

# Power Converter Systems

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## Graduate Course EE8407

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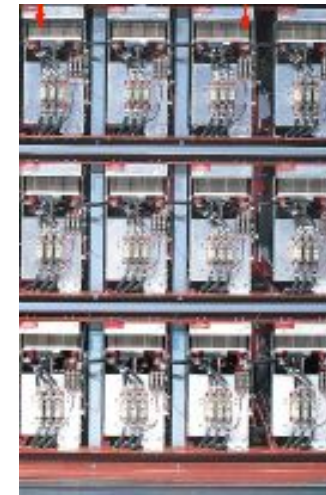
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**Ryerson Campus**

# Topic 6

## Multilevel Cascaded H-Bridge (CHB) Inverters



H-bridge power cells

**CHB Inverter Fed Drive**    **Source: Toshiba - General Electric**

# Multilevel CHB Inverters

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## Lecture Topics

- H-Bridge Inverter
- CHB Inverter Topologies
- Phase Shifted PWM
- Level Shifted PWM
- PWM Scheme Comparison

# Multilevel CHB Inverters

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## Why Use Multilevel Inverters?

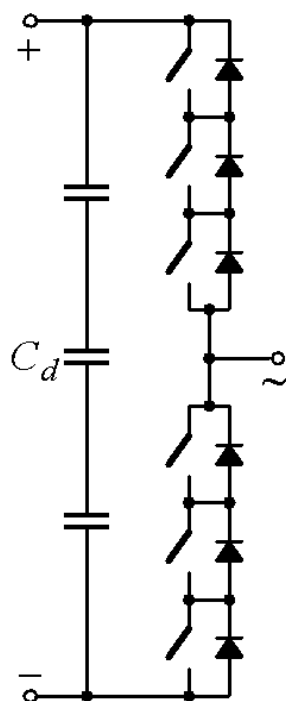
- To increase inverter operating voltage without devices in series
- To minimize THD with low switching frequencies  $f_{sw}$
- To reduce EMI due to lower voltage steps

Switching frequency for high power converters:

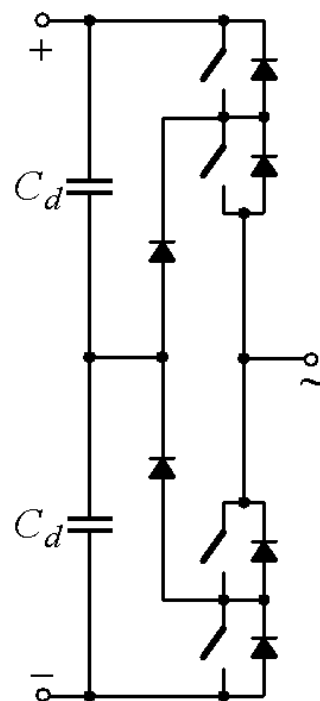
$$f_{sw} = 60\text{Hz} \sim 1000\text{Hz}$$

