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Motor protection fundamentals
We will begin at 2:00 pm EST, May 20, 2014
Bob is a Regional Technical Manager with ABB’s Substation Automation and Protection Division, providing technical support to customers throughout the South Central United States. Bob is a senior member of IEEE and has authored and presented several papers on power system protection at a variety of technical conferences throughout the United States. He is a Registered Professional Engineer in the states of Pennsylvania and Texas.

Bob graduated from Purdue University and joined Westinghouse Electric Corp. After receiving a Masters degree in Electrical Engineering from Carnegie Mellon University, Bob was a Systems Analysis Engineer responsible for software designed to automate system-wide coordination. He then transferred to Kansas City where he assumed the role of District Engineer and eventually moved to the Houston area where he currently resides.
Learning objectives

- In this webinar you’ll learn:
  - Basic motor electrical operation
  - How the different types of motors can be protected from potential hazards such as thermal damage, start-up, faults in the windings, etc.
Introduction

- There are many different types and sizes of motors and a variety of applications.
- Industry uses 50% of all electricity, of which 65% for electric motors…nearly one third of all electricity is used by motors.
Introduction

- A rotating magnetic field, which rotates at constant synchronous speed \((120*f)/p\), can be generated by means of a group of polyphase windings displaced in space over an armature, if the currents flowing through the windings are also displaced in time.
Induction motors
General observations

- Stator (armature)
  - Single and three-phase
  - Windings connected to power system

- Rotor
  - Winding not connected to power system
    - Wound rotor, conductors are insulated and brought out through slip rings for connection to starting or control devices
    - Squirrel-cage, conductors are connected together on the rotor ends (not brought out)
Induction motors
General observations

- Energy is transferred to rotor through magnetic induction:
  - The induction motor is a double excitation machine because it has an AC voltage applied to its stator winding and to its winding rotor
  - The voltage applied to the stator winding is an excitation voltage, usually of constant voltage and constant frequency
  - The voltage applied to the rotor winding is a variable frequency induced voltage, arising as a result of the relative speed of the rotor with respect to the synchronous speed
Synchronous motors
General observations

- Stator (armature)
  - Single and three-phase
  - Windings connected to power system
- Rotor
  - Windings are connected to dc source
    - Poles (usually salient or “sticking out”)
    - Poles are wound with many turns (field windings) and dc current circulated to create alternately north and south magnetic flux poles
  - Dc excitation
    - Brush rigging and slip rings for external excitation
    - Brushless – ac exciter, rectifier and control mounted on rotor
    - Not applied until at synchronous speed
Synchronous motors
General observations

- Damper windings
  - Similar to induction motor (shorted on ends)
  - Needed to start synchronous motor
Induction motors

Construction

- The squirrel cage induction motor is the workhorse of modern industry and is found in virtually every phase of manufacturing.
- The rotor is a cylinder mounted on a shaft. Internally, it contains longitudinal conductive bars (usually made of aluminum or copper) set into grooves and connected together at both ends by shorting rings forming a cage-like shape. The name is derived from the similarity between this rings-and-bars winding and a squirrel cage.
- The bars are not always parallel to the axial length of the rotor but can be arranged at an angle to prevent electromagnetic hum and to produce a more uniform torque.
Induction motors
General observations

Squirrel cage induction motor qualities:
- Simple and rugged design
- Low-cost
- Low maintenance
- Slightly lower efficiency compared to synchronous motors
A wound rotor induction motor has a stator like the squirrel cage induction motor, but a rotor with insulated windings brought out via slip rings and brushes. However, no power is applied to the slip rings. Their sole purpose is to allow resistance to be placed in series with the rotor windings while starting. Squirrel cage induction motors draw 500% to over 1000% of full load current (FLC) during starting. While this is not a severe problem for small motors, it is for large (10's of kW) motors. Placing resistance in series with the rotor windings not only decreases start current, locked rotor current (LRC), but also increases the starting torque and locked rotor torque.
Wound rotor induction motor qualities:

- Excellent starting torque for high inertia loads
- Low starting current compared to squirrel cage induction motor
- Speed control. Speed is resistance variable over 50% to 100% full speed.
- Higher maintenance of brushes and slip rings compared to squirrel cage motor
Induction motors

- 1. Windings
- 2. Slip rings
- 3. Brushes
- 4. Connections for external resistors
Induction motors

Starting Characteristic
Induction motors, at rest, appear just like a short circuited transformer and if connected to the full supply voltage, draw a very high current known as the "Locked Rotor Current." They also produce torque which is known as the "Locked Rotor Torque."
Induction motors

STARTING CHARACTERISTIC
The starting current of a motor with a fixed voltage will drop very slowly as the motor accelerates and will only begin to fall significantly when the motor has reached at least 80% of the full speed.

