Selecting Motor Controls for Mining Process Torque Demands

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Selecting Motor Controls for Mining Process Torque Demands

1. Overview
2. Mine Loads' Speed and Torque Requirements
3. Basic Motor Characteristics
4. Motor Control Categories
5. Unique Applications

Conclusion
Purposes Today

• View typical mine equipment & processes with torque-speed characteristics
• Review typical motor speed and torque capabilities
• Review key motor control methods and how they affect motors and loads
• Provide comparisons and matches between motors, controls and mine loads
Controlling Speed

- Some processes work well at fixed speed – control for these motors is focused on **reliable, safe starting**.
- Some processes can benefit from variable speed - control for motors is focused on **optimum speed setting**
- Many mine processes have widely changing loads - control for motors is focused on **adapting speed to load**
Controlling Torque - Basics

• Mine process torque profiles are all over the map – some wildly swinging, some smoothly predictable.

• Torque and motor current are roughly equivalent.

• Torque Control for motors focuses on:
  ✓ Providing adequate torque for load over all operating points
  ✓ Protecting equipment and people from excess torques and currents.
Equipment Protection

A Proper Motor Control Must Work Within:

- Driven equipment **mechanical limits** [couplings, gearboxes, pressures, speeds …]
- Driven equipment **electrical limits** [voltages, currents, frequencies …]
- **Process limits** [temperatures, flows, material feed, viscosities …]
A Proper Motor Control Must:

- Recognize and work within available system voltage limits
- Be able to start and run their loads with actual voltages available after system voltage drop
- Live inside limits on utility system voltage and current harmonic distortion
Motor Characteristics & Limits

A Proper Motor Control Must:

- Recognize and work with actual motor torque, voltage and current characteristics
- Protect motors from damaging currents and voltages
- Feed voltage, frequency, and current to the connected motor to produce the required speeds and torques.
Drive & Motor Characteristics & Limits

- **Drive & Motor Characteristics**: Torque control, voltage & speed control, response to load, power system volts and amps and power factor, harmonics, motor speed range
- **Drive Limits**: maximum torque, max & min speeds, voltage levels in / out, environment
- **Drive & Motor Energy Consumption** – speed & torque matching to load & resulting electrical energy consumed by process
Load, Speed, Torque – General

- The load type, physical load, and equipment determines the curve.
- Actual conditions [physical load, uphill, sets the level.}
Constant Torque vs. Variable Torque Loads
How Torque Varies with Operating Speed
# Mining Loads & Their Categories

<table>
<thead>
<tr>
<th>Constant Torque</th>
<th>Variable Torque</th>
</tr>
</thead>
<tbody>
<tr>
<td>✓ Grinding Mills</td>
<td>✓ Variable Torque</td>
</tr>
<tr>
<td>✓ Excavators</td>
<td>✓ Pumps</td>
</tr>
<tr>
<td>✓ Hoists</td>
<td>✓ Fans</td>
</tr>
<tr>
<td>✓ Conveyors</td>
<td>✓ Rotary compressors</td>
</tr>
<tr>
<td>✓ Crushers</td>
<td></td>
</tr>
<tr>
<td>✓ Recip Compressors</td>
<td>Mixed / In between</td>
</tr>
<tr>
<td></td>
<td>✓ Slurry Pumps</td>
</tr>
<tr>
<td></td>
<td>✓ Separators</td>
</tr>
</tbody>
</table>
Load, Speed, Torque – Quadrants

- Q1, Q4 Motoring = Torque and Speed are in same direction
- Q2, Q4 Regeneration = Torque and Speed are opposite direction
Mining Load “Family Tree”
Variable Torque Loads and “In-Between” Loads
Variable Torque Loads – Pumps & Fans & Centrifugal Compressors

- Flow Rate Varies Proportionally with Speed
- Pressure & Load Torque Varies as the Square of the Speed
- Motor shaft Horsepower varies as the Cube of the Speed
Loads In-Between Constant Torque & Variable Torque

