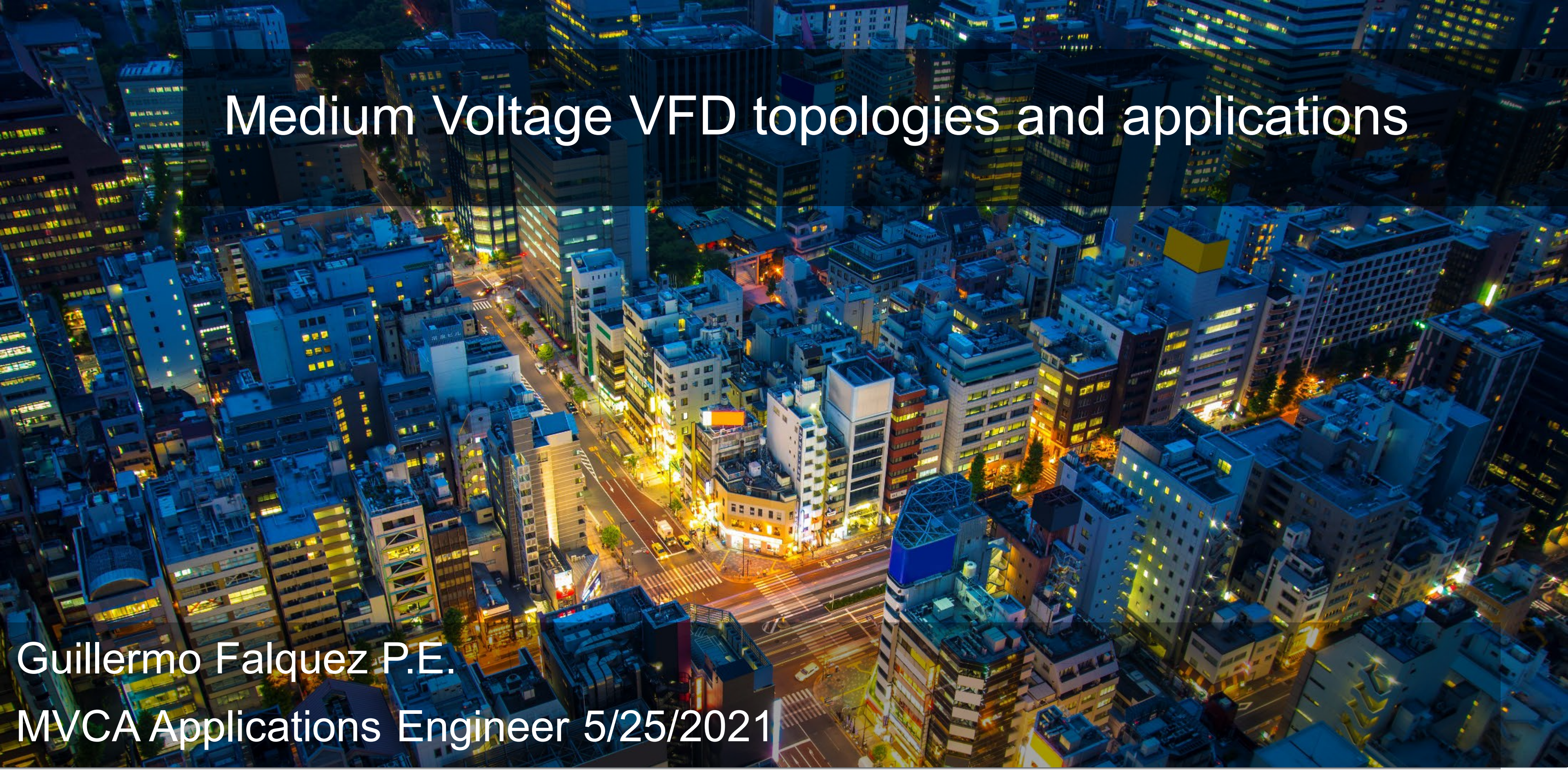


Medium Voltage VFD topologies and applications

Guillermo Falquez P.E.
MVCA Applications Engineer 5/25/2021

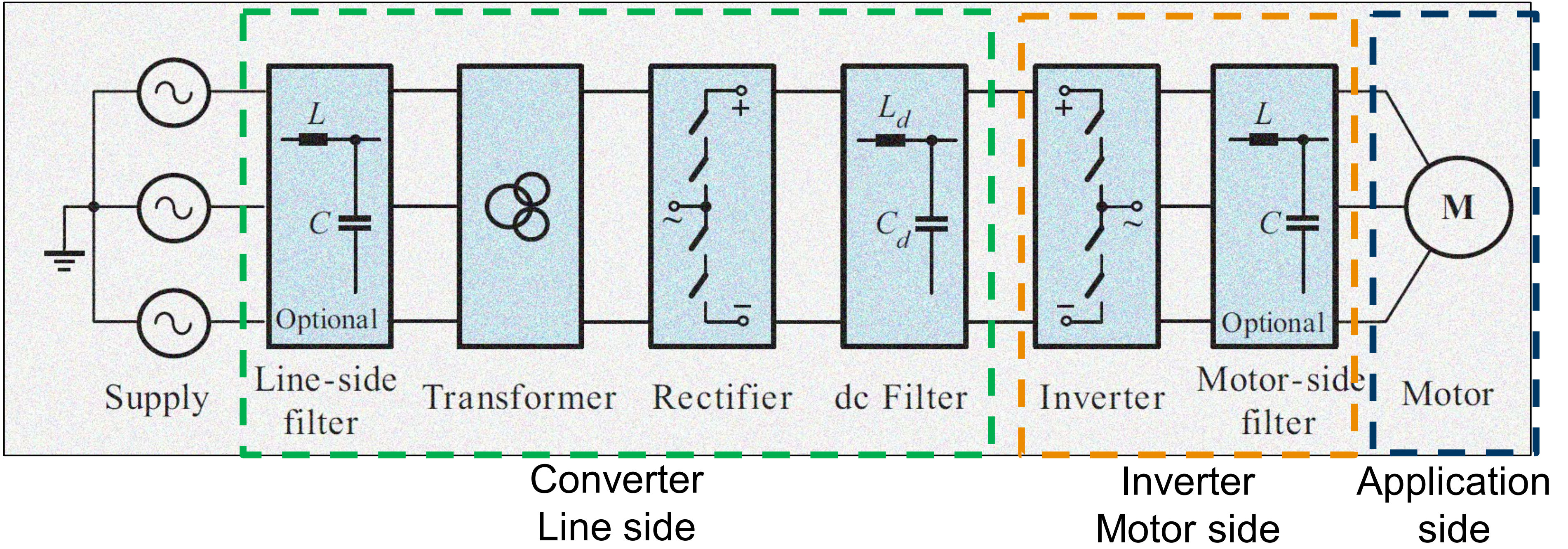
EATON
Powering Business Worldwide

Agenda

- VFD Components
- Line side concerns
- PFE converters
- AFE converters
- Load side concerns
- MV VFD Topologies
    - PWM CSI
    - 2L VS
    - NPC
    - CHB

What are the components of a medium voltage VFD?

What are the components of a MV VFD?



What are some of the line side concerns?