Sample Load Torque Curve

- Full Voltage Stator Current
- Full Voltage Starting Torque
- Breakdown Torque
- Pull-up Torque
- Pull-out Torque

Current (% of Motor Full-Load Current)

- 7 x FLC
- 6 x FLC
- 5 x FLC
- 4 x FLC
- 3 x FLC
- 2 x FLC
- 1 x FLC

Torque (% of Motor Full-Load Torque)

- 2 x FLT
- 1 x FLT

Rotor Speed (% of Full Speed)

10% 20% 30% 40% 50% 60% 70% 80% 90% 100%
## Table 2. NEMA Torque Designs For Three-Phase Motors

<table>
<thead>
<tr>
<th>NEMA Design</th>
<th>Locked Rotor Torque</th>
<th>Breakdown Torque</th>
<th>Locked Rotor Current</th>
<th>Percent Slip</th>
<th>Relative Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>B</td>
<td>70 - 275%*</td>
<td>175 - 300%*</td>
<td>600 - 700%</td>
<td>0.5-5%</td>
<td>Medium or High</td>
</tr>
<tr>
<td></td>
<td><strong>Applications:</strong> Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>200 - 250%*</td>
<td>190 - 225%*</td>
<td>600 - 700%</td>
<td>1-5%</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td><strong>Applications:</strong> Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>275%</td>
<td>275%</td>
<td>600 - 700%</td>
<td>5 - 8%</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>8 - 13%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>15 - 25%</td>
<td></td>
</tr>
<tr>
<td></td>
<td><strong>Applications:</strong> High peak loads with or without flywheels, such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping, and wire-drawing machines.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on NEMA Standards MG 10, Table 2-1. NEMA Design A is a variation of Design B having higher locked-rotor current.

*Higher values are for motors having lower horsepower ratings.
Motors standards

IEC

IEC is a European-based organization that publishes and promotes worldwide, the mechanical and electrical standards for motors, among other things. In simple terms: the IEC is the international counterpart of the NEMA.

IEC standards are associated with motors used in many countries. These standards can be found in the IEC 34-1-16. Motors which meet or exceed these standards are referred to as IEC motors.
Motors standards

The IEC torque-speed design ratings practically mirror those of NEMA. The IEC Design N motors are similar to NEMA Design B motors, the most common motors for industrial applications. The IEC Design H motors are nearly identical to NEMA Design C motors. There is no specific IEC equivalent to the NEMA Design D motor.

The IEC Duty cycle ratings are different from NEMA

NEMA specifies:

- Continuous
- Intermittent
- Special duty

IEC uses nine different duty cycle designations (IEC 34-1).
Glossary

**Synchronous Speed:** Speed the motor’s magnetic field rotates

**Rated Speed:** Speed the motor runs at when fully loaded and supplied with rated nameplate voltage

**Slip:** Percent difference between a motor’s synchronous speed and rated speed

**Starting Current:** The current required by the motor during the starting process to accelerate the motor and load to operating speed. Maximum starting current at rated voltage is drawn at the time of energizing

**Starting Time:** The time required to accelerate the load to operating speed
**Glossary**

**Starting Torque:** The rated motor torque capability during start at rated voltage and frequency

**Pull Up Torque:** The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs

**Breakdown Torque:** The maximum torque that a motor will develop with rated voltage at rated frequency, where an abrupt drop in speed will not occur

**Stall Time:** Permissible locked rotor time
Selection of motor protection scheme

Selection of the specific protection schemes should be based on the following factors:

- Motor horsepower rating and type
- Supply characteristics, such as voltage, phases, method of grounding, and available short-circuit current
- Vibration, torque, and other mechanical limits
- Nature of the process
- Environment of motor, associated switching device, hot and cold permissible locked-rotor time and permissible accelerating time
- Time vs. current curve during starting
- Frequency of starting
Motor nameplate

