tree™

Total Resource Efficiency Education

# Variable – Frequency Drives

Training solutions brought to you by ecova™

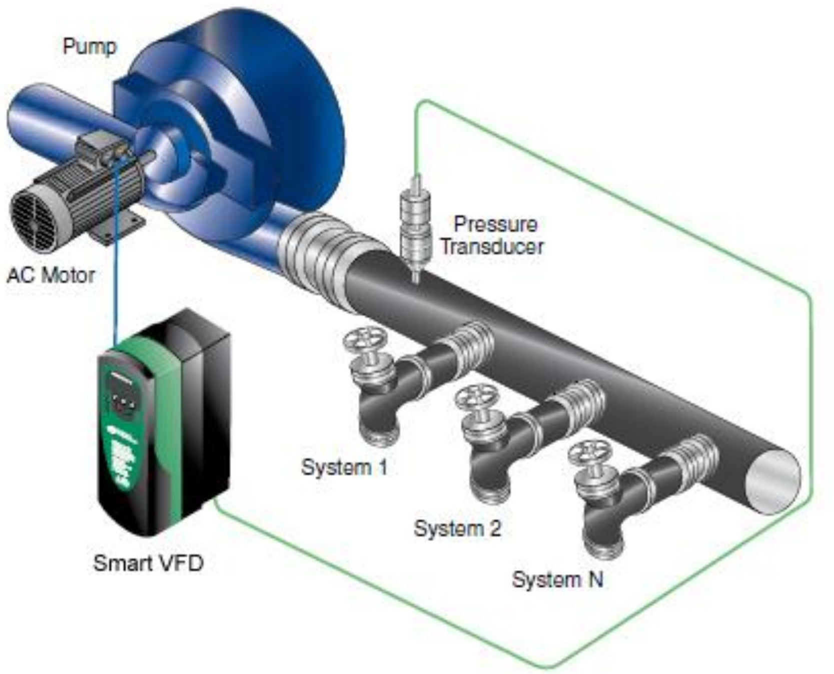
## Meet Your Panelists

Mike Carter

Mark Farrell

## Contents



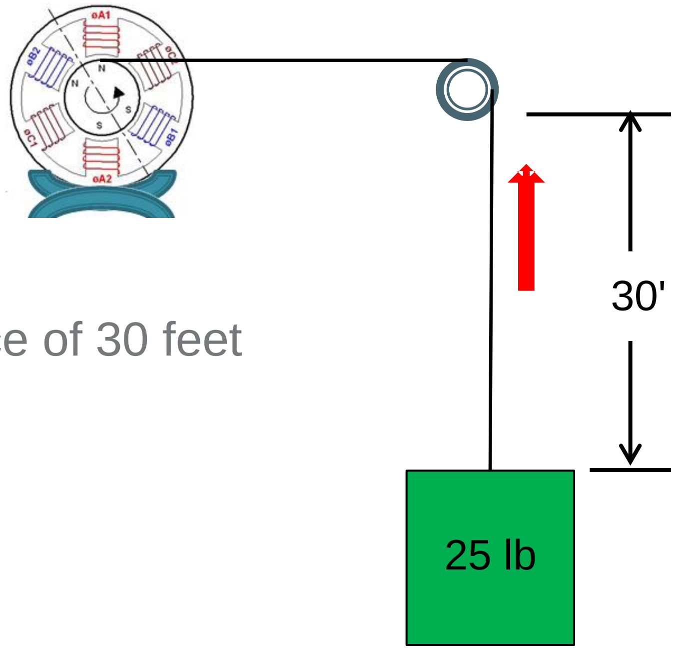



Source: Emerson Industrial Automation

# Basics

Work

- Applying a force over a distance
- Must result in movement
- W = F (lb) x D (ft)
- Example: Move 25 pounds a distance of 30 feet
  - W = 25 lb x 30 ft = 750 lb-ft



## Basics

Torque

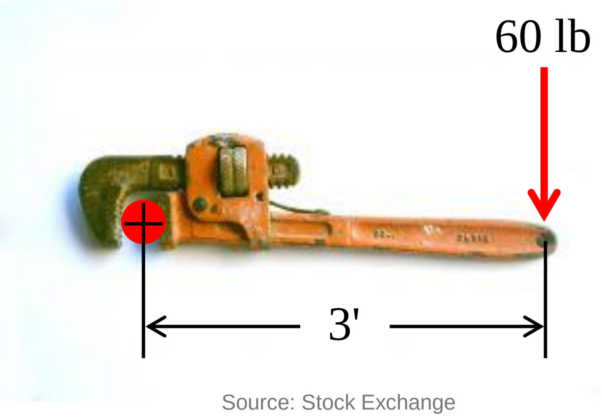
A force that produces rotation

Torque exists even if no movement occurs

T = F (lb) x D (ft)

Example: A 60 pound force pushing a 3 foot lever arm

F = 60 lb x 3 ft = 180 lb-ft




Source: Stock Exchange

## Basics

Horsepower (HP)

A measure of the rate at which work is done


Source: www.sxc.hu

1 HP = 746 watts = 33,000 lb-ft/min = 550 lb-ft/sec

Power (kW) = HP x 0.746/eff

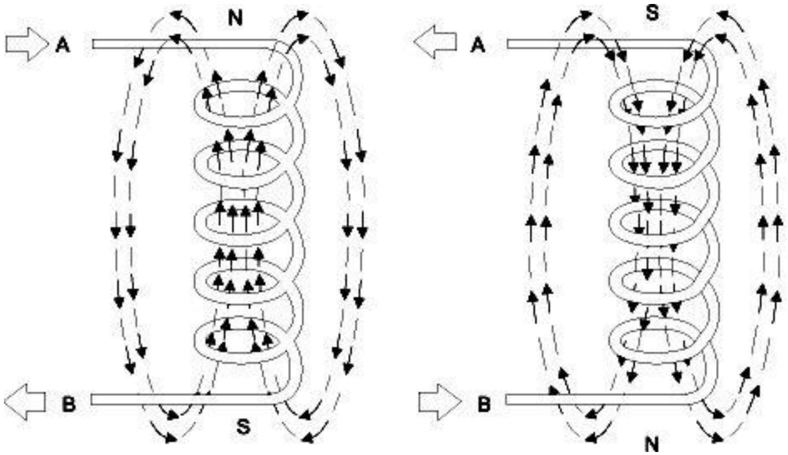
Example: What is electrical power for a 200 HP motor?

