

Power Converter Systems

Graduate Course EE8407

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Ryerson Campus

Topic 7

Multilevel Neutral Point Clamped (NPC) Inverters



Three-Level NPC Inverter Based MV Drive

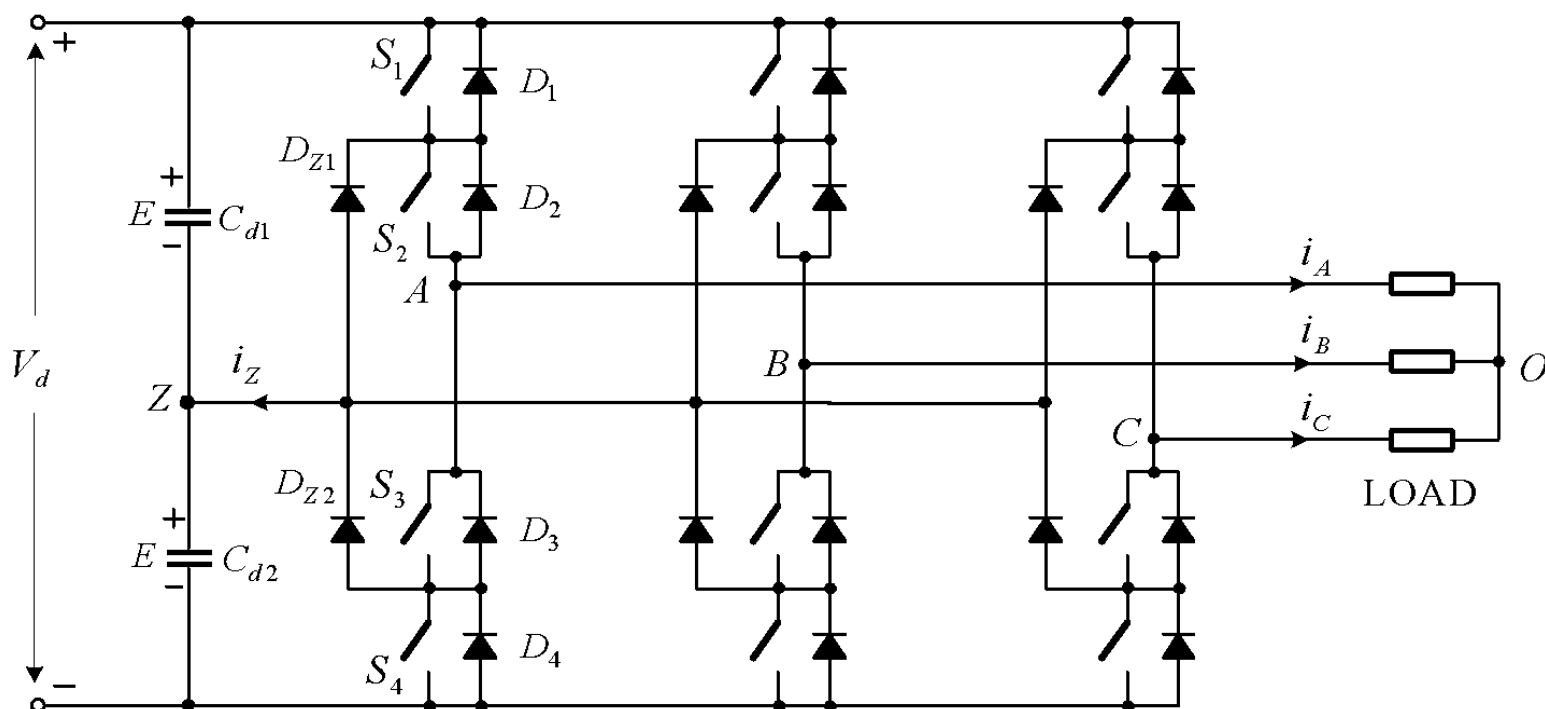
Multilevel NPC Inverters

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

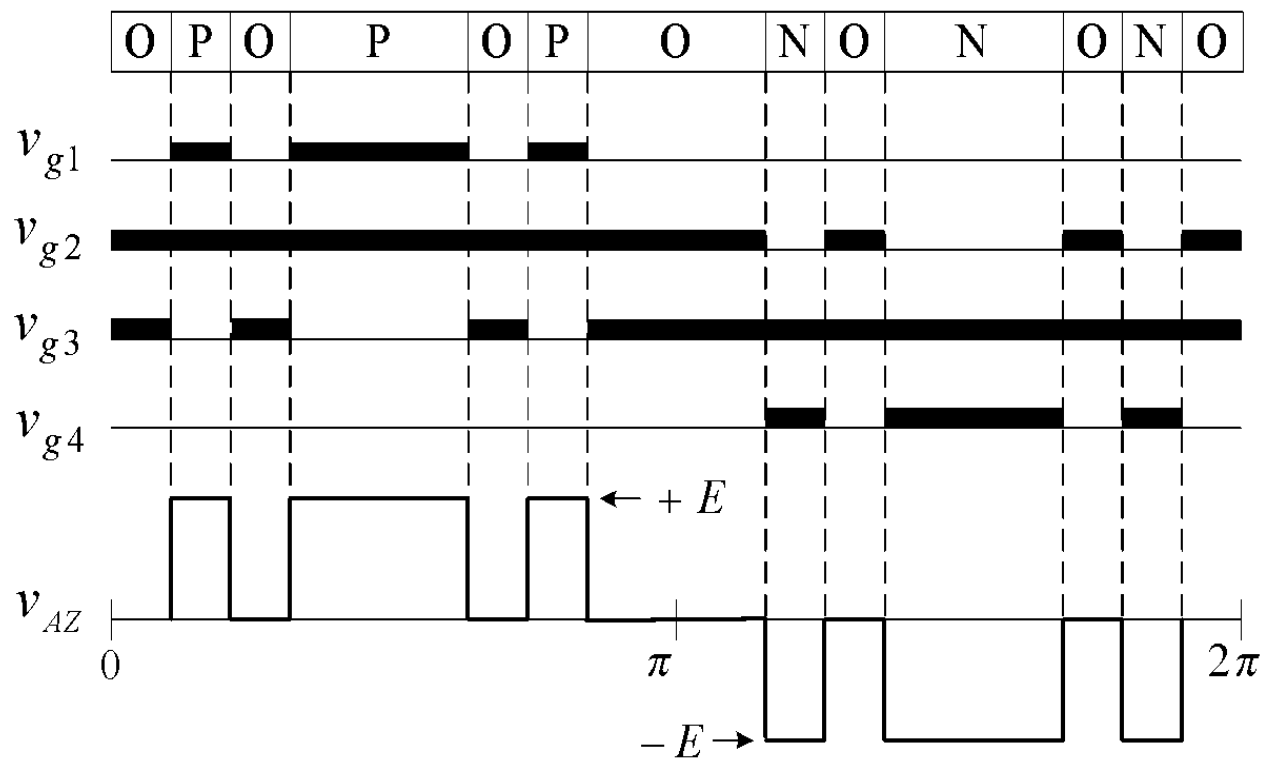
Switching State	Device Switching Status (Phase A)				Inverter Terminal Voltage V_{AZ}
	S_1	S_2	S_3	S_4	
P	On	On	Off	Off	E
O	Off	On	On	Off	0
N	Off	Off	On	On	$-E$

Complementary Switch pairs:

S_1 and S_3 ; S_2 and S_4 ;

Three-Level NPC Inverters

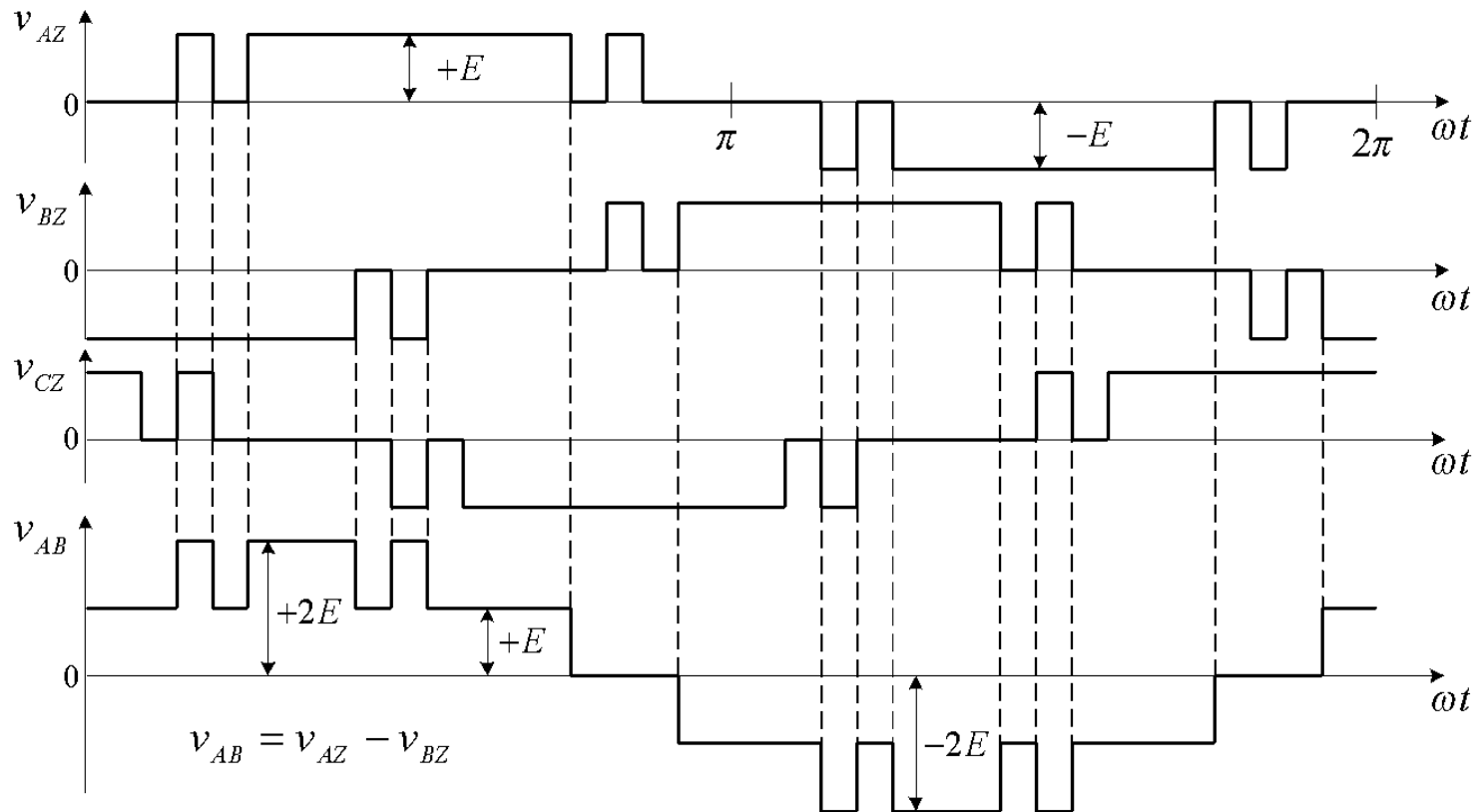
• Gate Signal Arrangements



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**

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

- **Two-phase voltages**

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

- **Space vector representation**

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

(2) → (3)

