What we will be covering today!!!

Basics of Variable Frequency Drives (VFDs)
Benefits of VFDs
Problems and pitfalls of using VFDs
How VFDs save you energy
AC POWER BASICS

A sine wave is the fundamental alternating current and alternating voltage waveform.

Sine waves are characterized by the amplitude and period. The **amplitude** is the maximum value of a voltage or current; the **period** is the time interval for one complete cycle.

The amplitude \((A)\) of this sine wave is \(20\, \text{V}\).

The period is \(50.0\, \mu\text{s}\).
AC POWER BASICS

Frequency

Frequency \((f)\) is the number of cycles that a sine wave completes in one second.

Frequency is measured in hertz (Hz).

If 3 cycles of a wave occur in one second, the frequency is: 3 Hz

In the U.S. we use 60 Hz power

That means the lights are turning off and on 60 times a second! No wonder you have a headache right now!!

AC POWER BASICS

There are several ways to specify the voltage of a sinusoidal voltage waveform. The amplitude of a sine wave is also called the peak value, abbreviated as \(V_p\) for a voltage waveform.

The peak voltage of this waveform is 20 V.

In the U.S. we usually refer to voltage in RMS or Root Mean Square terms

If you knew the peak value of 480 Volts RMS you would be shocked!
AC POWER BASICS

The voltage of a sine wave can also be specified as either the peak-to-peak or the RMS value. The peak-to-peak is twice the peak value. **The RMS value is 0.707 times the peak value.**

The peak-to-peak voltage in this example is 40 V. The RMS voltage is 14.1V

For U.S. systems, 460 V (RMS) has a peak of 650 Volts!!

AC MOTOR BASICS

What is an Electric Motor?

- **Electromechanical device that converts electrical energy to mechanical energy**

- **Mechanical energy used to e.g.**
  - Rotate pump impeller, fan, blower
  - Drive compressors
  - Dry wood!!!!

- **Motors in industry: 70% of electrical load**
## AC MOTOR BASICS

### Three types of Motor Load

<table>
<thead>
<tr>
<th>Load Type</th>
<th>Description</th>
<th>Motor loads</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant torque</td>
<td>Output power varies but torque is constant</td>
<td>Conveyors, rotary kilns, constant-displacement pumps</td>
</tr>
<tr>
<td>loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Variable torque</td>
<td>Torque varies with square of operation speed</td>
<td>Centrifugal pumps, fans</td>
</tr>
<tr>
<td>loads</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Constant power</td>
<td>Torque changes inversely with speed</td>
<td>Machine tools</td>
</tr>
<tr>
<td>loads</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
AC MOTOR BASICS

Two parts: stator and rotor
- Stator: stationary electrical component
- Rotor: rotates the motor shaft

Two types
- Synchronous motor
- Induction motor

AC MOTOR BASICS

AC Motors – Induction motor
- Most common motors in industry
  - Advantages:
    - Simple design
    - Inexpensive
    - High power to weight ratio
    - Easy to maintain
    - Direct connection to AC power source
AC MOTOR BASICS

AC Motors – Induction motor

How induction motors work

• Electricity supplied to stator
• Magnetic field generated that moves around rotor
• Current induced in rotor
• Rotor produces second magnetic field that opposes stator magnetic field
• Rotor begins to rotate

Speed and slip

• Motor never runs at synchronous speed but lower “base speed”
• Difference is “slip”
• Typical slip is 3% (1800 = 1750 RPM)
• Calculate slip using the formula below:

\[
\% \text{ Slip} = \frac{N_s - N_b}{N_s} \times 100
\]

Ns = synchronous speed in RPM
Nb = base speed in RPM

\[
N_s = \frac{120 \times f}{P}
\]

F = freq.  P = # of poles

1800 = 120*60/4
AC MOTOR BASICS

AC motor speed change can be accomplished in three ways:

• Change the number of poles in the motor; this means separate windings;
• Change the slip characteristics of the motor; this is done with varying resistors, such as is done with a wound-rotor motor or by varying the stator voltage; or
• Change the frequency of the power supplied to the motor.

This is the method of choice !!!

Relationship load, speed and torque

At start: high current and low “pull-up” torque

At Base speed: torque and stator current are zero
AC MOTOR BASICS

VFD Fundamentals

BASIC OPERATION
PWM Drive
How do we vary motor speed?

Speed = \( \frac{120 \times \text{Frequency}}{\# \text{ of poles in motor}} \)

Speed across the line = \( \frac{120 \times 60 \text{ Hz}}{4 \text{ poles}} \) = 1800 rpm

- By varying the frequency, the motor speed will vary.
- When we vary the frequency, we must also vary the voltage.

