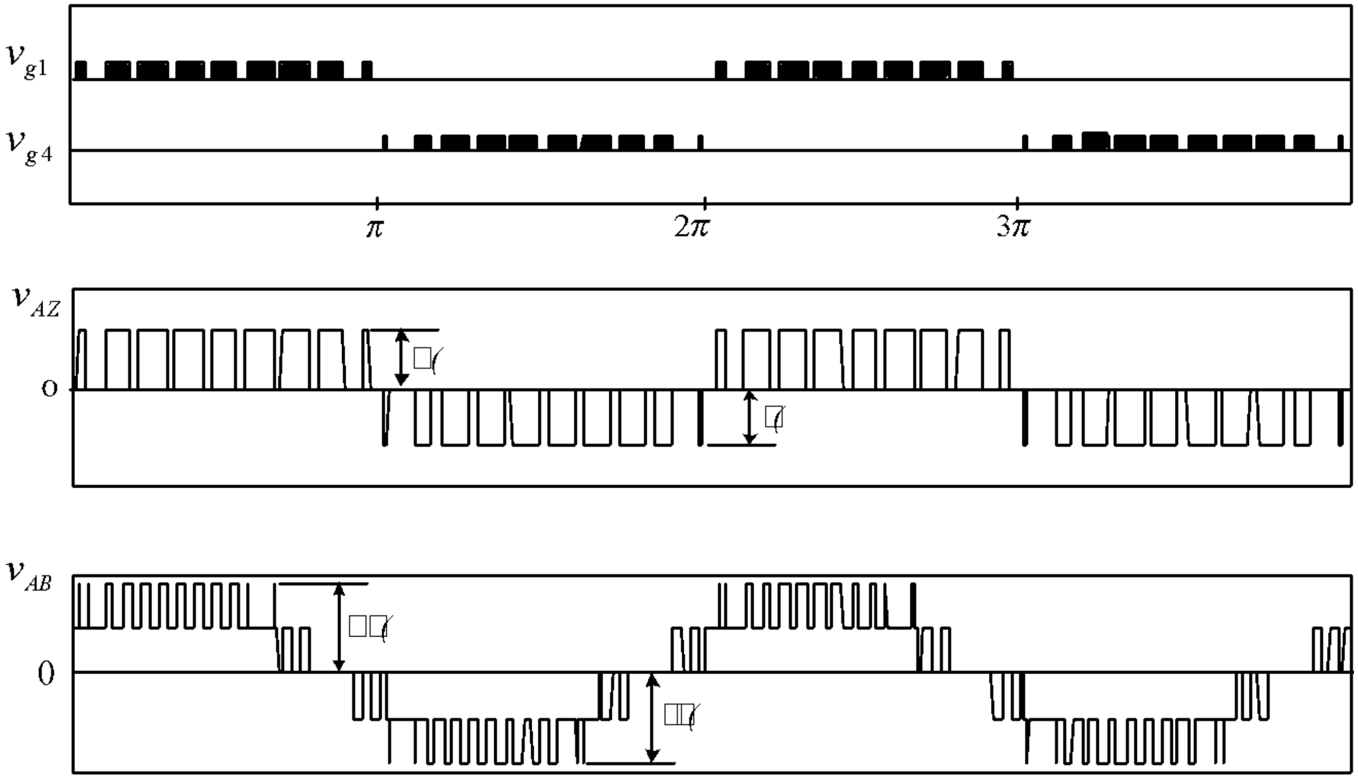
Fundamental frequency:

$$f_1$$

Switching sequence requirement *b*) is satisfied.

Space Vector Modulation

- **Simulated Waveforms** (Seven-segment)

