TUTORIAL - B

EFFECTS OF MEDIUM VOLTAGE DRIVES ON POWER SYSTEMS

Manish Verma
Member IEEE TMEIC

Douglas Phares
Senior Member IEEE TMEIC

Barry Dick
Member IEEE TMEIC

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TUTORIAL AGENDA

- Basics of ASD  (VFD = ASD = VFDS = etc, etc)  
  Barry Dick

- Effects of ASD on Power Systems
  Break // Q&A – 10 min

- How to be successful in ASD application
  Break // Q&A – 10 min

- Specifying Adjustable Speed Drives
  Q&A

Manish Verma

Douglas Phares
Section 1 – Basics of ASD and effects on power systems
Section 1 – MV AC Drive Basics and Effects on Power Systems
Session 1 Overview

- AC Drives Basics
  - Induction Motor Characteristics
  - Drive Topologies
  - Drives Method of Operation

- Effects on Power Systems
  - Voltage, Power Factor
  - Response to Power System Transients
  - Motor Starting with Drives
  - Harmonics: Definition, Causes
  - Mitigation of Harmonics
  - IEEE 519
Typical Induction Motor Torque Speed Profile

- **A** Locked Rotor Tq
- **B** Pull Up Torque
- **C** Peak [Breakdown] Torque, BDT
- **D** Sync RPM
- **E** Rated RPM
- **F** Rated Slip RPM

- **Sync RPM = 120 x Freq. / #Poles**
- **Rated Slip RPM = Sync - Rated RPM**

**Formulae:**

- **Rated RPM**
  - Rated Slip RPM = Sync - Rated RPM

**Definitions:**

- **Sync RPM**
  - Sync RPM = 120 x Freq. / #Poles
INDUCTION MOTOR STARTING CHARACTERISTICS

Current and Torque vs. Speed

- Current
- Torque

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AC Drives Accelerate Load by Increasing Volts and Frequency

Ideal Family Of Speed Torque Curves as Function of RPM [Holding Volts/Hz Ratio Constant]

Controlled, Increasing Volts and Frequency

Operational torque must be regulated to remain in the shaded near-linear zones.
Low voltage PWM drive

3 Phase Diode Bridge

AC Incoming Line

Cap Bank

PWM Motor Voltage

DC Bus Rectified Power

Motor Amps

Rectifier output voltage

For Reference Only
Typical AC Inverter System

**Transformation**
- Utility Supply

**Conversion**
- AC TO DC
- ENERGY STORAGE
- DC TO AC

**Utilization**
- Load
- AC MOTOR

**AC Inverter Technology**
*Up To 97% Efficiency, including transformers*
**Time Line of Power Semiconductors & Drives**

**Transistor Family**
- Bipolar Power Transistor (BPT)
- Low Voltage Insulated Gate Bipolar Transistor (LV IGBT)
- Medium Voltage Insulated Gate Bipolar Transistor (MV IGBT)
- Injection Enhanced Gate Transistor (IEGT)

**Thyristor Family**
- Silicon Controlled Rectifier (SCR)
- Gate Turnoff Thyristor (GTO)
- Integrated Gate Commutated Thyristor (IGCT)
- Symmetrical Gate Commutated Thyristor (SGCT)

**LV / Low kW Drives**
- Diode (D)
- Low Voltage Insulated Gate Bipolar Transistor (LV IGBT) Inverter

**MV / High kW Drives**
- DC
- Multi-level MV LV-IGBT Inverter
- IEGT Inverter
- GCT Inverter
- MV IGBT Inverter
- Cycloconverter
- GTO Inverter
- LCI
GTO to GCT Evolution

1980’s GTO Stack

Current GCT Device
3 Level → 5 Level Inverter Circuit

- 3 Level, Regen Converter
- 3kV Class output
- Large capacity
  3kV - 15MVA

- 5 Level, Diode Converter
- Up to 6kV Class output
- Twice as clean waveform

Two 3 Level Legs for each phase of motor

6kV～7kV, 8MVA～120MVA
High voltage, VERY large capacity, clean waveform
Example MV IGBT NPC Voltage Source Drive Details

- Neutral Point Clamped [NPC] reduces voltage to ground
- 5 / 9 level waveform < 2% motor current distortion
- 24 pulse diode converter <2% line current distortion, better than IEEE 519 limits

Example 5/9 level motor voltage & current waveforms
# MV Drive Effects on Power System

<table>
<thead>
<tr>
<th>Power System Characteristic</th>
<th>MV Drive Effect</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>Generally low if source is sized to carry loads</td>
</tr>
<tr>
<td>Availability</td>
<td>Generally low</td>
</tr>
<tr>
<td>Voltage</td>
<td>Low or High: Depends on type of ASD and load</td>
</tr>
<tr>
<td>Harmonic Distortion</td>
<td>Low or High: Depends on type of ASD and source</td>
</tr>
</tbody>
</table>
MV ASD Effects on Voltage