- Pump loads with solids – slurry pumps
- Fan loads with heavy concentrations of dust / solids – cyclones & separators

Slurry Pump Courtesy Weir Pumps
Typical Constant Torque Mining Loads
Mining Conveyors

Application Issues

- Starting Torque
- Belt Tension over wide weather range
- Protection of belt from over torque
- Variation in material weight
Typical Application Factors, Long Conveyor

Conveyor Mechanical Application Considerations

- Stretch, Length, Belt weight, load weight, speed
- Friction
- Tension Ratios, Dynamic Response, Programmed Torque, Load Sharing
Uphill / Level Conveyor or Mill Loading

Typical Induction Motor Char on 60 Hz power

- Breakaway Torque
- Conveyor Typical Demand

SPEED, RPM
Downhill Conveyor - Example

Downhill:
Net (-) Torque = Regeneration

Typical Induction Motor Char on 60 Hz power

Conveyor Demand
Crushers

• Breaks materials into more uniform size
• High Peak Torques!
• Potential for jamming
• Often used with controlled speed feed conveyor
Grinding Mill Types & Operation

- **Autogenous Mill**: Ore is crushed by collisions with itself.
- **Semi-Autogenous [SAG] Mill**: 10-15% Ball Charge, Ore is crushed by steel balls & collisions with itself.
- **Ball Mill**: ~30% Ball Fill, Ore is crushed by collisions with steel balls.

CONSTANT TORQUE
Selecting Motor Controls for Mining Process Torque Demands

SAG Mill Viewed From Top

Motor #1 of 2
Gearbox #1 of 2
Mill Drum
Motor #2 of 2
Selecting Motor Controls for Mining Process Torque Demands

Typical Induction Motor Speed-Torque Profile

- Locked Rotor Tq
- Mill Starting can be a challenge!!
- MILL TORQUE NEEDED!
- Peak [Breakdown] Torque, BDT
- Rated Torque
- Rated Slip RPM = Sync - Rated RPM
- Sync RPM = 120 x Freq. #Poles

Mill Starting can be a challenge!!

MILL TORQUE NEEDED!
High Pressure Grinding Roll (HPGR)

- Material is crushed between two independently driven rolls
- Hydraulic pressure is applied to maintain a specified gap
- An autogenous layer forms on the rolls to protect the roll surface
Maintaining the same roll tangential velocity is important:

- Helps maintain the autogenous layer
- Minimizes roll wear
- Increases uptime
Excavators: Draglines & Shovel Motions

- Loads are “constant torque”
- BUT loads vary widely and often wildly
- All are 4 quadrant loads – motoring and regenerating
- Require responsive controls
Excavators: Electric Blast Hole Drills

- Rotary, Propel and pull down motions
- High peak torque
- Special modes: reverse direction high torque breaking [unscrewing] of drill stem
MOTORS CHARACTERISTICS
Basic Motor Characteristics

- DC Motors still in wide use in Draglines and shovels - specialty applications
- For today we will consider only AC motors
  - Induction
  - Synchronous
  - Utility Fed – Fixed Speed
  - VFD fed – VFD Start only & Variable Speed
INDUCTION MOTORS
Selecting Motor Controls for Mining Process Torque Demands

Induction Motor Model

One Phase Model

- AC Power on stator sets up rotating field magnetic flux
- Rotor acts as shorted transformer secondary, current produces induced rotor field flux, torque results
- Rotor voltage dependent on difference between stator wave & rotor rpm = slip  **NO SLIP = NO POWER!**
- Power Factor is always lagging
Induction Motor Speed-Torque Profile

- Locked Rotor Torque (A)
- Pull Up Torque (B)
- Rated Torque (C)
- Peak Torque, BDT (D)
- Rated Slip RPM = Sync - Rated RPM (E)
- Sync RPM = 120 x Freq. / #Poles (F)

