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Advanced protection and control IEDs from ABB

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.



ABB Protective Relay School Webinar Series

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Welcome to the ABB Webinar Motor Protection Fundamentals

Presenter



Joe Xavier

Joe graduated in Electrical & Electronics Engineering from Mahatma Gandhi University, India and joined ALIND Relays Division. In 1996 he joined ABB India and served over 13 years before moving to the United States. Over these years Joe has been involved with Application and Marketing of Protection & Control, Automation and other Power Products & Systems.

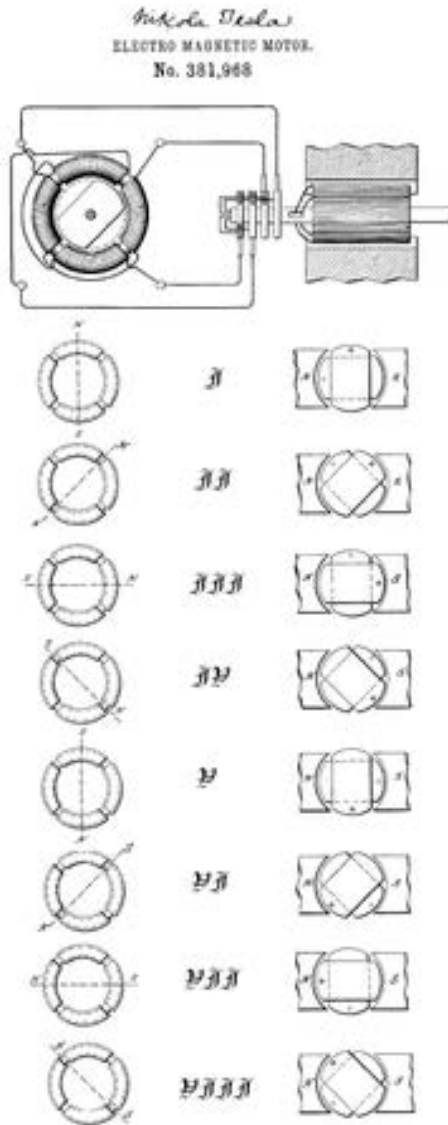
Currently, Joe is the Regional Technical Manager serving the North West region for ABB, located in Camas WA. He is responsible for business development and technical support for Distribution Automation & Protection Products.

Joe is a member of IEEE PES.

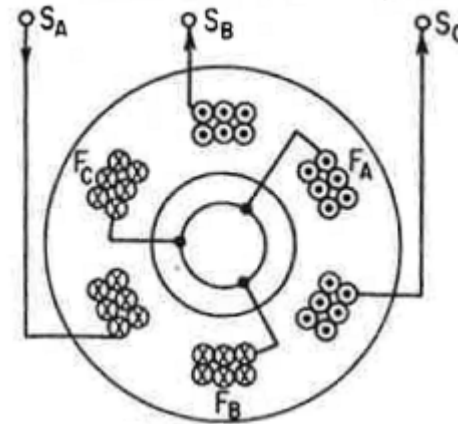
Learning objectives

- In an easy to understand way, you'll learn:
 - Basic motor electrical theory
 - How the different types of motors can be protected from potential hazards such as thermal damage, start-up, faults in the windings, etc.