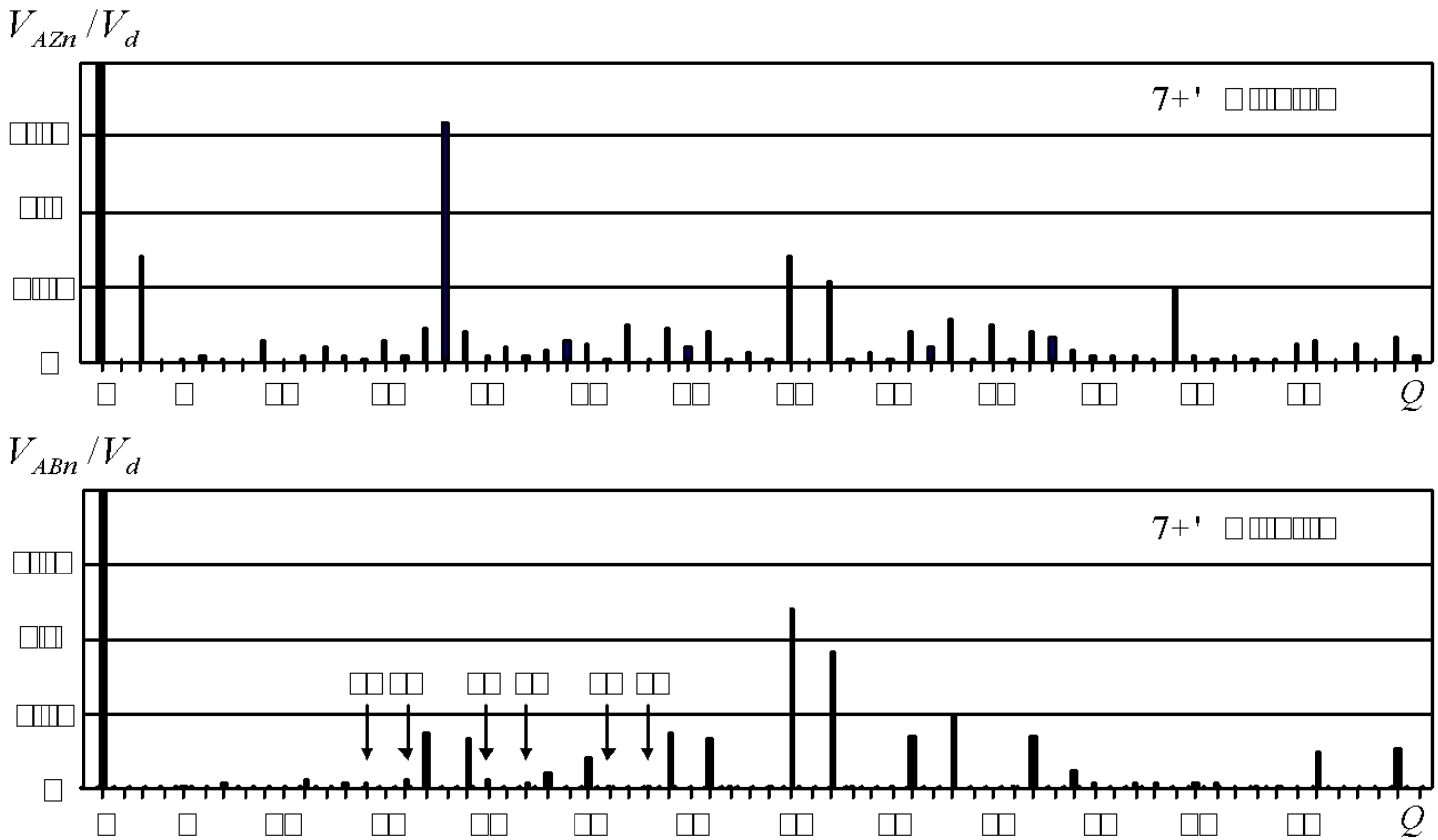


f_1 = 60Hz, T_s = 1/1080 sec, m_a = 0.8, f_{sw} = 570Hz

v_{AB} is not half wave symmetrical; and contains both even- and odd-order harmonics.

Space Vector Modulation

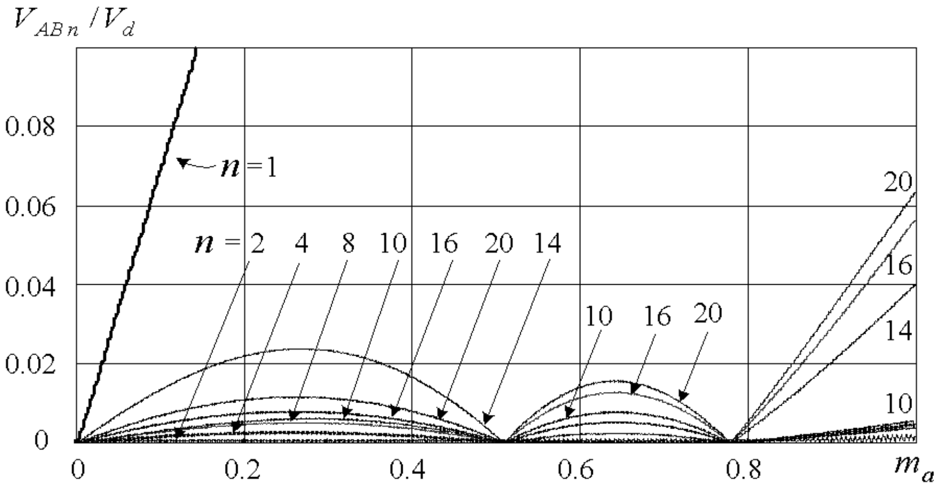
• Simulated Waveforms (Seven-segment)



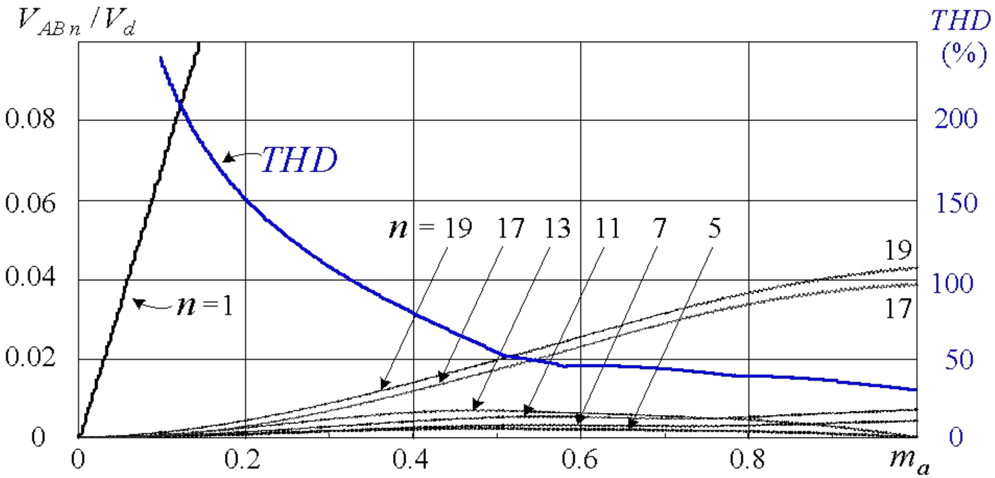
f_1 = 60Hz, T_s = 1/1080 sec, m_a = 0.8, f_{sw} = 570Hz

Space Vector Modulation

- **Harmonic Content** (Seven-segment)