# Multilevel Inverter Topologies

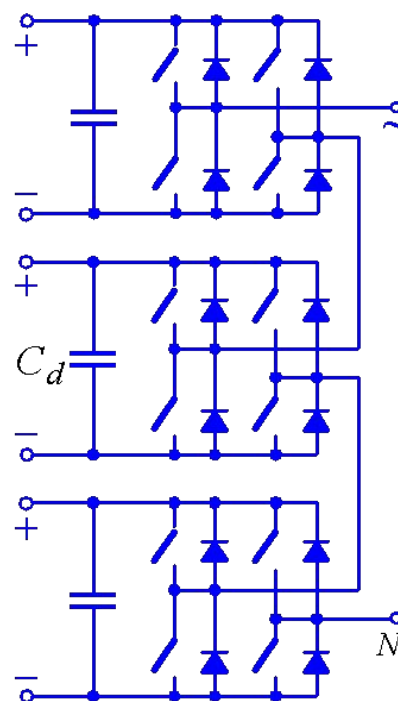
## • Per-Phase Diagram



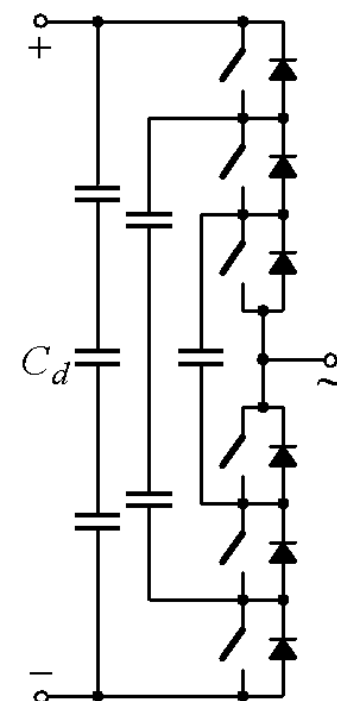
Two Level  
Inverter



Neutral Point  
Clamped (NPC)  
Inverter



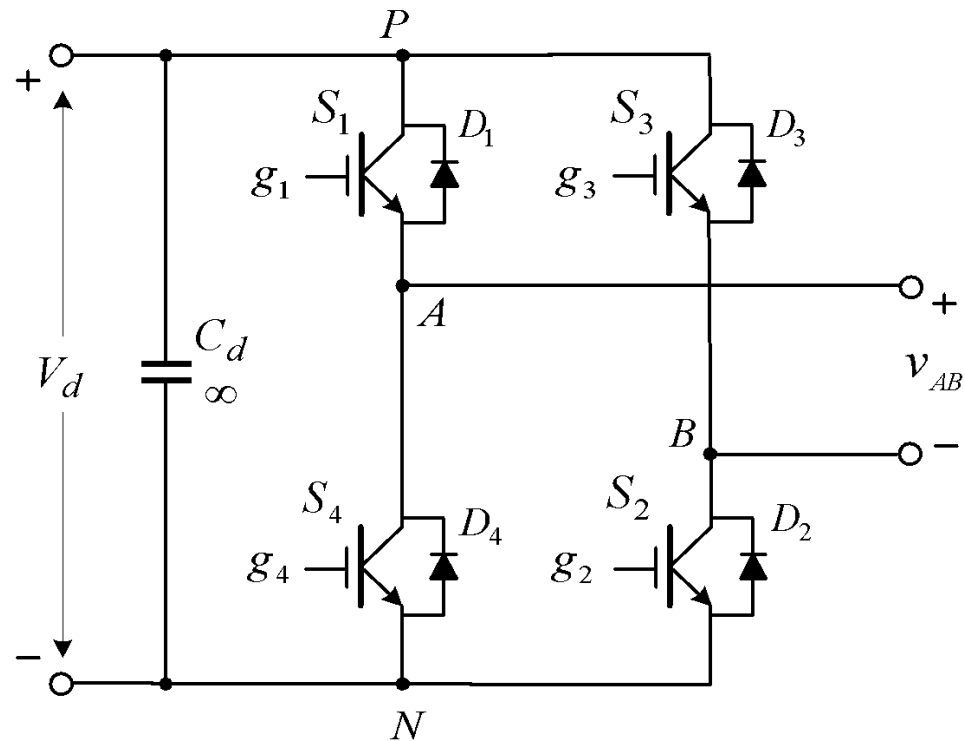
Cascaded  
H-bridge (CHB)  
Inverter



Flying Capacitor  
Inverter

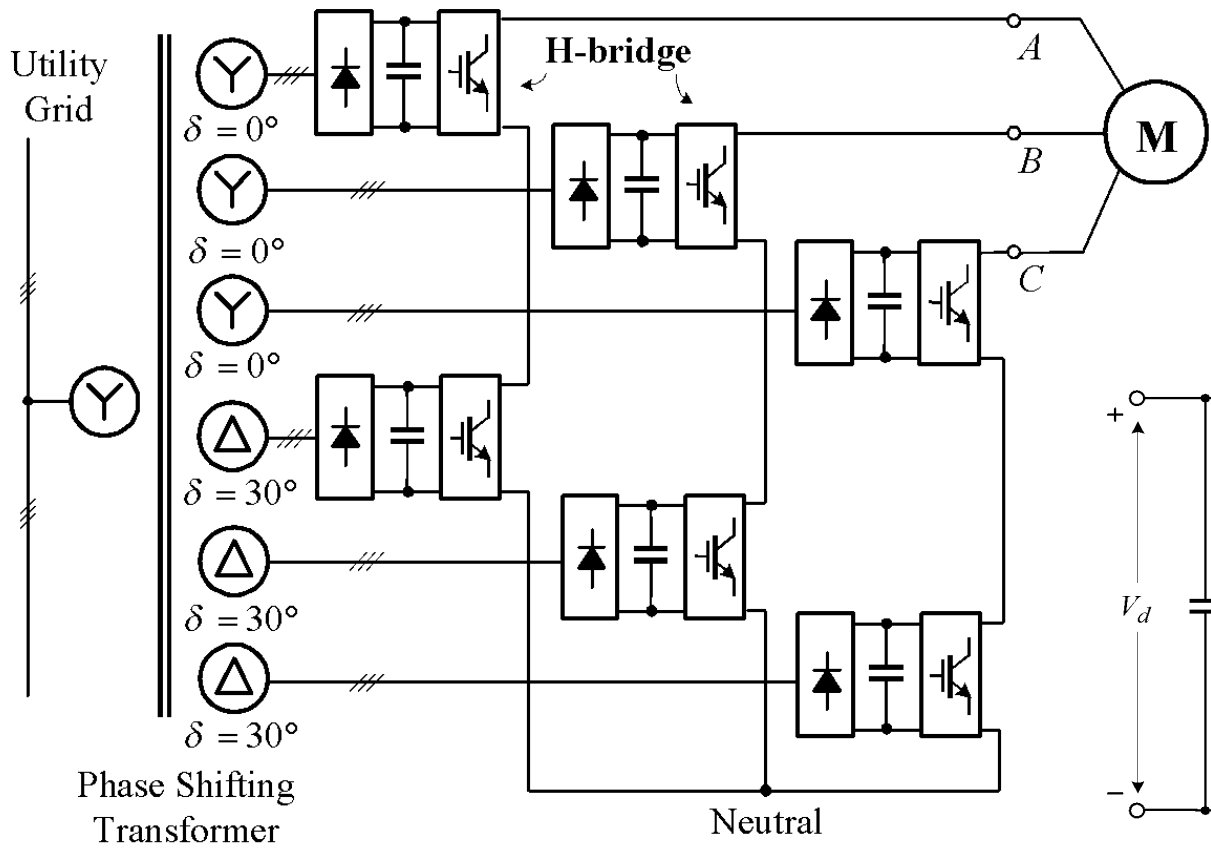
# H-Bridge Inverter

- H-bridge Power Cell

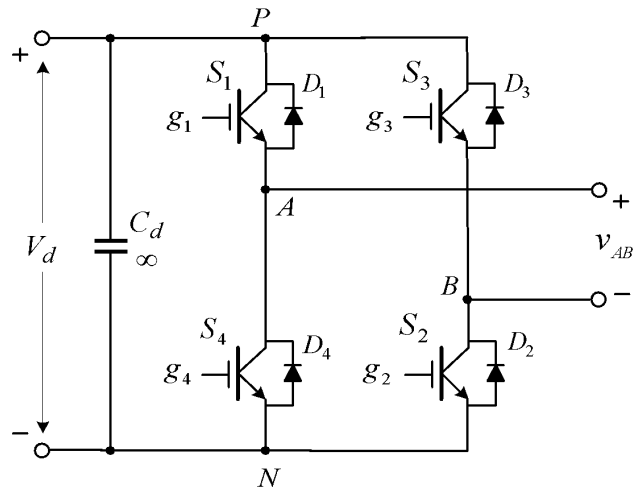


# H-Bridge Inverter

- Typical Industrial Applications



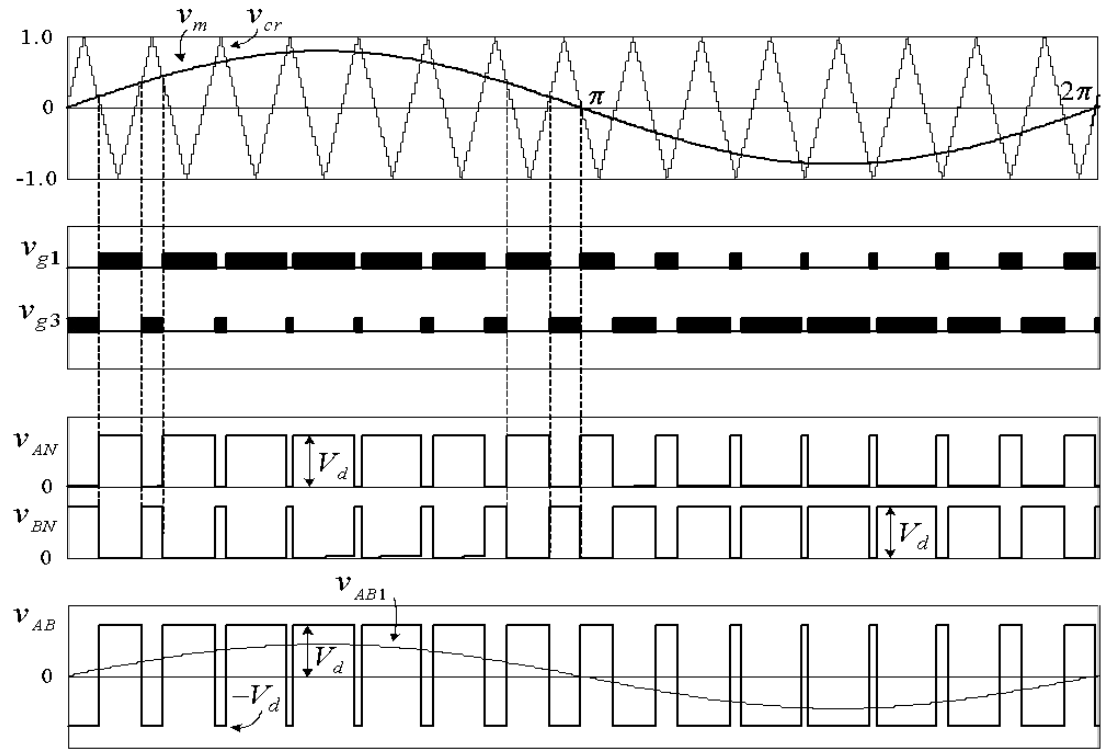
Five-level CHB inverter



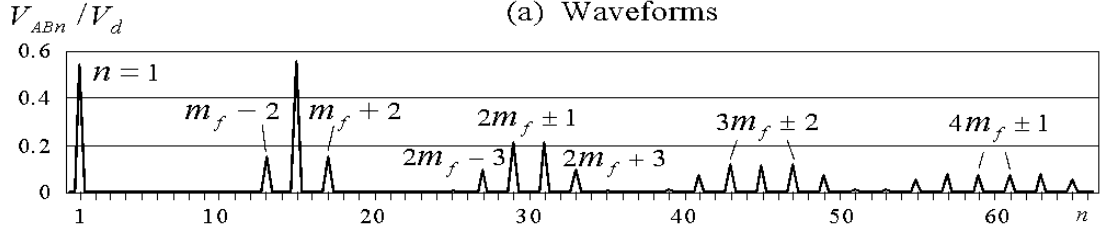
H-bridge Power Cell

# H-Bridge Inverter

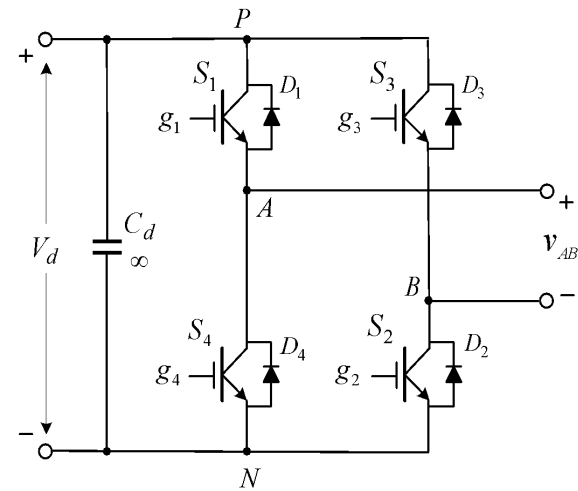
## • Bipolar Modulation



(a) Waveforms