Hypothetical points:
- Point A: Locked Rotor
- Point B: Pull Up
- Point C: Peak Torque [Breakdown]
- Point D: Sync RPM
- Point E: Rated Slip RPM
- Point F: Sync RPM
Starting Induction Motors

- Motors connected across the line at start draw large currents ~ 600% rated
- Current remains high through most of start
- Torques are determined by motor design.
1. Top Curve is defined by motor and voltage available
2. Lower curve is defined by load [above is typical of a fan, centrifugal compressor, or pump].
3. Inertia of load is accelerated by difference torque.
**Motor Starting Characteristics And Starting Time**

[Exaggerated to show the process]

- **Rated torque**
- **Rated speed**
- **Synchronous speed**
- **Locked rotor torque**
- **Motor current**
- **Motor torque**
- **Break down torque**
- **Load torque**
- **Constant Torque Load 1**
- **Rated current**
- **No load current**
- **Starting time(s) = Wk^2 \times \text{Delta RPM} / (308 \times \text{Torque})**
Selecting Motor Controls for Mining Process Torque Demands

Induction Motor Starting and Thermal Curves (2C/1H)

- **Type**: ICFT
- **Form**: CHCN
- **Ins. Class**: F
- **Pole**: 4
- **Voltage (V)**: 4160
- **Rated Current**: 370 (A)
- **Output (kW)**: 2300
- **Frequency (Hz)**: 50
- **Frame No.**: 500-1800
- **Continuity**: 连续
- **J₀ = (GD²/4) (kgm²)**: 136.
- **J₁ = (GD²/4) (kgm²)**: 578.

**Starting Current**

- Starting at 100%V: Time (sec) 13, Current (A) 370
- Starting at 80%V: Time (sec) 32, Current (A) 370

**Minimum Accelerating Torque**

- Load Torque
- Torque at 100%V
- Torque at 80%V

**Minimum Thermal Margin**

- Cold to Hot
- Calculated Margin
Wound Rotor Induction Motor [WRIM] Basics
Comparing Wound Rotor Machine to Standard Induction Machine

Squirrel Cage rotor, current & torque fixed by Motor design

Wound rotor, current and torque set by external resistor or control

ONE-PHASE EQUIVALENT CIRCUIT
STANDARD INDUCTION MOTOR

ONE-PHASE EQUIVALENT CIRCUIT
WOUND ROTOR INDUCTION MOTOR
WRIM Popularity & Tradeoffs

• **Historical Popularity of WRIM vs Standard Induction Motors**
  - WRIM easier to start, & with simple equipment
  - Higher starting & running controlled torque levels
  - Lower WRIM inrush amps allows large motors to start on weak power systems
  - Fixed [full] speed application most common
  - Wound rotor machines were the earliest Electrical AC Adjustable Variable Speed Drives.
  - Operation below top speed is possible if rotor power can be taken off with resistors or sent back to power line

• **Down-side of WRIM**
  - Brushes and slip rings – wear and maintenance
  - Variable speed operation energy wastes energy if resistors are used.

**WRIM Mining Applications**
- Pumps
- Ball and Sag Mills
- Cranes
- Fans and Blowers
- Conveyors
Induction Motor Behavior with VFD

• Voltage and frequency are both adjusted very accurately – to **match** process needs
• High starting currents and stresses are eliminated, no starts per hour limit
• Utility amp starting surge eliminated and power factor is good over whole speed range
• Motor can be controlled to make **rated torque** (or more) over the whole speed range
Induction Motor Torque vs. Speed with VFD
SYNCHRONOUS MOTORS
Synchronous Motor Model - Starting