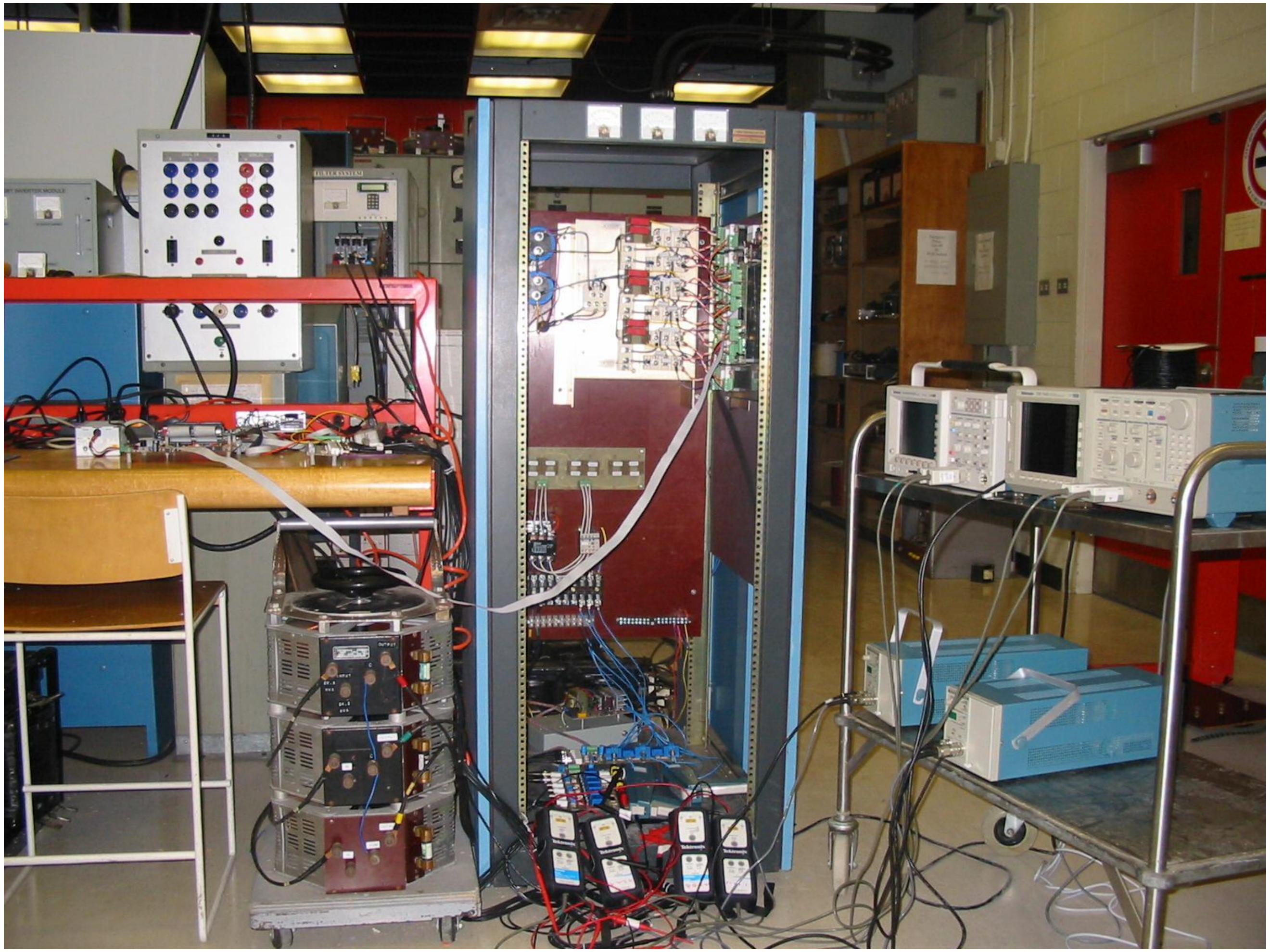
(a) Even order harmonics



(b) Odd order harmonics

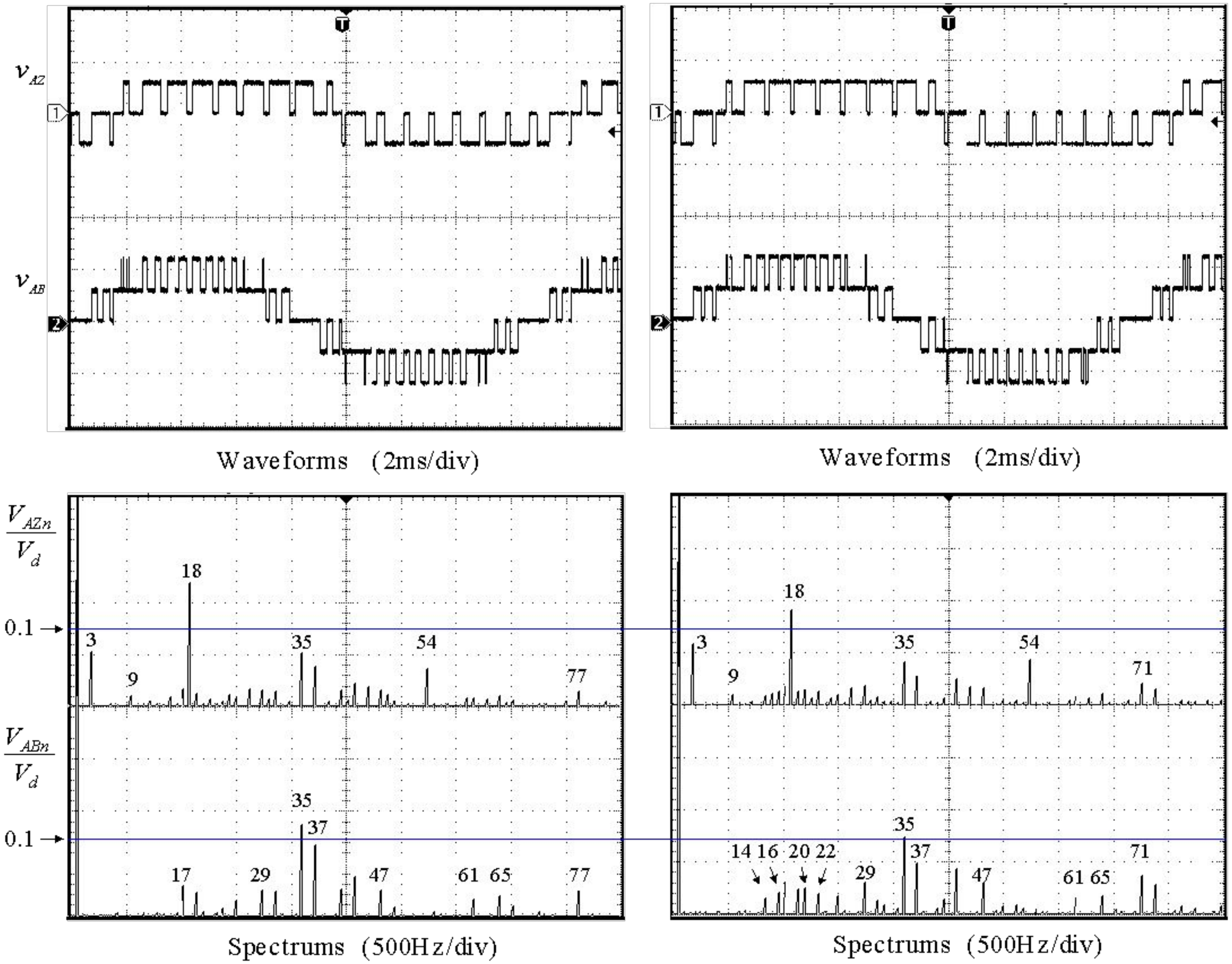
Space Vector Modulation

- Laboratory Prototype at Ryerson



Space Vector Modulation

