Fundamentals of Medium Voltage Adjustable Speed Drives

Manish Vema

TMEIC
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Agenda

- Basic Electrical fundamentals & Mechanical Equivalents
- Starting strategies for large capacity motor / compressors
- What is an ASD, how does it work & its benefits for compression/pumping
- ASD application overview & installation considerations
- ASD cooling methods and standards
Applicable dimension of today’s tutorial

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Service types</td>
<td>Rotating machinery such as pumps, compressors, extruders, fans, blowers, etc.</td>
</tr>
<tr>
<td>Power Level (HP)</td>
<td>500HP – 130,000HP</td>
</tr>
<tr>
<td>Voltage range(kV)</td>
<td>Medium Voltage, &gt; 1.0 kV</td>
</tr>
</tbody>
</table>
## Electrical Equivalents

<table>
<thead>
<tr>
<th>Variable / Function</th>
<th>Electrical Element</th>
<th>Fluid Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Variable</td>
<td>Voltage ((V))</td>
<td>Pressure ((p))</td>
</tr>
<tr>
<td>Through Variable</td>
<td>Current ((I))</td>
<td>Flow Rate ((q_v))</td>
</tr>
</tbody>
</table>

### Resistor

\[
\begin{align*}
V_1 - V_2 &= I R \\
I &= \frac{V_2}{R} \\
p_1 - p_2 &= q_v R_t
\end{align*}
\]

### Capacitor

\[
\begin{align*}
i &= C \frac{dV_2}{dt} \\
q_v &= C \frac{dV_2}{dt}
\end{align*}
\]

### Inductor

\[
\begin{align*}
V_{21} &= L \frac{di}{dt} \\
p_{21} &= L \frac{dq}{dt}
\end{align*}
\]
Electrical Equivalents

<table>
<thead>
<tr>
<th>Variable / Function</th>
<th>Electrical Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Across Variable</td>
<td>Voltage (V)</td>
</tr>
<tr>
<td>Through Variable</td>
<td>Current (i)</td>
</tr>
</tbody>
</table>

Energy Consumption

\[
\text{Power} = \frac{V_1 \cdot V_2 \cdot i}{R} \quad \text{Watts}
\]

1000hp = 746kW
1hp = 746 watts
Typical Motor Starting Characteristics

![Graph showing motor starting characteristics with axes labeled as follows:
- Motor Speed - Per Unit
- Motor Current - PU
- Motor Torque - PU]
Motor starting strategies

Available Motor Starting Methods

- Direct-On-Line (DOL)
- Reduced Voltage
- Other Mech. Methods
- Adj. Speed Drives

Constant Utility Frequency (50 or 60Hz)

Adj. Freq.


Direct-on-line Starting

System Configuration

Motor Speed – Torque Curve
Reduced Voltage Starting

Method of operation (applicable to all RV starting methods):
• Motor voltage is reduced
• With reduced voltage
  • Motor current is reduced by a proportional factor
  • BUT, available motor torque is also reduced

Remember

\[(V_{\text{motor}})^2 \propto T_{\text{motor}}\]
\[V_{\text{motor}} \propto I_{\text{motor}}\]

• For Eg:
  • At 80% Motor Voltage only 64% Torque is available \((0.8 \times 0.8 = 0.64)\).
  • At 80% Motor Voltage 480% inrush amps (assume 600% Start Current).

Reduce Voltage starters DO NOT change the motor frequency
Pony Motor Starting (Mech.)

System Configuration

Motor Speed – Torque Curve

- Dependent on starting conditions, mechanical configuration
Reduced Voltage Starting

System Configuration

Motor In rush Current

Motor Full Load Current

Starting Torque

Full Load

AC Utility Line Amps

Motor In rush Current (650% FLA)

AC Utility Line Amps

Starting Torque

Motor Full Load Current

Full Load

Frequency, RPM

Torque, Amps

Torque, Amps

Frequency, RPM

Utility Voltage Up to 13.8kV

Utility Voltage Up to 13.8kV

Circuit breaker

Circuit breaker

VFD System

VFD System

Bypass contactor

Bypass contactor

Input contactor

Input contactor

Output contactor

Output contactor

Driven Equipment
(Pumps, Compressors)

