Understanding & Managing Variable Frequency Drives

Presented by: Greg Stark, P.E.

September 10, 2014

Sponsored by:

Massachusetts Energy Efficiency Partnership

MAEEP

nationalgrid

Variable Frequency Drives (VFD's)

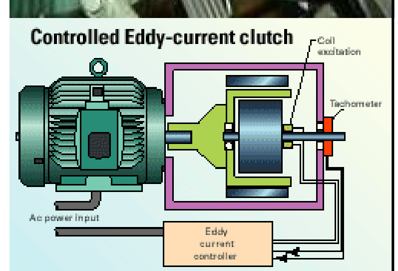
- Popular speed control devices used in industrial, commercial and residential applications.
  - Huge energy savings potential operating centrifugal fans, pumps and compressors
- Vary frequency of electrical supply to an induction motor to vary the motor speed.
  - Vary the speed/flow of the operation/application.

VFD Applications

- Industrial
  - Fans, Pumps, Compressors
  - Conveying Systems
- Commercial
  - HVAC Compressors
  - Pumps and Air Handlers
- Residential
  - Variable Speed HVAC equipment
  - Energy Efficient Washing Machines

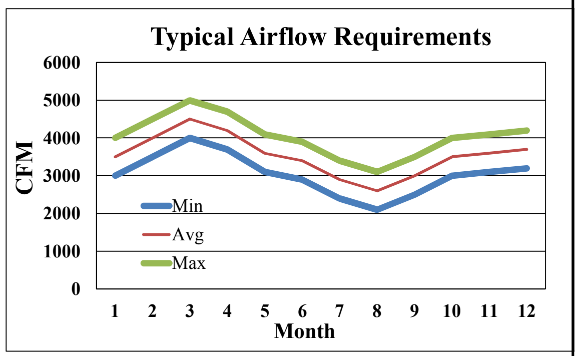
How Have We Varied Speed Historically?

- Change Speed
  - Belts & pulleys
  - Chains & sprockets
  - Gear drives
  - Multi-speed motors
- Vary Speed
  - Variable pitch belts & pulleys
  - Eddy current clutch
  - Hydrostatic drives
  - Wound rotor motor
  - DC Drives
  - AC Variable Frequency Drives



How Have We Varied Flow Historically?

- Size motor/system for maximum flow
- Use throttling devices on fans, pumps & compressors to reduce flow rates
  - Valves
  - Vanes & Dampers



Considerations?

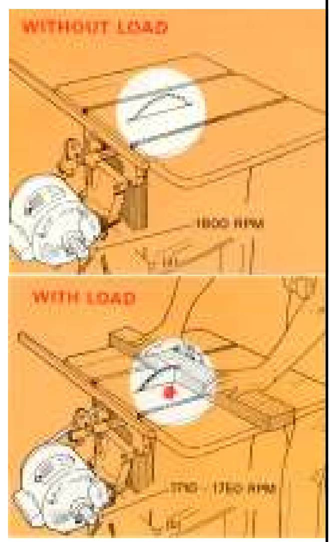
- Initial Cost
  - VFD vs other device
- Maintenance Cost
  - VFD vs other device
- Maintenance Issues (Downtime, etc)
- Effectiveness
  - How well does it do what I really want/need it to do?
- Others?

Induction Motor = Constant Speed???

- Synchronous Speed
  - Speed the motor's magnetic field rotates.
  - Theoretical speed with no torque or friction.
  - A well built motor may approach synchronous speed when it has no load.
  - Factors
    - Electrical Frequency (cycles/second)
    - # of poles in motor

  Speed = (120 * Frequency)/(# of poles)

- Rated Speed
  - Speed the motor runs at when fully loaded and supplied rated nameplate voltage.

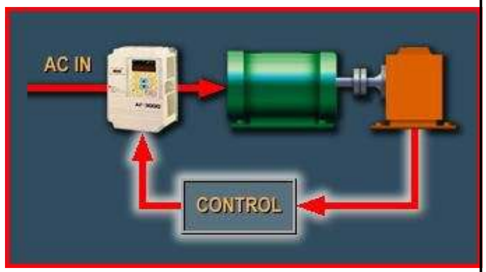


VFD Principles of Operation

- Motor speed can be varied by changing the frequency, # of poles, or both.
- Example:
  - 4 pole motor @ 60 hertz = 1800 rpm
  - 4 pole motor @ 50 hertz = 1500 rpm
  - 4 pole motor @ 40 hertz = 1200 rpm

Drive Function

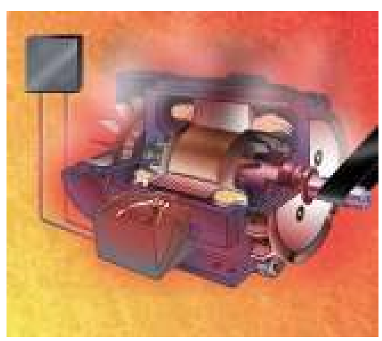
- Input:
  - 60 hertz AC & rated voltage
- Converter
  - Rectifies to DC & changes frequency to desired value
- Inverter
  - Converts DC back to AC
- Regulator
  - Adjusts voltage level to desired value as a % of speed/frequency value.
  - Volts/Hertz Ratio
    - (480/60 = 8)
- AC Output:
  - Desired frequency and voltage for speed requirement.



Torque vs Speed

HP = RPM x TORQUE / 5252

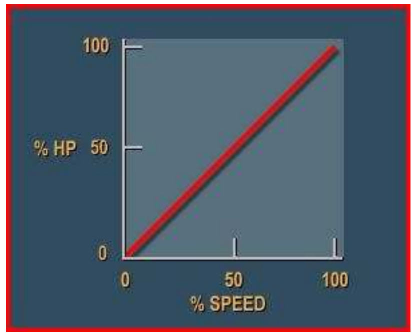
- What happens to torque when speed is decreased?
  - Torque increases
- If torque increases, current increases and produces additional heat in the windings.



However!!!!

HP = RPM x TORQUE / 5252

- For many types of loads, as speed drops, torque requirements also drop.
- What happens when speed AND torque decrease?
  - Reduced Horsepower - Reduces our energy costs!



Increase Speed?

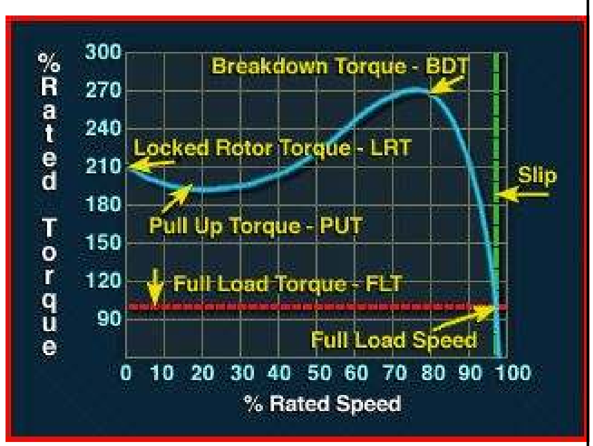
- What about increasing speed above the motor's synchronous speed using frequency higher than 60 hertz?
  - 4 pole motor @ 60 hertz = 1800 rpm
  - 4 pole motor @ 70 hertz = 2100 rpm
- Most motors were not balanced to operate above synchronous speed.
- The load may not have been balanced above this speed either.

Common Applications

- Constant Torque Loads
  - conveyor belts, augers, reciprocating pumps & compressors, extruders, gear pumps.
- Variable Torque Loads
  - centrifugal fans, pumps, and compressors
- Constant Horsepower Loads
  - winding machines

Torque-Speed Curve

- Amount of Torque produced by motors varies with Speed.
- Torque Speed Curves
  - Starting Torque
  - Pull Up Torque
  - Breakdown Torque

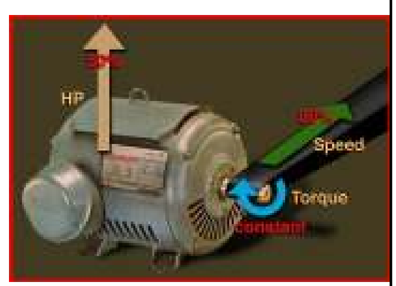


Torque-Speed Issues

- Some single phase motors have starting and running windings
- The starting windings can not be energized continuously
- If a VFD is used and speed is reduced too much the starting windings burn out.

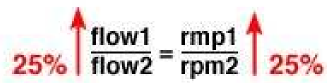
Constant Torque Loads

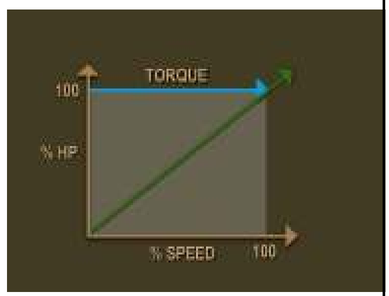
- Require the same amount of torque at low speeds as high speeds.
  - For a given weight on the belt, the torque to turn the belt is always the same regardless of speed.
- Horsepower increases or decreases as a direct function of speed.
- Examples:
  - Conveyor belts, reciprocating pumps & compressors



Constant Torque Loads

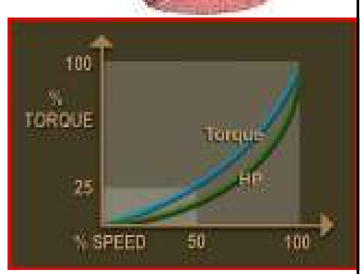
- Horsepower increases or decreases as a direct function of speed.
  - A 50% drop in speed produces a 50% reduction in power required to turn the load.
- Energy savings using a VFD to control the speed of a constant torque load is a direct function of speed reduction.





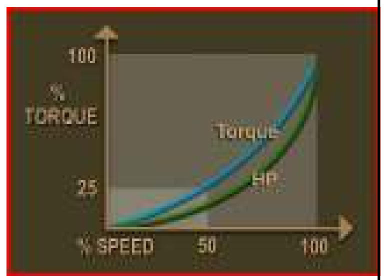
Variable Torque Loads

- Require much lower torque & horsepower at low speeds than at high speeds.
- Power required varies as the cube of the speed.
- Examples:
  - Centrifugal fans, pumps & compressors, mixers and agitators.