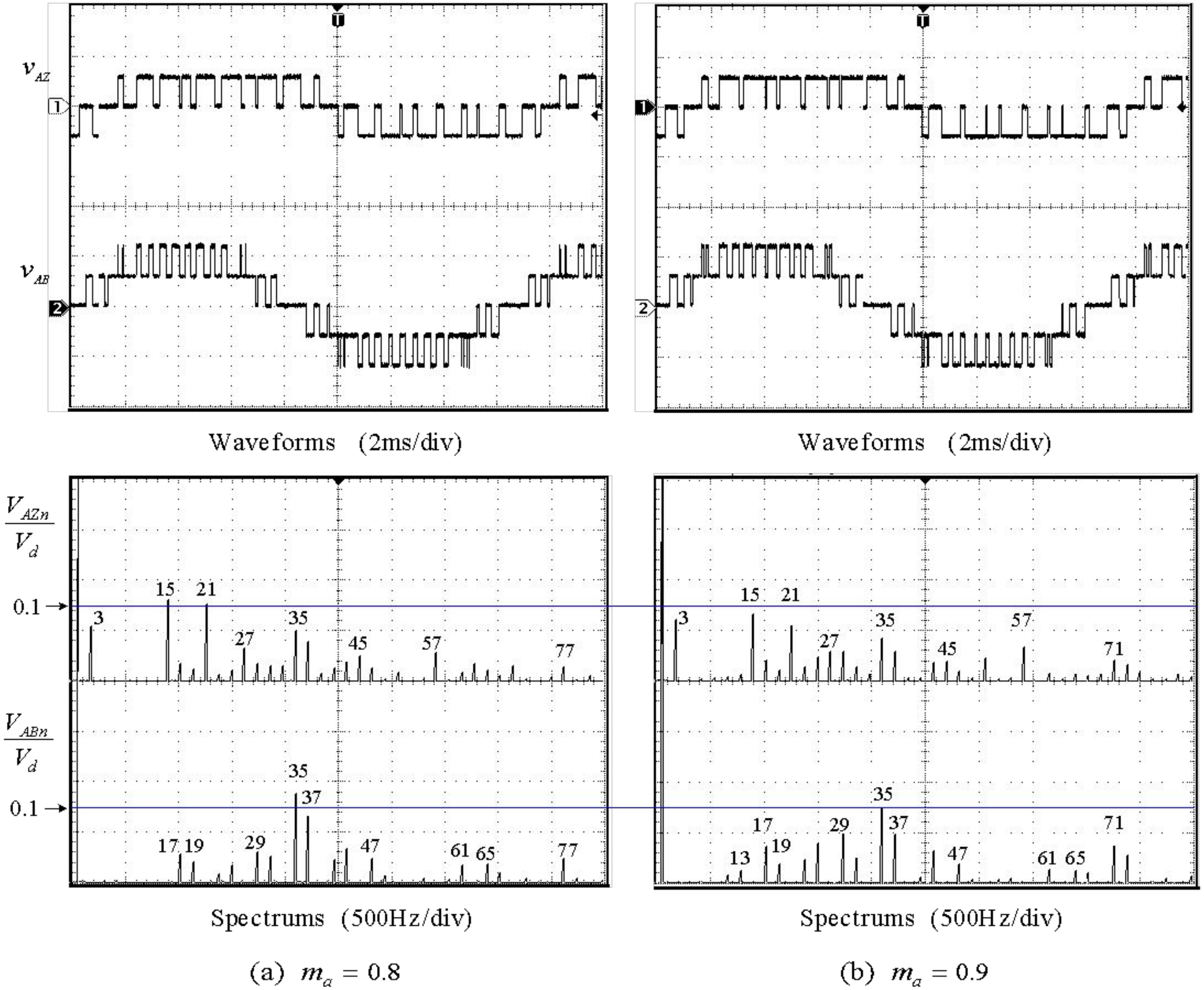
• Measured Waveforms



(a) $m_a = 0.8$ (b) $m_a = 0.9$

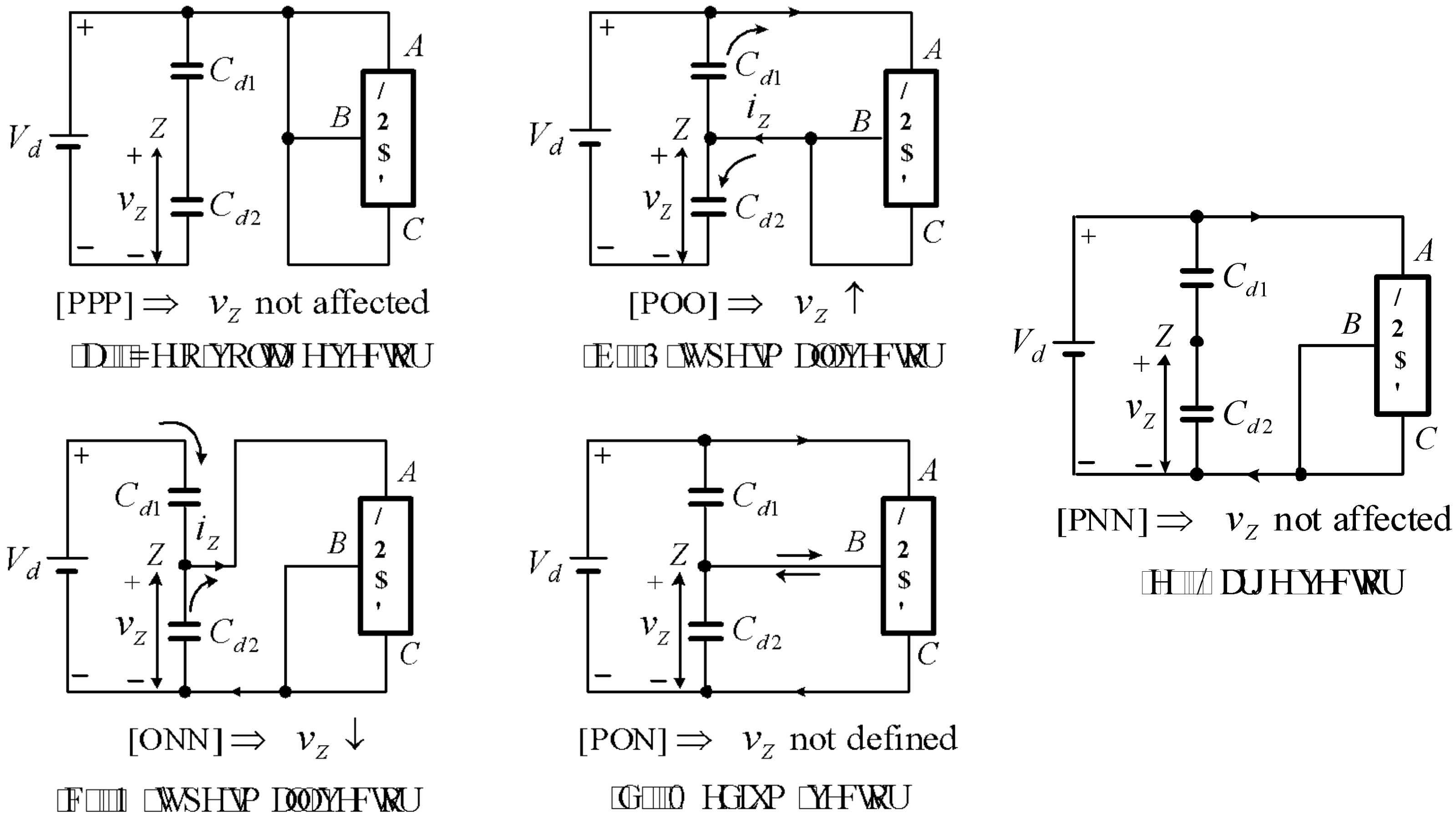
Space Vector Modulation

- **Measured waveforms** (with even-order harmonic elimination)



