LV VFD & Harmonic Mitigation

Educational Seminar

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Gerry Feldmeier
VFD Sales Manager – Central Region

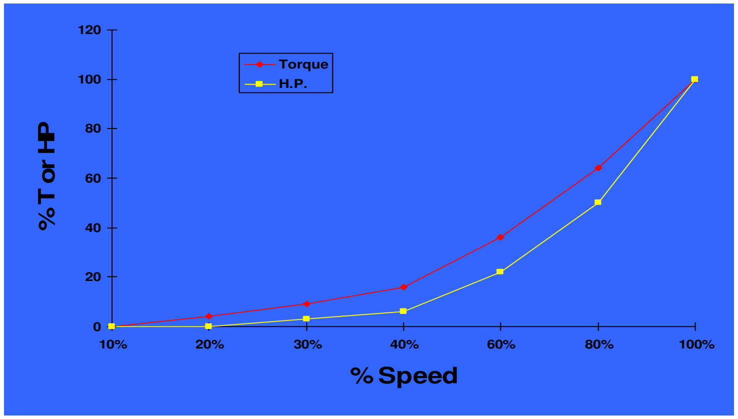
Agenda

- Quick VFD overview
- Line side harmonics
- VFD topologies
- Load side harmonics
- Applications

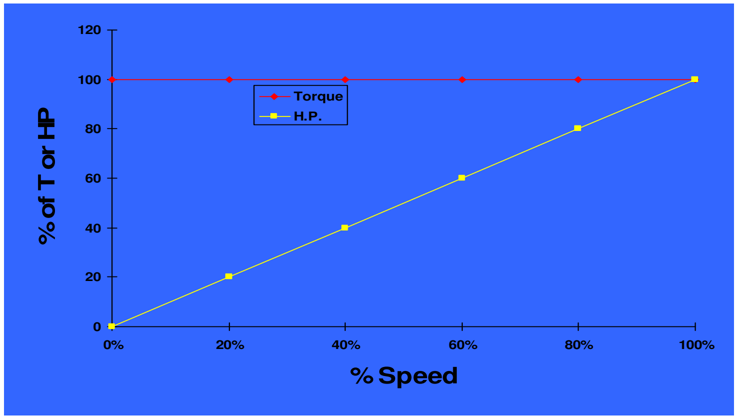
Quick VFD overview

VFD load profiles

- Variable Torque (low overload)
  - Rated for 110% current for one minute
  - Torque increases with speed
  - Pumps and fans (centrifugal loads)



- Contestant Torque (high overload)
  - Rated for 150% current for one minute
  - Torque is constant with speed
  - Conveyors and machine tool



Why use VFDs

- Incredible energy savings on centrifugal loads
  - Affinity law, power increases to the third power of RPM
- Reduce mechanical shock
- Operate between 0 and 400Hz (eliminate valves and dampers)
- Will catch a spinning load
- Virtually eliminate inrush
- Can create max torque across the entire speed range

Application considerations

- Constant HP above synchronous speed
- Only capable of 200% current for a short time
  - What an across the line starter may start a VFD may not
- VFDs are amperage rated devices
  - 100HP at 1800RPM = 113A
  - 100HP at 900RMP = 133A
- Poor power quality can affect VFD performance
- May produce line side harmonics

Line side harmonics

IEEE 519-2014

The Institute of Electrical and Electronics Engineers (IEEE) has set **recommendations** for applying limits to the level of harmonic distortion that a utility customer may inject into the power system. The recommendations pertain to percent harmonic current and voltage distortion at the point of common coupling (PCC), which is defined as the point where the utility connects to multiple customers and not the individual point load generating the harmonics.

EATON
Powering Business Worldwide

Where do harmonics come from video

All Videos: PSEC Videos

This Video: Who Cares about Harmonics

Which came first?.....

Voltage Distortion

Current Distortion

In this case…the Egg!

- Current distortion causes Voltage distortion
- Voltage distortion is created by pulling distorted current through an impedance
- Amount of voltage distortion depends on:
  - System impedance (NOTE: Generator impedance is typical higher than utility – worst case)
  - Amount of distorted current pulled through the impedance
  - If either increases, V_{THD} will increase

IEEE 519 - Current Distortion Limits

Not THD

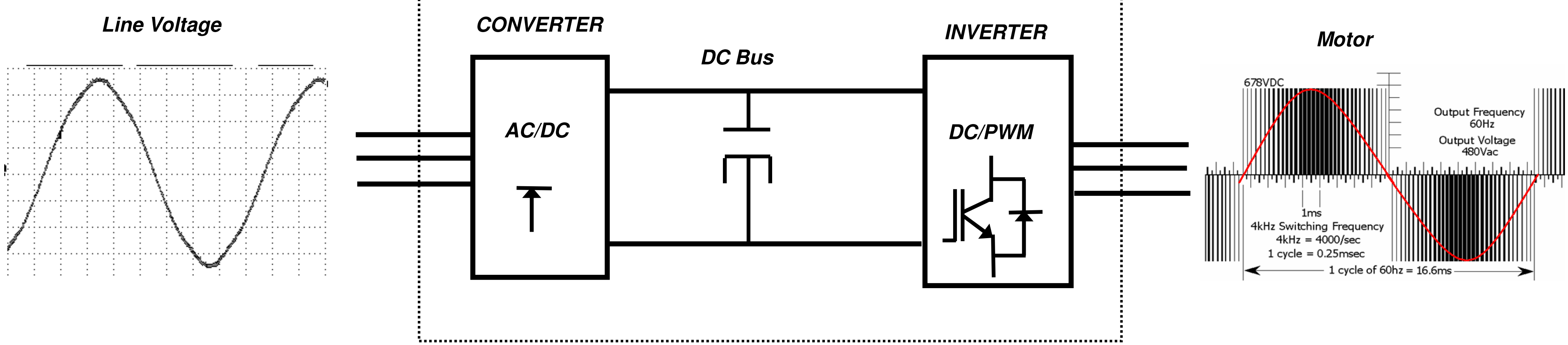
Harmonic Current Distortion Limits (I_h and TDD) in % of I_L (≤ 69kV)

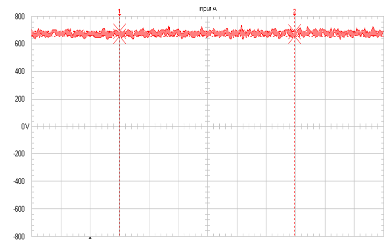
I_{SC}/I_L	<11	11≤h<17	17≤h<23	23≤h<35	35≤h	TDD
<20	4.0	2.0	1.5	0.6	0.3	**5.0**
20<50	7.0	3.5	2.5	1.0	0.5	**8.0**
50<100	10.0	4.5	4.0	1.5	0.7	**12.0**
100<1000	12.0	5.5	5.0	2.0	1.0	**15.0**
>1000	15.0	7.0	6.0	2.5	1.4	**20.0**