(b) Harmonic spectrum



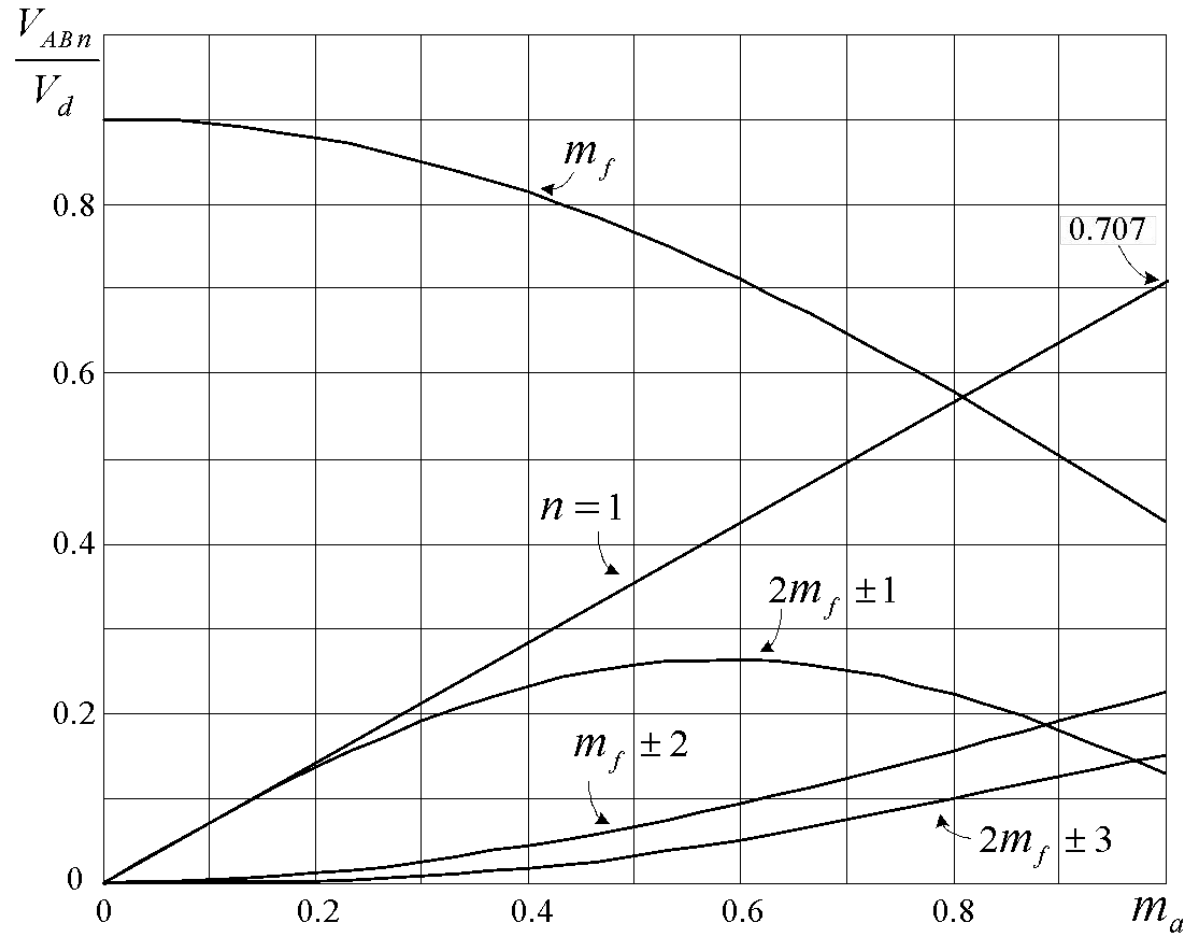
**Bipolar PWM:**

**$V_{AB}$  from  $-V_d$  to  $+V_d$   
or from  $+V_d$  to  $-V_d$**



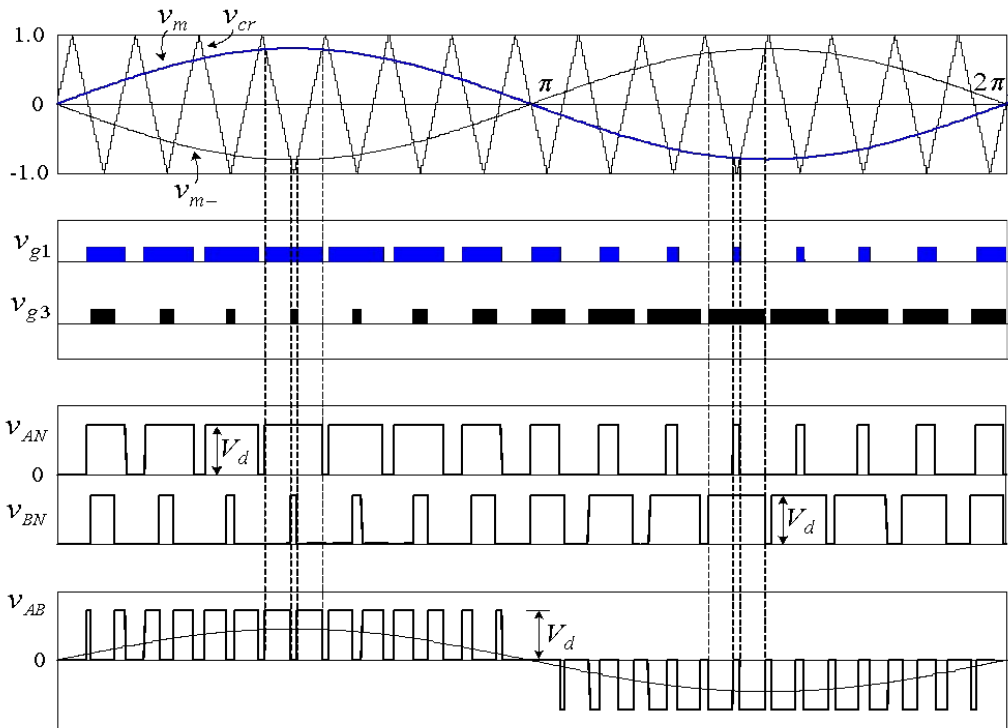
# H-Bridge Inverter

## • Bipolar Modulation (FFT)

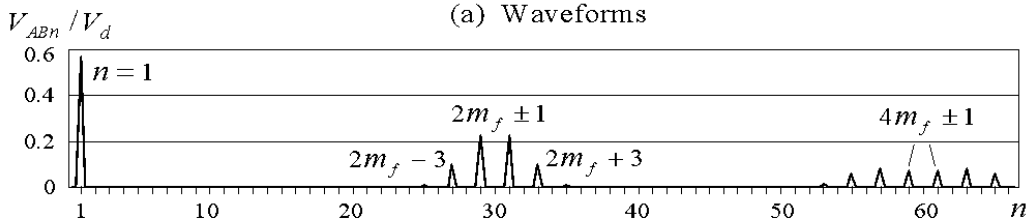


# H-Bridge Inverter

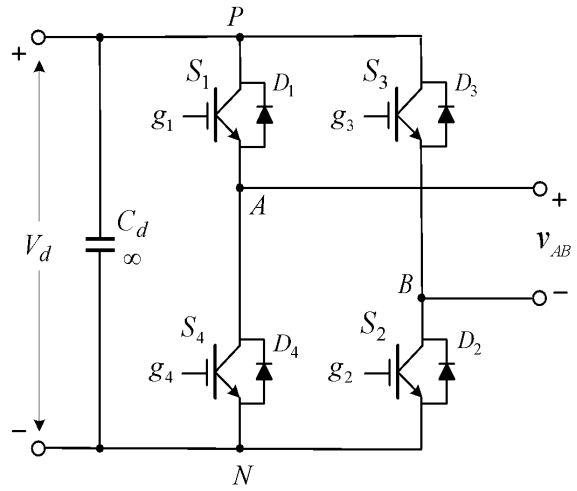
## • Unipolar Modulation (1)



(a) Waveforms



(b) Harmonic spectrum



- Two modulation waves

$V_m$  and  $V_{m-}$

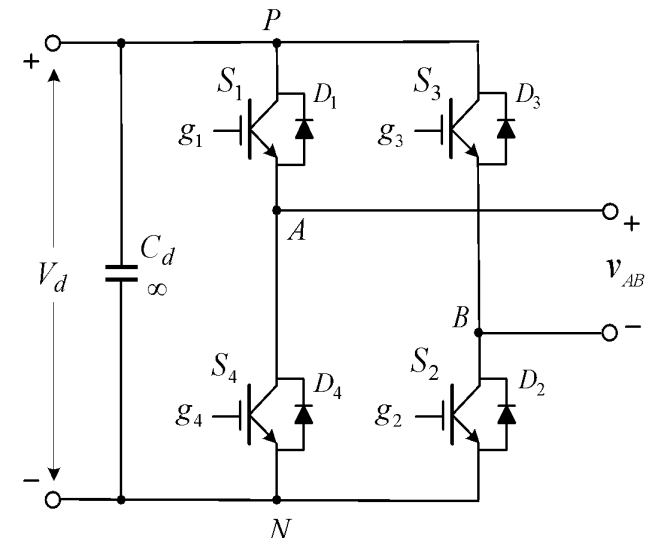
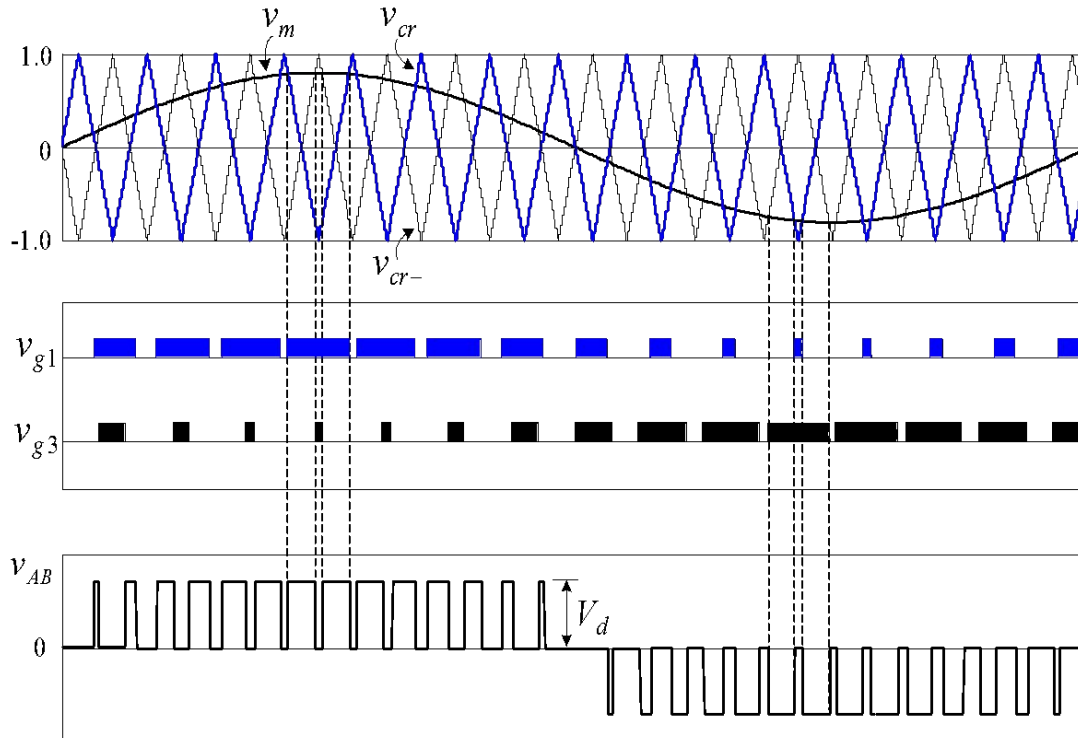
- One carrier wave  $V_{cr}$

- Unipolar PWM:

$V_{AB}$  from 0 to  $+V_d$   
or from 0 to  $-V_d$

# H-Bridge Inverter

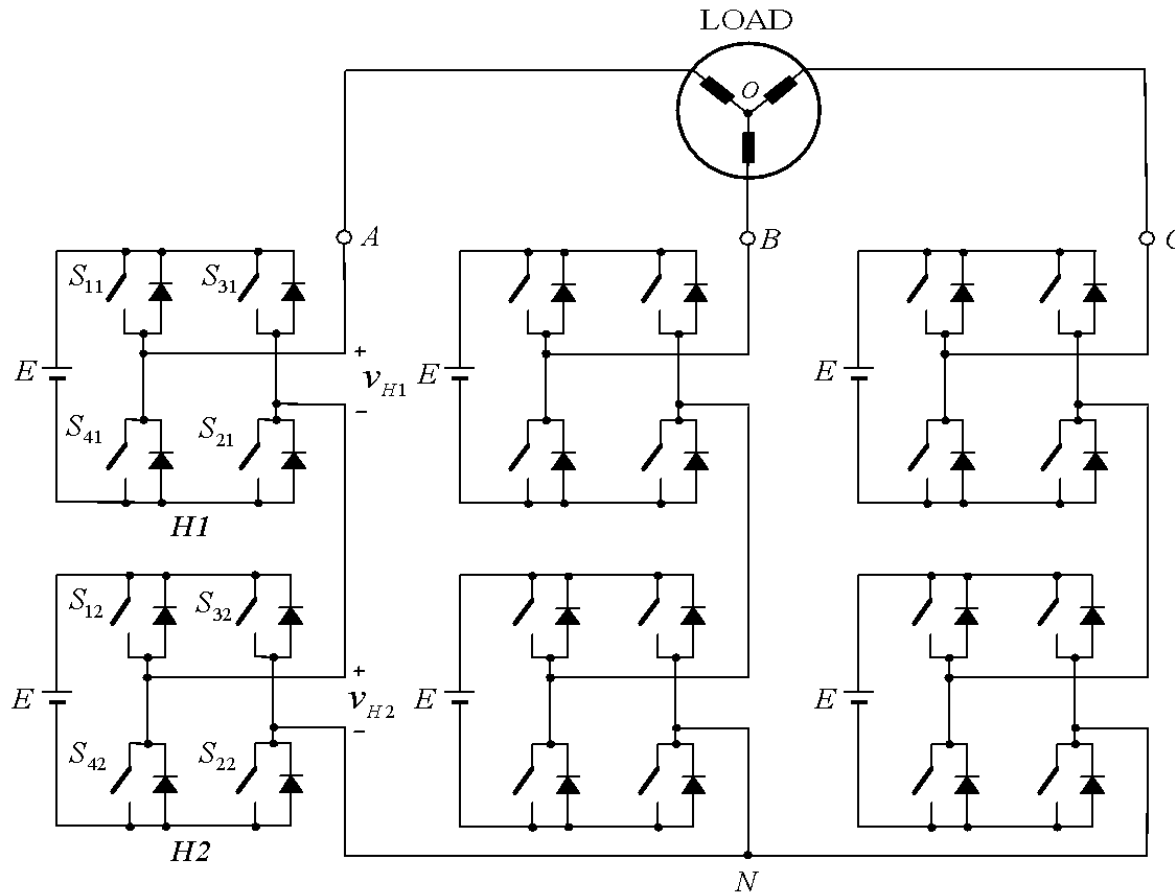
## • Unipolar Modulation (2)