Power (kW) = 200 HP x 0.746/0.90 = 166 kW

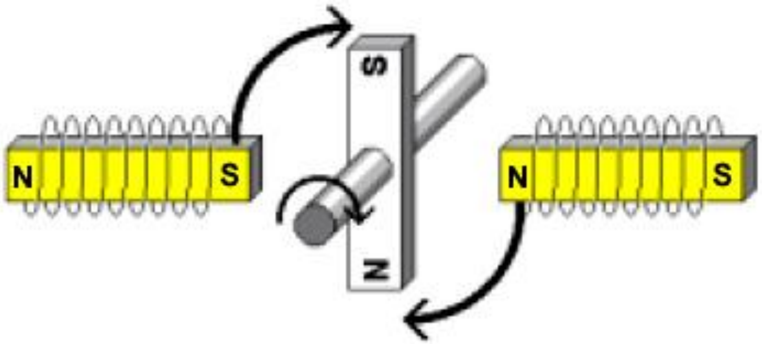
# Basics

## Electric motors

### Direction of current flow changes poles




Source: Reliance Electric

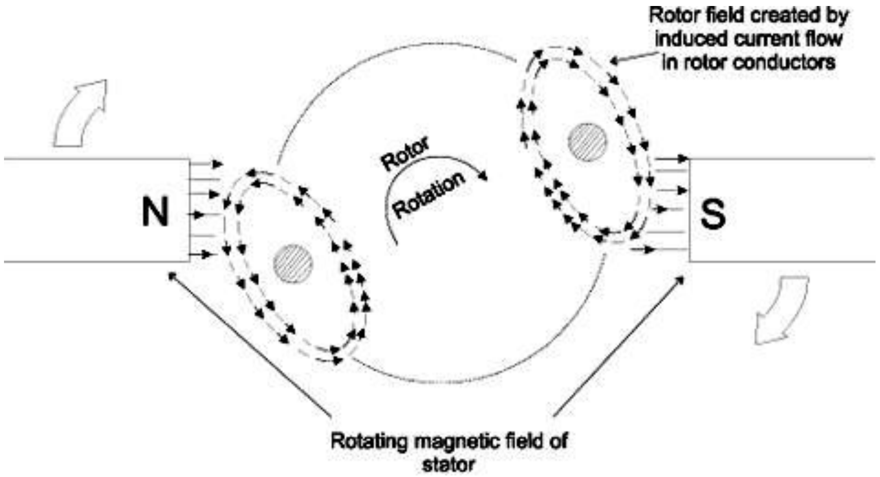



Source: Danfoss

# Basics

## Electric motors

Stator field induces current flow in rotor conductors




Source: Reliance Electric

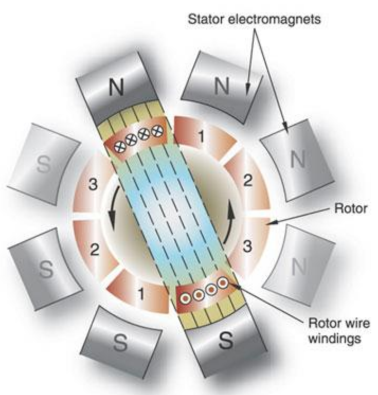
# Basics

Synchronous speed of rotating stator field

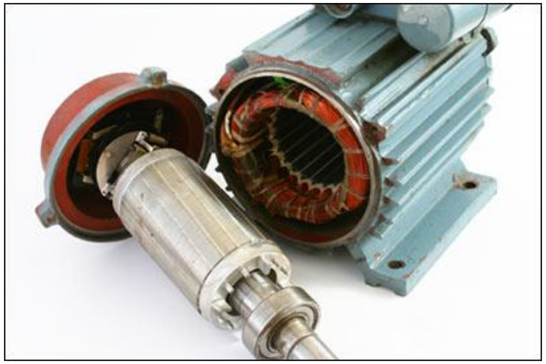
$$\text{Speed} = \frac{120 \times f}{\#\ \text{Poles}}$$

Typically 5% slip for induction motors

| # Poles | RPM |
|---|---|
| 2 | 3,600 |
| 4 | 1,800 |
| 6 | 1,200 |
| 8 | 900 |
| 10 | 720 |



Source: Wenatchee High School


Source:  Maxim Integrated Products

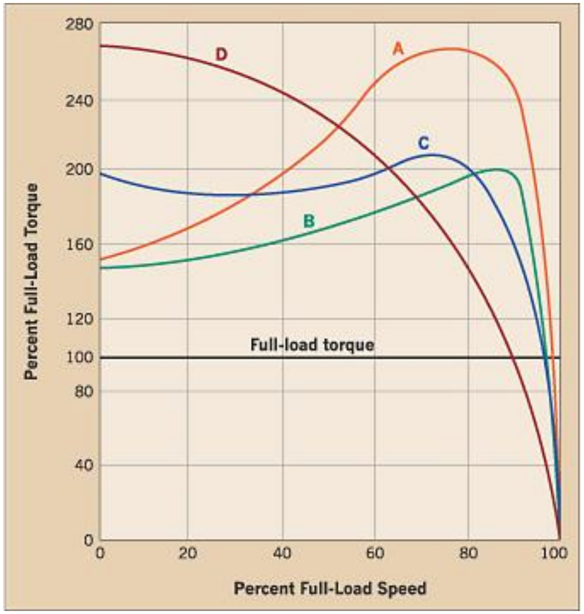
# Basics

Motor torque

- Related to horsepower and speed
- T (lb-ft) = (HP x 5252)/rpm
- Example: A 30 HP motor operating at 1725 rpm
- T = (30 HP x 5252)/1725 rpm = 91 lb-ft

Also related to voltage and frequency

Volts per hertz (V/Hz)




Source: Baldor Electric

## Motor Loads

Constant torque/Variable HP

Torque independent of speed.

Not the best VFD application.

Rotary/screw compressors

Ball mills

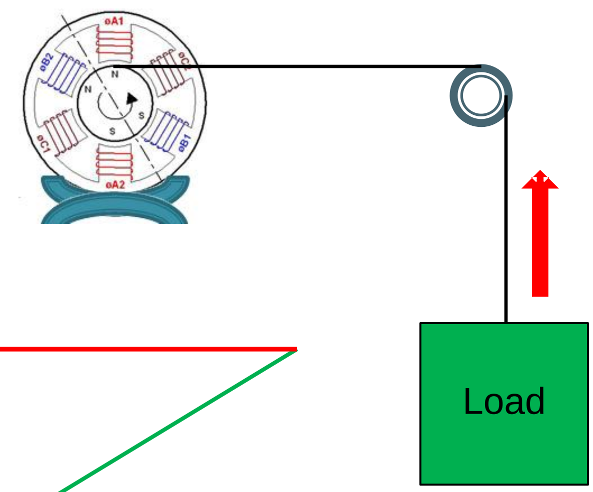
Conveyors

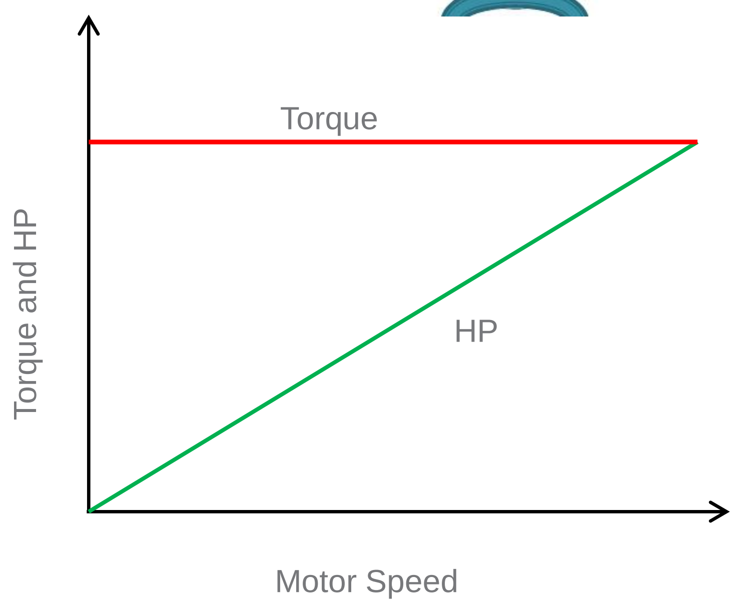
Band saws

Chippers

Drills

Lathes



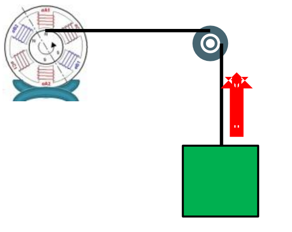
## Motor Loads

Speed, Torque, and HP

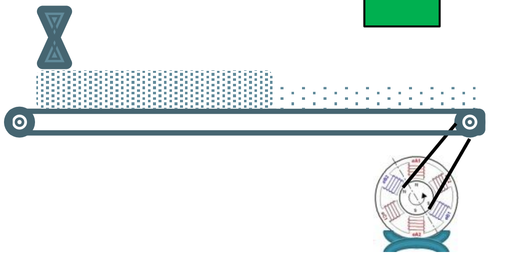
T = (HP x 5252)/rpm

| Speed | Torque | HP |
|---|---|---|
| ↑ / ↓ | = | ↑ / ↓ |
| = | ↑ / ↓ | ↑ / ↓ |
| ↑ / ↓ | ↓ / ↑ | = |