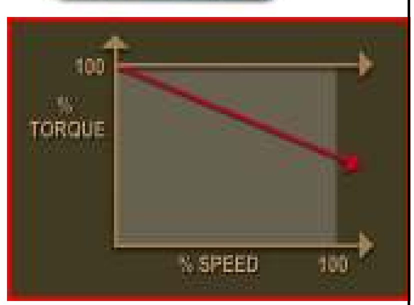
Variable Torque Loads

- Horsepower increases or decreases as cubic function of speed.
  - A 50% drop in speed produces almost an 88% reduction in power required to turn the load.
- Energy savings using a VFD to control the speed of a variable torque load can be very large due to how centrifugal loads operate.



Constant Horsepower Loads

- Constant horsepower loads include equipment such as grinders, winders, and lathes.
  - Since the power required remains the same regardless of torque or speed requirements of the operation, there are no direct energy savings from installing VFD's with constant horsepower loads.

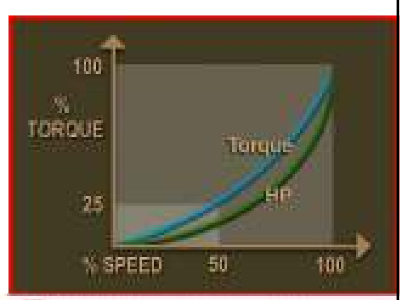


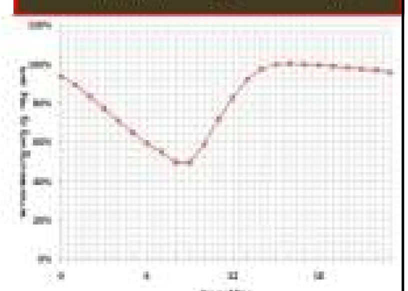
Constant Horsepower Loads

- Traditionally considered DC Drive applications
- Some movement to use of newer AC Flux Vector Drives
- The only justification for installation of an VFD would be based on improvement in the process control of the operation.

Advantage: Energy Savings

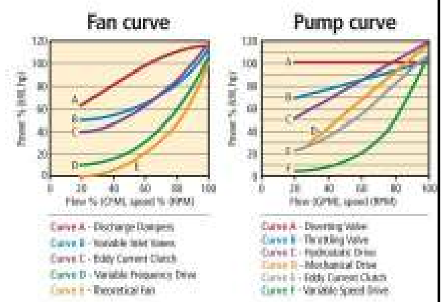
- Traditionally used to justify installation.
- Centrifugal Fans, Pumps, Compressors
  - As the speed of the device is slowed, the torque and power required to run the operations is significantly reduced.

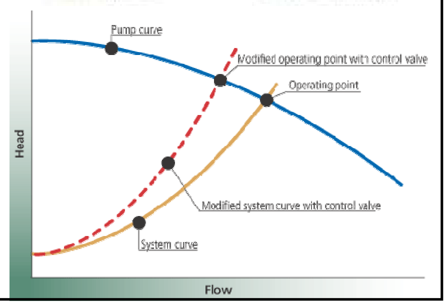




Throttling Flow May Not Save Energy

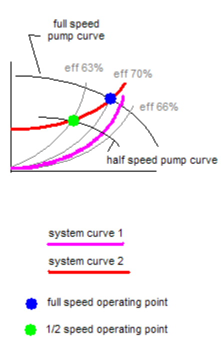
- Traditional methods of reducing flow by throttling (dampers, vanes, valves) don't consistently provide energy savings.
- Depending on where the system is on the pump curve, reducing flow has the result of increasing pressure on the back side of the pump and changing the pump efficiency.





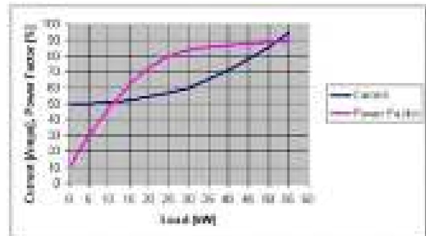
Energy Savings With VFDs

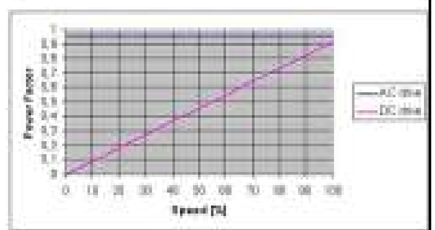
- Using a VFD can result in significant energy savings when throttling flow for centrifugal fans, pumps and compressors.
- The reduction in flow and pressure in the system from controlling flow with fan/pump speed will result in a decrease in power required to turn the device resulting in energy savings at the reduced flow rate.



VFD's Increase Power Factor

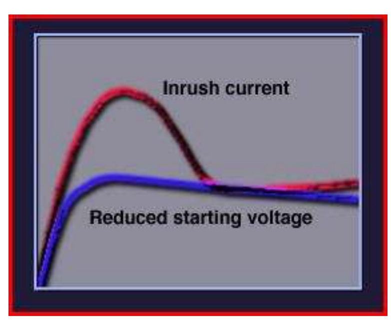
- Power Factor Penalties can be a part of commercial and industrial electric bills
- VFD's have two types of power factor
  - Total Power Factor
  - Displacement Power Factor
- Utilities measure displacement power factor so a VFD can improve power factor of a system without adding capacitors





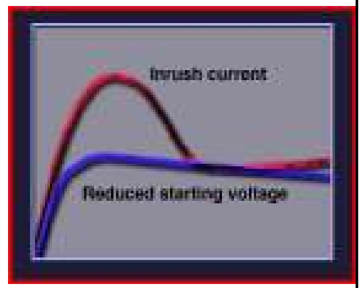
Advantage: Reduced Voltage Starting

- An VFD acts like a reduced voltage starter to limit the in-rush current when the motor starts.
- VFD's can generally limit in-rush current to a maximum of 150% of a motors FLA/RLA if desired.
  - What is the downside of limiting starting amps?



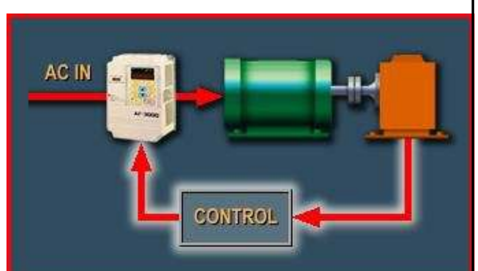
Why Reduced Voltage (Soft) Starting

- Reduce motor in-rush current and the associated voltage drop when starting the motor for power quality benefits.
  - Can cause nuisance tripping of sensitive electronic equipment.
- Reduce mechanical shock to products and drive systems during startup.



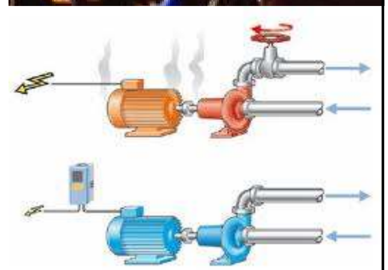
Advantaged: Improved Process Control

- Can be linked into process control systems to provide feedback to DCS and PLC's.
- More consistent control of manufacturing operation.
  - Better dissolved oxygen control?



Advantage: Lower System Maintenance

- Eliminate need for maintenance items in some system.
- Extend operating life of equipment that is occasionally overloaded and the system is not optimized.
- Reduces motor cycling and associated driveline shock in some systems.

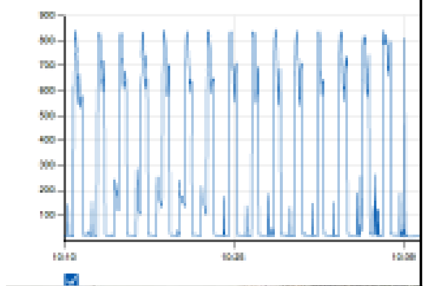


Can Eliminate Some Maintenance Requirements

- May eliminate the need for complex belt, gearboxes, valve and damper systems and the associated maintenance requirements.

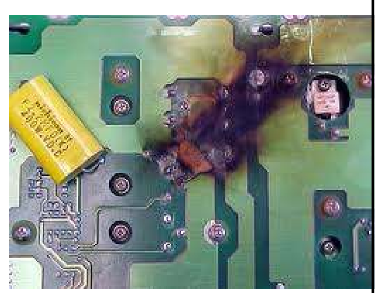
Maintenance: Reduced Short Cycling

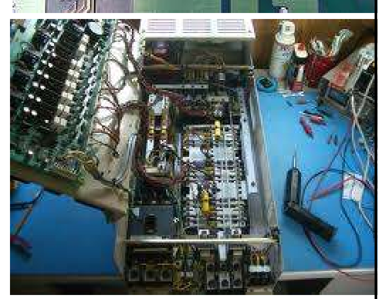
- Frequently starting and stopping motors can significantly reduce their operating life.
- A VFD can reduce input flow rate so that pumps do not have to be frequently started and stopped.