- AC Power on stator sets up rotating field magnetic flux
- For starting, rotor Amortisseur acts as shorted transformer secondary, current produces rotor flux like induction motor
- Torque produced accelerates load to near sync speed
- DC field poles shorted by “discharge” resistor during start
- Near sync speed, DC field is applied, rotor syncs to line
Typical Sync Motor Starting Curves
**Typical Torque/Speed - 4 Pole Salient Rotor**

**NOTE** – Pulsating Torque NOT produced for VFD Start

- **Pulsating Tq 100-120 Hz**
- **Pulsating Tq 0 Hz**

*Average of Induction And pulsating torque*

Best to Apply Field @ (+) Torque Peaks
Synchronous Motor Starting and Thermal Curves

- **Starting Current**
- **Minimum Accelerating Torque**
- **Pulsation torque at 100% voltage**
- **Load torque**
- **Power factor**
- **Armature current at 100% voltage**
- **Armature current at 80% voltage**

- **Maximum Thermal Margin**
- **Minimum Thermal Margin**
- **STARTING CURRENT**
- **COLD HOT**
- **RUNNING CONDITION**
- **STALLED CONDITION**

**Graphs**:
- Torque vs. Power factor [p.u.]
- Current vs. Time [s]
- Stator Current [p.u.]

**Equation**:
- SSBLD-4P-27400kW-1500min-1-CHCWXN-10000V-1616A-50Hz-1.0PF
Sync Motor Model

Effect of DC Field

• Sync Motor KVAR
  ✓ Exported with strong DC field [leading pf]
  ✓ Imported with weaker field [lagging pf]

• Increases torque capability [power output]
Salient Pole Sync Motor

After Synchronizing, With DC Field Applied

Rotor follows stator magnetic wave at sync RPM

✓ Like an elastic band
✓ Torque “stretches” band and rotor trails stator by an angle called the torque angle $\delta$

Torque Angle $\delta$

Sync Rpm = 120 x Freq. / #Poles
Sync Motors on VFDs

Starting

1. The field is energized FIRST -> AC exciter or slip ring DC power
2. The motor is synchronous as it starts to turn.
3. This allows for very high starting torque.
4. Must know rotor position with absolute encoder / or by detecting rotor position by calculation
5. Amortisseur bars (dampening windings) are important for impact or erratic loads
6. Motor starting characteristics not utilized
7. Motor may be transferred to utility by switchgear when volts, frequency & phase match
Sync Motors on VFDs

Running

Variable Speed Control by Stator Frequency

✓ Constant volts per hertz applied to maintain constant flux
✓ Can run motor at high frequencies for high RPM
✓ Control changes field current based on load to maintain unity PF (minimum current)
✓ Zero speed [near DC] is difficult for drive power devices.
✓ As in fixed speed application any load change creates load angle change and instantaneous speed change.
Induction Motors Compared With Sync Motors

**Induction Motors**

**Similarities:** Follow rotating 3-phase magnetic flux wave, RPM is dependent on frequency of source

**Differences:**
- **AC Rotor field**, induced by transformer action
- Rotor field depends on AC line voltage
- Always turns slower than sync speed by slip %
- Always runs lagging p.f.
- Torque falls ~ Volts^2

**Synchronous Motors**

- **DC Rotor Field**, ext. fed or generated by DC exciter
- Rotor field set independently
- Always turns exactly at sync speed – NO SLIP
- Can run leading or lagging p.f.
- Torque falls ~ Volts
Selecting Motor Controls for Mining Process Torque Demands

SM & IM Speed vs KW Capacity Application

- Sync motors best suited for very high outputs, low RPM
- Induction motors best suited for high speed
- Considerable overlap exists to allow best choice to be made for each application
Why Pick Sync or Induction Motor Technology?