VFD line side concerns

Converts AC to constant DC voltage

- Affects the performance on the utility side

Pulse count

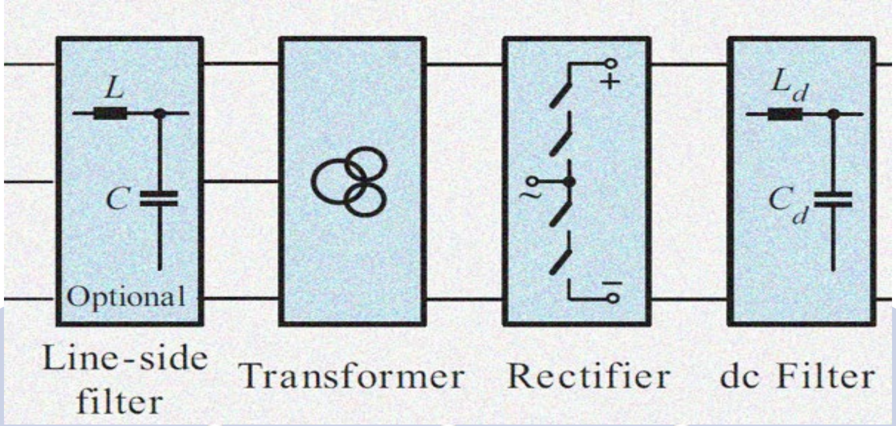
- 6, 12, 18, 24…

DC-Link

- Filters ripple and it serves as reactive power energy storage

Application main concerns

- Do not produce harmonics into the system – meet IEEE 519 requirements at VFD input
- Do not degrade the system power factor >.95 lag
- Avoid LC resonance

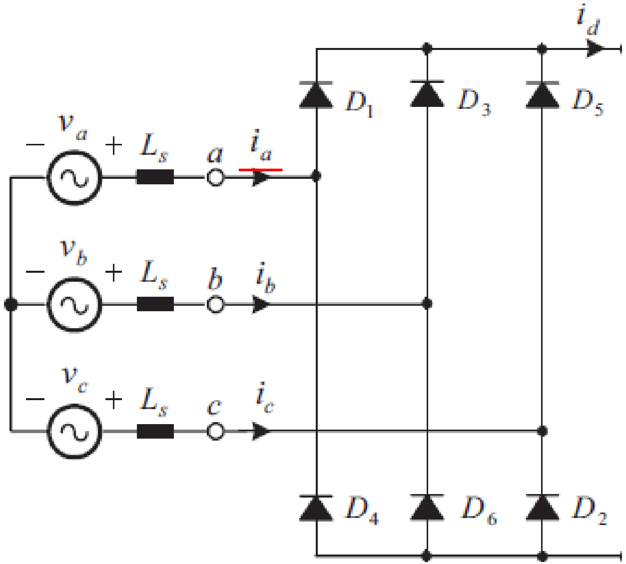


Line-side filter	Transformer	Rectifier	dc Filter
Input harmonics	Number of pulses	AFE or PFE	Current Source (CS)
Power factor	Inrush current mitigations	Number of pulses	Voltage Source (VS)
Efficiency	Integrated or remote	Component's ratings	Type of capacitors
System resonance	Heat losses		Pre-charge, SoftMag

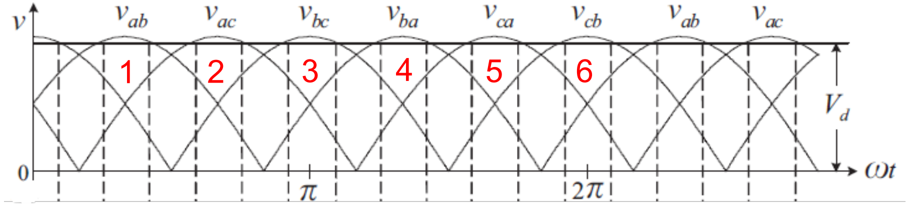
EATON
Powering Business Worldwide

Passive Front End Converters

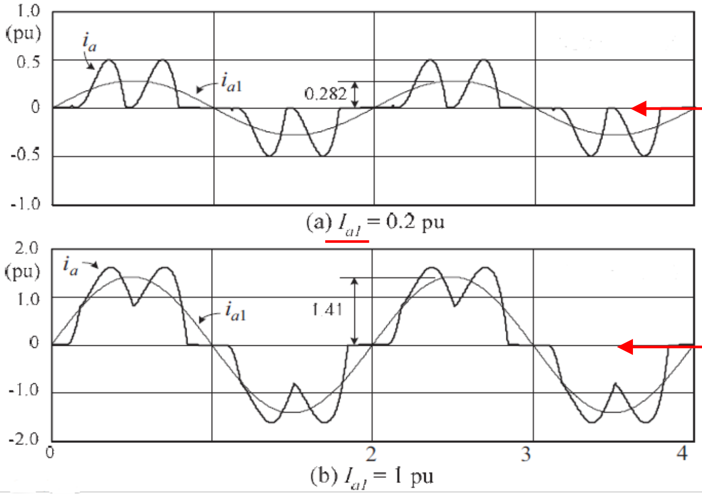
Converter Passive Front End (PFE) – 6 - pulse rectifier



6 pulse diode rectifier circuit



6 pulse diode rectifier - voltage



Low load
High THD

Rated load
Low THD

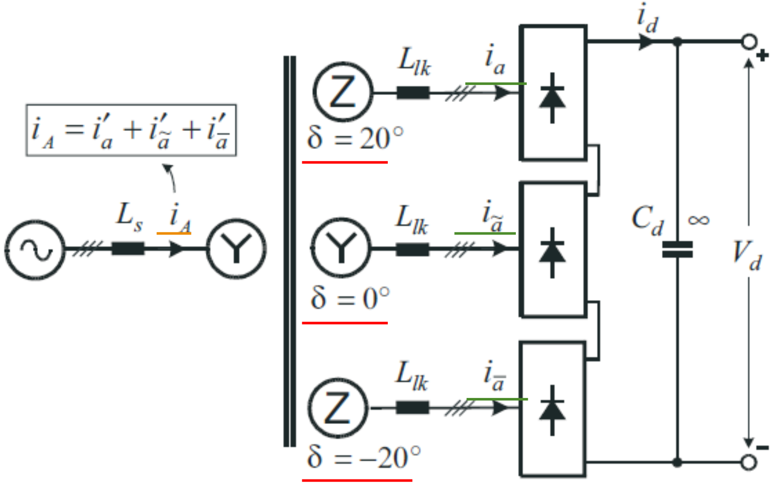
6 pulse diode rectifier – input current

EATON
Powering Business Worldwide

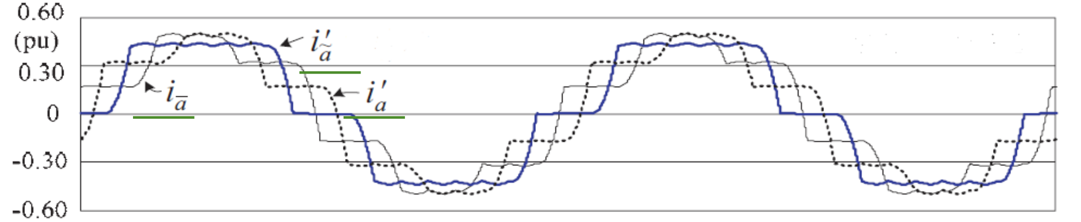
From High Power Converters and AC Drives – Bin Wu

Converter PFE – 18 - pulse series connected rectifier

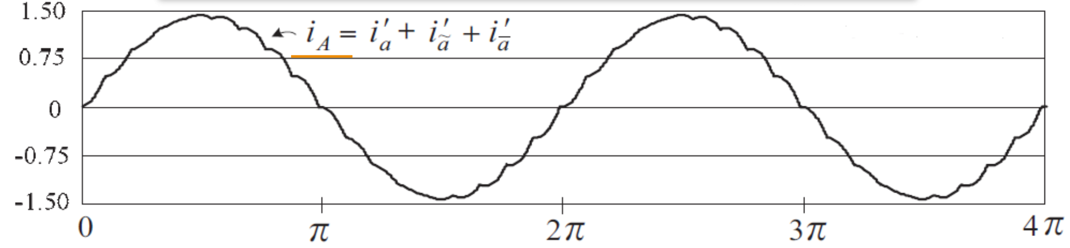
Marginal IEEE 519 compliance depending on system impedance