• Voltage Effects are primarily due to reactive power consumption
  □ Low reactive power demand means less voltage drop
    • High input pf
    • Low load with low input pf
  □ High reactive demand means voltage drop that must be corrected
    • High load with Low input pf
Power factor would be like the ratio of beer (KW) to beer plus Foam (KVA).

\[
P.F. = \frac{KW}{(KW^2 + KVAR^2)^{1/2}} = \frac{Beer}{Beer + Foam}
\]

Typical motor power factor = 0.85

Typical drive power factor = 0.95 – 0.97
Voltage Effects of Current Source ASD

Voltage Drop vs Motor Speed
Current Source ASD with 5% Series Impedance

Voltage Drop (pu)

Motor Speed

Constant torque load
Variable torque load
Voltage Effects of Voltage Source ASD

Voltage Drop vs Motor Speed

Voltage Source ASD with 5% Series Impedance

Motor Speed

Voltage Drop

- Constant torque load
- Variable torque load
Voltage Effects of MV ASD’s

• Conclusion: MV ASD’s don’t usually cause excessive voltage drop, except in extreme cases:
  - Very weak source
  - Constant torque load with current source drive and weak source

• Voltage effects of MV ASD’s are much less severe than starting motors across the line
Sources of Reactive Power

- Capacitors (including those in harmonic filters)
- PWM power converters
- Fixed speed synchronous motors
- Generator (Steam, gas, diesel, water, wind, etc)
- Synchronous condenser
Capacitors for PF and Voltage Control

• Well-understood techniques for correcting pf
  - Calculate or measure real load
  - Calculate or measure pf of load
  - Add kVAR to correct to desired pf

• Correcting low pf will usually fix voltage sag conditions
PF Correction Capacitor Issues

• Fixed bank of capacitors may be good at some load conditions, but cause voltage rise with light load conditions
  - Capacitor switching schemes may have to be adopted
  - Static VAR regulating systems are also available

• Adding untuned capacitor banks to a system with harmonic currents and voltages almost always causes problems – must be studied
  - Avoid problems by making capacitor banks into harmonic filters
MV Drives Responses to Power System Transients

- Fault on supply bus
  - No fault current contribution by drive
  - Generally drive will shut down

- Voltage dip / phase loss
  - Response depends on how low voltage goes
  - Phase loss usually results in decreased output
  - Bus transfer: drive can suspend output and restart when voltage is restored

- Fault on output of drive: PWM drives can shutoff output quickly to prevent damage to drive and motor
Using a Drive as a Motor Starter (1)

- A drive controls frequency and voltage applied to motor so high (>100%) torque at low speeds with better control of motor current is possible.
- A drive may be more costly, but it can start the large inertia loads on weak power systems.
- The ASD can be rated at a fraction of the motor rating if the motor can be unloaded at synchronizing speed.
- Either synchronous or induction motors can be started with a ASD.
- Synchronous motors are started with field current applied, so an exciter must supply current at standstill.
Example ASD Starting System

Motor/generator unit (typical of 4)

Start bus

Start breaker

Unit breaker

220 kV

13.8 kV

ASD Starter

DC link reactor

Output transformer bypass breaker

12-pulse source converter

Load converter

Output transformer

Output breaker

Isolation transformer

Output transformer

Slide #25
Harmonics and MV ASD’s

- What is meant by harmonics?
- Why do ASD’s make harmonic currents and voltages?
- What are the effects of harmonics in the power system?
- What design features in ASD’s reduce harmonics?
Harmonics Defined

- Harmonic currents and voltages are usually integer multiples of the fundamental power system frequency.
  - For example, a 300 Hz current is a 5th harmonic current in a 60 Hz system.
  - Non-integer harmonics can be made by system voltage imbalances or PWM converters.
Why do ASD’s make harmonics?

- AC to DC power conversion in a non-linear process
  - Power semiconductors allow current flow in only one direction
  - Switching on-off introduces non-linearities
- ‘Passive’ and ‘Active’ power converters make different types of harmonics
  - Passive converters use diodes and thyristors
  - Active converters use IGBT’s, GCT, or other self-switched devices
Passive Converter Harmonics

- Diodes and thyristors are usually grouped in 3-phase bridge rectifiers.
- Each 3-phase bridge is a 6-pulse converter.
- A 6-pulse converter has a distinct harmonic current signature.
- A 6-pulse converter has at least 30% harmonic current distortion.
6-pulse Converter (rectifier) Waveforms

Blue: Current
Red: Voltage
Note: Current inverted to separate waveforms
6-pulse Converter Harmonic Spectrum

Typical Harmonic Spectrum
6-pulse diode converter

THD = 32%
Voltage Harmonics

- Diode and thyristor converters behave like multi-frequency current sources
  - Harmonic currents from the converter depend on fundamental load current and gating angle (if thyristor)
- Harmonic currents cause voltage distortion
  - Power system impedances determine voltage distortion on buses
Why Limit Voltage Harmonics?