Driven Equipment
(Pumps, Compressors)

Motor

Motor

MPR – Motor Protection Relay

MPR – Motor Protection Relay

System Configuration

Motor Speed – Torque Curve

Motor Speed – Torque Curve

AC Utility Voltage

Up to 13.8kV

Circuit breaker

Aux ct

MPR

MPR

Motor

Motor

Starting Torque

Motor Full Load Current

Full Load

AC Utility Line Amps

Motor In rush Current (650% FLA)

AC Utility Line Amps

Starting Torque

Motor Full Load Current

Full Load

Frequency, RPM

Torque, Amps

Torque, Amps

Frequency, RPM
General application considerations

- Evaluate load speed torque curve
- Process requirements and need for variable speed
- Based on power decide whether air or liquid cooled VFD
- Cost benefit analysis
- Review details with OEM, motor and VFD vendor
How are drives sized for starting duty?

- Virtually all VFDs have a short term (min 60 seconds) overload (OL) rating
- Common OL ratings are 110%, 115%, 150%, 200%, 300%
- Most variable loads require 110% or 115% OL rating
- Most constant torque loads require 150% OL rating
How are drives sized for starting duty?

<table>
<thead>
<tr>
<th>Loaded</th>
<th>Unloaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Per Unit Speed</td>
<td>Per Unit Torque</td>
</tr>
</tbody>
</table>

\[ \text{Difference in Torque} \approx 70\% \]

VFD expected to be sized for 30% of compressor full load rating

Actual VFD size = 25.5%

Using 115% VFD OL
Operating Sequence

1. VFD Ready
2. VFD accelerates the motor & load up to speed set-point
3. Operator requests VFD to transfer motor to the line
4. VFD accelerates the motor to the exact power grid voltage and frequency
5. The grid and VFD output: Voltage, Frequency and Phase angle are matched
6. VFD control activates the closing of the bypass contactor
7. VFD monitors the current flowing through the bypass contactor
8. VFD opens the output contactor & stops

Drive is matched in frequency, phase and volts to line and bypass contactor is closed.

MOTOR AMPS AND TORQUE ARE SMOOTH THROUGH THE WHOLE PROCESS.
Motor Sync-to-line video demonstration
Single VFD / single motor

<table>
<thead>
<tr>
<th>Simple Electrical One-line</th>
<th>Voltage Level Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility → VFD → Motor → Compressor</td>
<td>Utility = VFD, VFD = Motor</td>
</tr>
<tr>
<td>Utility &gt; VFD → VFD → Motor → Compressor</td>
<td>Utility &gt; VFD, VFD = Motor</td>
</tr>
<tr>
<td>Utility → VFD → XFMR → VFD → Motor → Compressor</td>
<td>Utility = VFD, VFD ≠ Motor</td>
</tr>
</tbody>
</table>
Redundant Starter – Representative configuration
Redundant Starter – Representative configuration
Redundant Starter – with Tie Contactor
Representation starter – with tie breakers
Representation starter – with two starting bus
Motor protection guidance - Sync-transfer systems

- Primary protection for the motor is contained within the drive itself
- No need of Motor protection relays (MPR) for motor or ASD
- MPR protection may be added in addition for:
  - Differential Current Protection
  - RTD

Considerations:
- Check if MPR can work at all freq.
- MPR protection is inhibited
  - Typically very little added benefit & Philosophical decision

- Initial protection for the motor is contained within the drive itself
- MPR’s needed for bypass circuit
- MPR operation is inhibited when motor is running on ASD
- Thermal Overload relay can also be used as inexpensive option
Procurement guidance

- VFD Vendor (minimum)
- VFD
- PLC Co-ordination
- Switchgear specification guidance

- Others
  - Switchgear
  - Motors
  - Installation, etc
How to select motor starting strategy??

Key Considerations:-
- Available Short Circuit Amps
- Allowable Voltage drop on Utility
- Motor vs. Compressor ST Capabilities
- Max allowable Motor Starts / Hour
- Torsional effect on drive train
- Cost of DOL motor vs. VFD motor
- Motor power factor as seen by utility

Does driven equipment benefit / require variable speed?