18 pulse diode rectifier circuit



18 pulse diode rectifier – input current (secondary)

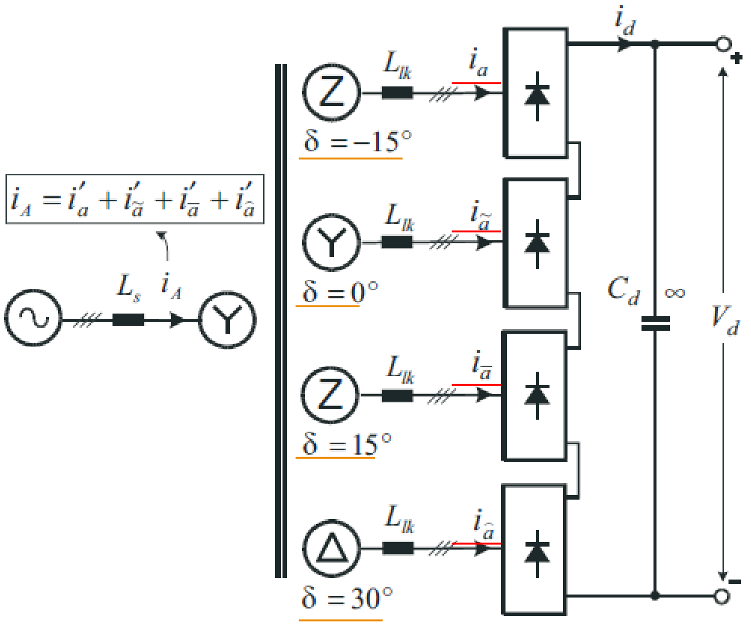


18 pulse diode rectifier – input current (primary)

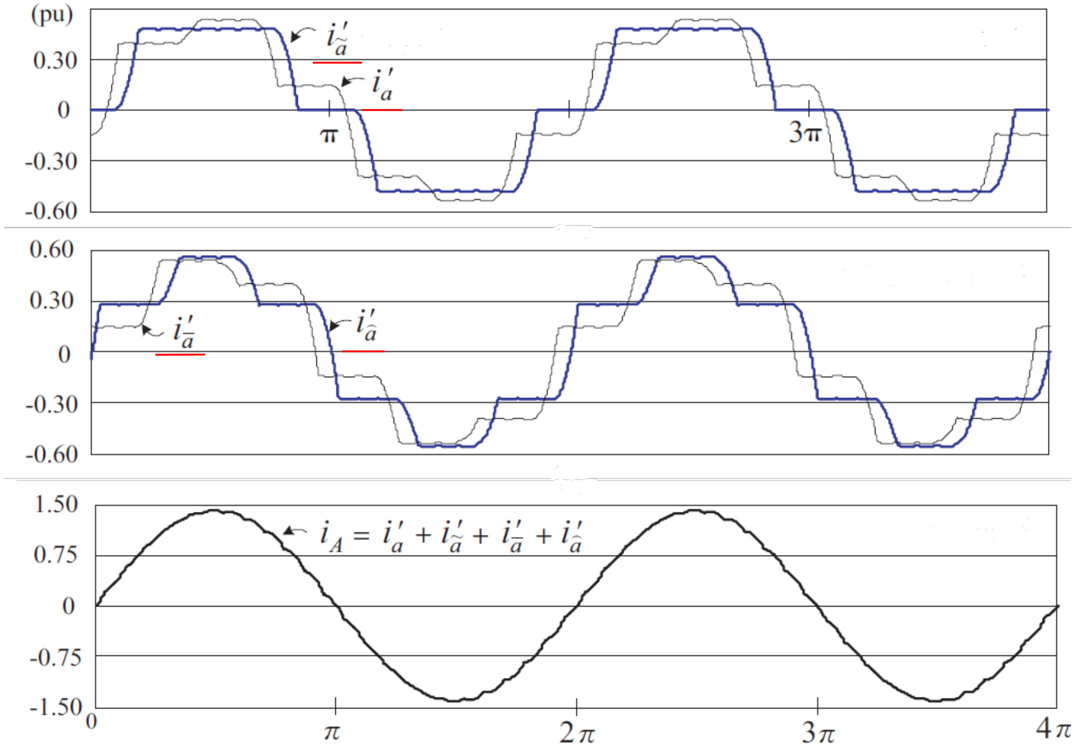
From High Power Converters and AC Drives – Bin Wu

Converter PFE – 24 - pulse series connected rectifier

Fully compliant with IEEE 519



24 pulse rectifier

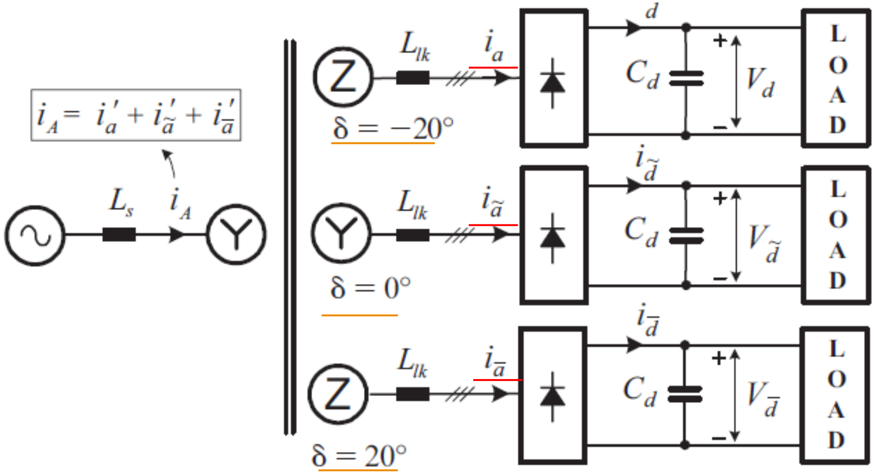


24 pulse diode rectifier – input current (primary)

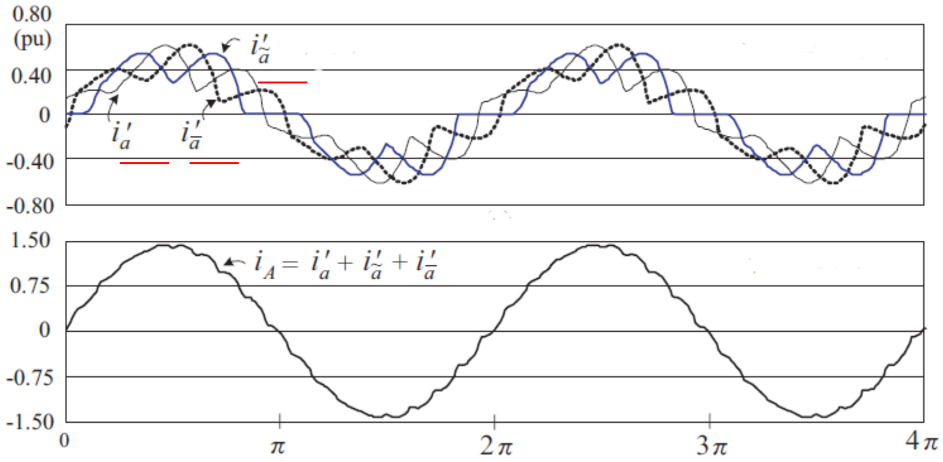
From High Power Converters and AC Drives – Bin Wu

Converter PFE – 18 - pulse separate-type rectifier

- Used in Cascaded H-bride inverter topology
- Slightly better THD with marginally lower pf



