Motor Starting
Dynamic Acceleration
Why to Do MS Studies?

- Ensure that motor will start with voltage drop
  - If $T_{st} < T_{load}$ at $s=1$, then motor will not start
  - If $T_m = T_{load}$ at $s < s_r$, motor can not reach rated speed
  - Torque varies as $(voltage)^2$

- Ensure that voltage drop will not disrupt other loads
  - Utility bus voltage >95%
    - 3% Sag represents a point when light flicker becomes visible
    - 5% Sag represents a point when light flicker becomes irritating
  - MCC bus voltage >80%
  - Generation bus voltage > 93%
Why to Do MS Studies?

• Ensure motor feeders sized adequately
  (Assuming 100% voltage at Switchboard or MCC)
  • LV cable voltage drop at starting < 20%
  • LV cable voltage drop when running at full-load < 5%
  • HV cable voltage drop at starting < 15%
  • HV cable voltage drop when running at full-load < 3%

• Maximum motor size that can be started across the line
  • Motor kW < 1/6 kW rating of generator (islanded)
  • For 6 MW of islanded generation, largest motor size < 1 MW
Motor Sizing

• Positive Displacement Pumps / Rotary Pumps

\[ BHP = \frac{p \times Q}{\eta \times 1714}. \]

- \( p \) = Pressure in psi
- \( Q \) = fluid flow in gpm
- \( \eta \) = efficiency

• Centrifugal Pumps

\[ H = \frac{p \times 2.31}{SG} \text{ (feet of water)} \]

\[ BHP = \frac{\left( \frac{H \times SG}{2.31} \right) \times Q}{\eta \times 1714} = \frac{H \times Q \times SG}{\eta \times 3960}. \]

- \( H \) = fluid head in feet
Motor Types

- Synchronous
  - Salient Pole
  - Round Rotor

- Induction
  - Wound Rotor (slip-ring)
    - Single Cage CKT Model
  - Squirrel Cage (brushless)
    - Double Cage CKT Model
Induction Motor Advantages

• Squirrel Cage
  • Slightly higher efficiency and power factor
  • Explosive proof

• Wound Rotor
  • Higher starting torque
  • Lower starting current
  • Speed varied by using external resistances
Typical Rotor Construction

- Rotor slots are not parallel to the shaft but skewed
Wound Rotor

Schematic

Isometric View
Operation of Induction Motor

- AC applied to stator winding
  - Creates a rotating stator magnetic field in air gap
  - Field induces currents (voltages) in rotor
  - Rotor currents create rotor magnetic field in air gap
  - Torque is produced by interaction of air gap fields
Slip Frequency

• Slip represents the inability of the rotor to keep up with the stator magnetic field

• Slip frequency

\[ S = \frac{\omega_s - \omega_n}{\omega_s} \quad \text{where } \omega_s = 120f/P \]
\[ \omega_n = \text{mech speed} \]
Static Start - Example

Base = 100 MVA

200 MVA

Zsys

5 MVA

11% Z

Zxfmr

Base MVA

System Short Circuit MVA

100
200

Base MVA * Xfrm Z

100 * 0.11

Xfrm MVA (OA)

5

Base MVA * X"d

Motor MVA

100 * 0.17

X"d = 17%

4.16 kV

126 amps

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Static Start - Example

Base = 100 MVA

Zsys = 0.5 pu

Zxfmr = 2.2 pu

Vsys = \frac{Zxfmr + Z\text{ mot}}{Zsys + Zxfmr + Z\text{ mot}}

Vsys = \frac{2.2 + 18.7}{0.5 + 2.2 + 18.7}

Vsys = 0.97 pu

Z\text{ mot} = 18.7 pu

Vmot = \frac{Z\text{ mot}}{Zsys + Zxfmr + Z\text{ mot}}

Vmot = \frac{18.7}{0.5 + 2.2 + 18.7}

Vmot = 0.87 pu
Service Factor

Horsepower versus temperature for a constant speed AC motor with Class B insulation in an open enclosure.
# Inrush Current

\[
I_{\text{inrush}} = \frac{\text{code letter value} \times \text{horsepower} \times 577}{\text{voltage}}
\]