- 1. Type designation
- 3. Duty
- 5. Insulation class
- 7. Degree of protection [IP class]
- 21. Designation for locked-rotor kVA/HP (NEMA)
- 22. Ambient temperature [°C] (NEMA)
- 23. Service factor (NEMA)
Motor nameplate
Insulation class and service factor

<table>
<thead>
<tr>
<th>Class of Insulation System</th>
<th>Temperature, Degrees C</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>75</td>
</tr>
<tr>
<td>B</td>
<td>95</td>
</tr>
<tr>
<td>F</td>
<td>115</td>
</tr>
<tr>
<td>H</td>
<td>130</td>
</tr>
</tbody>
</table>

**SERVICE FACTOR—AC MOTORS**

- The service factor of an AC motor is a multiplier which, when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the service factor (see 14.37).
Potential motor hazards

- Short circuits (multiphase faults)
- Ground faults
- Thermal damage
  - Overload (continuous or intermittent)
  - Locked rotor
- Abnormal conditions
  - Unbalanced operation
  - Undervoltage and overvoltage
  - Reversed phases etc.
- Loss of excitation (synchronous motors)
- Out-of-step operation (synchronous motors)
- Overheating due to repeated starts
Motor protection
Bearings

- Lubricant issues
  - Grade, contaminants, availability
- Mechanical
  - Excessive radial loading, axial loading
- Vibration
Motor protection

Failure statistics

<table>
<thead>
<tr>
<th>Failure Contributor</th>
<th>%</th>
<th>Failed Component</th>
<th>%</th>
<th>Average %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Persistent Overload</td>
<td>4.2%</td>
<td>Stator Ground Insulation</td>
<td>23.00%</td>
<td>Electrical Related Failures</td>
</tr>
<tr>
<td>Normal Deterioration</td>
<td>26.40%</td>
<td>Turn Insulation</td>
<td>4.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Bracing</td>
<td>3.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Core</td>
<td>1.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cage</td>
<td>5.00%</td>
<td></td>
</tr>
<tr>
<td>Electrical Related Total</td>
<td>30.60%</td>
<td>Electrical Related Total</td>
<td>36.00%</td>
<td></td>
</tr>
<tr>
<td>High Vibration</td>
<td>15.50%</td>
<td>Sleeve Bearings</td>
<td>16.00%</td>
<td>Mechanical Related Failures</td>
</tr>
<tr>
<td>Poor Lubrication</td>
<td>15.20%</td>
<td>Antifriction Bearings</td>
<td>8.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trust Bearings</td>
<td>5.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotor Shaft</td>
<td>2.00%</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rotor Core</td>
<td>1.00%</td>
<td></td>
</tr>
<tr>
<td>Mechanical Related Total</td>
<td>30.70%</td>
<td>Mechanical Related Total</td>
<td>32.00%</td>
<td></td>
</tr>
<tr>
<td>High Ambient Temp.</td>
<td>3%</td>
<td>Bearing Seals</td>
<td>6.00%</td>
<td>Environmental Maintenance &amp; Other Reasons Related Failures</td>
</tr>
<tr>
<td>Abnormal Moisture</td>
<td>5.8%</td>
<td>Oil Leakege</td>
<td>3.00%</td>
<td></td>
</tr>
<tr>
<td>Abnormal Voltage</td>
<td>1.5%</td>
<td>Frame</td>
<td>1.00%</td>
<td></td>
</tr>
<tr>
<td>Abnormal Frequency</td>
<td>0.6%</td>
<td>Wedges</td>
<td>1.00%</td>
<td></td>
</tr>
<tr>
<td>Abrasive Chemicals</td>
<td>4.2%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Poor Ventilation Cooling</td>
<td>3.9%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other Reasons</td>
<td>19.7%</td>
<td>Other Components</td>
<td>21.00%</td>
<td></td>
</tr>
<tr>
<td>Environmental Reasons &amp; Other Reasons Total</td>
<td>38.70%</td>
<td>Maintenance Related &amp; Other Parts Total</td>
<td>32.00%</td>
<td></td>
</tr>
</tbody>
</table>

- Motor failure rate is conservatively estimated as 3-5% per year
  - In mining, pulp and paper industry, motor failure rate can be as high as 12%.
- Motor failures divided in 3 groups:
  - Electrical (33%)
  - Mechanical (31%)
  - Environmental, maintenance, & other (36%)
- Motor failure cost contributors:
  - Repair or replacement
  - Removal and installation
  - Loss of production
Thermal protection
Motor thermal characteristics