Neutral Point Voltage Control

• Neutral Point Voltage Deviation



The neutral point voltage v_z can be controlled by P- and N-types of small vectors

Neutral Point Voltage Control

- **Neutral Point Voltage Control**

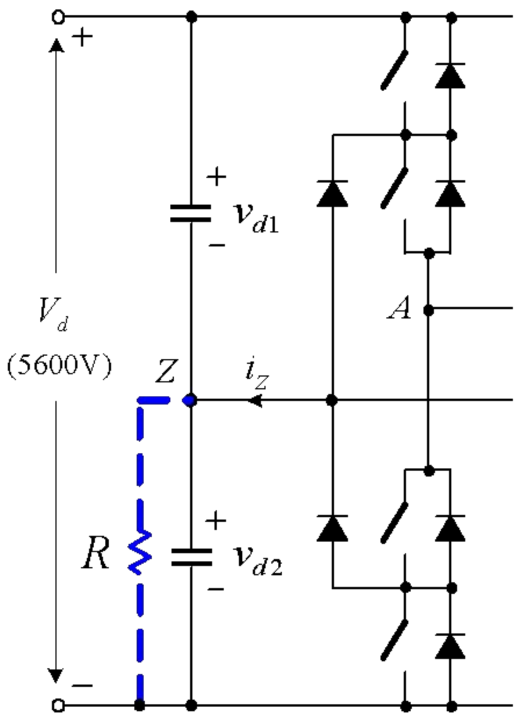
$$T_a = T_{aP} + T_{aN}$$

$$\begin{cases} T_{aP} = \dfrac{T_a}{2}\left(1+\Delta t\right) \\ T_{aN} = \dfrac{T_a}{2}\left(1-\Delta t\right) \end{cases} \qquad -1 \le \Delta T \le 1$$

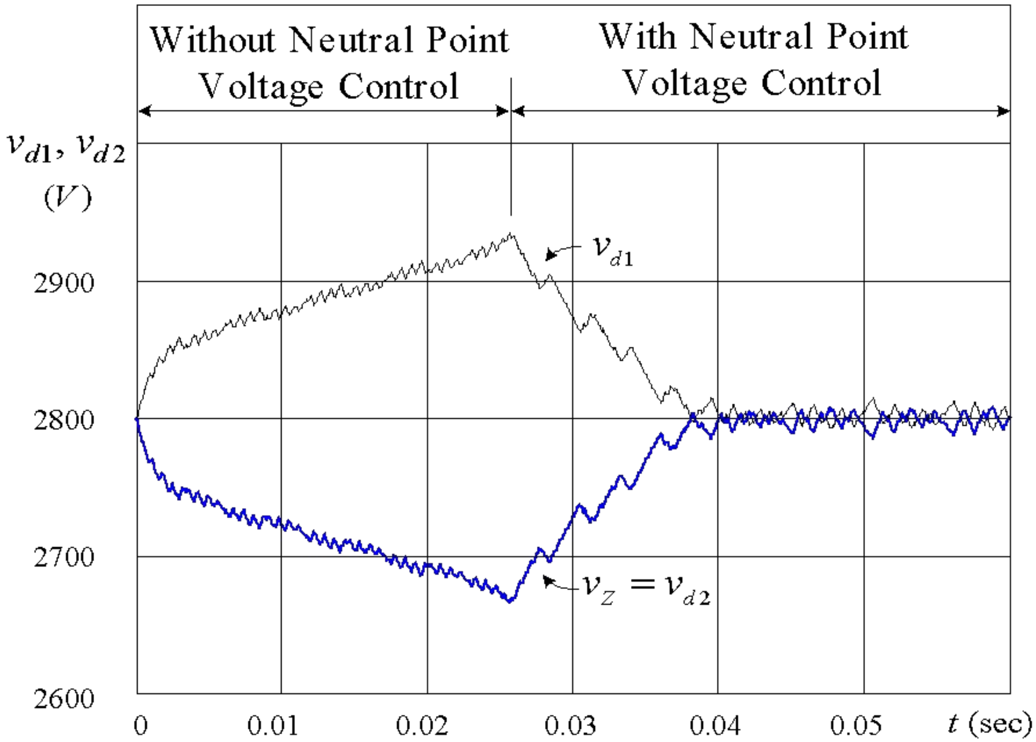
Neutral Point Deviation Level	Motoring Mode $i_d > 0$	Regenerating Mode $i_d < 0$
$(v_{d1} - v_{d2}) > \Delta V_d$	$\Delta t > 0$	$\Delta t < 0$
$(v_{d2} - v_{d1}) > \Delta V_d$	$\Delta t < 0$	$\Delta t > 0$
$\lvert v_{d1} - v_{d2} \rvert < \Delta V_d$	$\Delta t = 0$	$\Delta t = 0$
ΔV – maximum allowed voltage deviation ($\Delta V_d > 0$).		

Neutral Point Voltage Control

- **Neutral Point Voltage Control**



(a)