- Current distortion limits are dependent on the "stiffness" of the source (I_{sc}/I_L)
  - A stiffer source has lower impedance = more distortion allowed
  - A softer source (i.e. generator) has higher impedance = less distortion allowed
- Current distortion limits are typically much more difficult to reach than Voltage distortion limits
- At PCC typical THDv will be 5%

VFD block diagram

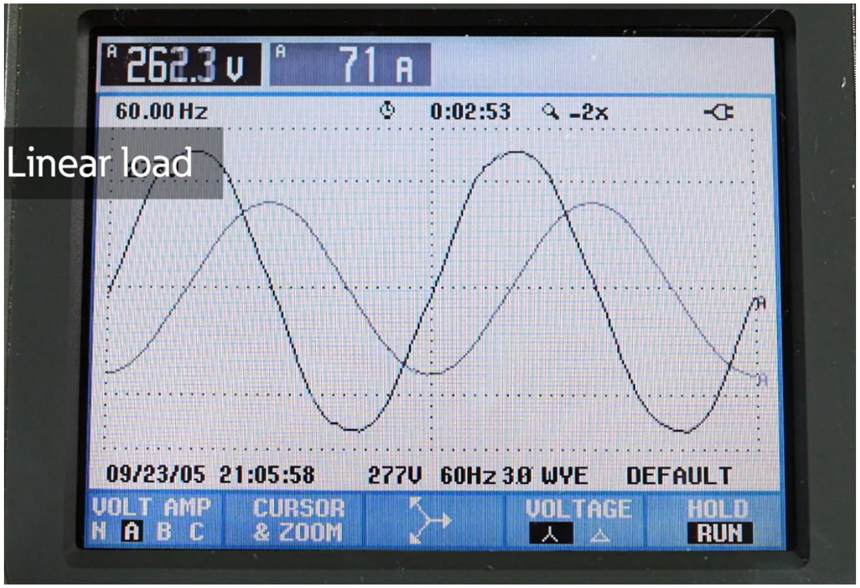
Converts AC to DC and then inverts DC back to AC

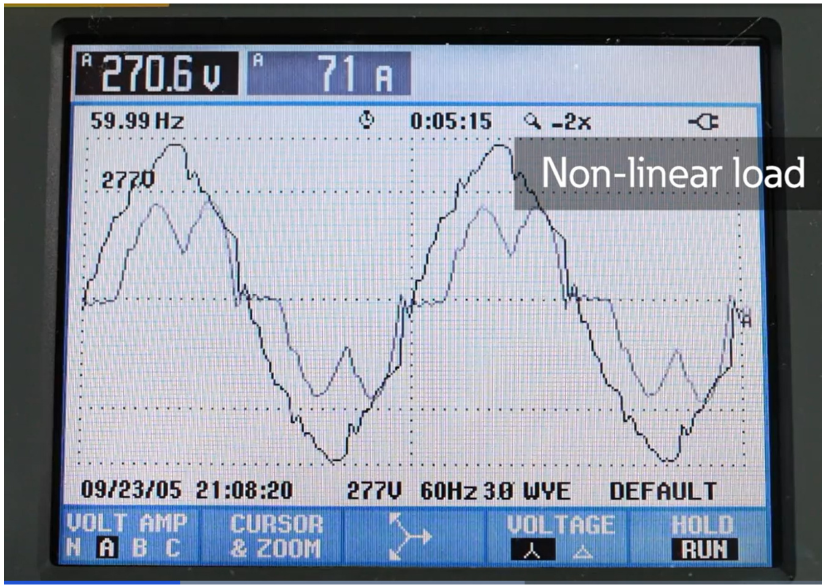




What are harmonics?