Heat is developed at a constant rate due to the current flow:

- Light load
  - Low current
  - Small heat development
- Rated
  - Rated current
  - Nominal heat development
- Overload
  - High current
  - High heat development
Motor thermal characteristics

Heating follows an exponential curve

- Rate of temperature rise depends on motor thermal time constant $t$ and is proportional to square of current

$$\theta \approx K \times \left( \frac{I}{I_{FLC}} \right)^2 \times \left(1 - e^{-t/\tau}\right)$$

- $K$ = constant
- $t$ = time
- $\tau$ = time constant
- $I$ = highest phase current
- $I_{FLC}$ = Full Load Current
Motor thermal characteristics

Cooling also follows an exponential curve

- Rate of temperature drop depends on cooling time constant (can be different when the motor is stopped)
Motor thermal characteristics

- Heating with different loads
  - High load
  - Low load

- Heating with different time constants
  - Small $\tau$
  - Big $\tau$
Thermal overload conditions are the most frequently occurring abnormal conditions for industrial motors.

- Reduced cooling or an abnormal rise in the motor running current results in an increase in the motor's thermal dissipation (conversion of electric energy into heat) and temperature.
- Thermal overload protection prevents premature degradation of the insulation and further damage to the motor.
Abnormal conditions that can result in overheating include:

- Overload
- Stalling or jam
- Failure to start
- High ambient temperature
- Restricted motor ventilation
- Reduced speed operation
- Frequent starting or jogging
- Low/imbalanced line voltage
- Low frequency
- Mechanical failure of the driven load, improper installation, and unbalanced line voltage or single phasing
A rule of thumb has been developed from tests and experience to indicate that the life of an insulation system is approximately halved for each 10 °C incremental increase of winding temperature, and approximately doubled for each 10 °C decrease (the range of 7 °C–12 °C is indicated for modern insulation systems). Thus, insulation life is related to the length of time the insulation is maintained at a given temperature.
Motors are ordinarily rated for use in a maximum ambient temperatures no higher than 40 °C. Operating the motor at a higher-than-rated ambient temperature, even though at or below rated load, can subject the motor windings to over temperature similar to that resulting from overloaded operation in a normal ambient. The motor rating may have to be appropriately reduced for operation in such high ambient temperatures.

Motors installed at high altitudes operate in an atmosphere of lower-than-normal air density with reduced cooling effectiveness. This again can result in a higher-than-normal temperature rise, and the motor rating may have to be reduced.
Thermal overload protection

- Thermal limit curves
  - Hot (motor initially at ambient)
  - Cold (motor initially at ambient)
- Motor starting (accelerating)
  - Time-current (normal starting)
  - Thermal limit
  - 80, 90, 100 %
- Apply protection characteristics that will:
  - Provide thermal overload protection - 49M
  - Not operate for motor starting - 48
Motor start-up supervision & runtime jam protection

Start-up supervision:
- Excessive starting time
- Locked rotor conditions
- Excessive number of start-ups (blocks the motor from restarting)
- Time between starts

Emergency start:
- Overrides the cumulative start-up and thermal overload protection functions
- Enables one additional start-up of the motor

Runtime jam protection:
- Protection in mechanical jam situations while the motor is running
- The function is blocked during motor start-up
When a motor is started, it draws a current well in excess of the motor's full load rating throughout the period it takes for the motor to run up to the rated speed. The motor starting current decreases as the motor speed increases and the value of current remains close to the rotor locked value for most of the acceleration period. The startup supervision of a motor is an important function because of the higher thermal stress developed during starting.
Locked rotor or failure to accelerate

- Failure of a motor to accelerate when its stator is energized can be caused by:
  - Mechanical failure of the motor or load bearings
  - Low supply voltage
  - Open circuit in one phase of a three-phase voltage supply.

- When a motor stator winding is energized with the rotor stationary, the motor performs like a transformer with resistance-loaded secondary winding.

- During starting, the skin effect due to slip frequency operation causes the rotor resistance to exhibit a high locked-rotor value, which decreases to a low running value at rated slip speed.
Using a typical locked-rotor current of six times the rated current and a locked-rotor resistance of three times the normal running value:

\[ I^2R \sim 6^2 \times 3, \text{ or } 108 \text{ times that at normal current.} \]

\( I^2R \) defines the heating effect and \( I^2t \) defines the thermal capability.