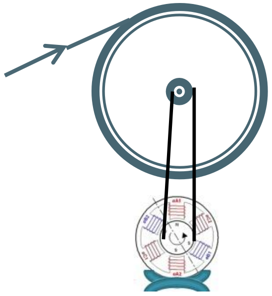
T ≈ HP/rpm



rpm ≈ HP/T



HP ≈ T x rpm

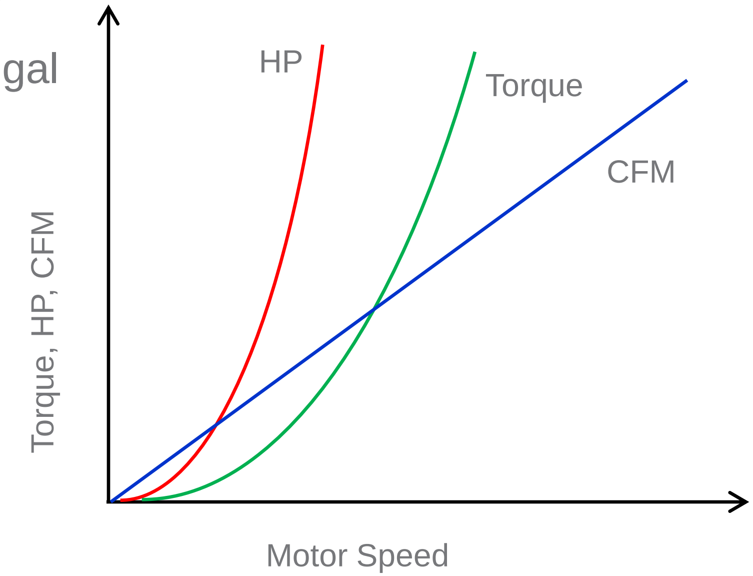


## Motor Loads

Variable torque/Variable HP

- Volume ≈ rpm
- T ≈ rpm2
- HP ≈ rpm3
  - Compressors
    - Centrifugal
  - Pumps
  - Blowers
  - Fans

Source: Stock Exchange



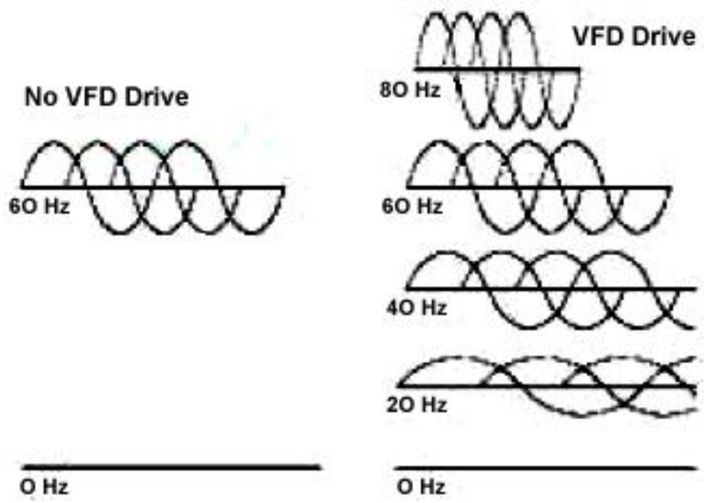
# VFD Operation

Synchronous speed of rotating stator field.

$$\text{Speed} = \frac{120 \times f}{\# \text{ Poles}}$$

Vary speed by varying frequency

- Vary frequency from 0 Hz to 60 Hz or more




Source: Danfoss

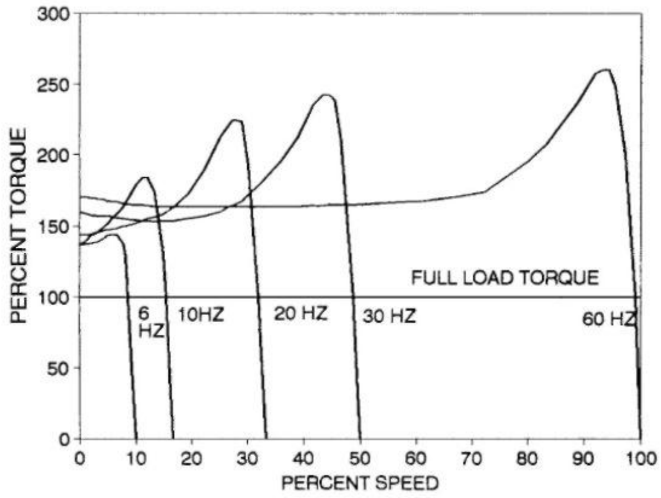
## VFD Operation

Torque is proportional to volts divided by frequency

$$T \approx V/Hz$$

If you decrease frequency, volts must decrease also to achieve constant torque

| Volts 60 Hz | V/Hz | Volts 30Hz |
|---|---|---|
| 480 | 8.0 | 240 |
| 220 | 3.7 | 110 |
| 120 | 2.0 | 60 |

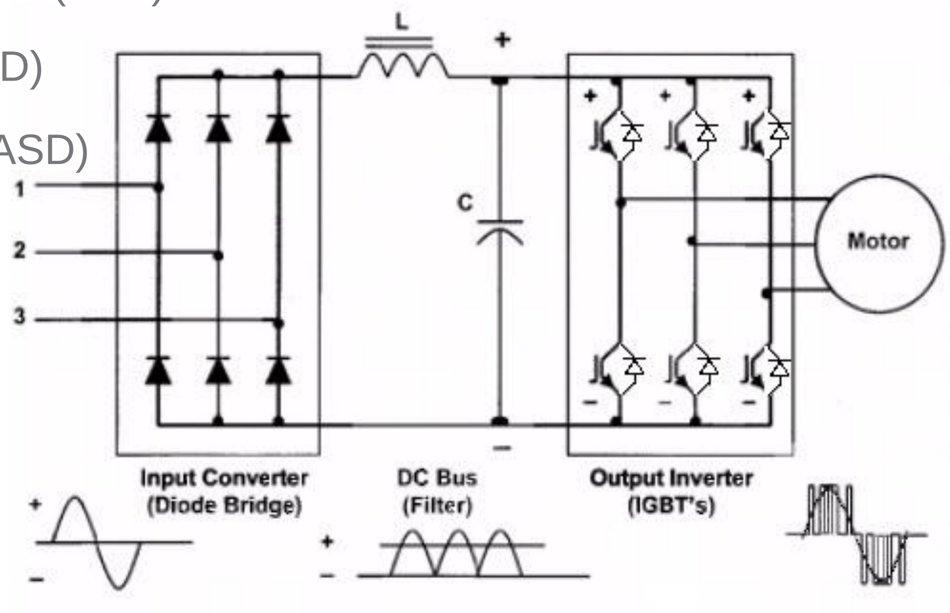



Source: The Crankshaft Knowledge Bank
For more information on
POLYPHASE INDUCTION MOTORS