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

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

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

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

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

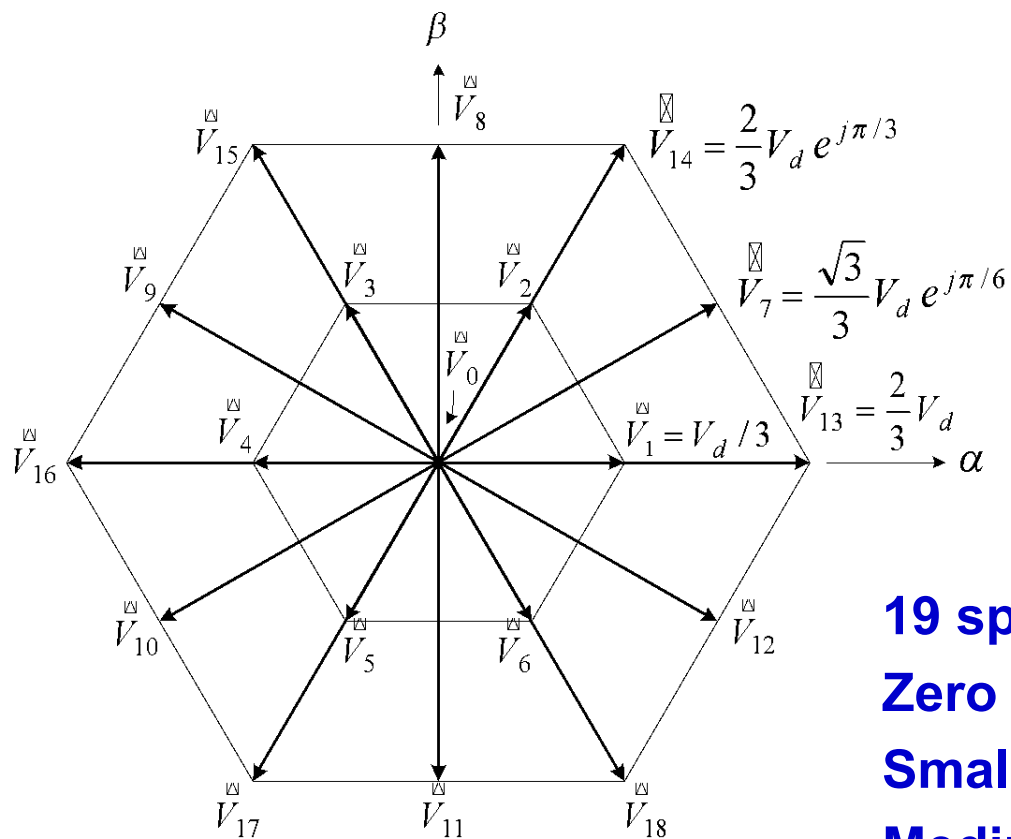
$$\vec{V}_1 = \frac{1}{3}V_d e^{j0} \quad (6)$$

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
V_0	[PPP][OOO] [NNN]	Zero Vector (ZV)	0
V_1	V_{1P} [POO]	Small Vector (SV) P-type Small Vector (PSV) N-type Small Vector (NSV)	$\frac{1}{3}V_d$
	V_{1N} [ONN]		
V_2	V_{2P} [PPO]		
	V_{2N} [OON]		
V_3	V_{3P} [OPO]		
	V_{3N} [NON]		
V_4	V_{4P} [OPP]		
	V_{4N} [NOO]		
V_5	V_{5P} [OOP]		
	V_{5N} [NNO]		
V_6	V_{6P} [POP]		
	V_{6N} [ONO]		

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

Space Vector Modulation

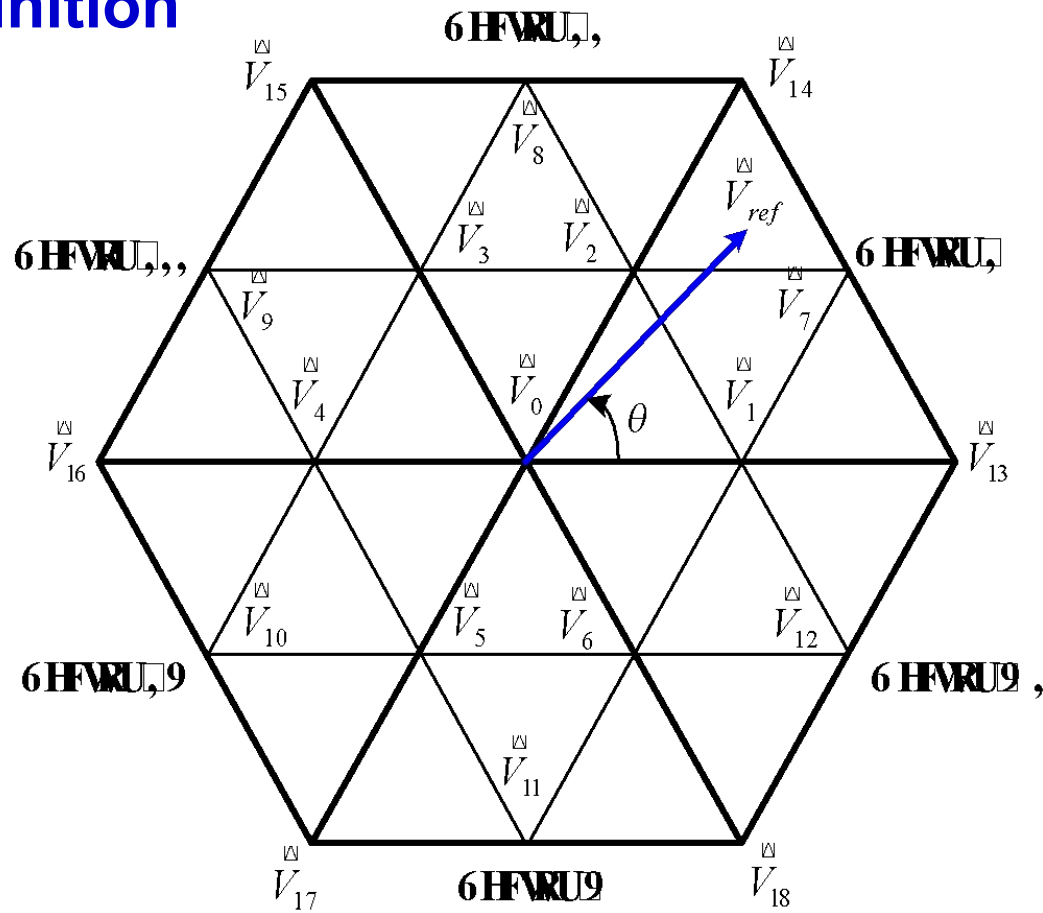
• Switching States and Space Vectors

Space Vector	Switching State	Vector Classification	Vector Magnitude
V_7	[PON]	Medium Vector (MV)	$\frac{\sqrt{3}}{3}V_d$
V_8	[OPN]		
V_9	[NPO]		
V_{10}	[NOP]		
V_{11}	[ONP]		
V_{12}	[PNO]		
V_{13}	[PNN]	Large Vector (LV)	$\frac{2}{3}V_d$
V_{14}	[PPN]		
V_{15}	[NPN]		
V_{16}	[NPP]		
V_{17}	[NNP]		
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

