QUESTLINE

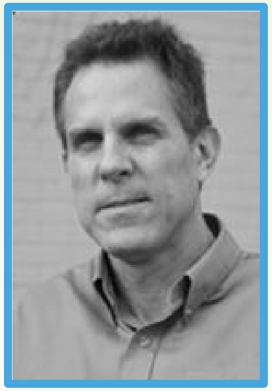
We Make Energy Engaging

Variable–Frequency Drives

Questline Academy

Meet Your Panelist

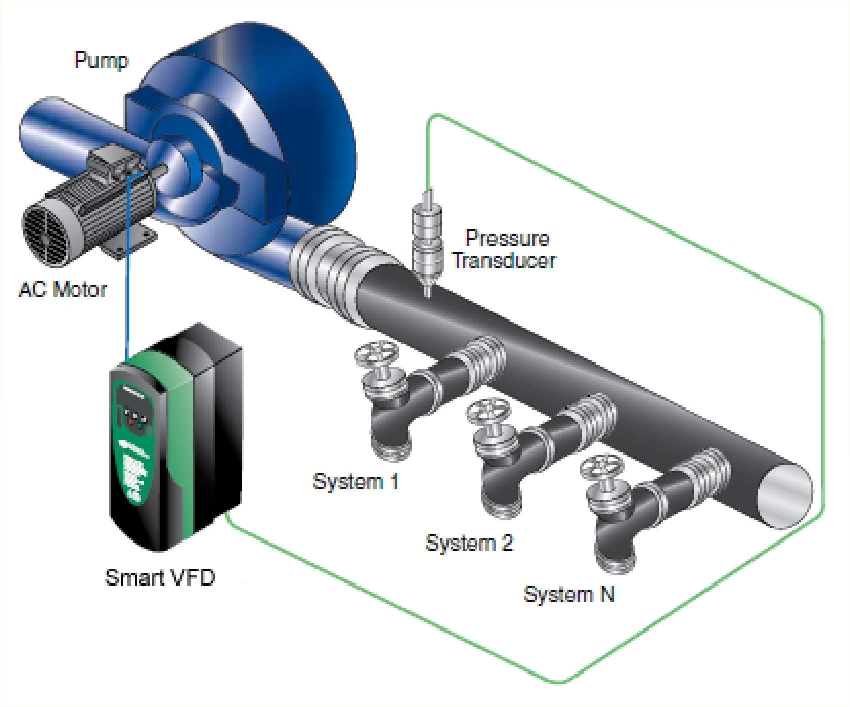
- Mike Carter



ENLIGHTEN EDUCATE ENGAGE

Contents

- Basics
- Motor Loads
- Operation
- Advantages/ Disadvantages
- Sizing a VFD
- Power Quality Issues



Source: Emerson Industrial Automation

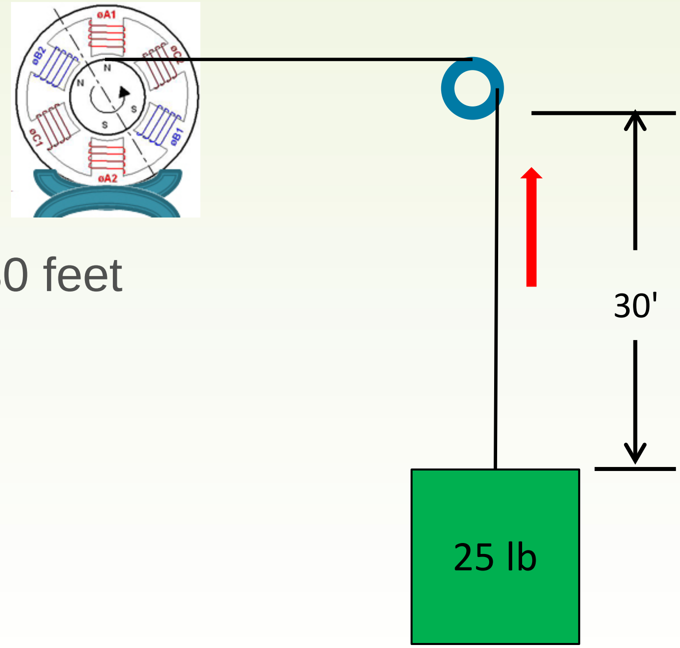
Basics

- Work
  - o 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



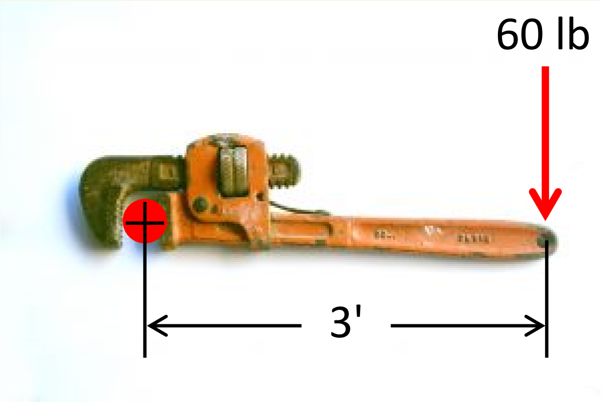
Basics

- Torque
  - o 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

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

Power (kW) = HP x 0.746/eff

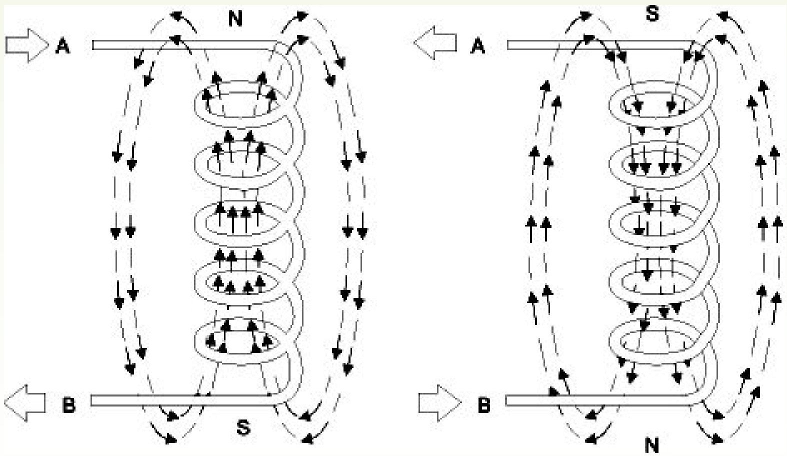
Example: What is electrical power for a 200 HP motor?

Source: www.sxc.hu

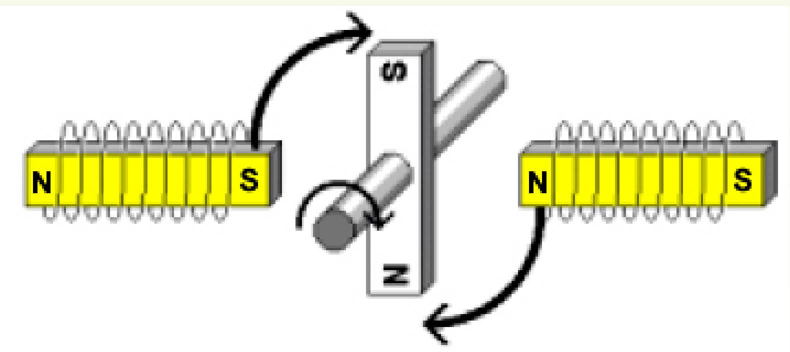
Power (kW) = 200 HP x 0.746/0.90 = 166 kW

Basics

- Electric motors
  - o Direction of current flow changes poles.