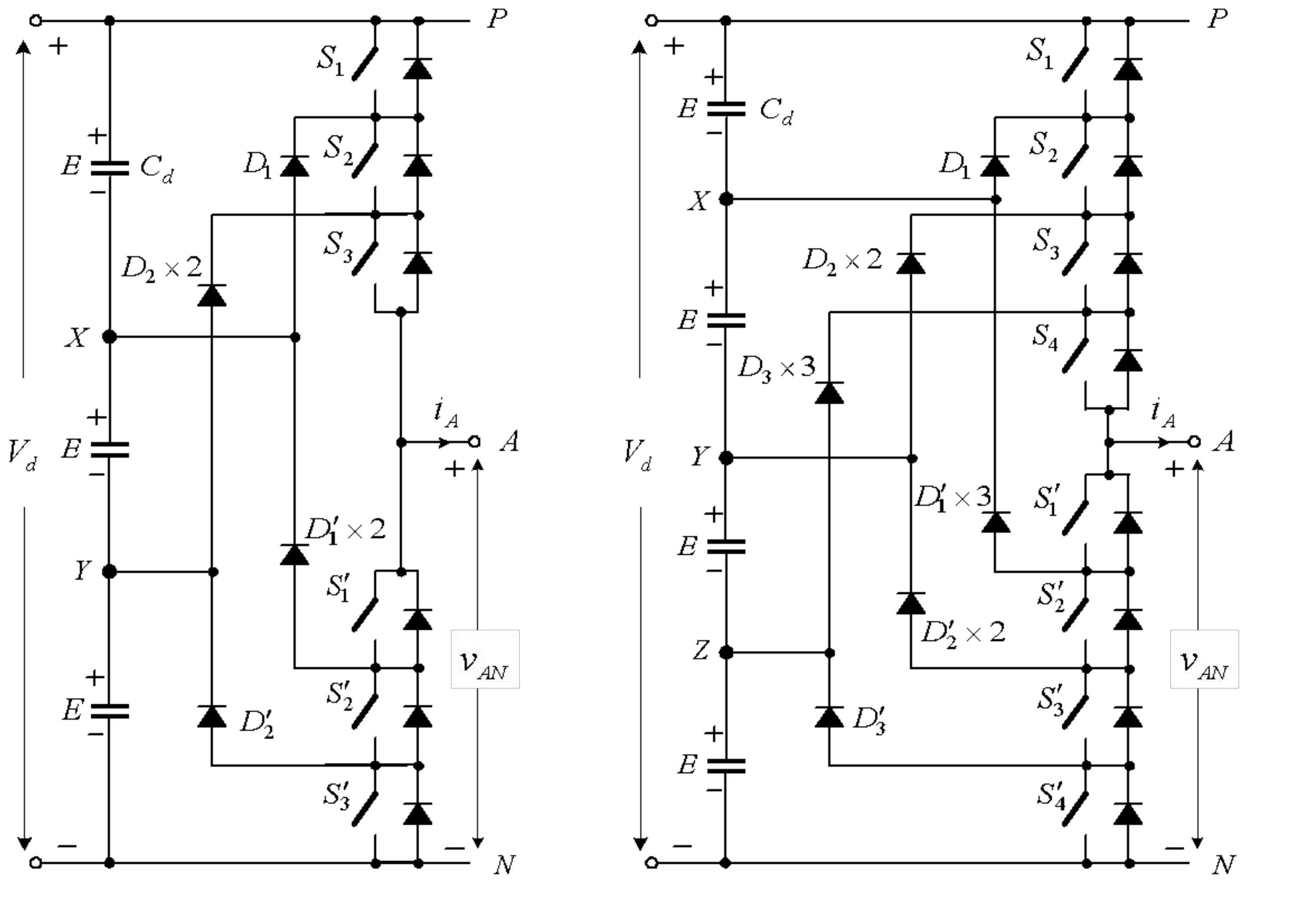


(b)

***R* is used on purpose to make the dc voltage unbalance.**

High-Level NPC Inverters

- Inverter Topologies



(a) Four-level (m = 4) (b) Five-level (m = 5)

High-Level NPC Inverters

• Switching State

Switch Status						v_{AN}
Four-level Inverter						
S_1	S_2	S_3	S'_1	S'_2	S'_3	
1	1	1	0	0	0	**3*E***
0	1	1	1	0	0	**2*E***
0	0	1	1	1	0	***E***
0	0	0	1	1	1	**0**

Five-level Inverter								v_{AN}
S_1	S_2	S_3	S_4	S'_1	S'_2	S'_3	S'_4	
1	1	1	1	0	0	0	0	**4*E***
0	1	1	1	1	0	0	0	**3*E***
0	0	1	1	1	1	0	0	**2*E***
0	0	0	1	1	1	1	0	***E***
0	0	0	0	1	1	1	1	**0**

High-Level NPC Inverters

- **Component Count**

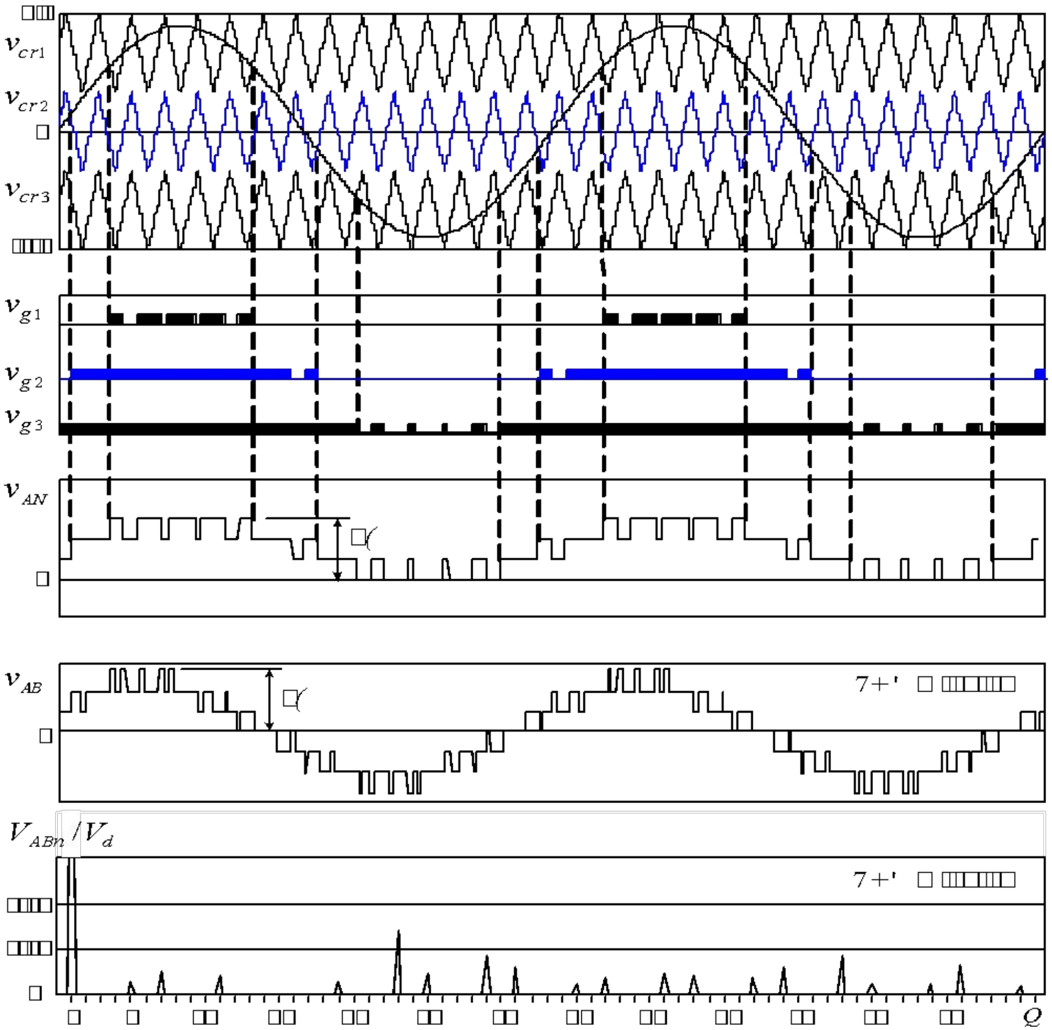
Voltage Level	Switches	Clamping Diodes*	dc capacitors
m	$6(m-1)$	$3(m-1)(m-2)$	$(m-1)$
3	12	6	2
4	18	18	3
5	24	36	4
6	30	60	5