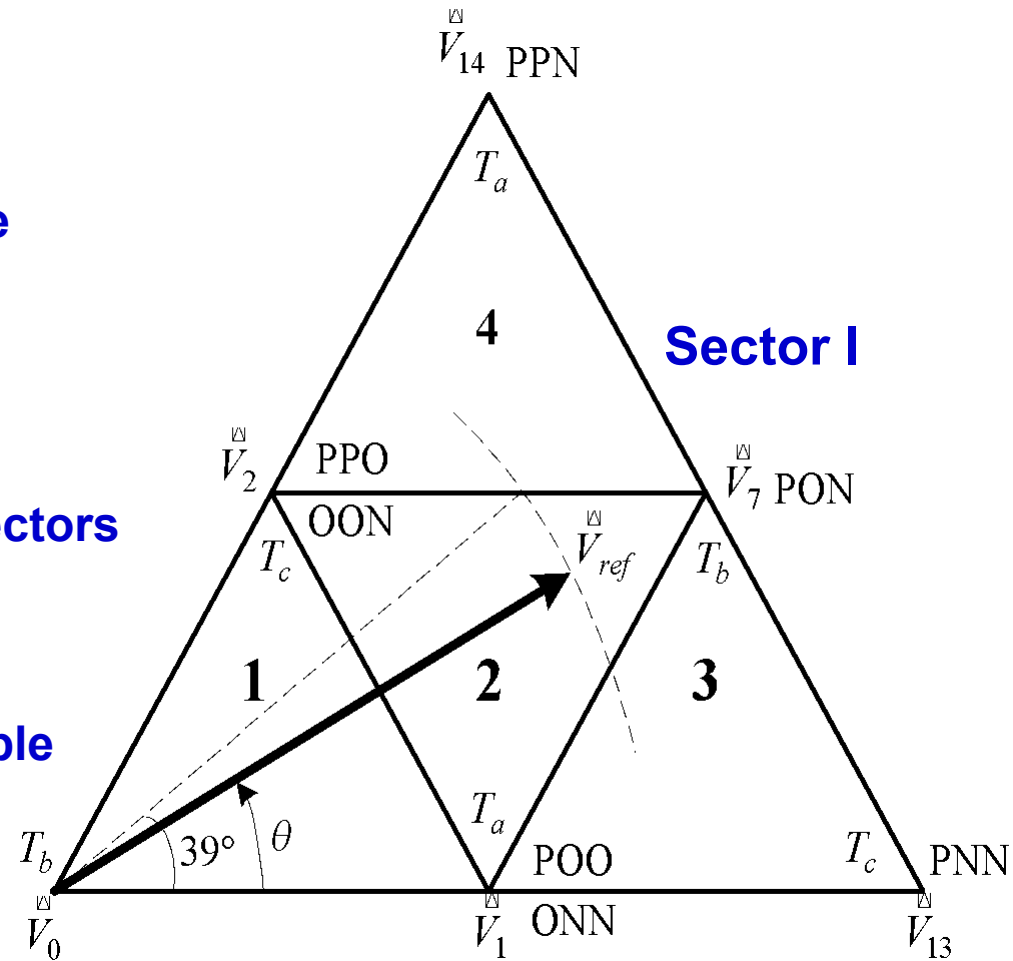
Dwell time is the duty-cycle time of selected switches during the sampling period T_s .

- Select three nearest stationary vectors

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

- Use volt-second balancing principle

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



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

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

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

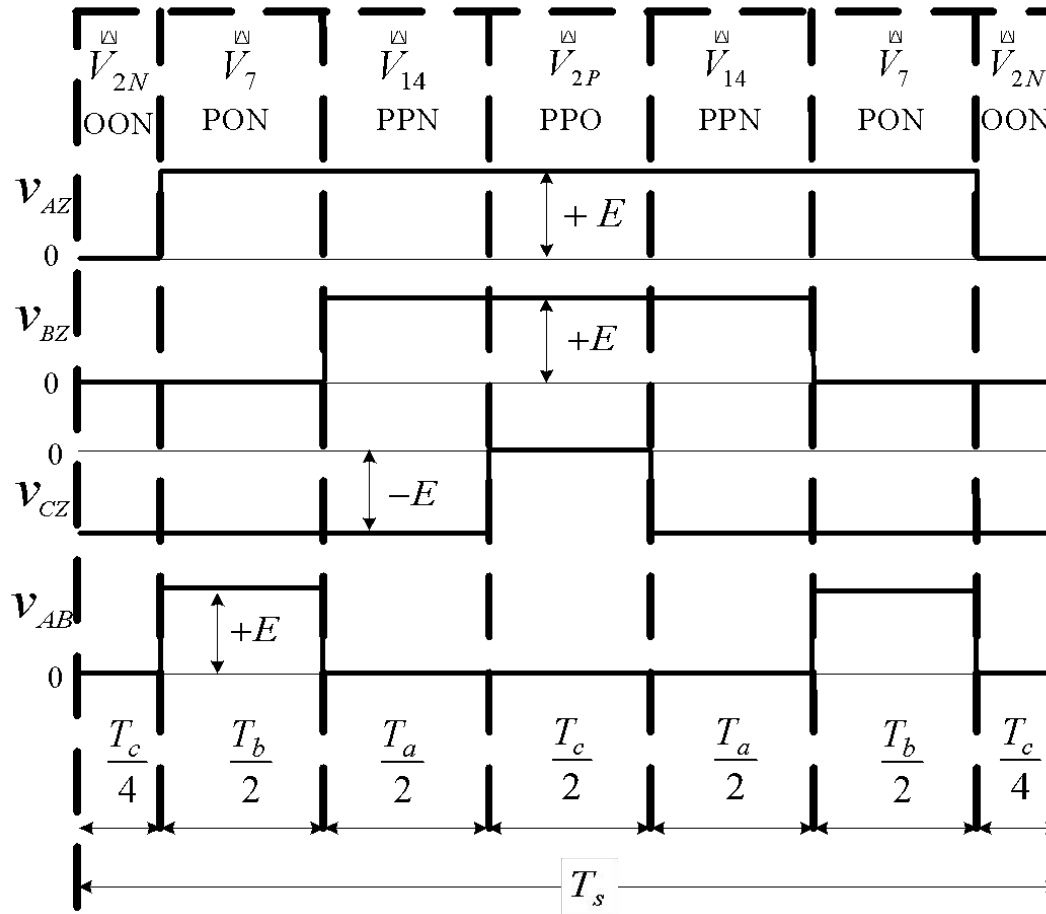
- Switching Sequence (Seven-segment)

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

Voltage Vector		V_{2N}	V_7	V_{14}	V_{2P}	V_{14}	V_7	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
$[P] = E, [O] = 0, [N] = -E.$								

Space Vector Modulation

- Switching Sequence (Seven-segment)



Switching sequence requirement a) is satisfied.

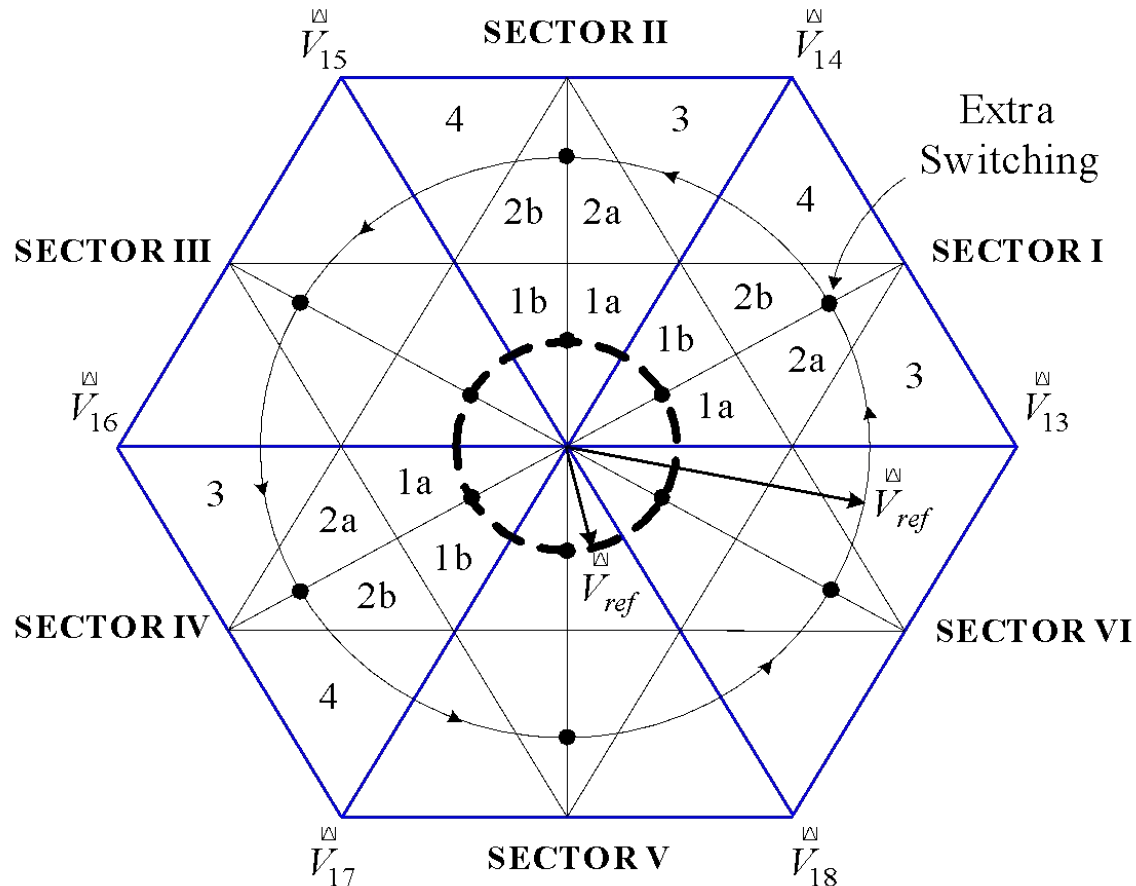
Space Vector Modulation

- 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:

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

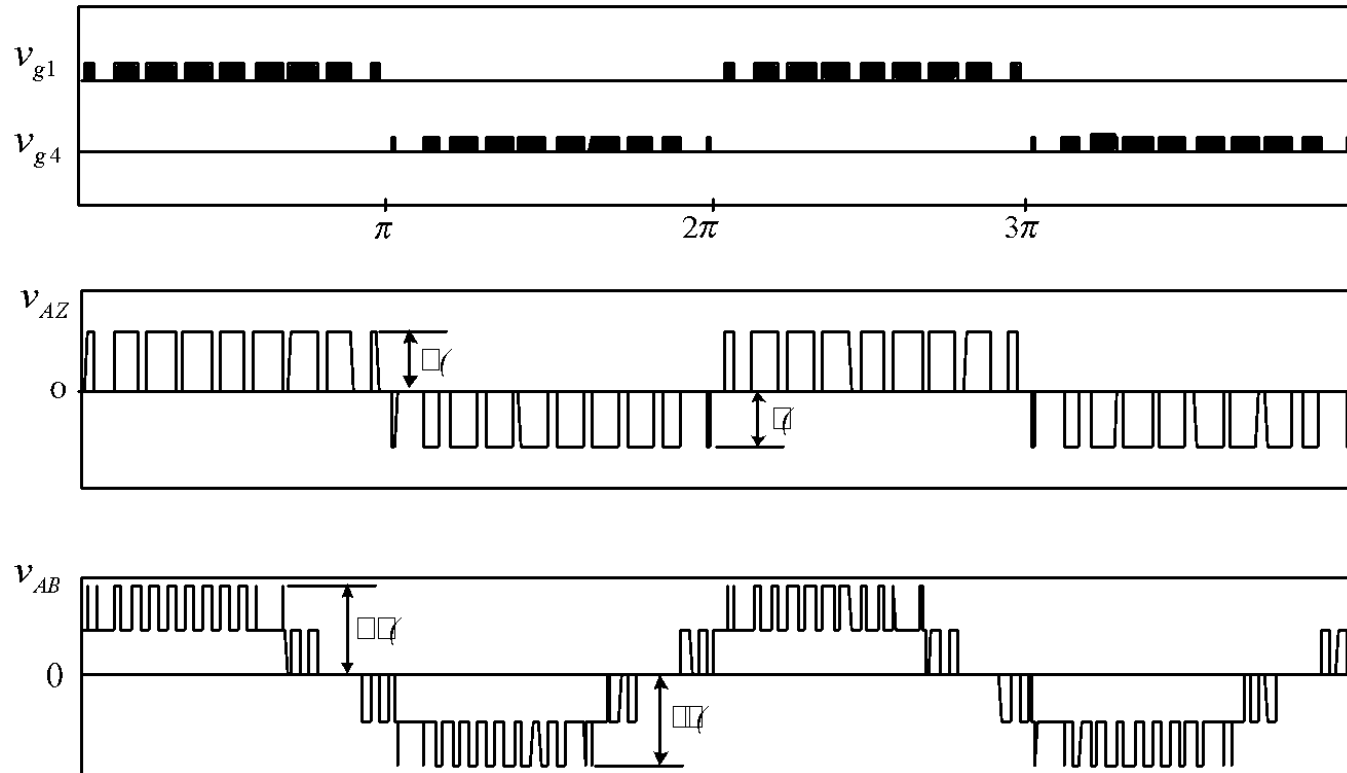
Fundamental frequency:

$$f_1$$

Switching sequence requirement b) is satisfied.

Space Vector Modulation

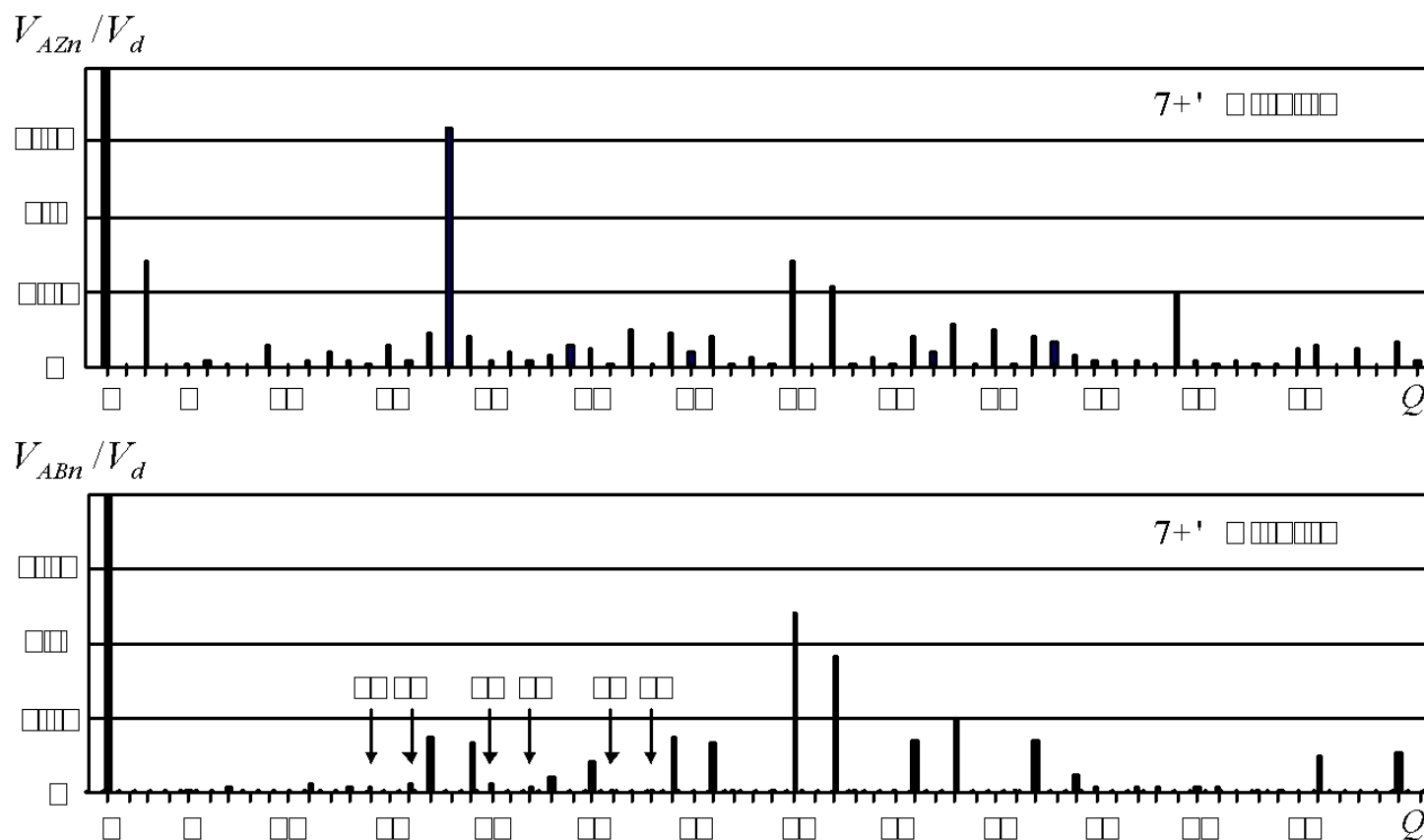
- Simulated Waveforms (Seven-segment)



$f_1 = 60\text{Hz}$, $T_s = 1/1080 \text{ sec}$, $m_a = 0.8$, $f_{sw} = 570\text{Hz}$
 v_{AB} is not half wave symmetrical; and
 contains both even- and odd-order harmonics.

Space Vector Modulation

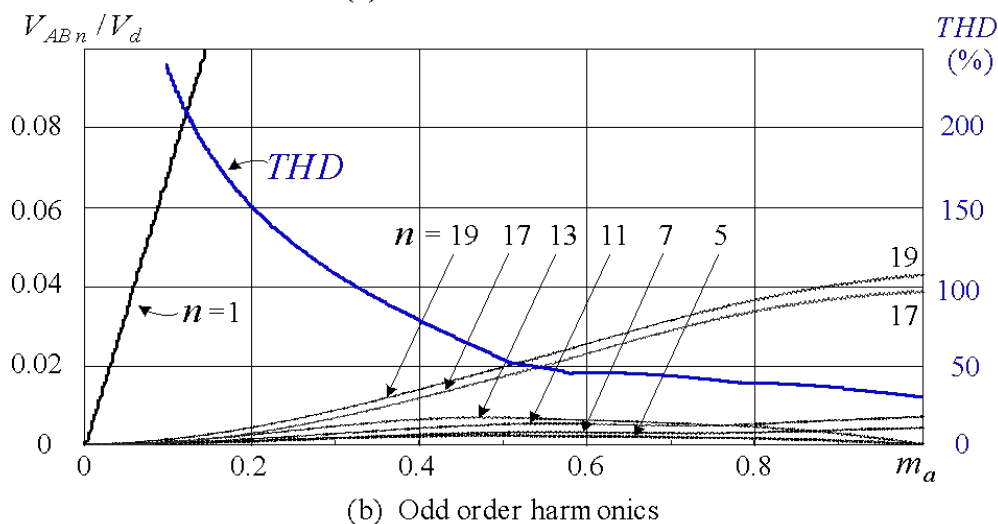
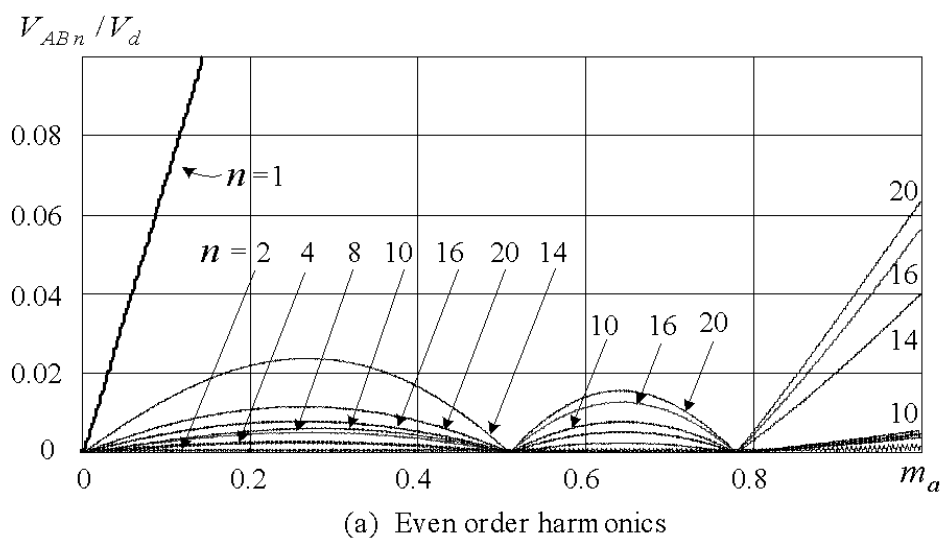
- Simulated Waveforms (Seven-segment)



