Technology Day

Use Motor Technology for Variable Speed
Dan Stelzner-Business Manager
Chemical, Oil and Gas Industry

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Baldor
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Motor Technologies in Variable Speed Applications
Topics for Discussion

- Motor Configurations
- Types of Variable Speed Motors
- Typical Applications
- Additional Features
The Type AS Motor in 1905

- “Type AS” (adjustable speed) Motor developed in 1905
- First customer was Lodge & Shipley
  - Machine Tool Application
  - Graphite rods for street lights
- Motor and speed control in a single package
Speed, frequency, and poles

\[ N_1 = 120 \times \frac{f}{P} \]

N1 = rotational speed of stator magnetic field in RPM (synchronous speed)

f = frequency of the stator current in Hz

P = number of motor magnetic poles
## AC MOTOR SYNCHRONOUS (NO LOAD) SPEEDS AT 50 AND 60 Hz INPUT FREQUENCIES

<table>
<thead>
<tr>
<th>POLES</th>
<th>SYNCHRONOUS RPM</th>
<th>FREQUENCY (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3000</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td>3600</td>
<td>60</td>
</tr>
<tr>
<td>4</td>
<td>1500</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>1000</td>
<td>1200</td>
</tr>
<tr>
<td>8</td>
<td>750</td>
<td>1800</td>
</tr>
<tr>
<td>10</td>
<td>600</td>
<td>1800</td>
</tr>
<tr>
<td>12</td>
<td>500</td>
<td>1200</td>
</tr>
<tr>
<td>14</td>
<td>429</td>
<td>600</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Poles</th>
<th>Speed</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>1800</td>
<td>90</td>
</tr>
<tr>
<td>6</td>
<td>1200</td>
<td>60</td>
</tr>
<tr>
<td>6</td>
<td>900</td>
<td>45</td>
</tr>
<tr>
<td>6</td>
<td>720</td>
<td>36</td>
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<td>6</td>
<td>600</td>
<td>30</td>
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<td>6</td>
<td>514</td>
<td>25.7</td>
</tr>
<tr>
<td>6</td>
<td>300</td>
<td>15</td>
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</tbody>
</table>
Typical Current & Torque Relationship for Squirrel Cage Induction Motor

<table>
<thead>
<tr>
<th>Nema Des.</th>
<th>Starting Torque</th>
<th>LR amps</th>
<th>BD torq</th>
<th>FL slip</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Normal</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Mach. Tools, fans</td>
</tr>
<tr>
<td>B</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>General Industrial</td>
</tr>
<tr>
<td>C</td>
<td>High</td>
<td>Normal</td>
<td>Normal</td>
<td>Normal</td>
<td>Conveyor</td>
</tr>
<tr>
<td>D</td>
<td>Very High</td>
<td>Low</td>
<td>na</td>
<td>High</td>
<td>Hoists</td>
</tr>
</tbody>
</table>
Rotor Slot Types

Type I  Type II  Type III  Type IV
Typical Current & Torque Relationship for Squirrel Cage Induction Motor
AC Induction Motor

Speed Torque Curve

PERCENT TORQUE

BREAKDOWN RPM

AVAILABLE LOAD
RANGE OF ADJUSTABLE FREQUENCY OPERATION

PERCENT OF SYNCHRONOUS SPEED
Speed - Torque with Constant Terminal V/Hz
AC Induction Motor
Steady State Operation

PERCENT CURRENT

PERCENT TORQUE
Variable Speed Terms

- **Base speed** – the speed point at which the motor changes from constant torque to constant power operation. This is normally the point at which the motor transitions from constant volts per hertz to constant volts.
- **Minimum Speed** – the minimum speed the motor can constantly operate.
- **Maximum Speed** – the maximum speed the motor can constantly operate.
- **Maximum Safe Speed** – the maximum speed the motor can safely operate.
Variable Speed Terms

- **Variable torque application** – load torque varies as the square of the speed and cube of the horsepower. Usually below base speed where the motor flux is constant.

- **Constant torque range** – the speed range that the rated continuous torque is constant. Usually this is the operation range below base speed where the motor flux is constant.