Why Induction Motor?
- Lower first cost
- Very High RPM
- Lower complexity [no DC field supply]

Why Sync Motor?
- Higher efficiency
- Low RPM - <200 RPM
- Very high Power - > 20 MW to >100 MW
- Correct system power factor to reduce voltage drops
MOTOR & LOAD CONTROL
Starting & Controlling Connected Loads

Ground Rules and Assumptions

1. Motor available torque must ALWAYS exceed the connected load Torque requirement
   ✓ During starting
   ✓ During acceleration
   ✓ Over peaks during the duty cycle
   ✓ Considering available utility voltage including the effect of voltage drop

2. Motor must remain within its design thermal limits

3. Acceleration time of the load must be acceptable

4. Regenerated load power from the motor and its load must be controlled if required.
Selecting Motor Controls for Mining Process Torque Demands

Will It Start?

Conveyor Load: NO!

Pump Load: YES!

Torque (Nominal) = 5893 Lbf ft / 7993 Nm

K 8409S 8 POLES 1000 HP 900 RPM 4160 VOLTS 126 AMPS 1.00 SF 60 Hz

100% V

90% V

80% V

100% V Rated torque

90% V 81% Torque

80% V 64% Torque

Speed

Current

Torque
Starting Large Motors

- A “large motor” is usually considered to be 1,000 HP or larger
- Why is starting a large motor stressful?
  - Motor must be magnetized, which draws high current at low pf
  - The motor and load must be accelerated, which requires high current
  - The motor counter-EMF has to build up, so the motor initially looks like a short circuit
  - High currents cause high mechanical stresses in the motor
Factors To Consider - Motor Starting

• Inrush Amps and Duration
• Motor Limit on Number of Starts Per Hour
• Motor Connected Inertia Limits
• Load Mechanical Issues
  - Pumps, Piping & Hydraulic issues
  - Coupling Stress
• Starting Torque vs. Load Requirements
Effects of Motor Starting

- Starting such a large motor Directly On the Line (DOL) is stressful
  - On the motor due to high current (4 to 6 times rated current) and mechanical stress
  - On the load (high torques)
  - On the power system (voltage drop)
  - On other loads (power interruptions)
- What are strategies for avoiding DOL starts with large motors?
Motor Starting Power System Impact

• Processes & equipment in rest of facility may suffer from voltage drop

• Utility company restrictions
  ✓ “Being a good neighbor” – to nearby users & utility power quality guarantees to them
  ✓ Limitations of utility power delivery & transmission equipment

• Recent trends
  ✓ Remote locations on long power lines
  ✓ Many new motors applications are very high power
Starting Large Motors Intelligently

• A reduced voltage starting system may be applicable
  ✓ Reactor or autotransformer
  ✓ Reactor - Capacitor starter
  ✓ Solid state starter

• A VFD may be required
  ✓ Weak power system (relative to load)
  ✓ High inertia load
Reducing Starting Current

• Various Methods – all work by reducing motor terminal volts.

• All apply full utility frequency to the motor.

• As volts are reduced:
  ✓ Current falls directly
  ✓ Torque falls with $1/volts^2$ [e.g. $65\%V = 42\%$ torque]
  ✓ Percent voltage drop to motor falls directly
Effects of Reduced Voltage Start (1)

- 90% V
- 100% V
- 80% V

100% V Rated torque
90% V 81% Torque
80% V 64% Torque

Torque (Nominal) = 5893 Lbft / 7993 Nm

K 8409S 8 POLES 1000 HP 900 RPM 4160 VOLTS 126 AMPS 1.00 SF 60 Hz

Current
Torque
Load

SPEED - PU
0.00 0.10 0.20 0.30 0.40 0.50 0.60 0.70 0.80 0.90 1.00

POWER FACTOR
1.00 1.50 2.00 2.50 3.00

TORQUE - PU
1.00 1.50 2.00 2.50 3.00

CURRENT - PU
1.00 2.00 3.00 4.00 5.00 6.00
Effects of Reduced Voltage Start (2)

- Motor torque is proportional to voltage^2
  - Current is proportional to voltage, so voltage must be reduced to reduce current
  - Torque drops off quickly as voltage is reduced