VFD Maintenance

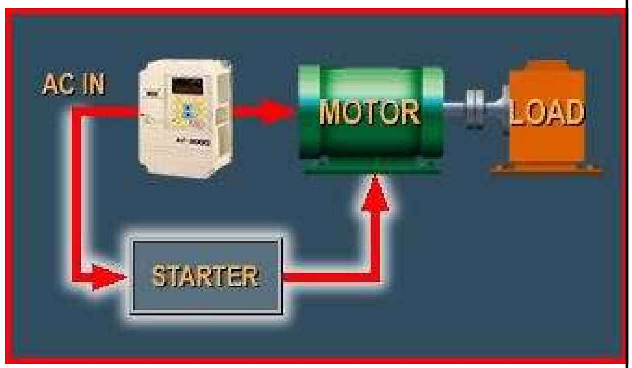
- Drives are similar to a power supply & computer
  - Keep it Clean
  - Keep it Dry
  - Keep connections Tight
- NEMA 1 or NEMA 12 are the most common enclosures
  - NEMA 1 dust and moisture issues occasionally are an issue





Advantage: Bypass Capability

- If there is a problem with the drive, it can be bypassed easily and the motor operated without the drive. (Although without speed control)



Advantage: Multi-Motor Control

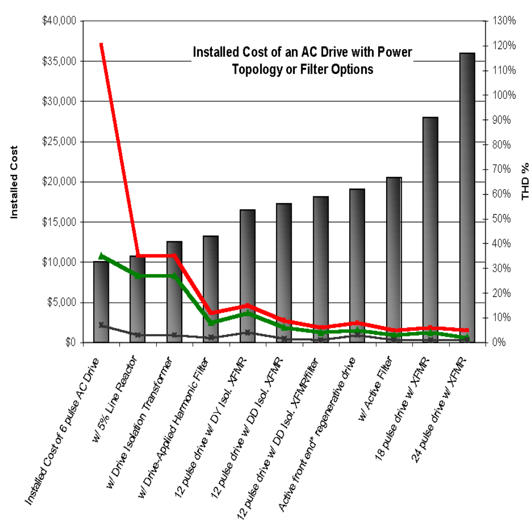
- Some VFD’s can control multiple motors from the same drive.
- Reduces size requirements and the initial cost.

Advantage: Phase Conversion

- VFD's can be used to operate 3-phase motors from single phase power supplies.
- Motor starting currents of 150% producing full torque starts up to 125 Hp
- Issues:
  - Cost of VFD vs Phase Converter
  - Drive is 95% efficient
  - Need for Reduced Voltage Start?
  - Eliminates need for "Pump Panel"
  - Multi-motor control (center pivot)
  - * Harmonic output is usually higher when used single phase

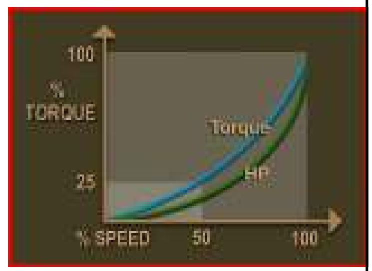
Disadvantage: Initial Cost

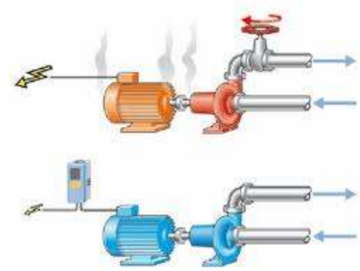
- Initial cost of an VFD is greater than the cost of other types of variable speed control equipment.
- Energy savings is generally low for applications where average speed requirements are near the motors rated speed.



VFD on a Constant Speed Pump?

- Are there energy savings from using a VFD on a constant speed/flow pump?
  - Flow is never throttled so flow and energy use will never be lowered.
  - There might be other advantages like maintenance, soft start, etc.
- How about a pumping system where multiple pumps feed multiple systems and valves are used to match the number of pumps with the amount of flow needed for the number of systems operating?



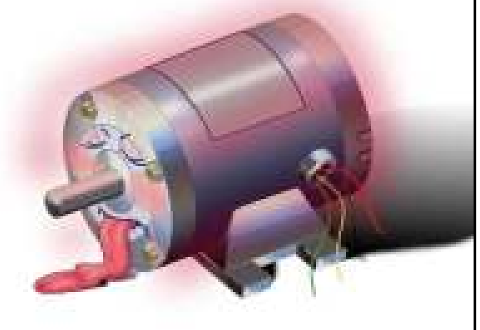


Disadvantage: Complexity

- VFD's like other solid state devices require specialized troubleshooting knowledge.
- Manufacturer's are making progress with simplicity & self diagnostic programs.

Disadvantage: Motor Heating

- VFD’s used to run constant torque loads (conveyor belts) at slow speeds have potential for overheating.
  - At low speed, the fan on the motor produces less cooling air.
- Constant torque requirements with reduced cooling air results in motor heating.

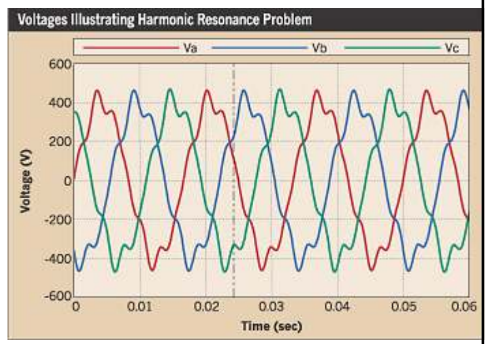


VFD Slow Speed/Heating Options

- Increase cooling air flow
  - Add Pony Motor/Fan ($)
- Use better motor insulation
  - General Purpose Motor with a higher than standard insulation class (Class F, H, N, etc) ($)
  - Invertor Ready Motor ($)
  - Invertor Duty Motor ($)

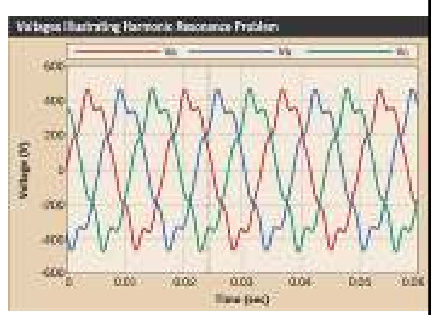
Disadvantage: Power Quality

- VFD's can produce significant input & output waveform distortion including harmonic distortion, noise and line notching.
- Input Side
  - Can cause multiple problems impacting sensitive electronic devices, transformers, capacitors, neutral conductors and neighboring services.
- Output Side
  - Causes multiple issues for motors and circuit conductors.



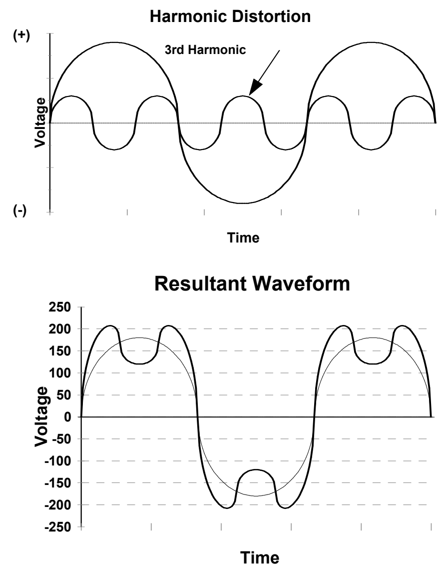
Drives As Power Quality Problem Sources

1. Induce harmonic distortion on the incoming supply lines.
   1. Interfere with other electronics at the same service or neighboring services
   2. Overload neutrals and transformers
   3. Strange breaker trips
   4. Capacitor failures
2. Produce harmonic distortion on the output circuit to the motor/load.
   1. Excessive motor heating
   2. Excessive bearing vibration/wear
   3. Voltage overshoot on motors & cables.



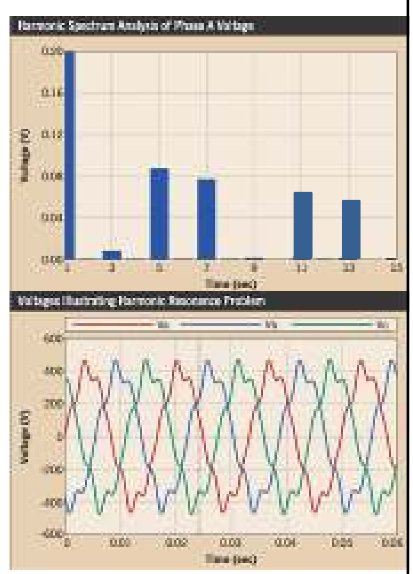
Harmonic Distortion

- Harmonic distortion is “noise” created by the operation of electronic devices with “internal AC to DC power supplies”
- It causes the system to resonate at different frequencies of the 60 hertz fundamental.
  - 2nd is 2 X 60 = 120
  - 3rd is 3 X 60 = 180
  - 4th is 4 X 60 = 240
- Odd harmonics are usually the problematic frequencies.



Harmonics Can Be Quantified

- VFD’s produce specific harmonic frequencies with high magnitudes.
  - This “fingerprint” can help determine where harmonics are coming from
- Standard Electronic Harmonics
  - Odd harmonics stairstep down
  - 3rd, 5th, 7th, 11th, 13th, 15th, etc.
- VFD harmonics
  - Function of drive “pulse number”
  - Produce “pairs” of odd harmonics
  - 5th& 7th, 11th & 13th, etc.

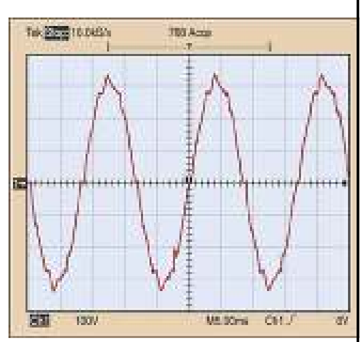


Total Harmonic Distortion (THD)

- Common way of quantifying "how much harmonic distortion" is present.
  - The amount of distortion from each harmonic frequency in a waveform can be measured as a percentage of the fundamental frequency.
  - The individual harmonic % is squared, summed and the square root taken to determine the total harmonic distortion (THD) content.
  - Example: 7% voltage THD
    - 7% of the total voltage is non 60 hertz frequencies
- This is commonly done for both voltage and current.

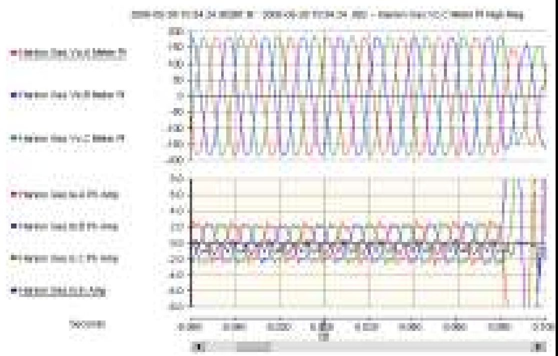
Line Side-Harmonic Distortion Interferes with Operation of Electronics

- Line side harmonic current from drives can distort the distribution voltage within your facility and at other customer locations.
- Distorted current interacts with the system impedance to distort the voltage somewhere else.
- If the harmonics are large enough, they can impact the operation of electronics equipment and VFD's at neighboring customer locations.