# VFD Operation

## Typical circuit diagram

- Adjustable Frequency Drive (AFD)
- Variable Speed Drive (VSD)
- Adjustable Speed Drive (ASD)

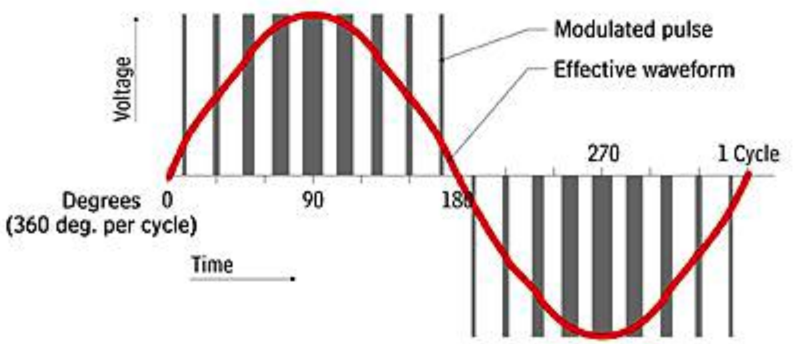



Source: HVACRedu.net

# VFD Operation

Constant voltage inverter

- Pulse width modulation (3.5KHz to 15 kHz)
  - Constant power factor
  - High efficiency (up to 98%)
  - Long ride-through




Source: Sebesta Blomberg & Associates

## VFD Costs

Rule of thumb is $200 to $500 per HP installed

- Example: 30 HP motor operating 5,000 hours annually costs $6,200 in electricity at $0.05/kWh
  - Assume 50% energy savings at $3,000
  - VFD costs is 30 HP x $250/HP = $7,500
  - A little over a two year payback

## VFD Advantages

- Reduced power and energy
  - Energy savings 25%-85%
- Improved power factor
  - 95%+
- Improved speed control

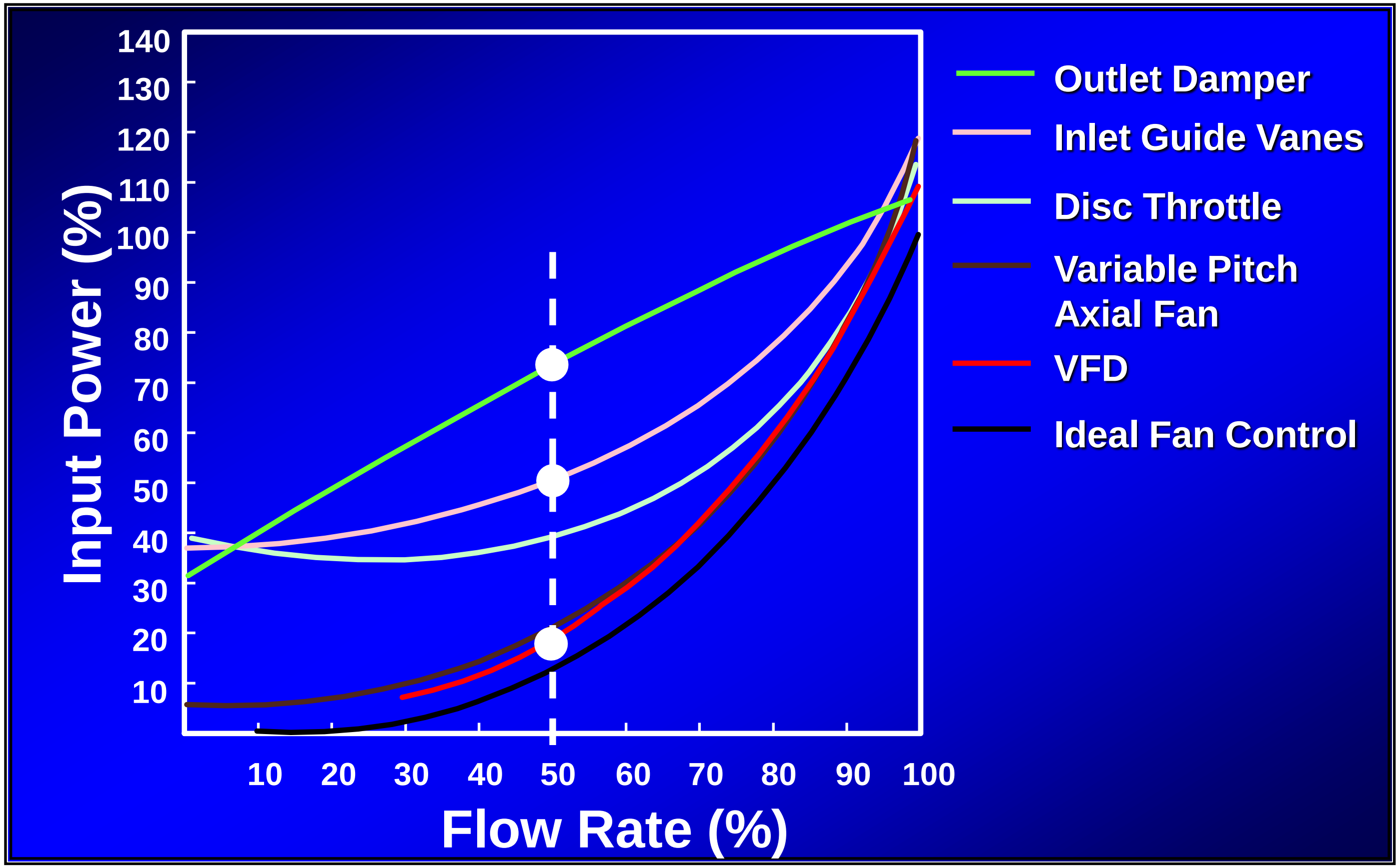
## VFD Advantages

- Increased reliability
  - Decreased mechanical impact from soft-start
- Decreased maintenance costs
  - Increased equipment life
  - No need for throttles/dampers
- Built-in soft starting

Source: Emerson Industrial Automation

# VFD Energy Savings

Power Input




Source: Emerson Industrial Automation

## VFD Energy Savings

Power Output

$HP \approx rpm^3$

Example: speed reduction to 50%

$HP_{0.5} = HP1 \times (0.5)^3 = HP1 \times 0.125$

| VT/VH Power vs Speed | |
|---|---|
| Speed | Power |
| 100% | 100% |
| 90% | 73% |
| 80% | 51% |
| 70% | 34% |
| 60% | 22% |
| 50% | 13% |
| 40% | 6% |
| 30% | 3% |
| 20% | 1% |
| 10% | 0.1% |

*VT/VH = Variable Torque/Variable Horsepower

# VFD Energy Savings

At 50% speed, VFD saves 75-85% versus output damping and variable inlet speed control

| Control | Motor HP Input vs Speed (100 HP) | | |
|---|---|---|---|
| | 25% | 50% | 75% |
| Damper | 50 | 73 | 93 |
| Inlet Vane | 44 | 60 | 73 |
| VFD* | 3.6 | 16 | 47 |

*Adjusted for part-load motor and drive efficiencies

## VFD Energy Savings

Assume a 25 HP fan motor operating 23 hrs/day

Energy consumption VFD/Damping = 10.3/19.9 = 50%

50% savings!