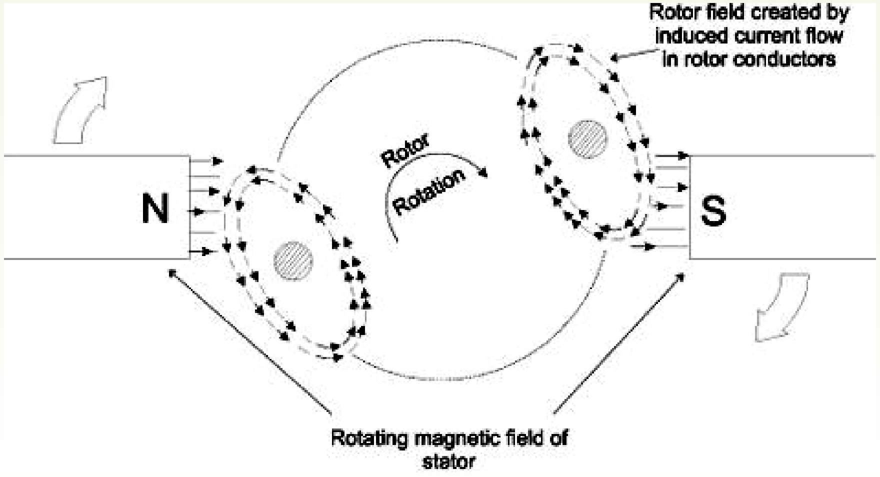
Source: Reliance Electric



Source: Danfoss

Basics

- Electric motors
  - Stator field induces current flow in rotor conductors.



Source: Reliance Electric

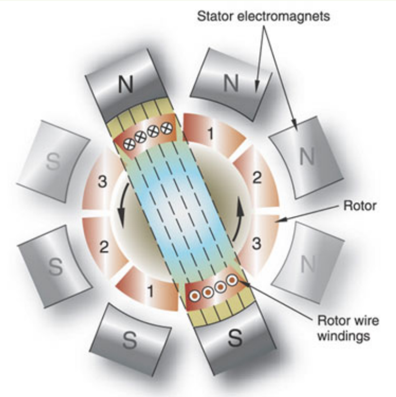
Basics

- Synchronous speed of rotating stator field.

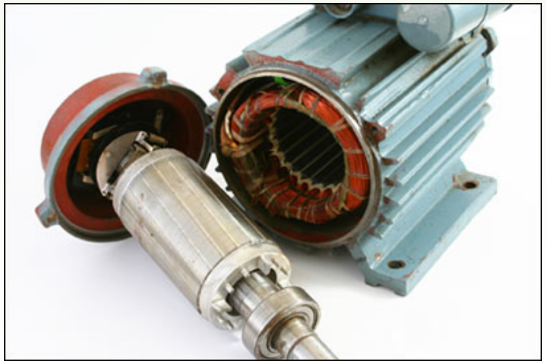
$$\text{Speed} = \frac{120 \text{ x } f}{\#\text{Poles}}$$

  - 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

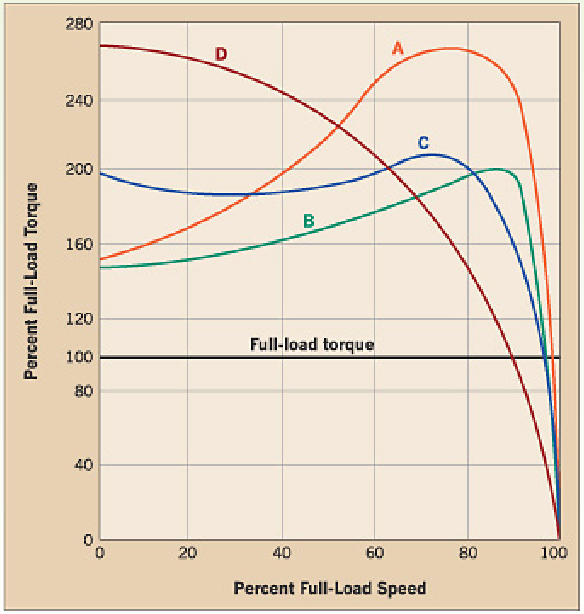
Basics

- Motor torque
  - o 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

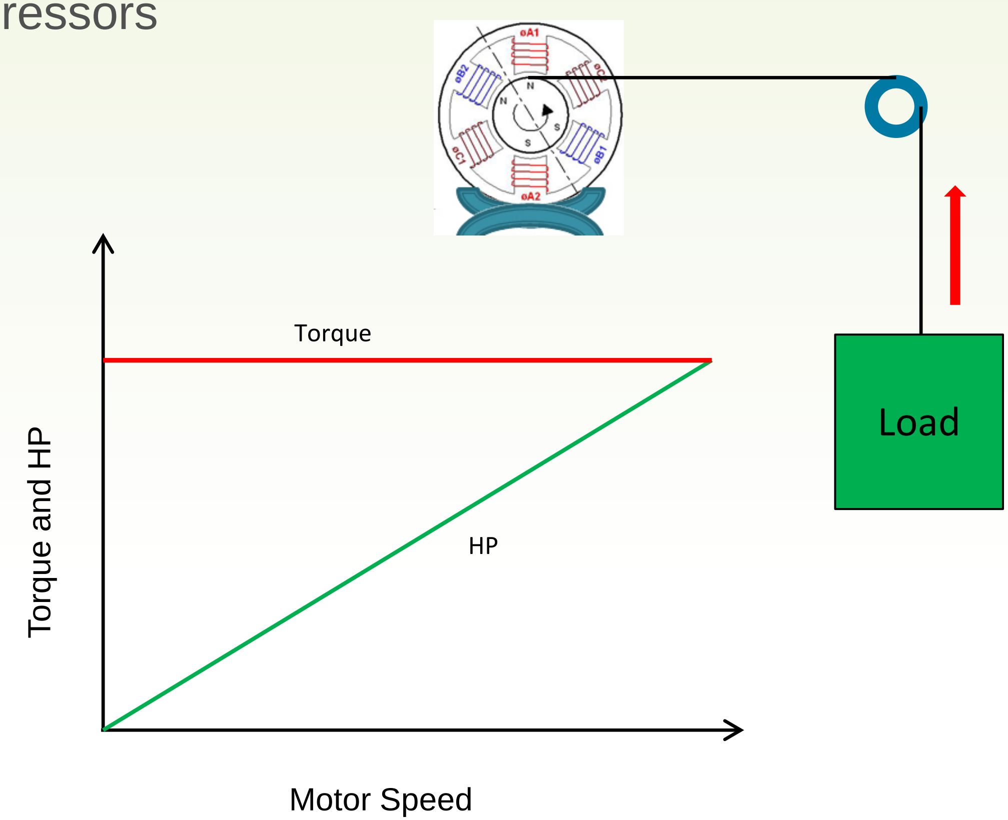


Source: Baldor Electric

  - o Also related to voltage and frequency
    - Volts per hertz (V/Hz)