Consequently, an extreme temperature must be tolerated for a limited time to start the motor.

To provide locked-rotor or failure-to-accelerate protection, the protective device must be set to disconnect the motor before the stator insulation suffers thermal damage, or the rotor conductors melt or suffer damage from repeated stress and deformation.
Locked rotor or failure to accelerate

- Allowable accelerating times are commonly specified for 100%, 90%, and 80% starting voltages.

- The acceleration time of the motor will also change due to the starting voltage. The approximate effect on the motor torque capability is an inverse relationship with the square of the voltage; thus, at 90% voltage, approximately 81% of rated starting (locked rotor) torque capability will be available from the motor. Since the load torque characteristics are not changed, the acceleration time is increased.
Repeated starts can build up temperatures to dangerously high values in stator or rotor windings, or both, unless enough time is provided to allow the heat to dissipate.

In repeated starting and intermittent operation, the running period is short so that very little heat is carried away by the cooling air induced by rotor rotation.
Induction motors and synchronous motors are usually designed for the starting conditions indicated in NEMA MG1-1998, Articles 12.50, 20.43, and 21.43. These standards provide for two starts in succession—coasting to rest between starts with the motor initially at ambient temperature—and for one start when the motor is at a temperature not exceeding its rated load operating temperature.

It may be necessary to provide a fixed-time interval between starts, or limit the number or starts within a period of time to ensure safe operation. A microprocessor-based motor protection system may include this feature.
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Frequent starting or intermittent operation

Table 2. NEMA Torque Designs For Three-Phase Motors

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<tr>
<th>NEMA Design</th>
<th>Locked Rotor Torque</th>
<th>Breakdown Torque</th>
<th>Locked Rotor Current</th>
<th>Percent Slip</th>
<th>Relative Efficiency</th>
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<td>B</td>
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<td>175 - 300%*</td>
<td>600 - 700%</td>
<td>0.5-5%</td>
<td>Medium or High</td>
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<td>Applications: Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.</td>
<td></td>
<td></td>
<td></td>
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<td>C</td>
<td>200 - 250%*</td>
<td>190 - 225%*</td>
<td>600 - 700%</td>
<td>1.5%</td>
<td>Medium</td>
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<td></td>
<td>Applications: Conveyors, crushers, stirring machines, agitators, reciprocating pumps and compressors, etc., where starting under load is required.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>D</td>
<td>275%</td>
<td>275%</td>
<td>600 - 700%</td>
<td>5 - 8%</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>8 - 13%</td>
<td>15 - 25%</td>
<td></td>
<td></td>
<td></td>
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<td>Applications: High peak loads with or without flywheels, such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping, and wire-drawing machines.</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on NEMA Standards MG 10, Table 2-1. NEMA Design A is a variation of Design B having higher locked-rotor current.

*Higher values are for motors having lower horsepower ratings.
Frequent starting or intermittent operation

Table 3. Allowable Starts And Starting Intervals

(Design A and B Motors)

<table>
<thead>
<tr>
<th>HP</th>
<th>2 Pole</th>
<th></th>
<th>4 Pole</th>
<th></th>
<th>6 Pole</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>A</td>
<td>B</td>
<td>C</td>
<td>A</td>
<td>B</td>
<td>C</td>
</tr>
<tr>
<td>1</td>
<td>15</td>
<td>1.2</td>
<td>75</td>
<td>30</td>
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<tr>
<td>1.5</td>
<td>12.9</td>
<td>1.8</td>
<td>76</td>
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<tr>
<td>2</td>
<td>11.5</td>
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<td>77</td>
<td>23</td>
<td>11</td>
<td>39</td>
</tr>
<tr>
<td>3</td>
<td>9.9</td>
<td>3.5</td>
<td>80</td>
<td>19.8</td>
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<td>83</td>
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<td>44</td>
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Where:

\[ A = \text{Maximum number of starts per hour}. \]
\[ B = \text{Maximum product of starts per hour times load Wk}^2. \]
\[ C = \text{Minimum rest or off time in seconds between starts.} \]

Allowable starts per hour is the lesser of (1) A or (2) B divided by the load Wk^2—i.e.,

\[ \text{Starts per hour} \leq A \text{ or } \leq B/Wk^2, \text{ whichever is less}. \]
Motor protection
Loss of load supervision

- Detects sudden loss of load which is considered as a fault condition
- Trips the circuit breaker when the load current rapidly falls below the set value due to:
  - Transmission gear failures
  - Conveyor belt breakages
  - Pumps running dry
Motor protection
Negative sequence overcurrent protection

Neg. Seq. overcurrent protection situations:
- Phase loss/single phasing
- Unbalance load
- Unsymmetrical voltage

- If the nature of the unbalance is an open circuit in any phase, the combination of positive and negative sequence currents produces phase currents of approximately 1.7 times the previous load in each sound phase.

