Variable – Frequency Drives
Meet Your Panelists

Mike Carter

Mark Farrell
Contents

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

Source: Emerson Industrial Automation
Basics

Work

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

Torque
A force that produces rotation
Torque exists even if no movement occurs

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

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

\[ F = 60 \text{ lb} \times 3 \text{ ft} = 180 \text{ lb-ft} \]

Source: Stock Exchange
Basics

**Horsepower (HP)**

A measure of the rate at which work is done

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

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

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

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

Electric motors

Direction of current flow changes poles

Source: Reliance Electric

Source: Danfoss
Basics

Electric motors

Stator field induces current flow in rotor conductors

Source: Reliance Electric
Basics

Synchronous speed of rotating stator field

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

Typically 5% slip for induction motors

<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
Basics

Motor torque

Related to horsepower and speed

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

Example: A 30 HP motor operating at 1725 rpm

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

Also related to voltage and frequency

Volts per hertz (V/Hz)

Source: Baldor Electric
Motor Loads

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

Speed, Torque, and HP

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

<table>
<thead>
<tr>
<th>Speed</th>
<th>Torque</th>
<th>HP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\[ T \approx \frac{HP}{rpm} \]

\[ rpm \approx \frac{HP}{T} \]

\[ HP \approx T \times rpm \]
Motor Loads

Variable torque/Variable HP

Volume $\approx$ rpm

$T \approx$ rpm$^2$

$\text{HP} \approx$ rpm$^3$

Compressors

Centrifugal

Pumps

Blowers

Fans

Source: Stock Exchange
VFD Operation

Synchronous speed of rotating stator field.

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

Vary speed by varying frequency

Vary frequency from 0 Hz to 60 Hz or more

Source: Danfoss
VFD Operation

Torque is proportional to volts divided by frequency

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

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

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

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

Typical circuit diagram

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

Source: HVACRedu.net
VFD Operation

Constant voltage inverter

Pulse width modulation (3.5KHz to 15 kHz)

Constant power factor

High efficiency (up to 98%)

Long ride-through

Source: Sebesta Blomberg & Associates
VFD Costs

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

Example: 30 HP motor operating 5,000 hours annually costs $6,200 in electricity at $0.05/kWh

Assume 50% energy savings at $3,000

VFD costs is 30 HP x $250/HP = $7,500

A little over a two year payback
VFD Advantages

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

Increased reliability
  Decreased mechanical impact from soft-start

Decreased maintenance costs
  Increased equipment life
  No need for throttles/dampers

Built-in soft starting

Source: Emerson Industrial Automation
VFD Energy Savings

Power Input

Source: Emerson Industrial Automation
VFD Energy Savings

Power Output

\[ \text{HP} \approx \text{rpm}^3 \]

Example: speed reduction to 50%

\[ \text{HP}_{0.5} = \text{HP}_1 \times (0.5)^3 = \text{HP}_1 \times 0.125 \]

*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

Assume a 25 HP fan motor operating 23 hrs/day

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

50% savings!

<table>
<thead>
<tr>
<th>Damping Pwr vs Speed @Hrs</th>
<th>Speed</th>
<th>Power</th>
<th>Hours</th>
<th>HP-Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>100%</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>93%</td>
<td>8</td>
<td>7.4</td>
</tr>
<tr>
<td></td>
<td>67%</td>
<td>85%</td>
<td>8</td>
<td>6.8</td>
</tr>
<tr>
<td></td>
<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></td>
<td><strong>19.9</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VFD Pwr vs Speed @Hrs</th>
<th>Speed</th>
<th>Power</th>
<th>Hours</th>
<th>HP-Hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%</td>
<td>105%</td>
<td>2</td>
<td>2.1</td>
</tr>
<tr>
<td></td>
<td>75%</td>
<td>50%</td>
<td>8</td>
<td>4.0</td>
</tr>
<tr>
<td></td>
<td>67%</td>
<td>40%</td>
<td>8</td>
<td>3.2</td>
</tr>
<tr>
<td></td>
<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></td>
<td><strong>10.3</strong></td>
</tr>
</tbody>
</table>
Soft-starting

LRT ≈ I2 ≈ V2

<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
VFD Disadvantages

Less efficient at 100% rated motor speed

Possible winding insulation breakdown
  Inverter-rated motors recommended

Harmonics
  Many possible preventive measures available

Possible voltage reflected wave from long lead lengths

Higher first cost
  Payback from lower energy consumption
VFD Best Applications

All variable torque applications

Compressors
  Centrifugal

Pumps
  Chilled water
  Condenser water
  Building supply
  Chemical dosing

Blowers

Fans

Source: Emerson Industrial Automation
VFD Best Applications

When pump and system curves are close to perpendicular

Source: Emerson Industrial Automation
VFD Best Applications

Some constant torque applications

Does improve the process

Reduced speed operation in 50% to 75% range

Current limited starting required

Smooth acceleration required

Source: Emerson Industrial Automation
VFD Best Applications

When not to use VFDs

Pump and system curves are parallel
  - High lift
  - Minimal pipe friction

No variability in speed
  - Use impeller trim
  - Adjust the motor fixed speed (change gears)

Pump operates efficiently ON/OFF
  - Example: sump pump

Source: LLNL
Sizing a VFD

Do not size the VFD based on horsepower ratings

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

Variable torque

- Must meet amperage rating of motor

Constant torque

- Obtain the highest peak current readings under the worst conditions
  - Check motor full-load amps (FLA) to see if the motor is already overloaded

Starting torque modes

- High overload is 150% torque for one minute
- Breakaway torque allows 180% torque for 0.5 seconds
- Normal overload is 110% torque for one minute

Engage a VFD supplier for consultation
Sizing a VFD

Determine why the load operation needs to be changed.