Motor Loads

- Constant torque/Variable HP
  - o Torque independent of speed.
  - o Not the best VFD application.
    - Rotary/screw compressors
    - Ball mills
    - Conveyors
    - Band saws
    - Chippers
    - Drills
    - Lathes



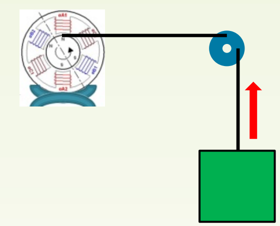
Motor Loads

- Speed, Torque, and HP

  T = (HP x 5252)/rpm

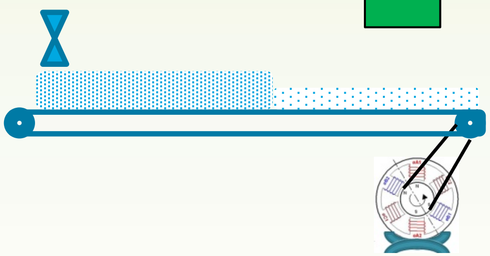
Speed	Torque	HP
↑↓	=	↑↓

T ≈ HP/rpm



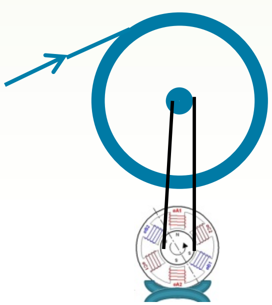
Speed	Torque	HP
=	↑↓	↑↓

rpm ≈ HP/T



Speed	Torque	HP
↑↓	↓↑	=

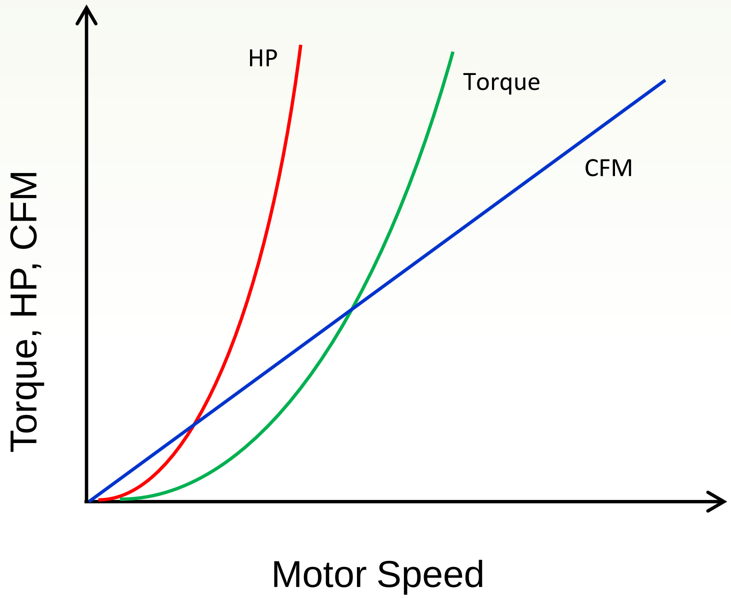
HP ≈ T x rpm



Motor Loads

- Variable torque/Variable HP
  - o Volume ≈ rpm
  - o $T \approx rpm^2$
  - o $HP \approx rpm^3$
    - Compressors
      - o Centrifugal
    - Pumps
    - Blowers
    - Fans

Source: Stock Exchange

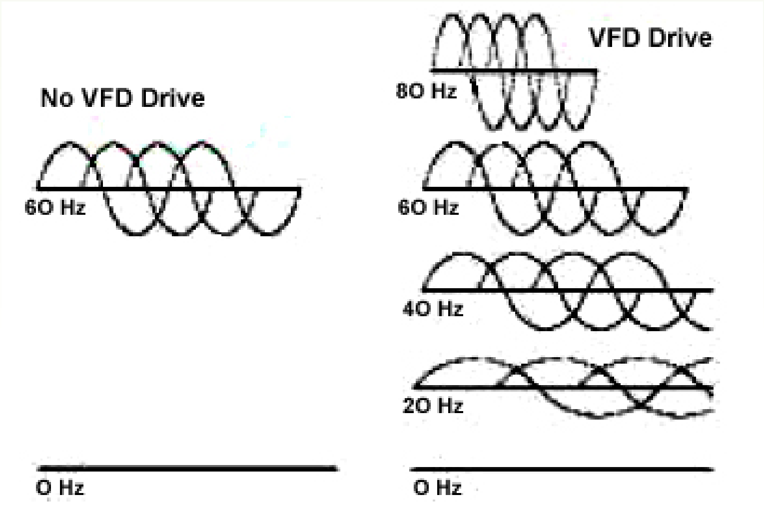


VFD Operation

- Synchronous speed of rotating stator field.

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

- Vary speed by varying frequency.
  - o Vary frequency from 0 Hz to 60 Hz or more



Source: Danfoss

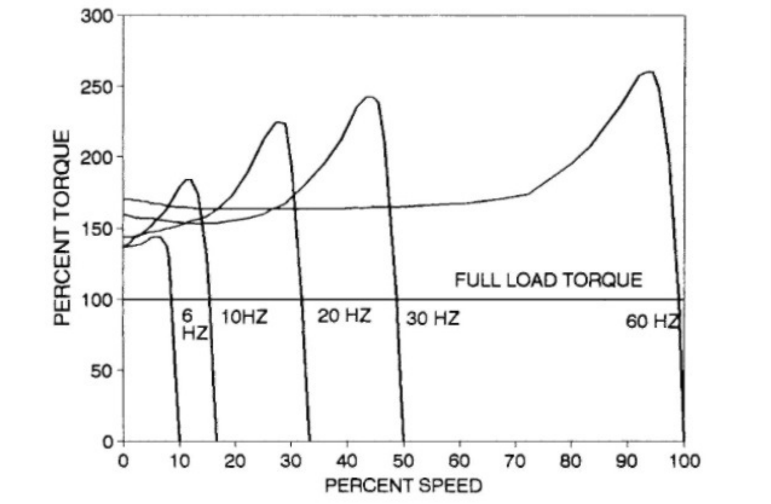
VFD Operation

- Torque is proportional to volts divided by frequency.