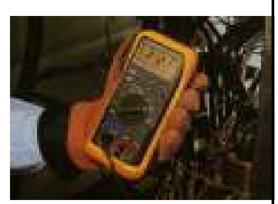
Harmonic Current Distortion = Data Interference Problems

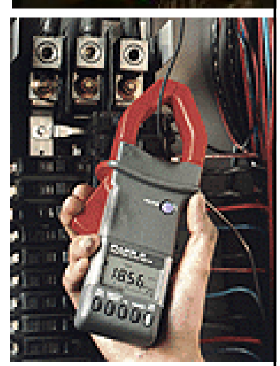
- AC currents generate electromagnetic fields
- The higher the current frequency, the higher the electromagnetic field frequency
- These fields can interrupt data flow causing; data errors, lost data, and slower data transmission rates



Line Side-Unusual Breaker Tripping

- Customers often report having bad breakers that trip below rated levels.
  - If measuring the current trip point without a True RMS device, the current value may not be measured accurately.
    - Non-True RMS meters don’t really measure the RMS voltage, they calculate it based on assuming a pure sine waveform.
    - Non-True RMS ammeters commonly measure low when attempting to measure a highly distorted current.
- Most true RMS meters usually indicate on their cover that they are true RMS meters. Others will say in their specifications that they are a true RMS sensing meter.
  - A quick check with the vendor or manufacturer can verify any questions.



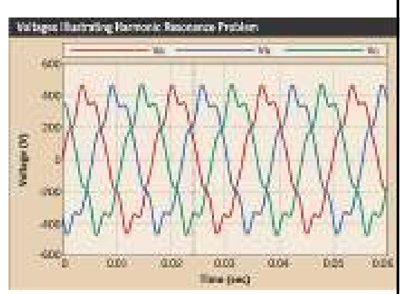


Line Side-Overloaded Transformers

- Current harmonics produce abnormal heating in transformer windings.
  - Heating reduces the life of the transformer
- K-Factor Transformers
  - Transformer with a higher grade of insulation to better withstand the additional heating from the harmonics.
  - Should be used where significant harmonic distortion is present.
- K-Factor can be calculated from monitoring the harmonic content of the system.
  - Select a higher K-Factor Transformer than the calculated K-Factor of your system.

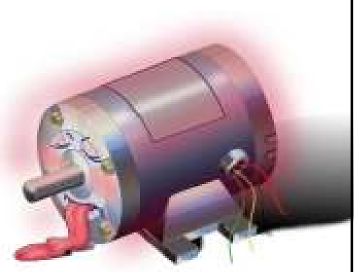
Line Side-Harmonics & Capacitors

- Capacitors near the input side of drives (in the plant or close to the service) should be carefully analyzed (tuned) to avoid problems.
- Harmonic resonance
  - Causes heating and reduced life in capacitors.
  - Capacitors tuned to one of the characteristic frequencies (5^{th}, 7^{th}, etc) will have dielectric failure or rupture the capacitor.



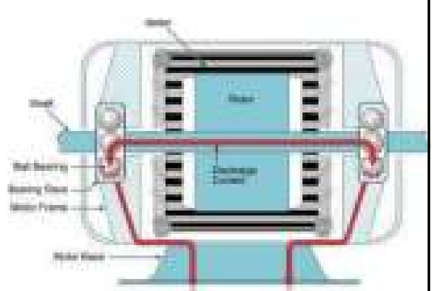
Load Side-Motor Heating

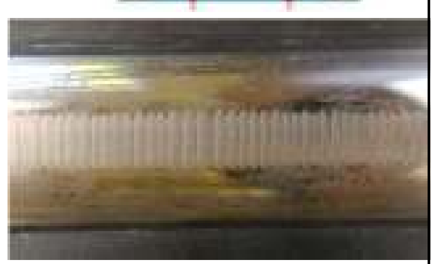
- Reverse sequence harmonics (5, 11, 17, 23, etc) are opposite polarity currents that produce opposing magnetic fields in the windings
  - Try to run induction motors in the opposite direction and create heating
  - Enough distortion in these frequencies causes excessive motor heating.
  - The more harmonic distortion in these frequencies, the higher the excess heating.
- In addition, what happens to airflow when you run a motor at low speed?
  - The fan runs slower and airflow is significantly reduced.



Load Side – Bearing Fluting

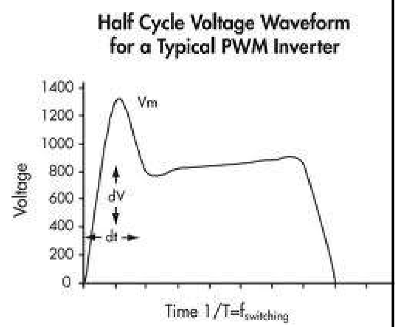
- Excess bearing vibration and wear problems with VFD's can come from:
  - Resonant Frequencies
  - Common Mode Noise from Triplen Harmonics (3,9,15, etc)
- Results in premature bearing failure.

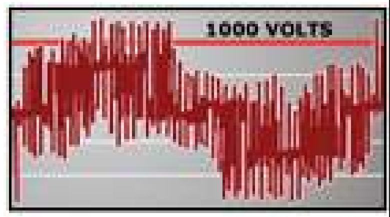




Load Side - Voltage Overshoot

- Also called dV/dT or "slew rate"
- VFD's use power electronics that switch at very high rates resulting in a voltage "pulse" with a high rate of rise in a short amount of time.
  - When put in front of an induction motor, the pulses in combination with the cable and motor impedance generate repetitive voltage overshoots at the motor terminals.
- Voltage overshoot affects the insulation life of the conductor and motor.
  - Common problem where long conductors are used between the drive and the motor.



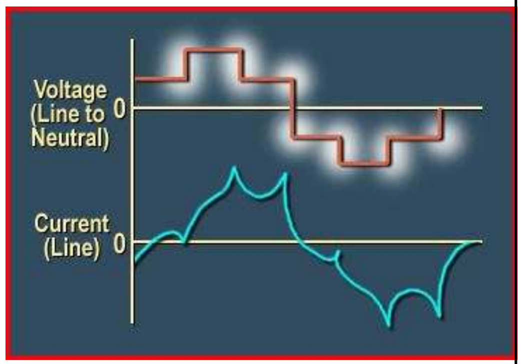


Types of AC Drives

- Variable Voltage Input (VVI)
  - Oldest drive technology
- Current Source Input (CSI)
- Pulse Width Modulated (PWM)
  - Newest drive technology
  - Variable Voltage-
    Variable Frequency Drives
  - Flux Vector Drives
    - Standard Flux Vector (Closed Loop)
    - Sensorless Drives (Open Loop)

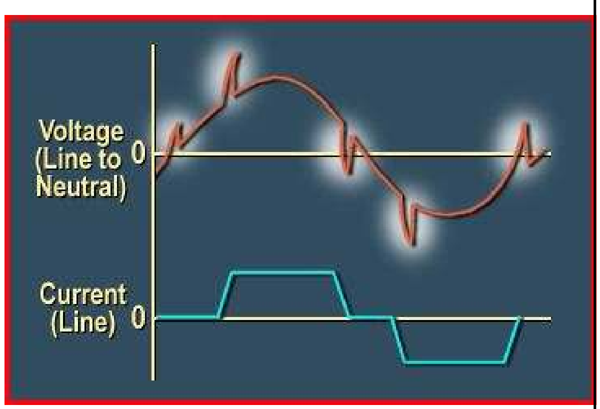
Variable Voltage Input (VVI)

- 1st AC Drive to gain acceptance.
- Called "Six-Step Drive"
- Advantages
  - Good speed range
  - Multiple motor control
  - Simple control
- Disadvantages
  - Power factor
  - Poor ride through
  - Significant output harmonics
  - Low speed cogging
  - Isolation Transformer



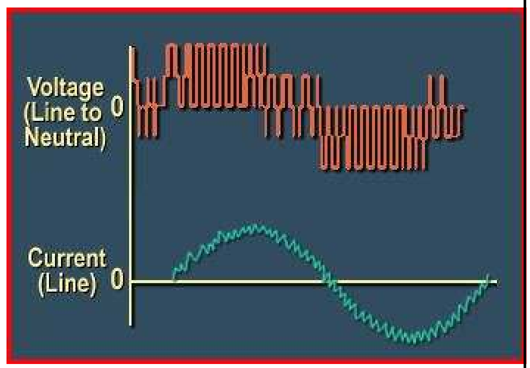
Current Source Input (CSI)

- Voltage closer to output expected by motor.
- Sold as motor/drive package.
- Advantages
  - High efficiency
  - Regeneration
- Disadvantages
  - Power factor
  - Low speed cogging
  - Poor ride through
  - Isolation transformer
  - Large physical size



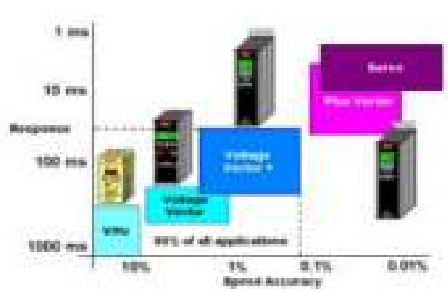
Pulse Width Modulated (PWM)

- Newest technology & lowest price.
- Best current waveform to the motor.
- Advantages
  - High efficiency
  - Wide speed range
  - High power factor
  - No cogging
- Disadvantages
  - Complexity of equipment
  - Significant audible noise



PWM Drive Control Types

- PWM drives are sometimes referred to by their control type
  - Variable Voltage Variable Frequency (VVVF) Drive
    - Constant Volts/Hertz ratio
  - Flux Vector
    - Can vary volts & hertz separately
    - Closed Loop
      - Original Flux Vector Drives
    - Open Loop
      - Sensorless Vector Drives



Variable Voltage Variable Frequency (VVVF)

- The standard type of control in early modern PWM drives.
  - Varies output in a constant Volts/Hertz ratio to control speed.
- Works well for loads where the change in speed doesn't have to be instantaneous.
  - Mostly steady state conditions
  - Fans and pumps
- Lower cost than a Flux Vector Drive

Flux Vector Drive (Closed Loop)

- Uses a more sophisticated drive controller to modify both the magnitude and flux direction of the output to the motor.
  - Faster, more precise speed response and control
- Can be important for very sensitive types of applications and certain types of constant torque loads.
  - Traditionally done with DC Drives and specialty motors.
- Lower cost than a DC Drive but higher cost than a standard VVVF drive.
  - Requires use of closed loop controls to monitor and regulate the driven load precisely.