- **Constant power range** – the speed range that the rated continuous power is held constant. Usually a limited speed range above base speed.
Motor nameplate Horsepower is achieved at Base RPM:

\[ HP = \frac{\text{Torque} \times \text{Speed}}{5252} \]

Note that motor nameplate horsepower is only achieved at and above base speed, NOT BEFORE.
## Motor Insulation Classifications

<table>
<thead>
<tr>
<th>Insulation Class</th>
<th>Temperature Classification (C.)</th>
<th>Motor Temperature Rise (C.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>105</td>
<td>55</td>
</tr>
<tr>
<td>B</td>
<td>130</td>
<td>80</td>
</tr>
<tr>
<td>F</td>
<td>155</td>
<td>105</td>
</tr>
<tr>
<td>H</td>
<td>180</td>
<td>130</td>
</tr>
</tbody>
</table>
AC Motor Construction

- Stator Laminations
- Stator Winding Assembly
- Die-cast Rotor Assembly
- Motor Shaft
- 3 Phase Winding Circuit w/Connections T1, T2 & T3
Apply Fixed Speed Motors on AFD Power

- **Issues:**
  - Motor Design Type
  - Temperature Rise at Base Speed
  - Temperature Rise throughout speed range
  - Insulation system
  - Cable length
NEMA Design Type

- NEMA Design A or B motor are preferred for AFD operation.
- Avoid NEMA Type C and D motors, if possible.
- High frequency harmonics may cause excessive bar heating for design C and D.
NEMA Part 30 defines derating factor for motor.
- Good rule of thumb, temperature at base speed will increase one insulation class.
- Example, Class B (80°C) rise on sine wave, Class F (105°C) on inverter.
Motor Heating

- Motor losses in a constant torque application decrease with speed.
- Motor thermal capacity also decreases with speed when shaft mounted fans are used.
- The motor thermal capacity decreases more rapidly than the motor losses.
- The thermal capacity of the motor over the speed range must be considered.
- Variable torque loads are not thermally limited.
Constant Torque Range

- TEAO-BC Thermal Capacity
- Motor Losses
- TEFC Thermal Capacity

![Graph showing losses and speed relationship with different thermal capacities.](image)
Constant Torque Range

<table>
<thead>
<tr>
<th>Losses</th>
<th>Speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEAO-BC Thermal Capacity</td>
<td>Base Speed</td>
</tr>
<tr>
<td>TEFC Thermal Capacity</td>
<td></td>
</tr>
<tr>
<td>Motor Losses</td>
<td></td>
</tr>
</tbody>
</table>

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Motor Derate vs Speed

- NEMA Part 30 defines derate for standard motors.
- Curve below is for TEFC per NEMA.
- Derate varies with speed.
Induction motors have five basic loss components:

- Stator $I^2R$
- Rotor $I^2R$
- Core losses (hysteresis and eddy current losses in the laminations)
- Friction & windage
- Stray load losses
At low speeds the $I^2R$ losses exceed frame’s heat dissipation capability.
Total Losses are the same at base speed

Lower $I^2R$ losses plus higher cores losses add up to the same loss at base speed

$I^2R$ losses are lower and constant for constant load
I²R losses are below the dissipation capability of the motor at rest.

At zero speed, total losses = I²R losses.
Typical Cooling Curve of 1000:1 CT motor

Example of R/R on TEFC 1000:1

Temperature (°C)

RPM
Torque & R/R vs Speed

Motor Performance Curve

Rpm

Rated Speed

Torque FL (lb·ft) (1)

Rise/Resistance (deg C) (2)
Insulation System

- Fast switching inverters can create high peak voltages and dV/dt at the motor terminals
- Corona inception in the motor winding will eventually lead to insulation system failure
  - Phase to phase from high Vpeak
  - Turn to turn from high dV/dt
- Corona resistant wire does not eliminate corona damage
- Vpeak and dV/dt at the motor depends on more than lead length.
NEMA $dv/dt$ (risetime) definition

$$\frac{dV}{dt} = \frac{\Delta V}{\Delta t}$$
Insulation System

Corona elimination is the only way to provide long inverter duty motor life

Do this by reducing the voltage gradient in air

› In the motor
  • Control coil - coil spacing / insulation
  • Improved varnish systems to keep air away from regions of high voltage gradient

› In the installation
  • Limit peak Voltage (shorter leads or install a Terminator)
  • Reduce dV/dt (line filters)
Insulation System

Long life motor insulation requirements:

- **Eliminate corona with a system that has high corona inception voltage levels (CIV)**
  - Proper phase paper placement and varnish coverage for phase to phase.
  - Varnish penetration and coverage for turn to turn (dv/dt)

- **460 V motors capable of:**
  - Max Vpeak of 1600 Volts (NEMA 1426 Volts).
  - Max dV/dt of 10,000 V/µsec.