- When a three-phase induction or synchronous motor is energized and one supply phase is open, the motor will not start. Under these conditions, it overheats rapidly and is destroyed unless corrective action is taken to de-energize it. The heating under these circumstances is similar to that in a three-phase failure to start, except that the line current is slightly lower (approximately 0.9 times the normal three-phase, locked-rotor current).
Motor protection
Negative sequence overcurrent protection

- A small-voltage unbalance produces a large negative-sequence current flow in either a synchronous or induction motor.

- \( Z_2 \sim \frac{1}{ILR \text{ pu}} \)
  - \( ILR = 6 \text{ pu}, \text{ then } Z_2 \sim 0.167\text{pu} \)
  - Assume a \( V_2 = 0.05 \text{ pu} \) is applied to the motor
  - From \( V_2 = I_2 Z_2 \), \( I_2 = 0.30 \text{ pu} \)
  - Negative sequence current will produce negative torque
  - Major effect is to increase the heat delivered to the motor

- Thus, a 5% voltage unbalance produces a stator negative-sequence current of 30% of full-load current. The severity of this condition is indicated by the fact that with this extra current, the motor may experience a 40% to 50% increase in temperature rise.
Standing negative sequence (current imbalance) causes heating in both the stator and rotor.

Negative sequence overcurrent protection for motors

NEMA

DERATING FACTOR

PERCENT VOLTAGE UNBALANCE

Current Imbalance Derates Thermal Capacity
Negative sequence overcurrent protection for motors

- Typical setting for the negative phase sequence voltage protection (47) is 5%
- Typical setting for the unbalance current protection (46) is 20% of nominal current
- Which protection, 46 or 47, should be applied for the unbalance protection?
  - Selective protection against voltage and current unbalance is accomplished by using 46 protection
  - Negative-sequence voltage is most useful for detecting upstream open phases i.e. between the V2 measurement and the supply (selectivity not achieved) - 47 is mostly used as backup protection or to give alarm
RTD applications

- Nickel, copper or platinum RTD are used. RTD have well defined ohmic characteristic vs. temperature.
- To measure the resistance of the RTD, lead resistance should be compensated
- Responds slowly to temperature change
- Applications
  - Ambient temperature
  - Bearings
  - For larger motors RTD detector are placed in the motor at the most probable hot spot
RTD applications

- A simple method to determine the heating within the motor is to monitor the stator with RTDs.
- Stator RTD trip level should be set at or below the maximum temperature rating of the insulation.
- For example, a motor with class F insulation that has a temperature rating of 155°C could have the Stator RTD Trip level be set between 140°C to 145°C, with 145°C being the maximum (155°C - 10°C hot spot)
- The stator RTD alarm level could be set to a level to provide a warning that the motor temperature is rising
Multi-purpose protection, MAP

The function block can be used for any general analog signal protection, either under-value or over-value. The setting range is wide, allowing various protection schemes for the function.

The temperature protection using the RTD sensors can be done using the function block. The measured temperature can be fed from the RTD sensor to the function input that detects too high temperatures in the motor bearings or windings.
38 – RTD based thermal protection

- Set threshold
- Set trip delay
- Add bias
Motor protection
Phase reversal

- Used for detecting reversed connection of the phases causing the motor to rotate in reverse direction
- Detection by monitoring the negative phase sequence current during the start-up of the motor
- Operates when the negative sequence current exceeds the defined value
Phase fault protection

- Instantaneous non-directional overcurrent relay (50) can be used if there is a significant difference between starting current and minimum phase-to-phase fault current.
- Otherwise, differential protection is required.
Phase fault protection

- Set relay above the asymmetrical locked rotor current and below minimum phase-to-phase fault current
  - $I_{PU} > 1.6 \times I_{LR}$
    - Symmetrical, including $X_{S1}$ (source impedance)
  - $I_{3f} > 5 \times I_{LR}$
    - Desirable, but not a rigid rule
Phase fault protection