Harmonics are generated by non-linear loads
Result is a distorted AC sine wave





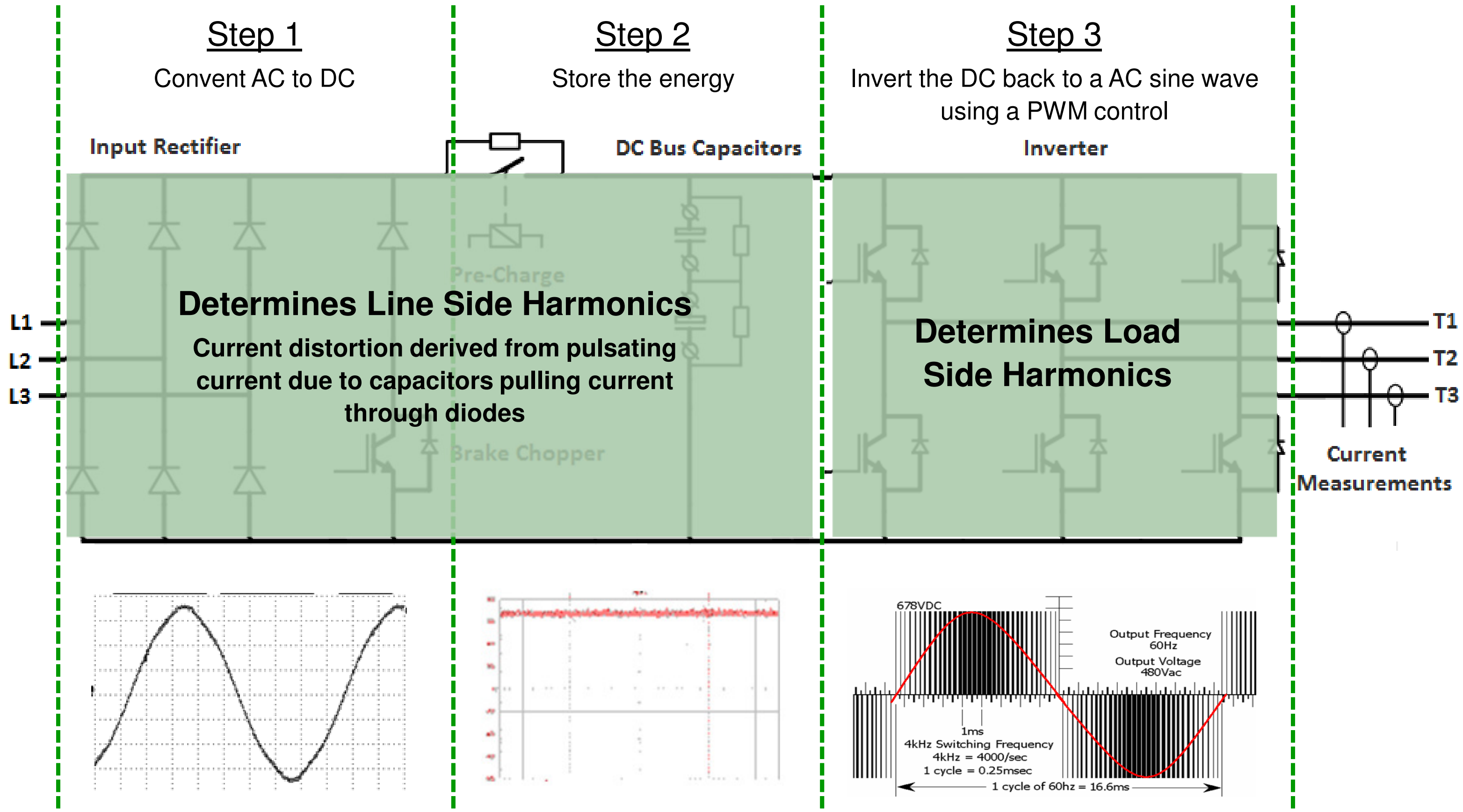
What causes harmonics

Source	Typical Harmonics*
6 Pulse Drive/Rectifier	5, 7, 11, 13, 17, 19…
12 Pulse Drive/Rectifier	11, 13, 23, 25…
18 Pulse Drive	17, 19, 35, 37…
Switch-Mode Power Supply	3, 5, 7, 9, 11, 13…
Fluorescent Lights	3, 5, 7, 9, 11, 13…
Arcing Devices	2, 3, 4, 5, 7…
Transformer Energization	2, 3, 4

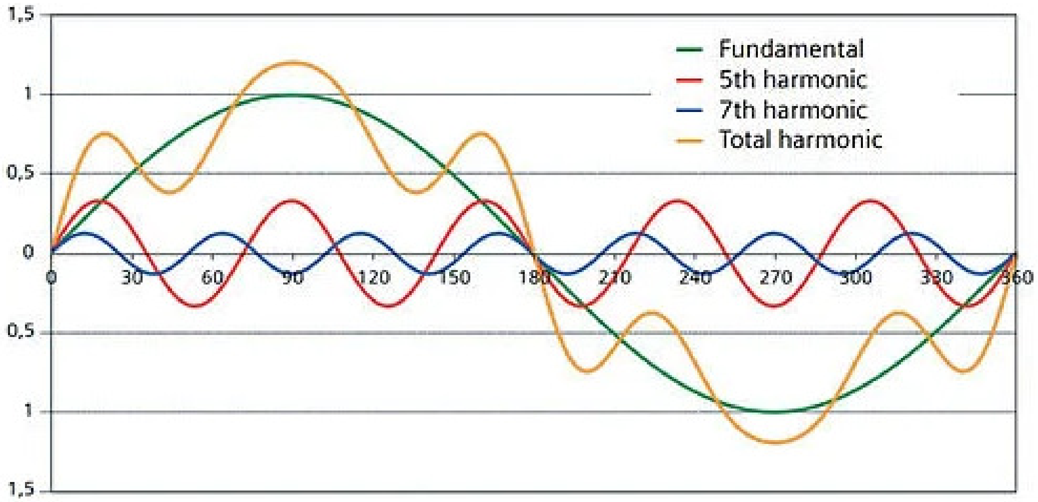
Harmonics = # Pulses +/- 1

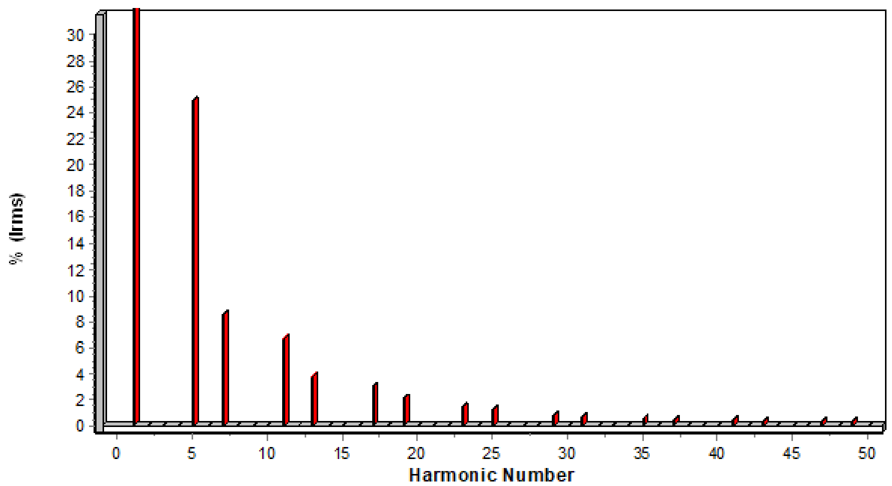
Triplen (3^{rd}, 9^{th}, 15^{st},…) are the odd multiple of the third harmonic. These harmonics are zero sequence harmonics which are damaging because the currents circulate between the phase and neutral causing high neutral currents.

VFD block diagram



6 pulse VFD harmonics





Harmonics are additive

Fundamental = 60Hz

5th harmonic = 5 x 60Hz or 300Hz

7th harmonic = 7 x 60 Hz or 420Hz

The higher the harmonic is, the less the magnitude…this is why 5th harmonic traps work so well controlling harmonics. The 11th and 13th will be a fraction of the 5th and 7th.

Harmonic sequencing

+	1^{st}	7^{th}	13^{th}	19^{th}	Forward (ABC)	Excessive Heating Effect
0	3^{rd}	9^{th}	15^{th}	21^{st}	None	Adds Voltages and/or Currents in Neutral Wire causing Heating
-	5^{th}	11^{th}	17^{th}	23^{rd}	Reverse (CBA)	Motor Torque Problems

Positive sequence harmonics are undesirable because they are responsible for overheating of conductors and transformers due to the addition of waveforms

Negative sequence harmonics circulate between the phases and has a backwards rotation, thus causing problems with induction motors as it weakens the field in the motor

Note a 6 pulse VFD creates 5^{th} and 7^{th}, then 11^{th} and 13^{th} …so both positive and negative