T ≈ V/Hz

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

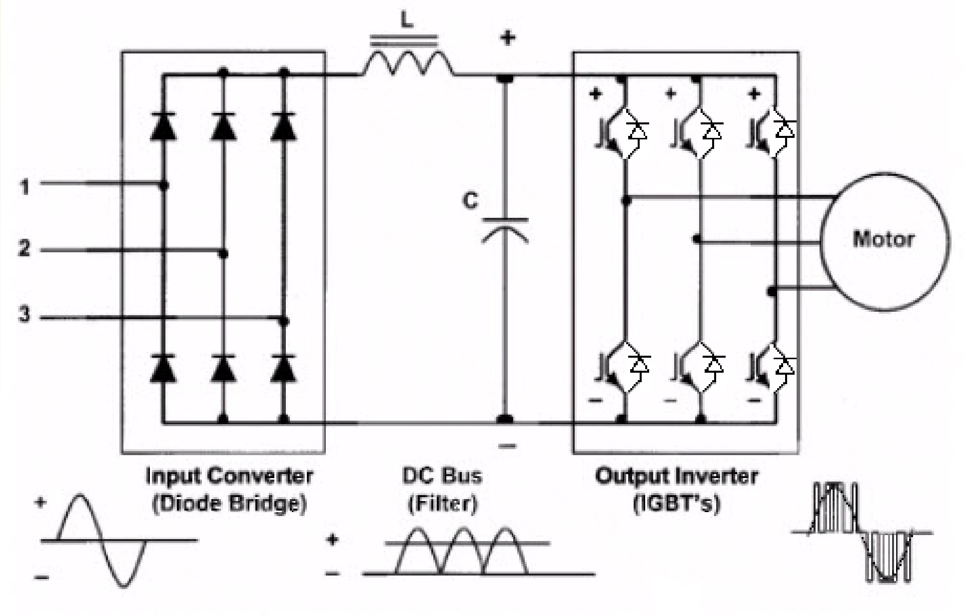
  - If you decrease frequency, volts must decrease also to achieve constant torque.



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

VFD Operation

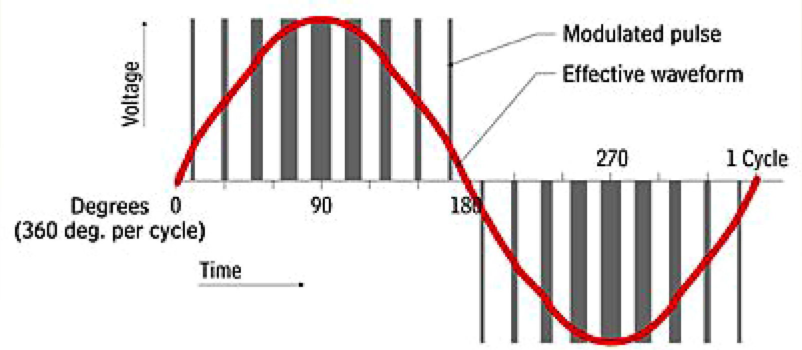
- Typical circuit diagram
  - o Adjustable Frequency Drive (AFD)
  - o Variable Speed Drive (VSD)
  - o Adjustable Speed Drive (ASD)



Source: HVACRedu.net

VFD Operation

- Constant voltage inverter
  - o 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
  - o Energy savings 25%-85%
- Improved power factor
  - o 95%+
- Improved speed control

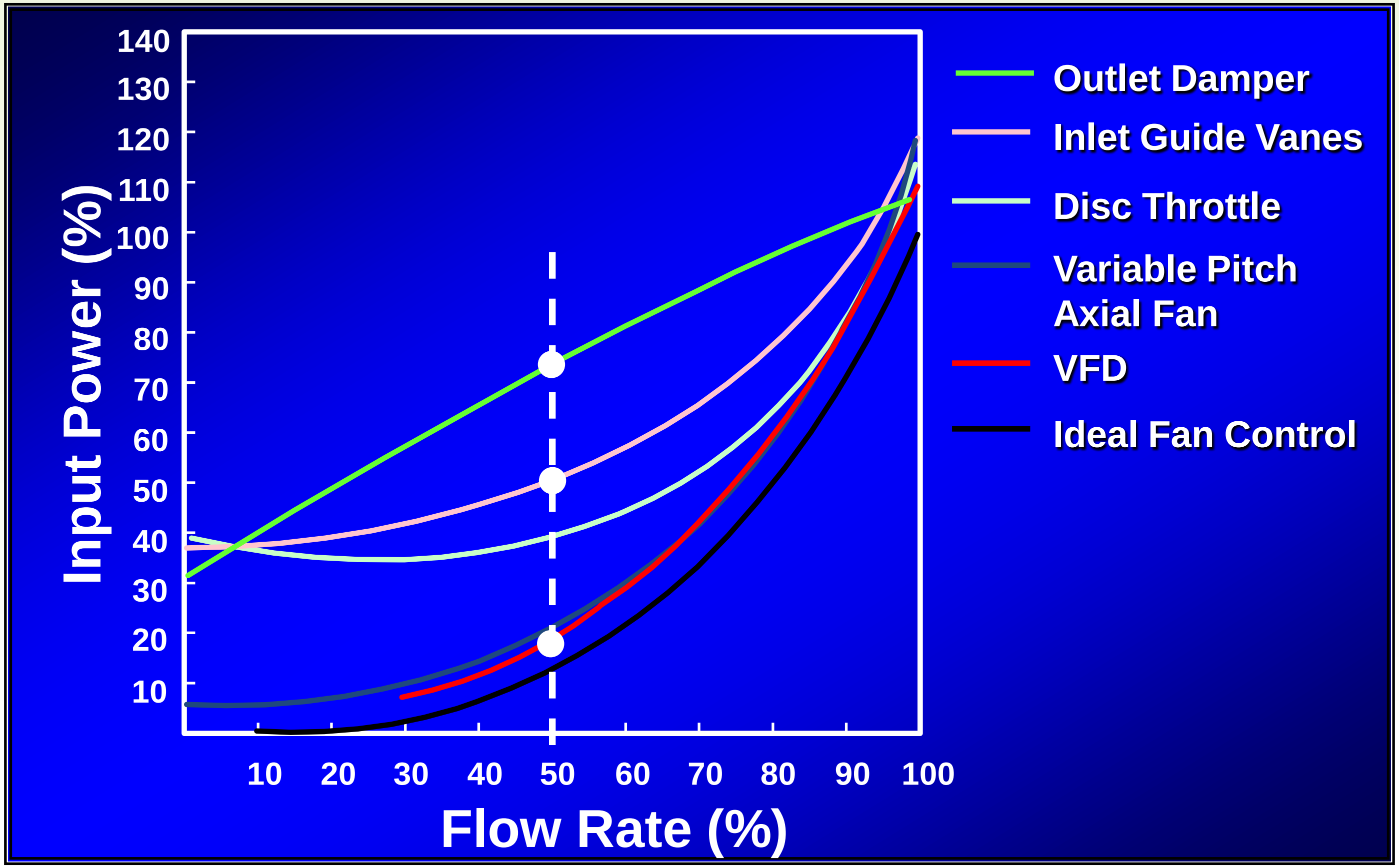
VFD Advantages

- 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%

$HP_{0.5} = HP_1 \times (0.5)^3$
$= HP_1 \times 0.125$

*VT/VH = Variable Torque/Variable Horsepower

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%

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

- Comparison with mechanical dampening
- Assume a 25 HP fan motor operating 23 hrs/day
  - o Energy consumption VFD/Damping = 10.3/19.9 = 50%
  - o 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