- Calculation of $I_{LR}$ and $I_{ff}$

\[ I_{LR} = \frac{1}{X_{S1} + X_{LR}} \]

\[ I_{3\phi} = \frac{1}{X_{S1}} \]

\[ I_{\phi\phi} = \frac{0.866}{X_{S1}} \]

- $X_{S1}$ is the maximum system equivalent source impedance
- $X_{LR}$ is the motor equivalent reactance (stator + rotor)
Motor protection
Short circuit protection

- The short circuit element provides protection for excessively high over current faults
- Phase-to-phase and phase-to-ground faults are common types of short circuits
- When a motor starts, the starting current (which is typically 6 times the full load current) has asymmetrical components.
- These asymmetrical currents may cause one phase to see as much as 1.7 times the RMS starting current.
- To avoid nuisance tripping during starting, set the short circuit protection pick up to a value at least 1.7 times the maximum expected symmetrical starting current of the motor.
Differential protection with conventional type CT
If for a motor, the motor kVA rating is less than half of the supply transformer kVA rating, over current relays may be relied upon. In this case, there is sufficient difference between a 3-phase short circuit at the motor terminals and the natural motor starting current to use instantaneous overcurrent protection.

However, in case of high voltage motors (commonly called “big” motors), whose kVA rating is more than half of the supply transformer kVA rating, the current for a 3-phase fault may be less than 5 times the current for locked rotor condition. In such cases, there is not enough difference between the 3-phase fault current at the motor terminals and the natural motor starting current to use instantaneous overcurrent protection. For this case, it is recommended to use percentage differential protection.
Low voltage starting

- Motors are specified to successfully start with terminal voltage as low as 70 to 85% of rated voltage
- Low voltage encountered while the motor is started may prevent it from reaching its rated speed or cause the acceleration period to be extended resulting in the excessive heating
Low voltage starting

- Protected by
  - Motor start supervision
  - Low voltage setting with time delay

Normal Operating Speed
Stall Speed
Low voltage while running

- Low voltage, while the motor is running causes an increase in slip. The motor slows down and draws more current from the supply.
- In synchronous motors the low voltage results in the higher currents with the possibility of the motor pulling out of synchronism.
- Typical Setting
  - 75% of the nominal voltage
  - Time delay of 2 sec to 3 sec
Overvoltage protection

- Operation of induction and synchronous motors on moderate overvoltage is not generally considered injurious.
- If motor load current is constant and the motor magnetization current increased due to overvoltage, then motor temperatures would increase.
- During the starting, locked rotor current is greater due to overvoltage. Locked-rotor protection protects motor against thermal damage when the voltage is not more than 10% above rated voltage at the time of start.
- Transient overvoltages can be dangerous for motors. Surge arresters are used to accomplish this type of protection.
- Typical setting for the overvoltage protection is 10% above nominal voltage with time delay of 2-3 seconds.
Abnormal frequency

- Motors are designed to operate successfully under running conditions at rated load with a variation of 10% of rated voltage, 5% of rated frequency
- Motor speed varies directly with the applied frequency
- A decrease in frequency without corresponding voltage reduction results in an increased flux density and increased heating losses
- Protection is achieved using the frequency relay
Synchronous motor protection

- Protection applied to the induction motors is applicable to synchronous motors
- Additional protection is required for field and asynchronous operation
- Reduction or loss of excitation requires reactive power from the system. Power factor relays are recommended
- Loss of the synchronism or “pull out” protection is provided for the motors that may experience large voltage dips or sudden increase in load that exceed the pull out torque of the motor
- A power factor relay is a good solution for out of step operation since the power factor is very low during “pull out” operation
Relion® Advanced Motor Protection
REM615 and REM620 common features

- Both have
  - Draw-out & draw-in construction with automatic CT shorting
  - Built-in DHCP server (web browser)
  - Standard communication protocols including Modbus RTU/ASCII, DNP and IEC61850
  - Optional differential protection and arc flash protection
  - Customizable screen displays including graphics
  - Small footprint
  - 11 programmable alarm LEDs
Relion® Advanced Motor Protection
REM615 and REM620 common features

Draw-out/draw-in Construction

- Speeds up installation, maintenance, and testing of the protection
- Allows the cases to be installed and wired before the plug-in units are delivered
- Automatic CT secondary short circuiting while plug-in unit removed from the case...safer
- Contributes to a shortened MTTR (mean time to repair)...faster replacement
- Sealable pull-out handle to prevent accidental (or unauthorized) withdrawal of the plug-in unit
Relion® Advanced Motor Protection
REM615 and REM620 common features