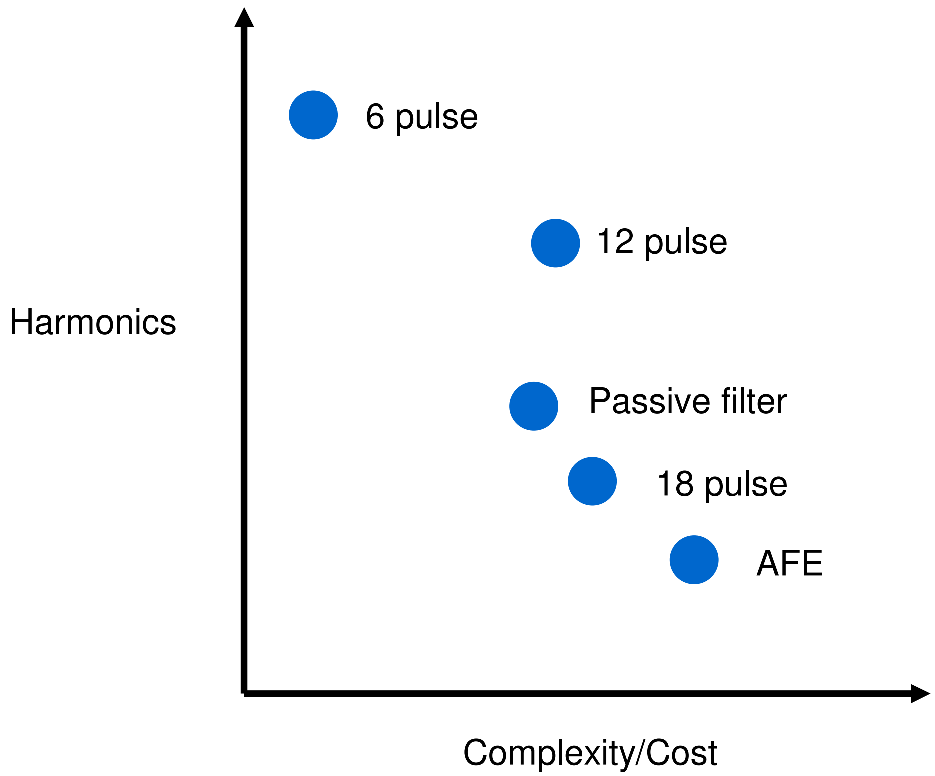
Line side harmonic issues

Line-side harmonics can have far-reaching effects on the power system

- Distribution transformers
- PFC banks
- Standby generators
- Communications equipment
- Switchgear and relays
- Computers, computer systems
- Diagnostic equipment

VFD topologies

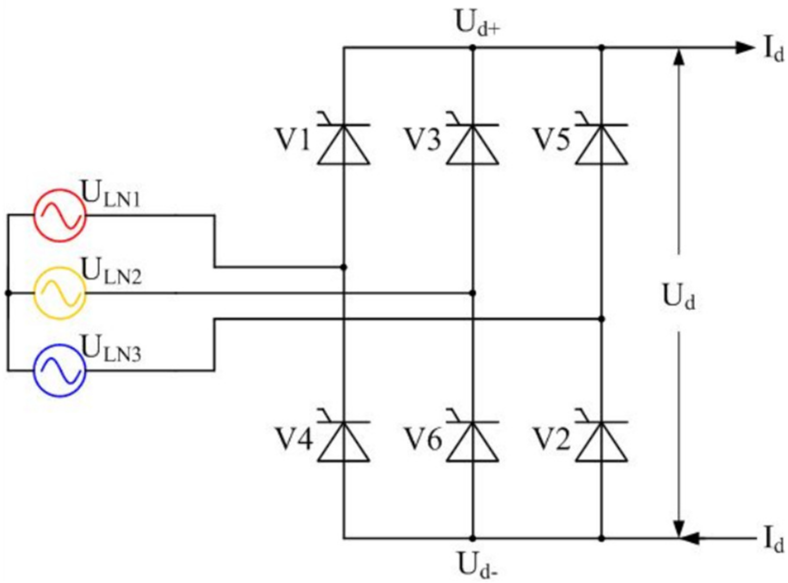
Converter topologies



The converter section is typically designed specifically to address harmonics or to address regeneration of power. Most common solution will be a 6 pulse with DC link choke.

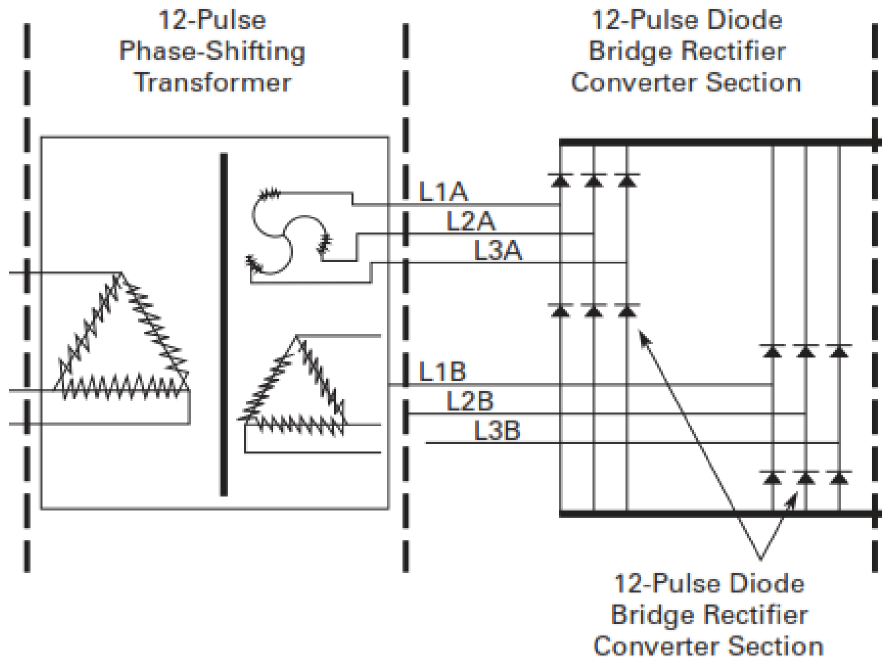
6 pulse converter

- Most common
- Least complex
- 6 diodes create 6 pulses
- Fed from 3 phase source
- Harmonics start at the 5th and 7th order
- Harmonics will be between 75% and 35% depending on choke options
- Most common