VFD Energy Savings

- Comparison at lower speeds but longer run hours
  - o Assume a 50 HP (41.4 kW) motor operating at reduced speeds (but equivalent flow)

Full load energy consumption = 41.4 kW x 16 hr
= 662 kWh

VFD energy consumption = 352 kWh

Savings = 310 kWh

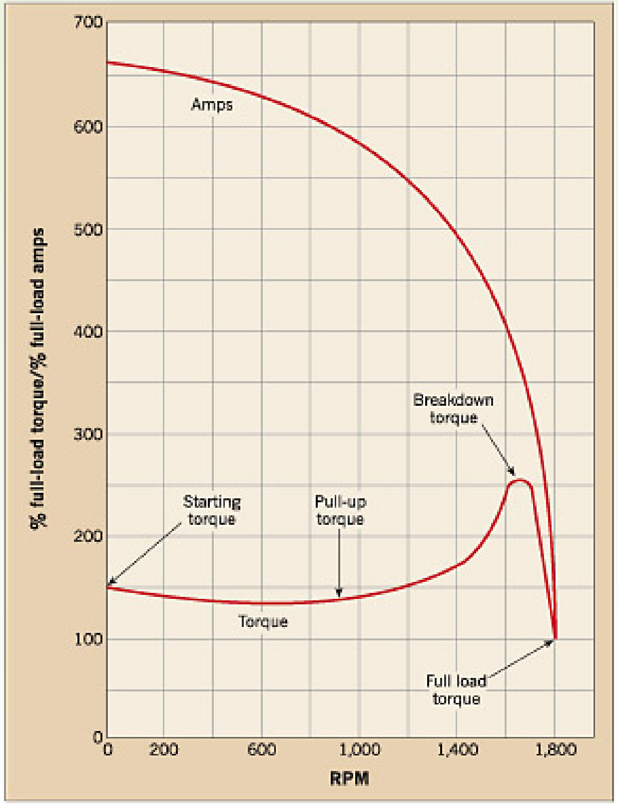
50 HP VFD Pwr vs Speed @Hrs				
Speed	Power	kW	Hours	kWh
100%	105%	43.5	2	87
75%	42%	17.4	8	139
67%	30%	12.4	8	99
50%	13%	5.4	5	27
		Totals	23	352

Soft-starting

- Soft-starting

  LRT ≈ I^2 ≈ V^2

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

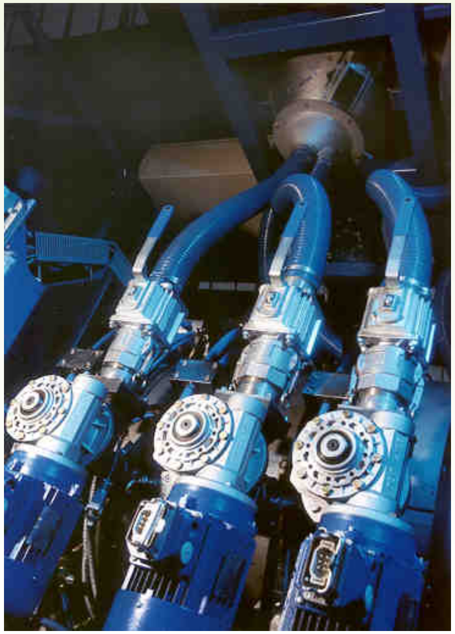
- o Soft-start draws 400-600% of rated amps during motor start.
- o A VFD draws only 100% to 120% of rated amps at 100% rated torque.

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

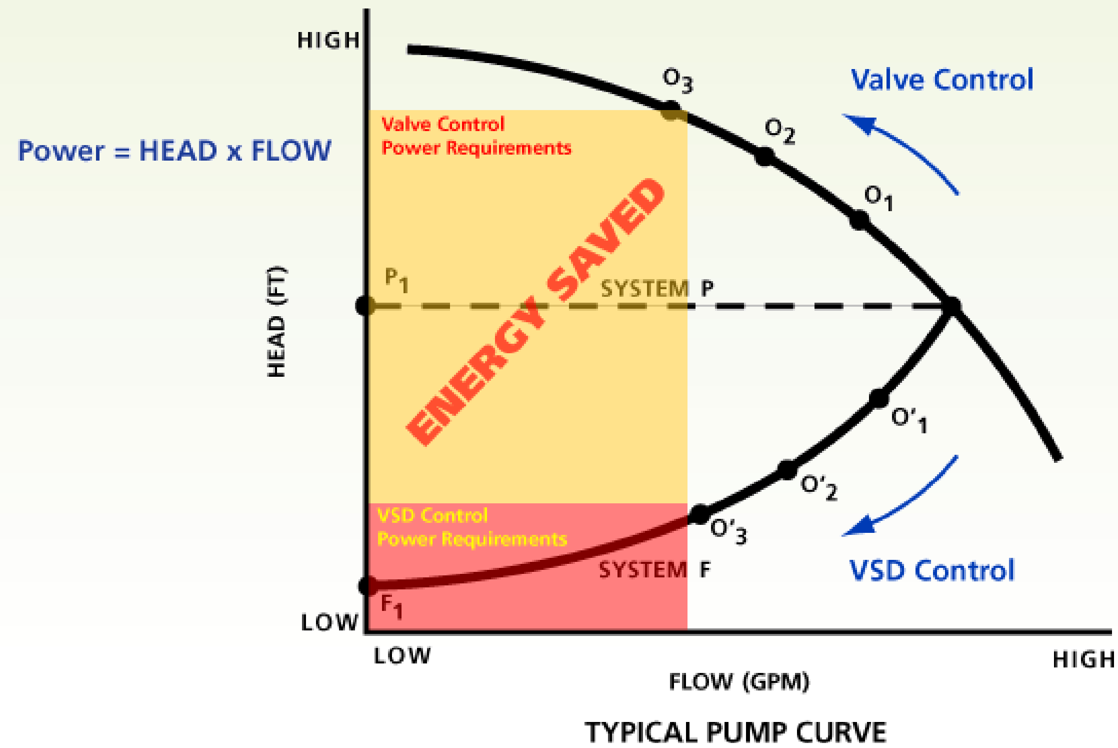
- All variable torque applications
  - Compressors
    - Centrifugal
  - Pumps
    - Chilled water
    - Condenser water
    - Building supply
    - Chemical dosing
  - Blowers
  - Fans



Source: Emerson Industrial Automation

VFD Best Applications

- When pump and system curves are close to perpendicular



Source: Emerson Industrial Automation

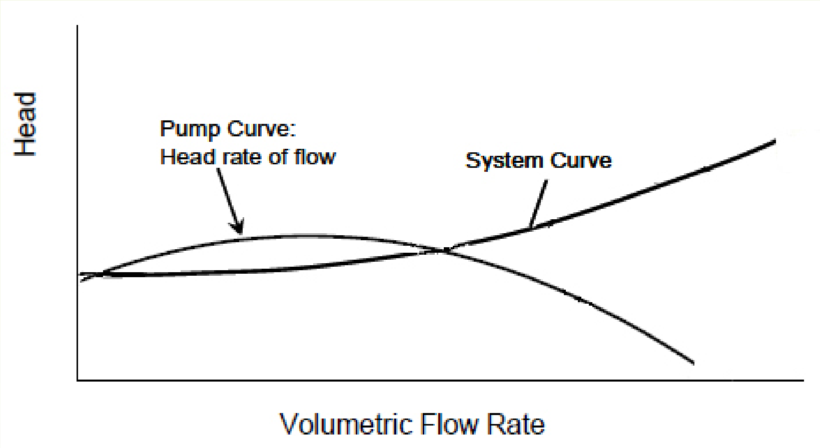
VFD Best Applications

- 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
  - o Pump and system curves are parallel
    - High lift
    - Minimal pipe friction
  - o No variability in speed
    - Use impeller trim
    - Adjust the motor fixed speed (change gears)
  - o 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

