Meet Your Panelist

- Mike Carter
- Justin Kale
NEEA Northwest Industrial Training

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- **Chilled Water and Cooling Towers:**
  
  **Energy Efficiency of Chilled Water Systems and Cooling Towers**
  
  August 27—28: Missoula, MT
  October 1—2: Portland, OR
  October 28—29: Spokane, WA

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Upcoming In-Class Trainings continued

• **Compressed Air:**
  
  Compressed Air Challenge – Level 1
  
  July 17: Spokane, WA  
  September 18: Seattle, WA  
  November 6: Hermiston, OR  
  November 13: Vancouver, WA

• **Electric Motors:**
  
  Adjustable Speed Drive Applications and Energy Efficiency
  
  June 26: Yakima, WA  
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  Motors Systems Management Best Practices
  
  July 29: Medford, OR

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• **Lighting:**
  
  *Efficient and Effective Industrial Lighting*
  
  July 23: Redmond, OR

• **Refrigeration and HVAC:**

  *Air Cooled Refrigeration and Energy Efficiency*
  
  August 6, Boise ID
  
  September 30: Pocatello, ID

  *Energy Efficient Industrial HVAC and Refrigeration Systems*
  
  December TBD: Moses Lake, WA

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- **Compressed Air:**
  - Compressed Air for Small Industrial (PGE)
    - May 29: 8-9am PST
    - October 23: 8-9am PST
  - Compressed Air for Large Industrial (PGE)
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- **Energy Management:**
  - Energy Auditing and Troubleshooting (NEEA)
    - October 21: 9-10am PST

- **Lighting:**
  - Introduction to Efficient Lighting & Controls (PGE)
    - May 21: 11am-noon PST
  - Efficient Industrial Lighting-Tips on What’s Best for Your application
    - October 21: 9-10am PST

- **Operations:**
  - Operation & Maintenance Opportunities (PGE)
    - May 21: 11am-noon PST

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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

\[ W = F \text{ (lb)} \times D \text{ (ft)} \]

Example: Move 25 pounds a distance of 30 feet

\[ W = 25 \text{ lb} \times 30 \text{ ft} = 750 \text{ lb-ft} \]
• Torque
  o A force that produces rotation.
    • Torque exists even if no movement occurs.

\[ T = F \text{ (lb)} \times D \text{ (ft)} \]

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

\[ F = 60 \text{ lb} \times 3 \text{ ft} = 180 \text{ lb-ft} \]
• **Horsepower (HP)**
  - A measure of the *rate* at which work is done

  \[ 1 \text{ HP} = 746 \text{ watts} = 33,000 \text{ lb-ft/min} = 550 \text{ lb-ft/sec} \]

  \[
  \text{Power (kW)} = \text{HP} \times 0.746/\text{eff}
  \]

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

  \[
  \text{Power (kW)} = 200 \text{ HP} \times 0.746/0.90 = 166 \text{ kW}
  \]

  *Source: www.sxc.hu*
• Electric motors
  o Direction of current flow changes poles.
Basics

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

Source: Reliance Electric
Poll Question

• 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
Basics

- Synchronous speed of rotating stator field.

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

- Typically 5% slip for induction motors.

<table>
<thead>
<tr>
<th># Poles</th>
<th>RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3,600</td>
</tr>
<tr>
<td>4</td>
<td>1,800</td>
</tr>
<tr>
<td>6</td>
<td>1,200</td>
</tr>
<tr>
<td>8</td>
<td>900</td>
</tr>
<tr>
<td>10</td>
<td>720</td>
</tr>
</tbody>
</table>

Source: Wenatchee High School

Source: Maxim Integrated Products
• Motor torque
  o Related to horsepower and speed

\[ T \text{ (lb-ft)} = \frac{(HP \times 5252)}{rpm} \]