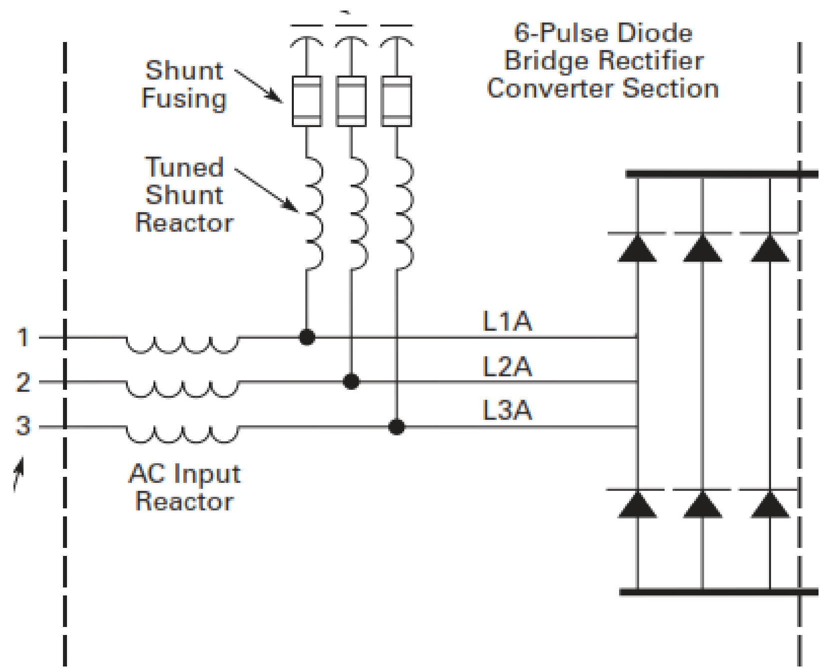
12 pulse converter

- Magnetics are used to create 2 three-phase circuits
- 12 diodes create 12 pulses
- Harmonics start at the 11^{th} and 13^{th} order
- Weight, size and cost are all greater than a 6 pulse
- Harmonics can be as low as 12% THDi
- Not very common any more



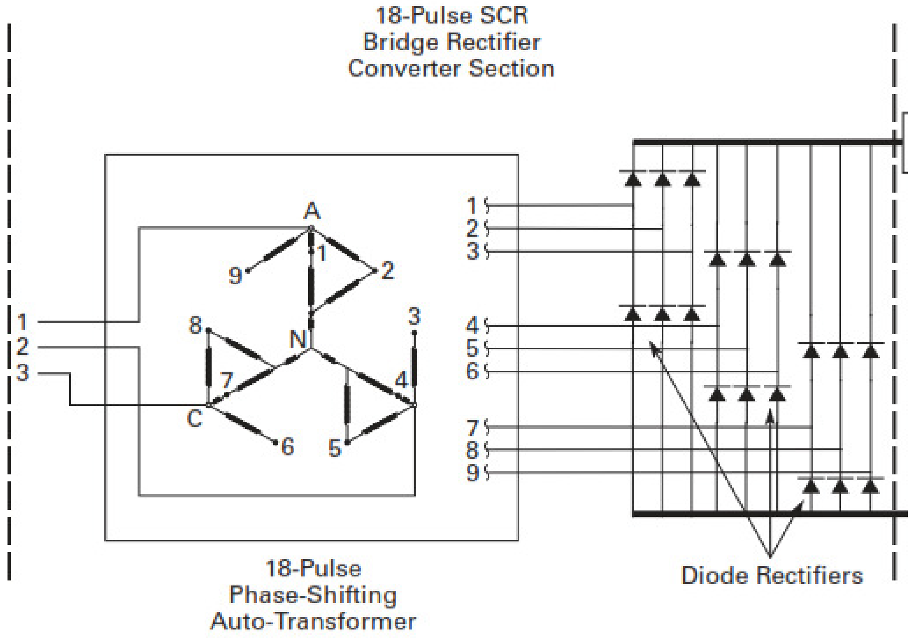
Passive filter

- Tuned filter for 6 pulse VFDs
- Will mitigate the 5th and 7th harmonics
- Will cost more than a 6 pulse and less than a 12 pulse
- Can reduce harmonics to 5% THDi
- Always specify with capacitor contactor
- Very common



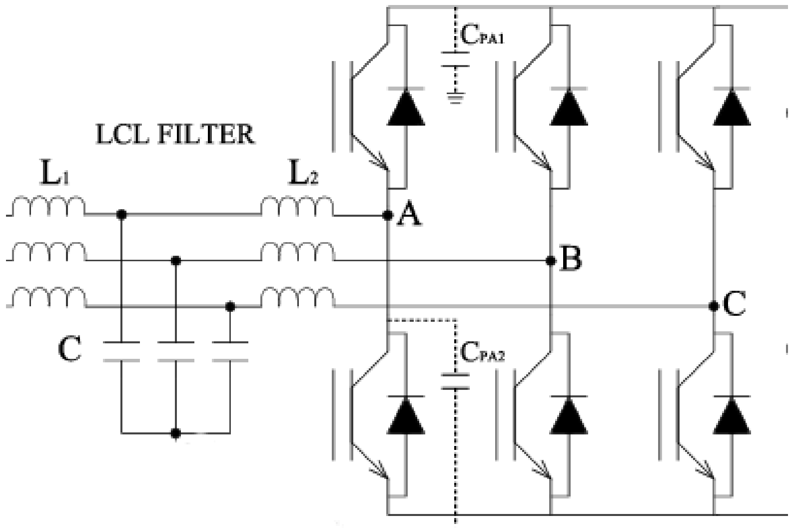
18 pulse converter

- Magnetics are used to create 3 three-phase circuits
- 18 diodes create 18 pulses
- Harmonics start at the 17th and 19th order
- Weight, and cost are all greater than a 12 pulse and passive filter
- Harmonics can be as low as 4% THDi
- Very common

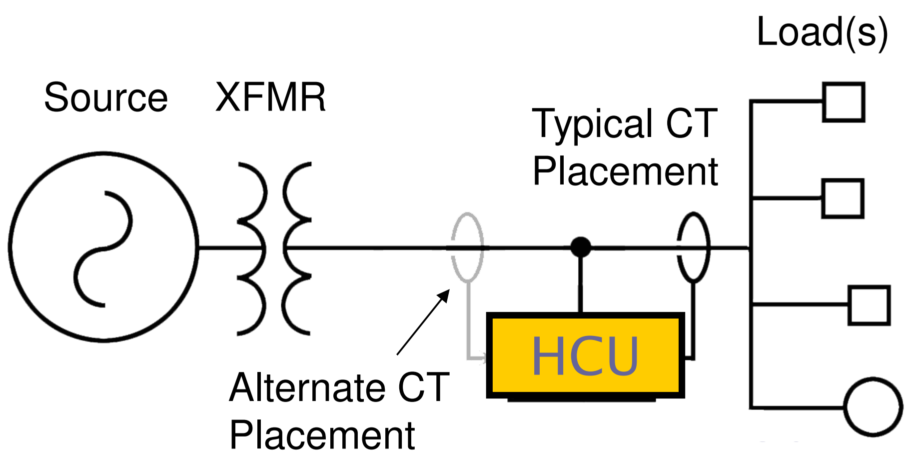


Active front end (AFE)

- Most complex
- 6 IGBTs are used instead of diodes
- Fed from 3 phase source
- Harmonics typically will be above the 50th order
- Harmonics will be less than 5%
- Are bidirectional by design
- Becoming more common