- Selecting starting components is a tradeoff between allowable current (and bus voltage drop) and torque

- Amps jump to what they would have been at that stage if full voltage start applied at beginning

- Remaining torque at any time MUST be above load torque!
Reduced Voltage Starters – Reactor Example

- Reactor starter as shown simply places impedance between motor and power system
- After a time delay for acceleration, the reactor is shorted out, applying full volts
Selecting Motor Controls for Mining Process Torque Demands

Reactor Start

- Reactor Start
- Bypass Rx

Average motor torque, 1pu = 5835 ft-lbs
Load torque, 1pu = 5835 ft-lbs
Utility current, 1pu = 4.6 A

Prepared by: Dave Peters
Date: 25-Jul-02

200 MVA Short Circuit Capacity at the Utility Bus
T1:  5 MVA 0.11 pu Z - Reactor 3.00 mH/Phase bypassed at 0.85 pu Speed

Drawing No.: adsfasdf
Autotransformer Start

- More effective than reactor as it transforms & decreases line current while setting motor current
- Select autotransformer for sufficient voltage & torque at standstill
- Works better to limit line amps, but costs more than reactor
Solid State Starter

- Most costly of reduced voltage starters
- Same as reactor at breakaway, usually better at 70 – 80% speed
- Allows controlled acceleration
  - Can limit current
  - Accel for preset time
  - Reduces torque shock to mechanical loads
Using a VFD as a Starter

- A VFD controls frequency and voltage applied to motor
- VFDs can produce high (>100%) torque at low speeds, with better control of motor current
- A VFD may be more costly, but it can start the largest inertia loads on weak power systems
AC Drives Accelerate Load by Increasing Volts and Frequency

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

Torque vs. Freq %

Controlled, Increasing Volts and Frequency

Operational torque must be regulated to remain in the shaded near-linear zones.
More Notes on Using a VFD as a Starter

• The VFD 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 VFD
• Synchronous motors are started with field current applied, so an exciter must supply current at standstill
Typical VFD With Synchronized Bypass

M: Induction motor
Converter-Inverter: Rectifier & inverter
M1 & M1A: Input & pre-charge
PT: Voltage transformer
Drive control: With VFD & Sync Logic
L-1: Output isolation inductor
M2: Drive isolation contactor
M3: Bypass contactor
CTO: Current sensing transf.
Relay 25: Synch check relay
Starter Duty Rating

- Point C is about 3900 HP
- Point B is achieved by throttling / valving / baffling flow, and is about 1872 hp
- For start duty, VFD can be selected for B [2000 HP]
- Since PF for this motor is nearly constant from 50% to 100% load, total amps at 50% load is about 50% of full load.
- Load is synchronized to the line with the VFD, and the flow released to run at C.
Synchronized Start Sequence

Drive is made ready for operation
Drive accelerates load to running speed required by the process
User process requests load to be transferred to the utility
Drive ramp accelerates load to speed voltage and frequency & phase exactly match utility
PT feedback monitored by control.
Relay 25 verifies V & F & phase match M3 contactor is closed [point A]
Current from CTO verifies utility amps to motor and M2 opens
Inverter output switches are turned off. Control sequence repeats for each motor to be synchronized.

MOTOR AMPS AND TORQUE ARE SMOOTH THROUGH THE WHOLE PROCESS
VFD Controlled, Synchronized & Utility Fed Motors

Some Notes

• **Production Related:**
  ✓ No Limit on number or frequency of starts
  ✓ Production optimization

• **Energy Related**
  ✓ For < 100% production, slowing process can save energy
  ✓ At 100% speed, drive’s ~3.5% energy can be saved.

