INTRODUCTION TO MULTILEVEL INVERTERS

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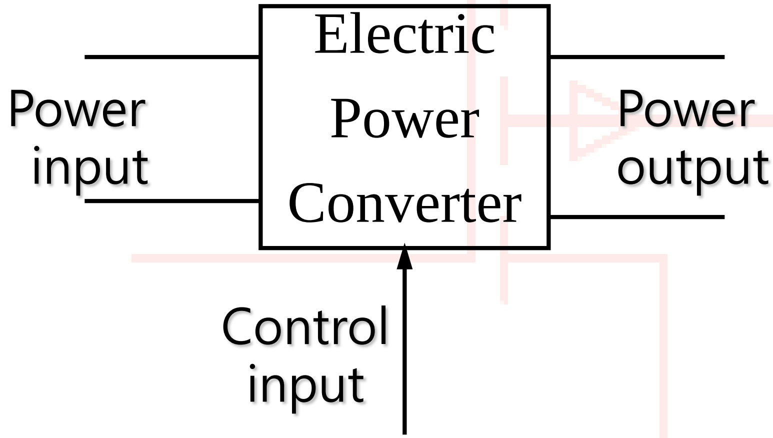
What is power electronics?

- Definition
- Conversion of electric power
- The interdisciplinary nature
- Position and significance in the human society

What is power electronics?

- **Power Electronics:**
  - is the electronics applied to conversion and control of electric power.
- Range of power scale :
  - milliwatts(mW) → megawatts(MW) → gigawatts(GW)
- **A more exact explanation:**
- The primary task of power electronics is to process and control the flow of electric energy by supplying voltages and currents in a form that is optimally suited for user loads.

Conversion of electric power



- Other names for electric power converter:
  - -Power converter
  - -Converter
  - -Switching converter
  - -Power electronic circuit
  - -Power electronic converter

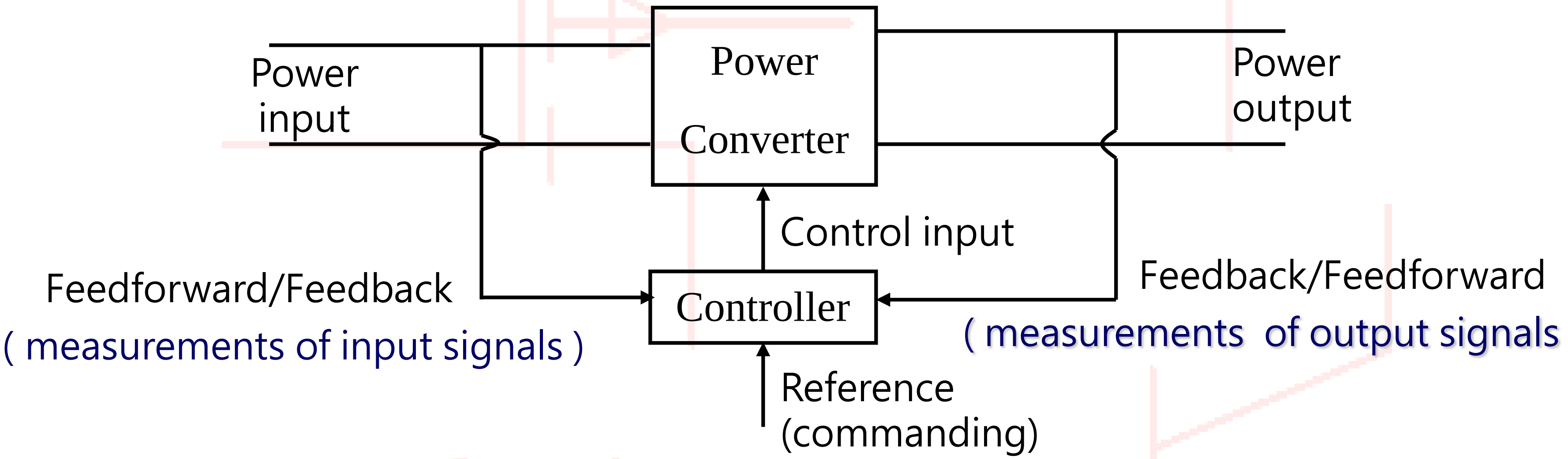
Two types of electric power	Changeable properties in conversion
DC(Direct Current)	Magnitude
AC (Alternating Current)	Frequency, magnitude, number of phases

Classification of power converters

Power input \ Power output	DC	AC
AC	AC to DC converter (Rectifier)	AC to AC converter (Fixed frequency : AC controller Variable frequency: Cycloconverter or frequency converter)
DC	DC to DC converter (Chopper)	DC to AC converter (Inverter)

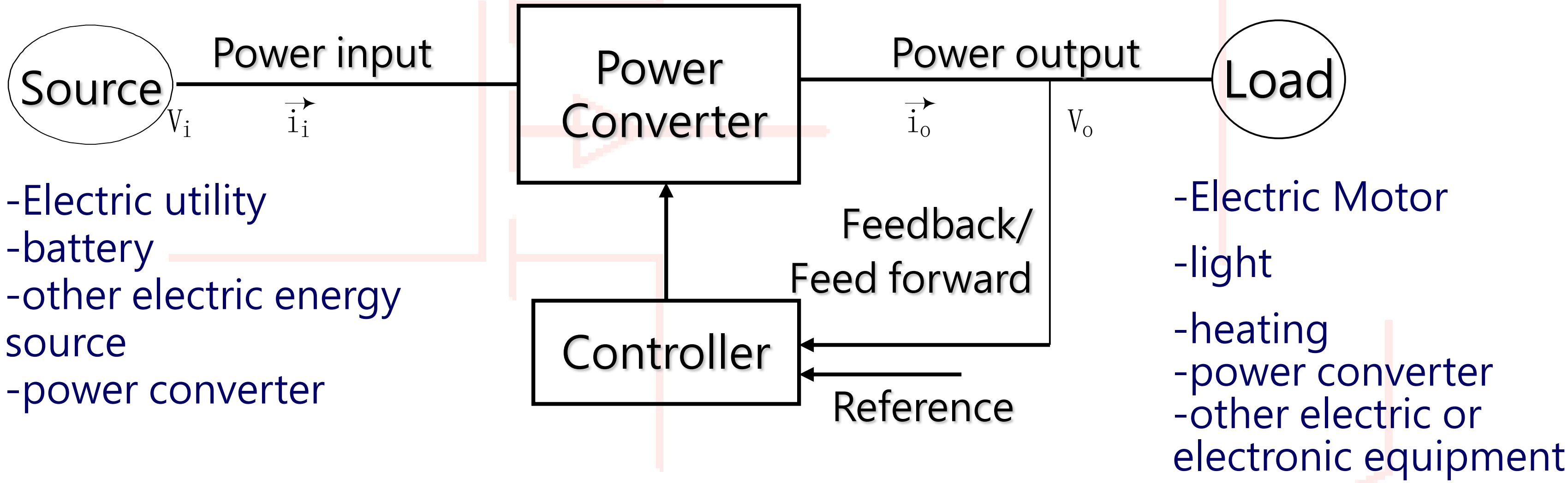
Power electronic system

Generic structure of a power electronic system



- Control is invariably required.
- Power converter along with its controller including the corresponding measurement and interface circuits, is also called power electronic system.

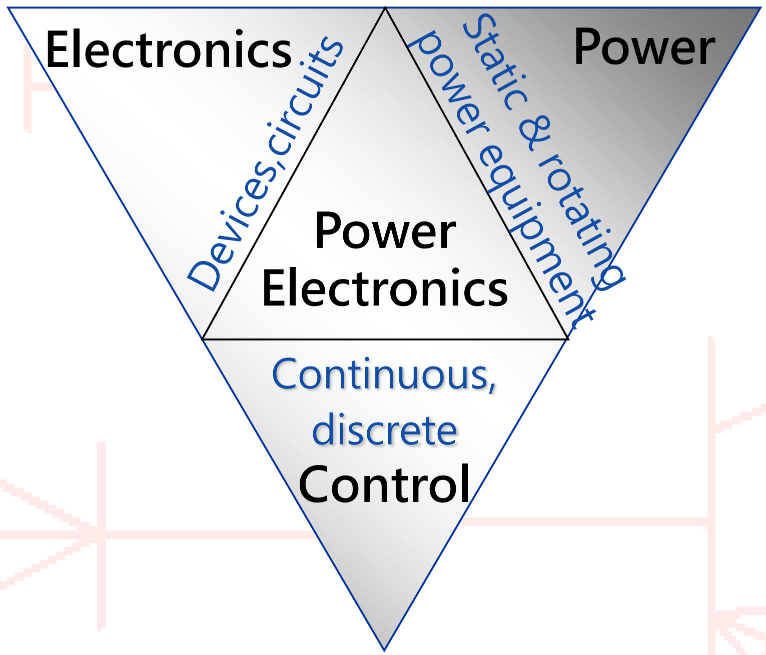
Typical power sources and loads for a power electronic system



- The task of power electronics has been recently extended to also ensuring the currents and power consumed by power converters and loads to meet the requirement of electric energy sources.

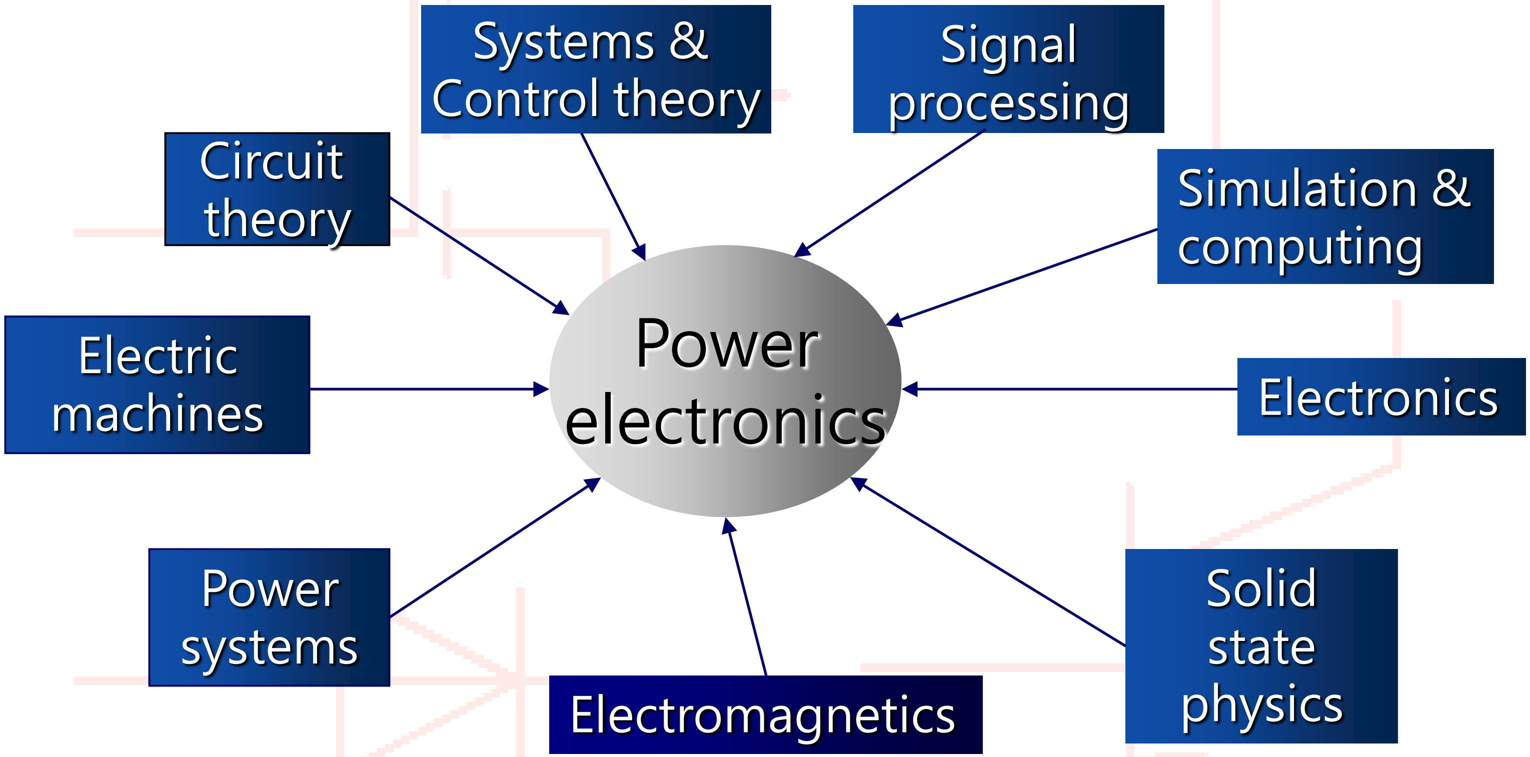
The interdisciplinary nature

William E. Newell’ s description



➢Power electronics is the interface between electronics and power.