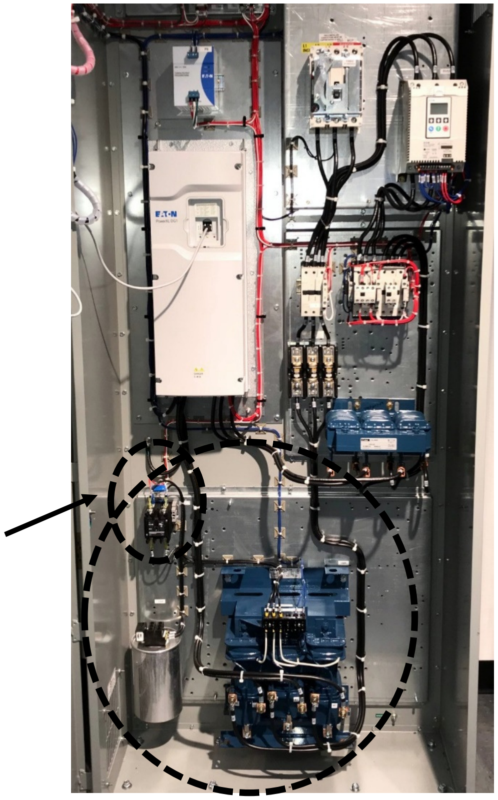
Harmonic correction units



- Installed external to the nonlinear loads
- Actively senses harmonics
- Injects equal and opposite currents to cancel harmonic currents
- Multiple units operate in parallel to get additional capacity
- Can also use extra capacity to correct power factor
- Good soliton when the site realizes there is a problem

VFD styles

6 Pulse	Passive filter (LCL)
200HP 82x30x24	200HP 82x30x24
Low cost	Medium cost
Smallest (until larger HP)	Smaller than multiphase
35% THDi	5% THDi
Least complex	Low complexity
Can cause issues with high inductance sources	Shunt contactor is required when used with high inductance sources
0.99 PF	0.98 PF
0.98% efficient	0.97 % efficient



VFD styles

Multiphase	Active front end (AFE)
200HP 90x48x27	200HP 90x48x24
High cost	High cost
Transformer and bridge adds extra size and weight	Configuration has AFE inverter, converter and LCL
3% THDi	2-3% THDi
Medium complexity	Most complex
Generator safe	May have to oversize generator
Transformer helps absorb transients	Can be used to regenerate power back to the system
0.98 PF	PF adjustable (lead / lag)
0.96% efficient	0.93% efficient

AFE technology

Pros

- 4 quadrant by design
- Very low line side harmonics
- Control can provide unity power factor (power factor correction)
- Some mfg have a very small footprint below 150HP
- Meets IEEE 519-2014
- Immune to voltage unbalance
- Built in voltage sag ride through
- No multiphase transformers

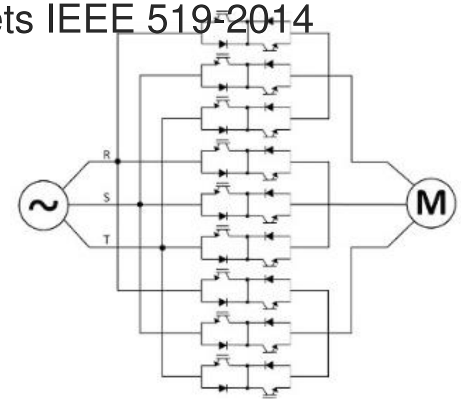
Cons

- Requires input LCL
- Less efficient than passive filter or 18-pulse
- More expensive than passive filter
- More active parts, requiring more control and more opportunity to fail
- Generator must be oversized compared to 18-pulse (**WP040006EN**)
- More susceptible to power disturbances
- Consumes energy even when not running a motor (front end is still switching)
- High upstream EMI/EMC, which can affect power system
- Lightly loaded AFE and high impedance sources can have poor interactions, which may lead to premature failure of the AFE and over-excitation of generators
- High phase to ground voltages

Matrix (AC to AC) technology

Pros

- No reactive components (DC link)
- Very low line side harmonics
- Small footprint
- Power factor can be controlled to get to unity
- 4 quadrat by design
- All-in-one solution
- Meets IEEE 519-2014

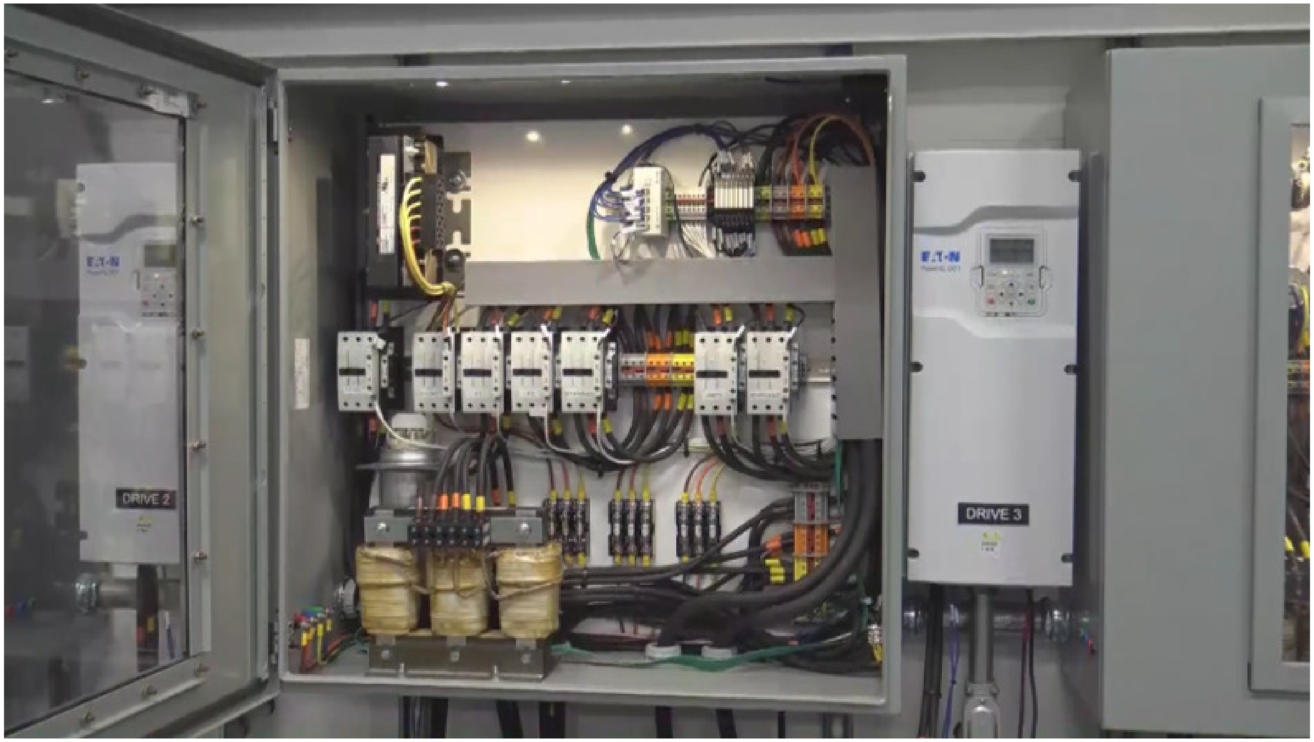


Cons

- Output limited to 87% of input V (torque issues)
- Supply waveform deterioration when optimized to go larger than 87% V
- Not as efficient as a 6-pulse VFD
- Input LCL required
- More expensive than passive filter
- Contains 18 IGBT's and 18 diodes, more complex, more control parts to fail
- Lack of DC bus means no ride through
- More susceptible to power disturbances
- High upstream EMI/EMC, which can affect power system and high impedance sources

http://www.eurekamagazine.co.uk/design-engineering-features/technology/the-truth-about-matrix-converters/3206/