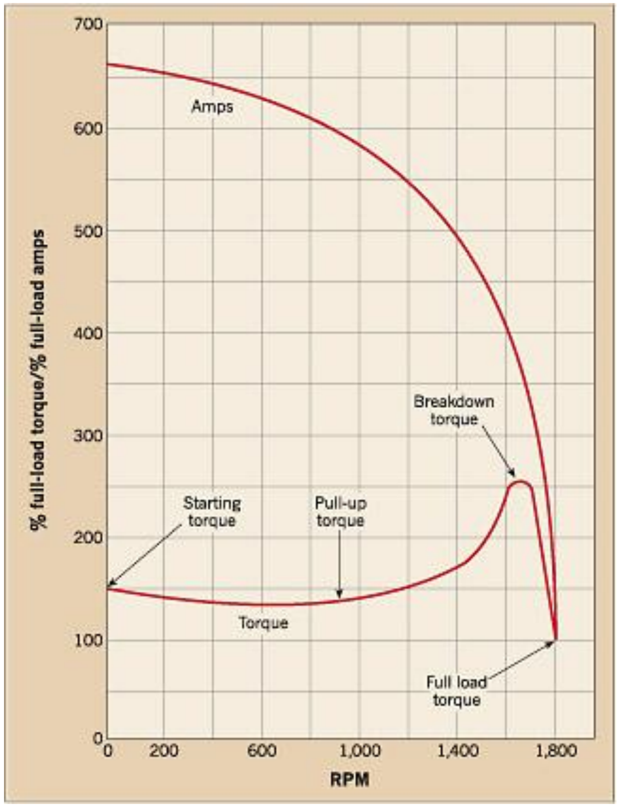
| Damping Pwr vs Speed @Hrs | | | |
|---|---|---|---|
| Speed | Power | Hours | HP-Hr |
| 100% | 100% | 2 | 2 |
| 75% | 93% | 8 | 7.4 |
| 67% | 85% | 8 | 6.8 |
| 50% | 73% | 5 | 3.7 |
| | | Total | 19.9 |

| VFD Pwr vs Speed @Hrs | | | |
|---|---|---|---|
| Speed | Power | Hours | HP-Hr |
| 100% | 105% | 2 | 2.1 |
| 75% | 50% | 8 | 4.0 |
| 67% | 40% | 8 | 3.2 |
| 50% | 19% | 5 | 1.0 |
| | | Total | 10.3 |

# Soft-starting

LRT ≈ I2 ≈ V2

| Reduced Voltage Starter | | |
|---|---|---|
| %V or %I | %FLA | %FLT |
| 100 | 660 | 150 |
| 90 | 595 | 122 |
| 82 | 540 | 100 |
| 70 | 460 | 74 |
| 58 | 380 | 50 |




Source: Exponent Failure Analysis Associates

Soft-start draws 400-600% of rated amps during motor start

A VFD draws only 100% to 120% of rated amps at 100% rated torque

## VFD Disadvantages

- Less efficient at 100% rated motor speed
- Possible winding insulation breakdown
  - Inverter-rated motors recommended
- Harmonics
  - Many possible preventive measures available
- Possible voltage reflected wave from long lead lengths
- Higher first cost
  - Payback from lower energy consumption

## VFD Best Applications

All variable torque applications

Compressors

- Centrifugal

Pumps

- Chilled water
- Condenser water
- Building supply
- Chemical dosing

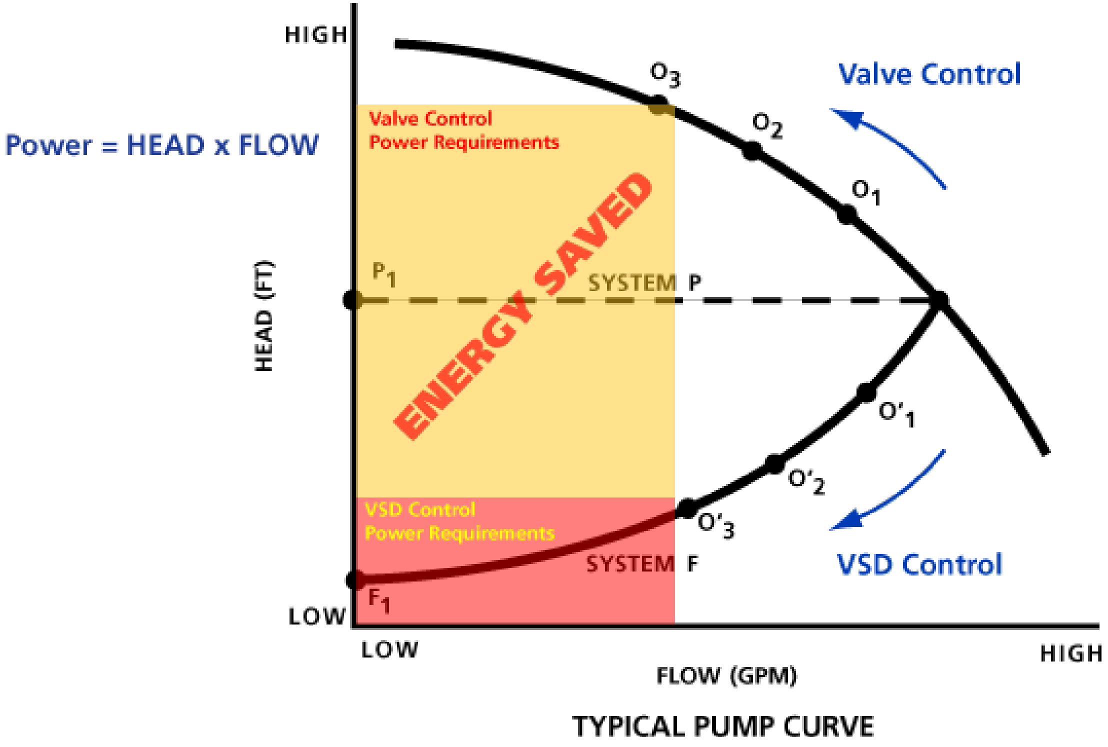
Blowers

Fans

Source: Emerson Industrial Automation

# VFD Best Applications

When pump and system curves are close to perpendicular




Source: Emerson Industrial Automation

## VFD Best Applications

Some constant torque applications

- Does improve the process

Reduced speed operation in 50% to 75% range

Current limited starting required

Smooth acceleration required

Source: Emerson Industrial Automation

## VFD Best Applications

When not to use VFDs

Pump and system curves are parallel

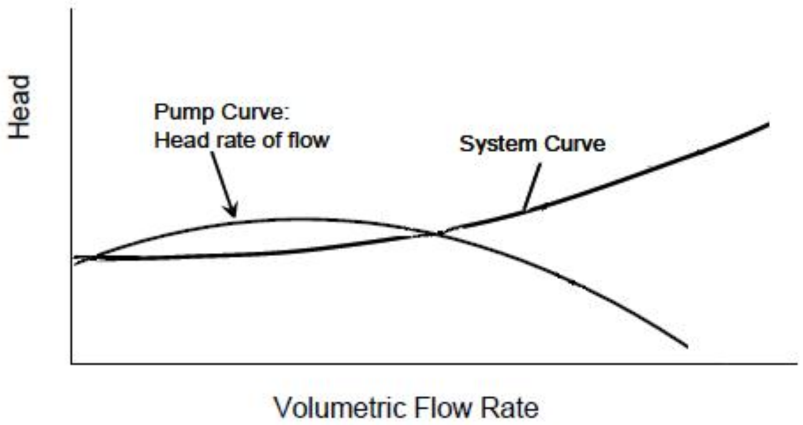
- High lift
- Minimal pipe friction

No variability in speed

- Use impeller trim
- Adjust the motor fixed speed (change gears)

Pump operates efficiently ON/OFF

- Example: sump pump




Source: LLNL

## Sizing a VFD

Do not size the VFD based on horsepower ratings

Define the operating profile of the load to which the VFD is to be applied

Variable torque

- Must meet amperage rating of motor

Constant torque

- Obtain the highest peak current readings under the worst conditions
    - Check motor full-load amps (FLA) to see if the motor is already overloaded
- Starting torque modes
    - High overload is 150% torque for one minute
    - Breakaway torque allows 180% torque for 0.5 seconds
    - Normal overload is 110% torque for one minute
    - Engage a VFD supplier for consultation

## Sizing a VFD

Determine why the load operation needs to be changed.