• High harmonic voltages on bus can cause
  - Equipment overheating
  - Equipment misoperation and failure

• IEEE voltage limits are written for utility, but are a good guideline for power bus within a plant
Controlling Harmonics

Reducing Converter Harmonics

- Filters applied to ASD
  - System interaction problems
  - Complexity issues (protection, disconnects)
  - Better applied to system than ASD

- Multi-pulse source converters
  - Adds transformer windings
  - Less complex than filters
  - No system interactions, predictable performance
  - Reduces harmonic currents at source
Present Practice in Low Harmonic ASD’s

- Multi-pulse systems are most common in MV ASD’s
- Competition has pushed suppliers to deliver IEEE compliant ASD’s
How Does Multi-pulse Harmonic Cancellation Work?

- Transformer phase shifts cause harmonics from different converters to cancel.
- 12-, 18-, 24-pulse connections are possible.
- Each converter must have a separate transformer winding.
- 12-pulse system has $30^\circ$ phase shift, 18-pulse has $20^\circ$, 24-pulse has $15^\circ$. 
Phase Shifting Causes Reduction

• 12-pulse circuit requires a delta winding and a wye winding, for 30° phase shift
Mechanics of Harmonic Reduction

• It’s all in the phase shift:
  - 60 Hz shift is 30° between windings
  - 5th harmonic phase shift is 150°
  - The 150° shift plus the 30° offset results in 180° difference, which is cancellation

• 12-pulse is easy; higher pulse numbers require more complex winding arrangements
Example Harmonic Effects Demo

- The 1’s in the top row show the “classic” $1/N_h$ content of current as in 6-pulse phase controlled rectifier.
- Waveform of current shows the current as it would show in the feeder to the load.
- If the rectifier feeds capacitors, then the components could grow – a lot! Depending on the feeder impedance.
- Click on the sheet to experiment – change a component to zero to eliminate, 0.1 to show achievable cancellation with phase-shift transformer, or >1 for other illustration.

![Fundamental vs Sum of Fundamental & Harmonics](image)
IEEE 519-1992 Harmonic Current Limits

- IEEE 519 recommended limits for harmonic currents at the point of common coupling with utility

**CURRENT DISTORTION LIMITS FROM IEEE 519**
(For conditions lasting more than one hour. Shorter periods increase limit by 50%)

<table>
<thead>
<tr>
<th>Harmonic Current Limits for Non-Linear Load at the Point-of-Common Coupling with Other Loads, for voltages 120 - 69,000 volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Odd Harmonic Current Distortion in % of Fundamental Harmonic Order</td>
</tr>
<tr>
<td>$I_{SC} / I_{LD}$</td>
</tr>
<tr>
<td>&lt;20*</td>
</tr>
<tr>
<td>20&lt;50</td>
</tr>
<tr>
<td>50&lt;100</td>
</tr>
<tr>
<td>100&lt;1000</td>
</tr>
<tr>
<td>=&gt;1000</td>
</tr>
</tbody>
</table>

* Power generation equipment regardless of $I_{SC} / I_{L}$
IEEE 519-1992

• IEEE 519 was conceived to apply at the interface between utility and user
  □ Limits on harmonic currents injected into system are imposed on user
  □ Limits on harmonic voltage distortion are imposed on utility

• IEEE 519 is now commonly applied inside plants, with potential cost implications
Which Converters Meet Limits?

• If limit is 5% current THD or less, an 18 pulse converter usually does
• 24-pulse is used also, provides more margin
• 12-pulse can meet limits in some cases with strong sources
• Multi-pulse circuits work for diode and thyristor converters
Voltage Harmonic Control in Plant Power Systems

- Keep harmonic voltage distortion within limits on plant buses
  - What are recommended limits? (IEEE 519)
    - Critical power bus: 3% THD
    - General power bus: 5% THD
    - Dedicated system: 10% THD
  - Control voltage harmonics by
    - Managing impedance
    - Managing harmonic currents
Example Power System

- Utility Source
- Transmission Voltage
- Distribution Voltage
- Substation bus
- Plant

- MV load
- LV load with harmonics
- LV loads
- Harmonic currents

For Reference Only
Managing Harmonic Currents

- Use ASDs and loads that cause very low harmonic currents in power system
  - Obvious choice – Very low harmonic current means very low voltage distortion
  - More difficult if this feature is very costly or not available

- Harmonic Filters
Harmonic Filters

• Harmonic filters for diode/SCR sources
  - Usually tuned to trap current of discrete frequencies
  - Relatively simple in concept
    • Series reactor and capacitor – single frequency
    • High-pass filter – limits impedance at higher frequencies
  - Also add capacitance and kVAR to bus
Types of Passive Harmonic Filters

- **Notch Filter**
  - (Low impedance at single frequency)

- **High Pass Filter**
  - (Low impedance at high frequency)
Frequency Response of Filters

Notch Filter

High Pass Filter
Filter Complications

• Filter selection appears simple, but
  □ System resonances are always present
  □ Harmonic magnitudes must be assessed in the system
  □ Components must be specified properly
  □ Circuit protection must be provided

• IEEE has new standard for harmonic filters: IEEE 1531-2003
Power System with Filter

- Utility Source
- Transmission Voltage
- Distribution Voltage
- Plant Substation bus