11 Programmable Alarm/Target LEDs

Configurable Screen with Active
Relion® Advanced Motor Protection
REM615 and REM620 common features

- Local or remote IED access using an internet web browser
- Functions:
  - Viewing of alarm LEDs and event lists
  - Saving of event data
  - Parameter setting
  - Signal monitoring
  - Measurement viewing
  - Phasor diagram viewing
  - Reading of disturbance records
- User access level authentication
Relion® Advanced Motor Protection
REM615 and REM620 common features

Embedded Native IEC61850

- High speed (4 ms) relay-to-relay GOOSE communications for faster control schemes
- Does not rely on proprietary relay-to-relay communications or hardware...standard open protocol using Ethernet
- Ability to customize logic to meet special requirements
# Relion® Advanced Motor Protection
## REM615

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<thead>
<tr>
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<tbody>
<tr>
<td>A</td>
<td>Overcurrent and load loss protection for small motors</td>
</tr>
<tr>
<td>B</td>
<td>Differential, overcurrent, load loss and RTD protection for medium to large motors</td>
</tr>
<tr>
<td>C</td>
<td>Overcurrent, load loss, phase and ground voltage and frequency protection and power system metering for medium motors</td>
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<td>Overcurrent, load loss, phase and ground voltage, frequency and RTD protection and power system metering for medium motors</td>
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<td>F</td>
<td>Overcurrent, load loss, phase and neutral voltage, frequency and RTD protection and power system metering for medium to large motors</td>
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Relion® Advanced Motor Protection
REM615 without differential protection

- 27 - Phase under voltage (2 instances)
- 47 - Negative sequence voltage (2 instances)
- 59 – Phase overvoltage (2 instances)
- 81 - Under/over frequency (2 instances)
- 66/51LRS – $I^2T$ motor start supervision and frequent start protection
- 50P/51P - Phase fault protection
- 49M - Thermal overload model
- 46M - Negative sequence overcurrent (2 instances)
- 37 - Loss of load
- 50G/51G – Ground fault protection
- Optional (3) AFD arc flash sensors
- Optional (6) RTDs
Relion® Advanced Motor Protection
REM615 with differential protection

- 66/51LRS – $I^2T$ motor start supervision and frequent start protection
- 50P/51P - Phase fault protection
- 46M - Negative sequence overcurrent (2 instances)
- 37 - Loss of load
- 50G/51G – Ground fault protection
- 87 - Differential protection
- Optional (3) AFD arc flash sensors
- Optional (6) RTDs
### Relion® Advanced Motor Protection

**REM620**

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<td>Overcurrent, load loss, phase and neutral voltage, frequency, RTD protection and power system metering for medium to large motors</td>
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</table>

| **B** |
| Differential, overcurrent, load loss, phase and neutral voltage, frequency and RTD protection and power system metering for medium to large motors |

| **C** |
| Differential, overcurrent, load loss, phase and neutral voltage, frequency and extended RTD protection and power system metering for medium to large motors |

Additionally, the RER620 adds 16 programmable control buttons and allows up to 14 RTD inputs.
Relion® Advanced Motor Protection
REM620

- 66/51LRS – $I^2T$ motor start supervision and frequent start protection
- 50P/51P - Phase fault protection
- 27 - Phase undervoltage
- 49M - Thermal overload model
- 46M – Unbalanced currents (2 instances)
- 37 - Loss of load
- 47 – Unbalanced voltages
- 50G/51G - Ground fault protection
- 81 Under/Over frequency
- 59 - Phase overvoltage
- Optional (3) AFD arc flash sensors
- Optional (14) RTDs
Relion® Advanced Motor Protection
REM620

- 66/51LRS – I^2T motor start supervision and frequent start protection
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- 50G/51G - Ground fault protection
- 81 Under/Over frequency
- 59 - Phase overvoltage
- Optional (3) AFD arc flash sensors
- Optional (14) RTDs
Relion. Thinking beyond the box.

Designed to seamlessly consolidate functions, Relion relays are smarter, more flexible and more adaptable. Easy to integrate and with an extensive function library, the Relion family of protection and control delivers advanced functionality and improved performance.
Power and productivity for a better world™
Thank you for your participation

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