18 pulse separate - type rectifier



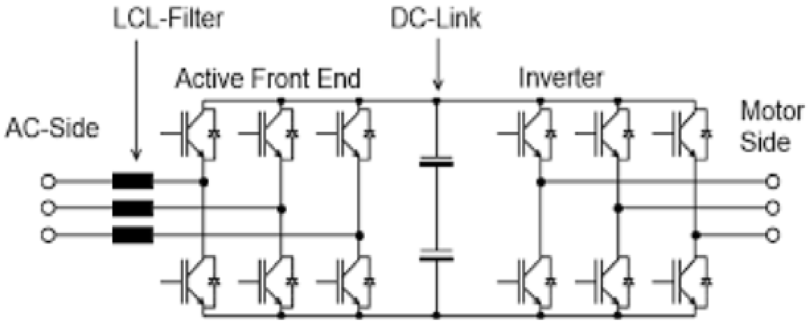
18 pulse diode rectifier
Input current (primary & secondary)

EATON Powering Business Worldwide

From High Power Converters and AC Drives – Bin Wu

Active Front End Converters

What are the components of a medium voltage VFD? – Converter Active Front End (AFE)



AFE Converter

- Not a topology but a type of converter circuit
- Diodes are replaced by transistors (active devices) to control low order harmonics
- Makes use of LCL passive filter to reduce high order input harmonics caused by switching frequency of transistors

"Friendly" AFE topologies

- Voltage Source
  - Neutral Point Clamped (NPC) – 3L, 5L
  - Modular Multilevel Converter (M2C)
- Current Source
  - LCI
  - 2L-CSI

Advantages – Why AFE?

- Dynamic braking or power regeneration
  - Large fans
  - Downhill conveyors
  - Elevators
  - Cranes
  - Centrifuges
  - Wind tunnels
- Low THD levels (<50th harmonic)
- Excellent power factor control (i.e. active VAR compensation applications)

Disadvantages

- LCL filter may cause resonance issues with electrical system i.e. generators, transformers, capacitor banks, etc.
  - Not adaptable to electrical system changes
- Higher cost
- Lower efficiency
- Larger footprint due to filter
- "Complex" controls

Powering Business Worldwide

What are some of the load side concerns?

VFD Motor side concerns

Converts constant DC to PWM waveform

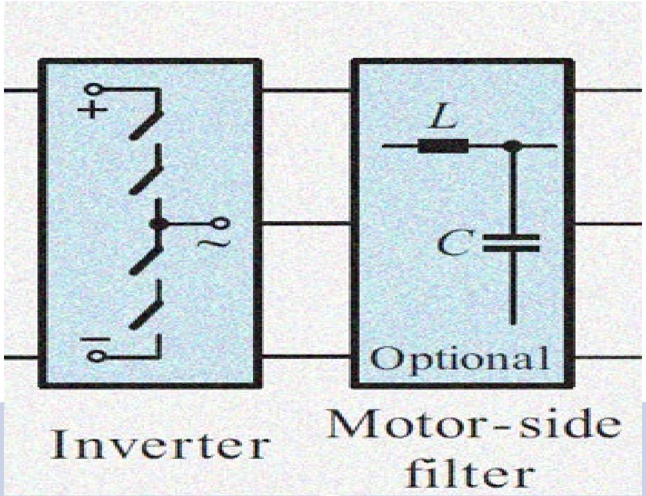
- Affects the performance on the motor side

Output levels

- 2-3, 3-5, 4-7, 5-9, 9-17…

Application main concerns

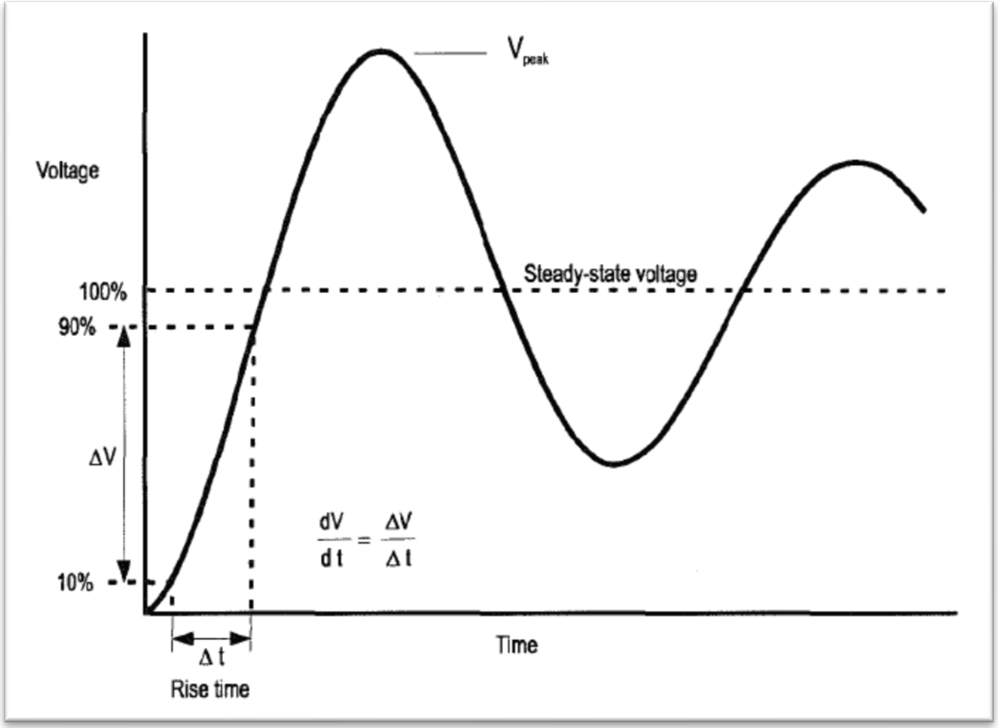
- Do not damage the motor (standard and inverter duty)
  - dv/dt and wave reflections
  - Low common-mode voltage stress
  - LC resonance
  - Limited motor harmonics



Inverter	Motor-side filter
Topology	Motor type
Number of levels	Efficiency
Heat losses	dv/dt
Components rating	Cable length
Control method	Output harmonics
	Integrated or remote

EATON
Powering Business Worldwide

MG-1 Motor voltage stress ratings



Typical voltage response at motor terminals

Part 30 - Standard duty motor voltage stress ratings

- Motors with base rating voltage $V_{rated} \leq$ 600V
  - **$V_{peak} \leq$ 1kV**
  - **Rise time ≥ 2 μs**