<table>
<thead>
<tr>
<th>CODE LETTER ON MOTOR NAMEPLATE</th>
<th>KVA PER HORSEPOWER WITH LOCKED ROTOR MINIMUM</th>
<th>KVA PER HORSEPOWER WITH LOCKED ROTOR MEAN VALUE</th>
<th>KVA PER HORSEPOWER WITH LOCKED ROTOR MAXIMUM</th>
</tr>
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<tbody>
<tr>
<td>A</td>
<td>0</td>
<td>1.57</td>
<td>3.14</td>
</tr>
<tr>
<td>B</td>
<td>3.15</td>
<td>3.345</td>
<td>3.54</td>
</tr>
<tr>
<td>C</td>
<td>3.55</td>
<td>3.77</td>
<td>3.99</td>
</tr>
<tr>
<td>D</td>
<td>4</td>
<td>4.245</td>
<td>4.49</td>
</tr>
<tr>
<td>E</td>
<td>4.5</td>
<td>4.745</td>
<td>4.99</td>
</tr>
<tr>
<td>F</td>
<td>5</td>
<td>5.295</td>
<td>5.59</td>
</tr>
<tr>
<td>G</td>
<td>5.6</td>
<td>5.945</td>
<td>6.29</td>
</tr>
<tr>
<td>H</td>
<td>6.3</td>
<td>6.695</td>
<td>7.09</td>
</tr>
<tr>
<td>J</td>
<td>7.1</td>
<td>7.545</td>
<td>7.99</td>
</tr>
<tr>
<td>K</td>
<td>8</td>
<td>8.495</td>
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<td>10.595</td>
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<td>11.845</td>
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<tr>
<td>P</td>
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<td>16</td>
<td>16.995</td>
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</tr>
<tr>
<td>T</td>
<td>18</td>
<td>18.995</td>
<td>19.99</td>
</tr>
<tr>
<td>U</td>
<td>20</td>
<td>29.2</td>
<td>22.39</td>
</tr>
<tr>
<td>V</td>
<td>22.4</td>
<td></td>
<td>NO LIMIT</td>
</tr>
</tbody>
</table>

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Motor Torque – Speed Curve
Resistance / Reactance

- Torque Slip Curve is changed by altering resistance / reactance of rotor bars.
- Resistance $\uparrow$ by $\downarrow$ cross sectional area or using higher resistivity material like brass.
- Reactance $\uparrow$ by placing conductor deeper in the rotor cylinder or by closing the slot at the air gap.
Rotor Bar Resistance $\uparrow$

- Increase Starting Torque
- Lower Starting Current
- Lower Full Load Speed
- Lower Efficiency
- No Effect on Breakdown Torque
Rotor Bar Reactance ↑

- Lower Starting Torque
- Lower Starting Current
- Lower Breakdown Torque
- No effect on Full Load Conditions
Motor Torque Curves

Speed-Torque Curves of NEMA A, B, C, D and F motors.
Rotor Bar Design

- Cross section Large (low resistance) and positioned deep in the rotor (high reactance). (Starting Torque is normal and starting current is low).

- Double Deck with small conductor of high resistance. During starting, most current flows through the upper deck due to high reactance of lower deck. (Starting Torque is high and starting current is low).
Rotor Bar Design

• Bars are made of Brass or similar high resistance material. Bars are close to surface to reduce leakage reactance. (Starting torque is high and starting current is low).
Load Torque – ID Fan

Typical speed-torque curve for induced-draft fans
Load Torque – FD Fan

Typical speed-torque curve for ventilating and forced-draft fans
Load Torque – C. Pump

Typical speed-torque curve for centrifugal pumps
Double Cage Motor

Combined double cage characteristic

Torque

Inner cage

Outer cage

100% $n_s$

0

Speed

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Motor Full Load Torque

- For example, 30 HP 1765 RPM Motor

\[
HP = \frac{T \times RPM}{5250}
\]

\[
T = \frac{HP \times 5250}{RPM}
\]

\[
T = \frac{30 \times 5250}{1765}
\]

\[T = 89.2 \text{ Lb-Ft}\]
Motor Efficiency

- $kW\text{ Saved} = HP \times 0.746 \times (1/\text{Old} - 1/\text{New})$
- $\$\text{ Savings} = \text{kW Saved} \times \text{Hrs/Year} \times \$/\text{kWh}$
Acceleration Torque

- Greater Acceleration Torque means higher inertia that can be handled by the motor without approaching thermal limits.
Acceleration Torque

\[ T_{\text{max}} = \text{Breakdown torque} \]
\[ T_R = \text{Rated torque} \]
\[ T_{\text{st}} = \text{Starting torque} \]
\[ S_{T_{\text{max}}} = \text{Slip at } T_{\text{max}} \]
\[ S_R = \text{Rated slip} \]

\[ S_{T_{\text{max}}} = 2.5 \text{ to } 3.0 \text{ times the rated slip (rule-of-thumb)} \]
\[ T_{\text{load}} \propto w_m^2 \quad ( T_{\text{load}} = k_1 + k_2 w_m^n, \text{ } n \text{ ranges from } 2 \text{ to } 3 ) \]
\[ HP \propto w_m^3 \]
Operating Range