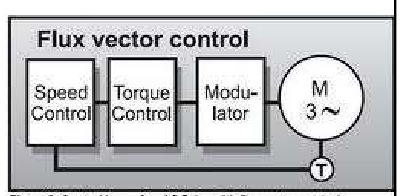


Figure 3: Control loop of an AC Drive with flux vector control using PWM

Sensorless (Open Loop) Vector Drive

- Attempts to provide performance of a Closed Loop Flux Vector system without using as many sensors and feedback devices.
  - Closed Loop system uses shaft encoder on motor to measure exact position
  - Sensorless uses an algorithm programmed in the drive.
- Most advantages of a Closed Loop Flux Vector setup without additional cost and complexity of sensors.
  - Accuracy of the algorithm for motor voltage and frequency control compared to the actual needs of the system?
  - How do you handle variations not in the model?

What About DC Drives?

- DC drives still have their place in the industry.
  - Allow more precise speed control
- However, they tend to be;
  - Expensive
    - Sophisticated drives
    - More complex DC motor
  - DC motors historically required significant maintenance

ECM Motors?

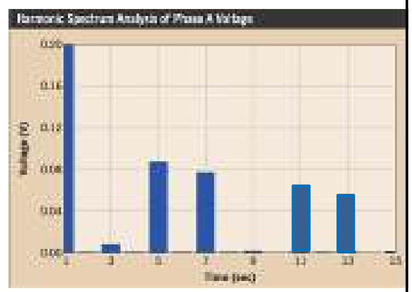
- Newer technology combining a DC Drive and a DC motor in one enclosure
- Higher efficiency than many single phase motors.
- Lower cost than AC VFD and AC motor
- Lower maintenance costs than traditional DC motors

AC VFD Drive Pulse Ratings

- Number of current pulses per cycle depends on rectifier configuration.
- 3 Phase VFD's use multiples of 6
  - (6, 12, 18, 24, etc.)
- The problematic odd harmonic frequencies can be calculated based on drive pulse number and compared to the measured harmonic frequencies.
- Higher the pulse #:
  - Lower harmonics
  - More complex & costly the drive

VFD Harmonics

- VFD's produce specific harmonic frequencies with high magnitudes.
  - This "fingerprint" can help determine where harmonics are coming from.
- The drive pulse number can be found from the manufacturer or drive specification sheet.
  - The higher the drive pulse number, the higher the problematic harmonic frequencies become.
  - Because the lower order harmonic frequencies are generally the most problematic, a higher drive pulse number eliminates the most common problem frequencies.



Pulse Ratings & Harmonics

- Characteristic harmonic current is: $h = n \times p \pm 1$
  - Where h is the harmonic, n is an integer, and p = drive pulses

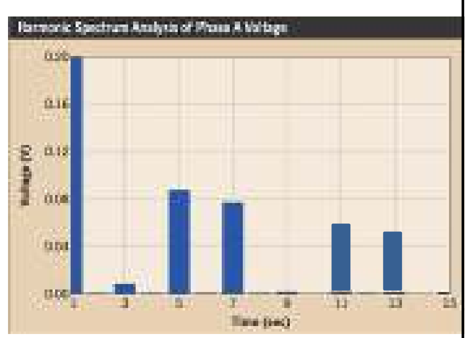
- 6 Pulse Drive

  $h = 1 \times 6 \pm 1 = 5$ & 7

  $h = 2 \times 6 \pm 1 = 11$ & 13
- 12 Pulse Drive

  $h = 1 \times 12 \pm 1 = 11$ & 13

  $h = 2 \times 12 \pm 1 = 23$ & 25



- As the pulse rating increases, the lower order harmonics (the most problematic) disappear.

Utility Policies are Changing

- Some electric providers are mandating certain types of drives and/or mitigating equipment in an attempt to reduce harmonics.
- Example:
  - 12 or 18 pulse drive can be used without line side harmonic mitigation (filters, chokes or reactors)
  - 6 pulse drive must have line side harmonic mitigation (filters, chokes or reactors)

Drive Application & Purchase Considerations

- Cost/Benefit Ratio?
  - Historically energy savings were used to justify.
- Improved Process Control
  - More consistency and less off spec product?
- Maintenance
  - Reduce scheduled downtime/maintenance requirements?
- Power Quality
  - Can I use my existing motors and do I need filters?

NEMA Application Guide for AC Adjustable Speed Drive Systems

- Developed by NEMA in 2001 to assist users in proper selection & application of drives. (81 pages)

- Price:
  - $93 for hardcopy
  - Electronic download is FREE
- www.nema.org and search for title of document.

NEMA Drive Selection & Application Factors

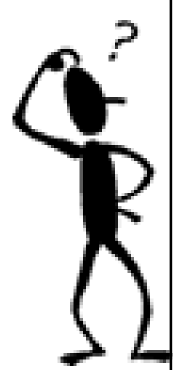
- Motors
  - Suitable for the application such that drive operating conditions will not substantially reduce the life of the motor.
- Drive Type
  - Selected and installed to limit power quality disturbances to a minimum
- Electric Supply
  - Within NEMA tolerances to ensure the equipment will operate correctly
- Mechanical Installation
  - Within NEMA tolerances to ensure the equipment does not have reduced life
- Controls
  - Life Safety
  - Fuses or Breakers as specified
  - Data acquisition or PLC systems

VFD Sizing Considerations

- Breakaway Torque
  - Sufficient to start and accelerate the load
- Accelerating Torque
  - Adequate to bring the load to speed within a given time
- Running Torque
  - Amount necessary to keep the load moving at all operating speeds
- Peak Torque
  - Does the load vary occasionally?
- Holding Torque
  - Is it required to operate as a brake and/or hold he load in place after it stops?

Special Considerations

- The VFD operates multiple motors
- Is the load hard to start and are starting and stopping time critical?
- Will the load be spinning or coasting when the VFD is started?
- Will the power supply source be switched while the drive is running?
- Are external motor disconnects required?
- Are p.f. correction capacitors being switched on/off in the building?



NEMA Motor Concerns

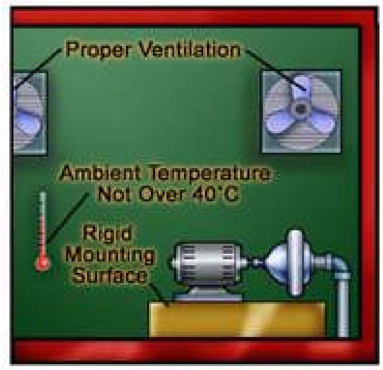
- Issues:
  - Motor Heating
  - Bearing Failures
  - Insulation Degradation from Voltage Overshoot
- Motor Type Selection
  - General Purpose Motor
    - NEMA Type A,B,C, or D
  - Inverter Ready
  - Invertor Duty Motor

NEMA Drive Type Concerns

- Issues:
  - Input & Output Waveform Distortion
  - Voltage Overshoot
  - Regeneration
  - Low Speed Cogging
- Drive Type Selection
  - Variable Voltage Input (VVI)
  - Current Source Input (CSI)
  - Pulse Width Modulated (PWM)
  - Pulse #: 6, 12, 18, 24, 30, etc

NEMA Installation Concerns

- Installation Issues
  - Ambient Temperature:
    - < 40° C (104° F)
    - If not, derate motor and drive
  - Altitude:
    - < 3300 feet
    - If not, derate motor and drive
  - Enclosure Type
    - Appropriate for environment
    - Limit condensation
  - Mounting
    - Rigid mounting



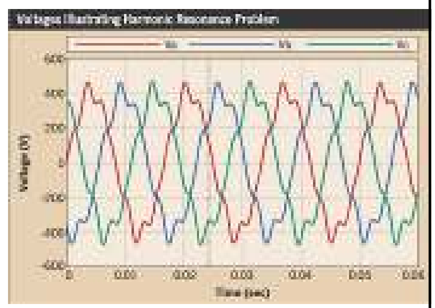
[redacted]

NEMA Electric Supply Concerns

- Voltage
  - Limit voltage variations to the nameplate ratings of the particular motor.
    - NEMA Motors: $\pm$ 10%
    - NEMA Drives: $\pm$ 15%
    - Most power supplier limits are $\pm$ 10% or LESS.
- Voltage Unbalance
  - Do not exceed 3%
    - Most electric supplier limits are 3%
- Single Phasing
  - Some drives can operate single phased…check current flow values to see if it is within ratings. If not, protect the drive/motor from single phasing.
- Frequency
  - $\pm$ 3% (generally not a problem with grid power)
- Power Factor Correction Capacitors
  - Be careful when applying capacitors in front of drives.
    - Calculate resonant frequencies for capacitors based on drive and system parameters to ensure you don't have major resonance problems.

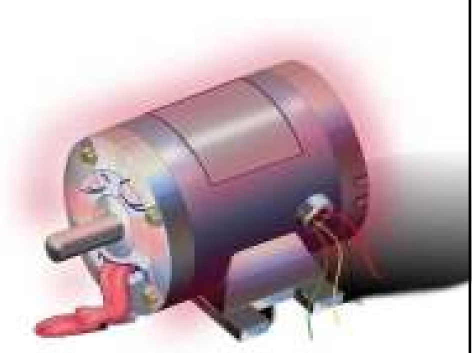
Drives As Power Quality Problem Sources

1. Induce harmonic distortion on the incoming supply lines.
   1. Interfere with other electronics at the same service or neighboring services
   2. Overload neutrals and transformers
   3. Strange breaker trips
   4. Capacitor failures
2. Produce harmonic distortion on the output circuit to the motor/load.
   1. Excessive motor heating
   2. Excessive bearing vibration/wear
   3. Voltage overshoot on motors & cables.