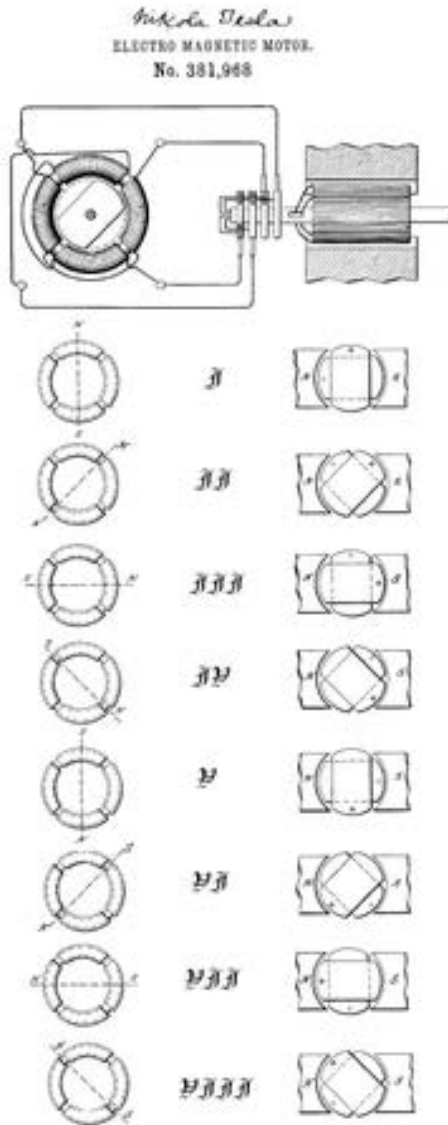
Introduction



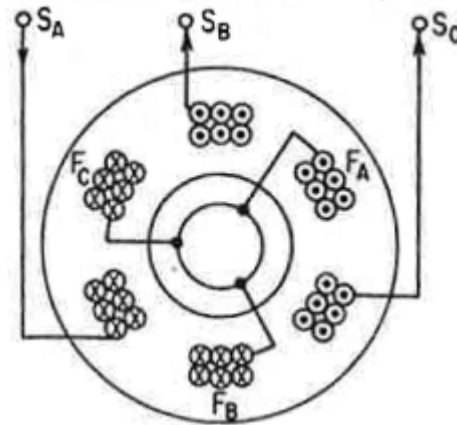
- Motor protection is far less standardized than generator protection. There are many different types and sizes of motors for variety of applications.
- Of all the electricity produced, industries use 50% of it. Out of this 65% is consumed by electric motors!