- One modulating wave:  $V_m$
- Two carrier waves:  $V_{cr}$  and  $V_{cr-}$

# CHB Inverter Topologies

## • Five-Level CHB Inverter



Complementary  
Switch pairs:

$S_{11}$  and  $S_{41}$ ;  
 $S_{31}$  and  $S_{21}$ ;

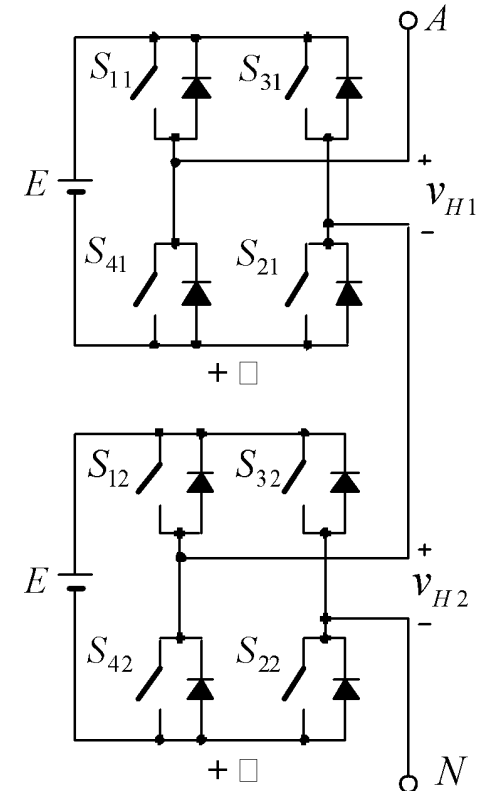
$S_{12}$  and  $S_{42}$ ;  
 $S_{32}$  and  $S_{22}$ ;

Converters in cascade, but no switching devices in series.

# CHB Inverter Topologies

## • Output Voltage and Switching Status (five-level)

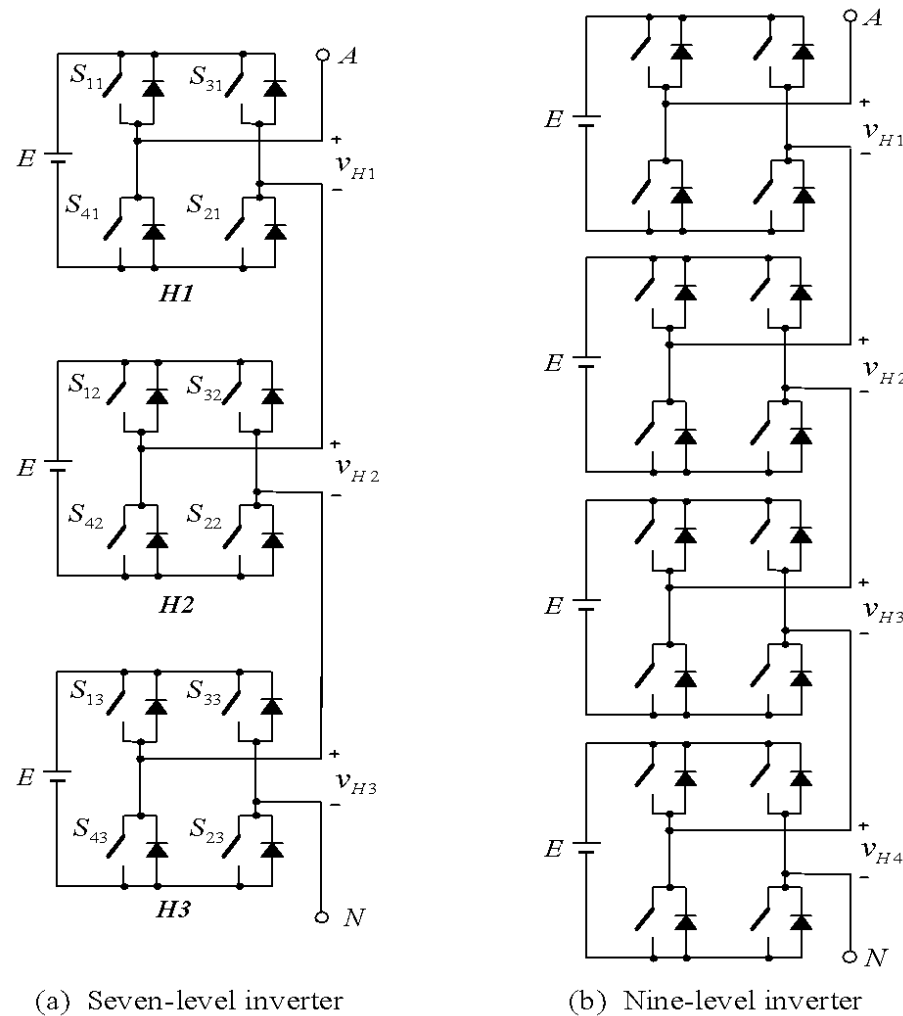
Output Voltage $v_{AN}$	Switching State				$v_{H1}$	$v_{H2}$
	$S_{11}$	$S_{31}$	$S_{12}$	$S_{32}$		
$2E$	1	0	1	0	$E$	$E$
$E$	1	0	1	1	$E$	$0$
	1	0	0	0	$E$	$0$
	1	1	1	0	$0$	$E$
	0	0	1	0	$0$	$E$
$0$	0	0	0	0	$0$	$0$
	0	0	1	1	$0$	$0$
	1	1	0	0	$0$	$0$
	1	1	1	1	$0$	$0$
	1	0	0	1	$E$	$-E$
$-E$	0	1	1	0	$-E$	$E$
	0	1	0	0	$-E$	$0$
	1	1	0	1	$0$	$-E$
	0	0	0	1	$0$	$-E$
$-2E$	0	1	0	1	$-E$	$-E$



Waveform of  $V_{AN}$  is composed of five voltage levels:  $2E$ ,  $E$ ,  $0$ ,  $-E$ , and  $-2E$

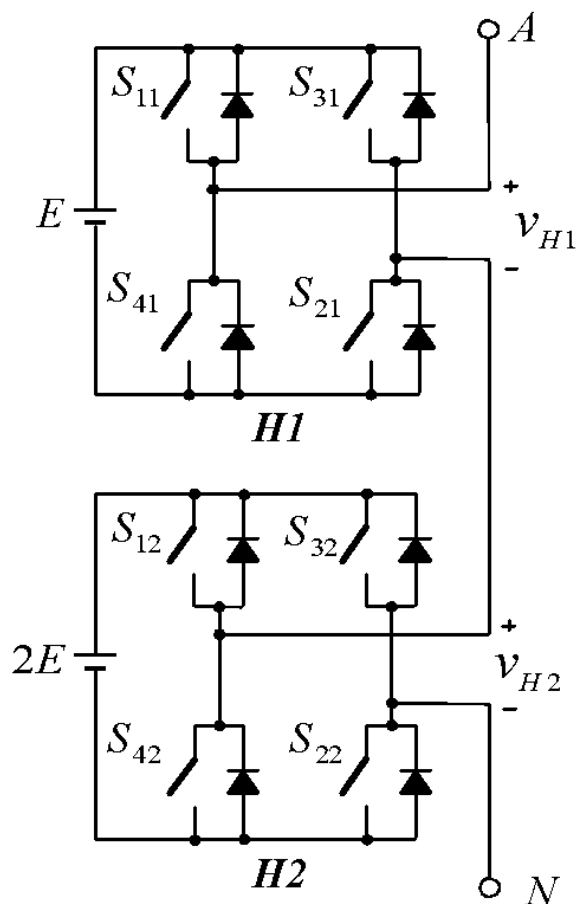
# CHB Inverter Topologies

- Seven- and Nine-Level Inverters (Per phase diagram)

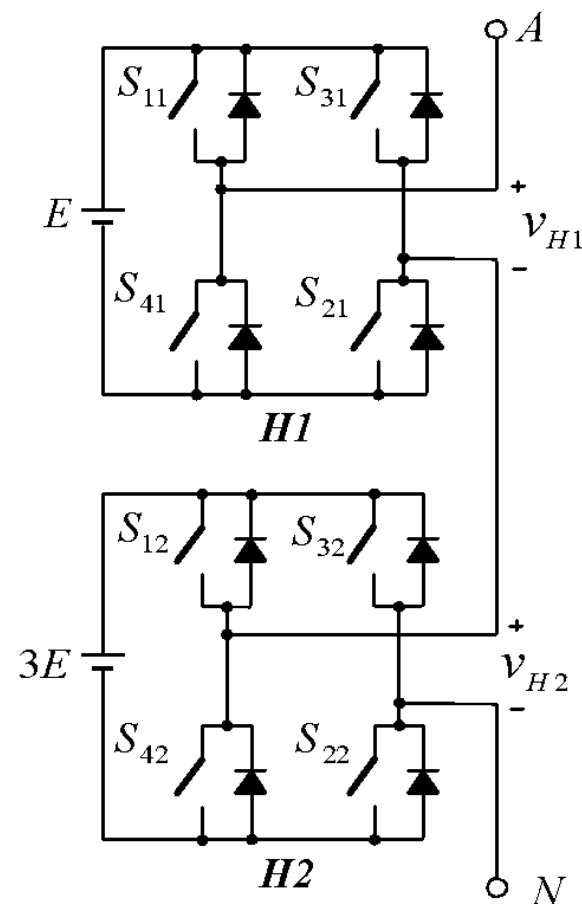


# CHB Inverter Topologies

- Unequal dc Bus Voltages



(a) Two-cell seven-level topology

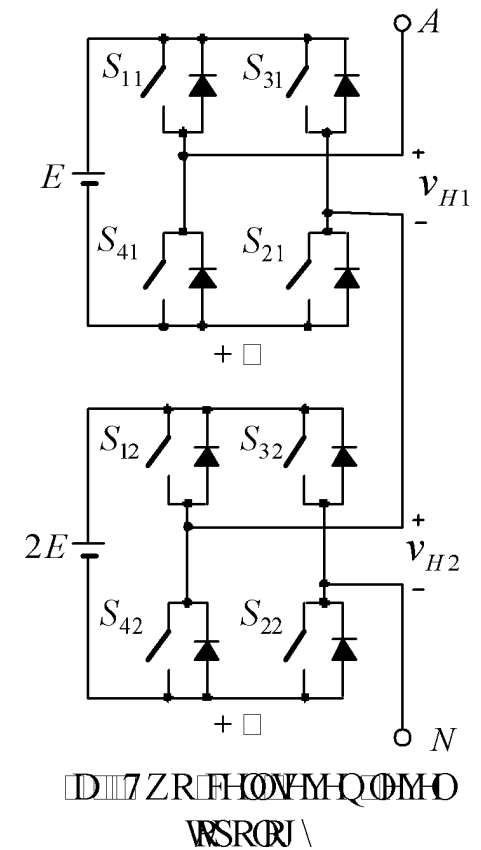


(b) Two-cell nine-level topology

# CHB Inverter Topologies

- Unequal dc Bus Voltages (Two-cell seven-level topology)