Drive Load Side Considerations

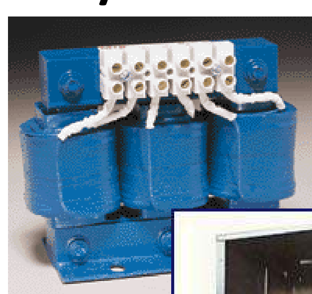
- Potential Problems
  - Motor heating
    - Slower fan speed
    - Reverse sequence harmonics
  - Bearing vibration & wear
    - Harmonic distortion
  - Voltage overshoot
    - Harmonic distortion



Load Side-Harmonic Trap Filters

- Used to mitigate harmonic distortion from systems with a high percentage of non-linear load compared to system load.
  - Target multiple harmonic frequencies…not just a few frequencies.
- Filters can be tuned to the most problematic frequencies for the system to eliminate them.
- When the system load changes, individual filters may be turned on and off to "follow the load".

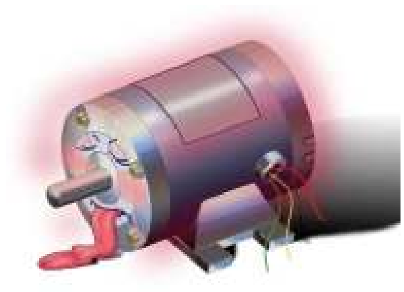
Load Side-Reactors/Chokes



- Reactors and chokes are increasingly being incorporated into many newer and existing VFD installations.
  - Line and load reactors or chokes are a very specific type of "filter".
  - If the problematic harmonic frequency(s) is known, a reactor or choke that filters that specific frequency can be installed to remove it. (Tuned or De-tuned)
- Can be much cheaper when only a couple of harmonic frequencies are the problem.

Load Side-Motor Heating

- Concern
  - Airflow reduction at reduced speed?
  - Negative sequence harmonics (5,11,17) have reverse polarity.
- Potential Solutions
  - Increase cooling airflow
  - Load side filters, chokes or reactors
  - Higher pulse number drive
  - Better motor insulation
    - Better General Purpose Motor
    - Definite Purpose Motor

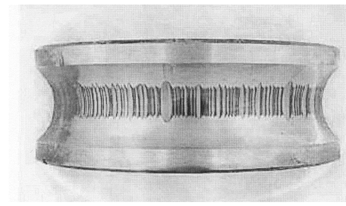


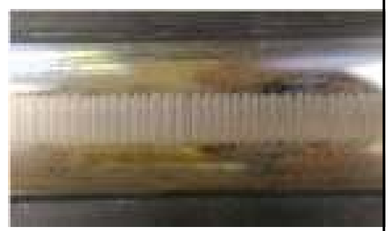
Inverter Ready/Duty Motors

- General Purpose Motors
  - Built in NEMA standard sizes for “general purpose”
  - Can work fine in many drive applications.
  - Insulation Class B standard unless service factor > 1.0
- Inverter Ready Motors
  - General purpose motor built with anticipation a drive may be added in the future. (Class H insulation)
  - Will generally have a distance limit the motor can be placed away from the drive
  - May require drive filters, etc outside specific very specific operating limits
- Inverter Duty Motors
  - Specially built for most any inverter application
  - H insulation class with “inverter spike resistant” (ISR) insulation
    - Peak voltage limits to 1600 volts
    - Corona voltage requirements
  - Usually no limits on distance the motor is placed from the drive.
  - Will not generally require drive filters, etc unless the application is far outside normal boundaries.

Load Side – Bearing Vibration & Wear

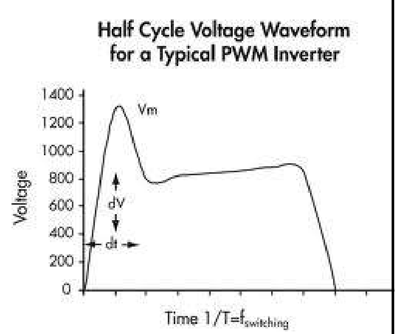
- Concern
  - Excess bearing vibration and wear problems can come from:
    - Resonant Frequencies
    - Common Mode Noise from Triplen Harmonics (3,9,15, etc)
- Solutions
  - Shaft grounding systems
  - Insulated bearings
  - Load side filters, chokes or reactors.
  - Some invertor duty motors

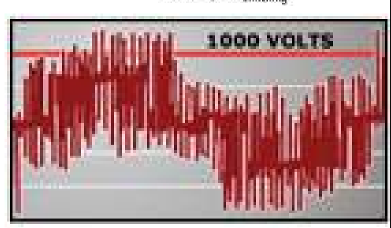




Load Side - Voltage Overshoot

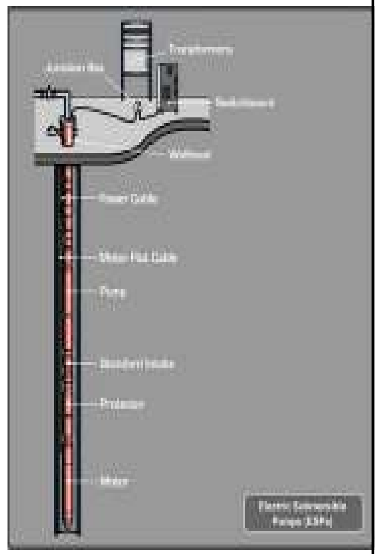
- Also called dV/dT or "slew rate"
- VFD's use power electronics that switch at very high rates resulting in a voltage "pulse" with a high rate of rise in a short amount of time.
  - When put in front of an induction motor, the pulses in combination with the cable and motor impedance generate repetitive voltage overshoots at the motor terminals.
- Voltage overshoot affects the insulation life of the conductor and motor.
  - Common problem where long conductors are used between the drive and the motor.





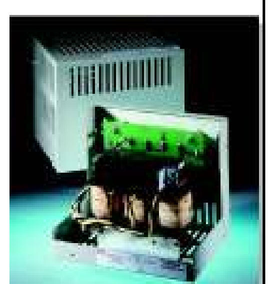
Load Side - Voltage Overshoot

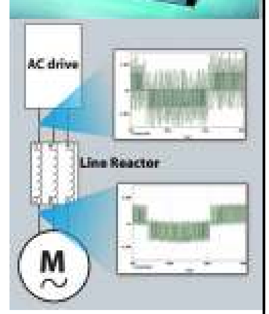
- Primary concern is more than 35-50 feet between drive and motor.
  - Down-hole submersible pumps
  - Long runs from control panels to pumps
- Primary factors
  - Pulse Rise Time, Cable Length, Minimum Drive Pulse Number, Transition Type (single vs double), Use of Multiple Motors
- NEMA defines Category I & II installations.
  - Category I – Low probability of problems
  - Category II – High probability of problems



Solutions to Voltage Overshoot Problems

- Use inverter duty motor
- Use a lower supply voltage (Wire 230/460 motors at 230).
- Avoid running multiple motors in parallel from one drive.
- Establish a Category I or II installation.
  - Category I:
    - Motor meeting NEMA MG-1 Part 31 voltage limits should provide normal service life.
  - If Category II, do one or both of the following:
    - Use a motor with a peak voltage rating that exceeds the expected voltage overshoot for the installation.
    - Measure the peak voltage at the motor's terminals. If the terminal voltage is greater than the motor's peak voltage rating, use a dV/dT (slew rate) filter or reactor between the drive and motor.



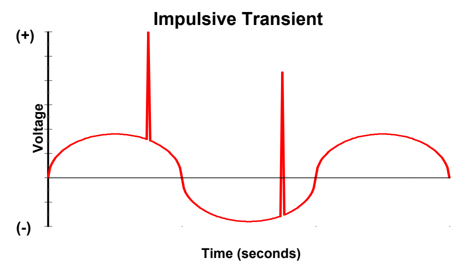


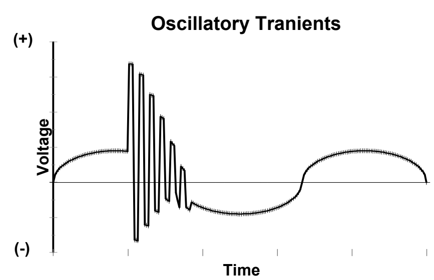
Drive Line Side Considerations

- Potential Problems
  - Harmonic Distortion
    - Neutral heating
    - Transformer heating
    - Faulty operation of other electronic loads
    - Capacitor failure
    - Utility/neighboring service complaints
  - Nuisance Drive Trips
    - Transients
    - Interruptions
    - Harmonic distortion from elsewhere
- Possible Solutions
  - Line side harmonic filters, reactors or chokes.
  - Upsized neutrals
  - K Factor Transformers
  - Check resonant frequency of capacitors vs harmonics produced by drive
  - IEEE 519 Guidelines
  - Transient Voltage Surge Suppression (TVSS)
  - UPS or other ride through protection

Line Side-Transients (Spikes)

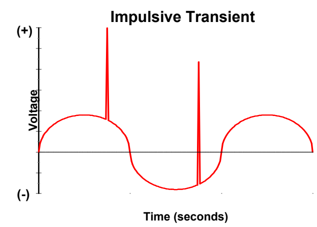
- Line side transients can cause internal damage, nuisance tripping and drive operation errors
  - Impulsive Transients
    - Lightning, Switching Operations, Fault Clearing/Breaker Operations
  - Oscillatory Transients
    - Capacitor and transformer switching
- Potential Solutions
  - Transient Voltage Surge Suppression (TVSS)
  - Line side chokes or reactors tuned to the oscillatory transient





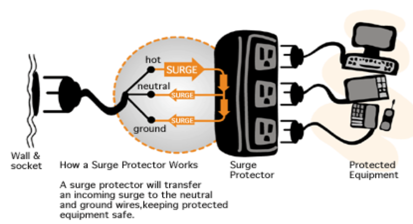
Transient Drive Failure Example

- A small machine shop in east Texas is complaining to their power supplier about impulsive transients measured at the Point of Common Coupling (PCC).
- Their drive manufacturer has replaced the same 250 Hp drive three times in the last year and has finally said “no more drives or boards under warranty”.
- Each failure is a problem with the electronics on the circuit boards exhibiting classic signs of overheating according to the drive manufacturer.
- Monitoring by the drive company shows a 3,000 volt transient (480 volt service) that occurs from 0 to thousands of times a day coming in at the electrical service.