- MV load
- MV loads
- LV loads
- LV loads
- LV load

- Harmonic currents
- Harmonic currents
- MV ASD

- Filter
- LV loads

For Reference Only
Frequency Response of Network

Frequency Scan - Injection on BUS-1

Magnitude

Harmonic

For Reference Only
System Equivalent Circuit

Other transformers and system impedance

Transformer

Load with harmonic currents

Filter
PWM Source Harmonics

• PWM, or regenerative, or active front end, source converters are very different from rectifier-type sources

• These sources are applied to drives that must regenerate to apply braking or supply VARs to the power system

• Not common outside metal processing drives at this time
PWM Source Harmonic Model

- A regen source behaves like a voltage source for harmonic purposes.
  - Produces voltage harmonics
  - Not necessarily synchronous to power system frequency
  - Impedance must be placed between regen source and power system
  - Analogous to a generator with a voltage source behind an impedance
Control of PWM Source Harmonics

- Presently, high power MV PWM sources operate at about 500 Hz
  - High quality asynchronous PWM is not possible
  - Switching patterns that reduce low order (<19\textsuperscript{th}) harmonic are used
Control of PWM Source Harmonics (2)

- Place high impedance between regen source and power system
  - Impedance limits current flowing between two voltage sources
  - Regen source draws unity pf current, so voltage drop is not a problem
  - Impedance increases with frequency
- Some cases need additional filtering of high frequency harmonics to meet IEEE 519
  - This filtering can be near regen source or upstream
Example PWM Source Circuit
MV ASD Power Quality Summary

• Any MV ASD with 18-pulse or higher input will have low harmonics

• Voltage source drives (capacitor dc link) with 18-pulse or higher input are excellent loads

• PWM sources differ from diode and thyristor sources
  - Different measures to attenuate harmonics
  - Capability to help regulate pf on bus
Section 2 - Adjustable Speed Drive application overview

How to be successful in Drive application?
ASD Application Overview
ASD System Considerations

Must consider the whole system in which the ASD will work

- From Utility to finished product or process
- Consider environment
- Consider effects on utility
- Consider the needs of the load
- Consider the effect on motors and load
An ASD Pictorial Overview
ASD Overall Success Factors

1. Minimum first cost, including installation
3. Good match to process & loads.
4. Long equipment life.
5. Ease of use for operators & technicians.
6. Minimum impact on nearby equipment.
7. Easy to maintain & repair.
Relation to Overall Success Factors

Application factors can be grouped into two major areas:

- Electrical/Load Application Factors
- Design & Installation Factors
Electrical/Power Application Factors

- Continuous kW or HP & duty cycle
- Torque & Power Overload Requirements
- Load factors: CT, VT, CHP, regenerative, non-regenerative.
- Drive and Motor Voltage
- Power system compatibility, efficiency
Solution Process – Start At Ends and Work Towards the Middle

#1 - Define the process loads and duty cycle

#2 - Define the power system and requirements

#3 – Determine best drive solution!
Know Your Drive Load

LOAD FACTOR

- Torque loading vs RPM
- Regen vs non regen
- Continuous operating points needed
- Peak torque needed to break load away
- Load inertia
- Speed-time ramps for accel & decel

AFFECTS

- Motor
- Drive type
- Motor thermal rating, Drive size
- Motor starting/breakdown torque rating, Drive Type & OL Rating
- Drive Tuning & stability
- Drive settings

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High Starting Torque Loading

Typical Induction Motor Characteristic on 60 Hz power

Breakaway Torque

Conveyor typical demand

FREQ, SPEED
Conveyor or Mill Loading

VFD CONTROLLED MOTOR - ENOUGH TORQUE ACROSS THE RANGE

Typical Induction Motor Char on 60 Hz power

Maximum Continuous Power Point

Max Continuous Power

Intermediate Continuous Power Points

BREAKAWAY TORQUE

TORQUE

FREQ, SPEED

B C D

conveyor typical demand

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Continuous Power Requirements

Continuous Power Needs Set Size of
- Power Delivery
- Transformers
- Drive and internal transformer
- Motor
- Gearbox
Peak Torque Requirements

Peak Torque Needs Affect the Size of
- Inverter [Switches, diodes, capacitors]
- Sensors
- Motor
- Gearbox
Conveyor or Mill Loading

VFD CONTROLLED MOTOR - ENOUGH TORQUE ACROSS THE RANGE

Typical Induction Motor Char on 60 Hz power

BREAKAWAY TORQUE

Intermediate Continuous Power Points

maximum Ct (Maximum Continuous Power Point)

FREQ, SPEED

conveyor typical demand

Max Continuous Power

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Duty Cycle Example

- Horsepower = Torque x RPM / 5252
- High torque at low speed = low HP

![Graph showing torque, speed, and horsepower over time.](image-url)
Drive Ratings and Torques

• **Variable Torque [VT]** ratings usually include 110 -115% OL rating for 60 seconds when starting from rated Temp

• **Constant Torque [CT]** rating usually includes 150% OL rating for 60 seconds when starting from rated Temp.
Variable Torque Curve