* The clamping diodes have the same voltage rating as other switches.

Note:
The number of clamping diodes increases substantially with the voltage level.

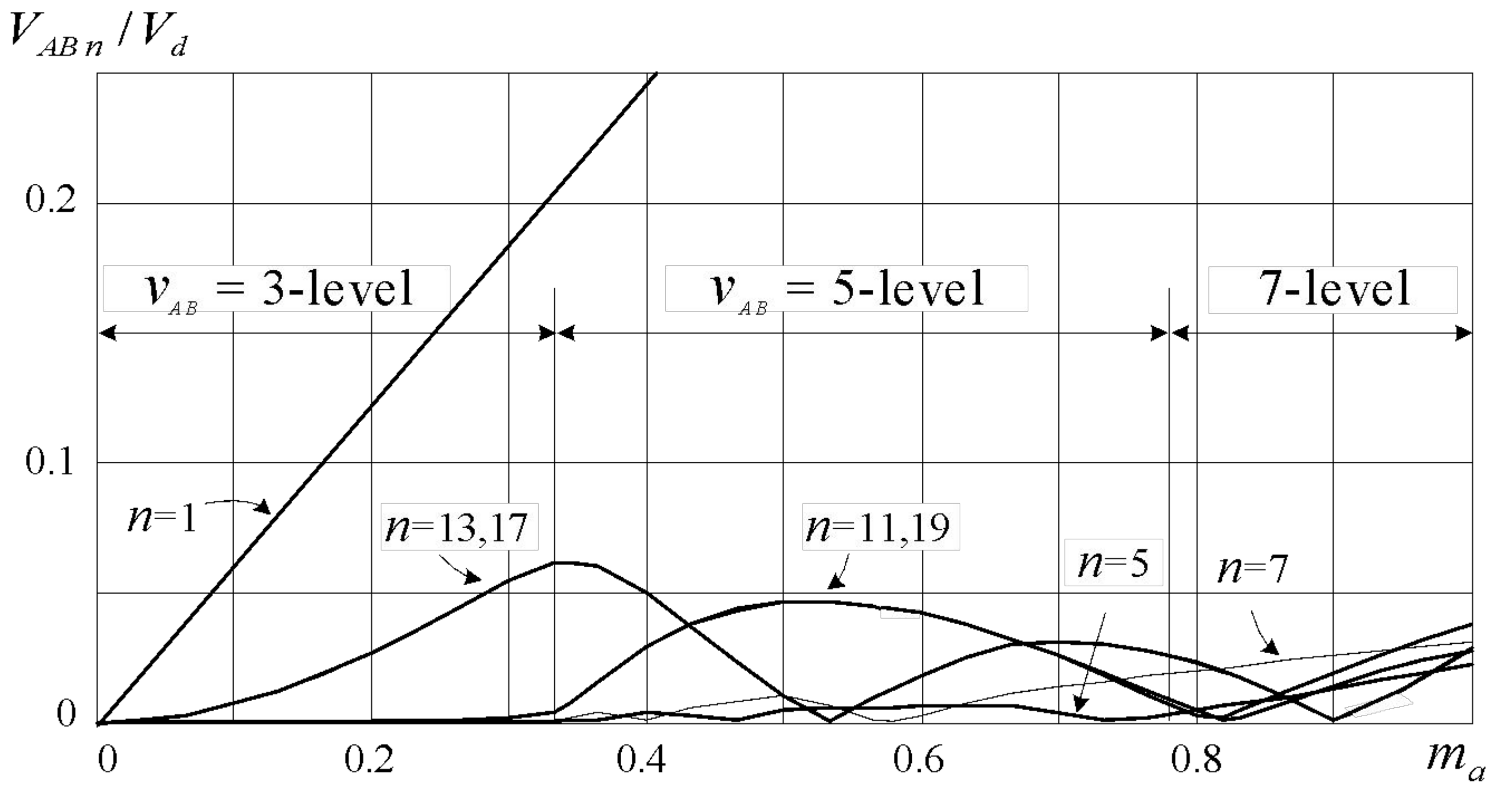
High-Level NPC Inverters

- **IPD Modulation** (four-level)