Relation with multiple disciplines

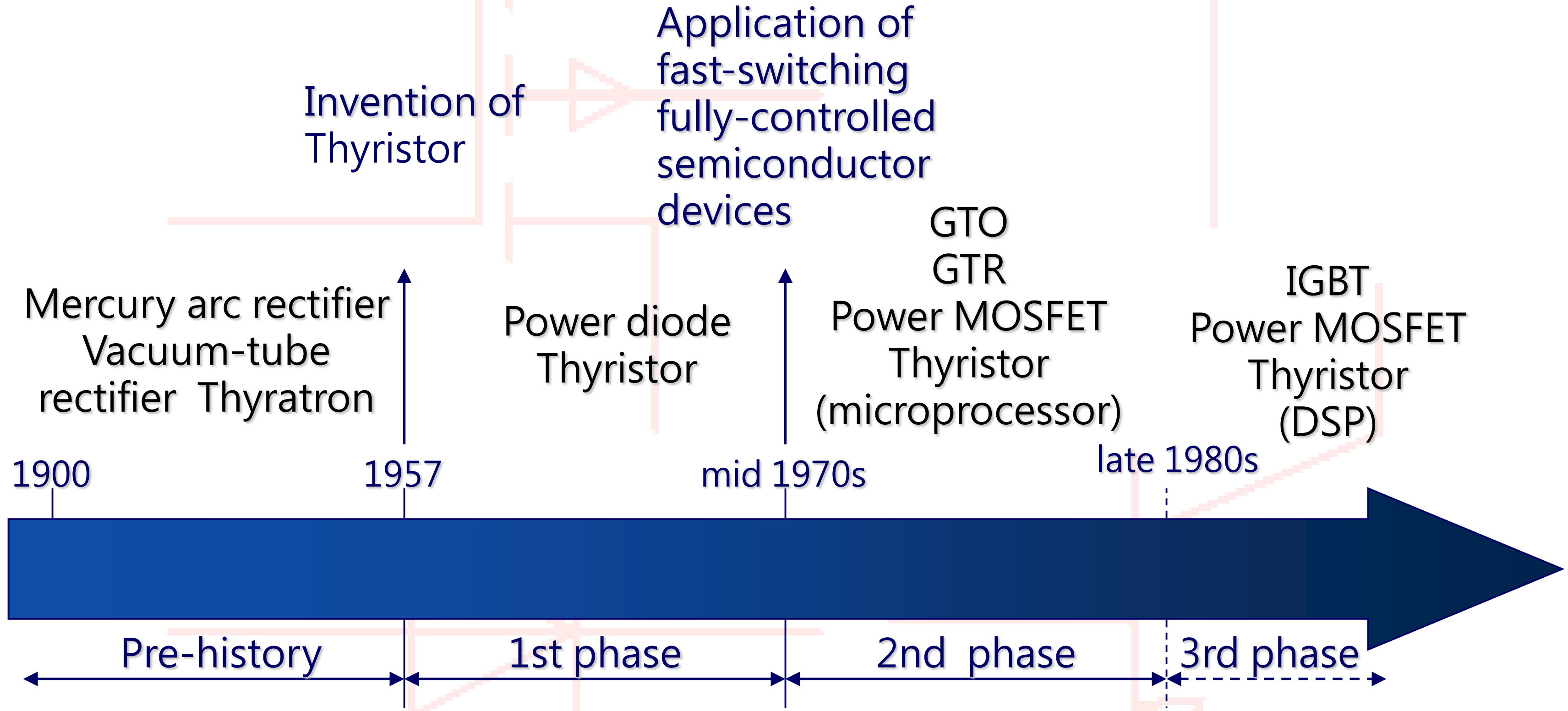


- Power electronics is currently the most active discipline in electric power engineering worldwide.

Position and significance in the human society

- Electric power is used in almost every aspect and everywhere of modern human society.
- Electric power is the major form of energy source used in modern human society.
- The objective of power electronics is exactly about how to use electric power, and how to use it effectively and efficiently, and how to improve the quality and utilization of electric power.
- Power electronics and information electronics make two poles of modern technology and human society——information electronics is the brain, and power electronics is the muscle.

The History



- The thread of the power electronics history precisely follows and matches the break-through and evolution of power electronic devices

Applications

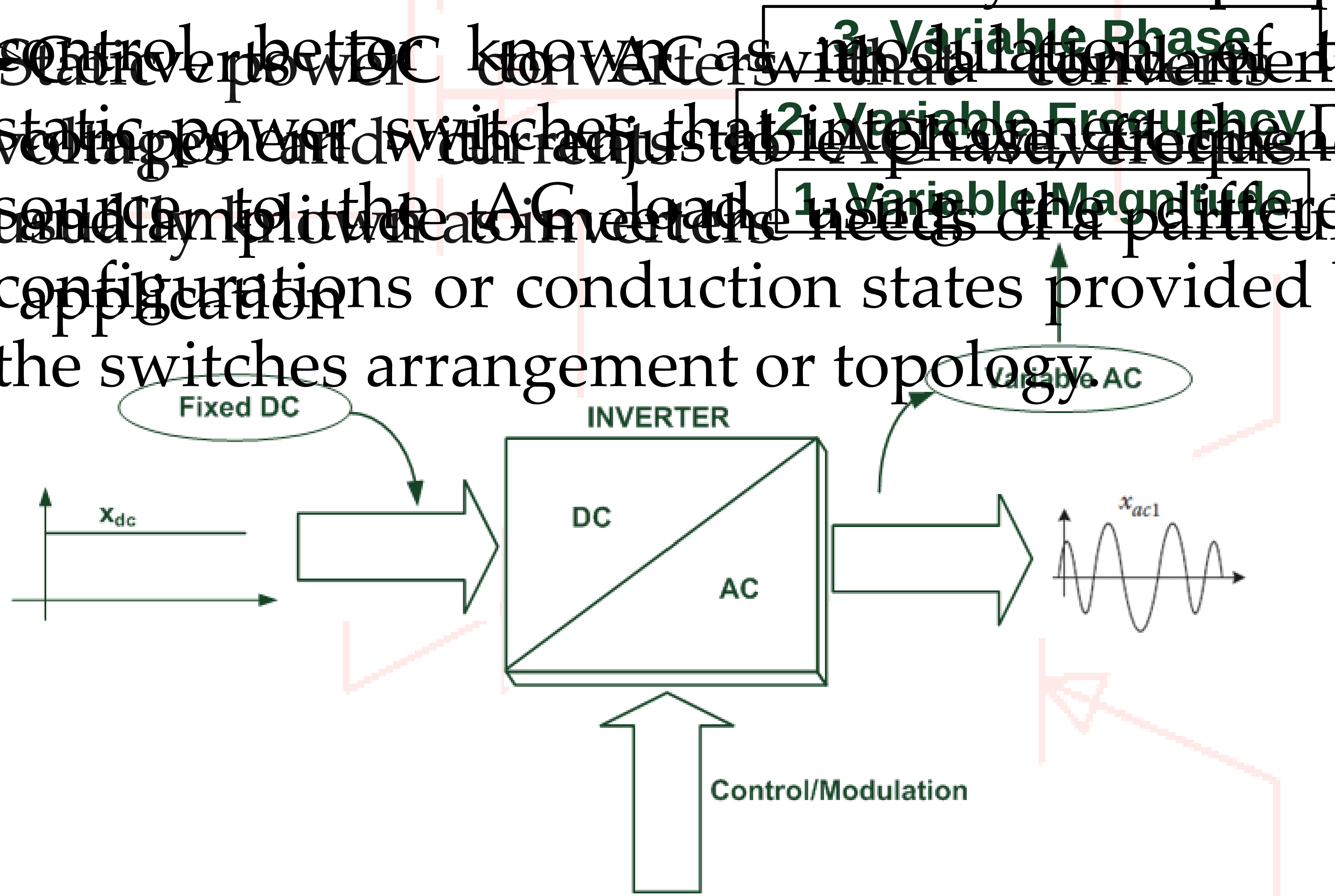
- Industrial
- Transportation
- Utility systems
- Power supplies for all kinds of electronic equipment
- Residential and home appliances
- Space technology
- Other applications

Inverters - Introduction

- This conversion is achieved by the proper control better known as modulation of the static power switches that interconnect the DC source to the AC load using different configurations or conduction states provided by the switches arrangement or topology.

- Static power converters that convert DC voltages and currents to AC waveforms are usually known as inverters

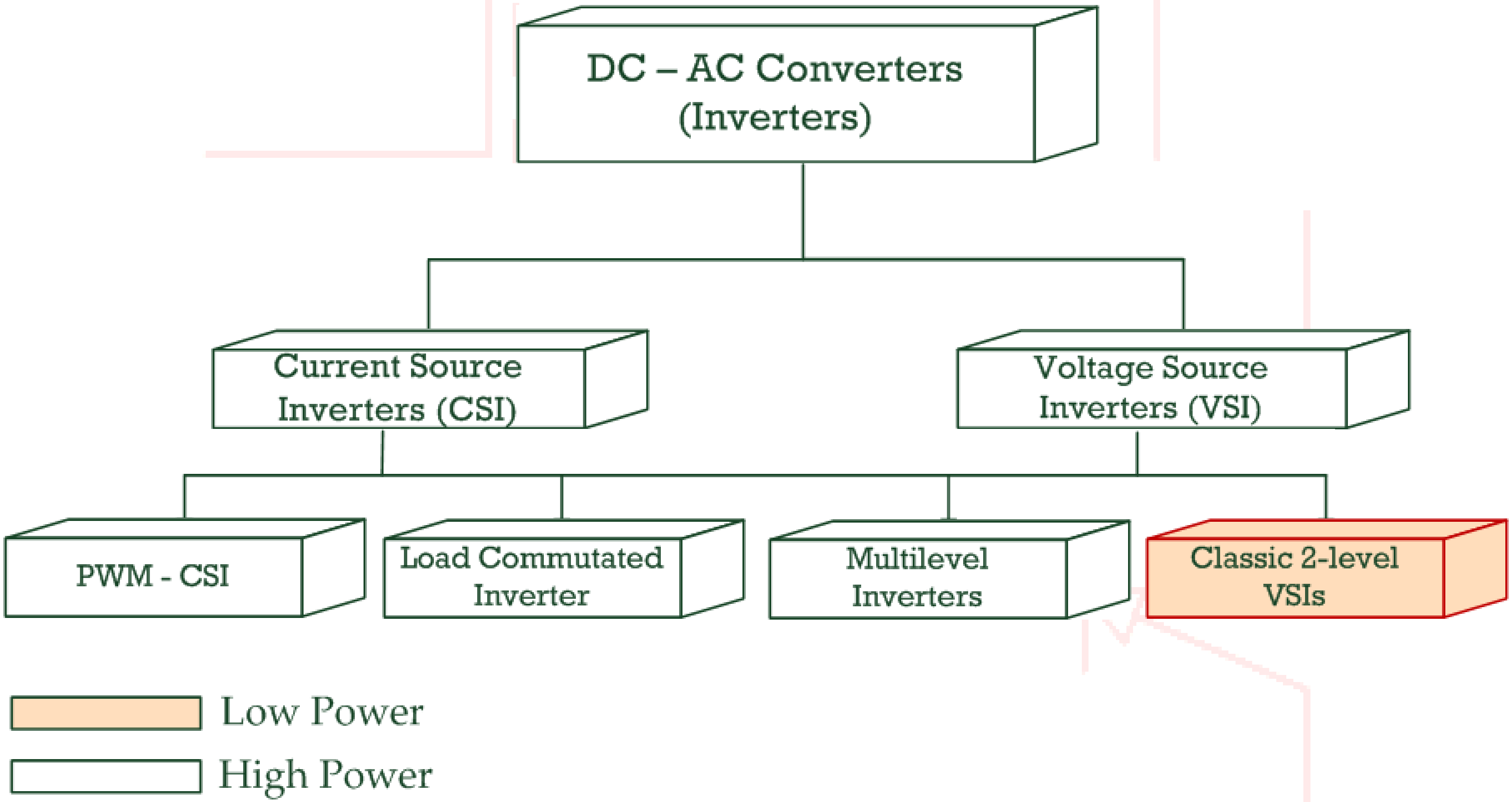
- DC to AC converters with a fundamental component with adjustable phase, frequency, and amplitude to meet the needs of a particular application



Inverters - Introduction

- Inverters convert DC voltage to variable magnitude, variable frequency AC voltage.
- Ideally, purely sinusoidal output voltage.
- Practically not possible.
- PWM Techniques makes the task of extracting sinusoidal voltage from output of inverters easier.