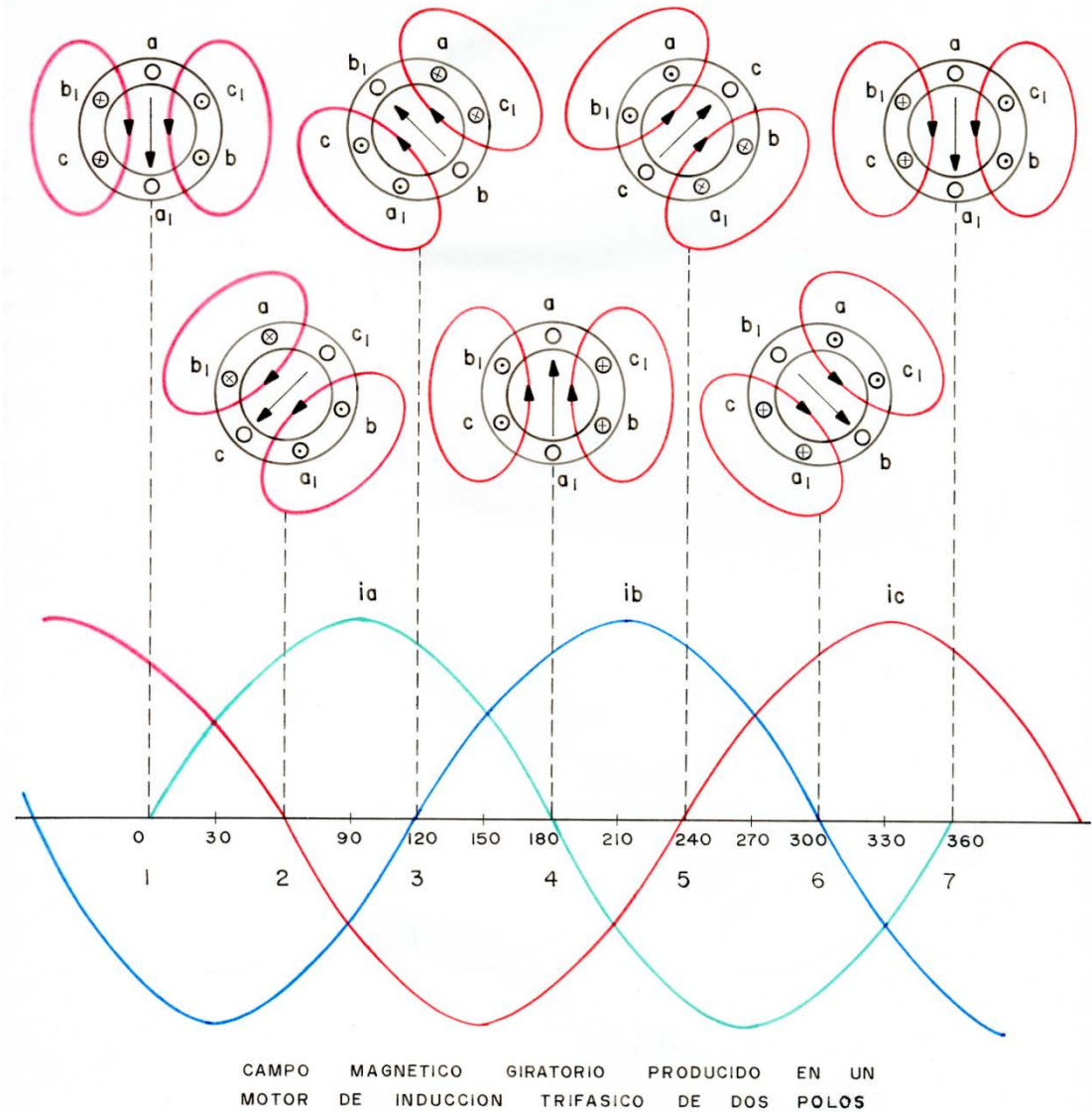
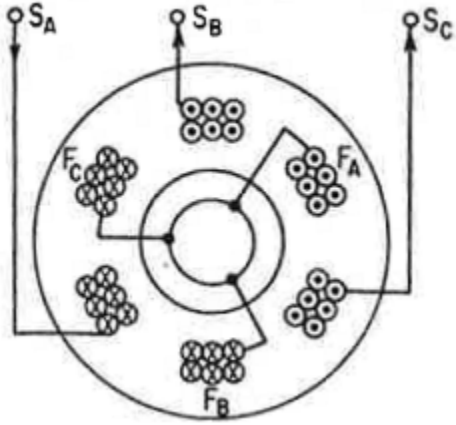
Introduction



- A rotating magnetic field which rotates at constant synchronous speed can be generated by means of a group of poly phase windings displaced in space over an armature if the currents flowing through the windings are also displaced in time.
- Synchronous speed = $(120 \cdot f) / p$