PWM Drive, Motor Flux

Applied Voltage vs. Frequency of Operation

- 60 Hz Motor
- Torque constant below 60 Hz
- Reduced Torque above 60 Hz
- Constant Volts per Hertz
  - (up to 60 Hz)
  - 3.83 V per Hz @ 230 VAC
  - 7.67 V per Hz @ 460 VAC
PWM VFD Hardware

Three Sections of the VFD

Input Converter
Diode Bridge
AC to DC
Reconstruct the Sinewave

DC Bus
Filters and
smooths
waveform

Inverter output-IGBT’s
Switch DC Bus on and off at
different intervals

ABB

PWM VFD Hardware

Input Converter
Diode Bridge
AC to DC
Reconstruct the Sinewave

DC Bus
Filters and
smooths
waveform

Inverter output-IGBT’s
Switch DC Bus on and off at
different intervals

ABB

Title goes here

11/6/2019
In half wave rectification, either the positive or negative half of the AC wave is passed, while the other half is blocked. Because only one half of the input waveform reaches the output it is very inefficient.

Full-wave rectification
A full-wave rectifier converts the whole of the input waveform to one of constant polarity (positive or negative) at its output. Full-wave rectification converts both polarities of the input waveform to DC (direct current), and is more efficient. Four diodes arranged this way are called a diode bridge or bridge rectifier:
Input Converter, Diode Bridge

3-phase AC input, half & full wave rectified DC output waveforms

PWM VFD Hardware

Input Converter Diode Bridge AC to DC Reconstruct the Sinewave
DC Bus Filters and smooths waveform
Inverter output-IGBT’s Switch DC Bus on and off at different intervals
The smoothing capacitor removes the DC ripple.

So we end up with a nice smooth DC Bus at 600VDC +/- (remember that’s based on peak voltage not RMS).
Mid Section of the Drive-DC Bus

- DC Link Reactors
  - Single DC Link
  - Dual DC Link
  - 1.5%-3% Commonly
  - 5% by some
- What do they Do?
  - Provide protection
  - Reduce Harmonics

PWM VFD Hardware

- Input Converter
  - Diode Bridge
  - AC to DC
  - Reconstruct the Sinewave
- DC Bus
  - Filters and smooths waveform
- Inverter output-IGBT’s
  - Switch DC Bus on and off at different intervals
The main objective of the VFD is to vary the speed of the motor while providing the closest approximation to a sine wave for current (while pulsing DC voltage to the motor).
The area within each pulse is the power delivered to the motor in volt-microseconds.
INVERTER OUTPUT - PWM

Pulse-width-modulated voltage and current waveforms.

Benefits and the Pitfalls of Variable Speed Drives
Jay Bradford - Motion Industries.
Benefits of VFDs

- Process control
- Low inrush starting (soft start)
- Overload protection
- Multi-motor operation
- High Power Factor
- Phase converting
- Over-speeding
- Critical speed rejection
- Energy Savings

Process control

- Decentralized control
  - PID regulator "built" into the VFD
  - Faster response to process changes
- Better process information through field bus
  - Process data
    - Actual process data
    - Power used data
  - Diagnostics
    - Faults
    - Maintenance triggers
    - Operation hours

Wide range of field bus options
- IndustrialIT
- Profibus
- DeviceNet
- ControlNet
- Modbus
- Ethernet
- ModbusTCP
- EthernetIP – in the future
Process control

HIGHLIGHTS: BETHLEHEM, MARCELLUS AND CLAYTON PLANTS:

Significant energy savings was found to be possible through the installation of positive displacement (PD) blowers. The proposed PD blower would be controlled by VFD and dissolved oxygen (DO) monitoring equipment. With the addition of DO monitoring equipment, DO levels can be recorded, logged and directly control the amount of air volume produced. This improvement would automate the aeration process to a predetermined DO target set point programmed into the DO transmitter/controller.

Low inrush starting (soft start)

Relationship load, speed and torque
Low inrush starting (soft start)

- Softer starts with VFD
- Reduced coupling and pump stress
- Slower pump and motor speeds
- Longer bearing life
- No valves to maintain

Lowers your peak demand charge!!
Overload protection

- Drive must be correct size for the motor and programmed accordingly to ensure motor is protected
  - Based on CEC 2-024, 28-300, 28-500
- Motor OL protection on a VFD is provided electronically
- Motor Data to be programmed during commissioning
  - Motor Nameplate information
    - Power (HP/KW)
    - FLA
    - SF
    - Volts
    - RPM
    - Frequency

For single motor applications the drive shall be programmed to protect the motor from overload conditions
- An electronic thermal overload I²T function emulates a thermal overload relay
- Models Class 10 OL
- This operation is based on three parameters;
  - [Motor NP FLA], [Motor OL Factor] and [Motor OL Hertz]
  - [Motor NP FLA] is multiplied by [Motor OL Factor] to allow the user to define the continuous level of current allowed by the motor thermal overload
  - [Motor OL Hertz] is used to allow the user to adjust the frequency below which the motor overload is de-rated.
Multi-motor operation