Inverters - Introduction



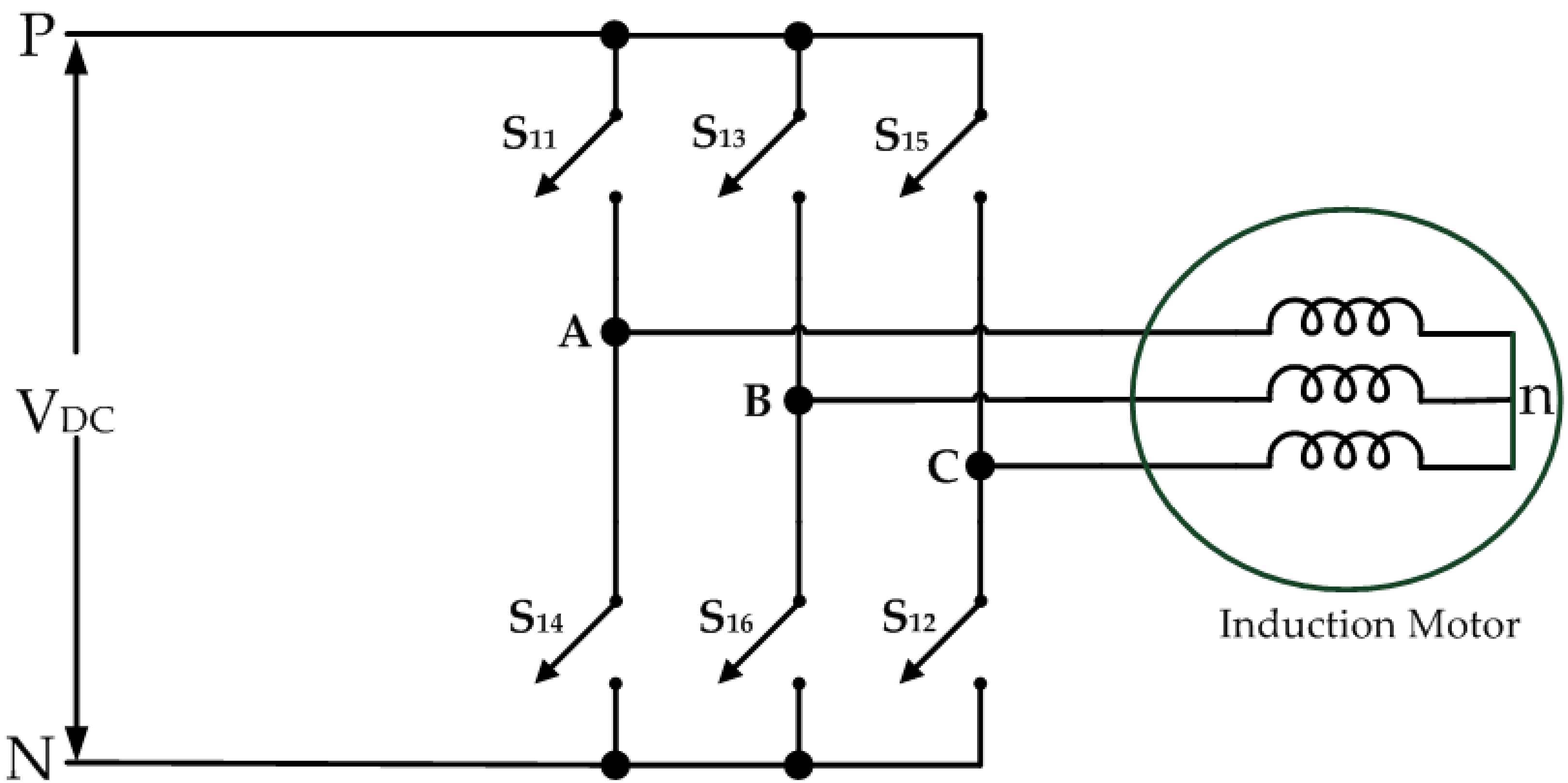
Inverters - Introduction

- The DC source is usually composed of a rectifier followed by an energy storage or filter stage known as DC link – Indirect Conversion

- CSI have been dominating in the medium-voltage high-power range with the pulse-width modulated CSI (PWM-CSI) and the load-commutated inverter (LCI)

- Single-phase and three-phase two-level VSIs are widely used in low- and medium-power applications. Recently, VSI have also become attractive in the medium-voltage high-power market with multilevel inverter topologies

Two-level Voltage Source Inverter



Three-phase Two-level VSI feeding Induction Motor

Two-level Voltage Source Inverter

- V_{AN}, V_{BN} & V_{CN} are known as pole voltages
- V_{An}, V_{Bn} & V_{Cn} are known as phase voltages
- V_{AB}, V_{BC} & V_{CA} are known as line voltages

$$V_{nN} = V_{nA} + V_{AN},$$

$$V_{nN} = V_{nB} + V_{BN} \; \&$$

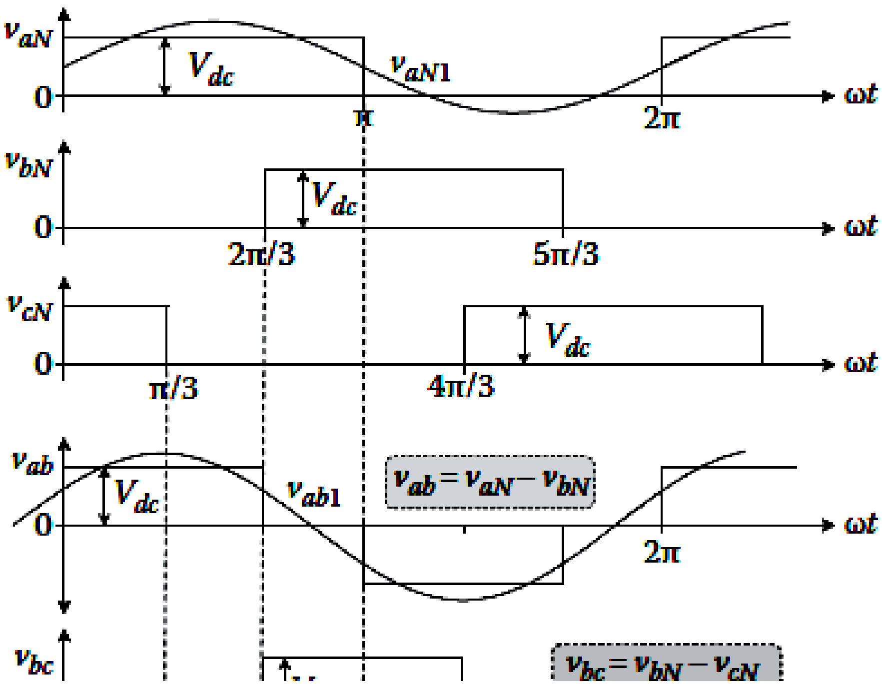
$$V_{nN} = V_{nC} + V_{CN}$$

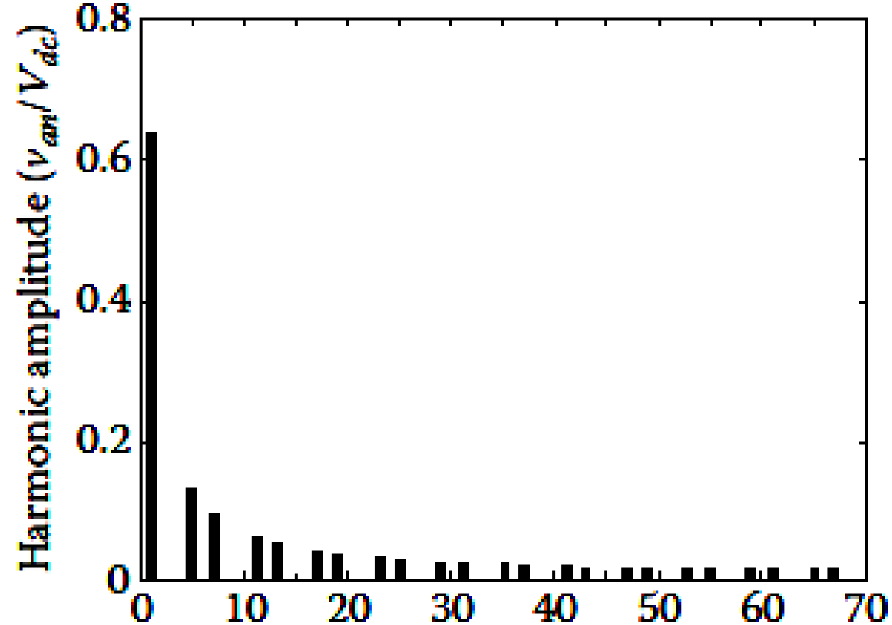
$$\therefore V_{nN} = \frac{(V_{AN} + V_{BN} + V_{CN}) + (V_{nA} + V_{nB} + V_{nC})}{3}$$

$$\because (V_{nA} + V_{nB} + V_{nC}) = 0$$

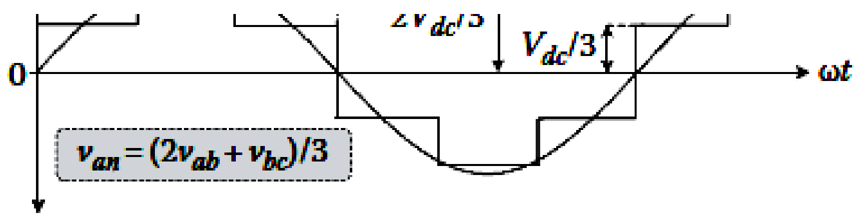
$$V_{nN} = \frac{(V_{AN} + V_{BN} + V_{CN})}{3}$$

Two-level Voltage Source Inverter

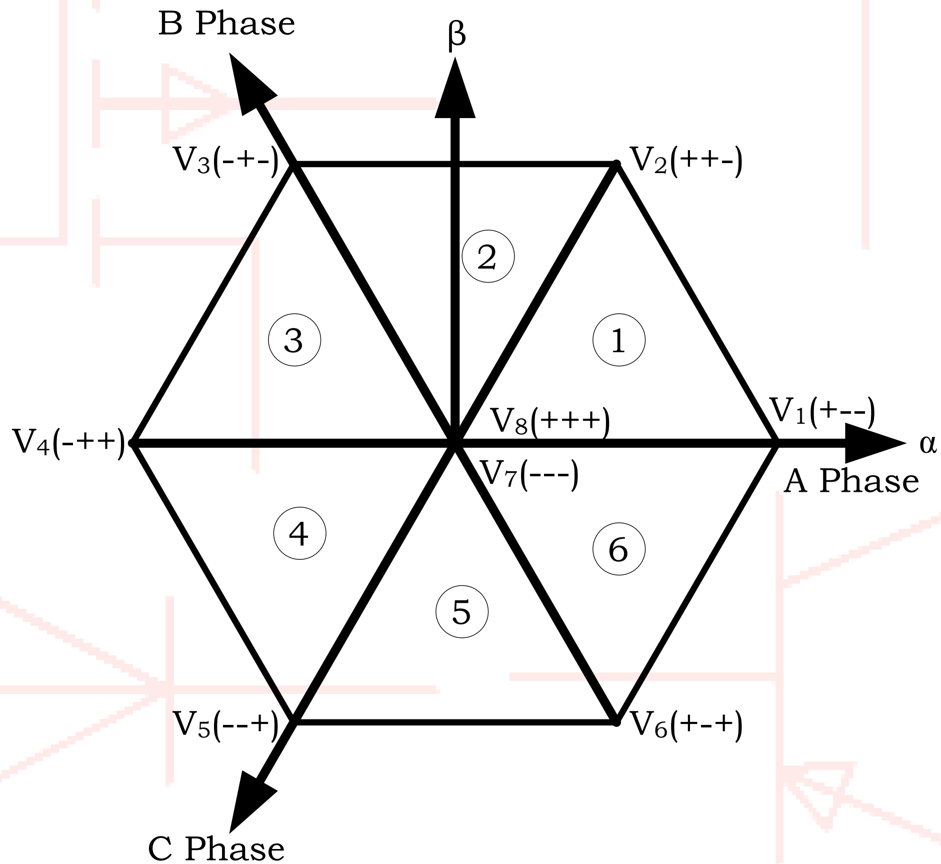




$$v_{an} = \frac{2V_{dc}}{\pi}\left[\sin(\omega t) + \frac{1}{5}\sin(5\omega t) + \frac{1}{7}\sin(7\omega t) + \frac{1}{11}\sin(11\omega t) + \frac{1}{13}\sin(13\omega t) + \cdots\right],$$