- **Load Torque Varies as the Square of the Speed**
- **Motor Horsepower varies as the Cube of the Speed**
Drive Ratings and Torques

• **Variable Torque [VT]** ratings usually include 110 - 115% OL rating for 60 seconds when starting from rated Temp

• **Constant Torque [CT]** rating usually includes 150% OL rating for 60 seconds when starting from rated Temp.
Regenerative Loads

• Load mass or inertia requires torque in opposite direction of RPM

• Torque x RPM = Negative

• Power Flows from motor (now acting as a generator)

• Examples:
  - Stopping a fan
  - Downhill conveyor
  - Lowering a load on a crane

• Drive converter design must accept power in reverse direction
  - Active front end
  - Diode fed will not regenerate
We’ve looked at the process loads, now let’s look at how to power the loads.

#1 - Define the process loads and duty cycle

#2 - Define the power system and requirements

#3 - Determine best drive solution!
Power System Compatibility
Including

- Power distribution (available utilization voltages)
- Protection.
- Harmonics limits.
- Power factor control.
- Efficiency.
Power System Compatibility

• Breakers, transformers, and cable must be rated to carry full kVA & harmonics. Selecting higher capacity utilization voltages may reduce drives impact on the customers power grid.

• Transformers need to be “drive isolation” rated with proper considerations for the drive type.

• Protective devices & settings consider harmonics and drive characteristics.
Power Line Harmonics

- "Harmonics" are voltages and currents at frequencies that are multiples of utility power frequency.

- Harmonic currents are drawn by loads such as drives, computers and ballasts that take their power in non-sine-wave format. These are so-called non-linear loads.
Power System & Drive Efficiency

- Drive itself is typically 98% or more efficient
  - With all fans, transformers, pumps, etc, efficiencies of 96-97% are common
  - Efficiency impact of drive varies with speed

- Efficiency effect of the drive can be eliminated at full speed by synchronous bypass.
We’ve defined the process loads and available power, now what’s the best solution??????

#1 - Define the process loads and duty cycle

#2 - Define the power system and requirements

#3 – Determine best drive solution!
MV vs LV AC Drives:
Cost Factors of Various Configurations

- MV drive $ / HP decreases with HP
- Harmonic content can be important:
- Installed cost must be considered
Drive Design For Reliability

- Minimum parts – fewest power components, and simplest firing circuits

- No “Weak links” like marginally rated capacitors, switching devices, etc

- Conservatively rated, fully qualified components
  - Quality built in not “burn-in tested”
  - Quality tracked
Drive Output Voltage & Motor Application

• Why Pick LV [<690v] Drive & Motor?
  - LV drives are lower cost / HP than MV
  - Reduces some safety & MV training concerns
  - HP range is small enough
  - Individual preference

• Why pick MV over LV?
  - Lower cost wiring, smaller cables
  - Lower power system harmonic impact
  - High HP LV require dual winding motors
  - Individual preference

Trend: Some users select MV at >250 HP
Many users select MV over 500 HP.
Some MV vs. LV Conclusions

- For drives > 1000 HP, MV makes sense.
- For long cable runs, MV makes sense.
- For drives < 500 HP, LV makes sense.
- If low power system harmonics are required, LV filter or multi-pulse cost adders can favor MV over LV.
- In the range 500 to 1000 HP the various application & installation factors apply.
- Final choice may boil down to user preference.
We’ve selected how to power our process, now let’s control it and keep it running!!!!!!
Speed & Torque Control Requirements

- Each application is unique
  - Simple, free-standing pumps
  - Complex – e.g. sync to utility, multiple motors per drive, multiple drives on same load

- Process control – usually 4-20 Ma for speed

- Go Tachless if possible
  - Precise speed control rare with MV drives and high KW level drives
  - High load torques [>150%] may require tach
Operator Control and Communication

- Interface with larger process
  - controls for operator –
    - Simple start-stop contacts
    - More complex HMI
  - Process equipment controls – system PLC

- LAN communication of drive status if/as needed to plant PLC or DCS

- Plan for remote diagnostics capability
Drive Software Interface
Important for Drive Success

Integrated Trend Window
- Drag and drop variables
- Real time trending or archiving to buffer for historical trending
- Auto scaling
- Zoom in/out function
- Different views by using variable hide feature
- Analyze specific time with cross hair
- Frequency-based analysis of trend with fast Fourier transform function

Easy to Understand Data Structure:
- Drive parameters and variables in tree structure

Animated Block Diagrams
Electrical Success
Factors Summary ..
# Successful Drive Application: Electrical Factors & How They Relate to Success

<table>
<thead>
<tr>
<th>Success Factor</th>
<th>Continuous kW or HP</th>
<th>Drive and Motor Voltage</th>
<th>Load factors: CT, VT, CIIP, regen, non-regen</th>
<th>Torque &amp; Power Overload Requirements</th>
<th>Power system compatibility, efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum first cost, including installation</td>
<td>I</td>
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<tr>
<td>Maximum long term payback</td>
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<td>Good match to process &amp; loads.</td>
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<td>Long equipment life</td>
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<td>Easy of use for operators &amp; technicians</td>
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<td>Minimum impact on nearby equipment.</td>
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<td>Reliable hardware</td>
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<td>Easy to maintain, repair</td>
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</tbody>
</table>