Part 31 - Inverter duty motor voltage stress ratings

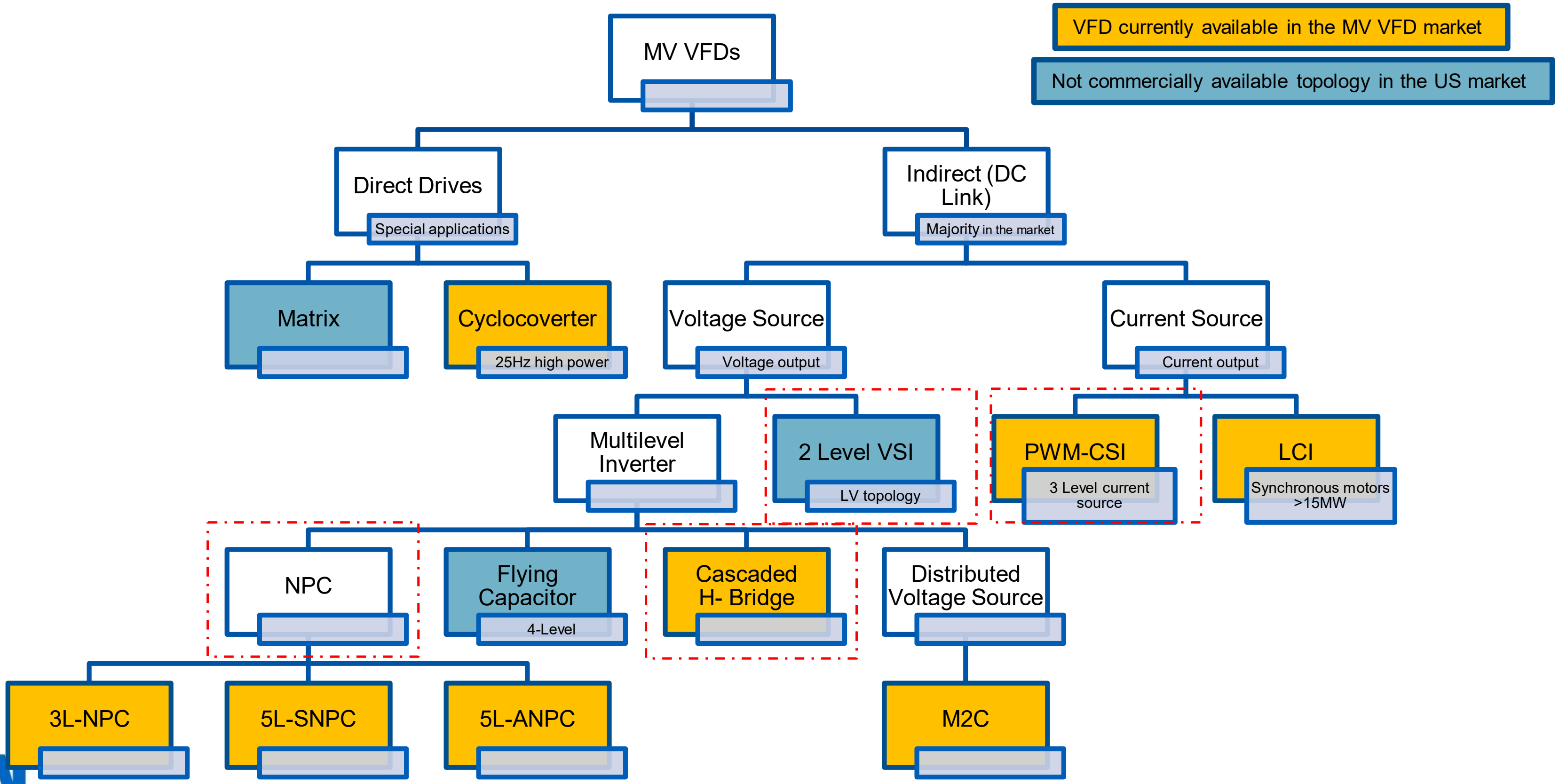
- Motors with base rating voltage $V_{rated} \leq$ 600V
  - **$V_{peak} \leq 3.1 * V_{rated}$**
  - **Rise time ≥ 1 μs**
- Motors with base rating voltage $V_{rated} >$ 600V
  - **$V_{peak} \leq 2.04 * V_{rated}$**
  - **Rise time ≥ 1 μs**

Where: V_{peak} is a single amplitude zero-to-peak line-to-line voltage.

EATON
Powering Business Worldwide

Inverter topologies for MV VFDs

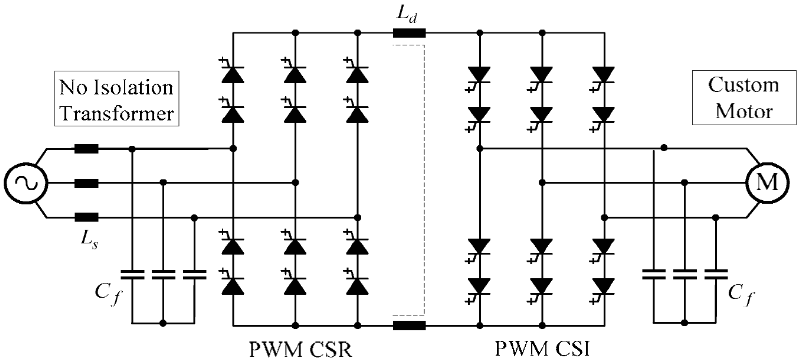
MV VFD Topologies



Powering Business Worldwide

Current Source Inverter PWM-CSI

Current Source Inverters – PWM-CSI Topology



From High Power Converters and AC Drives – Bin Wu

CSI Topology

- Fist type of MV VFDs available in the market utilizing SCRs
- Output filter always necessary
- Available configurations
  - “Transformer-less” – LCL filter input
  - Isolation transformer and 6, 12, or 18 pulse AFE rectifier

Advantages

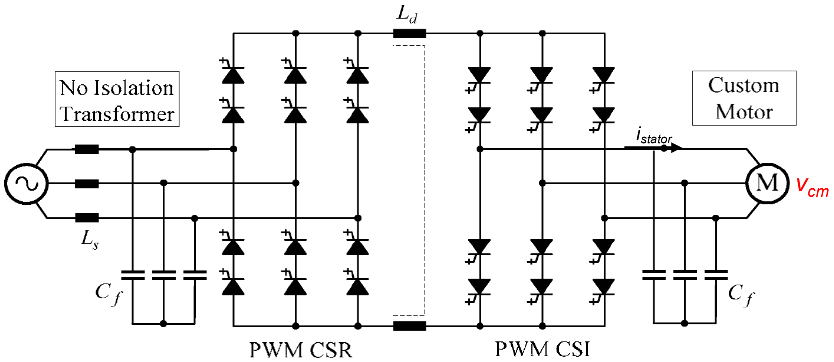
- Long input and output cables – low dv/dt rise time
- Excellent power factor with isolation transformer + AFE SGCTs
- Low component count
- 4-quadrant operation

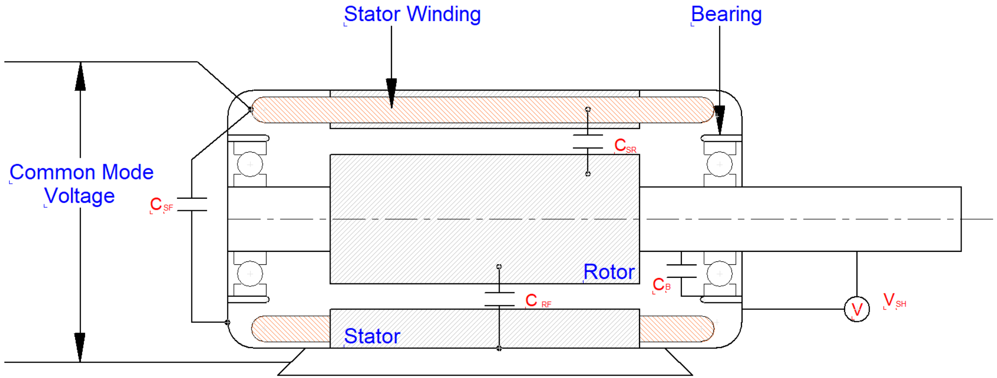
Disadvantages

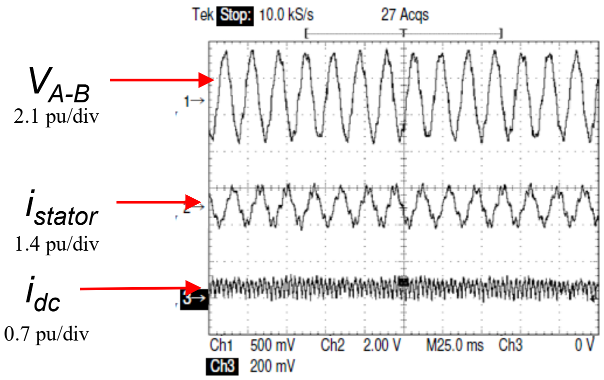
- Filter must be evaluated if system impedance changes
- Design relies on upstream protection to interrupt faults downstream inverter
- Lower efficiency due to current switching
- Limited dynamic performance when compared to VSI
- Large K ratings required to filter harmonics
- Common mode problems with “transformer-less” design

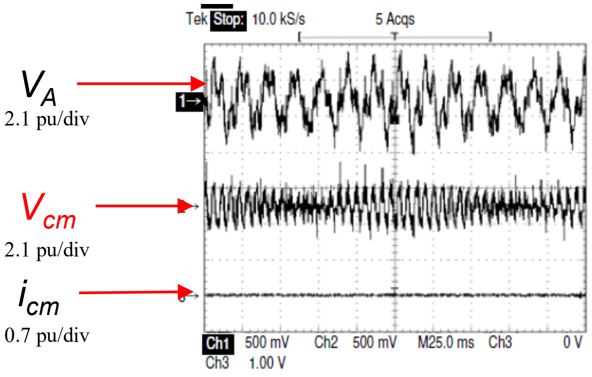
EATON Powering Business Worldwide

Current Source Inverters – Common mode voltage









Common mode voltage V_{cm}

- If not mitigated by DC choke or isolation transformer common mode voltage on motor neutral can cause insulation damage over time.