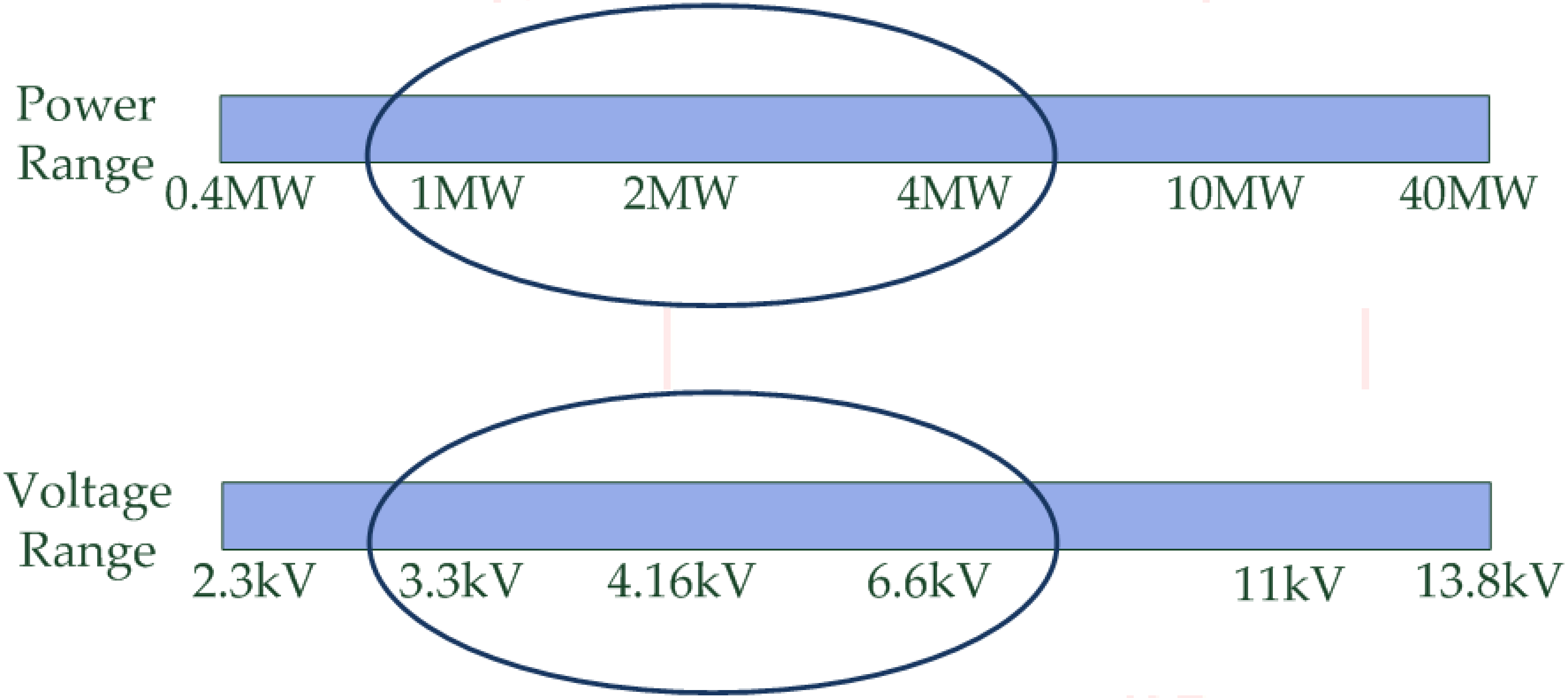


Two-level Voltage Source Inverter



Voltage space vector structure generated by a two-level VSI

Multilevel Inverters - Introduction



Power and Voltage ranges of the Medium Voltage drive

Source: Rockwell Automation

Multilevel Inverters - Introduction

<u>Drawbacks of two-level VSIs for MV Drives</u>

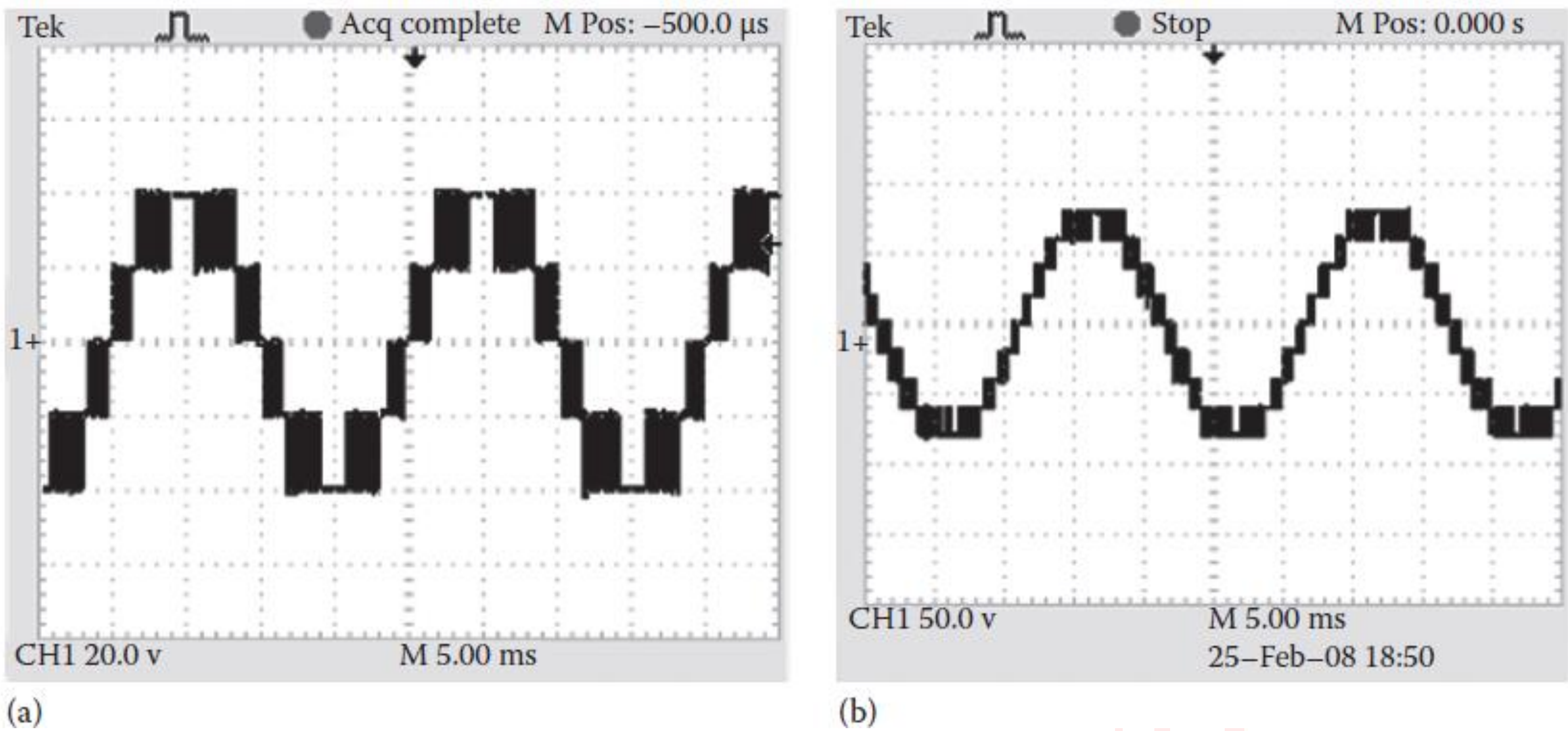
- High dv/dt in the inverter output voltage – as high as 10,000V/μs
- Motor harmonic losses

This can be solved by adding properly tuned LC filter.

It has some disadvantages

- Increased manufacturing cost
- Fundamental voltage drop
- Circulating current between the filter and DC circuit