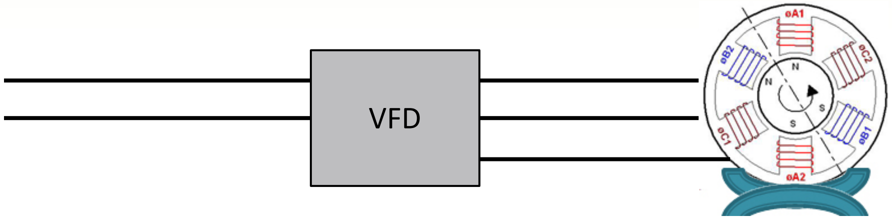
- Determine why the load operation needs to be changed.
  - How many speed changes required?
  - How often does speed need to be changed?
- Evaluate the possibility of required oversizing of the VFD.
  - Hard-to-start loads
  - Quick start or emergency stop
  - High temperature environment may require VFD derating.
    - Temperatures >104°F (40°C)

Sizing a VFD

- Using a 3-phase VFD with single phase power
  - o The 3-phase VFD HP rating x 2

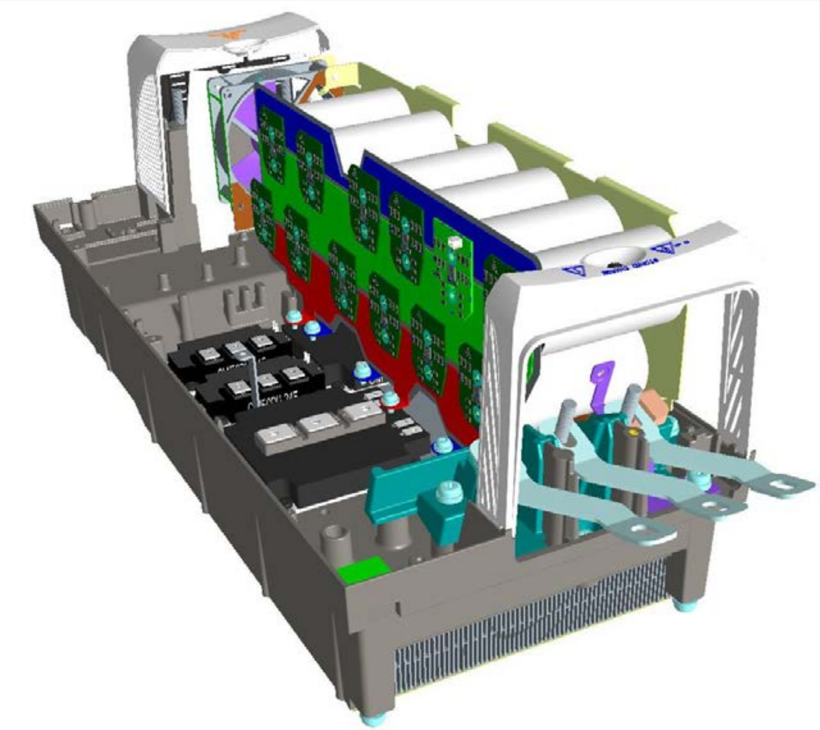
Example: 10 HP 230 Volt three phase motor
requires a 20 HP rated 3-phase VFD.

- 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



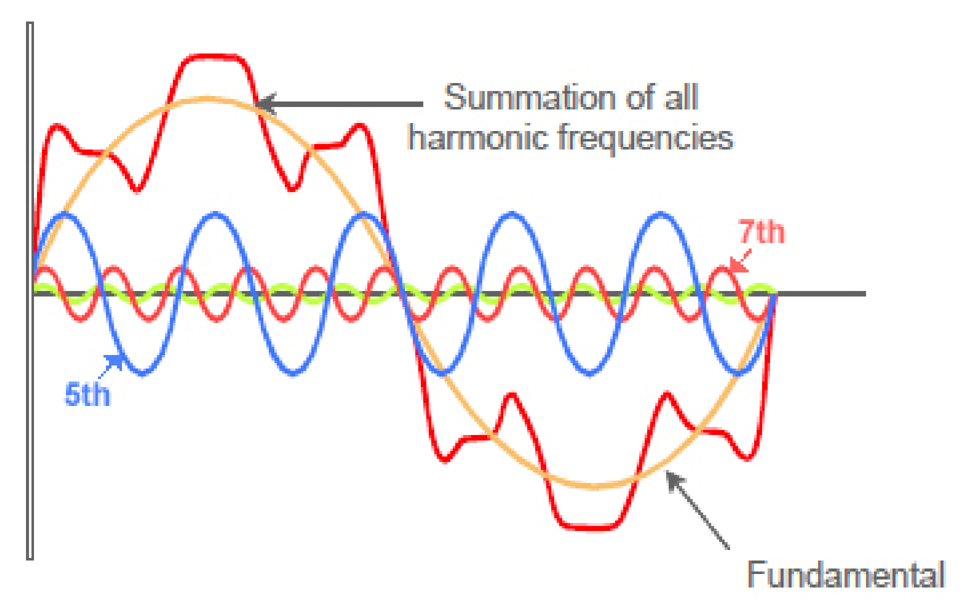
Source: Emerson Industrial

VFD Power Quality Issues

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

VFD Power Quality Issues

- Harmonic distortion solutions
  - o Move equipment to a different power supply.
  - o Use phase-shift transformer to serve two VFDs.
  - o Reactors and filters.

