Variable Frequency Motor Controllers ~30 Years of Lessons Learned

Wednesday, April 13th
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Lowering Lifecycle Costs with Intelligent Motor Control Centers (iMCCs)

- Who installs bypasses with VFDs?
- Who has pump stations with VFDs and starters?
- Who has installed VFDs outdoors?
- Who requires 18 pulse drives?

If I answer questions will I get free stuff?

How are you going to cover 2 hours of material in 30 minutes?
Variable Frequency Drives (VFDs)

Quick Facts

- Sometimes referred to as Adjustable Frequency Drive (AFD), Variable Speed Drive, Inverter, etc.
- Controls speed and torque by varying frequency and voltage to the motor
- Is a non-linear load because the voltage and current are a different shapes due to diode switching as the capacitor charges and discharges
- Consists of Rectifier, Inverter, Controls, Cooling and other components depending on application
- 6, 12, 18, or 24 pulse versions depending on the number of 6 pulse rectifiers and phase shifting transformers used
- Types: Open Frame or Enclosed, LV or MV, 1φ or 3 φ Input
What’s Changed?

Variable Frequency Drives
Misconceptions of the Past

Is This True?

- Reliability
  - VFDs must have bypass starters to be reliable
  - VFDs will be wiped out by electrical surges
  - VFDs have issues with standby generators and transfer switches
  - VFDs must be in a clean air conditioned environment

- Lifecycle Costs
  - VFDs won’t save much money in energy or if I install a VFD I will get lots of energy savings
  - VFDs are maintenance intensive
  - VFDs create harmonics and EMI that are expensive to mitigate
Misconceptions of the Past

Is This True?

- Application
  - VFDs require special motors
  - VFDs will destroy my motor’s windings and bearings
  - VFDs must be located near the motor
  - VFDs can't be used for this application
  - VFDs and controlled motors are noisy
  - VFDs over complicate my controls
The Next Generation of Variable Frequency Drives

What Has Changed?

• Reliability
  • Fewer parts
  • MTBF has more than doubled
  • Resilience to power quality
  • Environmental protection

• Lifecycle Costs
  • Lower installed and O&M costs
  • Footprints reduced by >25%
  • Higher efficiencies with less heat
  • O&M friendly

• Application
  • Built-in intelligence and communications
  • Increased functionality
  • Better harmonics and cleaner outputs
  • Application specific functions
  • Energy management
  • Safety

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Environment

VFDs Must be Protected from Heat, Moisture, Contaminates and Shocks

- UL/NEMA (1, 3R, 12) vs IEC IP Enclosure Ratings
  - IEC Chemical, Biological, Dust Ratings and conformal coating
  - Not covered: how it met rating, low temp, condensation, hot spots
- Ratings of Open, Enclosed, or panel mounted drives
- Altitude and temperature derating
- Cooling: Building HVAC, Enclosure, Fans & Heat Sinks, Panel A/C
- Outdoor Drives?
- Methods of enclosure intrusion
- Preventive Maintenance
  - Cleaning
  - Pom Poms?
Incoming Power Surges and Transients

Lightning, Utility Switching, Power Loss, Standby Generators and Automatic Transfer Switches

- Many devices are susceptible not just VFDs
  - i.e. Electronic circuit breakers, overloads, controls, etc.
- Rectifier diodes susceptible to large surges
- Voltage spike lower capacitor life
- Transients can cause nuisance trips that may be auto-reset
- Common Mode Failure is the main concern
- Protection
  - Some VFDs take control power taken from the DC bus
  - Surge Protection Devices (SPDs)
  - Input contactor for isolation
  - Spares
  - Bypass starters
  - Redundancy
Grounding Variable Frequency Drives

Consult Manufacturer Installation Manual

1. Incoming Power Ground
2. High Frequency Motor Ground connected directly to VFD
3. Grounded shielded power cable or dedicated metal conduit with ground wire at both ends
4. Internal EMC filter may need to be disconnected from ground depending on the incoming power system topology

5. Grounded shielded control cable at one end (PLC with common grounded). You may also ground at both ends with a capacitor in line with the ground at VFD end.
6. Motor shaft grounding may be needed for motors over 100hp where the motor does not insulate the path to ground for induced motor shaft currents.
Preventing Motor Bearing Current Issues

Not all installations experience this issue; proper system and equipment grounding is essential