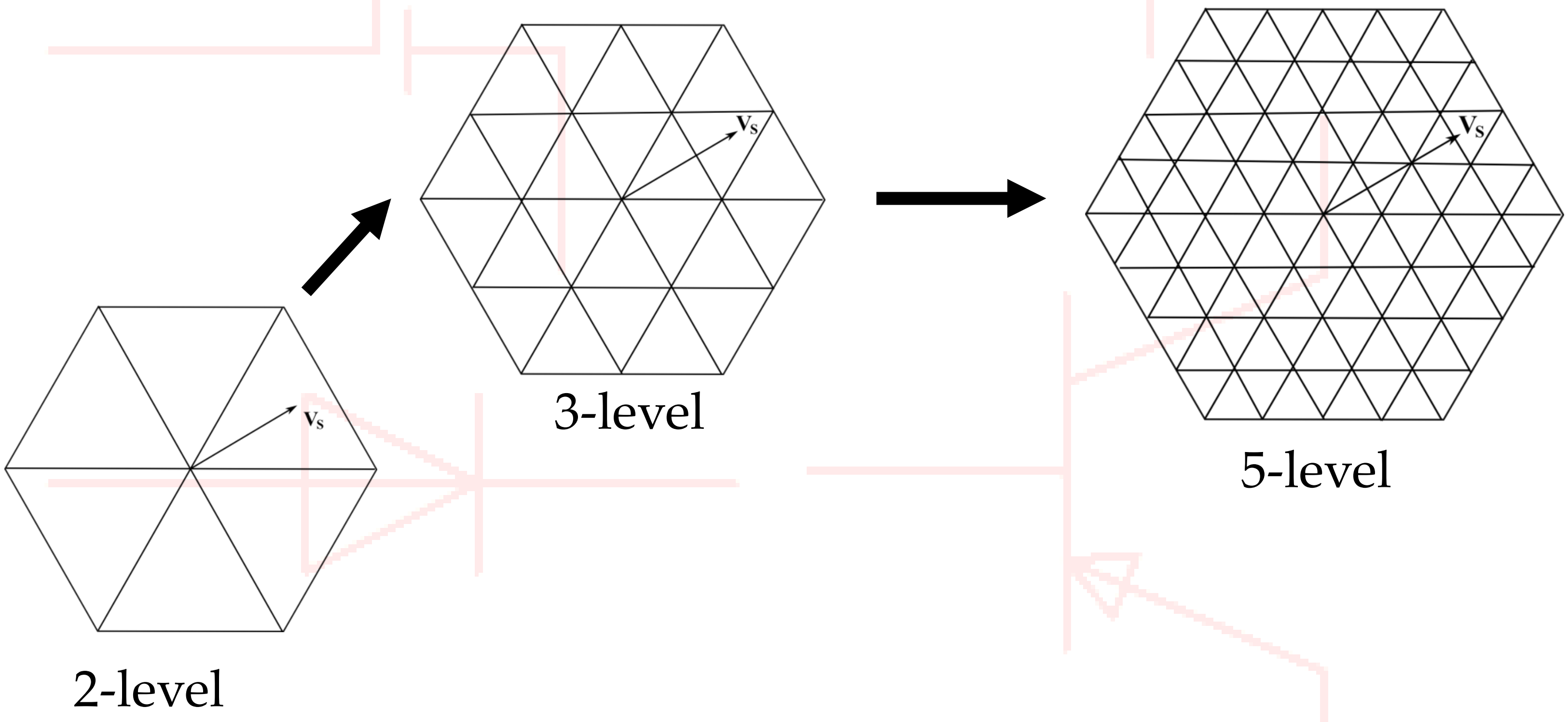
Multilevel Inverters - Introduction



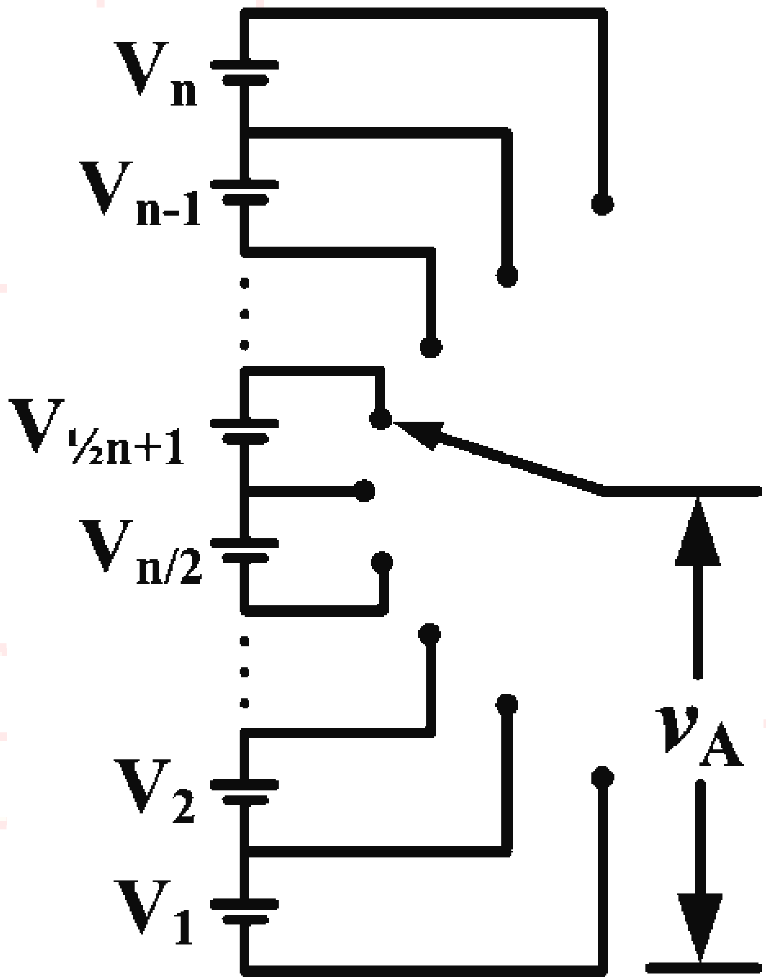
Multilevel inverter output voltage: (a) two-level and (b) nine-level.

Evolution of Multilevel Space vector structures

Hexagonal space vectors.



Multilevel Voltage Source Inverter



One phase leg of general n-level inverter

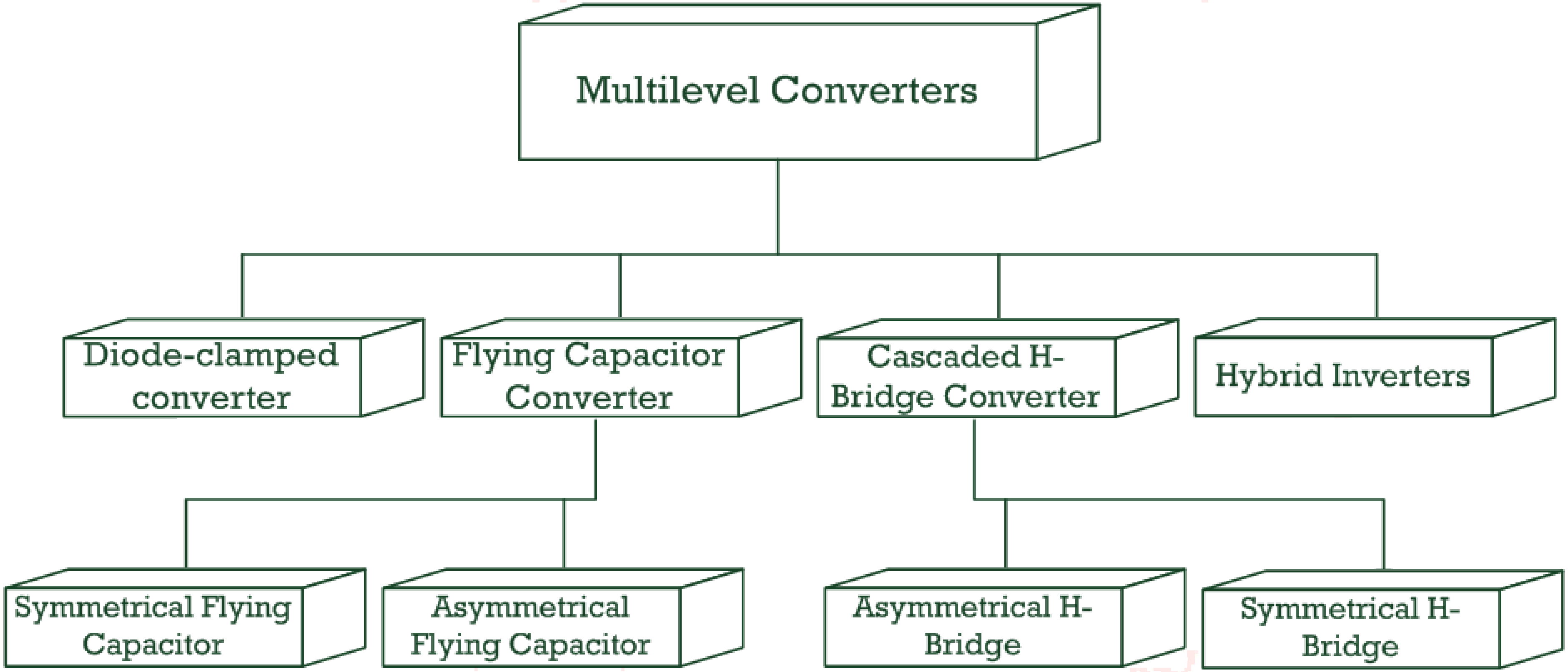
Multilevel Voltage Source Inverter

Multi-level inverters are the preferred choice in industry for the application in High voltage and High power application

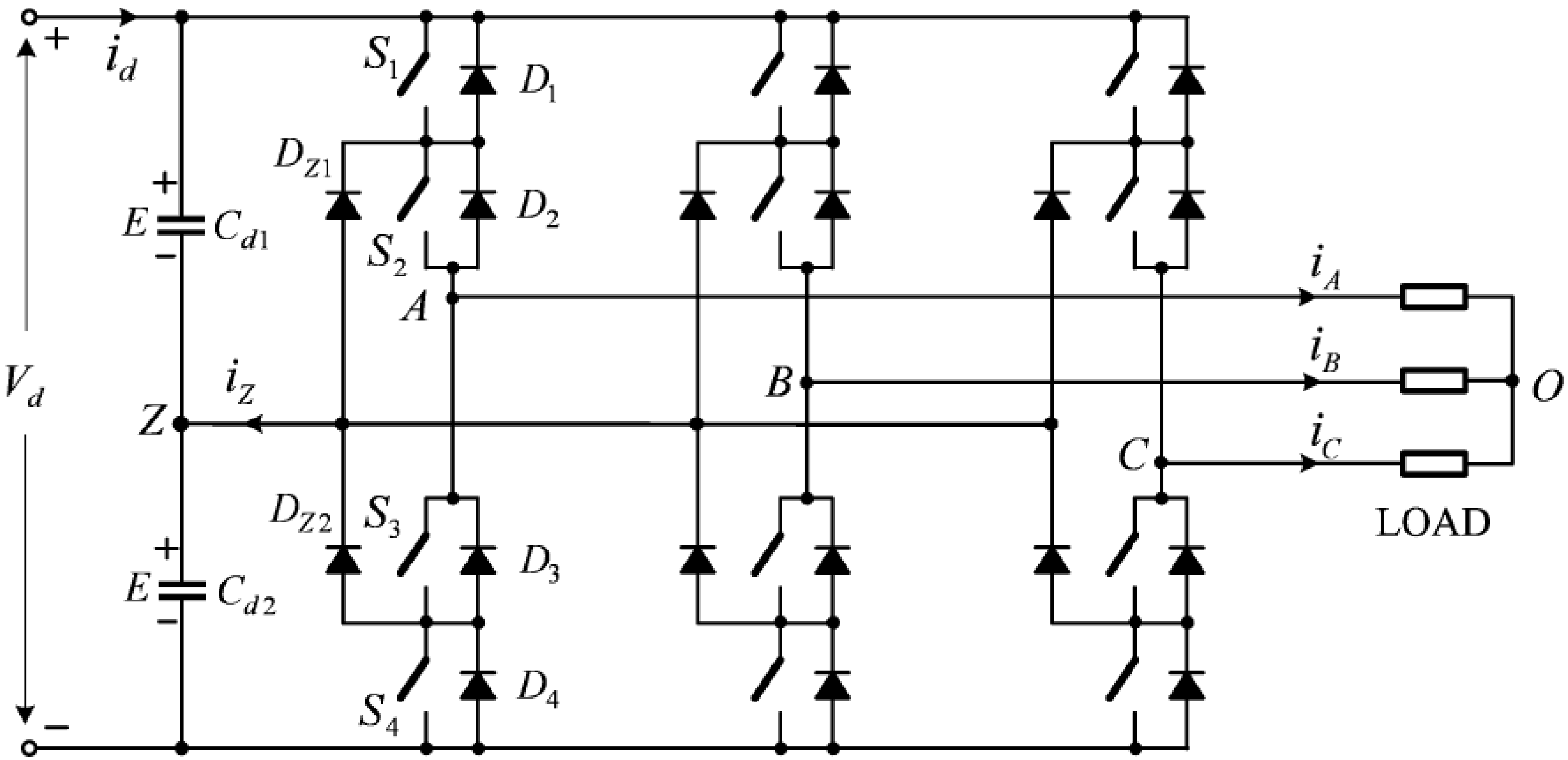
Advantages of Multi-level inverters

- Higher voltage can be generated using the devices of lower rating.
- Increased number of voltage levels produce better voltage waveforms and reduced THD.
- Switching frequency can be reduced for the PWM operation.