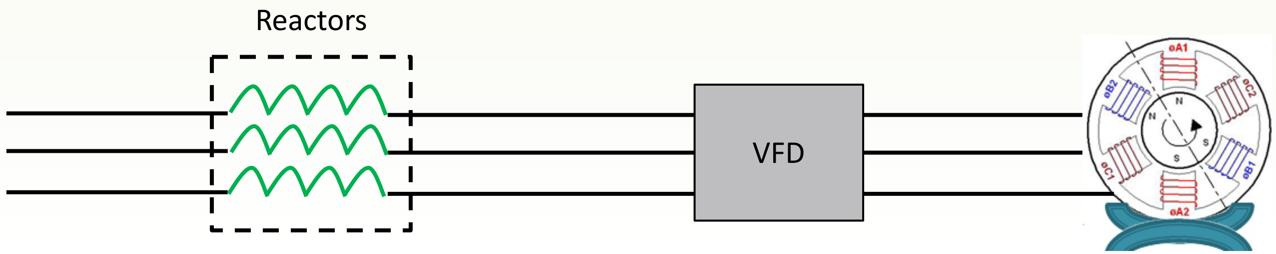


Source: Danfoss

VFD Power Quality Issues

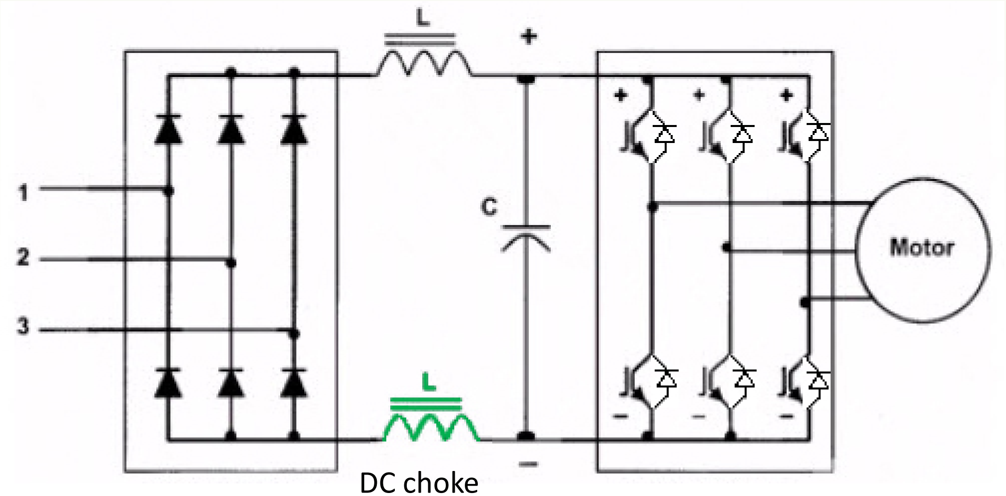
- AC input line reactors upstream of VFD
  - Reduces harmonic noise
  - Also can slightly reduce supply voltage level

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.

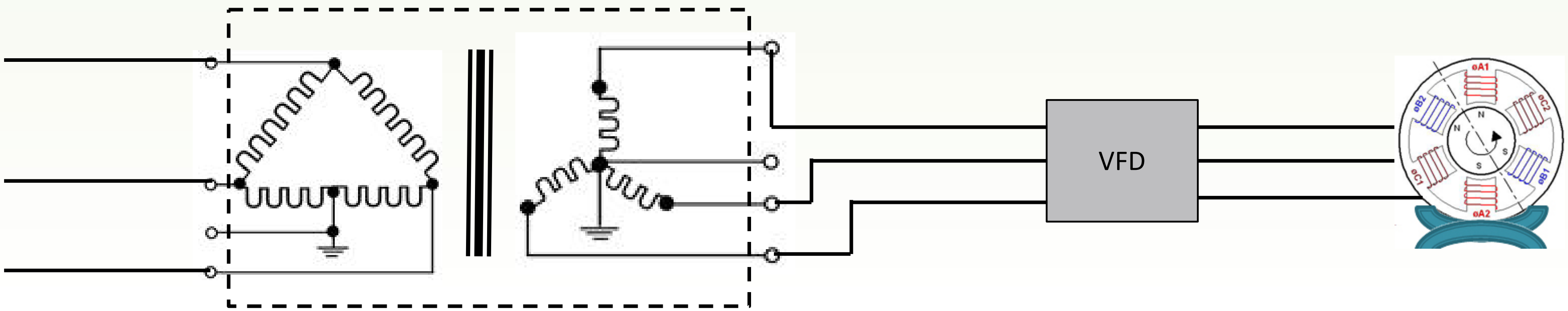


DC choke

Source: HVACRedu.net

VFD Power Quality Issues

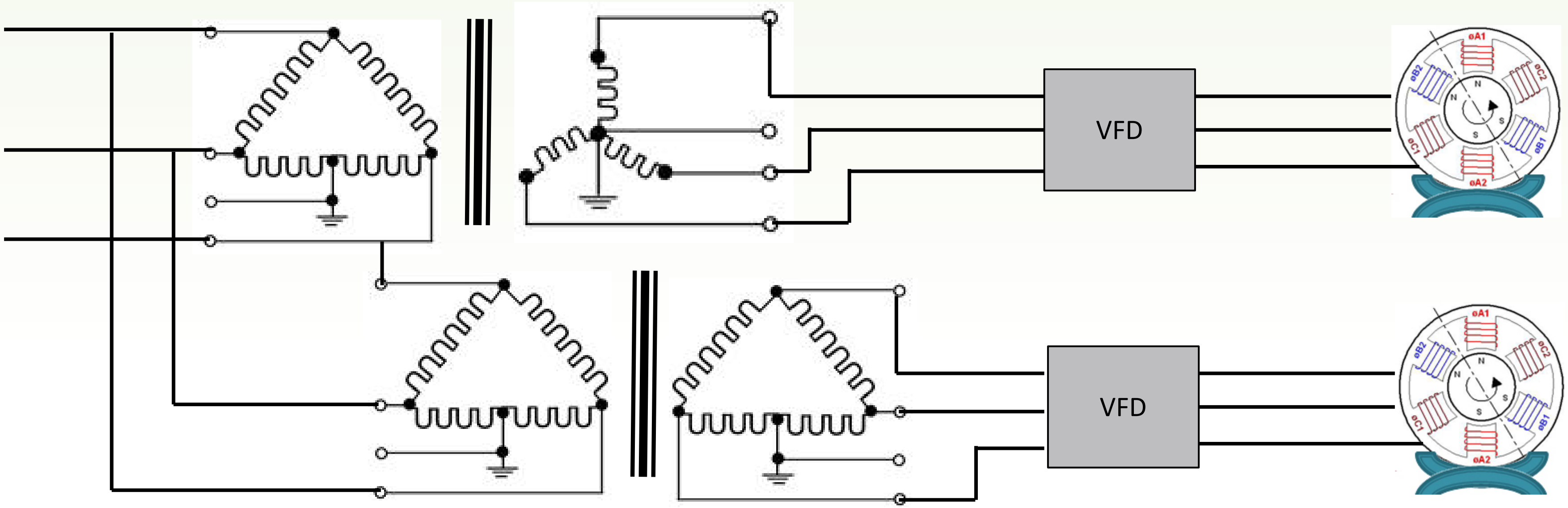
- Isolation transformers upstream
  - o Method for “living with” harmonics
- K-rated transformers upstream
  - o Method for “living with” harmonics
  - o K-factor (normally 1-20)