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

Evaluate the possibility of required oversizing of the VFD

- Hard-to-start loads
- Quick start or emergency stop
- High temperature environment may require VFD derating

Temperatures >104°F (40°C)
Sizing a VFD

Using a 3-phase VFD with single phase power

The 3-phase VFD HP rating x 2

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

Reduces life of filtering capacitors

Dedicated single phase VFDs over 20 HP are hard to find

Probably cheaper to use a phase converter
VFD Power Quality Issues

Protecting the VFD
Harmonic Distortion
Reactors
Transformers
Multi-pulse drives
Filters
Maintaining Your VFD

Source: Emerson Industrial
VFD Power Quality Issues

Protecting the VFD

Drops out below 70% voltage (30% sag).

Protect against high potential spikes (2xV for 0.1 cycle)

Fast acting Metal Oxide Varistor (MOV)

Zener diodes

Oversized DC bus capacitors

Drops out at >2% phase imbalance

UL requires fuses over circuit breakers before VFD

Locate power factor correction capacitors upstream of VFD
VFD Power Quality Issues

Harmonic distortion solutions

Move equipment to a different power supply

Use phase-shift transformer to serve two VFDs

Reactors and filters

Source: Danfoss
VFD Power Quality Issues

AC input line reactors upstream of VFD

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

<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

The DC choke provides a greater reduction primarily of the 5th and 7th harmonics

On higher order harmonics the line reactor is superior

Less voltage drop than line reactors

Source: HVACRedu.net
VFD Power Quality Issues

Isolation transformers upstream

Method for “living with” harmonics

K-rated transformers upstream

Method for “living with” harmonics

K-factor (normally 1-20)
VFD Power Quality Issues

Harmonic mitigating/Phase shifting/Quasi 12-pulse transformers

Provides substantial reduction (50-80%) in voltage and current harmonics

Must supply AFDs with equal HP and equal load
**VFD Power Quality Issues**

Multi-pulse drives

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

Filters

Passive

A combination of a reactor and capacitor elements

Tuned

Connected in a parallel shunt arrangement

Designed for a specific harmonic frequency (5th)

Protects multiple drives, including PF correction
VFD Power Quality Issues

Filters

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

Active
- Injects equal and opposite harmonics
- Expensive
- Easily adapts to varying loads
### VFD Power Quality Issues

<table>
<thead>
<tr>
<th>Device Type</th>
<th>$/KVA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Active Filter</td>
<td>$150</td>
</tr>
<tr>
<td>Broadband Blocking Filter</td>
<td>$100</td>
</tr>
<tr>
<td>Phase-Shifting Transformers</td>
<td>$50</td>
</tr>
<tr>
<td>Tuned-Switched Filter</td>
<td>$40-$50</td>
</tr>
<tr>
<td>Tuned Fixed Filter</td>
<td>$35</td>
</tr>
<tr>
<td>Switched Capacitors</td>
<td>$25</td>
</tr>
<tr>
<td>K-Rated Transformer</td>
<td>$20</td>
</tr>
<tr>
<td>Reactor (choke)</td>
<td>$3-$4</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
Case Studies

Erickson Air-Crane helicopter refurbishing facility

Existing plus rented modulating screw compressors

- Insufficient capacity (CFM) and pressure
- Loss of production waiting for pressure rise
- Moisture and air impurities
- High maintenance and energy costs

Replaced with one 150-hp screw compressor with VFD drive

- Annual energy cost reduced from $30,424 to $6,725
- 66% increase in capacity (CFM)
- Increased plant productivity
Case Studies

Demix Construction asphalt production plant

Dust collection system air outlets
Constant, full-speed operation 12 hours per day
VFD runs at 40% to 90% of full speed only when needed

$12,000 electricity cost savings
Payback of 2 to 3 years
Reduced noise level in plant
Decreased environmental footprint
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Upcoming Webinars and Trainings

Go to the NEEA calendar at [www.neea.org/industrial-events](http://www.neea.org/industrial-events) for other trainings and events scheduled around the Northwest region.

**Webinars:**

November 17, 2011: Webinar: Trends and Advances in Lamps and Ballasts

**In-Class Trainings:**

November 9, 2011: Pumping System Optimization (Twin Falls, ID)

November 10, 2011: Adjustable Speed Drive Applications and Energy Efficiency (Hermiston, OR)

November 10, 2011: Energy Data Analysis: Introduction to KPIs (Helena, MT)

November 16, 2011: Compressed Air Challenge - Level 1 (Yakima, WA)

Please take the online survey

Thank you