*I* = Important  
*A* = Applicable
Design and Installation Factors
Relating to Successful Application

- Physical Environment of drive
- Drive Design and Reliability
- Motor Installation & Connections
- Speed & Torque Control Requirements
- Operator Control and Communication
- Design for Maintainability and Installation
Environment – MV Equipment

Equipment is designed to be installed in a relatively clean, dry environment

- **Operation**
  - 0 to 40 or 50°C with a relative humidity of 95% maximum, non-condensing.

- **Storage**
  - Equipment is generally designed for a non-operating (storage) temperature range of –25°C to 70°C.
Environment at Location

- Altitude: De-rate current rating 2-3% per 1000 ft above 3000 feet. May have to de-rate voltage for very high altitudes.

- Temperature De-rate (air cooled drive): 1 - 1.5% per degree C above base rating [usually 40C] up to max [usually 50 C].

- Drives put out heat – must be removed or vented to outside.

- High-power drives (>5000HP) are usually liquid cooled with outdoor heat exchangers.

- In the presence of corrosives or dust or water - pick appropriate enclosure. [be careful of cooling!].
Facility Readiness

• Foundation Plans
  - Pads for transformers and switchgear
  - Pads or columns for Equipment houses

• Off loading equipment
  - Cranes, fork-trucks

• Personnel protection
  - Fences, signs, railings
  - Training
Foundation Planning
You can never have too big of a crane….says the crane salesman !!!
Site Planning
Equipment House Issues

• Placing Drives in Houses – Don’t Forget:
  - Drives sometimes come in many parts –
    - “some assembly required” – wiring, plumbing, etc.
  - Auxiliary power and cooling must be wired
  - How can drive be handled? Roll, fork, etc.
  - Placement must allow access and meet codes
    - Door swing, voltage clearance, cable termination, removable panels
  - Equipment heat dissipation (sensible heat) plus humidity removal (latent heat) must be considered
  - May require redundancy in cooling system to give best up-time on system
Cables From ASD to Motors

- Drives themselves are usually tolerant of most cable types & methods.

- BUT, Cabling affects EMI radiation or motor.

- Cables > 500 meters need special attention [cable capacitance]
# Motor-Drive Cable Methods And Tradeoffs

<table>
<thead>
<tr>
<th>Ref</th>
<th>Cable Type or Method</th>
<th>Relative Performance Area</th>
<th>Usefulness by Drive Type</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Open Tray, individual conductors</td>
<td>Poor</td>
<td>Not recommended</td>
<td>Use caution by separating other conductors from inverter to motor cables by 300 MM (12 inches) or more</td>
</tr>
<tr>
<td>B</td>
<td>3-conductor unshielded with 1 ground</td>
<td>Poor</td>
<td>Not recommended</td>
<td>Acceptable</td>
</tr>
<tr>
<td>C</td>
<td>3-conductor shielded with 1 non-centered ground</td>
<td>Good</td>
<td>Marginally acceptable</td>
<td>Acceptable</td>
</tr>
<tr>
<td>D</td>
<td>3-conductor shielded with 3 symmetrical grounds, continuous extruded aluminum armor</td>
<td>Good</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

^ NPC = Neutral Point Clamped Inverter Power Circuit

- Use caution by separating other conductors from inverter to motor cables by 300 MM (12 inches) or more
- Shield should be grounded at both drive power-common and motor frame
Design & Installation Success

Factors Summary . .
## Successful Drive Application: Design & Installation Factors & Relation to Success

<table>
<thead>
<tr>
<th>SUCCESS FACTOR</th>
<th>APPLICATION FACTOR</th>
<th>Physical environment at the drive location</th>
<th>Drive Design &amp; Reliability Factors</th>
<th>Speed &amp; torque control Precision &amp; coordination</th>
<th>Operator control &amp; digital communication and drive tools</th>
<th>Drive design for installation and maintainability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum first cost, including installation</td>
<td>I</td>
<td>I</td>
<td>A</td>
<td></td>
<td></td>
<td>I</td>
</tr>
<tr>
<td>Maximum long term payback</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>A</td>
<td>A</td>
<td></td>
</tr>
<tr>
<td>Good match to process &amp; loads.</td>
<td>I</td>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Long equipment life</td>
<td>I</td>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy of use for operators &amp; technicians</td>
<td>A</td>
<td></td>
<td>I</td>
<td>I</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>Minimum impact on nearby equipment</td>
<td></td>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliable hardware</td>
<td>I</td>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Easy to maintain, repair.</td>
<td>I</td>
<td></td>
<td>I</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

I = Important
A = Applicable
Q&A
Section 3 – Specifying Adjustable Speed Drives
Section 3 - Specifying Adjustable Speed Drives

Technical Specification Review
What are the VFD standards?