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

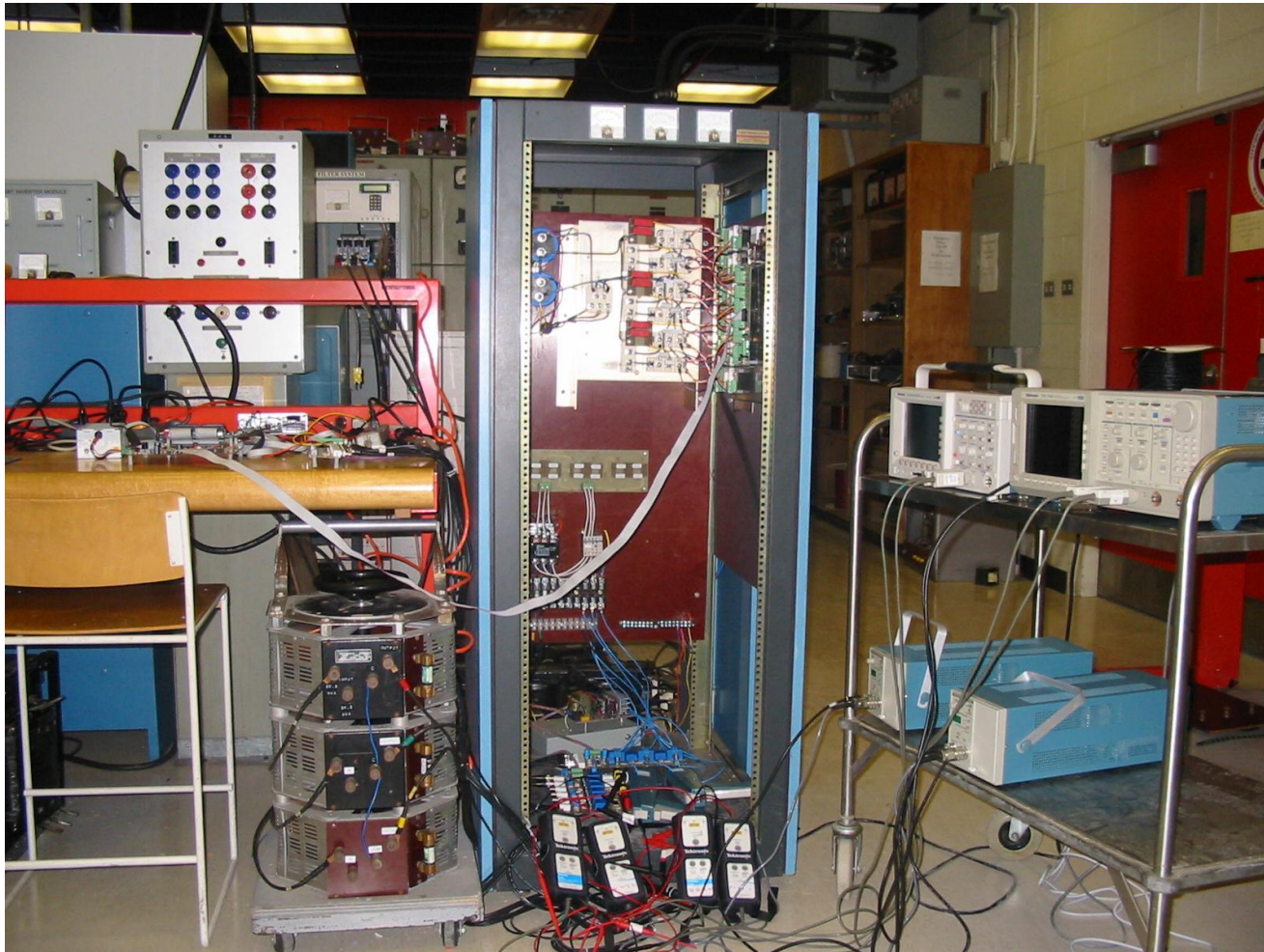
Space Vector Modulation

• Harmonic Content (Seven-segment)



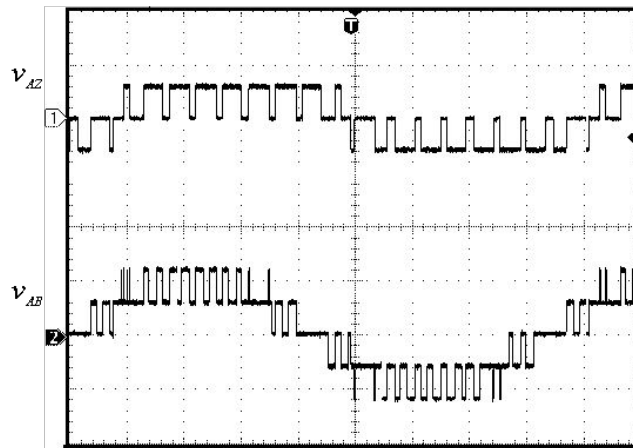
Space Vector Modulation

- Laboratory Prototype at Ryerson

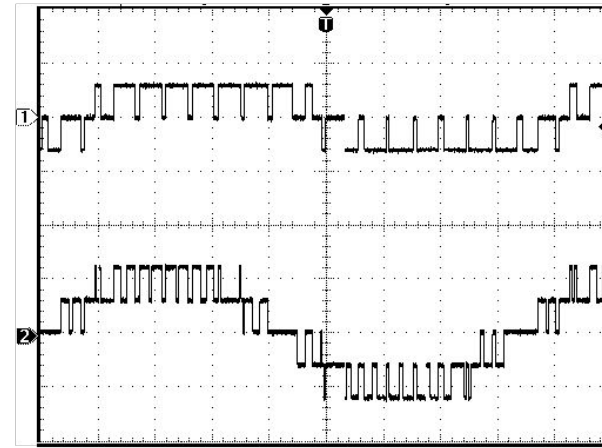


Space Vector Modulation

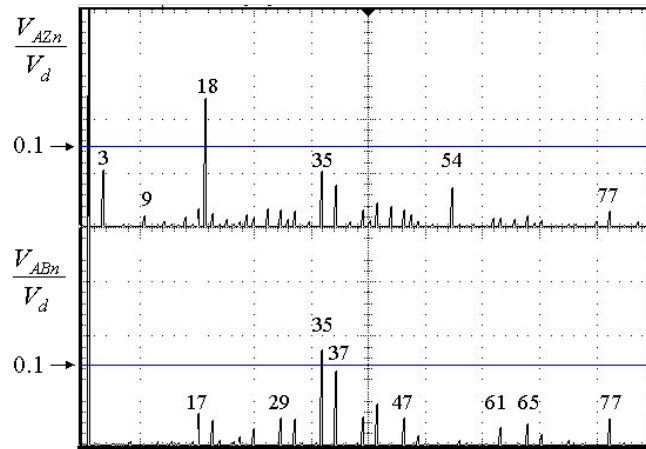
• Measured Waveforms



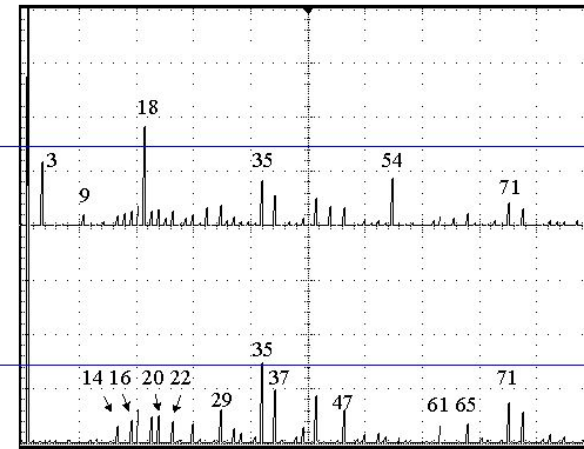
Waveforms (2ms/div)



Waveforms (2ms/div)



Spectrums (500Hz/div)