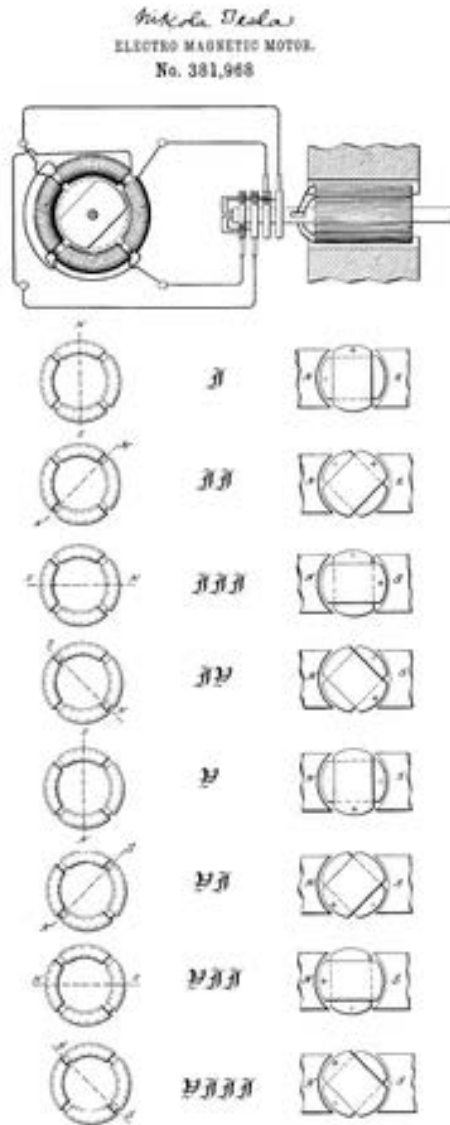


Introduction



<http://upload.wikimedia.org/wikipedia/commons/f/f1/3phase-rmf-noadd-60f-airopt.gif>

Introduction



- The idea of a rotating magnetic field was developed by François Arago in 1824
- Practical induction motors were independently invented by Nikola Tesla in 1883 and Galileo Ferraris in 1885
- In 1888, Tesla was granted U.S. Patent 381,968 for his motor
- Three phase squirrel-cage induction motors account for over 90% of the installed motor capacity

Introduction

- Two types of motors:
 - Induction motors (squirrel cage and wound rotor type)
 - Synchronous motors
- Protection and motor size:
 - Motors rated 600V or below are generally switched by contactors and protected by fuses or LV circuit breakers with built-in magnetic trips
 - Motors rated from 600 to 4800V are usually switched by a power CB or contactor
 - Motors rated from 2400 to 13,800V are switched by power CBs
 - Protective relays are usually applied only to large or higher voltage motors

Induction Motors

- Stator (Armature)
 - Windings connected to power system
 - Single phase OR three phase
- Rotor
 - Winding not connected to power system
 - Wound rotor conductors are insulated and brought out through slip rings for connecting to starting or control devices
 - Squirrel-cage, non-insulated conductors are connected together on the rotor ends (not brought out)

Synchronous Motors

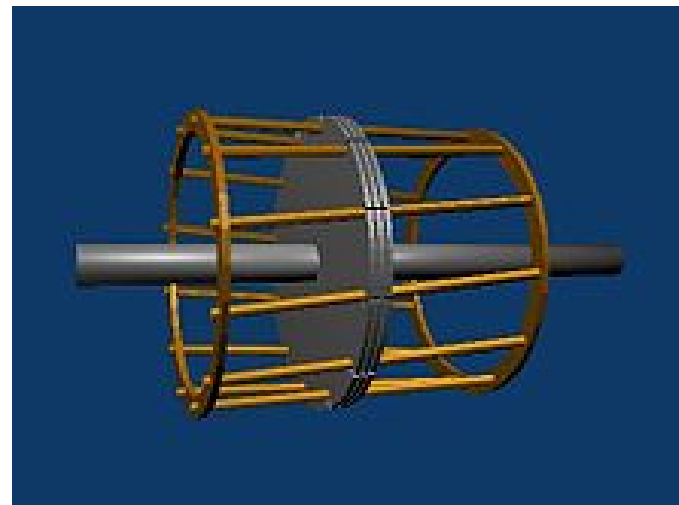
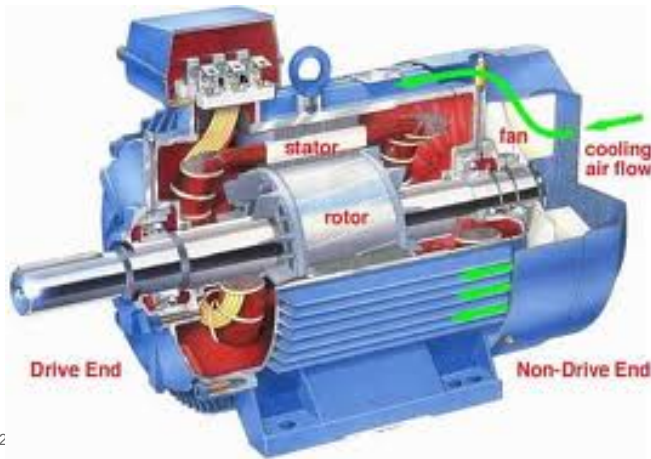
- Stator (Armature)
 - Windings connected to power system
 - Single phase OR three-phase
- Rotor
 - Windings are connected to dc source
 - Poles (usually salient) corresponding to the number of stator poles
 - Poles are wound with many turns (field windings) and dc current circulated to create alternately 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