- **575 V motors capable of:**
  - Max Vpeak of 1850 Volts. (NEMA 1783 Volts)
  - Max dV/dt of 10,000 V/µsec.
Constant Speed Motors on ASD’s

- Use only Design A and B motors
- ASD will increase motor temperature rise.
- Cooling over the motors speed range should be considered.
- Insulation system *must* be Inverter Capable.
- Cable length from drive to motor should be considered (Lengths over 200 ft should be reviewed.)
- Purchase VS motor when possible.
Laminated Frame Background

- Concept first introduced on D-C in 1967
  - Today, third generation of square laminated frames on RPM DC

- RPM AC needed to meet high performance variable speed market needs

- Developed in 1988

- Not limited by NEMA cast iron frame “constraints"
  - Available as standard or highly modified to meet application
    - Compact & lightweight
    - Special base speeds, high speeds, custom flanges, brakes and feedback devices
Laminated Frame Construction

- Clamp laminations in a high pressure press
- Permanently riveted with eight through-studs to cast iron end rings
- Frame is now a rigid single structure
- Strength and rigidity of cast iron
RPM AC Features - Higher power density for better space utilization

- More copper & magnetic steel in square frame design
- Inactive Cast Iron Frame - Reduced Heat transfer between stator and frame
- Larger rotor diameter produces higher torque

SAME NEMA SHAFT HEIGHT
## Frame Size Comparison

<table>
<thead>
<tr>
<th>HP @1750 RPM</th>
<th>Standard TEFC</th>
<th>RPM A-C TEBC</th>
<th>RPM A-C DPFV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>180</td>
<td>180</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>215</td>
<td>180</td>
<td>180</td>
</tr>
<tr>
<td>20</td>
<td>250</td>
<td>250</td>
<td>280</td>
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<td>30</td>
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<td>180</td>
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<tr>
<td>75</td>
<td>360</td>
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<td>125</td>
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<tr>
<td>500</td>
<td>500</td>
<td>440</td>
<td>-</td>
</tr>
<tr>
<td>1000</td>
<td>580</td>
<td>-</td>
<td>440</td>
</tr>
</tbody>
</table>

### RPM A-C vs Standard NEMA TEFC

1000 Hp in 440 frame
RPM AC vs. Nema AC Motors

<table>
<thead>
<tr>
<th>HP</th>
<th>TEAO-BC</th>
<th>DPFV</th>
<th>TEFC</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>1.99</td>
<td>1.69</td>
<td>3.5</td>
</tr>
<tr>
<td>50</td>
<td>6.60</td>
<td>3.12</td>
<td>7.5</td>
</tr>
<tr>
<td>100</td>
<td>17.3</td>
<td>6.60</td>
<td>24.0</td>
</tr>
<tr>
<td>200</td>
<td>64</td>
<td>17.3</td>
<td>67</td>
</tr>
</tbody>
</table>

Inertia in lb-ft²
RPM AC vs NEMA AC Motors

- **Acceleration Torque Comparison**
  - Assume 100 Hp, 1750 base speed & acceleration time of 1 second
    - Full load torque = 300 ft-lb
  - Accel. Torque = \( \frac{W K^2 \times RPM}{308 \times \text{time}} \)
  - NEMA Frame - 136.4 lb-ft = **45.5% of Motor Torque**
  - RPM A-C Frame - 37.5 lb-ft = **12.5 % of Motor Torque**

- More torque is available to accelerate the load - maybe downsize the continuous HP and Controller rating if they are “oversized” for accel duty cycle
Motor Configurations
Motor Configurations
Motor Configurations
Motor Technologies: Induction AC Motors

- Typical Induction Motor cross section
- Speed varied by controlling Stator Voltage and Frequency
- Slip is required to produce torque so the operation is intrinsically “asynchronous”
Motor Technologies: Induction AC Motors
Motor Technologies: Permanent Magnet (PM) AC Motors (Non-Salient)

- Typical Surface Magnet PM AC Motor cross section
- Speed varied by controlling Stator Voltage and Frequency
- Often called Brushless DC Motors
- Operation has “synchronism” between the applied frequency and the rotational speed
Motor Technologies: Permanent Magnet (PM) AC Motors – Salient Pole

