Adjustable Frequency (Inverter) Drive Ready Motors

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Agenda

1. Terminology
2. Types of Drives
3. Design Considerations for AFD “Inverter” Ready Motors
4. Implication of AFD Motor Design
5. AFD Motor Attributes
GE PC Products & Services for Customers Application Needs

Variable Speed Drive Systems

- Voltage Source Inverters (VSI) Technology MV 4000, 6000, & 7000 range: from 0.5 to 80 MW
- Current Source Inverter (LCI) Technology SD7000 range: from 5 to 100 MW

Motors

- Induction motors: from 0.1 to 80 MW
- Synchronous motors: from 4 to 100 MW
- High Speed: from 6,000 to 20,000 rpm, up to 25 MW

Generators

- For Gas & Steam Turbine: up to 70 MVA
- For Diesel & Gas Engine: up to 45 MVA

Energy Engineering Services & Repair Shop for Motors
Why use Adjustable Frequency Drives?

- More precise & optimization of process control
- Vary the speed (Hz)
- Vary the load (torque)
- Improve efficiency & power consumption of application/process (pumps, fans, compressors)
- Minimize the motor inrush current when starting
- Increase the number of starts of motor (Standard 2/1 starts)
- Reduce voltage dips of system when starting
- Improve power factor
Some terminology...

VSD (Variable Speed Drive) or ASD (Adjustable Speed Drive)
→ Can be an electrical, mechanical, hydraulic, etc. system

AFD (Adjustable Frequency Drive) =/or VFD (Variable Frequency Drive)

This presentation is about “AC” motors designed for electric drives (AFD/VFD) that change the speeds and torques by varying the frequency and voltage input to the motor.
Current Source Inverter (LCI)

Energy storage device is an inductor
Output voltage is controlled by the source bridge

Voltage Source - VSI

Energy storage device is a capacitor
Output voltage is controlled by the inverter bridge
Devices Used in Adjustable Frequency Drives

**Current Switch Devices**

- SGCT - Symmetrical Gate Commutated Thyristor
- IGCT - Integrated Gate Commutated Thyristor
- GTO - Gate Turn Off Thyristor
- SCR - Silicon Controlled Rectifier

Note: Require many more parts in firing / gate control than voltage switched devices.

**Voltage Switch Devices**

- IEGT – Injection Enhanced Gate Transistors
- IGBT – Insulated Gate Bipolar Transistors

Note: Require less parts in firing / gate control than current switched devices. Also have much lower switching losses.
Types of Drives Available to Drive Motors
Trend of Large Capacity Electric Drives

LEONARD (DCM) Thyristor

LCI (SM) Thyristor

VSI (IM, SM)

GTO

GCT/IEGT

DC drives to AC Drives (LCI)
- Easy Maintenance
- High Speed

Progress of AC Drives by VSI
- Friendly to Motor
- Friendly to Line
- High Efficiency

LCI  Load Commutated Inverter (Current source Inverter)
VSI  Voltage Source Inverter
GTO  Gate Turn-Off Thyristor
GCT  Gate Commutated Turn-off Thyristor
IGBT  Integral Gate Bi-polar Transistor
IEGT  Injection Enhanced (Hybrid IGBT)
DCM  Direct Current Motor
SM  Synchronous Motor
IM  Induction Motor
# Two Main VFD Technologies

<table>
<thead>
<tr>
<th>PRODUCT</th>
<th>TECHNOLOGY</th>
<th>POWER</th>
<th>MOTOR TYPE</th>
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<tbody>
<tr>
<td>MV7000</td>
<td>Voltage Source Inverter (VSI) – IGBT</td>
<td>250kW to 100 MW</td>
<td>Synchronous Motor</td>
</tr>
<tr>
<td></td>
<td>Current Source Inverters (CSI)</td>
<td>3 to 100 MW</td>
<td>Induction Motor</td>
</tr>
<tr>
<td>SD7000</td>
<td>Load Commutated Inverter (LCI) – Thyristors</td>
<td>3 to 100 MW</td>
<td>Synchronous Motor</td>
</tr>
</tbody>
</table>

**Diagram:**
- **LCI + Synchronous Motor**
- **VSI + Synchronous Motor**
- **VSI + Induction Motor**

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Different types of power devices

High power density, high efficiency, availability and scalability

Best trade-off between power and signal quality

Best practices from thyristor technology
- Same double-side press-pack
- Series connection (patented IGBT serialization)

High availability
- IGBT more reliable than IGCT due to simple gate driver
- IGBT Self limitation of short circuit current