- A voltage may be induced on the motor shaft causing current to flow through bearings and cause fluting and pitting.
- Not all installations experience this issue; proper system and equipment grounding is essential. Smoother output waveforms reduce impacts.
- The bearing current flow must be broken or an alternate path provided to prevent bearing damage
  - The bearing can be isolated using insulated sleeves or ceramic bearings.
  - The bearing currents can be diverted away from the bearings by grounding the shaft. A shaft brush or micro fiber shaft grounding ring can be used.
Preparedness

VFD Life Cycle Management

• Design life of 15-20 years
• Capacitors are Limiting Life Factor
  • Heat limits capacitor life
  • Overvoltage, spikes, harmonics limit life
• Corrective ⇒ Preventive / Predictive Maintenance
  • Maintaining Environment (inside and out)
  • Asset / Condition Management
  • Know when replacement will be necessary
• Readily Accessible Spare Parts
• Skilled Maintenance Staff
• Service Contacts / Contracts
• Documentation
Applying Variable Frequency Drives
Open verses Enclosed Variable Frequency Drives

Open Frame Drive
• Cost Effective
• Separate Mounting of Components
  • Over Current Protective Device
  • Harmonic / EMI Mitigation
  • Controls
• Standard Offer with Few Options

Enclosed Drive
• All in One Package that is tested and certified versus panel packaged drives
• Enclosure provides additional protection
• Customizable
• Possible smaller footprint than separately mounting components
• May have lower temperature rating and/or need additional heat removal
• May have higher Short Circuit Current Rating
• Easier to contain shock, flame, fire or explosion
Harmonics
What are Harmonics and their Impacts?

- Non-linear loads cause a distorted current waveform composed of a multiple of sine waves at different frequencies, including the fundamental power frequency of 60 Hz.
- Increased size and cost of electrical components due to higher RMS currents ~ up to 15%
- Increased energy loss
- Shortened equipment life from overheating, overvoltage, stresses
- Nuisance power system trips
- Potential resonance conditions with pF correction equipment
  - Magnification of voltage and current
  - Excessive voltage and overheating of PF correction capacitors
  - Tripping of PF protection equipment
  - Shutdown / damage to electronics
6 / 12 / 18 Pulse Variable Frequency Drive Harmonic Waveforms
Harmonic Mitigation Methods

Common Devices

- Line (input) Reactors or Chokes
  - Will smooth out the non-linear current and reduce the peak current
- Passive Filters
  - Tuned filter plus additional inductors
- 12 / 18 / 24 Pulse Drives
  - Phase shifting transformer and multiple 6 pulse rectifiers
  - Cancellation effect on harmonics
  - Input waveform closer to a sine wave with more pulses
- Active Filters
  - Injects current to cancel harmonics from VFD loads
  - Active Front End
    - Applied per drive
  - Active Harmonic Filter
    - System solution with additional benefits
<table>
<thead>
<tr>
<th>SOLUTION</th>
<th>ADVANTAGE</th>
<th>DISADVANTAGE</th>
<th>TYPICAL % TDDI</th>
<th>TYPICAL PRICE MULTIPLIER*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase Short Circuit Capacity</td>
<td>● Reduces THDv</td>
<td>● Increases TDDi</td>
<td>Dependent upon SCR***</td>
<td>Cost of transformer and installation change out</td>
</tr>
<tr>
<td>C-Less Technology</td>
<td>● TDD reduction</td>
<td>● Limited harmonic compliance</td>
<td>30 - 50% TDDi</td>
<td>0.90 - 0.95</td>
</tr>
<tr>
<td></td>
<td>● Simplified design</td>
<td>● Application and Size Limited</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>● Inexpensive</td>
<td></td>
<td></td>
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<tr>
<td>Impedance (3% Line Reactor or 5% DC Choke)</td>
<td>● Inexpensive</td>
<td>● Difficult harmonic compliance</td>
<td>30 - 40% TDDi</td>
<td>1.05 - 1.15</td>
</tr>
<tr>
<td></td>
<td>● Simple</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Harmonic Trap Filter</td>
<td>● Reduces 5th harmonic and total TDD</td>
<td>● Harmonic compliance for lower level harmonics</td>
<td>18 - 22% TDDi</td>
<td>1.20 - 1.45</td>
</tr>
<tr>
<td>Broadband Filter</td>
<td>● TDD reduction thru 13th harmonic</td>
<td>● Excessive heat generation</td>
<td>8 - 15% TDDi</td>
<td>1.25 - 1.50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>● Application limited</td>
<td></td>
<td></td>
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<tr>
<td>12-Pulse Rectifiers</td>
<td>● TDD reduction 5th thru 7th harmonic</td>
<td>● Very large footprint/heavy</td>
<td>8 - 15% TDDi</td>
<td>1.65 - 1.85</td>
</tr>
<tr>
<td></td>
<td>● Reliable</td>
<td>● Good for &gt;100 hp</td>
<td></td>
<td></td>
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<tr>
<td>18-Pulse Rectifiers</td>
<td>● TDD reduction 5th thru 13th harmonic</td>
<td>● Very large footprint/heavy</td>
<td>5 - 8% TDDi</td>
<td>1.65 - 1.85</td>
</tr>
<tr>
<td></td>
<td>● Reliable</td>
<td>● Good for &gt;100 hp</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Front End Converter</td>
<td>● Very good TDD reduction</td>
<td>● Large footprint/heavy</td>
<td>&lt; 5% TDDi</td>
<td>2.0 - 2.5</td>
</tr>
<tr>
<td></td>
<td>● Regeneration Possible</td>
<td>● Expensive</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>● Heat generation</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>● Interferes w/ nearby DC Rectifiers</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Active Harmonic Filter</td>
<td>● Very good TDD reduction</td>
<td>● Large footprint/heavy Δ</td>
<td>&lt; 5% TDDi</td>
<td>1.75 – 2.0 (single VFD)</td>
</tr>
<tr>
<td></td>
<td>● Optimal for multiple loads</td>
<td>● Expensive for single load Δ</td>
<td></td>
<td>1.25 – 1.5 (multiple VFDs)</td>
</tr>
<tr>
<td></td>
<td>● Load balancing and pF correction</td>
<td>● Heat generation Δ</td>
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</table>