Variable Speed is required

Use fully rated VFD to start

Direct-on-line start with loaded drive

Is Direct-on-line (DOL) start possible with loaded drive?

Use fully rated VFD to start

Re-evaluate drive train to unload

Is Direct-on-line (DOL) start possible with unloaded drive?

Is reduced voltage start possible with unloaded drive?

Use smaller VFD to soft start

Direct-on-line start with unloaded drive

Reduced Voltage start with unloaded drive
What is an ASD?

**Transformation**
- Fixed Voltage
- Fixed Frequency
- 4.16kV
- 60Hz

**Utility Supply**

**Power Conversion**
- **AC TO DC**
  - OR
  - CONVERTER
  - RECTIFICATION
- **DC TO AC**
  - OR
  - INVERTER
  - SWITCHING

**Utilization**
- Load
  - Var. Voltage
  - Var. Frequency
  - 0 – 4.16kV
  - 0 – 60Hz
What is an ASD? – Other common terminology

Transformation

Power Conversion

Pulses (DFE)
Harmonic performance equivalent (AFE)

Utility Supply

AC TO DC

DC TO AC

converter rectification

energy storage

inverter switching

AC MOTOR

Load

Output Voltage Levels / Steps

Voltage

Time

(time)

(higher the better, min 5-level from 0-Peak)
What is an ASD?

- Typical air cooled ASD
- 4.16kV, 60 Hz
- ~2,200 HP
What is an ASD? A look inside

- Typical air cooled ASD
- 4.16kV, 60 Hz
- ~2,200 HP
What is an ASD?
What is an ASD?

- Large Water cooled ASD
- 7.2kV Output
- ~38,000 HP
- Outdoor Transformer and cooling apparatus not shown
Typical Range of ASDs

- **Air Cooled**
- **Water Cooled**
Historical Overview of power semiconductor devices

Time Line of Adjustable Speed Drives
Major ASD Topologies

**Voltage Source Inverters (VSI)**

- Energy storage/DC Link is **Capacitor**
- Maintains constant Voltage at DC Link
- Converter (AC/DC) is either Passive (using diodes) or Active (using PWM)

**Current Source Inverters (CSI)**

- Energy storage/DC Link is **Inductor**
- Maintains constant current at DC Link
- Converter (AC/DC) is Active (using phase control or PWM)
Major VFD Topologies

Voltage Source Inverter

Load Committed Inverter
Drive Topologies: How does it matter??

• They affect:-
  • Efficiency & reliability of the VFD
  • Line-side voltage & current performance
  • Motor-side insulation and thermal rating
  • Cable sizing
  • Auxiliary equipment needed to support the VFD
  • Safety
  • Total Cost of Ownership

• For drives with lots more parts, they must be very conservatively applied if reliability is to be achieved.

• In-service reliability is the best indicator of real reliability.
What does an ASD mean for the motor and the process?

**Motor Starting**
- Reduced inrush current
- High Torque Loads
- Close to unity power factor

**Process Control**
- Energy Savings
- Speed Control
- Torque Control
- Optimized motor size (e.g., large inertial applications)

**Motor Running**
- Power factor improvement
- Unstable voltage supply
- Quick stopping (Regeneration)
- Reduced Mech. Wear / Tear
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 of ASD on the motor and drive train
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

#1 - Define the process loads and duty cycle

#2 - Define the power system requirements

#3 – Determine best drive solution!
Keep In Mind

Drives are sized & priced based on Motor Full Load Current, Operating Envelope & driven equipment Overload

Example:
1. 7000 HP, 1800 rpm, 4000V, FLA 910A
   ASD Rating = 6300 kVA
2. 7000 HP, 450 rpm, 4000V, FLA 1240A
   ASD Rating = 8600 kVA

~37% difference in rating
Power system compatibility - Keep In Mind

• Always provide and electrical one-line diagram
• Some tips for ASD voltage level selection