• **Maintenance Issues**
  ✓ Synchronized start reduces motor stress, possibly extending life of motor and drive train.
  ✓ At lower speeds provided by a VFD, mechanical wear can drop dramatically – if production allows.
Synchronous Motors vs Induction on VFDs

- Synchronous Motors always operate at a speed matching applied frequency.
- Sync motors require rotor field at standstill,
- Sync Motors can be 0.5 -2% more efficient than induction motors.
- Sync motors can improve system power factor, but only when fed directly by utility.
  - While on VFD, sync motor PF is seen only by drive, and utility sees drive PF only
  - Start mode VFDs quickly move motor to utility.
Typical VFD Synchronized Bypass System for Synchronous Motors

- VFD synchronizing system includes contactors and logic same as induction motor system.
- Synch motor field is controlled by VFD to hold unity pf.
- After connection to utility, control sync motor field is switched from the drive to an outside control.
- After connection to line, sync motor leading power factor can benefit the utility.
Tradeoffs For Multiple Motors per VFD

- **Complexity grows as number of motors grows** –
  - Switchgear and control, feedbacks and PLC
  - Complexity costs grow as the system control modes grow

- **Flexibility**
  - More modes of operation
  - Potential higher availability from 100% backup of critical VFD equipment

- **Costs** –
  - VFD system costs are affected by performance
  - VFD system costs sensitive to system configuration.
Applying ASD Synchronized Starting to Multiple Motors

Two-Motor
One ASD System

- Motor 1 or Motor 2 can be operated either across the line or on ASD.
- Connection will “bumplessly” connect to and from utility.
- Allows smooth increase in process output.
Table does not include the costs of installation nor give credit for process improvements, energy savings, or reduced maintenance.

The 100% cost = FULLY RATED 3000 HP 4160 VOLT VFD, no synchronized start.

**COLUMN A:**
- 32% cost adds one-motor synchronized starting
- Two, 3 or 4 motor synchronized cost adders are 54%, 71%, and 89% respectively

**COLUMN B** like **COLUMN A** except with a 50% rated drive for starting duty only, & max HP and torque limited to 50% of 3000 HP.

### Single ASD Synchronized Start System Shared Between Multiple Motors

<table>
<thead>
<tr>
<th>Number of Motors</th>
<th>Continuous ASD No Sync Start</th>
<th>COLUMN A Synchronized Start ASD Rated for One motor at a time at Full 3000 HP</th>
<th>COLUMN B Synchronized Start Torque Mechanically Limited to 50% of 3000 HP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>100%</td>
<td>132%</td>
<td>86%</td>
</tr>
<tr>
<td>2</td>
<td>154%</td>
<td>102%</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>171%</td>
<td>113%</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>189%</td>
<td>125%</td>
<td></td>
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</tbody>
</table>
Actual economics are sensitive to site, process, equipment ratings, manufacturer.

Economics need to consider all aspects:
- Equipment costs
- Utility supply impact and billing cost savings
- Process improvements from variable speed
- Increased equipment life and reduced maintenance.
Wound Rotor Induction Motor Review

Wound Rotor Speed-Torque

Starting Performance – Wound Rotor Induction Motor

Typical “Pump” Load

Percent of Synchronous Speed

Percent Full Load Current

Percent Full Load Torque

Amps @ 10%R

Torque @ 100%R

Amps @ 0%R

Torque @ 10%R

Full Load Torque Level

Wound Rotor Induction Motor

External Resistance

ONE-PHASE EQUIVALENT CIRCUIT
WOUND ROTOR INDUCTION MOTOR

3-phase stator connections

3-phase rotor connections

ROTOR

SLIPRINGS

STATOR

LINE-NEUTRAL VOLTAGE

WRIM Control Summary

• To Control inrush amps and set torque: CONTROL ROTOR AMPS.
• Rotor volts start high
• Rotor volts x rotor amps = rotor output power
• As speed increases, rotor volts decrease
• Therefore:
  ✓ High Torque at start = high rotor amps
  ✓ High volts and high amps = high power out from rotor
  ✓ As speed increases, rotor power at a particular torque decreases.
Applying & Controlling New Wound Rotor Motors