- Typical Interior Magnet PM AC Motor cross section

- Speed varied by controlling Stator Voltage and Frequency

- Operation has “synchronism” between the applied frequency and the rotational speed

- Hybrid blend of magnet and reluctance torque
Permanent Magnet (PM)
Motor Technologies: Synchronous Reluctance Motors

- Typical Synchronous Reluctance Motor cross section
- Speed varied by controlling Stator Voltage and Frequency
- Zero slip, synchronous operation without magnets
- Configuration as depicted here has no starting cage, so is run only on inverter power
Synchronous Reluctance
Motor Technologies: Switched Reluctance Motors

- Typical Switched Reluctance Motor cross section
- Speed varied by controlling current and frequency (current pulses)
- Currents are electronically commutated to be in proper slots with respect to the rotor position
Motor Winding Geometries

- Traditional Winding
- Concentrated Stator Windings
- Single Coil per Stator “Tooth”
VS Motor Technologies: Advantages

**DC**
- Wide constant power speed range
- Simple, accurate torque control
- Regeneration

**Induction**
- Higher speeds
- Simple construction
- Higher torque/inertia ratio
- Higher torque density
- Low cost
- No permanent excitation
- Common drive topology

**Interior PM**
- Line start capable
- Wide constant power speed range
- Higher torque density
- Very low rotor losses
- Common drive topology

**Synchr Rel**
- Common stator construction
- Virtually no rotor losses
- Low cost
- No permanent excitation
- Common drive topology

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Motor Technologies: Disadvantages

**DC**
- Lower maximum speed
- Motor cost
- Rotor losses (cooling)
- Low power density

**Induction**
- Rotor losses (cooling)
- Less constant power speed range
- Low power density

**Interior PM**
- Complex rotor
- Magnet costs
- Constant rotor excitation
- Permanent magnet temperature effects
- More complex control

**Synchr Rel**
- Complex rotor
- Lower power factor
Typical Applications

- Wide constant power speed range with a low base speed (winders)
- Simple control including regeneration
- Low voltage traction
- Cranes (Hoist, trolley, swing, boom, gantry)
- Test stands
Typical Applications – AC Induction

- Parallel motors with load-sharing or shock loads
- Simple loads such as fans, pumps, compressors (general purpose)
Typical Applications – AC Induction

- Parallel motors with load-sharing or shock loads
- Simple loads such as fans, pumps, compressors (general purpose)
- ... And every once in a while a not-so-simple one ...
Typical Applications – Salient pole (interior) PM

- Ultra high efficiency
- Ultra high power density (traction, drilling)
- EV traction (wide constant power speed range with high efficiency throughout)
Typical Applications – Synchronous Reluctance

- High power density
- Very high efficiency
- Fans, pumps, compressors (general purpose)
Motor Construction for variable speed

- Stator Insulation
- Insulated Bearings
- NEMA Part 30 vs Part 31
Inverter Duty Motors

- Stator Insulation
Inverter Duty Motors

- Bearing currents with sine wave power

**Fig 1** - Internally sourced motor bearing current paths due to alternating flux encircling the shaft.

Inverter Driven Induction Motor Bearing Current Solutions
Inverter Duty Motors

- Bearing currents with ASD power

Note: Stator winding to frame/shaft current is 10 to 60 times higher than other components

Fig. 2 - Capacitively coupled current paths in an inverter driven induction motor system
Inverter Duty Motors

- Solutions

Fig. 10 - One insulated bearing and shaft grounding brush and good high frequency grounding from motor to load and from motor to drive. This solution reduces or eliminates all bearing current components both sine wave and inverter induced.
Insulated bearings and shaft Ground
Inverter Duty Motors

- **NEMA MG1 Part 30 vs Part 31**
  - Part 30: Constant Speed Motors used on ASD’s
    - Part 30 is an application guide to be used by purchasers when applying a motor built to Part 12 or Part 20 on an ASD
  - Part 31: Definite Purpose Inverter Fed Polyphase Motors
    - Part 31 is for use by manufacturers as a guideline to design and apply a motor specifically for ASD operation, thus “Definite Purpose”. This section is also meant to be used as a guide for users just as Part 12 and Part 20 are.
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Motor Technologies: DC Motors

- Typical wound field DC motor cross section
- Speed varied by controlling Field Current and Armature Voltage
- Torque controlled simply by current
Motor Technologies: DC Motors
Motor Configurations
Motor Configurations