High efficiency
- Press-pack IGBT have lower losses than flat pack device

Different types of power devices

- Thyristor
- GTO
- IGCT
- IGBT press pack
- IGBT flat pack
- Mosfet

Powerful enough when put in serial

Synchronous motors only

<table>
<thead>
<tr>
<th>P (MW) (Power)</th>
<th>0.0</th>
<th>0.4</th>
<th>0.8</th>
<th>1.0</th>
<th>1.0</th>
<th>2.0</th>
<th>5.0</th>
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<tbody>
<tr>
<td>50</td>
<td>100</td>
<td>1000</td>
<td>2000</td>
<td>10000</td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

Switching frequency (Hz) (Signal quality)

- Maximum current: 5 kA
- Voltage rating: 4.5 kV

High enough to ensure high quality signal
Design Considerations for AFD Motors
Design Considerations for AFD Motors

- **Application**
  Example: Pump (Centrifugal or Positive Displacement) Compressor (Centrifugal or reciprocating)

- **Type and Characteristics of Drive (VSI or CSI)**
  Example:
  - VTHD < 3% (Greater levels will effect motor size and/or may require Dv/Dt Filter)
  - Torque ripple (to high in the motor can damage coupling &/or other components. CSI can ± 7% while VSI can be < 0.5% air gap torque).
  - Voltage Stress (Multi-Levels)

- **Shaft Currents** (protect bearings by insulating both bearings or insulate one and grounding the other)
Design Considerations for AFD Motors

- **Torque** (Variable or Constant)
- Speed Range (minimum and maximum)
- Load Points (Operating Envelop – Look for outliers)
- High Inertia Load
- Motor Enclosure (Cooling)
- Environment (ambient, altitude, hazardous area, Distance motor from drive, ...)
- Frequent Starting
- Others - Specifications, Standards, Frequency and intervals between starts, acceleration time, etc...
Variable Torque Duty Drive

- Momentary Torque
- Overload Torque
- Continuous Torque
Variable Torque
(Centrifugal Fans, Pumps, & Compressors)
NEMA MG1 2011 20.4.3.1 Variable Torque Linear

Torque varies directly with speed and the horsepower or kilowatt rating for the highest rated speed shall be selected from 20.3 (power & speed table). The horsepower or kilowatt rating for each lower speed shall be determined by multiplying the horsepower or kilowatt rating at the highest speed by the square of the ratio of the lower synchronous speed to the highest synchronous speed.

How does a Variable Torque machine affect the size of the motor?
If you have a 40,000 hp motor at 3,600 rpm and want to run it at 2,000 rpm, the motor will be sized to develop
40,000 hp x (2000/3600) \(^2\) = 12,346 hp
Constant Torque
(Reciprocating Compressors and Pumps Plus Extruders)

NEMA MG1 2011 20.4.2 Constant Torque

The horsepower or kilowatt rating for the highest rated speed shall be selected from 20.3 (power & speed table). The horsepower or kilowatt rating for each lower speed shall be determined by multiplying the horsepower or kilowatt rating at the highest speed by the ratio of the lower synchronous speed to the highest synchronous speed.

How does this effect the size of the motor?
If you have a 40,000 hp motor at 3600 rpm and want to run it at 2000 rpm, the motor will be sized to develop 40,000 hp \times \left(\frac{2000}{3600}\right) = 22,222 \text{ Hp}
Constant Torque Duty Drive

![Graph showing Torque vs Speed for Overload and Continuous Torque]

- Overload Torque
- Continuous Torque
Design Considerations for AFD Motors

- **Speed Range** (minimum and maximum)
- **Load Points** (Operating Envelop – Look for outliers)
- **High Inertia Load**
- **Motor Enclosure** (Cooling)
- **Environment** (ambient, altitude, hazardous area, Distance motor from drive, ...)
- **Frequent Starting**
- **Others** - Specifications, Standards, Frequency and intervals between starts, acceleration time, etc...
IMPLICATION OF AFD ON MOTOR DESIGN
The Problem

Weak Grid / Generator Capacity

• Low starting current requirement

Difficult load

• High starting torque requirement
• High load inertia

Process Demands

• Speed Variation
The Solution – Adj. Freq. Drive

Allows soft starting of motors

• Starting current limit to 1 X
• Can provide rated torque during run up
  o Ability to start difficult loads

Accurate Speed control

• Optimise operation of driven equipment
• Efficiency gains
Motor Sizing
VFD Applications

• NEMA MG 1, Pt 31

NOTES—
1 = Torque at minimum speed based on temperature considerations and voltage boost
2 = Lowest speed of the constant torque range based on temperature considerations
3 = Base rating point at upper end of constant torque range
4 = Maximum operating speed based on constant horsepower and any limitation on rotational speed
Mixed Flow Pump Curve

Fig. 2. Typical speed-torque curve for mixed-flow pumps

Alt. Motor Rating or Overload Condition

Motor Rating (DOL)

Motor Rating (VFD)
ELECTROMAGNETIC DESIGN
Design Considerations

VFD Applications

• Not constrained by pole numbers / frequency and also not constrained by starting performance

• Eg. For 200RPM application
  o For conventional 60Hz, this would be a 36 pole design
  o With VFD we can design for 12 pole at 20Hz to give us 200RPM
Design Considerations

VFD Applications

• Cooling will be provided by external blower units, if the speed range is from 0 to rated speed or higher.