There are North American and International ASD standards

The two applicable standards are IEC 61800-4 and UL-347A

Evaluate how the two standards compare.
Comparison of Standards

- UL 347A addresses only the medium voltage ASD
- IEC 61800-4 more broadly written to encompass the total medium voltage Power Drive System (PDS)
## Table of Comparison

<table>
<thead>
<tr>
<th>Standard Category</th>
<th>IEC 61800-4 Section reference</th>
<th>UL347-A Section reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scope</td>
<td>MV Adj speed AC drive systems including power conversion, control and motor</td>
<td>MV Adj speed AC drive systems including power conversion and control but excluding motors</td>
</tr>
<tr>
<td>Definitions/Glossary/Units</td>
<td>3</td>
<td>2, 3, 4</td>
</tr>
<tr>
<td>Drive system Topology</td>
<td>4</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Electrical Input/Service Conditions</td>
<td>5.1.1 Details given with level and acceptable range</td>
<td>5 Defines necessary parameters but no levels or ranges</td>
</tr>
<tr>
<td>Source Impedance</td>
<td>5.1.1.2</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Climate Conditions</td>
<td>5.1.2.1 Defines acceptable environment for drive</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Mounting/Vibration</td>
<td>5.1.2.2 defines normal vibration requirements for stationary equipment</td>
<td>Not addressed</td>
</tr>
<tr>
<td>Transportation &amp; Storage</td>
<td>5.2 and 5.3 Defines environmental, temperature and humidity ranges</td>
<td>Not addressed</td>
</tr>
</tbody>
</table>

**IEEE paper:** Comparing international standards to North American standards for Large Adjustable Speed Drives
Examples of Specifications

Example # 1

Cited many standards

- IEEE, ANSI, CSA, UL, NEMA, IEC

No Reference to specific sections

Extremely difficult to comply

- ASD vendor will take exceptions
- Provide price adder to comply
- Can prove expensive with no added value
Examples of Specifications

Example # 2

Primarily North American Standard
- NEMA, UL

Ignore IEEE standards
- IEEE 519 → Harmonic standard

Could result in harmonic nightmare

Good example of under-specifying

National Electrical Manufacturers Association (NEMA)
NEMA ICS 6 – Industrial Control and Systems Enclosures
NEMA ICS 7 – Industrial Control Systems Adjustable Speed Drives

National Fire Protection Association (NFPA)
NPFA 70 – National Electrical Code (NEC)

Underwriters Laboratory
UL 347A – Medium Voltage Power Conversion Equipment
Conclusions

• There is substantial agreement between IEC 61800-4 and UL 347A

• Specifying too many conflicting standards:
  - Can lead to confusion
  - Can result in a specification that cannot be met

• IEEE 1566 is an Adjustable Speed Drive performance standard
Standard – IEEE 1566

- Standard for Performance of Adjustable Speed AC Drives rated 375KW and Larger
  
- Created in about 2006
- New revision due out in early 2013
- Includes a set of data sheets
The challenge:

1. How did the industry standards meeting go?
2. Did you convince 83 companies to adopt standards that benefit only us while dooming the entire industry in the long run?
3. Or are you a complete failure?
4. Can I hear those choices again?
EXAMPLE OF HOW USING SPECIFICATION INCORRECTLY MAY CREATE CONFUSION:

- SPECIFICATION AND DATA SHEETS ARE INTEGRAL TO EACH OTHER

- MANY TIMES THE SPECIFICATION IS REFERRED TO BUT NO DATA SHEETS PROVIDED

- THIS RESULTS IN THE SPECIFICATION BEING MEANINGLESS AND IMPOSSIBLE TO MEET.
Example of how using this specification can increase drive cost:

- Section 6.3
  - Specifies that the VFD shall be "capable of a continuous capacity of at least 110% of full-load current.
  - Many motors will have a SF of 1.0 so they will not be able to be run at the 110% level.
  - Therefore, this excess requirement may be unnecessary and costly. The drive can be quoted at a 100% continuous rating which will be lower cost.
MV Drive Specification

- Don’t ask for more than is required
- Limit the spec to what is needed
Equipment Rating

- Include equipment rating (VT 115%, CT 150%).
- Remember -
  - Engineers refer to HP and Drive producers refer to Amps.

Example:

1. 700 hp, 1800 rpm, 4000V, VT, FLA 91A = 758 kVA
2. 700 hp, 450 rpm, 4000V, VT, FLA 124A = 1410 kVA
Enclosures

- NEMA 12 enclosures with ventilation are not true NEMA 12.
- Do include footprint encumbrances.
- Do include top/bottom cable entry requirements.
- Do include space limitations
- Do include access requirements

Example to avoid:

1. Air-cooled units shall be NEMA 12 Ventilated, or better degree of protection, with gasketed doors. All agency listed VFDs shall be Class I enclosures, NEMA 12 like construction.
Auxiliary Meters & Displays

• Do specify the style of meter.
• Don’t require duplicates of keypad displays.
• Do consider the drive location when specifying.
• Don’t over specify display meters.