Example of CSI VFD waveforms with no DC choke

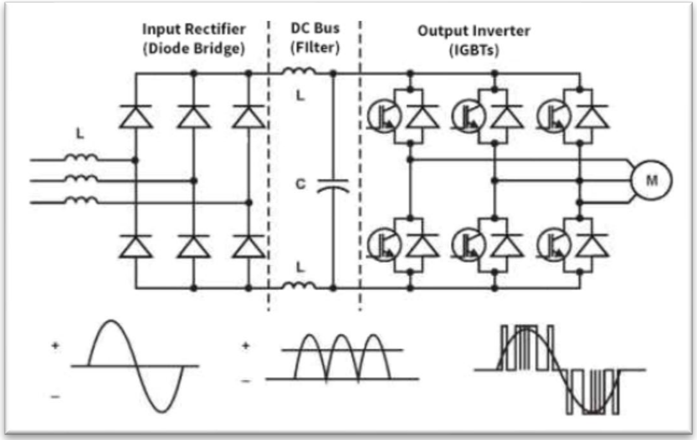
- Phase voltage V_A
  - Contains $V_{L\text{-}N}$ and V_{cm} (superimposed)

From High Power Converters and AC Drives – Bin Wu

Voltage Source Inverter Neutral Point Clamp

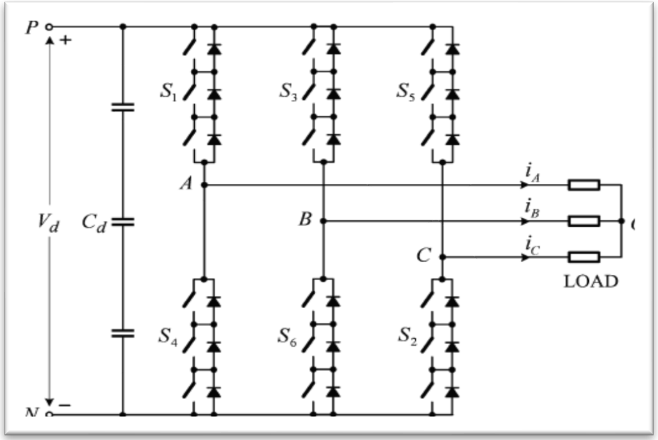
Powering Business Worldwide

Voltage Source Inverters – 2 Level Topology



2 Level inverter for LV applications

V_d = 5883V
For 4.16kV VFD

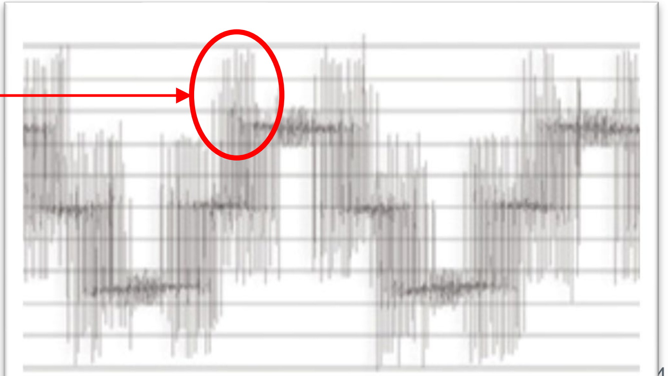


2 Level inverter for MV applications

2 Level Inverter

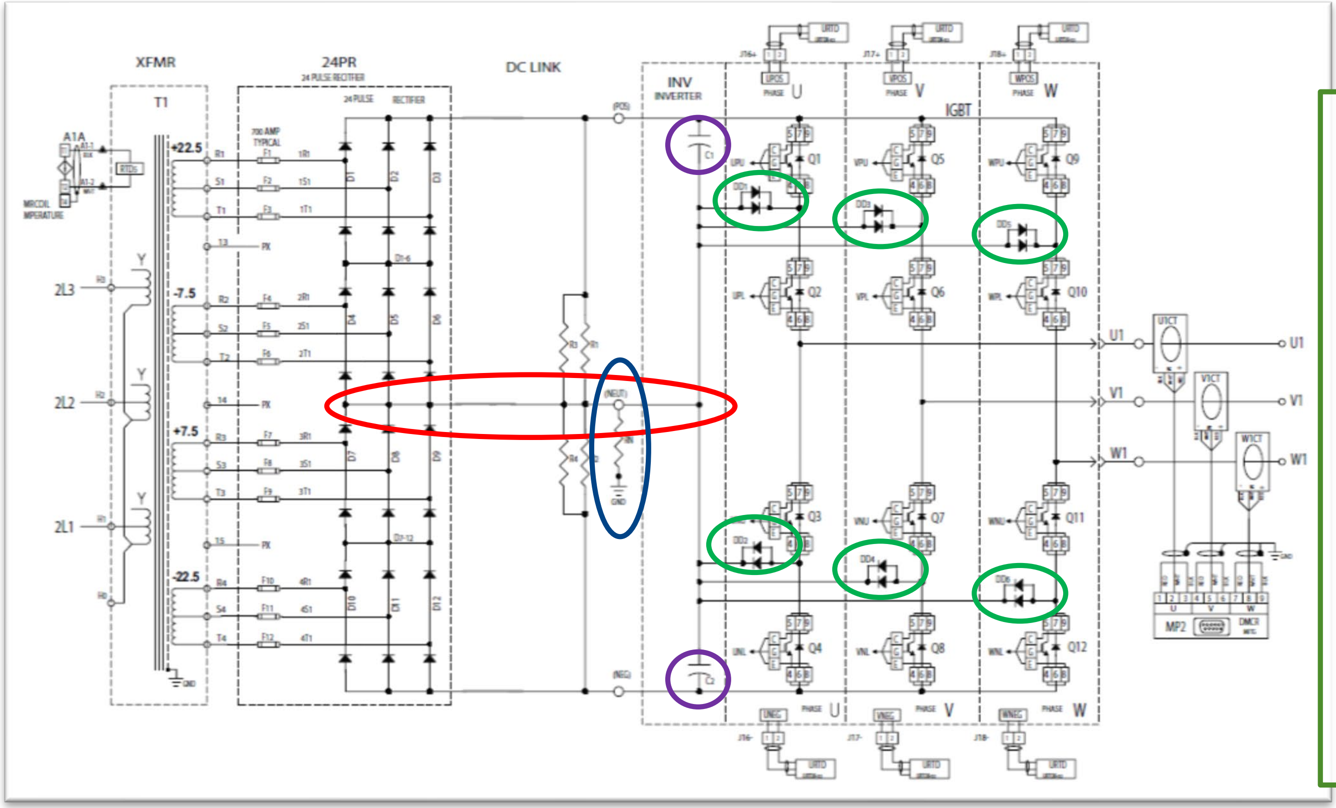
- Original VFD topology – building block of all other topologies
- 2 Level L-N / 3 Level L-L
- Not practical for MV VFD applications
- High step changes – Full DC bus voltage
- Not compatible with standard duty motors