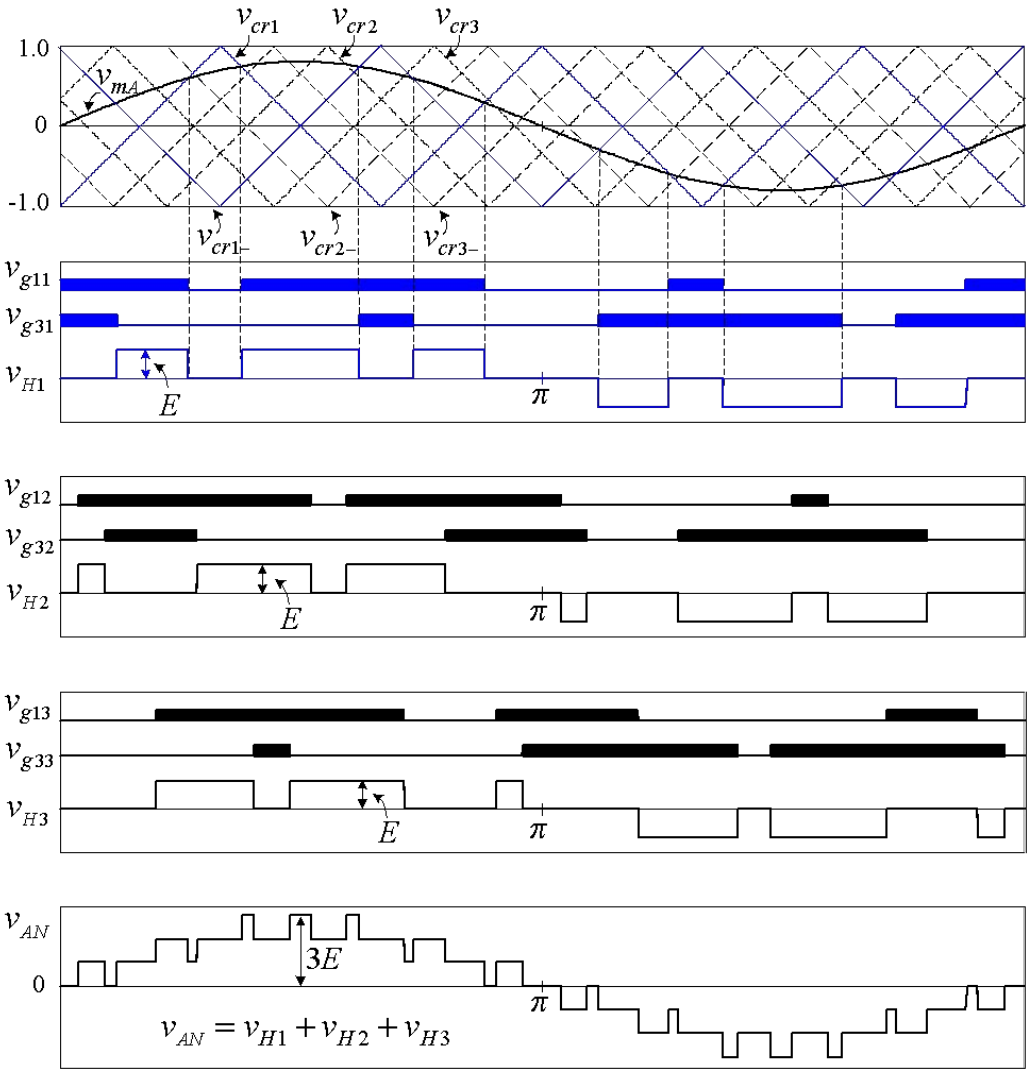
Output Voltage $V_{AN}$	Switching State				$V_{H1}$	$V_{H2}$
	$S_{11}$	$S_{31}$	$S_{12}$	$S_{32}$		
$3E$	1	0	1	0	$E$	$2E$
$2E$	1	1	1	0	$0$	$2E$
	0	0	1	0	$0$	$2E$
$E$	1	0	1	1	$E$	$0$
	1	0	0	0	$E$	$0$
	0	1	1	0	$-E$	$2E$
$0$	0	0	0	0	$0$	$0$
	0	0	1	1	$0$	$0$
	1	1	0	0	$0$	$0$
	1	1	1	1	$0$	$0$
$-E$	1	0	0	1	$E$	$-2E$
	0	1	1	1	$-E$	$0$
	0	1	0	0	$-E$	$0$
$-2E$	1	1	0	1	$0$	$-2E$
	0	0	0	1	$0$	$-2E$
$-3E$	0	1	0	1	$-E$	$-2E$





# Phase Shifted PWM

## • Carrier Based PWM – Phase Shifted



- # of voltage levels:  $m = 7$
- # of carriers:  $m_c = m - 1 = 6$
- Phase shift:  $360^\circ / m_c = 60^\circ$

Carriers for *H1* bridge:  
 $v_{cr1}$  and  $v_{cr1-}$

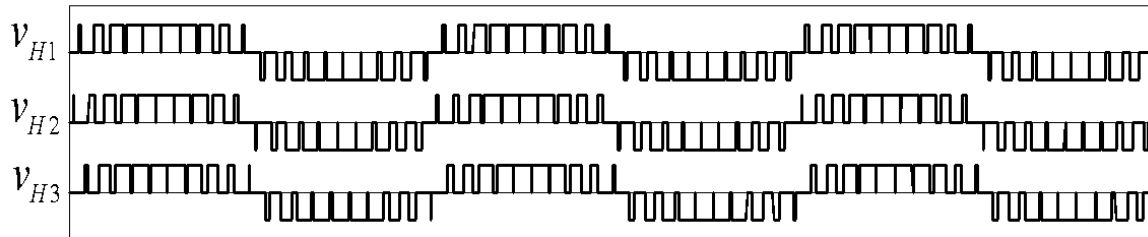
Carriers for *H2* bridge:  
 $v_{cr2}$  and  $v_{cr2-}$

Carriers for *H3* bridge:  
 $v_{cr3}$  and  $v_{cr3-}$

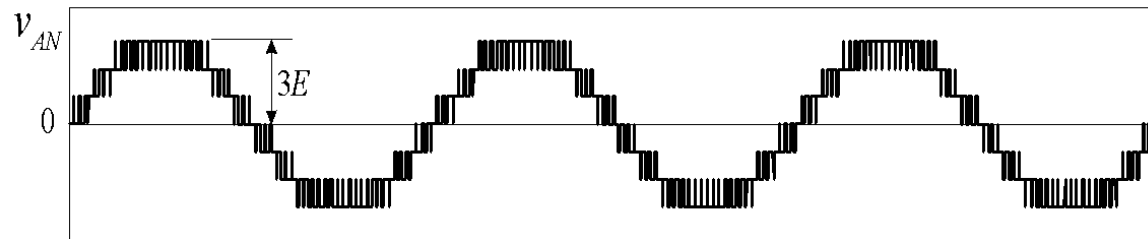
$m = 7$

# Phase Shifted PWM

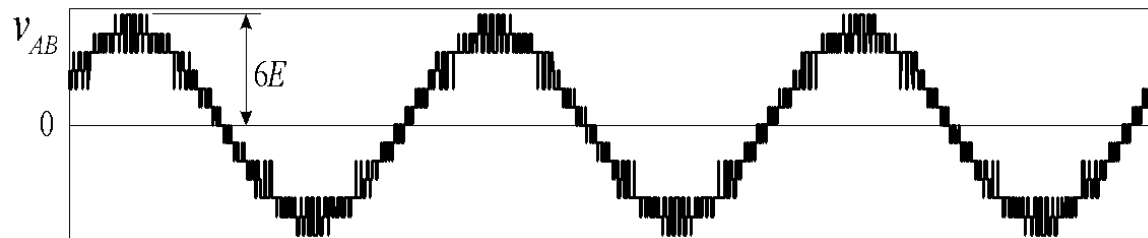
## • Inverter Waveforms (7-level, phase shifted)



- Switching occurs at different times
- $f_{sw(device)} = 60 m_f = 600\text{Hz}$



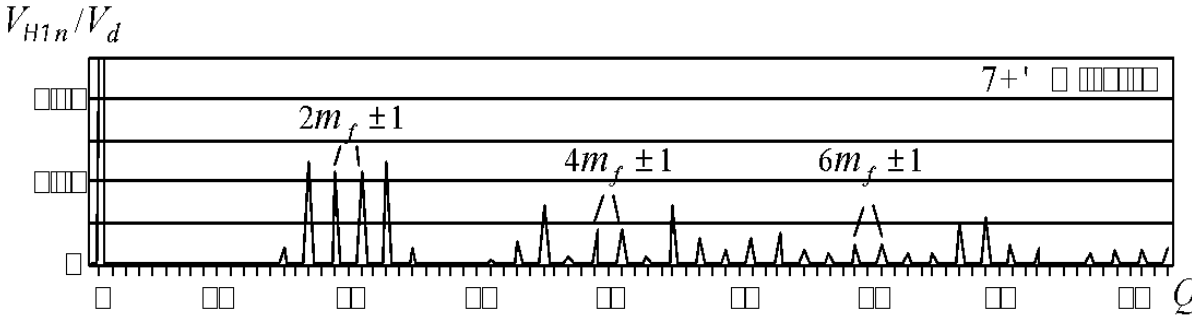
- Inverter phase voltage levels: 7
- Low EMI