- All motors run at same speed
- Drive size to be sum of all HP
- No limit to number of motors on one drive
- Motors do not need to be same HP rating
- All OL Relays to be tied together in series
- Drive would run in V/Hz mode
- Motor OL can be disabled in drive

High Power Factor

![High Power Factor Chart]

- Valve
- VFD
Phase converting

Methods of converting single-phase to three-phase power:

- Phase Converters
  - Rotary Phase Converters (RPC)
  - Static Phase Converters (SPC)
- Motor-Generator (M-G) Sets
- Variable Frequency Drives (VFDs)
  - Single-Phase input models
  - Three-Phase input models (with appropriate derating)

Phase converting

Methods of converting single-phase to three-phase power:

- Variable Frequency Drives (VFDs)
  - Single-phase input models
  - Three-phase input models (with appropriate “de-rate”)
  - Provide balanced three-phase voltage
  - Can easily vary the voltage and frequency
  - No tuning of capacitors to varying loads
  - Soft start feature, PI control, extensive flexibility/programmability
  - Provides superior protective features (overload, under-voltage, etc.)
  - Reliable/maintenance-free operation
Phase converting

Why is Drive derating required?
Three-phase VFD designed to accommodate 300/360Hz DC bus ripple (3-phase full wave rectification at 50/60Hz)

- Why is Drive derating required?
  - Single-phase 60Hz input results in 120Hz DC bus ripple!
    - DC bus capacitors need to provide more power
    - DC bus level will decrease a larger amount than with three-phase input during this time
Phase converting

- Why is Drive derating required?
  - Duration between bus peaks is longer in single-phase case
    - Dc bus circuit will have to supply power for longer period
    - More stress on input and DC bus components

Over-speeding

- Applied Voltage vs. Frequency of Operation
- 60 Hz Motor

---

Title goes here
Critical speed rejection

- **Critical Speeds Rejection**
  - This function avoids the possibility of running the motor at critical speeds that may provoke mechanical resonance on the motor/load system causing excessive noise or vibration.
  - Up to three speeds and a rejection band can be programmed.

Problems and Pitfalls of VFDs

- Reflected wave Phenomenon
- Induced Shaft currents
- Many others but these are the two most common today!
General Installation Issues

Reflective wave phenomenon

Voltage Reflection / Standing Waves

- Voltage Reflection Characteristics

Drive → Pulse goes out → M → Pulse is Reflected Back

Low HP
High Impedance
Motor
Will Voltage Reflection Be a Problem?

- All modern PWM inverters switch fast enough for voltage reflection to be a possible issue.
- Although the degree varies, all cables represent a significant impedance mismatch with their connected motors.
- Therefore, if the connecting cable is long enough voltage reflection is a certainty.

Is Cable Length a Problem?

- If the distance between the VFD and the motor exceeds several hundred feet, you should investigate!

Protecting Against Voltage Reflection

- Apply motors designed in accordance with NEMA MG1 part 31.4.4.2. (these motors are designed to be able to tolerate overvoltage stress)
- Apply line reactors at the inverter output (1.5% - 3.0%) (typically protects to about 500 ft)
- Apply dv/dt filters (RLC) at the inverter output (typically protects to about 2000 ft)
- Apply a sine filter at the inverter output (not distance limited)
- Apply a snubber circuit at motor (not distance limited)
General Installation, Voltage Reflection

Installed solution between VFD and Motor
- Output (Load) Reactor
- Output dv/dt Filter
- Sinewave Filter
- Motor Terminating Device

General Installation, Voltage Reflection

Motor Terminal Voltage With dv/dt Filter

DC Link Voltage

Voltage Reflection Spikes (75% reduction)
General Installation Issues
Motor cabling and bearing currents

Unique cabling issues:

- PWM drives inherently expose motors to high level common mode voltages and associated high dv/dt.
- These common mode voltages can introduce:
  - Damaging high frequency bearing currents
  - Stray high frequency ground currents which can lead to the malfunction of sensitive equipment (e.g., sensors)
- Prevention requires low impedance high frequency grounding between the inverter and the driven motor
- Acceptable cabling solutions include:
  - Continuous corrugated aluminum armored cable
  - Shielded cable (power)
  - Carefully installed conduit system
Bearing currents in AC motors

When motors are controlled by PWM variable frequency drives (VFDs) the pulse switching causes high dv/dt (high frequency voltage changes) which results in a capacitive induced shaft voltage. These voltages may cause bearing failures and substantially decrease bearing life by electrically discharging through the motor bearings to ground causing pitting and fluting failure. NEMA MG1 states that the capacitive induced voltage “…results in peak pulses as high as 10-40 volts from shaft to ground.” Guidance for mitigating bearing damage is also provided by insulating both bearings or “…Alternately, shaft grounding brushes may be used to divert the current around the bearing. It should be noted that insulating the motor bearings will not prevent the damage of other shaft connected equipment.”