Multilevel Converter Topologies



Diode Clamped (NPC) 3-level Inverter

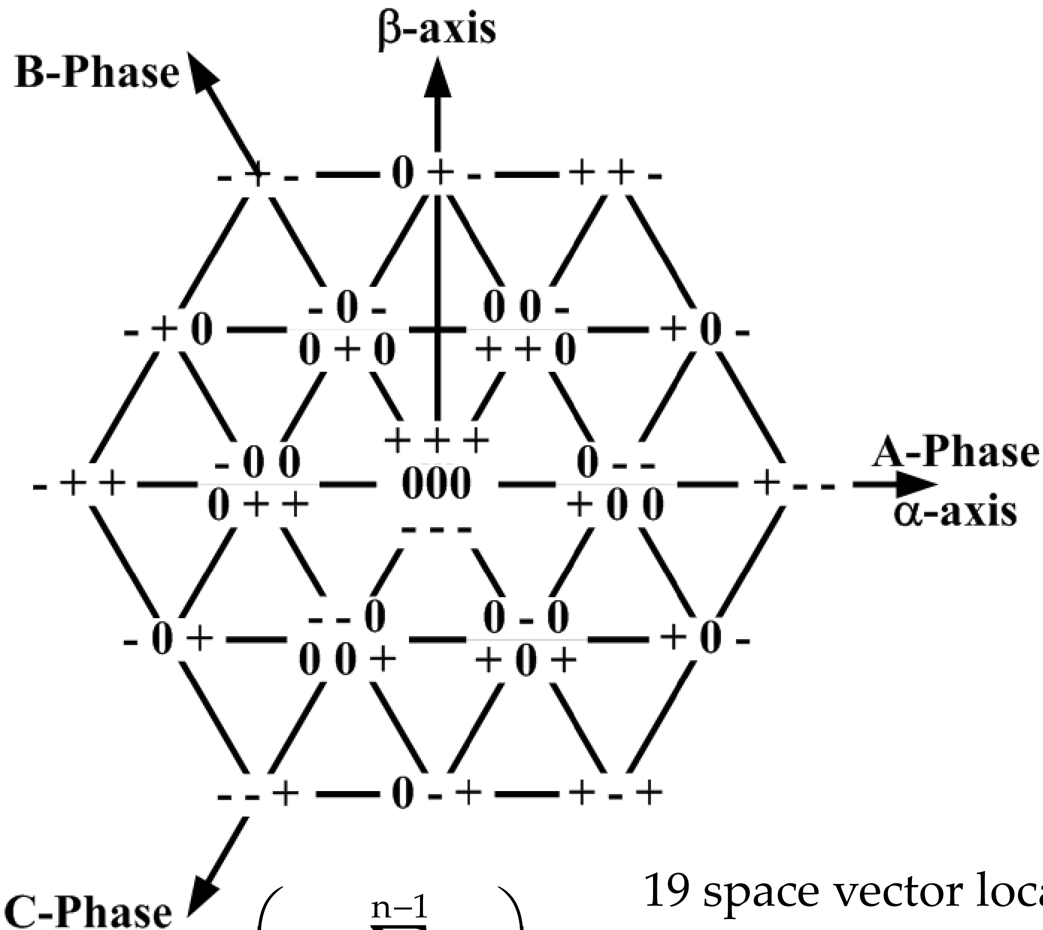


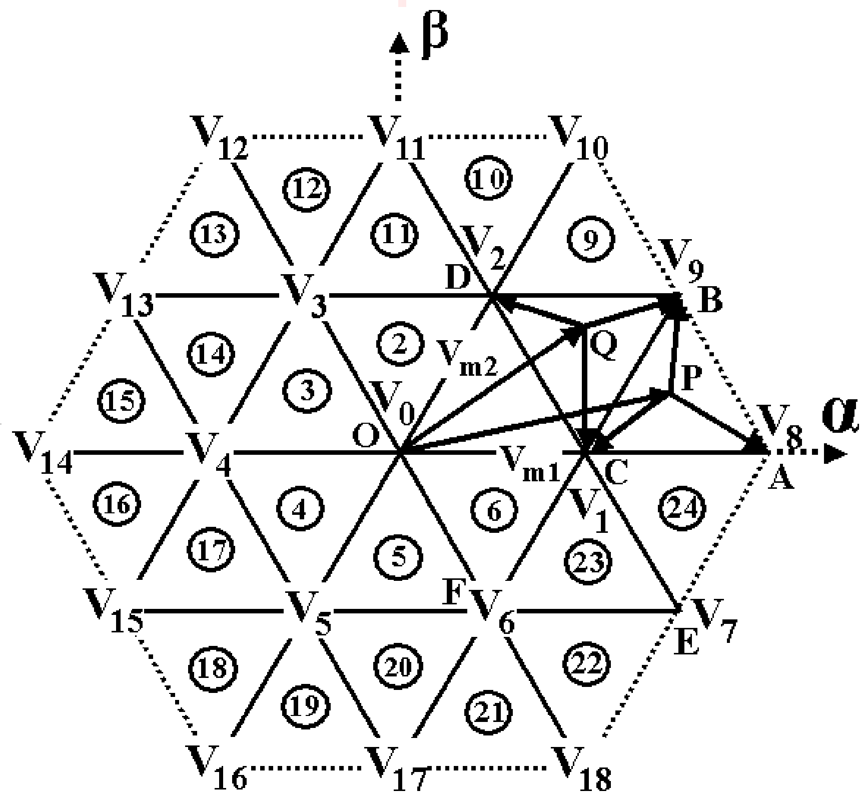
Three-phase three-level diode-clamped converter also called NPC converter

Diode Clamped (NPC) 3-level Inverter

- On the dc side of the inverter, the dc bus capacitor is split into two, providing a neutral point *Z*.
- *The diodes connected to the neutral point,* D_{Z1} *and* D_{Z2}*, are the* clamping diodes.
- When switches S_2 *and* S_3 *are turned on, the inverter output terminal A is connected to the neutral point through one of the clamping diodes.*
- *The voltage* across each of the dc capacitors is *E, which is normally equal to half of the total* dc voltage V_d. *With a finite value for* C_{d1} *and* C_{d2}*, the capacitors can be charged or* discharged by neutral current i_Z*, causing neutral-point voltage deviation.*

Diode Clamped (NPC) 3-level Inverter





19 space vector locations

$$\left(6*\sum_{m=1}^{n-1} m\right)+1,$$ where n is the number of levels in the inverter

27 switching states (n^3 , where n is the number of levels in the inverter)

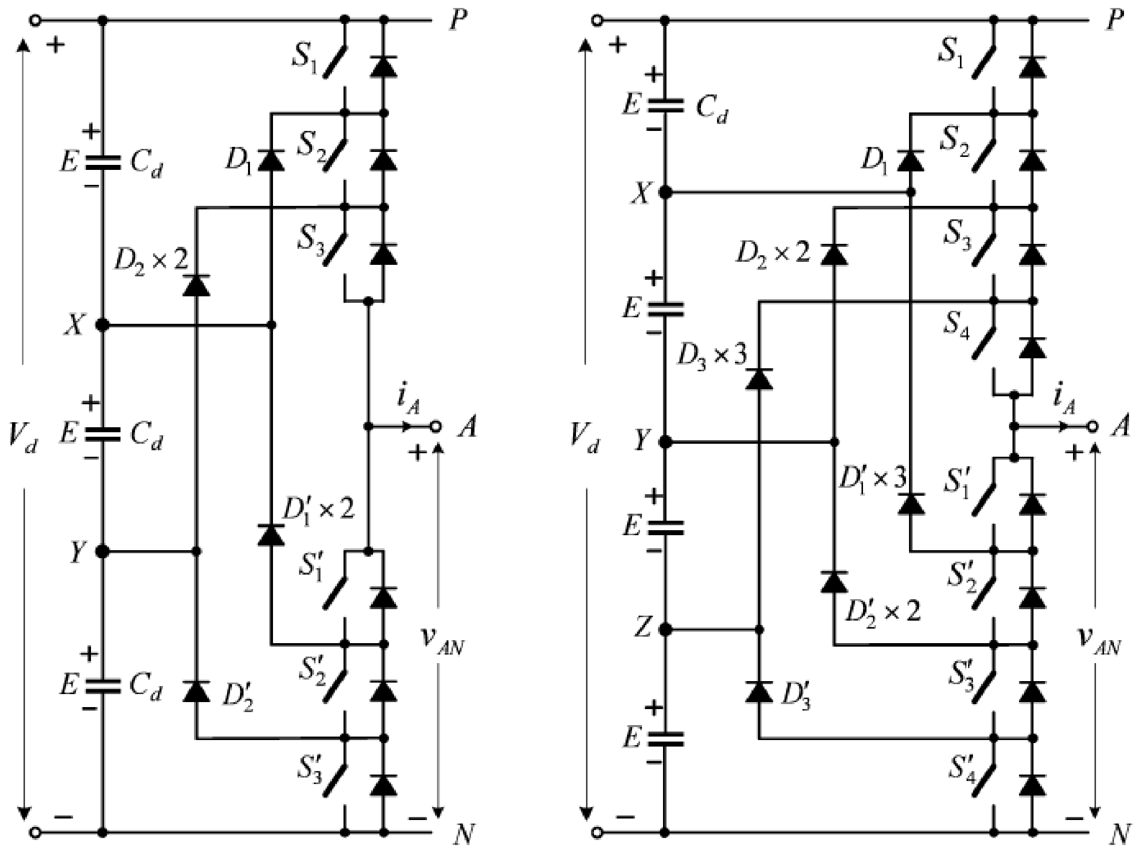
Diode Clamped (NPC) 3-level Inverter

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	$V_d/2$
O	OFF	ON	ON	OFF	0
N	OFF	OFF	ON	ON	$-V_d/2$

Diode Clamped (NPC) 3-level Inverter

- **No dynamic voltage sharing problem**: Each of the switches in the NPC inverter withstands only half of the total dc voltage during commutation.
- **Static voltage equalization without using additional components:** The static voltage equalization can be achieved when the leakage current of the top and bottom switches in an inverter leg is selected to be lower than that of the inner switches.
- **Low THD and *dv/dt:*** *The waveform of the line-to-line voltages is composed* of five voltage levels, which leads to lower THD and *dv/dt in comparison to* the two-level inverter operating at the same voltage rating and device switching frequency.

Diode Clamped (NPC) 4-level and 5-level Inverters

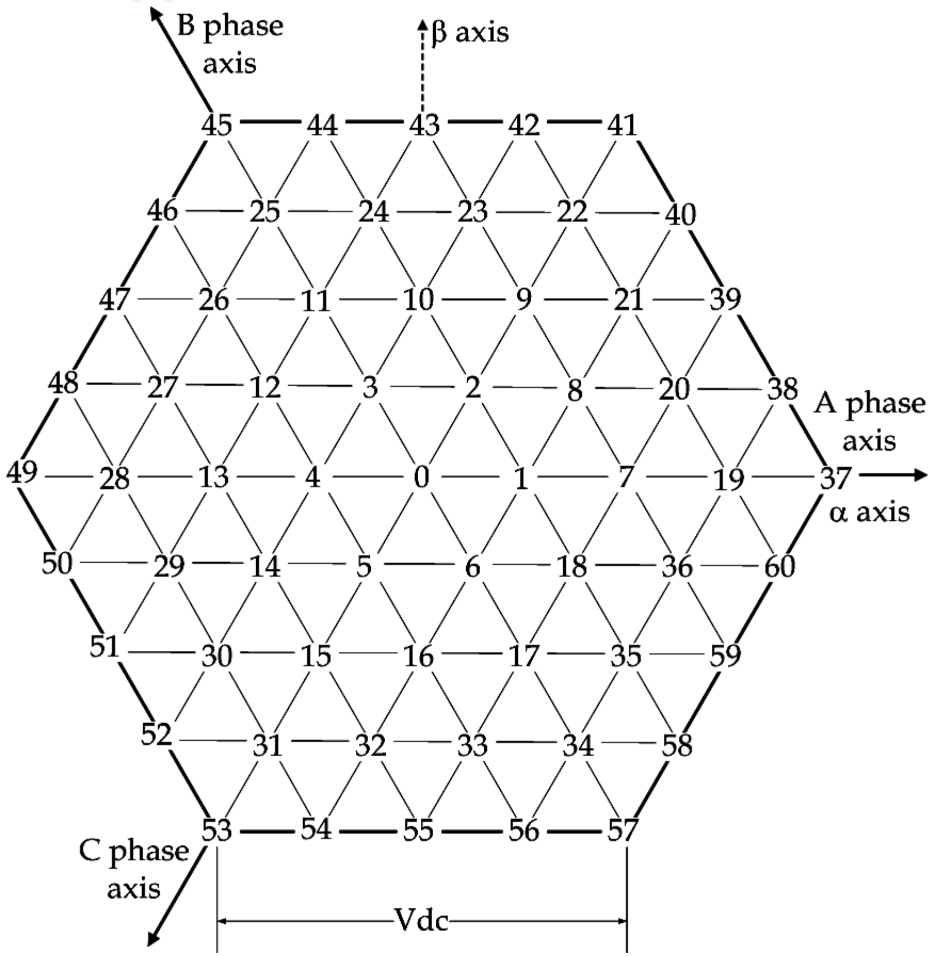


(a) Four-level ($m = 4$) (b) Five-level ($m = 5$)

Diode Clamped (NPC) 4-level and 5-level Inverters

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**

Diode Clamped (NPC) 4-level and 5-level Inverters



5-level space vector structure

Diode Clamped (NPC) multilevel Inverters

Component Count of Diode-Clamped Multilevel Inverters

Voltage Level m	Active Switches 6(m-1)	Clamping Diodes[a] 3(m-1)(m-2)	DC Capacitors (m-1)
3	**12**	**6**	**2**
4	**18**	**18**	**3**
5	**24**	**36**	**4**
6	**30**	**60**	**5**
7	**36**	**90**	**6**

[a]All diodes and active switches have the same voltage rating.