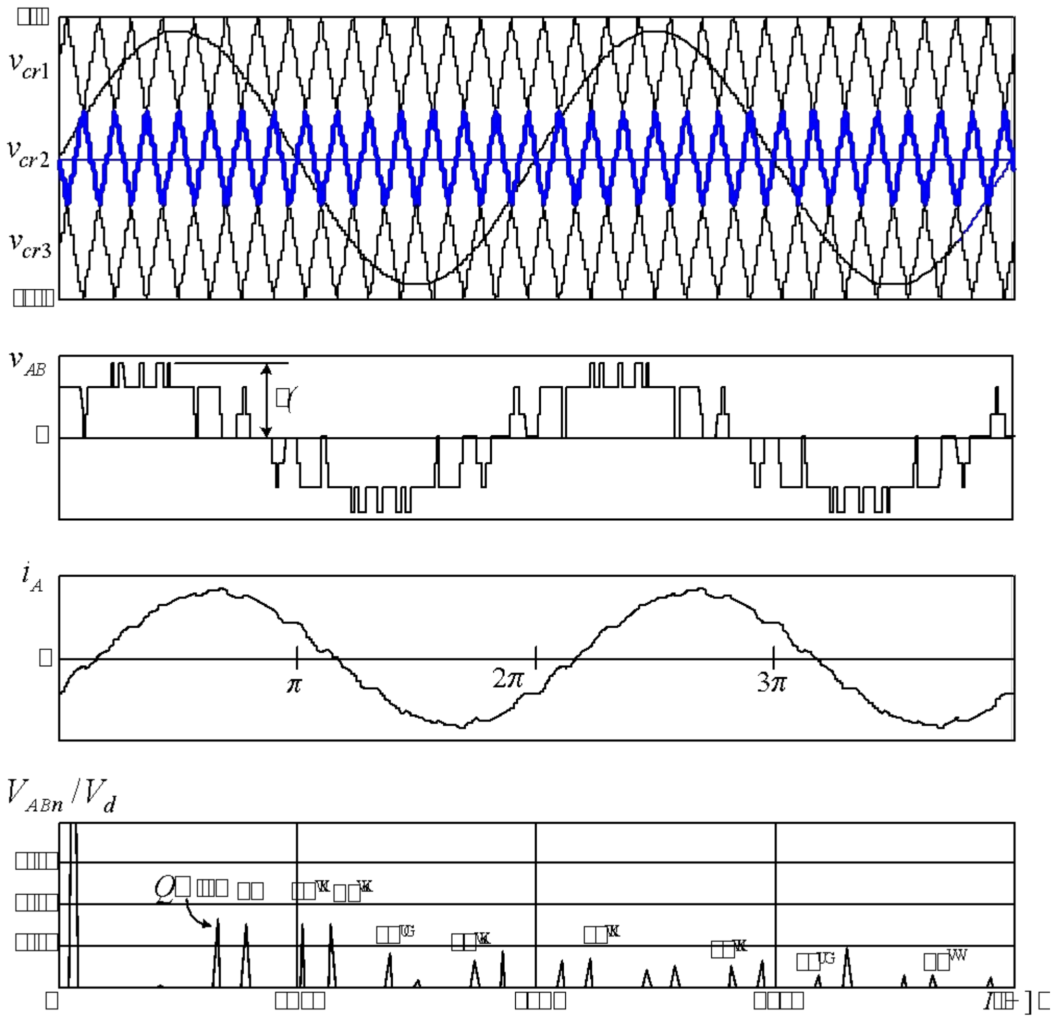
High-Level NPC Inverters

- **Harmonic Content** (four-level, IPD Modulation)



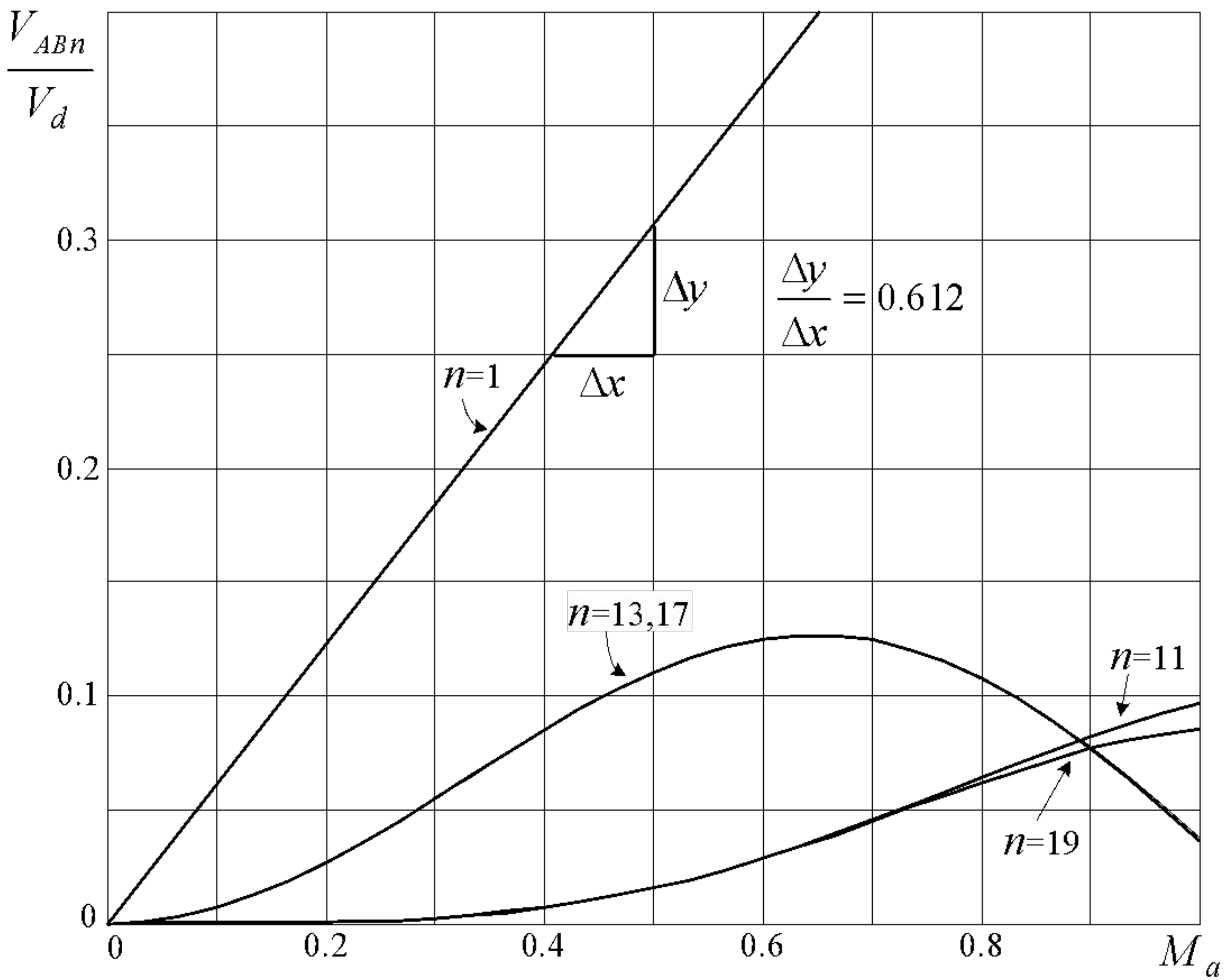
High-Level NPC Inverters

- **APOD Modulation** (four-level)



High-Level NPC Inverters

- **Harmonic Content** (four-level, APOD Modulation)



Summary

- The 3-level NPC inverter widely used in MV drives

  Main features

  - Low device count

  - No switches in series

  - Suitable for medium voltage operation

- The practical use of 4- or 5-level NPC inverters not reported

  Main reasons

  - Difficulties in dc capacitor voltage control

  - Large number of clamping diodes

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Thanks