- How many speed changes required?
- How often does speed need to be changed?

Evaluate the possibility of required oversizing of the VFD

- Hard-to-start loads
- Quick start or emergency stop
- High temperature environment may require VFD derating
- Temperatures >104°F (40°C)

## Sizing a VFD

Using a 3-phase VFD with single phase power

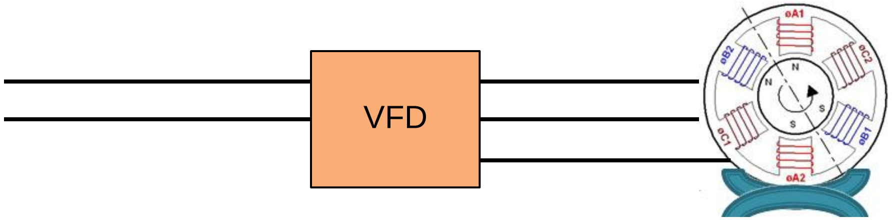
The 3-phase VFD HP rating x 2

- Example: 10 HP 230 Volt three phase motor requires a 20 HP rated 3-phase VFD

Reduces life of filtering capacitors

Dedicated single phase VFDs over 20 HP are hard to find

Probably cheaper to use a phase converter



## VFD Power Quality Issues

Protecting the VFD

Harmonic Distortion

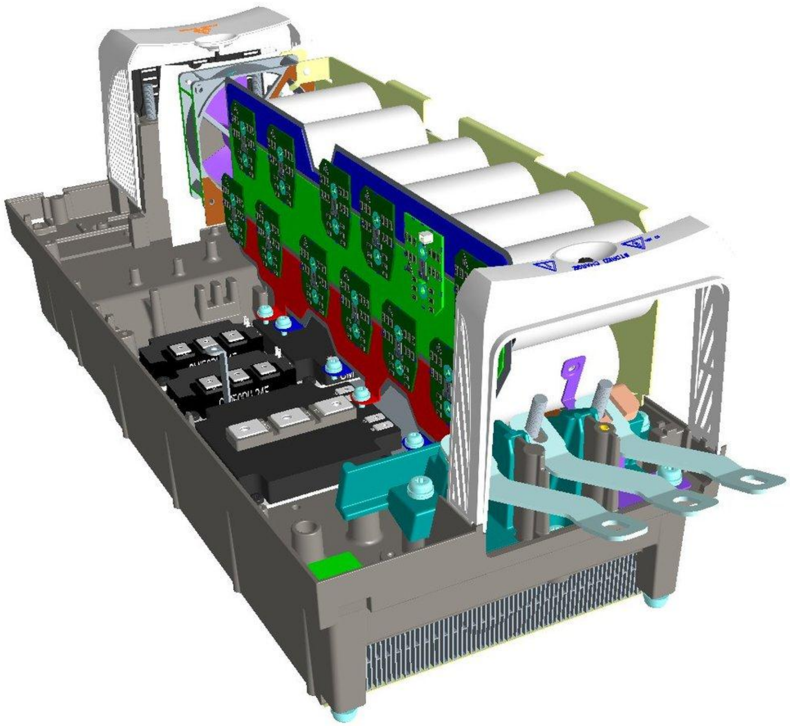
Reactors

Transformers

Multi-pulse drives

Filters

Maintaining Your VFD



Source: Emerson Industrial

## VFD Power Quality Issues

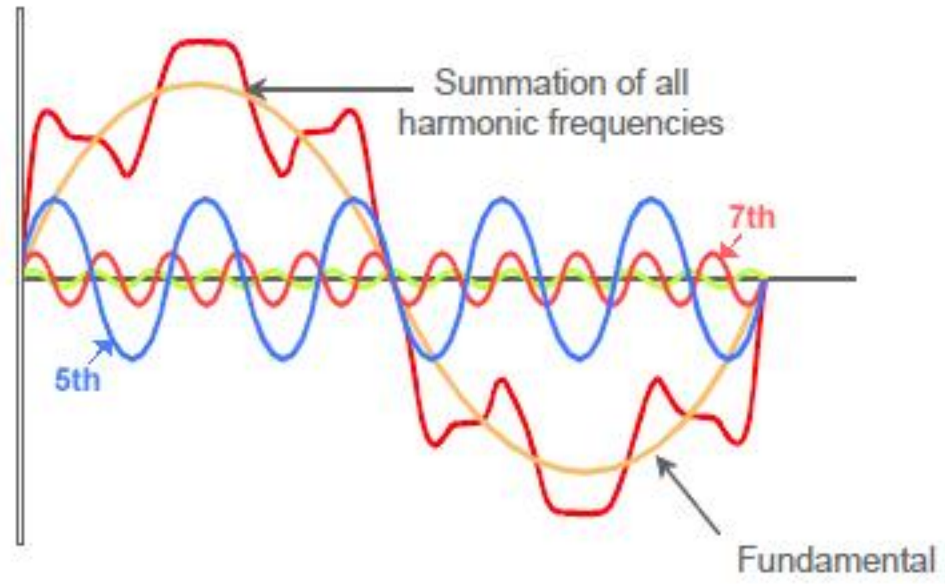
Protecting the VFD

- Drops out below 70% voltage (30% sag).
- Protect against high potential spikes (2xV for 0.1 cycle)
  - Fast acting Metal Oxide Varistor (MOV)
  - Zener diodes
  - Oversized DC bus capacitors
- Drops out at >2% phase imbalance
- UL requires fuses over circuit breakers before VFD
- Locate power factor correction capacitors upstream of VFD

# VFD Power Quality Issues

Harmonic distortion solutions

- Move equipment to a different power supply
- Use phase-shift transformer to serve two VFDs
- Reactors and filters