<table>
<thead>
<tr>
<th>Motor Power</th>
<th>ASD Input Voltage</th>
<th>Motor Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>250HP – 5000HP</td>
<td>2.3, 4.16, 4.16, 3.3, 6.6, 10, 11, 13.8 kV</td>
<td>2.3, 4.16, 4.16, 3.3, 6.6, 10, 11 kV</td>
</tr>
<tr>
<td>5000HP – 10,000HP</td>
<td>4.16, 6.6, 10, 11, 13.8, 25, 34, 66 kV</td>
<td>Matched to ASD output voltage</td>
</tr>
<tr>
<td>&gt;10,000HP</td>
<td>10, 11, 13.8, 25, 34, 66, 110, 138 kV</td>
<td>Matched to ASD output voltage</td>
</tr>
</tbody>
</table>

Note: if ASD is used for starting ONLY, then Motor Voltage = Utility Voltage (Max 13.8kV)
Medium Voltage versus Low Voltage – Which to use?

- MV drive $ / HP decreases with HP
- Harmonic content can be important:
  - Installed cost must be considered
  - Reliability & cable cost
  - Cost of Special VFD rated cables
  - Additional cost for harmonic filters to meet IEEE 219 Requirements

Recent Trend: Some users select MV >250 HP
Many users select MV >500 HP.
## Power Line Harmonics IEEE 519-2014 Table 10.3 $I_{TDD}$ Limits

### Maximum Harmonic Current Distortion in % of $I$-Load

<table>
<thead>
<tr>
<th>Isc to I-load Ratio</th>
<th>$h &lt; 11$</th>
<th>$h = 11$ to 17</th>
<th>$h = 17$ to 23</th>
<th>$h = 23$ to 35</th>
<th>$h = 35$ &amp; up</th>
<th>TDD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 20</td>
<td>4.0</td>
<td>2.0</td>
<td>1.5</td>
<td>0.6</td>
<td>0.3</td>
<td>5.0</td>
</tr>
<tr>
<td>20 &lt; 50</td>
<td>7.0</td>
<td>3.5</td>
<td>2.5</td>
<td>1.0</td>
<td>0.5</td>
<td>8.0</td>
</tr>
<tr>
<td>50 &lt; 100</td>
<td>10.0</td>
<td>4.5</td>
<td>4.0</td>
<td>1.5</td>
<td>0.7</td>
<td>12.0</td>
</tr>
<tr>
<td>100 &lt; 1000</td>
<td>12.0</td>
<td>5.5</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>15.0</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>15.0</td>
<td>7.0</td>
<td>6.0</td>
<td>2.5</td>
<td>1.4</td>
<td>20.0</td>
</tr>
</tbody>
</table>

**Notes:** Even Harmonics limited to 25% of the harmonic level

$TDD$ = Total Demand Distortion %, based on maximum demand current at the point of common coupling [PCC].

$I_{sc}$ = Maximum Short Circuit current or kVA at the PCC

$I$-load = Fundamental frequency load current or kVA at the PCC

Specifying a min. 24-Pulse VSI VFDs or Active Front End VFD is safest option for harmonic mitigation. Best to ask for V & I harmonic spectrum
Specifying ASDs to avoid harmonics nightmare

- ASD shall be IEEE 519 – 2014 compliant and the I(TDD) shall NOT Exceed 5%

- A minimum of 24-pulse or higher input converter shall be supplied

- Harmonic mitigation shall be accomplished *without* the use of external filters (active/passive)

- Vendor shall provide the harmonic spectrum and line side voltage and current waveform of the ASD

- Active front end ASDs shall be provided with an input transformer
Line Side Performance – Voltage & Current