- Motor, Generator, or Brake
Rated Conditions

- Constant Power

\[ P = T_m w_m \]

As \( V_t \) (terminal voltage) changes from 0.8 to 1.1 pu, \( w_m \) changes by a very small amount. Therefore, \( P \) is approx. constant since \( T_m (\propto w_m^2) \) is approx. constant.
Starting Conditions

- Constant Impedance

\[ kVA_{LR} = \text{Locked-rotor kVA at rated voltage} = \eta \, \text{HP} \]

\[ \eta \equiv \text{Code letter factor} \equiv \frac{kVA_{LR}}{\text{HP}} \]

\[ Z_{ST} = \left( \frac{kVA_B}{kVA_{LR}} \right) \left( \frac{kV_R}{kV_B} \right)^2 \]

where

\[ kV_R = \text{Rated voltage}, \quad kV_B = \text{Base voltage}, \quad kVA_B = \text{Base power} \]
Voltage Variation

- Torque is proportional to $V^2$
- Current is proportional to $V$
Frequency Variation

- As frequency decreases, peak torque shifts toward lower speed as synchronous speed decreases.
- As frequency decrease, current increases due reduced impedance.

Adjustable speed drive: Typical speed range for variable torque loads such as pumps and fans is 3:1, maximum is 8:1 (7.5 to 60 Hz)
Number of Poles Variation

- As Pole number increases, peak torque shifts toward lower speed as synchronous speed decreases.
Rotor Z Variation

- Increasing rotor Z will shift peak torque towards lower speed.
Modeling of Elements

- Switching motors – Zlr, circuit model, or characteristic model
- Synch generator - constant voltage behind X’d
- Utility - constant voltage behind X”d
- Branches – Same as in Load Flow
- Non-switching Load – Same as Load flow
- All elements must be initially energized, including motors to start
Motor Modeling

1. Operating Motor
   - Constant KVA Load

2. Starting Motor
   - During Acceleration – Constant Impedance
   - Locked-Rotor Impedance
   - Circuit Models
     Characteristic Curves
     After Acceleration – Constant KVA Load
Locked-Rotor Impedance

- \( Z_{LR} = R_{LR} + j X_{LR} \quad (10 - 25 \%) \)

- \( P_{FLR} \) is much lower than operating PD. Approximate starting PF of typical squirrel cage induction motor:
Circuit Model I

• Single Cage Rotor
  – “Single1” – constant rotor resistance and reactance
Circuit Model II

- Single Cage Rotor
  - “Single2” - deep bar effect, rotor resistance and reactance vary with speed [Xm is removed]
Circuit Model III

- Double Cage Rotor
  - “DB1” – integrated rotor cages
Circuit Model IV

- Double Cage Rotor
  - “DB2” – independent rotor cages
Characteristic Model

- Motor Torque, I, and PF as function of Slip
  - Static Model
Calculation Methods I

• Static Motor Starting
  – Time domain using static model
  – Switching motors modeled as ZI during starting and constant kVA load after starting
  – Run load flow when any change in system

• Dynamic Motor Starting
  – Time domain using dynamic model and inertia model
  – Dynamic model used for the entire simulation
  – Requires motor and load dynamic (characteristic) model
Calculation Methods II

Motor Acceleration (dynamic model)

- $I_{lr} =$ Locked Rotor Current (%)
- $I_s =$ Starting Load (%)
- $I_f =$ Final Load (%)

Motor Starting (static model)

- $t_{acc} =$ Acceleration Time (dynamically calculated)
- $t_{st} =$ Starting Time (fixed)
- $t_s =$ Beginning of Load Change after acceleration
- $t_f =$ End time for motor Load Change
Static versus Dynamic

• Use Static Model When
  – Concerned with effect of motor starting on other loads
  – Missing dynamic motor information

• Use Dynamic Model When
  – Concerned with actual acceleration time
  – Concerned if motor will actually start
MS Simulation Features

• Start/Stop induction/synchronous motors
• Switching on/off static load at specified loading category
• Simulate MOV opening/closing operations
• Change grid or generator operating category
• Simulate transformer LTC operation
• Simulate global load transition
• Simulate various types of starting devices
• Simulate load ramping after motor acceleration
Automatic Alert