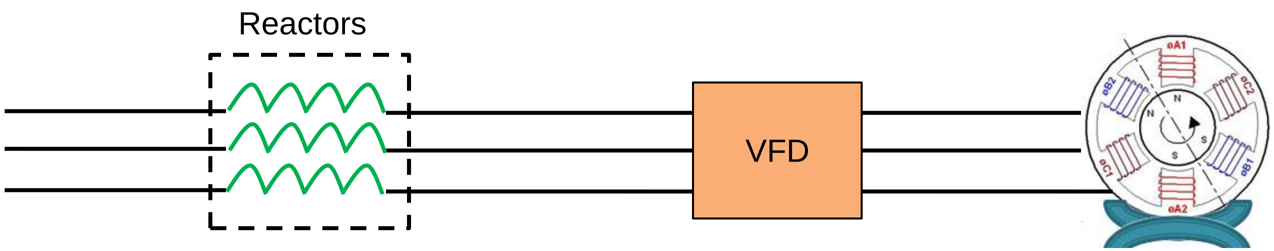

Source: Danfoss

# VFD Power Quality Issues

AC input line reactors upstream of VFD

- Reduces harmonic noise
- Also can slightly reduce supply voltage level

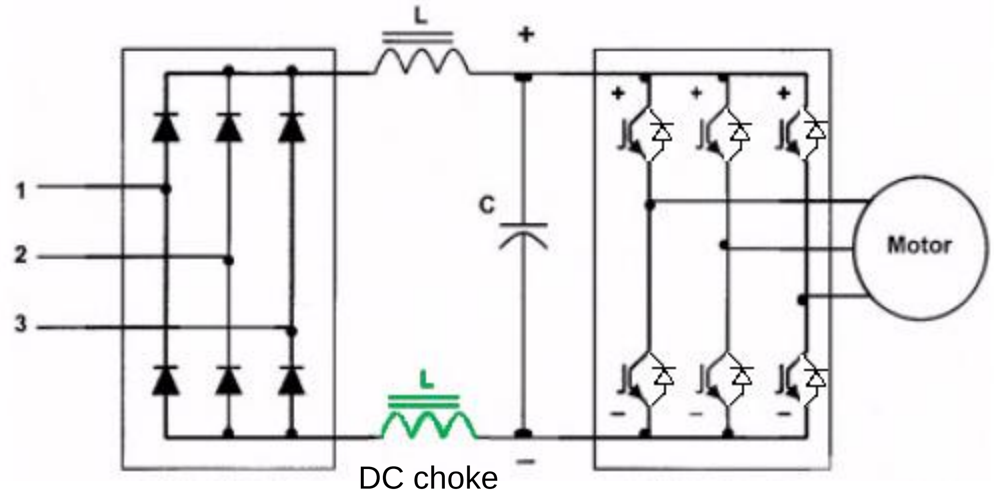
| Reactor Impedance | Harmonic Current Distortion |
|---|---|
| 1% | 80% |
| 3% | 35%-45% |
| 5% | 30%-35% |



## VFD Power Quality Issues

DC reactors/chokes built into the drive

- The DC choke provides a greater reduction primarily of the 5th and 7th harmonics
- On higher order harmonics the line reactor is superior
- Less voltage drop than line reactors




Source: HVACRedu.net

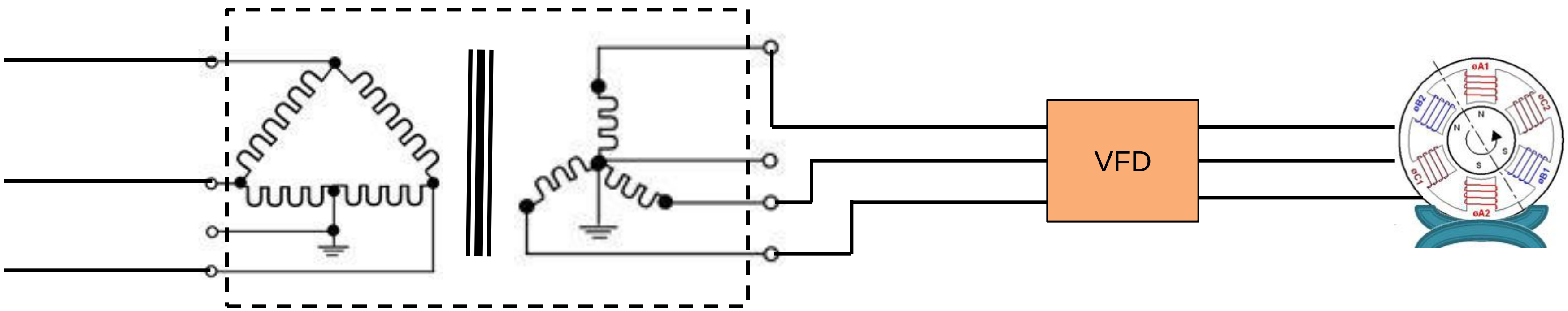
## VFD Power Quality Issues

Isolation transformers upstream

- Method for “living with” harmonics

K-rated transformers upstream

- Method for “living with” harmonics
- K-factor (normally 1-20)

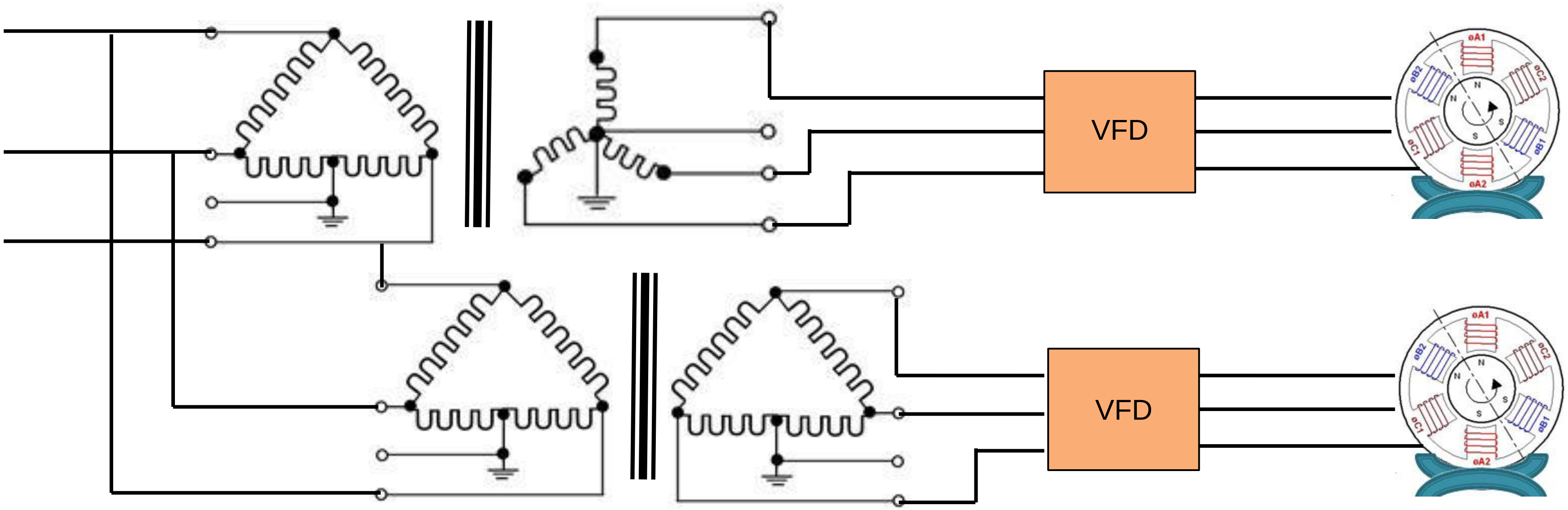



Isolation
Transformer

## VFD Power Quality Issues

Harmonic mitigating/Phase shifting/Quasi 12-pulse transformers

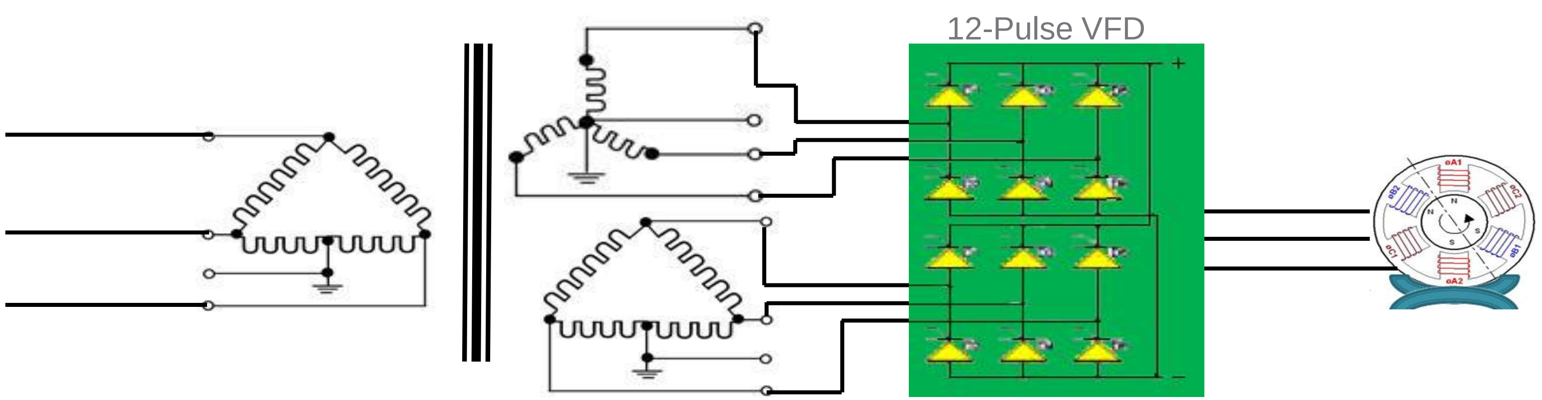
- Provides substantial reduction (50-80%) in voltage and current harmonics
- Must supply AFDs with equal HP and equal load