• For full, fixed-speed
  ✓ Resistor / liquid rheostat start
  ✓ Starting equipment matches load inertia and torque

• For Variable Speed ~60 or 70% to Top Speed
  ✓ Start with Resistor / liquid rheostat start
  ✓ Control rotor power with resistors – waste energy
  ✓ Control & recover rotor power with thyristor drive – poor PF, harmonics – OLD TECHNOLOGY
  ✓ Control & recover rotor power with LV PWM drive
Starting & Control Methods for WRIM

WRIM Full Speed Options

✓ Stator DIRECT ON LINE, with rings shorted – acts like standard induction motor, torque determined by motor design [VERY HIGH INRUSH!].

✓ Stator DIRECT ON LINE with stepped resistor rotor current control to top speed, then short rings.

✓ Stator DIRECT ON LINE with liquid rheostat for rotor current control to top speed, then short rings.
Selecting Motor Controls
for Mining Process Torque Demands

Example Liquid Resistor Rotor Control

Provides smooth control of torque as resistance is gradually removed from rotor circuit.

Not very fast response – tank has to fill and empty to follow a changing load.

Liquid Rheostat

Courtesy Eletele
WRIM PWM Slip Power Recovery

Simplified Diagram

- Utility Supply
- Three-phase Motor Stator
- Wound Rotor Induction Motor
- PWM Rotor Converter
- PWM Source Converter
- Utility Interface Transformer
- Power Flow at normal speeds
- Recovered power
- Brushes and Slip Rings
- Rheostat
- Starting duty rated
- TMdrive-10SPR
Example: Coordinating Grinder Load with 2 VFDs

- Grinder with independent rollers
- Initially no connection between rollers
- After material is entered, material itself “connects” the rolls.
- Goal: Share load, and minimize roller wear.
2 Drives on Same Load

- Give same speed reference to both drives.
- Drive 2 set to match torque of Drive 1
- When unloaded, drive 2 will speed up to max of 5% over speed ref
- Process control, min maintenance, smallest motors result from system
Review of Areas to Consider

- Loads – Select Constant Torque, Variable Torque, peak torques
- Consider System voltages
- Motor selection – OEM or site, with specifics such as speed-torque curves, inrush
- Controls – Operating mode Starting, Running, fixed speed, variable speed

A Chart might be helpful…
### Chart Relating Controls to Load Type

<table>
<thead>
<tr>
<th>Load Type / Application</th>
<th>Special Load Characteristics</th>
<th>Control Requirement</th>
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</thead>
<tbody>
<tr>
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<td>High Starting Torque</td>
<td>Load Power</td>
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<td></td>
<td>Regeneration</td>
<td>Speed Option</td>
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<td>Conveyors</td>
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<td>Uphill, Level</td>
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<td>Downhill</td>
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<tr>
<td>Crushers, Vertical Mills</td>
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<td>Grinding Mills</td>
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<td>SAG Mill</td>
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<tr>
<td>Ball, Rod Mill</td>
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<tr>
<td>High Pressure Mills</td>
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<td>Draglines</td>
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<td>Slurry Pumps</td>
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<tr>
<td>Separators / Cyclones</td>
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</tbody>
</table>

#### Legend of Applicable Controls

1. Full Voltage Starter [Contactor, Breaker]
2. Reactor Reduced Voltage Starter
3. AutoTrans Reduced Voltage Starter
4. Solid-State Reduced Voltage Starters
5. VFD - Full HP rated 110% OL
6. VFD - Full HP rated 150% OL
7. VFD - Full HP rated >150% OL
8. VFD - Start Duty Rated
9. WR Motor - Full Speed
10. WR Motor - SPR PWM Drive

#### Special Note / Suffix

- C: Clutch May be required
- R: VFD with Regen Converter
- PR: Starting mode Pressure Relief
- NR: Not Recommended
Thanks!