Voltage & Current

Voltage

Current

Harmonic Test Data

<table>
<thead>
<tr>
<th>Harmonic Number</th>
<th>Peak Input Amps</th>
<th>RMS Input Amps</th>
<th>Peak Input Volts</th>
<th>RMS Input Volts</th>
<th>Peak Output Amps</th>
<th>RMS Output Amps</th>
<th>Percent of Fund Amps</th>
<th>Percent of Fund Volts</th>
<th>RMS Output Volts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.09</td>
<td>1.197</td>
<td>15.18</td>
<td>10.732</td>
<td>2.33</td>
<td>1.646</td>
<td>0.0272%</td>
<td>10.629</td>
<td>12.540</td>
</tr>
<tr>
<td>2</td>
<td>3.62</td>
<td>1.852</td>
<td>15.50</td>
<td>11.664</td>
<td>2.80</td>
<td>1.978</td>
<td>0.7513%</td>
<td>22.136</td>
<td>25.653</td>
</tr>
<tr>
<td>3</td>
<td>2.59</td>
<td>0.417</td>
<td>5.44</td>
<td>1.727</td>
<td>3.80</td>
<td>0.210</td>
<td>0.0725%</td>
<td>7.685</td>
<td>15.544</td>
</tr>
<tr>
<td>4</td>
<td>2.10</td>
<td>1.467</td>
<td>16.51</td>
<td>14.420</td>
<td>6.29</td>
<td>2.126</td>
<td>0.653%</td>
<td>39.837</td>
<td>31.232</td>
</tr>
<tr>
<td>5</td>
<td>0.26</td>
<td>0.044</td>
<td>1.06</td>
<td>0.748</td>
<td>0.21</td>
<td>0.148</td>
<td>0.0024%</td>
<td>0.736</td>
<td>0.524</td>
</tr>
<tr>
<td>6</td>
<td>1.38</td>
<td>0.756</td>
<td>10.05</td>
<td>11.763</td>
<td>1.33</td>
<td>0.812</td>
<td>0.248%</td>
<td>9.840</td>
<td>1.288</td>
</tr>
<tr>
<td>7</td>
<td>2.13</td>
<td>0.312</td>
<td>3.38</td>
<td>0.573</td>
<td>0.20</td>
<td>0.131</td>
<td>0.0353%</td>
<td>2.523</td>
<td>1.754</td>
</tr>
<tr>
<td>8</td>
<td>0.42</td>
<td>0.010</td>
<td>0.54</td>
<td>4.552</td>
<td>0.83</td>
<td>0.580</td>
<td>0.0204%</td>
<td>2.508</td>
<td>1.774</td>
</tr>
<tr>
<td>9</td>
<td>0.36</td>
<td>0.172</td>
<td>3.48</td>
<td>1.978</td>
<td>0.20</td>
<td>0.143</td>
<td>0.0084%</td>
<td>2.508</td>
<td>1.774</td>
</tr>
<tr>
<td>10</td>
<td>0.30</td>
<td>0.008</td>
<td>0.29</td>
<td>0.200</td>
<td>0.10</td>
<td>0.084</td>
<td>0.0024%</td>
<td>0.200</td>
<td>0.100</td>
</tr>
</tbody>
</table>

Square Root, Sum of square Values

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.05</td>
<td>91.4</td>
</tr>
<tr>
<td>4.07</td>
<td>167.2</td>
</tr>
</tbody>
</table>

THD %, RMS / Fund. Amps

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Current</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.07%</td>
<td>2.34%</td>
</tr>
<tr>
<td>1.55%</td>
<td>4.12%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>INPUT</th>
<th>Volts</th>
<th>Amps</th>
<th>OUTPUT</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.05</td>
<td>91.4</td>
<td>4.07</td>
<td>167.2</td>
</tr>
</tbody>
</table>
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
Power System & Drive Efficiency

- Drive itself is typically 98% or more efficient
  - With all fans, transformers, pumps, 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.

For Air-cooled vs. Water-cooled Overall system efficiency some tips:

- 92% for air-cooled (Includes VFD and E-house HVAC)
- 96% for water-cooled (Includes VFD and E-House HVAC)
Drive Installation

- Kept clean from dust, dirt & atmospheric contaminants
- Free from damaging moisture
- Operate within their rated ambient temperature & altitude ratings
- Properly connected & integrated into a reliable electrical system
- Integrated into the overall plant facility including proper site, equipment rooms, equipment handling
- Properly stored BEFORE being installed
Enclosures for VFDs

**NEMA 1 (IP 20/21)**
- Indoor Use
- Protect from contact & falling dust
- Force ventilated
- Gasketed

**NEMA 3R (IP 23/33)**
- Outdoor use
- Protect from the elements
- Convection or passive cooling

**NEMA 12 (IP 51/52)**
- Indoor use
- Protect against dust & dripping liquids
- Non ventilated
- VFD control section typically hosted
Enclosures for VFDs

- NEMA 1 Gasketed enclosure
- NEMA 12
- NEMA 3R Enclosure
- Convection cooling
- Passive cooling
Enclosure

• NEMA 1 air-cooled VFD’s MUST be placed in climate controlled E-houses

• Special attention MUST be paid:
  • Air-cooled VFD’s in dusty environments like rubber & cement plants.
  • Water cooled might be better option >4000HP
  • Corrosive environments where H2S might be present like water / chemical plants

• Cost basis of NEMA 1: NEMA 3R = 1 : 2.5.