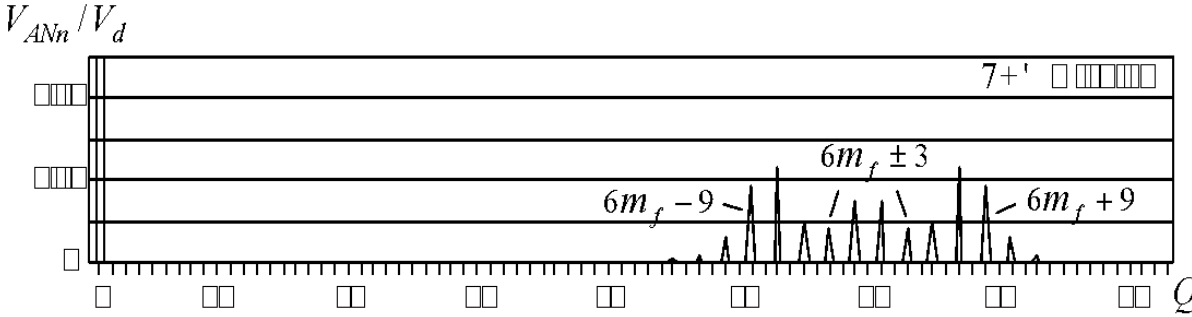
- Line-to-line voltage levels: 13
- Close to a sinusoid
- Low THD

# Phase Shifted PWM

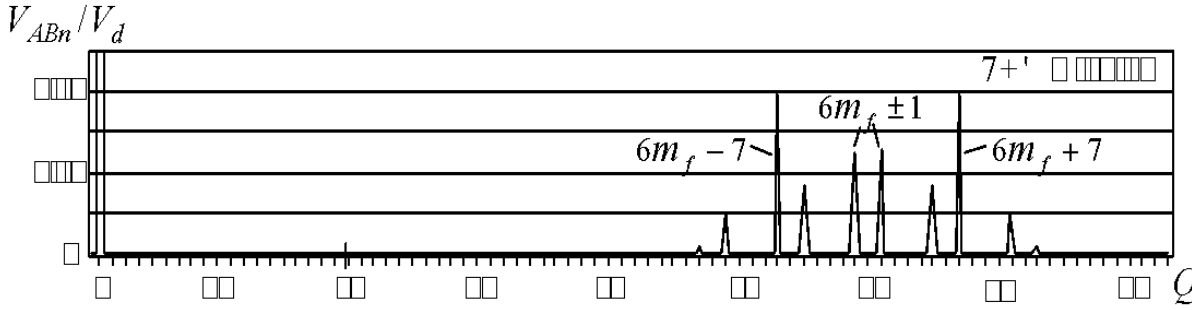
- **FFT** (7-level, phase shifted)



- **Lowest harmonics: around  $2m_f$**



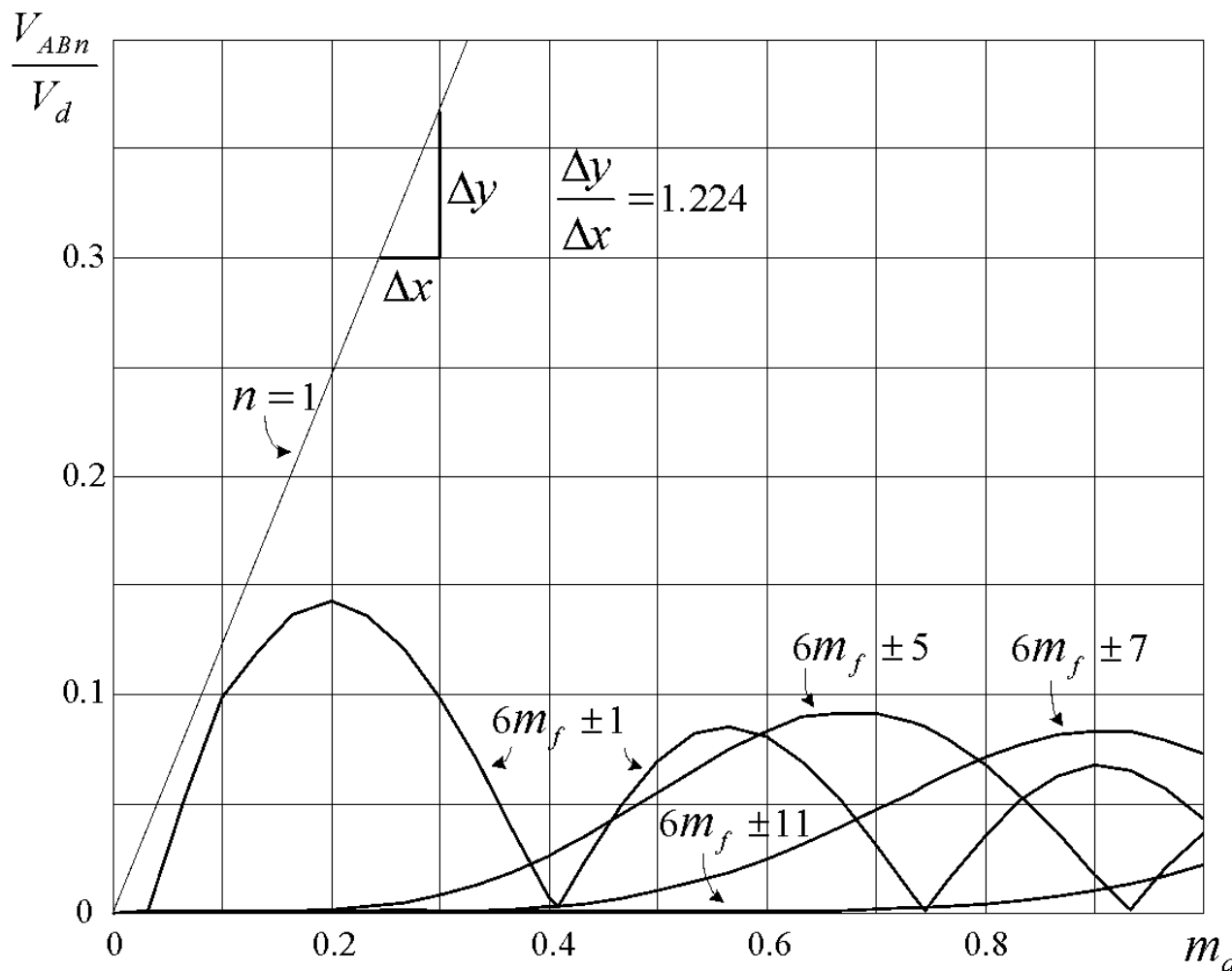
- **Lowest harmonics: around  $6m_f$**
- **Containing triplen harmonics**



- **No triplen harmonics**
- **Equivalent  $f_{sw(inverter)} = 60(6m_f) = 3600\text{Hz}$**

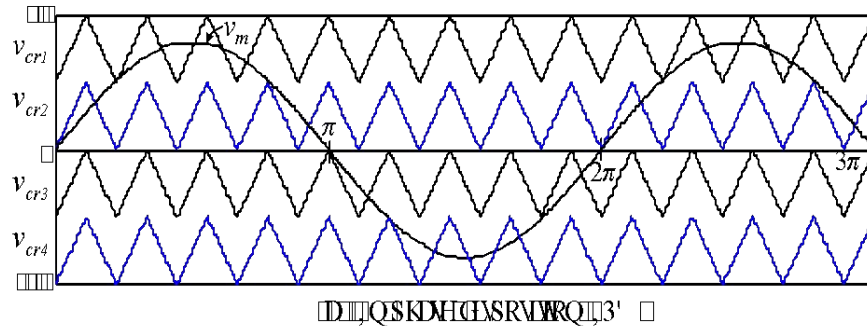
# Phase Shifted PWM

- Harmonic Content (7-level, phase shifted)