* PRICE COMPARED TO A STANDARD 6PULSE VFD.
** UTILITIES AND USERS ARE NOT LIKELY TO CHANGE THEIR DISTRIBUTION SYSTEMS.
*** INCREASING SHORT CIRCUIT CAPACITY (LOWER IMPEDANCE SOURCE OR LARGER KVA CAPACITY) RAISES TDD BUT LOWERS THDv.
Δ WHEN APPLIED TO MULTIPLE LOADS DECREASES PER LOAD.
Applying Harmonic Mitigation

Rules of Thumb and Guidelines

• Apply mitigation to the system not the individual load.
  • Avoid unnecessary mitigation by taking a system approach. Reducing harmonic emission at offending equipment is expensive and can reduce efficiency.

• Harmonic limits should be applied to the power distribution point and not the VFD terminals.
  • Most standards refer to power distribution point and should not be applied to individual equipment. When the point of common coupling (PCC) is defined as the Drive/VFD input terminals, harmonic mitigation beyond a 5% Line Reactor is required.

• Harmonics will be more of a concern if VFDs are the predominant system load.
  • Harmonic mitigation beyond a 5% Line Reactor is often required if the VFD loading (sometimes referred to as non-linear loading) is 50% or more or than the distribution transformer capacity. Small lift stations with VFD are good examples.

• Lower mitigation costs through analysis and measurements.
  • Take advantage of load diversity providing cancellation effects. Simultaneous operation at full load is unlikely. Harmonic assessment and measurements will be necessary.
  • Harmonic studies or calculation should be preformed if non-linear loading is more than 20% of the distribution transformer.
Variable Frequency Drive Output

Voltage Spikes with Long Motor Cables On VFDs

- A VFD will output a pulse width modulated (PWM) voltage waveform
- High dv/dt of the PWM waveform and a reflected wave phenomena can generate high voltage spikes at the motor terminals
- The magnitude of voltage spikes would be proportional to the motor cable length
- With long motor cable lengths, this phenomena can cause motor winding damage

Each pulse can have a voltage spike

PWM output voltage

Motor Winding Damage
Motor Protection from Voltage Spikes and Stresses

Extended Motor Cable Length Solutions

- **NEMA Inverter Duty Motor**
  - Higher insulation rating
  - Allows longer motor cable lengths alone or with filtering
- **Multi Level Inverter**
  - Stepped PWM waveform closer resembling sinewave
- **Output Reactor (~150’ Motor Cable Length)**
  - Reduces voltage peaks
- **dv/dt Filter (~500’ Motor Cable Length)**
  - Reduces voltage peaks and some high frequencies
- **Sine Wave Filter (>1000’ Motor Cable Length)**
  - Near sinusoidal waveform
  - Larger | More Costly | More Efficiency Loss

The closer to a sinusoidal wave form the output the less torque pulsations from high frequencies and stress
Lifecycle Costs
What are the Overall Pump Operational Costs?