• Follow manufacturer guidelines for air quality control requirements
Enclosure

Filtered, pressurized room, caulking, extra filters…

Extra filters with Velcro…
Enclosure

Dust!

There are lots of ways to run from dust, but you can’t hide!

Some time later!
Storage & running

Drip Shield – just in case!

Space heaters for storage
ASD Operational / Environmental limitations

- 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: 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
- ASDs are 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.
Specifying E-houses – Key to reliability

- Good standard to use is PIP ELSSG11, Electrical power center specification

If End User / EPC / OEM is supplying the ASD building

If End User / EPC / OEM splits the scope of building and ASD

ASD Vendor to supply:
- Heat Dissipation in kW
- Max. ASD Operating Temp.
- ASD Humidity & Air Quality Req.
- Weights & Dimensions
- Air flow requirement

Outline ultimate responsibility of the entire system

ASD Vendor

Building Vendor

Heat Dissipation in kW
Max. ASD Operating Temp.
ASD Humidity & Air Quality Req.
Weights & Dimensions
Air flow requirements
Clarify responsibility ASD hook-up, plumbing, wiring, check-out
E-house requirements

- Minimum requirements for ASD E-houses are:-
  - E-House NEMA rating, Typically 3R
  - Fire/Smoke detection
    - Note: Fire suppression is usually not provided and is optional (like FM200 waterless suppression)
  - N+1 HVAC based on ASD heat loss
  - 480V, 120V Panel boards for lights, control, ASD Aux
  - Bus Ducts or cable trays
  - PE stamp, certifications (if any), access restrictions
  - Local codes. Default is NEC
- Location of E-house final destination – For E-house estimating shipping splits
Sample E-house layouts
Sample E-house layouts

Preferable for ASD vendor to take responsibility of E-house specially for large ASDs
ASD Solutions

ICB / PCR for 5000 HP VFD
Redundant ACU

ICB / PCR for Starting Duty VFD
Low Capacity ACU
Temp. Controlled E-house versus ducting air out

• Many clients ask if they can duct-out hot air from the ASD to save on HVAC building
• YES, but:-
  • Make-up air must be provided: ~4500CFM to 17,000CFM
  • Air must be scrubbed off moisture content, fine dust, hazardous gases and other contaminants
  • Air must be heated if temperature gets to sub-zero. Big air heaters required
  • ASD might need to be de-rated for hot ambient conditions
  • Warranty might not be honored.
  • Installer / End user assumes all risk
  • Usually not suitable for very low/high ambient, high humidity, dusty or areas where gas might be present.
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]
Cable Sample Recommendations

Cable Recommendations for Power Cabling Rated 2000VAC or Above.

Selection and termination of power cabling is critical to the safe and reliable operation of this system. invoice with isolated electrical noise, to avoid potential for interference. Selection and termination of cables should comply with the requirements of the National Electrical Code of the USA. It is the responsibility of the installer to ensure that local codes are followed where they conflict with these recommendations.

Selection:

Recommended for inverter output is monopole dielectric type MV-105.

Converter input does not require MV-type cable or symmetrical ground. However, shielded power cable should be used as NEC guidelines. See Figure 2: Converter Cable Insulation Level specified should be equal to or higher than 6.28.

Termination at the Motor or Transformer:

Where MV cables are used, fittings should be used to ensure that there is a 360-degree electrical connection between the aluminum shield and the junction box. Any ground conductors should be terminated to the equipment grounding lug provided for that purpose. Individual conductors should be connected using compression lug.