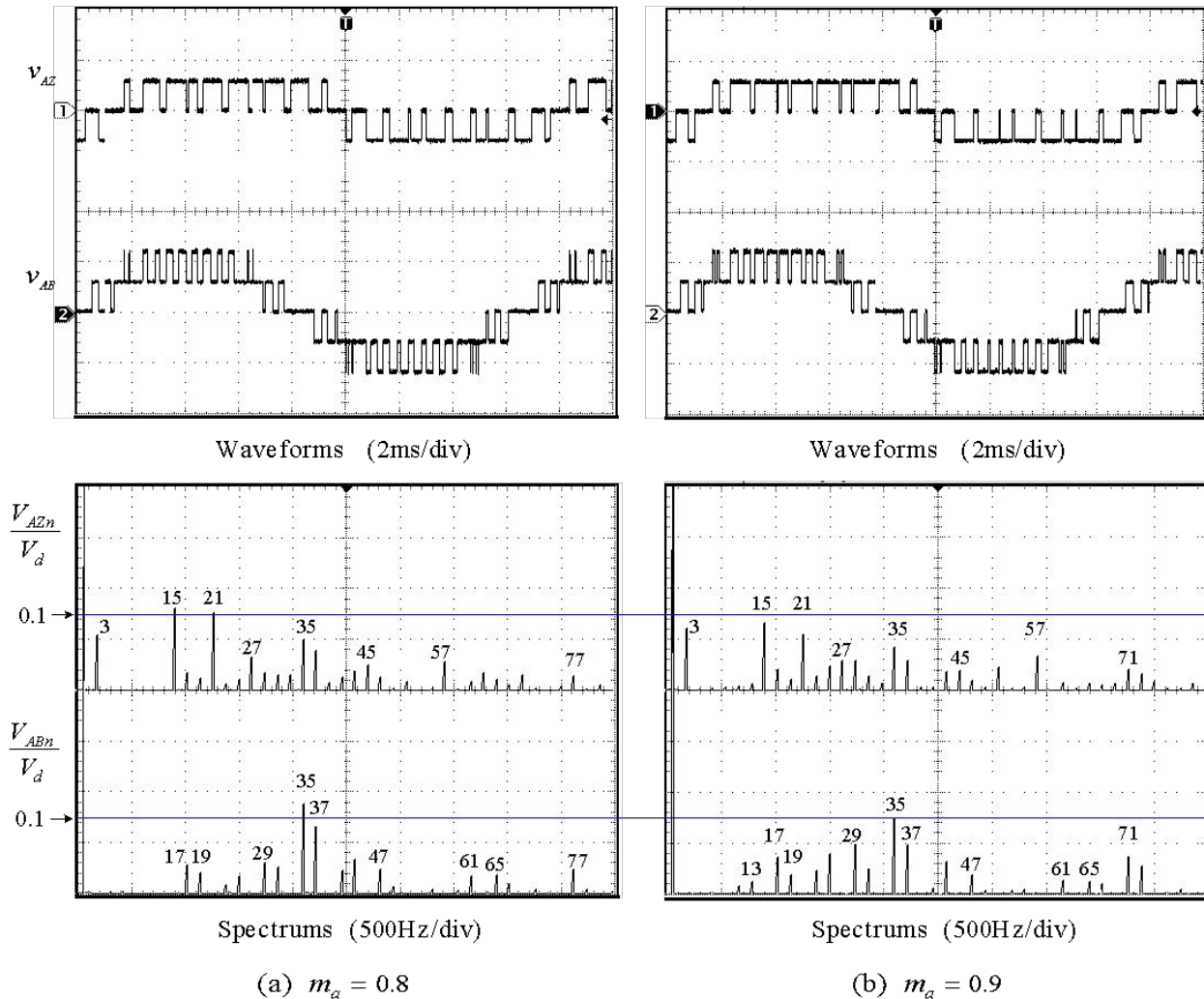
(a) $m_a = 0.8$ 

Spectrums (500Hz/div)

(b) $m_a = 0.9$

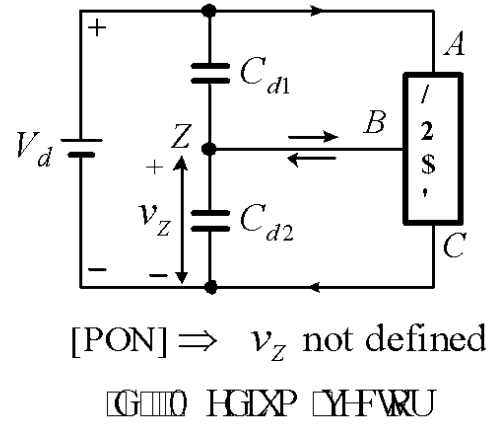
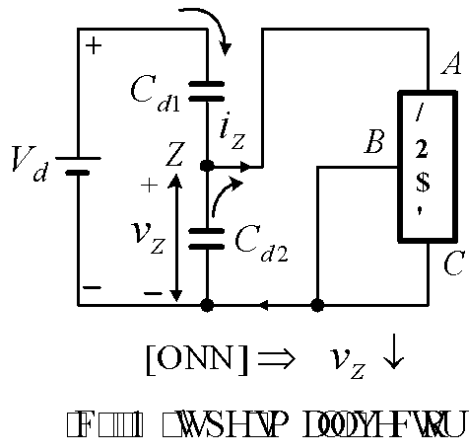
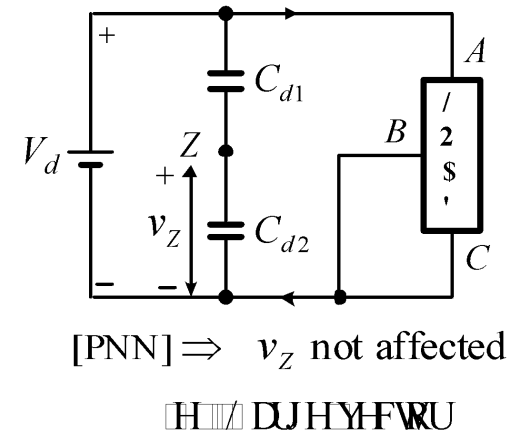
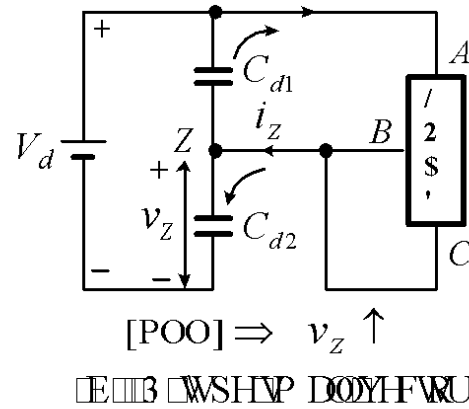
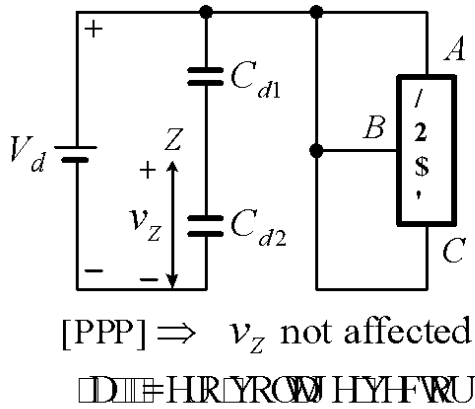
Space Vector Modulation

- 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

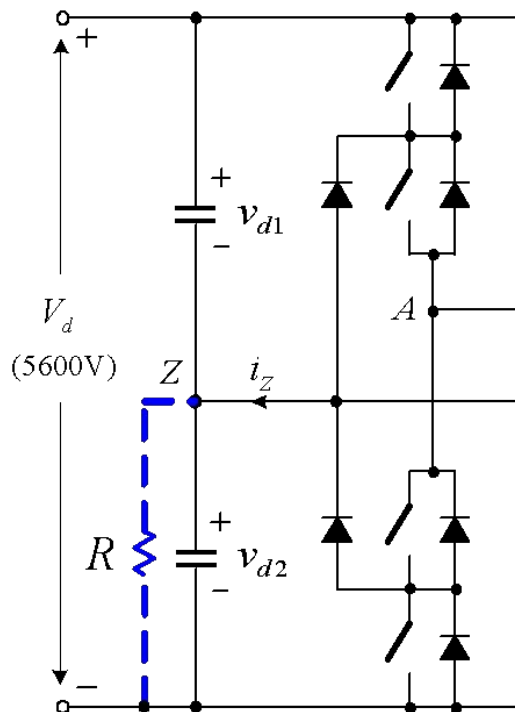
$$T_a = T_{aP} + T_{aN}$$

$$\begin{cases} T_{aP} = \frac{T_a}{2} (1 + \Delta t) \\ T_{aN} = \frac{T_a}{2} (1 - \Delta t) \end{cases} \quad -1 \leq \Delta T \leq 1$$

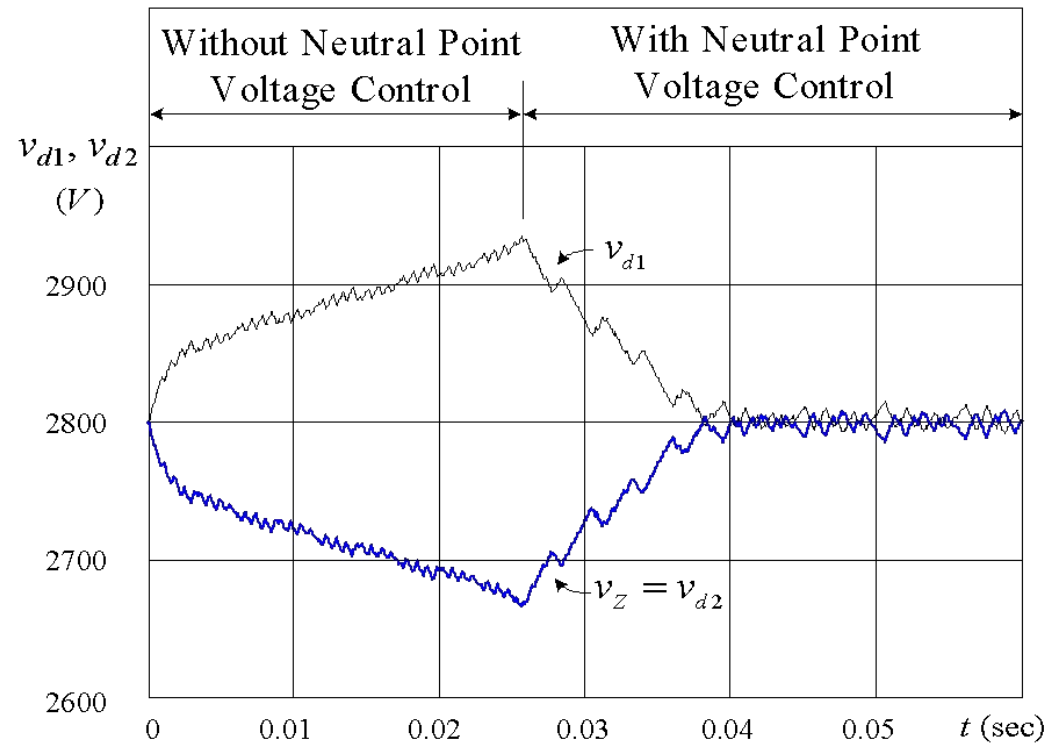
Neutral Point Deviation Level	Motoring Mode $i_d > 0$	Regenerating Mode $i_d < 0$
$(v_{d1} - v_{d2}) > \Delta V_d$	$\Delta t > 0$	$\Delta t < 0$
$(v_{d2} - v_{d1}) > \Delta V_d$	$\Delta t < 0$	$\Delta t > 0$
$ v_{d1} - v_{d2} < \Delta V_d$	$\Delta t = 0$	$\Delta t = 0$
ΔV – maximum allowed voltage deviation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