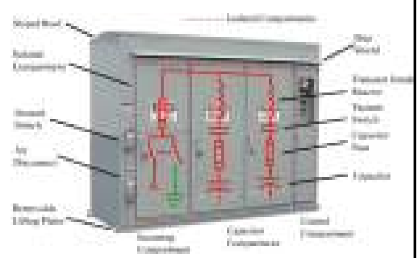
The Problem/Solution

- A welding shop ¼ mile down the road has an automatic welding process they occasionally run.
- Due to a grounding problem at the welding facility, when the welding machine struck an arc, a high voltage transient was created that propagated along the distribution system, interacted with the system impedance, resonated and grew.
- The Solution:
  - Welding shop fixed their grounding problem and transients were reduced.
  - Transient Voltage Surge Suppression (TVSS) added at the service of the shop with the drive issues and the problem disappeared.



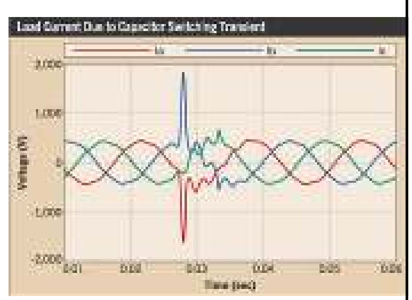
Drives, Harmonics & Capacitors

- The NEMA Drive Application Standard cautions users to be careful when applying capacitors near drives.
  - Oscillatory transients produced from switching capacitors on and off can cause drive nuisance tripping.
  - Line side harmonics from the drive can cause resonance and damage the capacitors
- NEMA recommends calculating the resonant frequencies for capacitors based on drive and system parameters to ensure you don't have major resonance problems.



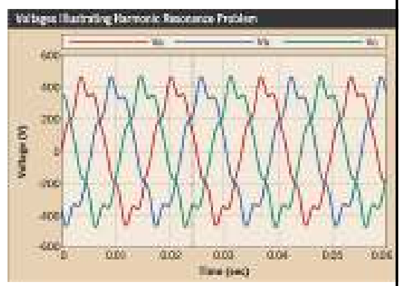
Nuisance Drive Tripping from Capacitor Transients

- Capacitors near the input side of drives (in the plant or close to the service) should be carefully placed and operated to avoid nuisance drive tripping problems.
  - Switching capacitors in and out of a system creates an oscillatory transient each time it is switched.
  - The oscillatory transient can cause drive trips which are generally shown as a "high voltage trip" on the drive.
  - Substation or line switching of capacitor banks by the utility can also be a problem.
- The drive can be protected from the oscillatory transient using Transient Voltage Surge Suppression (TVSS) devices or line side reactors or chokes.



Harmonics Can Cause Capacitor Failure

- Capacitors near the input side of drives (in the plant or close to the service) should be carefully analyzed (tuned) to avoid problems.
- Harmonic resonance
  - Causes vibration and potential physical damage if large enough.
  - Causes heating and reduced life in capacitors.
  - Capacitors tuned to one of the characteristic frequencies (5^{th}, 7^{th}, etc) will have dielectric failure or rupture the capacitor.
- Solution
  - Calculate the capacitors resonant frequencies and make sure they aren't going to be exposed to high amounts of those particular signals



Oscillatory Transient Problem

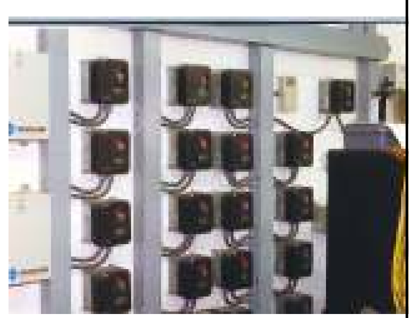
- A textile knitting mill in south Texas is experiencing numerous drive trips on their knitting machines.
- Sometimes all the drives will trip and sometimes only a handful will trip.
- Almost all the drive trip error messages indicate "high input voltage".
- The plant electricians tell management the utility is providing "dirty" power because the error message means surges are happening.
- The utility finds its service voltage within all applicable standards.

The Problem/Solution

- The textile mill installed a staged power factor correction capacitor system that automatically switches capacitors on/off to adjust the amount of reactive power as load changes on-site.
- Each time capacitors in the system are switched in and out, an oscillatory transient is produced resulting in a potential "over-voltage condition" on the drives.
- The Solution:
  - The company installed Transient Voltage Surge Suppression (TVSS) in front of the drive subpanels to remove the oscillatory transients created by their automated p.f. correction system.

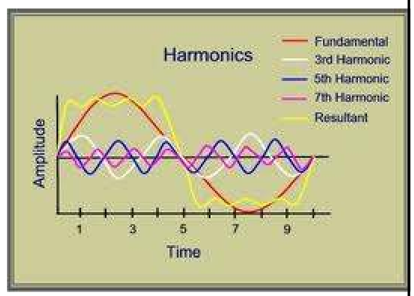
Harmonic Distortion Problem

- A food processing plant in New Mexico runs 20 drives (350 Hp total) that continually adjust pump speeds in a milk solids separating plant.
- The plant separates the milk solids from water and ships the solids to other food processors without having to pay to ship all the water.
- The electronic controls and computers in the plant freeze/lock up at least every 20 minutes.
- Power factor correction capacitors at the plant have been damaged by something as well.



The Problem

- Monitoring equipment shows the current THD to vary between 30 and 37% as the plant operates.
- A half cycle current waveform looked like a capital M.
- The Solution:
  - The drive manufacturer recommended installation of an isolation transformer between the subpanel serving the drives and the rest of the electronic and computer equipment in the plant.
  - Why not filters……..they were more expensive than the isolation transformer in this instance.



Harmonic Distortion Guidelines?

- NEMA Drive Application Guide:
  - It is difficult to suggest guidelines on how to control harmonics for each and every installation.
  - That about sums up where we are today with harmonics and drives.
- Wildcards
  - # of drives & other electronics (production & sensitivity)
  - Impedance of system (wiring, grounding, etc)
- More than 5-8% Voltage THD and you have a potential problem!
  - Sometimes it doesn't take that much.
  - I've seen much worse where it wasn't causing any problems.

How Much is Too Much?

- IEEE 519-1992; Recommended Practices & Requirements for Harmonic Control in Electrical Power Systems
  - Originally published in 1981….later upgraded in 1992.
  - Limits harmonics a customer can put back onto the utility line
  - Limits harmonic voltage THD a utility can have when supplying a customer.
- The electric utility “benchmark”…..this is what they will use and reference to evaluate whether or not you are putting too much into their system.
- Most utilities refer to this as the level you may not exceed in their contracts or tariffs with customers.

IEEE 519 Harmonic Limits

- Requires a calculation based on the harmonic distortion as a portion of overall load on site measured at the Point of Common Coupling (PCC) between customer & utility.
  - Limits amount of voltage distortion the utility can supply to 5% THD for most common services.
    - Provided the customer’s current THD doesn’t cause the voltage THD
  - Limits the amount of harmonic distortion a customer can inject back into the utility system.
    - Current THD < varies with service specifications.
- What is the utilities policy if customers exceed the current THD contribution from 519?
  - Politely ask them to fix the problem?
  - Warn with a grace period of X days?
  - Shut them off right now?

IEEE 519

- Current Total Demand Distortion (TDD) is measured at the Point of Common Coupling (PCC)
- I_{sc}/I_L is the ratio of maximum short circuit current to demand load current at the PCC.
  - **Current Distortion Limits for General Distribution Systems**

(120V through 69,000V)

Maximum Harmonic Current Distortion in Percent of I_L

I_{SC}/I_L	Individual Harmonic Order (Odd Harmonics)					
	< 11	11< h < 17	17 < h < 23	23 < h < 35	35 < h	TDD
< 20	4.0	2.0	0.6	0.5	0.5	5.0
20 < 50	7.0	3.5	1.0	0.5	0.5	8.0
50 < 100	10.0	4.5	1.5	0.7	0.7	12.0
100 < 1000	12.0	5.5	2.0	1.0	1.0	15.0
> 1000	15.0	7.0	2.5	1.4	1.4	20.0

- Even harmonics are limited to 25% of the odd harmonic limits.

Enforcement of IEEE 519

- Utilities generally don't measure & quantify harmonic distortion (THD) unless there is a problem or complaint from a neighboring customer.
- If IEEE 519 limits are being exceeded, the expect the utility to require compliance or face disconnection of your electric system from the grid until compliance can be gained.
- Issues
  - Who is being affected?
  - Is the solution complex or simple
  - Has it been an on-going issue

1990's Harmonic Enforcement Example

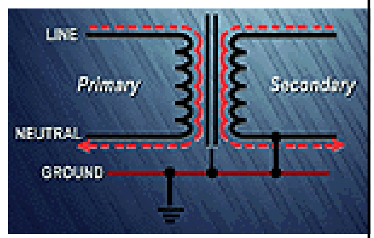
- A utility in the OK Panhandle is getting multiple complaints from customers in rural areas near oil company installations of submersible pumps operated by VFD's
  - Electronic equipment exhibits multiple operation problems and resets/reboots frequently.
  - Equipment manufacturer says the equipment is working fine when brought in and checked at the shop.
  - Checks by the utility show large amounts (8-12%) of voltage THD exceeding IEEE 519 levels on the utility system.
  - Customers are also complaining about frequent static on the rural phone system to the extent the phone is un-usable.
- The utility manager writes a letter to the oil companies (5 largest revenue customers) and politely asks them to add filters to their installations to eliminate the harmonics on the system.
  - The oil companies supply diesel generators and diesel to the neighboring customers.
  - The FCC eventually steps in and tells the utility manager "shut them off to clean up the phone system".
  - A judge sides with the FCC when the utility manager hesitates.
  - The oil companies install the necessary filters on their drives.