Termination at the Inverter or Converter:

It is necessary to remove enough cable shield and phase conductors shield to that terminal. Phase conductors can reach from the point the cable enters the equipment cabinet. To the AC connection points of the inverter or converter. Once the shield has been removed, fittings should be used to ensure that there is a 360-degree electrical connection between the aluminum shield and the cabinet ground lug. Multiple conductors should be connected to the E1 ground bus provided for that purpose. Phase conductors should be connected according to the equipment drawing. All conductors should be terminated using compression lug.

Shielded cables may be run in close proximity to other shielded power cables. As far as electrical coupling is concerned, rules regarding spacing for thermal reasons must be respected.

Note: Customer Requirement

All cables rated at or above 2000V shall use stress relief cords.
Cable Sample Recommendations

- Power Cable with armor and fittings
- Control Connections [bottom picture]
  - Segregated by voltage level
  - Segregated by signal type
All ASDs inject harmonic currents on the Motor
Harmonic Currents vary over speed range
  - Verify motor cooling can handle harmonic currents
ASDs also produce common mode voltage,
  - Verify motor insulation is suitably designed
  - Output filters might be needed with standard motor

For large applications, preferable to procure from the same Motor & ASD Vendor to avoid future issues
Motors application consideration – Retrofit Installs

If Fixed speed motor converted for variable speed operation

- ASD Vendor
- Existing Motor

- ASD Voltage/Current Waveform
- ASD Voltage/Current Harmonic Spectrum
- Need for Output filters & drive train studies
- Motor Insulation System
- Motor Cooling for speed range
- Motor Bearing
- Motor lubrication system
- Motor critical speed range avoidance
- Elimination of surge arrestors, & capacitors
- ASD to Motor Cabling / Distance
ASD Cooling Systems

- Cools the power cells & auxiliary components
- Enhances the life of the ASD
- Allows the ASD to deliver rated power in smallest footprint

However,

- Poor design can lead to pre-mature failure
- Operation beyond thermal limits → Safety hazard
- Poor choice of cooling type (Air vs. Water) can prove expensive
- Poor cooling materials (pipes, hoses, etc) can cause leaks and reduced reliability
Major Sources of Heat in an ASD System

- 1–1.5% ~ 2%
How Air Cooling Works?

- The most basic form of cooling
- Uses industrial fans
- Cool air suction from front or bottom and exhaust hot air to top or back
Advantages of Air-cooling

• Air cooled drive is simpler –
  • No pumps, filters, deionizers
  • Only need to keep the air filters clean

• HVAC knowledgeable people are easy to find

• Redundancy can be designed into both the VFD fans and HVAC.

• HVAC is required for any Medium Voltage VFD

• Typical VFD (s) rated for 40 deg C

• Can be used for starting duty ONLY for large motors
Disadvantages of Air-cooling

- Air cooled drive has a much larger footprint –
  - Will require much larger control room or E-house

- Higher noise level in control room (> 79 dB @ 1m)

- Must control level of dust in room to avoid frequent filter changes

- For higher reliability, redundancy will be required for both fans and air conditioning – driving HVAC & life cycle costs up

- HVAC power levels can be 8-9 times higher than water cooled
How liquid cooling system works?

- Major components of ASD liquid cooling
  - Pumps
  - Coolant reservoir
  - Heat Exchanger
  - De-ionizer
  - Control system

- Coolant is pumped through the ASD power cells and heat is extracted
- Hot coolant is pumped through a heat exchanger to cool the liquid
- Continuous process
Types of liquid cooled system

Closed Loop
- Liquid-to-Air Exchanger
- No plant liquid needed
- Redundancy on pumps and exchanger fans
- Expensive, need extra space, design dependent on ambient temperature

Open Loop
- Liquid-to-Liquid exchanger
- Specific plant water temp. needed
- Redundant pumps
- Less expensive and space saving
- Note: VFD loop is always closed unless a stainless steel air cooled HEX is used
Typical Pump Panel for water cooled VFDs

- Redundant Di Filter
- Redundant Pumps rated for 100% capacity
Evaluating liquid cooling systems

- Main liquid supply systems
  - All stainless steel construction
  - Tight regulation on liquid conductivity, pressure, flow & temperature
  - Factory tested at full rating
Water-cooled inverter unit

• Main Inverter/Converter Circuit

Quick Disconnect

Robust Piping
Water Cooled inverter unit

- Main Inverter/Converter Circuit
Water-cooled related specifications – Keep in mind

Avoidance of dissimilar metals in the liquid cooling systems.