- Damper windings
 - Similar to induction motor (shorted on ends)
 - Needed to start synchronous motor
- Synchronous motor thermal level generally much less than induction motor

Induction Motors – Squirrel Cage

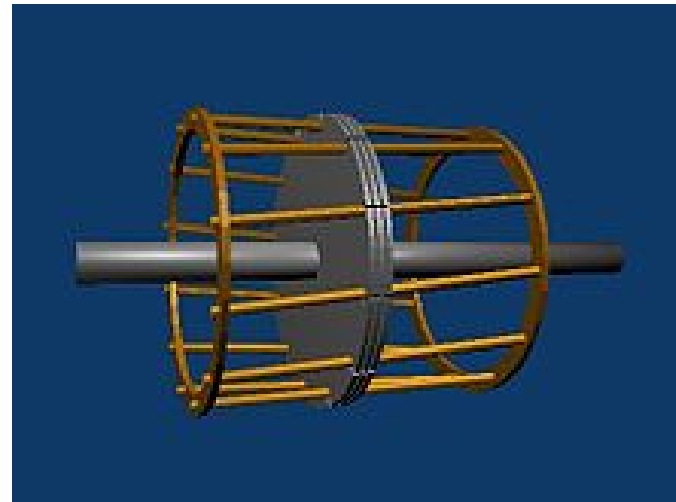
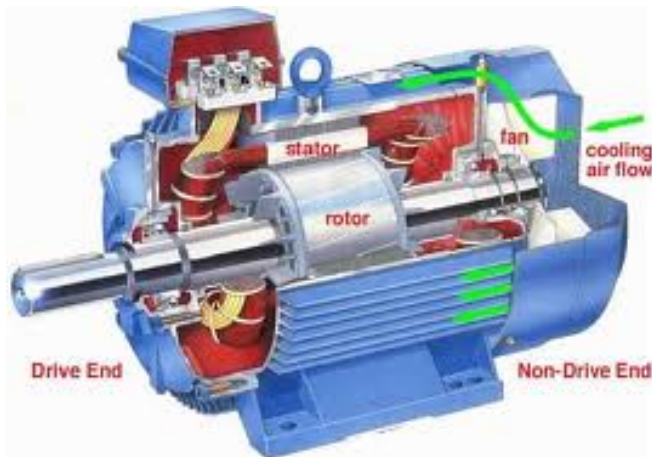
- The Squirrel Cage Induction Motor is the workhorse of the modern industry. They are found in virtually every phase of manufacturing.
- In a squirrel cage induction motor, rotor is a cylinder mounted on a shaft. Internally it contains longitudinal conductive bars (usually made of aluminum or copper) 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 in squirrel cage rotor not always remain parallel to the axial length of the rotor but can be arranged at an angle to prevent electromagnetic hum and produce a more uniform torque.



Induction Motors – Squirrel Cage

Squirrel Cage induction motor features:

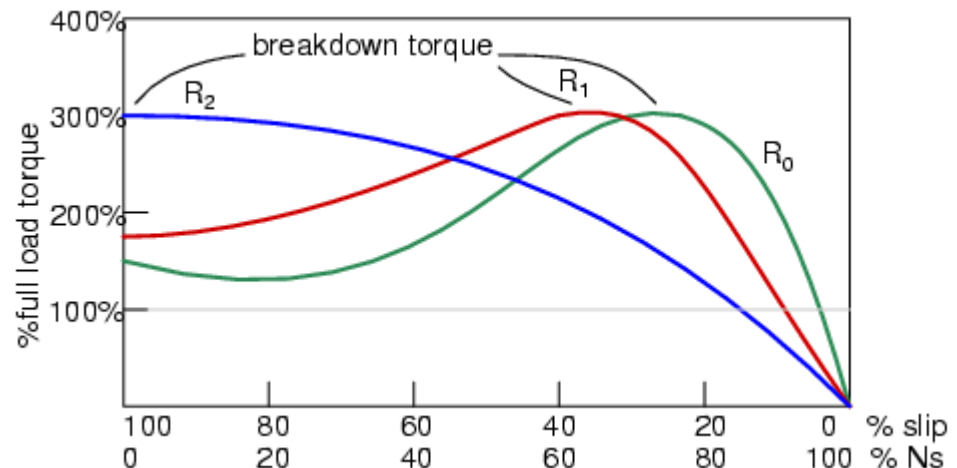
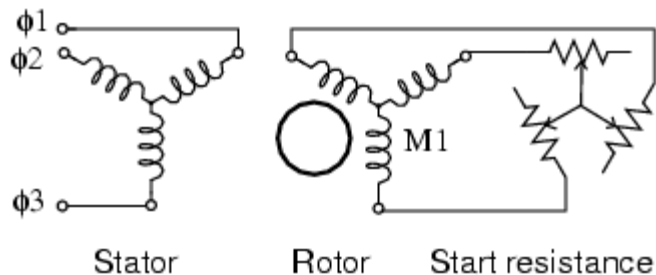
- Simple and rugged design
- Low-cost
- Low maintenance



Induction Motors – Wound rotor

- Stator similar to squirrel cage induction motor, but rotor has insulated windings brought out via slip rings and brushes
- No power applied to the slip rings. Their sole purpose is to allow resistance to be placed in series with the rotor windings while starting.

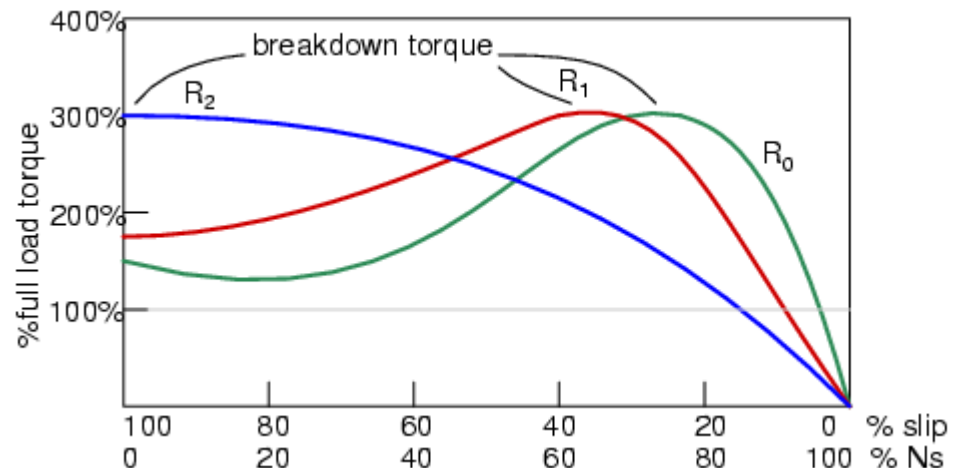
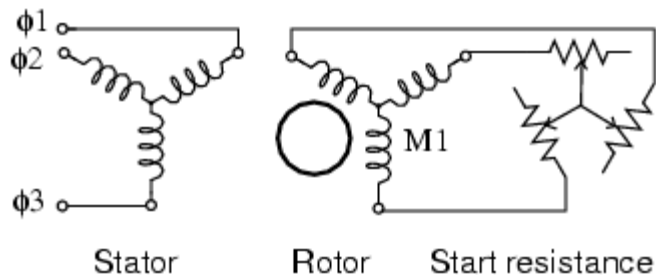
Squirrel cage induction motors draw 500% to over 1000% of full load current (FLC) during starting. This is not a severe problem for small motors, but it is for large (10's of kW) motors. Placing resistance in series with the rotor windings not only decreases start current, locked rotor current (LRC), but also increases the starting torque and locked rotor torque.