Example to avoid:

1. As a minimum, the following door mounted digital indications shall be supplied: Speed demand, input current, Output current, output freq, input voltage, output voltage, 3 phase kW, kWhr, Run Time Meter
Programmable Meters & Relays

- Do specify RTD monitors with or without communication
- Don’t specify power quality meters (PQM) on input or output
- Specifying extraneous meters could cost up to $20k!

Examples to avoid:

1. The device shall be capable of displaying the frequency distribution in graphic form and shall be capable of displaying the wave form in graphic form.
2. Input and output PQM meters shall be installed to monitor and display harmonic performance and allow direct measurement of VFD system efficiency. When supplied, these meters shall be used for harmonic and efficiency performance verification.
Programmable Meters & Drives

• Motor protection relays (MPR) are required for bypass.

• Typically no MPR is required for the drive circuit.

• If required, be selective on motor protection relays for drives.
  - Be sure the specified relay will work on PWM waveform

• Don’t specify motor protection relays for the drive input.
MPRs [Motor Protection Relays] & Drives

![Diagram of MPRs and Drives]
I/O & Communication

- Specify the minimum drive I/O count.
- Don’t specify more than is needed.
- Specify either discrete I/O or LAN com.
- Use combined LAN and discrete interfaces to critical applications
- Don’t specify proprietary LANs.

Examples to avoid:
1. Sixteen (16) isolated digital inputs and sixteen (16) isolated digital outputs shall be available as standard on the drive....

Examples to include:
1. Isolated analog signal interfaces (max 2)....with LAN interface must be Profibus™, Modbus, or DeviceNet™
System & I/O

- DB5i Drive
- MPR
- Customer Field Inputs
  - Current Feedback 4-20mA
  - Speed Feedback 4-20mA
  - Motor Run
  - Drive Fault
  - MPR Fault
  - Level Alarm
  - Valve Seq Alarm

- Customer Field Outputs
  - Spd Ref 4-20mA
  - Estop
  - Drive Start/Stop
  - Bypass start/Stop
  - Drive/Bypass Select
  - Valve Position
  - Level Position

- Graphic Interface
  - Other screens and reference mnemonics available
Transformer

• For dry type, 115°C is a good trade off between 80°C and 150°C for long life and middle cost.

• For oil, 65°C rise will be lower cost but often see 55°C rise for added life.

• Don’t “design” the drive transformer.

• As a minimum, specify the number of pulses. (example 24 or better)
Spares

- Do require spares or a spares list
- Do allow alternatives & open responses.
  This allows various vendor responses.

Examples to include:

1. Manufacturers must provide a standard spare parts kit of startup and operational spares.
2. Manufacturers using power semiconductor technologies other than those listed above shall provide comparable spare parts with the equipment.
Diagnostics

• All drives perform diagnostics to manage the drive performance and protection.
• Insure diagnostics can be done remotely.

Examples to avoid:
1. Field programmable gate arrays (FPGA) shall be utilized on drive control boards to provide high speed handling of diagnostics and fault handling routines.

Example to include:
1. After commissioning is completed, the ASD supplier shall have a remote diagnostic center available for troubleshooting.
Reliability

- The higher the better!
- Do require a high MTBF.
- Require a clear statement warranty

Examples to include:
1. Mean Time Between Failures – The VFD system shall be designed for a Mean Time Between Failures (MTBF) of 140,000 hours (16 years).
2. Seller shall warrant the equipment for a period of 1 year from date of shipment for equipment to be installed and operated in North America.
MV Motors

Specifications and Cost Drivers
• Since motors are sized in HP, the higher the speed, the smaller the motor frame size and cost
• Costs increase dramatically for speeds over 3600 rpm
Utility limits – starting across the line vs VFD start

- Direct On Line [DOL] start – utility must be strong enough to allow large start amps

- VFD starts motors with NO utility surge
- Motor for VFD starting is smaller, lower $

- Designing motor for dual starting – DOL AND utility will cost $$ - but may be needed

- Inertia of load is critical for DOL start design
• Motor Cooling –
  - the more sealed up the motor, the higher the cost, ie. WP2 vs TEFC
• Motor Standards -
  - Only include applicable standards

![Graph showing cost vs. motor standards]

Cost

standard

Motor Standards

API standards, CSA, UL, Exp, etc.

For Reference Only

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Motor Accessories

• Temperature sensing –
  - RTDs in windings – include on higher HP, high value motors
  - RTDs in bearings – useful especially in sleeve bearing machines

• Junction box – larger box usually worth the expense – installation ease & costs

• Mounting [sole] plates & dowel pins
Motor Accessories

- Special paint – adds $$ and may not add value
- Current Transformers in motor – only if required
- Coupling mounting, finish bore at motor factory – reasonable cost but can impact schedule!
- Surge capacitors – incompatible with VFD
Motor Accessories

• Use “provision for” accessories such as tachometers, vibration sensors – low cost and makes unit ready for field install if needed.

• Partial discharge sensors – applicable in higher voltage motors but must balance expense with value
Thank You!

Questions?