Example: A 30 HP motor operating at 1725 rpm

\[ T = \frac{(30 \text{ HP} \times 5252)}{1725 \text{ rpm}} = 91 \text{ lb-ft} \]

  o Also related to voltage and frequency
    • Volts per hertz (V/Hz)
Motor Loads

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

![Graph showing Motor Speed vs. Torque and HP](image)

Load

Torque and HP

Motor Speed
Motor Loads

- Speed, Torque, and HP

\[
T = \frac{(\text{HP} \times 5252)}{\text{rpm}}
\]

- Torque (T) is approximately equal to HP divided by rpm:
  \[T \approx \frac{\text{HP}}{\text{rpm}}\]

- RPM (rpm) is approximately equal to HP divided by Torque:
  \[\text{rpm} \approx \frac{\text{HP}}{T}\]

- HP is approximately equal to Torque (T) multiplied by RPM (rpm):
  \[\text{HP} \approx T \times \text{rpm}\]
### Motor Loads

- **Variable torque/Variable HP**
  - Volume $\approx$ rpm
  - $T \approx \text{rpm}^2$
  - HP $\approx \text{rpm}^3$
    - Compressors
      - Centrifugal
    - Pumps
    - Blowers
    - Fans

---

**Graph showing Torque, HP, CFM vs Motor Speed**

Source: Stock Exchange
Adjustable-Speed Drives

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

\[ T \approx \frac{V}{Hz} \]

<table>
<thead>
<tr>
<th>Volts 60 Hz</th>
<th>V/Hz</th>
<th>Volts 30Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>480</td>
<td>8.0</td>
<td>240</td>
</tr>
<tr>
<td>220</td>
<td>3.7</td>
<td>110</td>
</tr>
<tr>
<td>120</td>
<td>2.0</td>
<td>60</td>
</tr>
</tbody>
</table>

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

- Typical circuit diagram

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
Poll Question

• 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
• 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
  o Assume 50% energy savings at $3,000
  o VFD costs is 30 HP x $250/HP = $7,500
  o 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%

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

<table>
<thead>
<tr>
<th>VT/VH Power vs Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>100%</td>
</tr>
<tr>
<td>90%</td>
</tr>
<tr>
<td>80%</td>
</tr>
<tr>
<td>70%</td>
</tr>
<tr>
<td>60%</td>
</tr>
<tr>
<td>50%</td>
</tr>
<tr>
<td>40%</td>
</tr>
<tr>
<td>30%</td>
</tr>
<tr>
<td>20%</td>
</tr>
<tr>
<td>10%</td>
</tr>
</tbody>
</table>

*VT/VH = Variable Torque/Variable Horsepower*
VFD Energy Savings

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

<table>
<thead>
<tr>
<th>Control</th>
<th>Motor HP Input vs Speed (100 HP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25%</td>
</tr>
<tr>
<td>Damper</td>
<td>50</td>
</tr>
<tr>
<td>Inlet Vane</td>
<td>44</td>
</tr>
<tr>
<td>VFD*</td>
<td>3.6</td>
</tr>
</tbody>
</table>

*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
  - Energy consumption VFD/Damping = 10.3/19.9 = 50%
  - 50% savings!

### Damping Pwr vs Speed @Hrs

<table>
<thead>
<tr>
<th>Speed</th>
<th>Power</th>
<th>Hours</th>
<th>HP-Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>100%</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>75%</td>
<td>93%</td>
<td>8</td>
<td>7.4</td>
</tr>
<tr>
<td>67%</td>
<td>85%</td>
<td>8</td>
<td>6.8</td>
</tr>
<tr>
<td>50%</td>
<td>73%</td>
<td>5</td>
<td>3.7</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>19.9</strong></td>
</tr>
</tbody>
</table>

### VFD Pwr vs Speed @Hrs

<table>
<thead>
<tr>
<th>Speed</th>
<th>Power</th>
<th>Hours</th>
<th>HP-Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>105%</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td>75%</td>
<td>50%</td>
<td>8</td>
<td>4.0</td>
</tr>
<tr>
<td>67%</td>
<td>40%</td>
<td>8</td>
<td>3.2</td>
</tr>
<tr>
<td>50%</td>
<td>19%</td>
<td>5</td>
<td>1.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
<td><strong>10.3</strong></td>
</tr>
</tbody>
</table>
VFD Energy Savings