# Level Shifted PWM

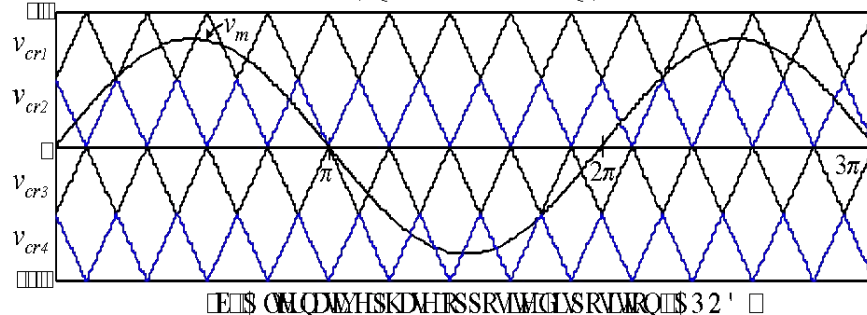
## • Carrier Based PWM – Level Shifted



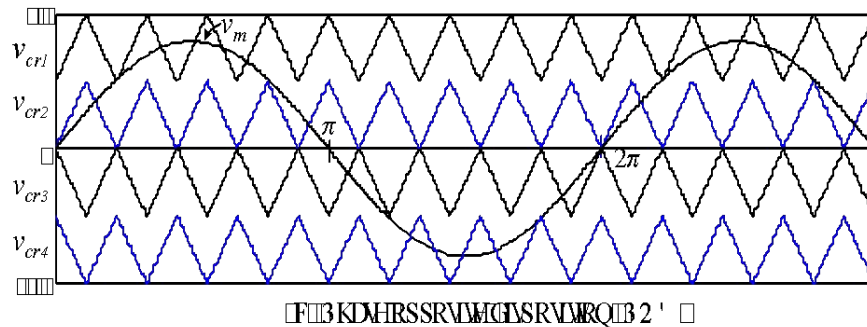
IPD

- # of voltage levels:  
 $m = 5$

- # of carriers:  
 $m_c = m - 1 = 4$



APOD

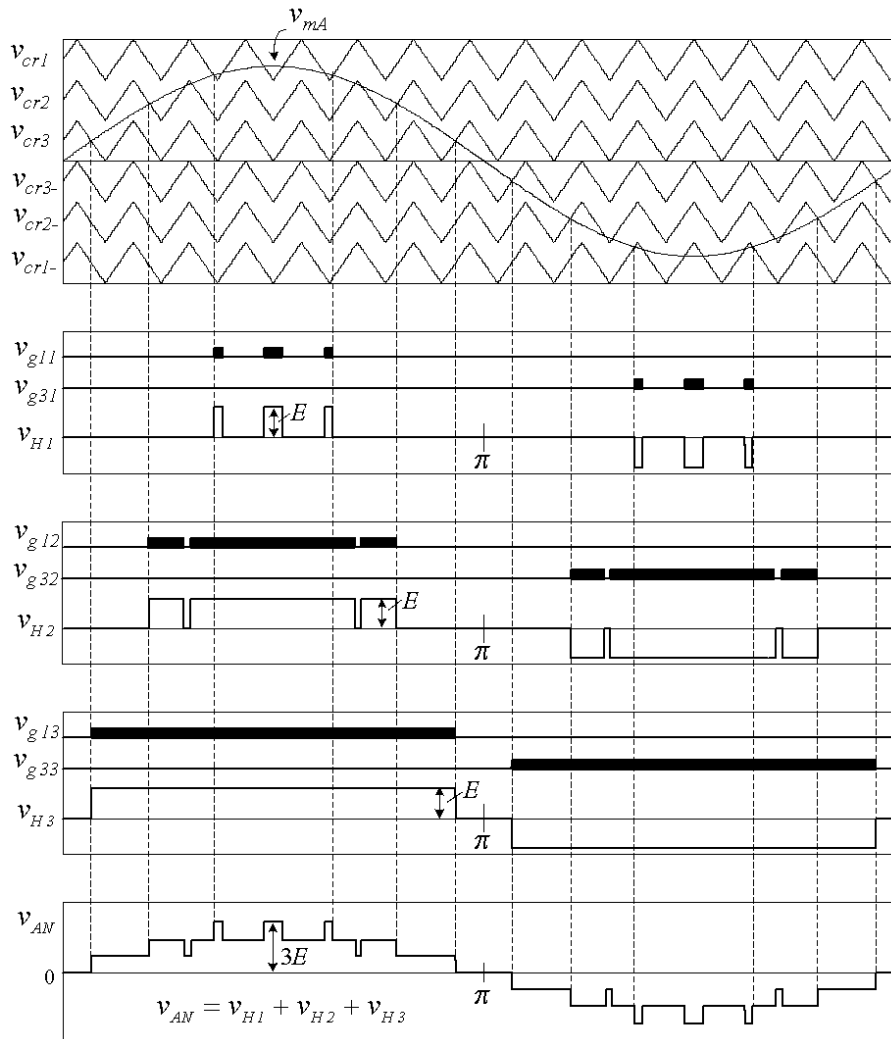


POD

IPD provides the best harmonic profile.

# Level Shifted PWM

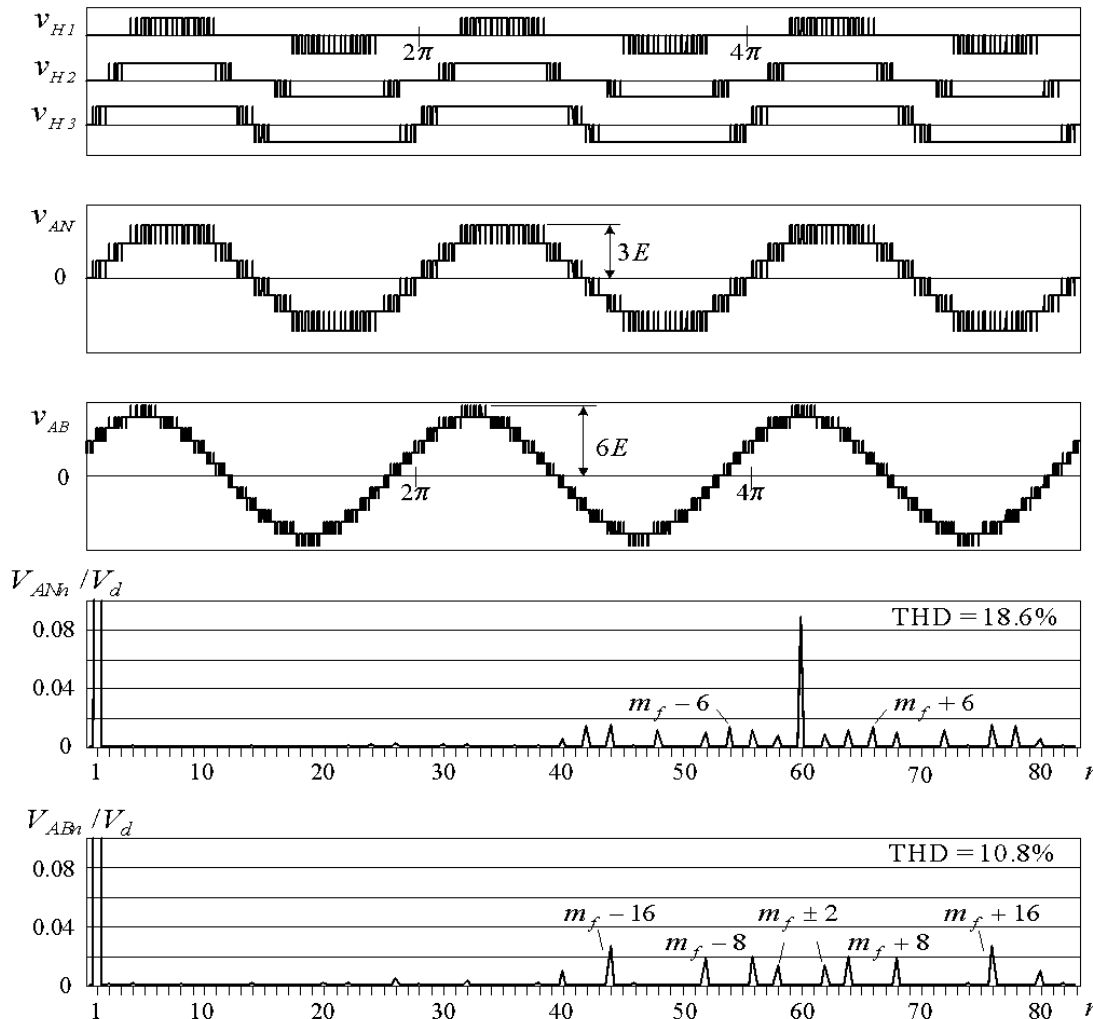
## • Gating Arrangement (7-level)



- # of voltage levels:  
 $m = 7$
- # of carriers:  
 $m_c = m - 1 = 6$
- $f_{sw(device)}$ :
  - not equal to  $f_{cr}$ , and
  - not the same for all switches.
- Device conduction angle:
  - not equal.
- Necessary to swap switching pattern.

# Level Shifted PWM

## • Inverter Output Voltages (seven-level)



- $m = 7$

- Switching occurs at different times

- $f_{sw(device)} = f_{cr} / m_c = 600\text{Hz (avg)}$

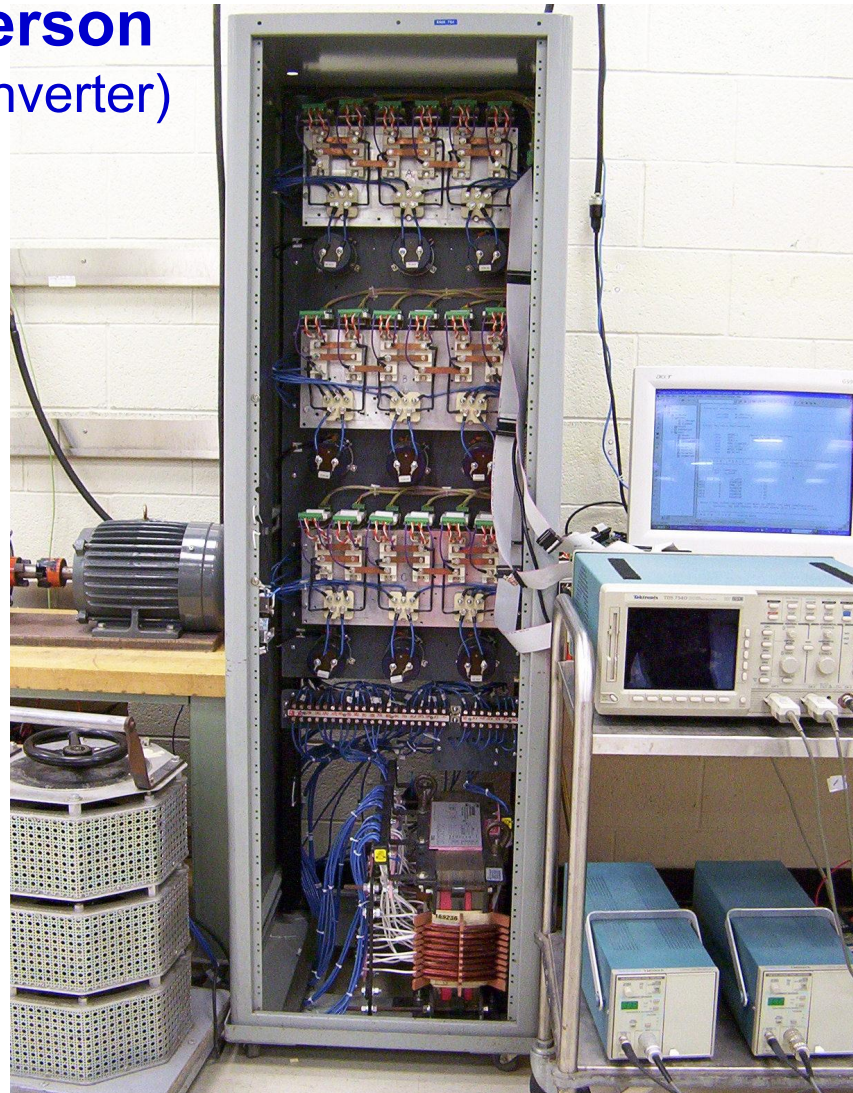
- $V_{AB}$  close to a sinusoid

- Low THD, low EMI

- $f_{sw(inv)} = f_c = 3600\text{Hz}$

# Level Shifted PWM

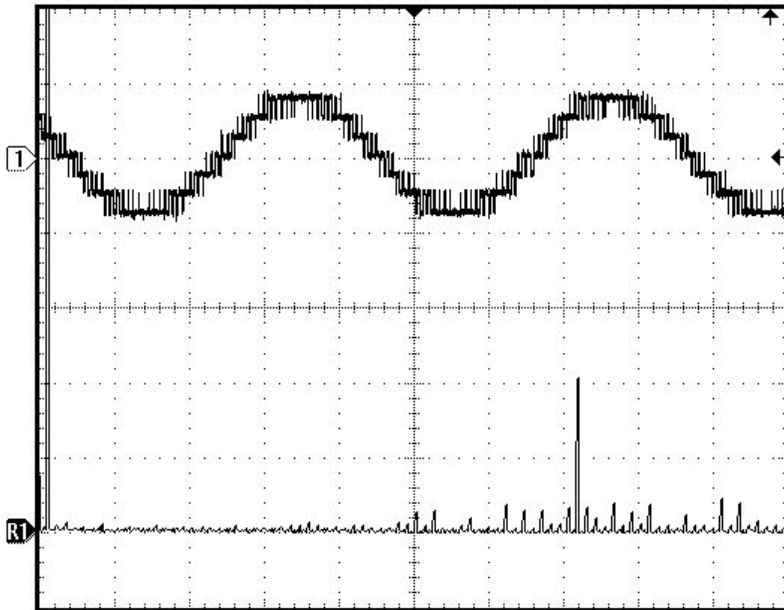
- **Prototype at Ryerson**  
(Seven-level CHB Inverter)