2010 Enforcement Example

- Harmonics produced by VFD's in a chemical plant in NM are causing occasional shutdowns of automatic oilers on a natural gas compression station down the road.
- The utility measures THD in excess of IEEE 519 standards and immediately tells plant management they cannot operate their VFD's until they can comply.
- The chemical plant loses several million dollars in revenue during the shutdown waiting for filters to be installed on the drives so they can commence operation.

Isolation Transformers

- Protect sensitive electronic equipment by buffering electrical noise and rejecting common mode line-to-ground noise.
  - Prevent harmonics from drives on the secondary side from causing problems for sensitive electronic devices upstream on the primary side.
  - Effective at protecting from oscillatory transients and noise and in some cases impulsive transients.
- Provide a "separately derived" power source and permit single point grounding.



Line Side-Overloaded Transformers

- Current harmonics produce abnormal heating in transformer windings.
- Potential Solutions
  - Harmonic filters, chokes or reactors on the line side of the transformers
  - K-Factor Transformers
    - K-Factor can be calculated from monitoring the harmonic content of the system.
    - Tables are available that ballpark the K Factor needed for certain applications
    - Select a higher K-Factor Transformer than the calculated K-Factor of your system.

VFD Energy Efficiency Savings

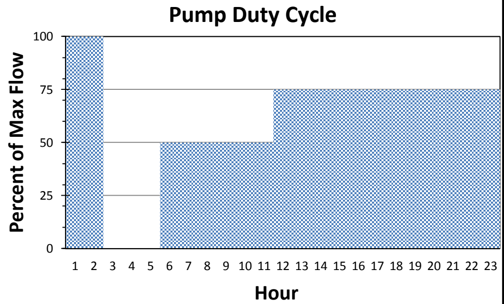
- Traditionally the energy savings of using a VFD on applications where a throttling device (valve, vane, damper) was used to choke flow for long periods was how we justified the cost/price of a drive.
- If the cost/benefit ratio was acceptable, the VFD was installed.

VFD Energy Savings Evaluations

- Motor/Pump Input & Output
  - Horsepower
  - Flow Rate
  - Pressure
  - Efficiency
  - etc.
- Duty Cycle
  - Operating points and times
  - Example: 100% for 1 hr, 80% for 10 hours and 60% for 8 hours.
- Energy Costs
  - Energy rate/charge
  - Demand rate/charge

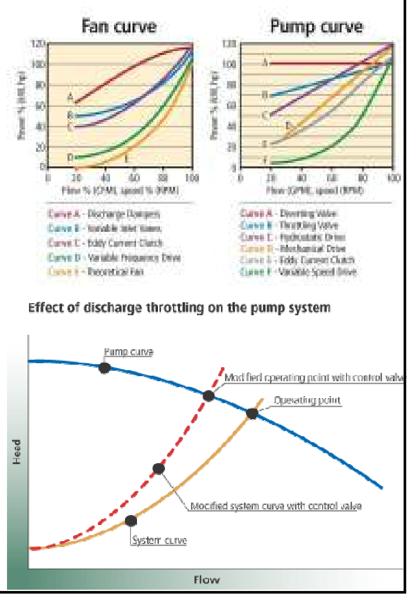
Example: Water Pump VFD Retrofit

- Existing Motor
  - 3-Phase, 100 Hp, 92% efficient motor drives a water pump utilizing an automated flow control valve to adjust water flow.
- Operates 20 hrs/day
  - 6 am – 12 noon: 50%
  - 12 noon-Midnight: 75%
  - Midnight-2 am: 100%
- Electric Rate
  - $0.05/kWh
  - $5/kW, 8 am-10 pm
- Is installation of an VFD feasible?



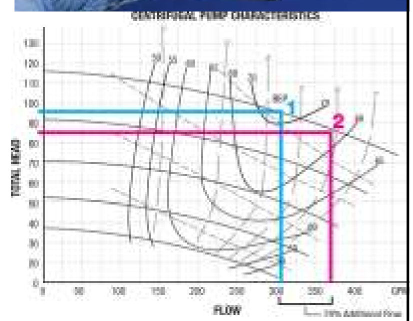
Does Throttling Flow Reduce Power?

- Maybe…..
  - What type of throttling device?
  - What does the fan or pump curve look like?
- Sometimes reducing flow using a throttling valve can increase power use.



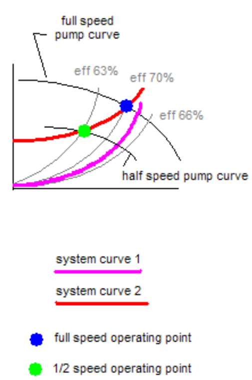
Fan/Pump Curves

- The Fan/Pump Curve becomes important.
  - Where are you starting from and moving to on the fan/pump curve?
- If you don't have this information you may find it from the manufacturer or obtain basic information from testing.



Using VFD's to Reduce Flow & Power

- Use of a VFD to control the speed of the fan/pump to control flow generally provides the best mechanical efficiency compared to use of a throttling valve to control flow.
- The affinity laws for centrifugal fans, pumps and compressors can result in significant energy savings when flow is reduced by slowing down the pump rather than pinching the flow.



The Present System

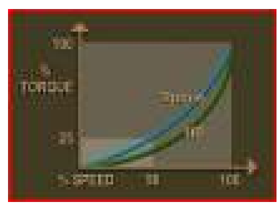
- Fully loaded 100 Hp motor @ 92% efficiency
  - (0.746 kW/Hp * 100 Hp)/0.92 = 81 kW
- Assumption: operating the valve to reduce flow has little impact on power requirements.
- Energy Use:

  81 kW*20 hr/day*7 day/wk*52 wk/yr = 589,680kWh/yr
- Electric Bill:

  81 kW * $5/kW/month* 12 months = $4,860.00

  589,680 kWh*$0.05kWh = $29,484.00
- Total Electric Bill = $34,344.00

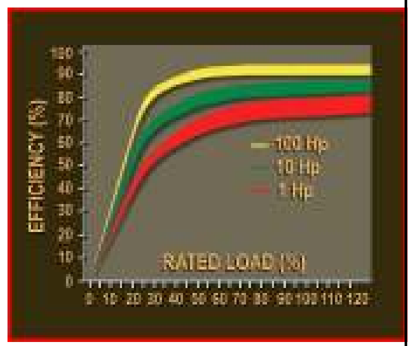
With the VFD??



- Pump Duty Cycle
  - 6 hrs/day @ 50% flow rate
  - 12 hrs/day @ 75% flow rate
  - 2 hrs/day @ 100% flow rate
- You can't assume 75% speed = 75% power (Affinity Laws)
  - 100% flow: 100 hp * 1^3 = 100 hp
    - This number shouldn't change should it?
  - 75% flow: 100 hp X $.75^3$ = 42.2 hp
  - 50% flow: 100 hp * $.5^3$ = 12.5 hp
- Power needs with VFD;
  - 6 hrs/day @ 12.5 hp
  - 12 hrs/day @ 42.2 hp
  - 2 hrs/day @ 100 hp

What Happens to Motor Efficiency at Low Loading?

- The efficiency of an induction motor drops significantly below about 40-50% loading.
- What would happen to motor efficiency if we normally ran a 100 Hp motor loaded to 42.5 or 12.5 Hp?



However; VFD's Have an Impact

- The system efficiency will be a combination of the VFD, the motor and the fan/pump.
- Data is available from:
  - Manufacturers
  - Computer calculators and databases

New Operating Points with VFD

- 100% Flow = No change….81 kW input
  - (0.746 kW/Hp x 100 Hp)/0.92 = 81 kW
- 75% Flow = 80% efficiency
  - (0.746 kW/Hp x 42.5 Hp)/0.8 = 39.6 kW input
- 50% Flow = 40% efficiency
  - (0.746 kW/Hp x 12.5 Hp)/0.4 = 23.3 kW input

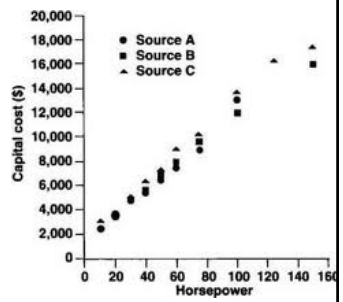
Calculate New Electric Bill

- *100% flow:*
  - 81 kW*2 hr/day*7 day/wk*52 wk/yr = 58,968kWh/yr
- *75% flow:*
  - 39.6 kW*12 hr/day*7 day/wk*52 wk/yr = 172,973kWh/yr
- *50% flow:*
  - 23.3 kW*6 hr/day*7 day/wk*52 wk/yr = 50,887kWh/yr
- Total Energy Use: 282,828 kWh/yr
- Electric Bill:

  39.6 kW * $5/kW/month* 12 months = $2,376.00

  282,828 kWh*$0.05/kWh = $14,141.40
- Total = $16,517.40

Economic Feasibility



- Cost Savings:

  $34,344.00-$16,517.40=$17,826.60
- Purchase/Installation: $15,000
  - (Late 1990's price)
- Current 100 Hp VFD Cost:
  - $4,000 to $12,000 or more depending on features.
  - VFD cost figures are available from manufacturers and in many online VFD energy savings calculators.

Economic Feasibility: Simple Payback

- Payback

  $15,000/$17,826.60 = 0.84 yrs or about 10 months
- Most VFDs are rated for 50,000 hrs life (similar to the motors they drive)

  50,000 hrs/7280 hrs/yr = 6.9 year drive life
- The VFD lasts 6.9 years at 7280 hours per year use and pays for itself with energy savings in 0.84 years (10 months) making it a very attractive energy efficiency measure to consider.

Additional Resources

- Drives Mag
  - www.drivesmag.com
- US Department of Energy
  - Improving Motor & Drive System Performance: A Sourcebook for Industry
- WI Focus on Energy
  - Control Your Energy Costs with VFDs
- ComEd
  - https://www.comed.com/sites/businesssavings/pages/bsmotors.aspx

The End

Thank you for attending the course and thank you to the course sponsor:

Massachusetts Energy Efficiency Partnership