Passive filter video



All Videos: [PSEC Videos]

This Video: [How a Passive Filter Operates]

Load side harmonics

Load side harmonics

- Motors are pretty resilient, they are designed to accept some harmonics
- Due to the fast switching of the PWM output dV/dt is created
- Since the sine wave is not perfect common mode voltages will be present
- Inverter duty motors are designed for higher peak to peak voltages (>1400V) and many can withstand higher temperatures

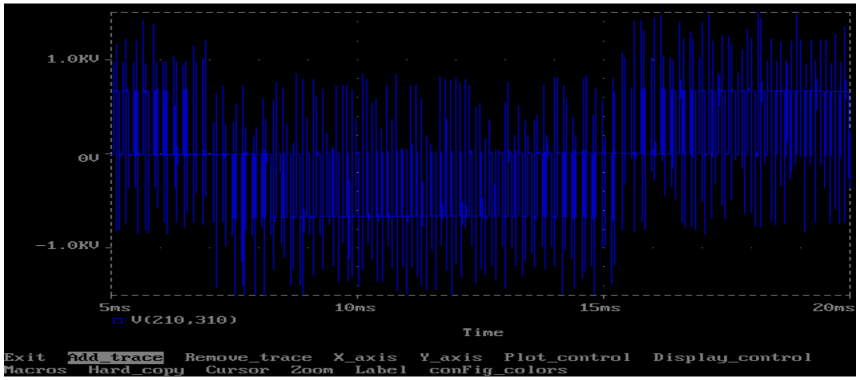
dV/dt – reflected wave

- Peak voltages from reflected waves can develop at the motor
  - Up to 2x the bus voltage (~1500 volts)
- Longer motor leads make the problem worse

	Std motor Std cable	Inverter motor Std cable	Std motor Inverter cable	Inverter motor Inverter cable
No filter	<100’	<150’	<300’	<300’
3% reactor	100-300’	150-350’	150-300’	300-650’
dV/dt filter	300-1000’	350-1000’	350-1000’	650-1000’
Sine wave	>1000’	>1000’	>1000’	>1000’

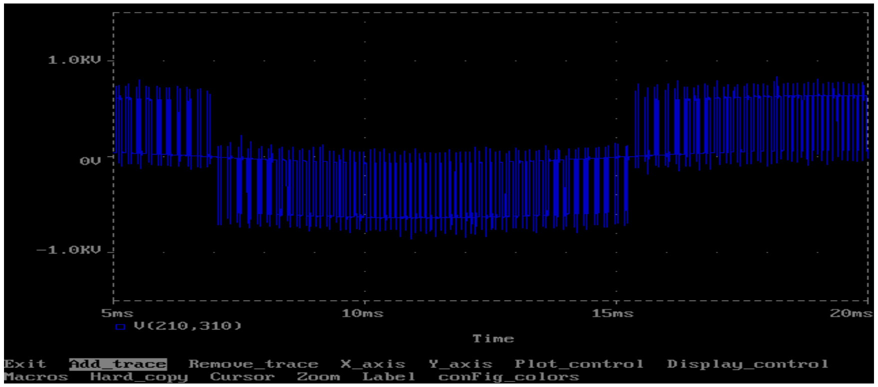
- These voltage can damage the end windings of a motor or cause failure of the insulation of the wire and at connection points
- Carrier frequency affects distance, lower will allow longer runs

dV/dt



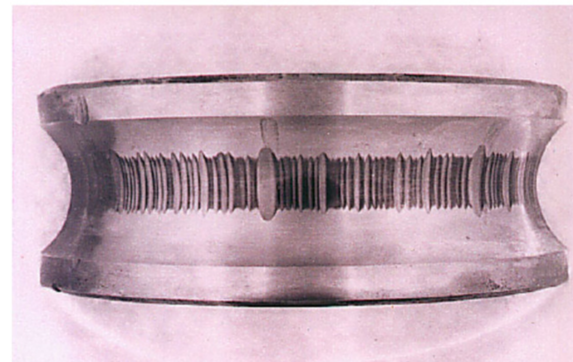
Example of a long motor lead length and no filter, the peak voltage is 1500V which is at the insulation rating of the motor.

Example of a long motor lead length with a dV/dt filter, the peak voltage is about 700V which is the peak voltage for a 480V RMS signal (480*1.4)