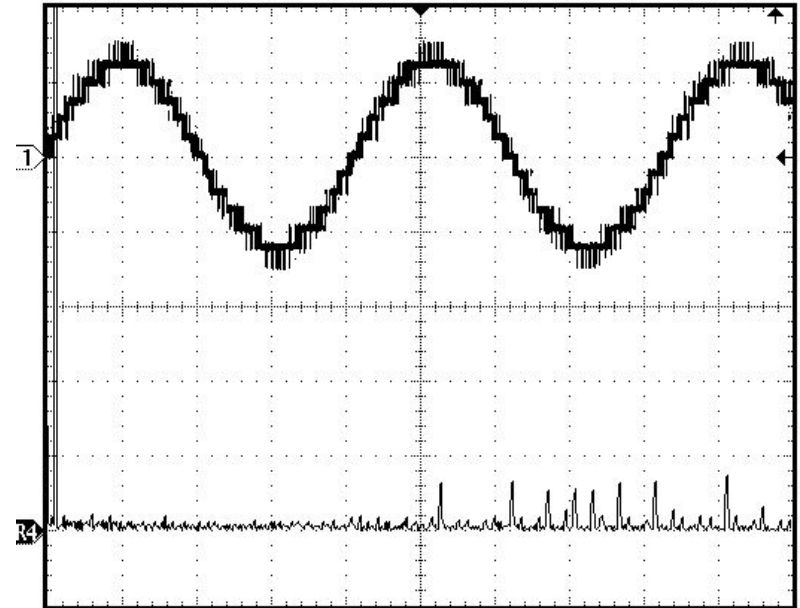


# Level Shifted PWM

- Measured Waveforms (IPD, 7-level)



Inverter phase voltage  $V_{AZ}$



Line-to-line voltage  $V_{AB}$

# PWM Scheme Comparison

- PWM at Low  $m_a$

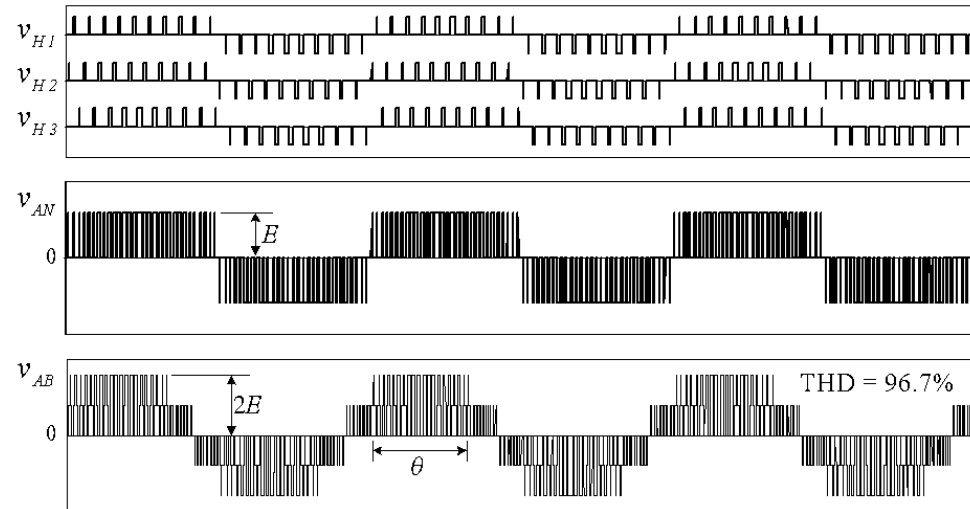
- At  $m_a = 0.2$ :

- Phase shifted PWM:

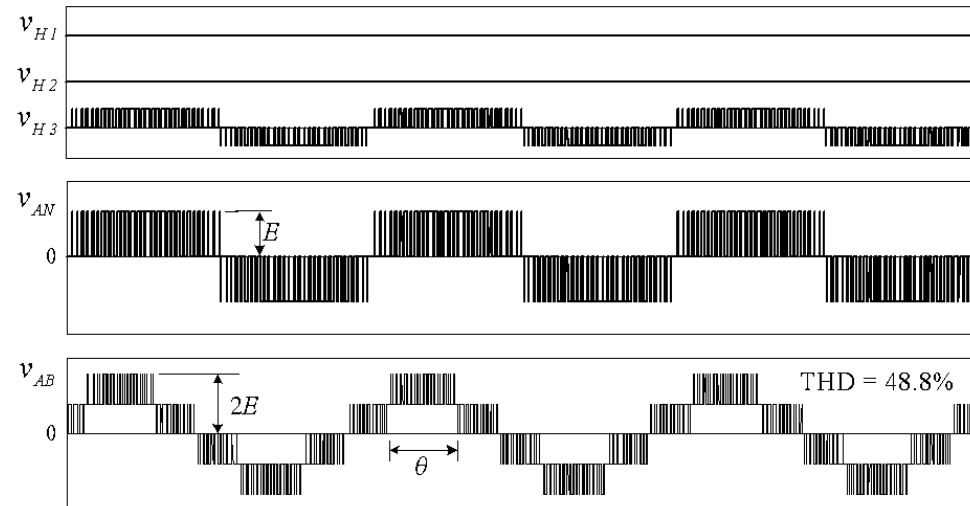
THD = 96.7%

- Level shifted PWM:

THD = 48.8%



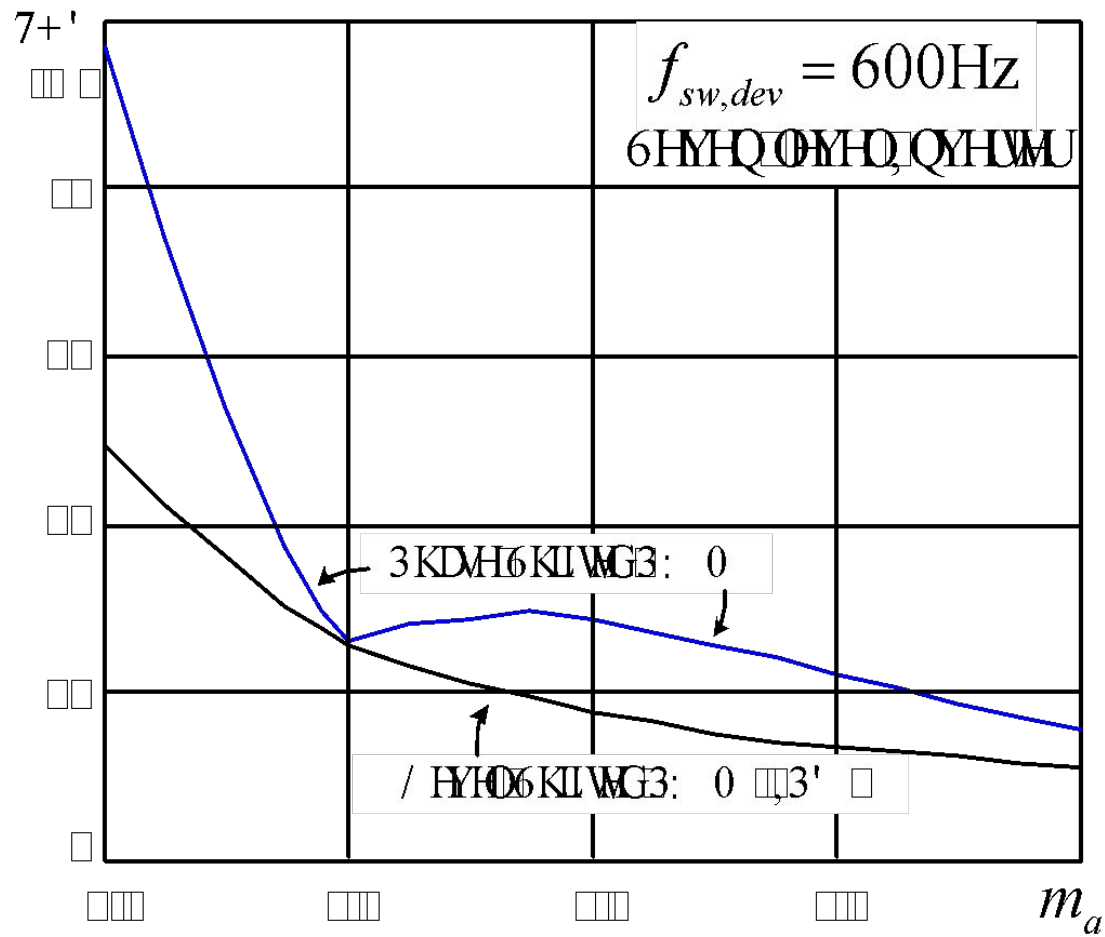
(a) Phase-shifted modulation



(b) Level-shifted modulation (IPD)

# PWM Scheme Comparison

- Total Harmonic Distortion (THD)



# PWM Scheme Comparison

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- Summary

Comparison	Phase-shifted Modulation	Level-shifted Modulation (IPD)
Device Switching Frequency	Same for all devices	Different
Device Conduction Period	Same for all devices	Different
Rotating of switching patterns	No required	Required
THD of inverter output line-to-line voltage	Good	Better
Low Order Harmonics	No	Yes (Very low amplitude)



Thanks