## VFD Power Quality Issues

Multi-pulse drives

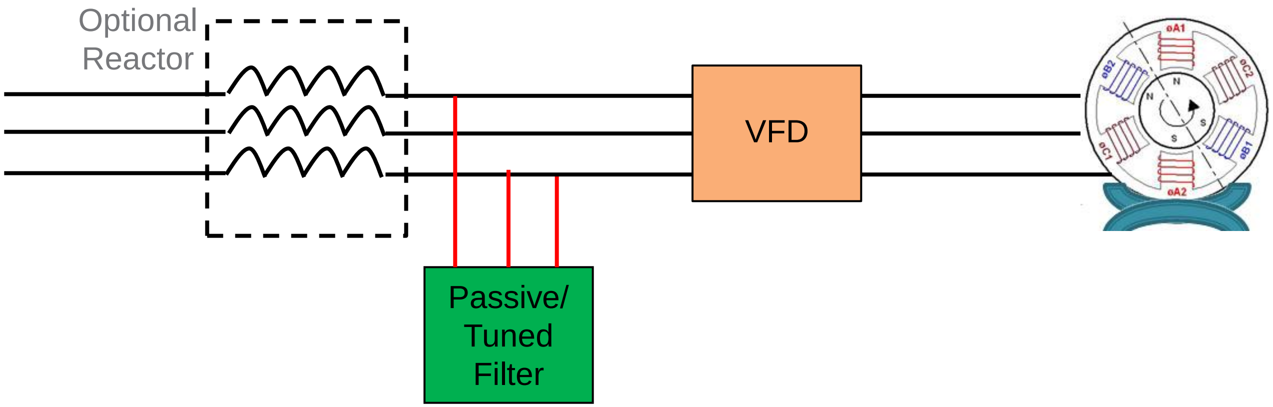
- 12- or 18-pulse converter
- Fed from equal impedance phase-shifted power sources
  - Harmonics (5th, 7th ) from the first cancels the second
  - A 50% harmonic reduction (up to 85%)
  - Good solution for drives >75 HP



# VFD Power Quality Issues

Filters

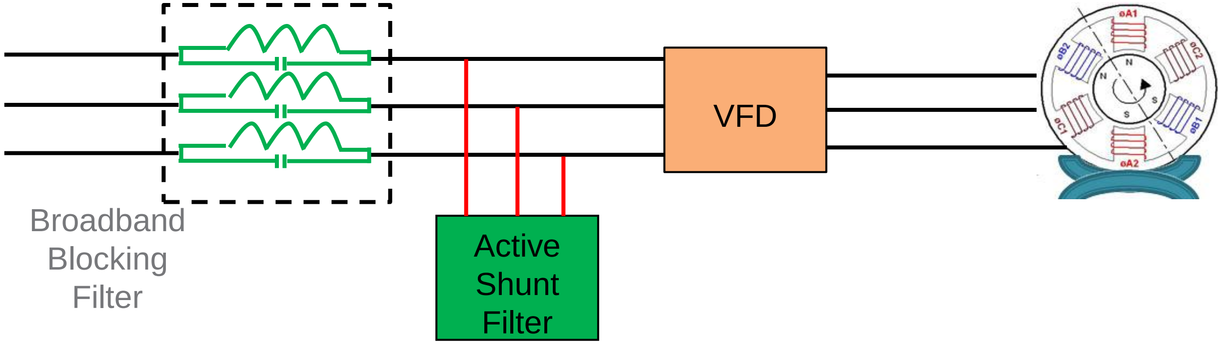
- Passive
  - A combination of a reactor and capacitor elements
- Tuned
  - Connected in a parallel shunt arrangement
  - Designed for a specific harmonic frequency (5th)
  - Protects multiple drives, including PF correction



## VFD Power Quality Issues

Filters

- Broadband blocking
  - Connected in series
  - Good for individual drives <50HP
  - Provides PF correction
- Active
  - Injects equal and opposite harmonics
  - Expensive
  - Easily adapts to varying loads



# VFD Power Quality Issues

| Estimated Cost of Harmonic Correction | |
|---|---|
| Device Type | $/KVA |
| Active Filter | $150 |
| Broadband Blocking Filter | $100 |
| Phase-Shifting Transformers | $50 |
| Tuned-Switched Filter | $40-$50 |
| Tuned Fixed Filter | $35 |
| Switched Capacitors | $25 |
| K-Rated Transformer | $20 |
| Reactor (choke) | $3-$4 |

# Maintaining Your VFD

## Keep it clean

- NEMA 1 category (side vents for cooling airflow) are susceptible to dust contamination
- Spray oil-free and dry air across the heat sink fan

## Keep it dry

- Use a NEMA 12 enclosure and thermostatically controlled space heater if you locate it where condensation is likely

## Keep connections tight

- Loose control wiring connections can cause erratic operation
- Use an infrared imaging unit to note hot connections

# Case Studies

Erickson Air-Crane helicopter refurbishing facility

- Existing plus rented modulating screw compressors
  - Insufficient capacity (CFM) and pressure
  - Loss of production waiting for pressure rise
  - Moisture and air impurities
  - High maintenance and energy costs
- Replaced with one 150-hp screw compressor with VFD drive
  - Annual energy cost reduced from $30,424 to $6,725
  - 66% increase in capacity (CFM)
  - Increased plant productivity

## Case Studies

Demix Construction asphalt production plant

- Dust collection system air outlets
- Constant, full-speed operation 12 hours per day
- VFD runs at 40% to 90% of full speed only when needed
  - $12,000 electricity cost savings
  - Payback of 2 to 3 years
  - Reduced noise level in plant
  - Decreased environmental footprint

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# Upcoming Webinars and Trainings

Go to the NEEA calendar at www.neea.org/industrial-events for other trainings and events scheduled around the Northwest region.

## Webinars:

**November 17, 2011: Webinar: Trends and Advances in Lamps and Ballasts**
http://www.neea.org/participate/calendar.aspx?eventID=3097

## In-Class Trainings:

**November 9, 2011: Pumping System Optimization (Twin Falls, ID)**
http://www.neea.org/participate/calendar.aspx?eventID=3156

**November 10, 2011: Adjustable Speed Drive Applications and Energy Efficiency (Hermiston, OR)**
http://www.neea.org/participate/calendar.aspx?eventID=2990

**November 10, 2011: Energy Data Analysis: Introduction to KPIs (Helena, MT)**
http://www.neea.org/participate/calendar.aspx?eventID=3132

**November 16, 2011: Compressed Air Challenge - Level 1 (Yakima, WA)**
http://www.neea.org/participate/calendar.aspx?eventID=3133

**November 30, 2011: Energy Management: Introduction to Best Practices (Vancouver, WA)**

http://www.neea.org/participate/calendar.aspx?eventID=2974

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