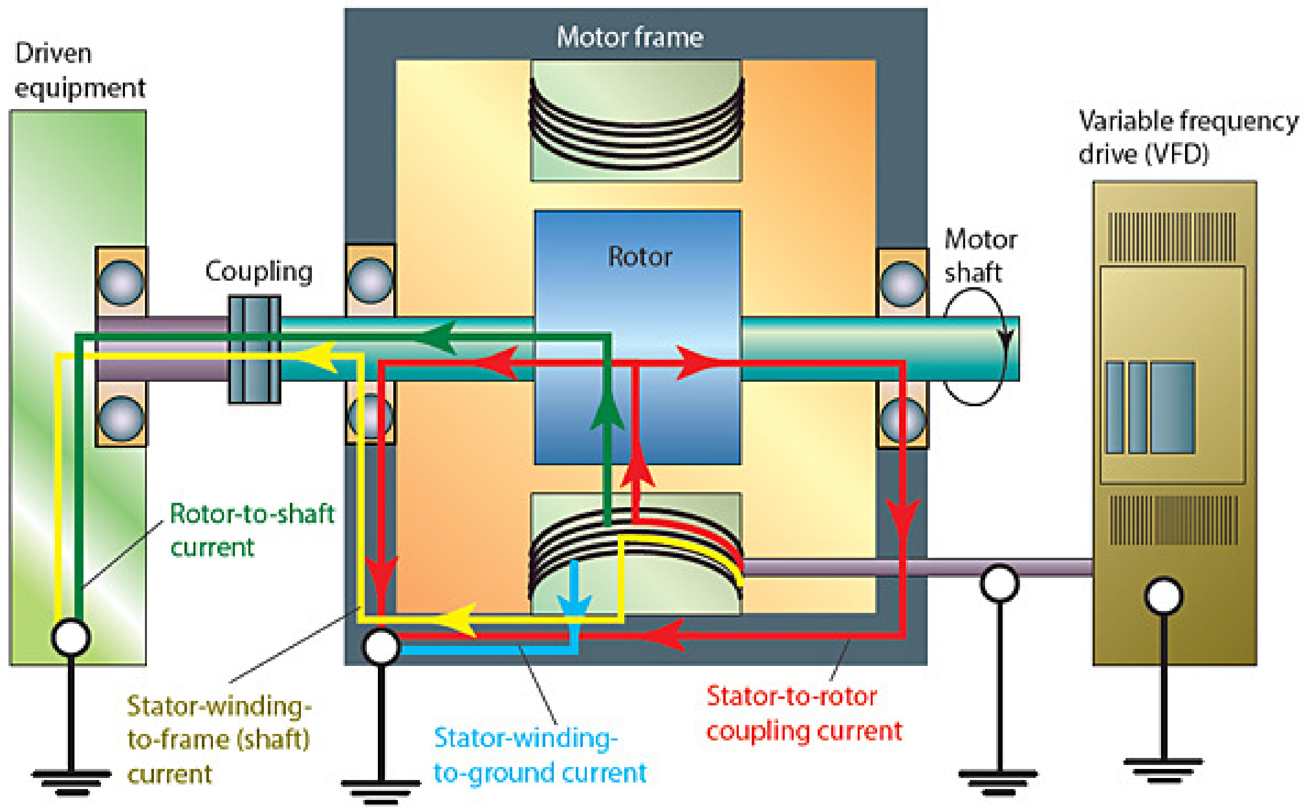


Common mode voltage

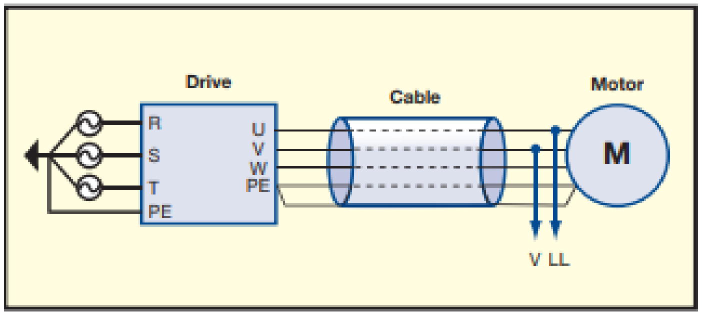
- High frequency switching of the AFD induces voltage on the motor shaft
- Induced voltage will discharge to ground through the motor bearings
- Causes “fluting” in the bearings and can eventually lead to pre-mature failure
- Grounding rings or chokes can be applied to dissipate induced voltage
- Many dV/dt filters will mitigate common mode voltages

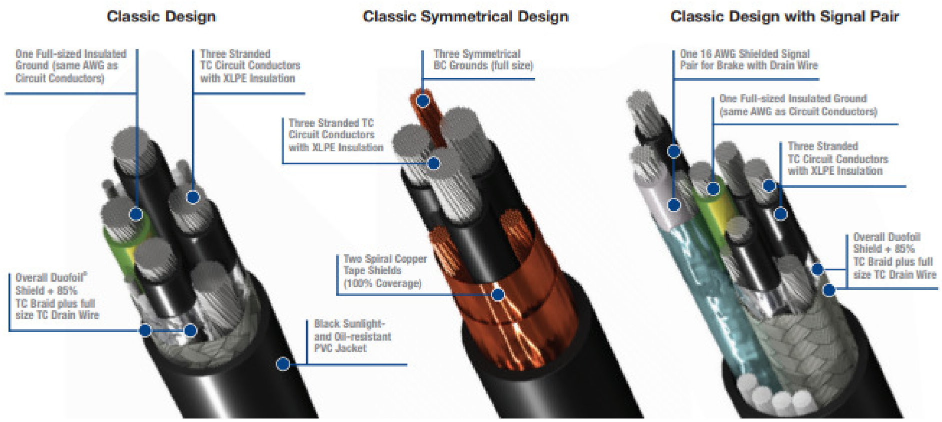


Current paths which damage bearings



Use of VFD wire



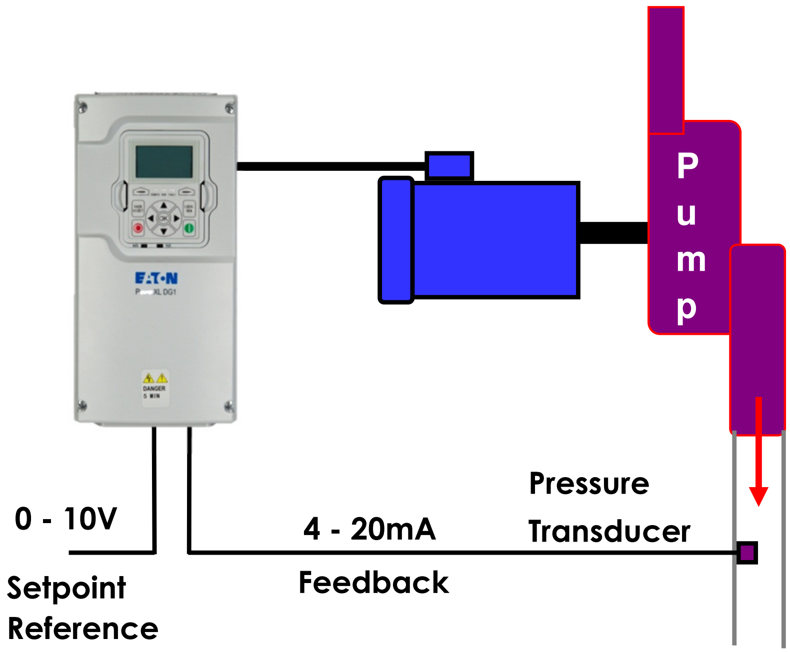


- Lower the risk of fluted bearings due to common mode voltage
- Longer distance before requiring a dV/dt filter
- Reduced cross talk in cable trays
- Higher voltage rating to handle reflected wave (up to 1,300V)

VFD applications

PID control

- Control flow or pressure
- Setpoint of control
- Feedback for control loop
- Features build in such as
  - Wake / sleep
  - Disable loop on stop
  - Feed forward



Pumping features

- Two stage starting
- Deragging
- Dry sump
- Pipe fill
- Loss of prime
- Broken pipe

Questions?