Neutral Point Voltage Control

• Neutral Point Voltage Control



(a)

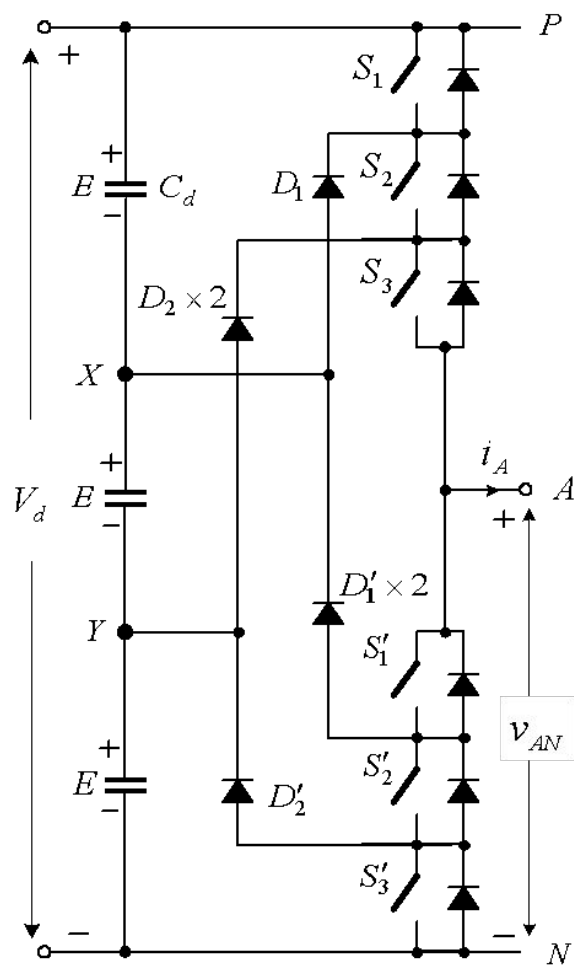


(b)

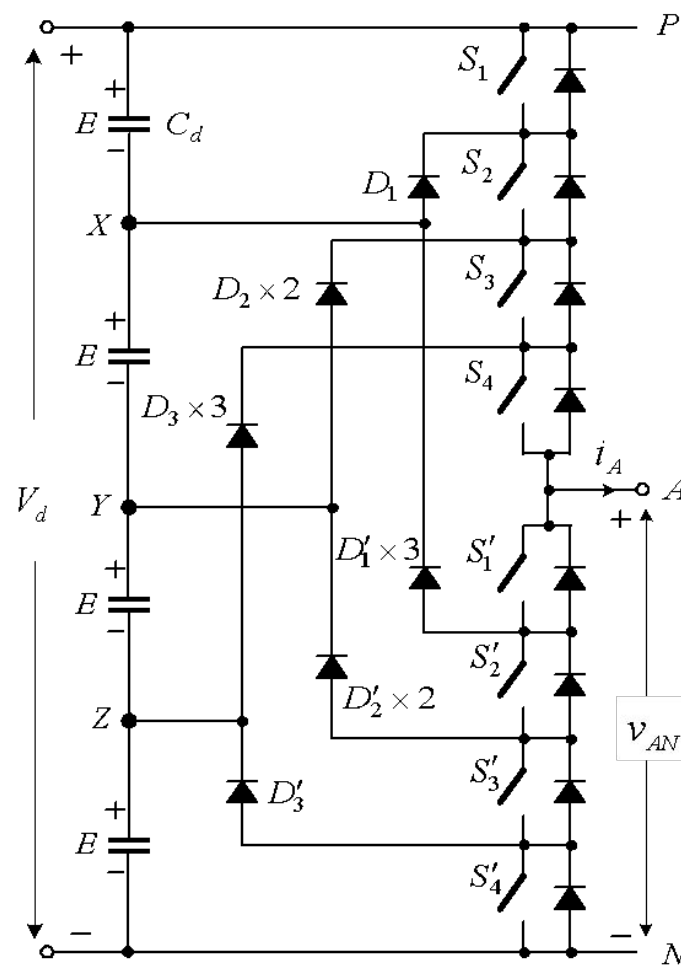
R is used on purpose to make the dc voltage unbalance.

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	3E		
0	1	1	1	0	0	2E		
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	4E
0	1	1	1	1	0	0	0	3E
0	0	1	1	1	1	0	0	2E
0	0	0	1	1	1	1	0	E
0	0	0	0	1	1	1	1	0

High-Level NPC Inverters

• Component Count

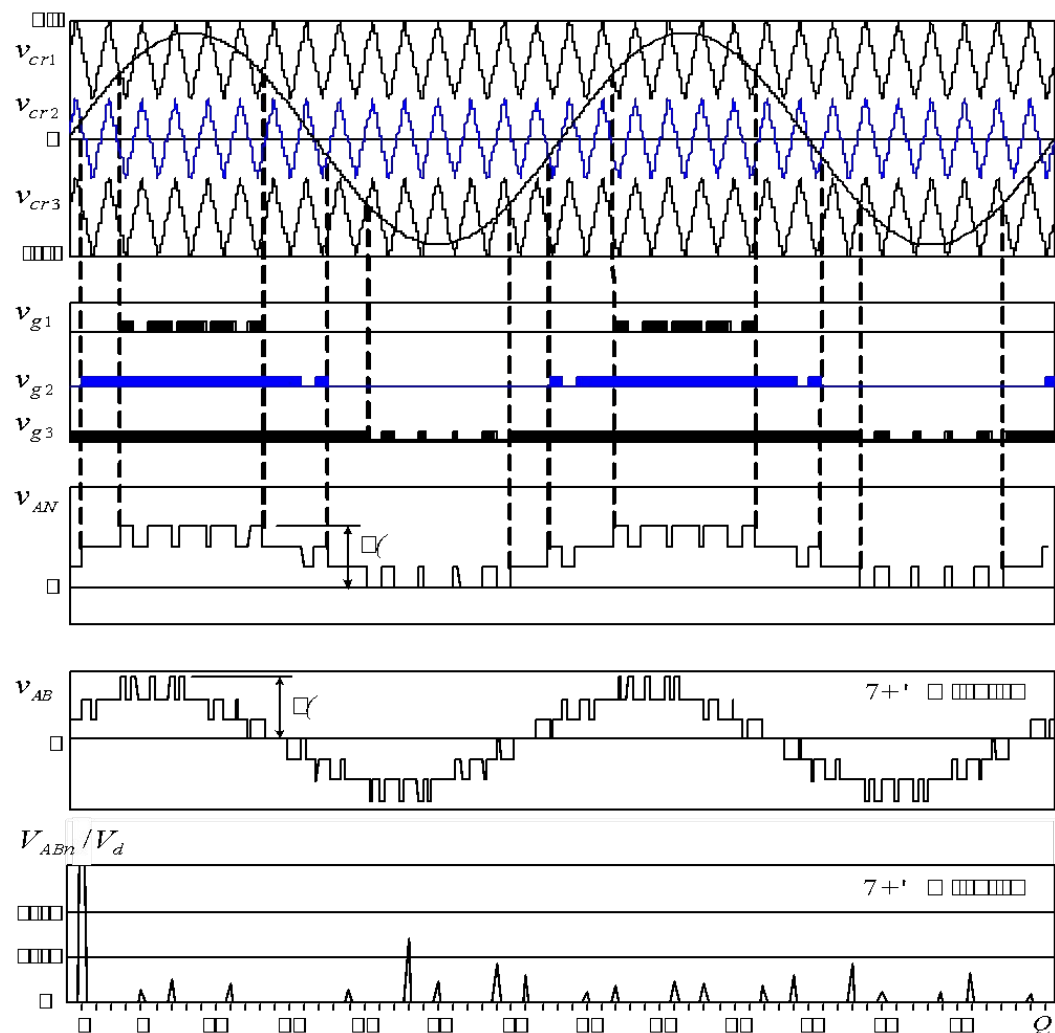
Voltage Level	Switches	Clamping Diodes*	dc capacitors
m	$6(m-1)$	$3(m-1)(m-2)$	$(m-1)$
3	12	6	2
4	18	18	3
5	24	36	4
6	30	60	5
* The clamping diodes have the same voltage rating as other switches.			