- Starting motor terminal V
- Motor acceleration failure
- Motor thermal damage
- Generator rating
- Generator engine continuous & peak rating
- Bus voltage
  - Starting motor bus
  - Grid/generator bus
  - HV, MV, and LV bus
- User definable minimum time span

![Motor Starting Study Case](image-url)
Starting Devices Types

- Auto-Transformer
- Stator Resistor
- Stator Reactor
- Capacitor at Bus
- Capacitor at Motor Terminal
- Rotor External Resistor
- Rotor External Reactor
- Y/D Winding
- Partial Wing
- Soft Starter
- Stator Current Limit
  - Stator Current Control
  - Voltage Control
  - Torque Control
## Starting Device

- Comparison of starting conditions

<table>
<thead>
<tr>
<th>Type of starter</th>
<th>Motor voltage</th>
<th>Starting torque full-voltage starting torque</th>
<th>Line current full-voltage starting current</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-voltage starter</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Autotransformer:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80 per cent tap</td>
<td>0.80</td>
<td>0.64</td>
<td>0.68</td>
</tr>
<tr>
<td>65 per cent tap</td>
<td>0.65</td>
<td>0.42</td>
<td>0.46</td>
</tr>
<tr>
<td>50 per cent tap</td>
<td>0.50</td>
<td>0.25</td>
<td>0.30</td>
</tr>
<tr>
<td>Resistor starter, single step (adjusted for motor voltage to be 80 per cent of line voltage)</td>
<td>0.80</td>
<td>0.64</td>
<td>0.80</td>
</tr>
<tr>
<td>Reactor:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>50 per cent tap</td>
<td>0.50</td>
<td>0.25</td>
<td>0.50</td>
</tr>
<tr>
<td>45 per cent tap</td>
<td>0.45</td>
<td>0.20</td>
<td>0.45</td>
</tr>
<tr>
<td>37.5 per cent tap</td>
<td>0.375</td>
<td>0.14</td>
<td>0.375</td>
</tr>
<tr>
<td>Part-winding starter (low-speed motors only):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>75 per cent winding</td>
<td>1.0</td>
<td>0.75</td>
<td>0.75</td>
</tr>
<tr>
<td>50 per cent winding</td>
<td>1.0</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

* The settings given are the more common for each type.
• C4 and C3 closed initially
• C4 opened, C2 is closed with C3 still closed. Finally C3 is open
Starting Device – AutoXFMR

• Autotransformer
Starting Device – YD Start

- During Y connection $V_s = V_L / \sqrt{3}$
- Phase current $I_y = I_d / \sqrt{3}$ and 3 to 1 reduction in torque
Starting Device – Rotor R

Diagram showing the starting device with main power switch, variable resistor, and relations between torque and slip.
Starting Device – Stator R

• Resistor

\[ \text{PF}_{ST} \text{ (with resistor)} = \sqrt{1 - \left[ \text{pu tap setting} \right]^2 \times \left[ 1 - \left( \text{PF}_{ST \text{ without resistor}} \right)^2 \right]} \]

\[ = \sqrt{1 - (0.5)^2 \times \left[ 1 - \left( \text{PF}_{ST} \right)^2 \right]} \]
Starting Device Stator X

• Reactor

\[
P_{F_{ST}} (\text{with reactor}) = (\text{pu tap setting}) \times P_{F_{ST}} (\text{without reactor})
\]
Transformer LTC Modeling

- LTC operations can be simulated in motor starting studies
- Use global or individual Tit and Tot
MOV Modeling I

- Represented as an impedance load during operation
  - Each stage has own impedance based on I, pf, Vr
  - User specifies duration and load current for each stage

- Operation type depends on MOV status
  - Open status → closing operation
  - Close status → opening operation
MOV Modeling II

- Five stages of operation
  - **Opening**
    - Acceleration
    - No load
    - Unseating
    - Travel
    - Stall
  - **Closing**
    - Acceleration
    - No load
    - Travel
    - Seating
    - Stall

- Without hammer blow \(\rightarrow\) Skip “No Load” period
- With a micro switch \(\rightarrow\) Skip “Stall” period
- Operating stage time extended if \(V_{mtr} < V_{limit}\)
MOV Closing

- With Hammer Blow- MOV Closing
MOV Opening

- With Hammer Blow - MOV Opening
MOV Voltage Limit

• Effect of Voltage Limit Violation