Consider:
1. Pump System Efficiency
2. System Asset Management
3. “True” Cost of Power

> Variable speed pumping equipment purchase represents only $.10 for every $1 spent over the life of the system!

> Must look at bigger picture!

> 90% of TCO spent after initial equipment purchase
Maximizing Energy Efficiency: Only Part of the Equation

Let’s not forget

- Affinity laws for centrifugal loads dictates power versus speed
- HP varies as the cube of speed reduction
- Physics have been main driver for applying VFD’s to these type loads
"Best Efficiency Point" (BEP) is Where You Want to Operate

- Inherent in the pump’s mechanical design
- Should be considered as a factor affecting system TCO
- Equipment life, maintenance costs impacted by operation away from BEP
- The BEP is achieved with the correct balance between head and flow
- Drives can be set to operate pump at or near BEP ALL THE TIME

Source: Courtesy of Barringer & Associates - “Pump practices & life”
Cost Mean Time Between Failure (MTBF) of Operating Away from BEP:

- Reduced equipment life
- 75% of pump systems are oversized by 30%, which causes operation away from BEP
- Reliability can decrease to 50% of design by operation of pump at -20% to +10% of BEP
- In extreme cases, operation from -30% to +15% of BEP decreases reliability by 90%!

Source: Courtesy of Barringer & Associates – “Pump practices & life”
Operating at 60% of BEP Can Result In:

Designing system to allow pump to operate at/near BEP is critical to system efficiency

- **50%**
  - 50% lifetime reduction of seals

- **20%**
  - 20% lifetime reduction of bearings

- **25%**
  - 25% lifetime reduction of casing and impeller

- **100%**
  - Approximately 100% increase of maintenance cost

Source: Barringer & Associates “Pump practices & life”
Impacts of Impeller Wear

- >30% Reduced Efficiency
- >30% Reduced Capacity

System Curve | Tested Head | Tested Efficiency | Factory Head | Factory Efficiency

Flow [gpm] vs. Head [ft]

- Factory Head: 85.5%
- Tested Efficiency: 59.5%
- Tested Head: 1502 gpm
- Flow: 1011 gpm

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How Can a Modern VFD Impact my TCO?

BEP operation can be key to both process and energy efficiency

- Must establish system parameters
- VFD can operate pump at or near BEP
- Alarm when out of tolerance

Smart pumping starts with inputting characteristics to determine pump curve
Thank you!
Note: The additional material presented hereafter is not part of the oral presentation, but is provided for reference within this document.
Variable Frequency Motor Controllers ~30 Years of Lessons Learned

Presentation Abstract

Modern Variable Frequency Drives (VFDs) have been used in the water industry for 30+ years. With the focus on cost reduction many have been looking to variable frequency drives (VFDs) for the answer, but all too often the anticipated savings aren’t achieved, and to make it worse, the misapplication of drive technologies can have significant negative impacts. There is a bright side! Technologies have improved dramatically enabling them to positively impact operations better than ever before. This presentation will discuss how to achieve the lowest life cycle costs using current drive technologies while avoiding the consequences of misapplications still commonly being applied today. Information will be of interest to maintenance, engineering, and management.

What are the lessons learned over the last 30 years? What are the best ways to lower pump lifecycle costs? When do I need a bypass starter? When/what harmonic mitigation is needed? What process applications can benefit the most? Etc.

Over the past 30 years VFD technologies have improved dramatically in terms of reliability, maintenance, connectivity, harmonic distortion, functionality, and costs. VFDs can lower energy costs using the affinity laws, protect and extend the life of mechanical assets, reduce water loss, lower utility demand charges, shrink the size of standby power generators, reduce voltage sag causing lights to dim or control relays to drop out, and allow the use of more reliable 3 phase motors when only single phase power is available. The dangers of misapplication include leftovers from past process designs and older technologies and can prevent you from receiving the full benefits. If misapplied, energy savings may be minimal or non-existent, system hydraulics may cause damage to assets, harmonics may cause interference or damage to other assets, motors and wiring may be damaged, or the technologies may not be applied cost effectively for the application.