Diode Clamped (NPC) multilevel Inverters

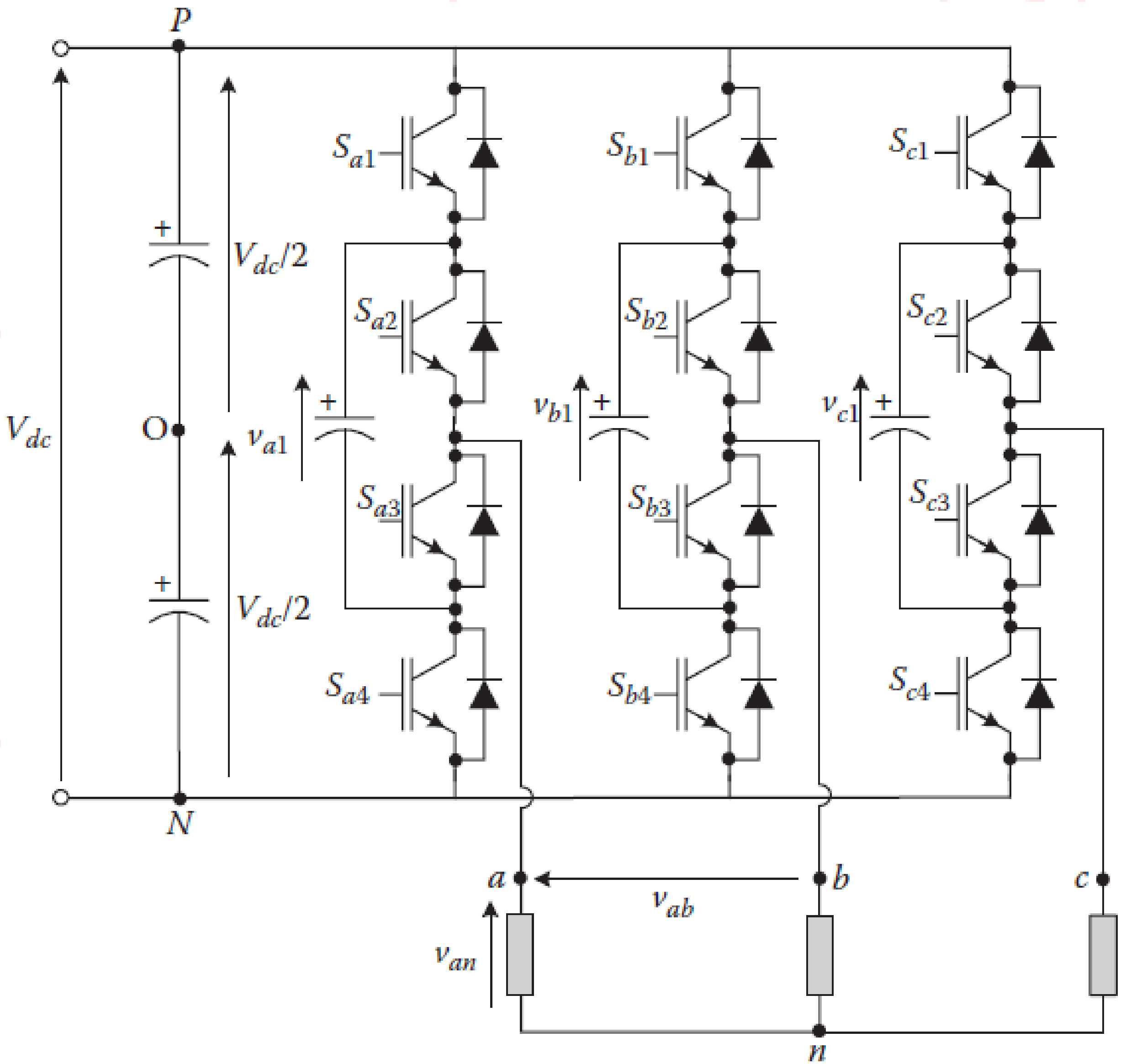
Disadvantages

- Uneven loss distribution in the devices

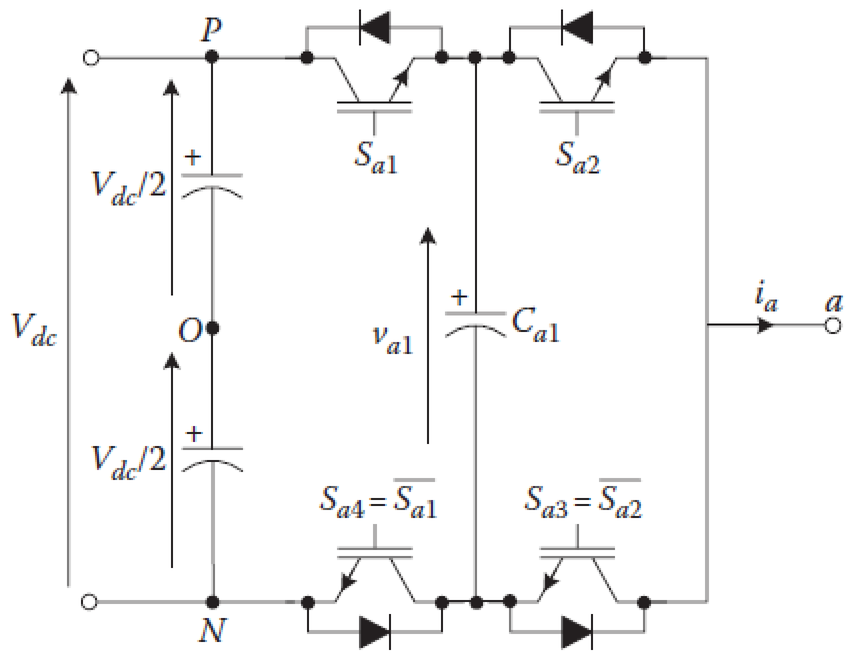
  In a fundamental cycle, the conduction period of the inner devices is more than the outer devices. This causes unequal losses in devices in a leg.

- The fluctuation of the dc bus midpoint voltage
- Additional clamping diodes.
- Complicated PWM switching pattern design

Flying Capacitor 3-level Inverter

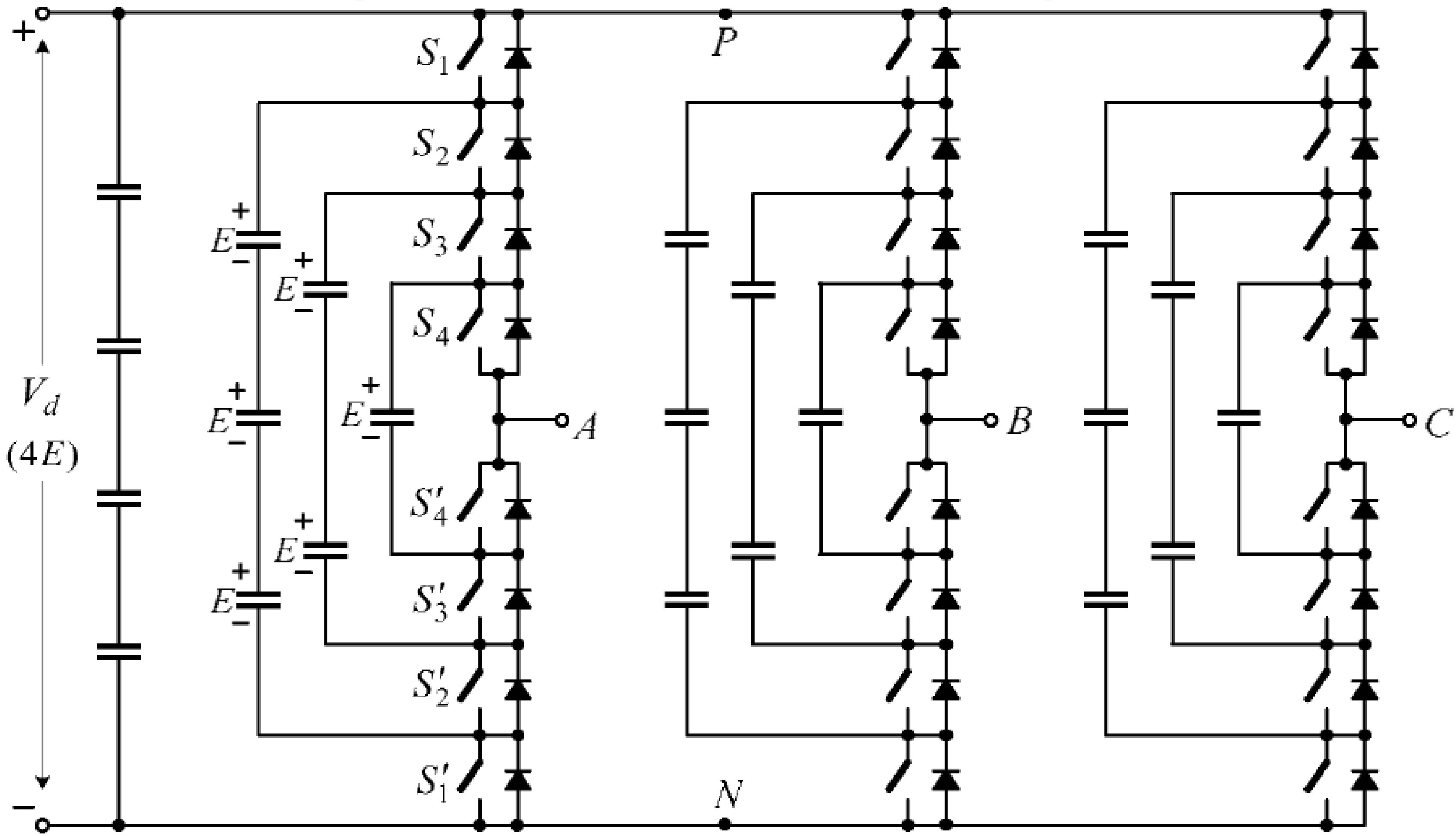


Flying Capacitor 3-level Inverter



S_{a1}	S_{a2}	S_{a3}	S_{a4}	Pole voltage, V_{aO}
1	**1**	**0**	**0**	$V_{dc}/2$
1	**0**	**1**	**0**	**0**
0	**1**	**0**	**1**	**0**
0	**0**	**1**	**1**	$-V_{dc}/2$