Note:

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

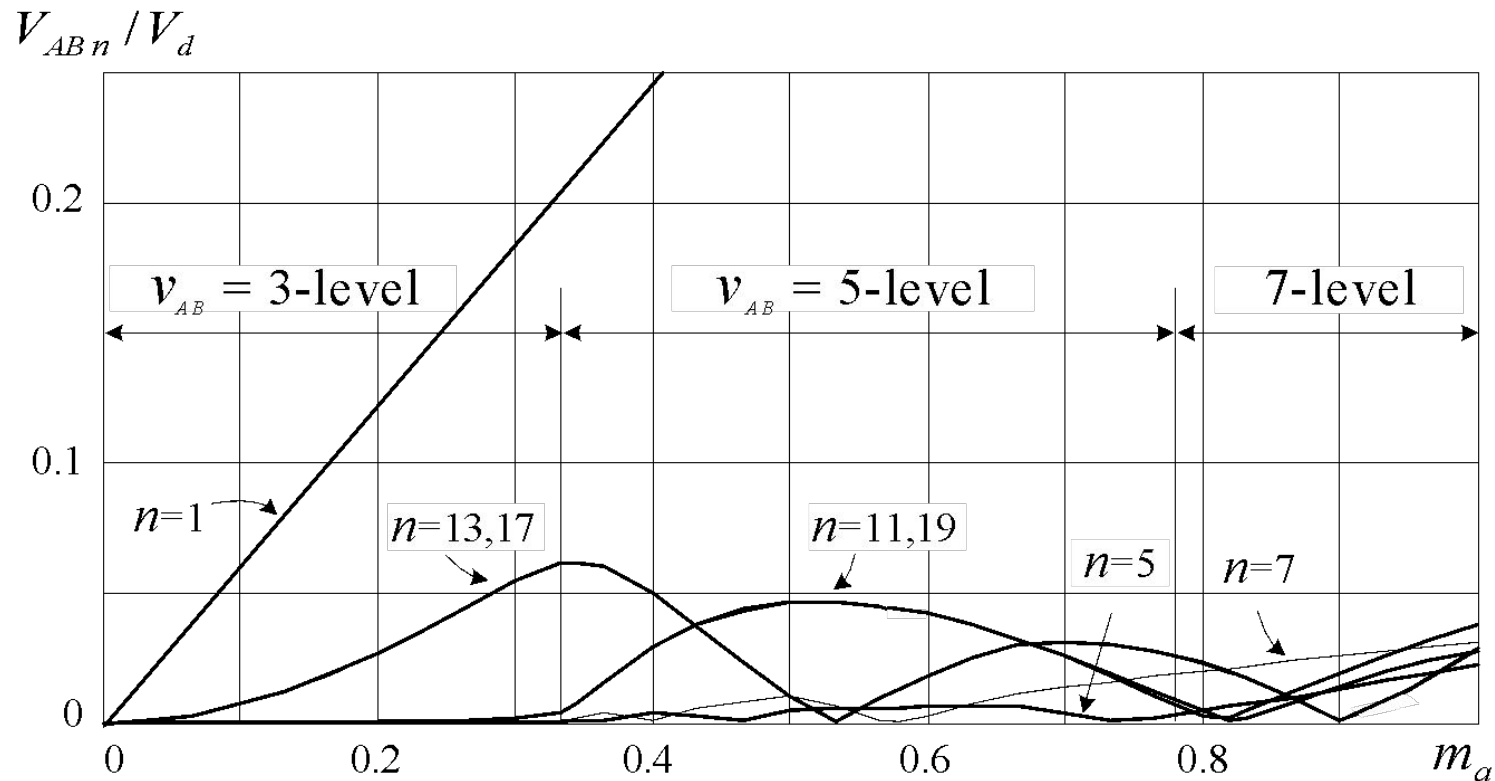
High-Level NPC Inverters

- IPD Modulation (four-level)



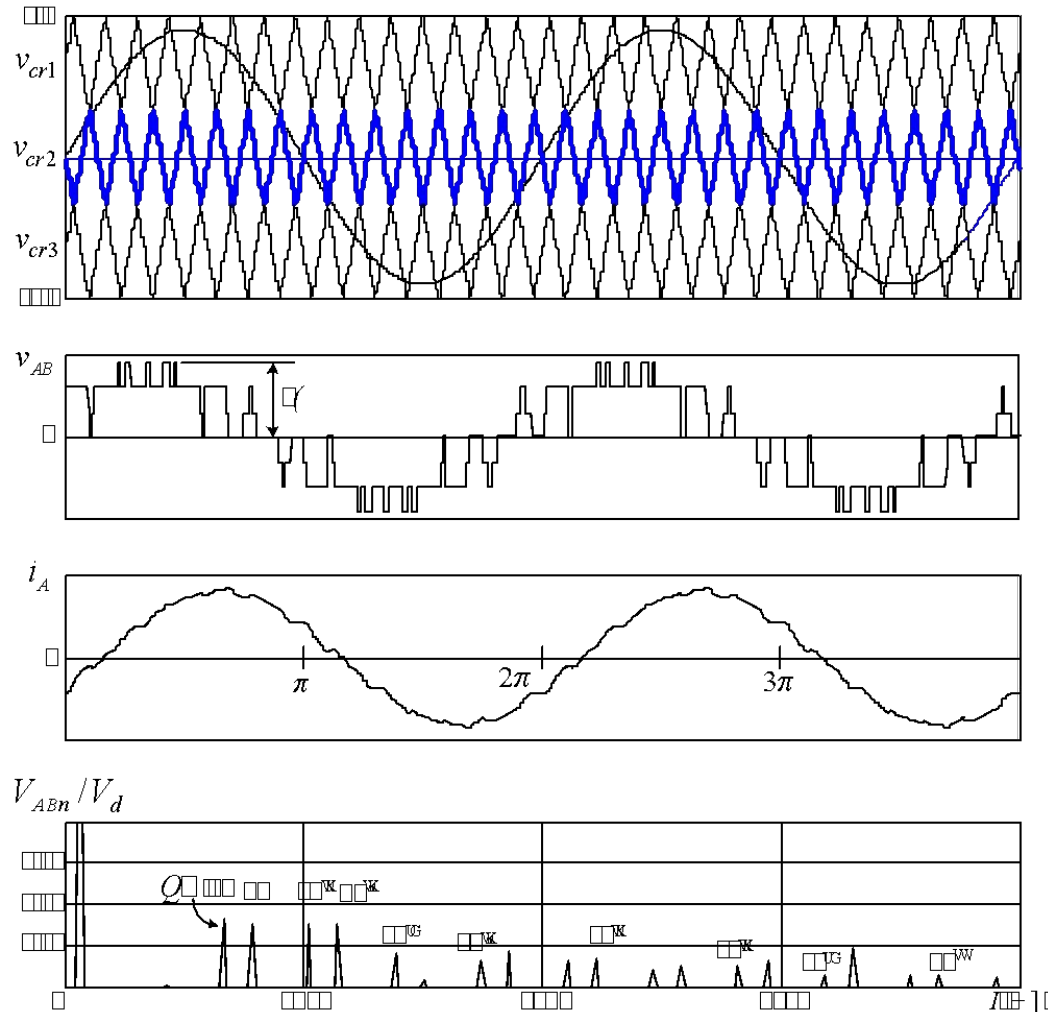
High-Level NPC Inverters

- Harmonic Content (four-level, IPD Modulation)



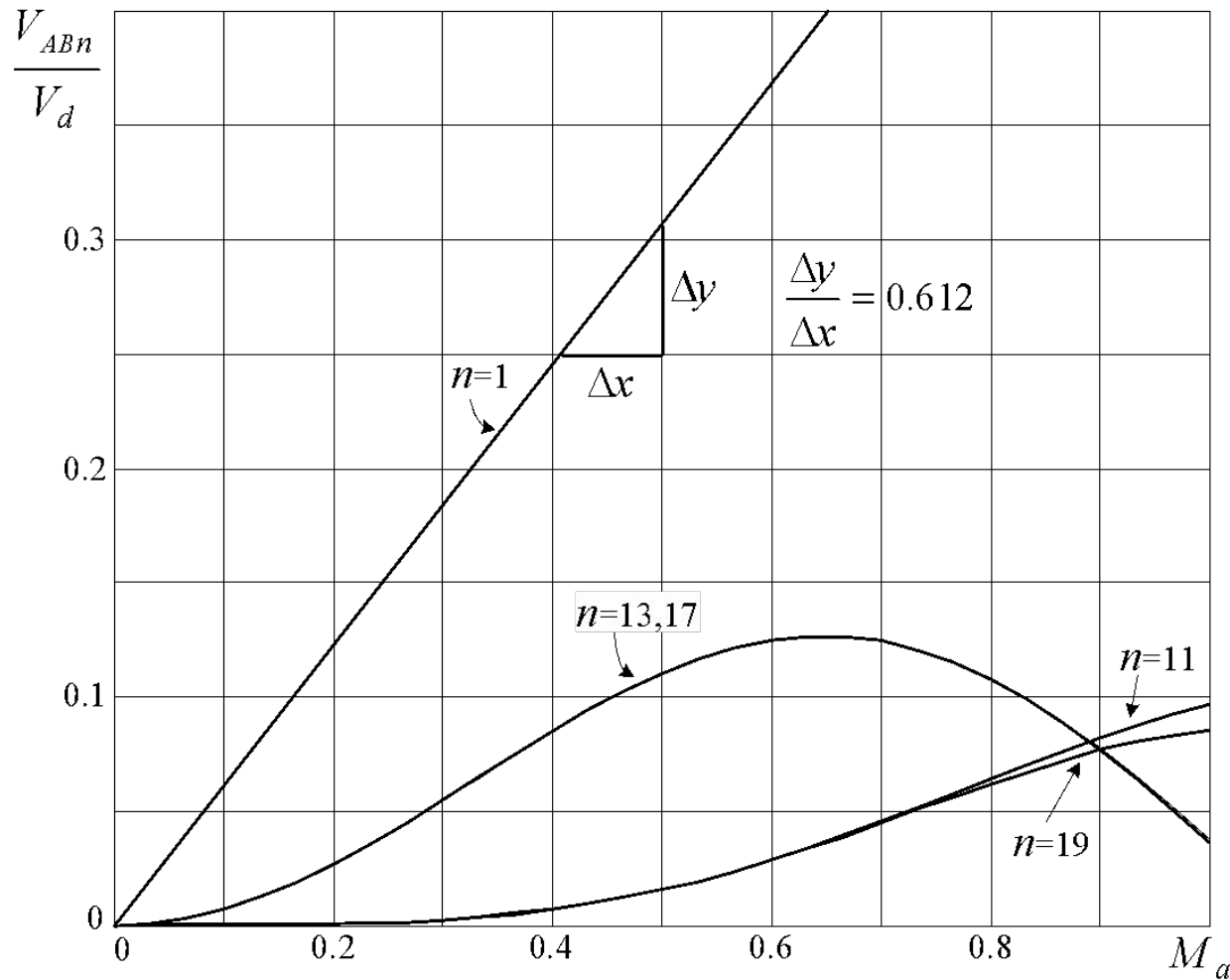
High-Level NPC Inverters

- 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



Thanks