Isolation
Transformer

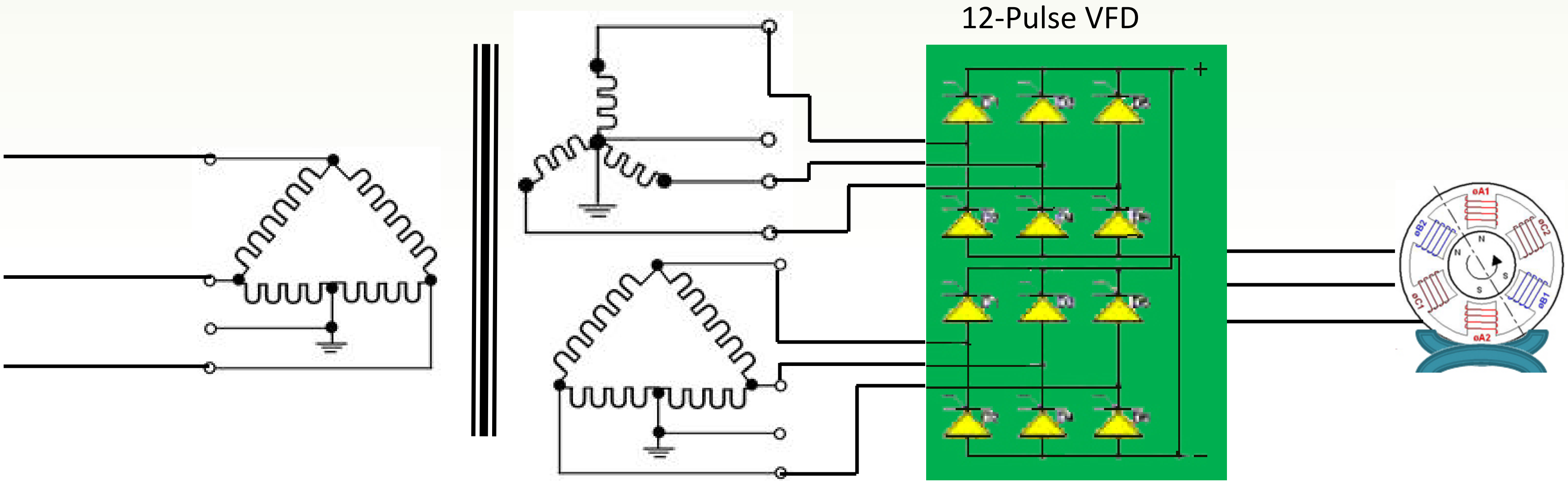
VFD Power Quality Issues

- Harmonic mitigating/Phase shifting/
  Quasi 12-pulse transformers
  - o Provides substantial reduction (50-80%) in voltage and current harmonics.
  - o Must supply AFDs with equal HP and equal load.



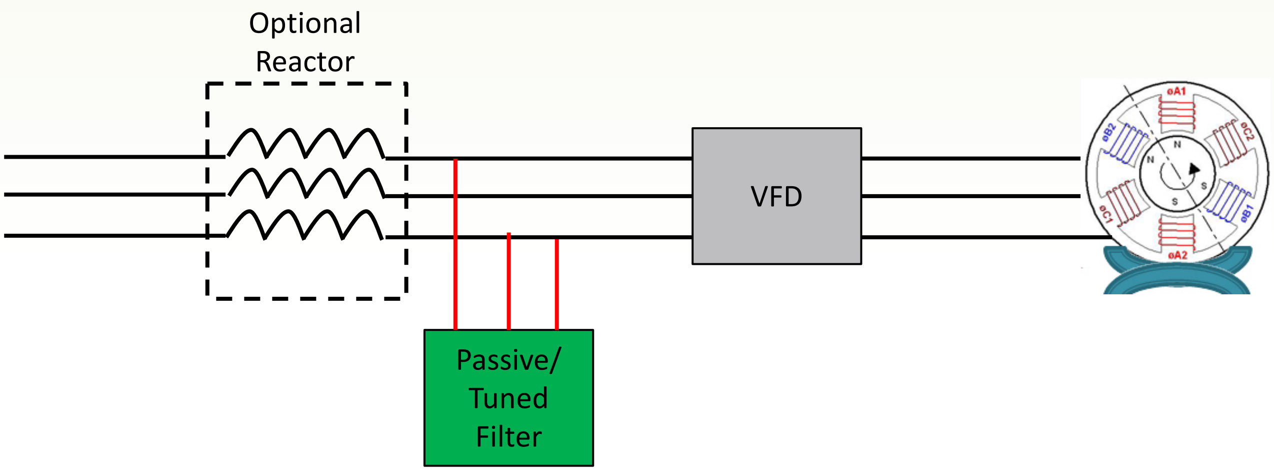
VFD Power Quality Issues

- Multi-pulse drives
  - o 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.



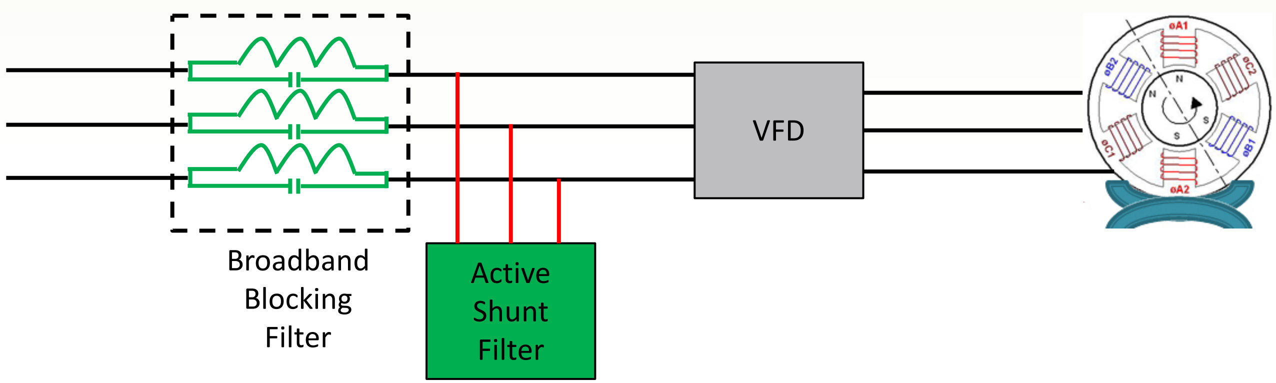
VFD Power Quality Issues

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



VFD Power Quality Issues

- Filters
  - o Broadband blocking
    - Connected in series
    - Good for individual drives <50HP
    - Provides PF correction
  - o 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.

Quiz

- Which one of the following is NOT TRUE of torque?
  a) Proportional to motor horsepower
  b) Measured in units of force (lbs)
  c) Exists even if no movement occurs

Quiz

- With a VFD, why do you need to keep the voltage-to-frequency ratio constant?
  a) To achieve constant speed
  b) It keeps the motor cool
  c) To achieve constant torque at all speeds

Quiz

- Which one of the following IS NOT an advantage of a VFD?
  a) Saves energy
  b) Increases power factor
  c) Most efficient operating at 100% of rated speed
  d) Built-in soft-starting

Quiz

- Which one of the following IS NOT an optimum application for a VFD?
  a) High lift or hard-to-start loads
  b) Operation mainly at <85% of rated speed
  c) Pump and system curves are close to perpendicular
  d) Variable torque loads

Quiz

- Which of the following are possible solutions for harmonics generated by VFDs?
  a) Filters
  b) Isolation or K-rated transformers
  c) Phase-shifted transformers
  d) Reactors/chokes

QUESTLINE

We Make Energy Engaging

Thank You!

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