High dv/dt &
Wave reflection issues



V_{L-L}

Voltage Source Inverters – 3L-NPC Topology



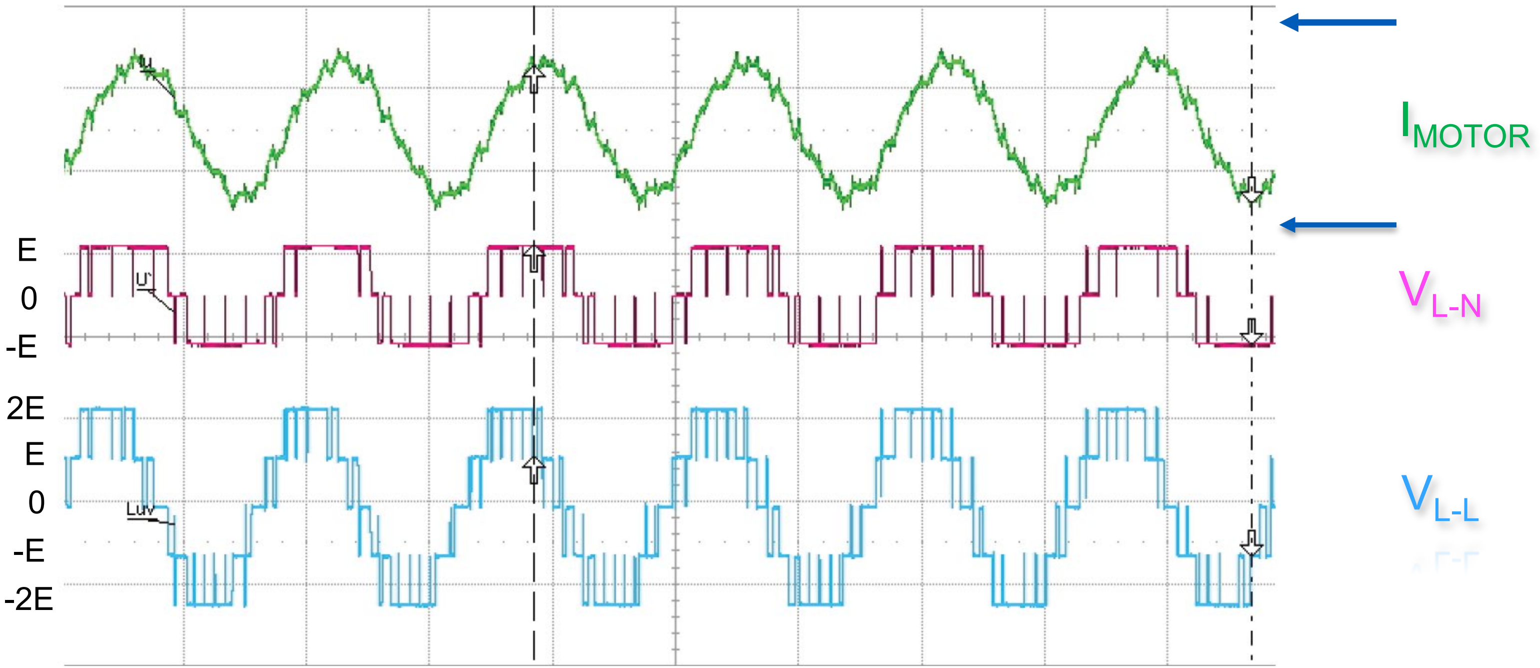
NPC Topology

- 2 level inverter foundation with:
  - Artificial neutral created to increase number of output steps
  - Clamping diodes used to “clamp” neutral voltage
  - Neutral can be grounded to mitigate common mode currents
  - 2 DC link capacitors dividing DC bus voltage
  - 3L-N- 0, +E, -E
  - 5L-L- -2E, -E, 0, +E, +2E