Flying Capacitor 5-level Inverter



Flying Capacitor 5-level Inverter

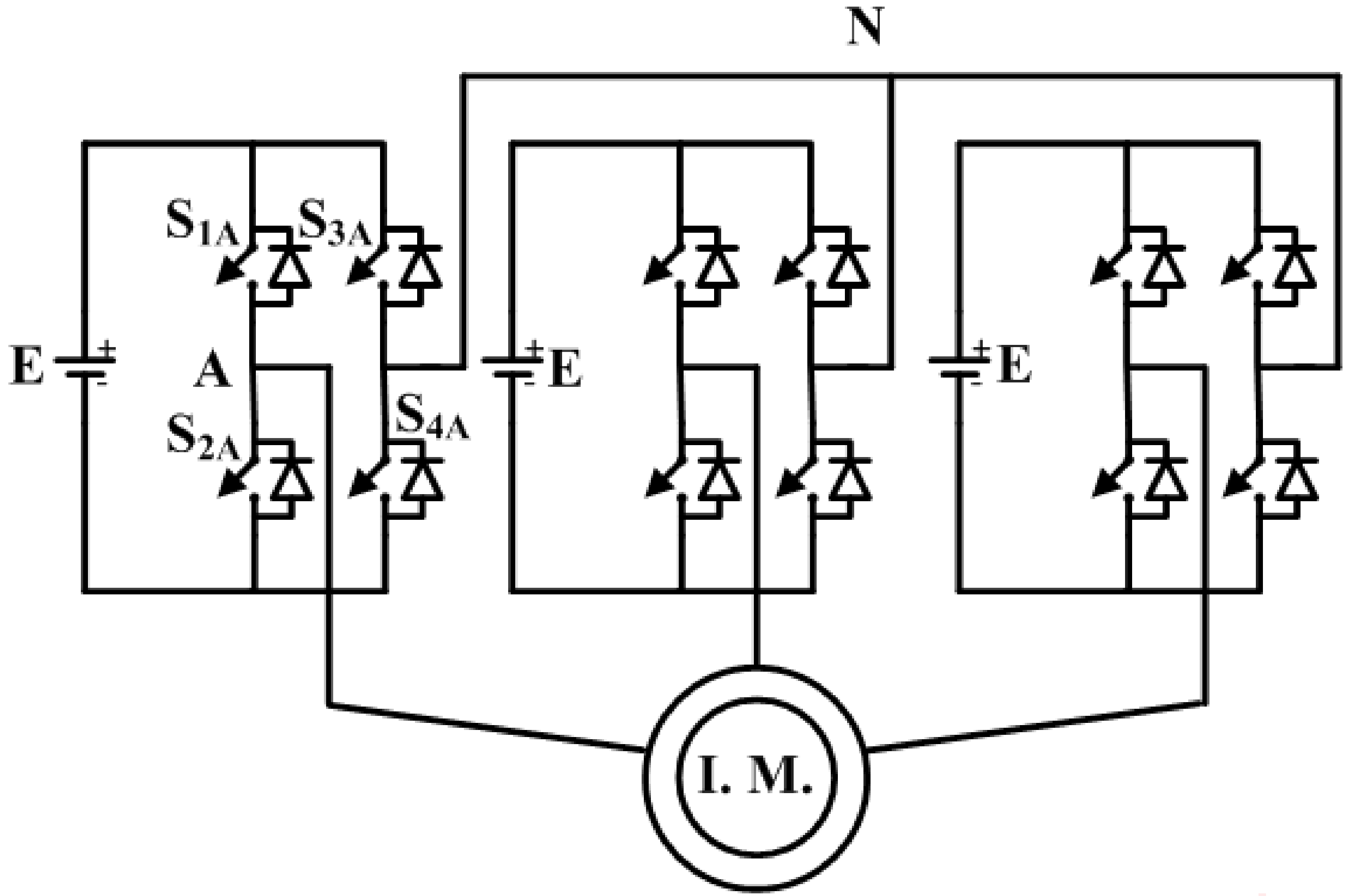
Switching State				Pole voltage, V_{AN}
S_1	S_2	S_3	S_4	
1	1	1	1	4E
1	1	1	0	3E
0	1	1	1	
1	0	1	1	
1	1	0	1	
1	1	0	0	2E
0	0	1	1	
1	0	0	1	
0	1	1	0	
1	0	1	0	
0	1	0	1	
1	0	0	0	E
0	1	0	0	
0	0	1	0	
0	0	0	1	
0	0	0	0	0

Flying Capacitor Multilevel Inverters

Component Count of Flying Capacitor Multilevel Inverters

Voltage Level m	Active Switches 6(m-1)	Clamping Diodes	DC Capacitors $(m-1)+3*(\sum_{k=1}^{m-2} k)$
3	12	0	5
4	18	0	12
5	24	0	22
6	30	0	35
7	36	0	51

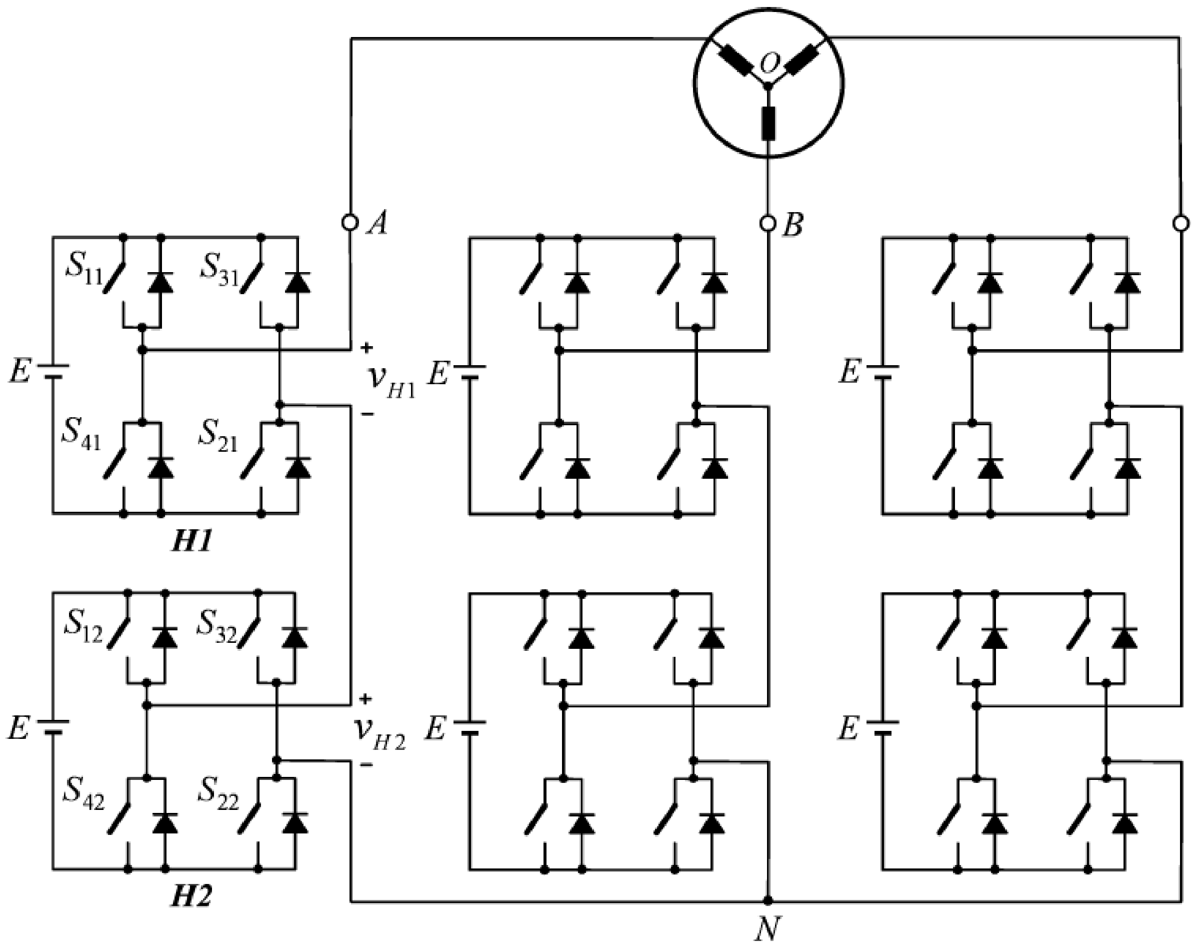
Multilevel (3-level) Cascaded H-Bridge Inverters - with equal voltages



Multilevel (3-level) Cascaded H-Bridge Inverters - with equal voltages

Switching State				Pole voltage, V_{AN}
S_{1A}	S_{2A}	S_{3A}	S_{4A}	
1	0	0	1	E
1	0	1	0	0
0	1	0	1	
0	1	1	0	-E

Multilevel (5-level) Cascaded H-Bridge Inverters - with equal voltages



Multilevel (5-level) Cascaded H-Bridge Inverters - with equal voltages

Switching State				V_{H1}	V_{H2}	Pole voltage, V_{AN}
S_{11}	S_{31}	S_{12}	S_{32}			
1	0	1	0	E	E	2E
1	0	1	1	E	0	E
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	1	1	0	0	
1	1	0	0	0	0	
1	0	0	1	E	-E	
0	1	1	0	-E	E	
0	1	1	1	-E	0	-E
0	1	0	0	-E	0	
1	1	0	1	0	-E	
0	0	0	1	0	-E	
0	1	0	1	-E	-E	-2E

Multilevel Cascaded H-Bridge Inverters – with equal voltages

The number of voltage levels in a CHB inverter can be found from

$$m = (2H + 1)$$

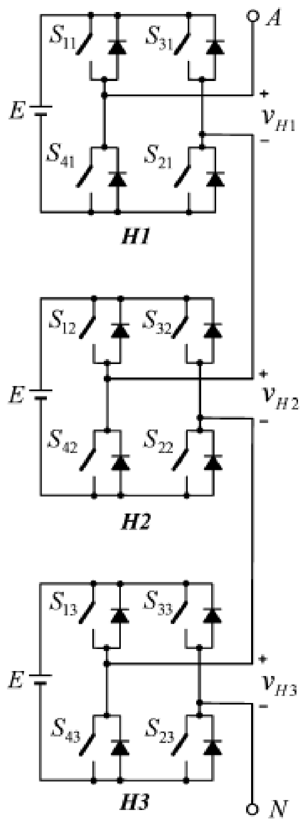
where H is the number of H-bridge cells per phase leg.

The voltage level m is always an odd number for the CHB inverter while in other multilevel topologies such as diode-clamped inverters, it can be either an even or odd number.

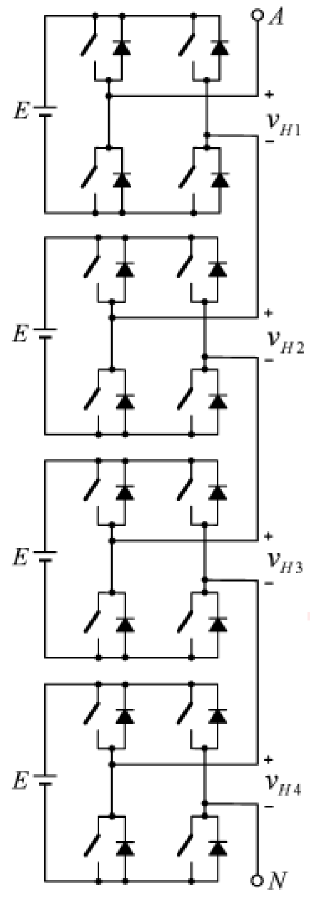
The total number of **active switches (IGBTs)** used in the CHB inverters can be calculated by

$$N_{sw} = 6(m - 1)$$

Multilevel Cascaded H-Bridge Inverters (7 and 9-level) – per phase diagram

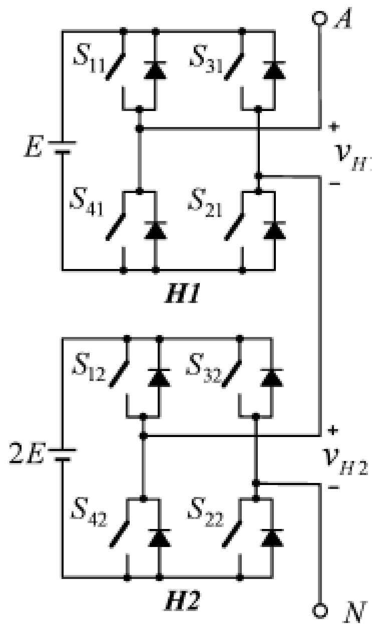


(a) Seven-level inverter

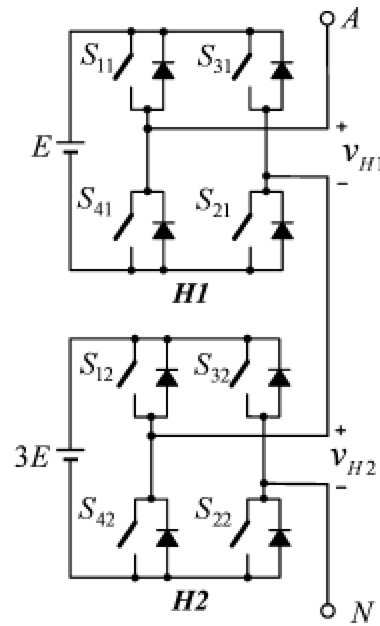


(b) Nine-level inverter

Multilevel Cascaded H-Bridge Inverters - with unequal voltages



(a) Two-cell seven-level topology



(b) Two-cell nine-level topology

Per phase diagram

Multilevel Cascaded H-Bridge Inverters - with unequal voltages

Voltage Level and Switching State of the Two-Cell Seven-Level CHB Inverter with Unequal dc Voltages

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

Cascaded H-Bridge Multilevel Inverters

Component Count of Cascaded H-Bridge Multilevel Inverters

Voltage Level m	Active Switches 6(m-1)	Clamping Diodes	DC Sources
3	12	0	3
5	24	0	6
7	36	0	9
9	48	0	12

References

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THANK YOU