General Installation, Motor Cabling

High Frequency Ground Return Paths

Proper motor cabling should provide a significantly lower impedance high frequency ground return path through direct paths than through indirect paths.
General Installation, Motor Cabling

Recommended Cable Construction

- Insulating/Protective Outer PCV Jacket
- Continuous Corrugated Aluminum Armor/Shielded
- Bare Copper Ground Conductors (3)
- Insulated Phase Conductors (3) sized per NEC for the application

Aluminum armor provides an excellent low impedance high frequency ground return path.

General Installation, Motor Cabling

Recommended Termination Method

Connector should provide:
- 360° contact with armor
- Grounding bushing for connection of safety grounds
- Metal to metal contact with mounting surface
Drive Basics

Application of VFD’s to fans

Applications, Types

- Constant Torque
- Constant Power
- Variable Torque
Applications, Types

- Constant Torque Loads
  - Conveyors
  - Positive Displacement Pumps
  - Extruders
  - Crushers
  - Mixers (material dependent)
  - Rotary Kilns
  - Hoists
  - Elevators

Constant Torque

Torque requirement is constant vs. speed

Power requirement is proportional to speed
Applications, Types

- Constant Power Loads
  - Machine Tools
  - Winders
  - Reel Drives
  - Traction Drives
  - Earth Moving Equipment

Applications, Types

- Variable Torque Loads
  - Fans
  - Centrifugal Pumps
  - Centrifugal Blowers
  - Mixers (material dependent)
Applications, Types

Affinity Laws

- \( Q \propto N \) flow rate proportional to rotary speed
- \( H \propto N^2 \) head (pressure) proportional to rotary speed squared
- \( P \propto N^3 \) power proportional to rotary speed cubed

Variable Torque

- Flow varies linearly with speed
- Torque requirement varies as the square of speed
- Power requirement varies as the cube of speed
Applications, Types

Conventional Flow Control

- **Bypass**
  - Bypass (pumps)
  - Suction

- **Outlet**
  - Outlet Device (pumps, fans, and blowers)
  - To Service

- **Inlet**
  - Inlet Damper (fans and blowers)
  - Variable Inlet Guide Vanes (fans and blowers)

- **Inlet Vane**

Applications, Fans and Blowers

Outlet Control - Operating Points

- **Throttled System Curves**
- **Operating Points**
- **Fan Curve**
- **Design System Curve**

- % Pressure vs. % Flow graph
  - 0 to 140 % Pressure
  - 0 to 160 % Flow
Applications, Fans and Blowers

Outlet Control - Power Requirement

![Graph showing outlet control - power requirement with a note: relatively small decrease in power requirement for large decrease in flow.]

Variable Speed - Operating Points

![Graph showing variable speed - operating points with curves for design system curve, rated speed fan curve, and reduced speed fan curves.]

Title goes here
Applications, Fans and Blowers

Variable Speed - Power Requirement

Large decrease in power requirement for relatively small decrease in flow

Applications, Fans and Blowers

Power Requirement Comparisons

Outlet
Inlet Vane
Variable Speed
Economic Justification

Applications, Economic Justification

- Two Representative Samples:
  - Fan, Variable Speed vs. Damper Control
  - Blower, Variable Speed vs. Inlet Vane Control

- Three Criteria:
  - Energy Usage
  - Efficiency Improvement
  - Annual Savings
Applications, Economic Justification

- Base Assumptions (both samples):
  - Full rated flow = 178,000 CFM @ 3 "H₂O
  - Fan / blower efficiency = 85%
  - Motor efficiency = 94%
  - Drive efficiency = 98%
  - Rated shaft power = 100 hp
  - Cost per kWh = $ 0.10

Applications, Economic Justification

Fan Energy Usage
Variable Speed vs. Damper Control

- Energy Usage (MWh)
- Flow

Graph showing energy usage comparison between Variable Speed and Damper control at different flow rates.
Applications, Economic Justification

Fan Efficiency Improvement
Variable Speed vs. Damper Control

Efficiency Improvement

0% 10% 20% 30% 40% 50% 60% 70%

30% 40% 50% 60% 70% 80% 90% 100%

Flow

Fan Annual Savings
Variable Speed vs. Damper Control

Savings

$0 $5,000 $10,000 $15,000 $20,000 $25,000 $30,000 $35,000

30% 40% 50% 60% 70% 80% 90% 100%

Flow

[$5,000]