• If the speed range is restricted to 70% to 100%, then it maybe possible to have shaft mounted fans, subject to the load change.
Design Considerations
Overloads / Speed Range

Induction

• Need to ensure design has a high breakdown torque to cope with overload torques and field weakening or voltage boost

Synchronous

• The field is normally forced i.e increased to cope with overloads and increases in speed.
Insulation

Surge Magnitude

Surge Count

Peak Rise Time
Insulation – Considerations

Insulation life is affected by:

- **Voltage Stress**
- **Frequency**
- **Rise time**
- **Temperature**
- **Mechanical Stress**

**PWM Waveforms, typically:**

- **Frequency**: 2 to 5 kHz
- **Rise time**: < 1μs

Voltage peak is much greater than the rms voltage
Must design for significant over-voltages
Design Considerations

Insulation

• Increased insulation on the design, could mean a larger machine
• Increased insulation on the thermal performance
• System trade with drive with respect to filtering i.e. dv/dt, sine wave
What can happen....

• If insulation is not considered carefully, the resultant impact can be discharge, which can lead to premature failure.

• With one machine, we experienced corona discharge at a low level, when the motor was operated. It was effectively an ozone generator.

• This led to intensive sample testing to arrive at the correct insulation system for PWM drives.
What can happen ...

Harmonics

Example – LCI + solid pole
Synchronous motor

Harmonics caused increased heating of the pole shoe which led to damage of the pole shoe and the field coil.
HARMONICS
Design Considerations

Harmonics

• Assess the losses on the thermal performance i.e temperature rise

• Assess the impact of harmonics on noise and mechanical/torsional design.

• Are there resonances that could be excited by the harmonics?
## Diode Front End Pulse Technology Examples

<table>
<thead>
<tr>
<th>Pulses</th>
<th>IEEE 519 V thd % &lt;1 kv</th>
<th>Drive V thd %</th>
<th>Require Filter to Comply</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>5.0%</td>
<td>9.9%</td>
<td>Yes</td>
</tr>
<tr>
<td>24</td>
<td>5.0%</td>
<td>2.5%</td>
<td>No</td>
</tr>
<tr>
<td>36</td>
<td>5.0%</td>
<td>1.6%</td>
<td>No</td>
</tr>
</tbody>
</table>

\[ V \text{ thd} = \text{Voltage total harmonic distortion} \]
MECHANICAL
Mechanical
VFD Applications
Torque Pulsations

• Need to assess the impact of the harmonics from the drive the shaft line, in terms of the torque pulsation coming from the motor. This is analysed to ensure that torsional there are no resonances excited by the torque pulsation.

• Highest on LCI + Synchronous motor vs. PWM + Induction
Mechanical VFD Applications

Critical Speed

• Generally if going full variable speed means that the operating speed range could be from zero speed up to full speed and even a maximum speed.

• Design for a rigid rotor system, however not always possible

• Need to consider if flexible “Well Damped” rotor, can you live with a dead band or

• Damped running on a critical
Mechanical
VFD Applications

Bearing Design

• If there is continuous slow speed operation, especially below 30 RPM, then High Pressure jacking units will be required for the bearings.

• Bearing currents (insulated both bearings or one insulated and the other grounded)

• Shaft grounding
Check Resonance with Drive Supply

Motor natural frequencies

Breath Mode
1923 Hz

2 lobes
478 Hz

3 lobes

4 lobes
2591 Hz

5 lobes
4191 Hz

1025 Hz

VFD drive frequencies

950 Hz

Excite Resonance

+ 15dB(A)

Theory

Experience

Noise Guarantee:
VFD + Motor

On going ...

/+− 15% on switching frequency

Impossible to define motor resonance before experiment

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AFD MOTOR READY ATTRIBUTES
Attributes of Adjustably Frequency Drive Motor

- Specific Duty Motor
- Application, Starting, & Operating Requirements Clearly Defined Before Purchase & Design
- Motor Insulation and Thermal Capacity matches output of drive
- Bearings are both insulated or use a grounding brush
- Provisions for tachometers
Summary Product Offering – Motors & Drives

Motor & Drive combination for a wide array of applications.

Med/High Voltage Sync Motor/Generator & Drive

Med/High Voltage Motor & Drive

Low/Med Voltage Motor & Drive

KW

HP

1.0

0.746

500

373

800

597

4000

2984

15,000

11,190

100,000

74,600

Power range
NEMA Standards Publication

Application Guide For AC Adjustable Speed Drive Systems

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Rosslyn, VA 22209

Available for free download at:
http://www.nema.org/ stds/acadjustable.cfm