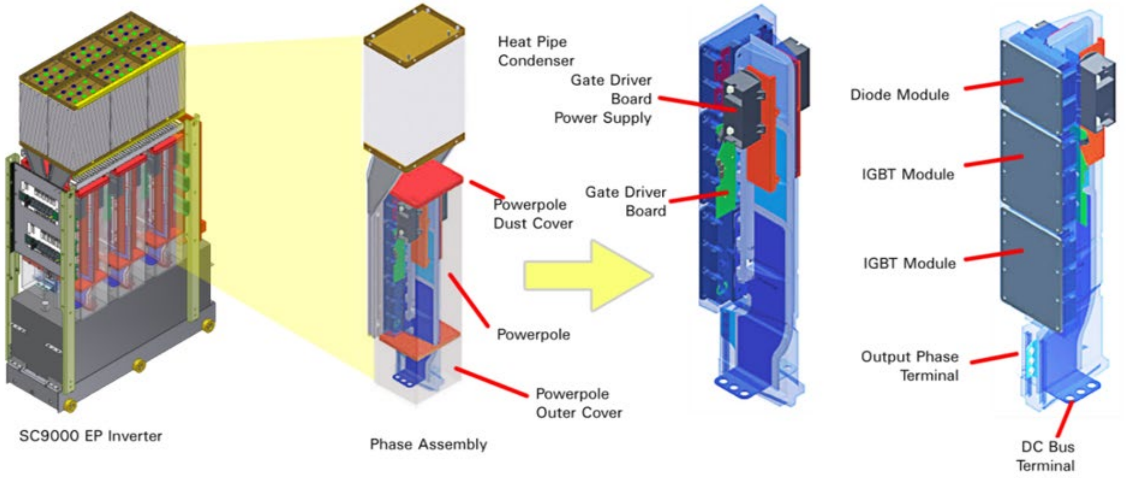
EATON
Powering Business Worldwide

Voltage Source Inverters – NPC Topology

3 Level Neutral Point Clamped Output

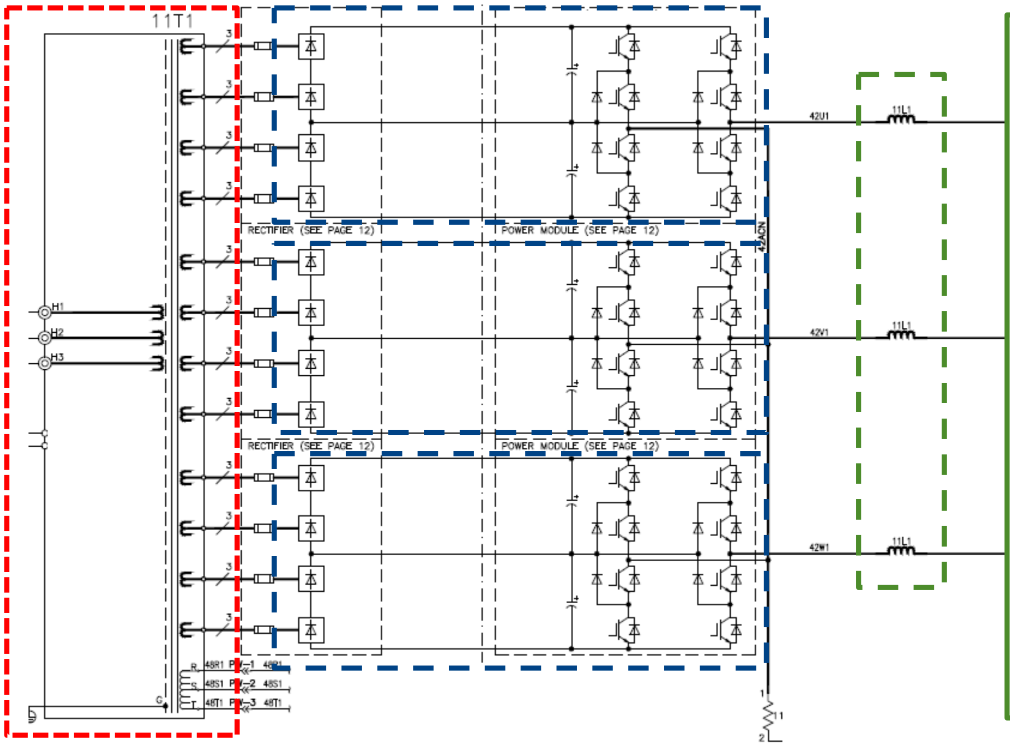


Voltage Source Inverters – NPC Topology



Neutral Point Clamp Inverter

Voltage Source Inverters – Series Cell NPC Topology



Series Cell NPC

- 24 Pulse Isolation Transformer
- Per phase
  - 24-pulse rectifier
  - 3L NPC Inverter
- Increased number of levels
  - 5L - L-N
  - 9L - L-L
- No remote transformer option
- Output reactor usually provided as standard
- Not AFE “friendly”
  - Individual converters per phase
  - Isolation transformer must be integral to the VFD

EATON
Powering Business Worldwide

Voltage Source Inverters – NPC Topology

Advantages

- Great power density inverters
- Improved output quality
- Less component count
  - 6.5kV or 3.3kV transistors
  - Lower heat losses
  - Greater efficiency
- No common mode voltage/currents due to isolation transformer
- Flexible footprint via remote transformer
- AFE friendly topology

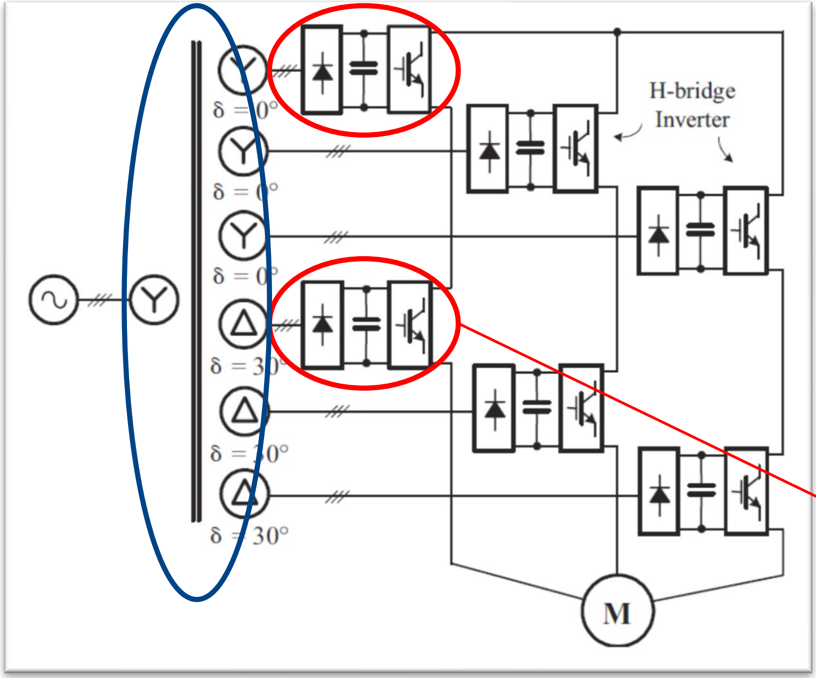
Disadvantages

- No cell redundancy
- Output filtering may be required
  - Cable distance
  - Motor type

EATON
Powering Business Worldwide

Voltage Source Inverter Cascaded H-Bridge

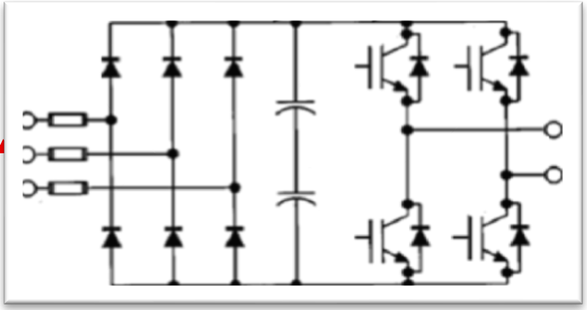
Voltage Source Inverters – CHB Topology



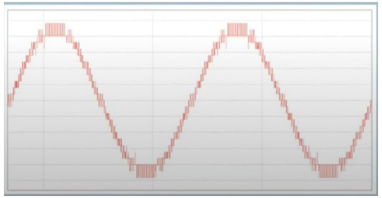
12-pulse separate diode rectifier CHB inverter

CHB

- Multiple units of low voltage single-phase H-bridge power cells connected in series
  - 6-pulse rectifier
  - 2 level H-bridge
- Isolation transformer with multiple secondary windings



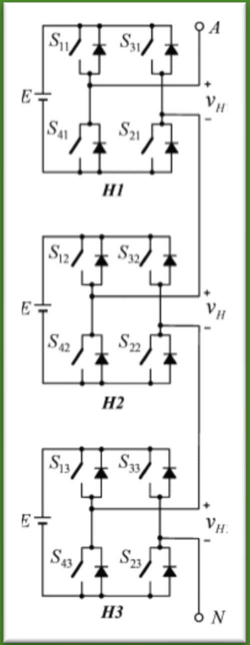
2-level H-bridge power cell



Powering Business Worldwide

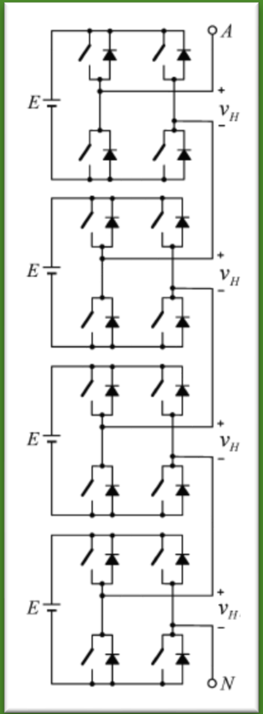
Voltage Source Inverters – CHB Topology

18-pulse 7-level CHB inverter



- Voltage Outputs
  - 3E
  - 2E
  - 1E
  - 0
  - -1E
  - -2E
  - -3E

24-pulse 9-level CHB inverter



- Voltage Outputs
  - 4E
  - 3E
  - 2E
  - 1E
  - 0
  - -1E
  - -2E
  - -3E
  - -4E

EATON
Powering Business Worldwide

Voltage Source Inverters – CHB Topology

Voltage Source Inverters – CHB Topology

Cascade H-Bridge (Equal DC Voltage)				
Cells per phase*	**Cells per VFD**	**Rectifier pulse count**	**L-N output levels**	**L-L output levels**
1	3	6	3	5
2	6	12	5	9
3	9	18	7	13
4	12	24	9	17
5	15	30	11	21
6	18	36	13	25
7	21	42	15	29
8	24	48	17	33
9	27	54	19	37
10	30	60	21	41
11	33	66	23	45
12	36	72	25	49
13	39	78	27	53
14	42	84	29	57
15	45	90	31	61
16	48	96	33	65
17	51	102	35	69

*Numbers may be different depending on manufacturer

EATON Powering Business Worldwide

Voltage Source Inverters – CHB Topology

Advantages

- Cell redundancy available
- Low input and output harmonics
- Low voltage steps => low dv/dt
- Output filter not required except for long cable distances

Disadvantages

- Less power density when compared to NPC
- Electrolytic capacitor
- High component count
  - Higher losses
  - Lower efficiency
- Not AFE friendly topology
  - Individual converters per cell
- Expensive isolation transformer
- Isolation transformer must be integral to the VFD

Powering Business Worldwide