Redundant temp/pressure/conductivity sensors for critical services.

Avoidance of condensation.

100% Redundant Pumps w/Auto Switchover.

Stainless Steel piping with Di-Water.

Specify liquid quality, pressure, temperature (Liquid/Liquid ONLY).
Water-cooled related specifications – Keep in mind

Clearly define the responsibilities between EU / EPC / ASD Vendor for plumbing, mounting and initial liquid fill-up
## Life Cycle Cost Comparison -- 6000 HP ASD

<table>
<thead>
<tr>
<th>Comparison Parameter</th>
<th>Liquid-Cooled Drive (4.4MW)</th>
<th>Air-Cooled Drive (4.4MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Base Cost of the ASD</td>
<td>$750,000</td>
<td>$600,000</td>
</tr>
<tr>
<td>2 HVAC Unit Costs</td>
<td>$4,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>3 HVAC Annual Operating costs ($0.04/kWh)</td>
<td>$400</td>
<td>$7,000</td>
</tr>
<tr>
<td>4 HVAC Life Cycle Cost (20 yr)</td>
<td>$18,000</td>
<td>$290,000</td>
</tr>
<tr>
<td>5 Spare Parts Cost</td>
<td>$100,000</td>
<td>$80,000</td>
</tr>
<tr>
<td>6 Annual Maintainence Cost</td>
<td>$1,300</td>
<td>$4,000</td>
</tr>
<tr>
<td>7 Training/Learning Cost</td>
<td>$5,000</td>
<td>$4,000</td>
</tr>
<tr>
<td>8 Downtime Costs (over 20 life) per year</td>
<td>$1,000</td>
<td>$5,000</td>
</tr>
<tr>
<td>9 Xfmr + Xchgr Installation cost</td>
<td>$15,000</td>
<td>$0</td>
</tr>
<tr>
<td>10 Commissioning Cost</td>
<td>$20,000</td>
<td>$10,000</td>
</tr>
<tr>
<td>11 Building cost (Per ASD sqft ONLY)</td>
<td>$8,000</td>
<td>$13,000</td>
</tr>
<tr>
<td><strong>GRAND TOTAL (Per VFD)</strong></td>
<td><strong>$922,700</strong></td>
<td><strong>$1,073,000</strong></td>
</tr>
</tbody>
</table>

Optimizing E-houses

- Proper selection of VFD cooling type: Air / Water
- Moving the transformer outdoors. Possible under limited cases. Eliminating transformer opens up other issues.
- Maintain temperatures up to 40 deg C. Less HVAC required.
- When using the VFDs for starting ONLY, HVAC can be sized for up to 25% of continuous duty application.
- No rear space requirement for TMEIC air-cooled VFDs
- Roof/Floor mounted HVACs instead of wall mounted.
ASD Cooling - Summary

- Specify cooling systems based on:
  - Motor Power
  - Environment

- Evaluate cooling systems based on:
  - Design for Safety
  - Cooling system design and redundancy
  - Data Sheets
  - Servicing intervals
  - Availability
  - Total Installed + Life cycle Cost
What are the VFD standards?

- There are North American and International ASD standards
- The two applicable standards are IEC 61800-4 and UL-347A
- These are design standards
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 <strong>and motor</strong></td>
<td>MV Adj speed AC drive systems including power conversion and control but <strong>excluding motors</strong></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 1566 – 2015 Standard

- Standard for Performance of Adjustable Speed AC Drives rated 375KW and Larger
- Created in about 2006
- Released in March 2015
- Includes a set of data sheets
Datasheets are available in Excel format and PDF –

- Three for Purchaser
- Three for Manufacturer
Additional reading material, Peer reviewed publications


Additional reading material, Peer reviewed publications


- Phares, Douglas, Joshua Karpen and Jason Shores “Applying VFDs to existing Motors,” Processing Magazine – Feb 2017
Questions?

The Curse of Knowledge