- Comparison at lower speeds but longer run hours
  - 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

<table>
<thead>
<tr>
<th>Speed</th>
<th>Power</th>
<th>kW</th>
<th>Hours</th>
<th>kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td>100%</td>
<td>105%</td>
<td>43.5</td>
<td>2</td>
<td>87</td>
</tr>
<tr>
<td>75%</td>
<td>42%</td>
<td>17.4</td>
<td>8</td>
<td>139</td>
</tr>
<tr>
<td>67%</td>
<td>30%</td>
<td>12.4</td>
<td>8</td>
<td>99</td>
</tr>
<tr>
<td>50%</td>
<td>13%</td>
<td>5.4</td>
<td>5</td>
<td>27</td>
</tr>
</tbody>
</table>

Total kWh: 352
Soft-starting

LRT $\approx I^2 \approx V^2$

<table>
<thead>
<tr>
<th>Reduced Voltage Starter</th>
<th>%V or %I</th>
<th>%FLA</th>
<th>%FLT</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>660</td>
<td>150</td>
<td></td>
</tr>
<tr>
<td>90</td>
<td>595</td>
<td>122</td>
<td></td>
</tr>
<tr>
<td>82</td>
<td>540</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>70</td>
<td>460</td>
<td>74</td>
<td></td>
</tr>
<tr>
<td>58</td>
<td>380</td>
<td>50</td>
<td></td>
</tr>
</tbody>
</table>

- 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.

Source: Exponent Failure Analysis Associates
Poll Question

• 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
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

![Diagram of pump and system curves](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.
• Determine why the load operation needs to be changed.
  o How many speed changes required?
  o How often does speed need to be changed?
• Evaluate the possibility of required oversizing of the VFD.
  o Hard-to-start loads
  o Quick start or emergency stop
  o High temperature environment may require VFD derating.
    • Temperatures >104°F (40°C)
• 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.
Poll Question

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

<table>
<thead>
<tr>
<th>Reactor Impedance</th>
<th>Harmonic Current Distortion</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>80%</td>
</tr>
<tr>
<td>3%</td>
<td>35%-45%</td>
</tr>
<tr>
<td>5%</td>
<td>30%-35%</td>
</tr>
</tbody>
</table>
VFD Power Quality Issues

• DC reactors/chokes built into the drive
  o The DC choke provides a greater reduction primarily of the 5th and 7th harmonics.
  o On higher order harmonics the line reactor is superior.
  o Less voltage drop than line reactors.
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)
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
  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
  o Passive
    • A combination of a reactor and capacitor elements
  o Tuned
    • Connected in a parallel shunt arrangement
    • Designed for a specific harmonic frequency (5\textsuperscript{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
Poll Question

• 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
## VFD Power Quality Issues

<table>
<thead>
<tr>
<th>Estimated Cost of Harmonic Correction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device Type</td>
</tr>
<tr>
<td>Active Filter</td>
</tr>
<tr>
<td>Broadband Blocking Filter</td>
</tr>
<tr>
<td>Phase-Shifting Transformers</td>
</tr>
<tr>
<td>Tuned-Switched Filter</td>
</tr>
<tr>
<td>Tuned Fixed Filter</td>
</tr>
<tr>
<td>Switched Capacitors</td>
</tr>
<tr>
<td>K-Rated Transformer</td>
</tr>
<tr>
<td>Reactor (choke)</td>
</tr>
</tbody>
</table>
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.
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  - Efficient Industrial Lighting-Tips on What’s Best for Your application
    - October 21: 9-10am PST

- **Operations:**
  - Operation & Maintenance Opportunities (PGE)
    - May 21: 11am-noon PST
    - http://neea.org/get-involved/calendar
Thank You

• Please take our online survey