Induction Motors – Wound rotor

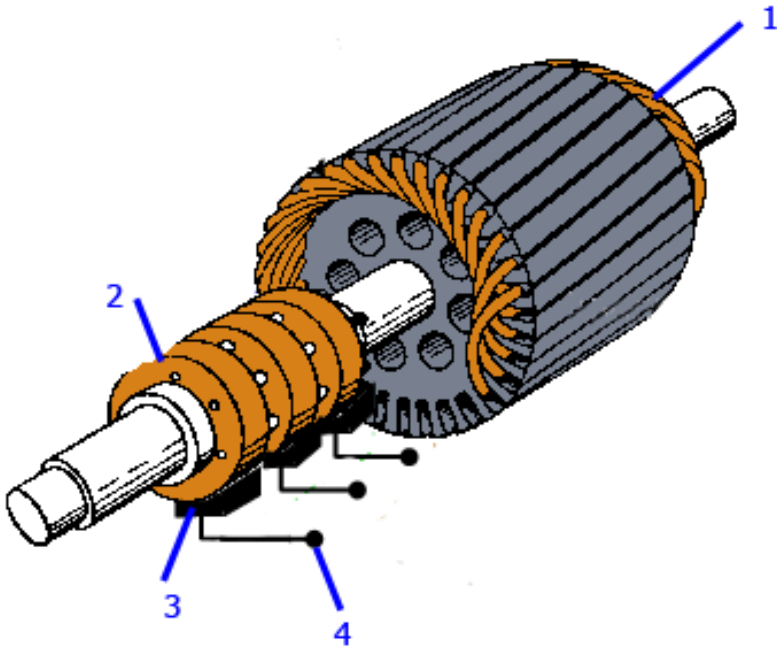
Features:

- 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

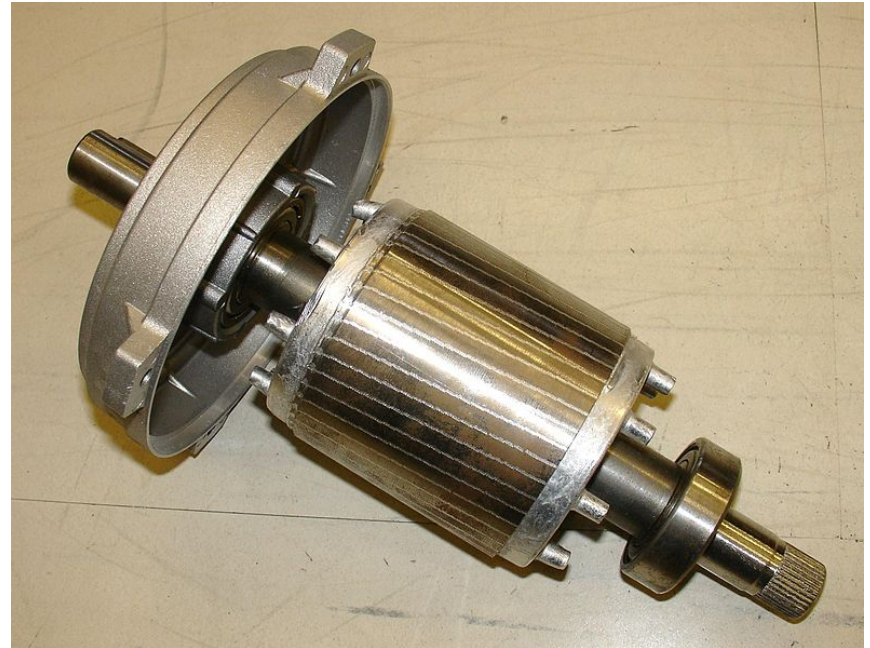


Induction Motors

- 1.-Windings
- 2.-Slip Rings
- 3.-Brushes
- 4.-Connections for External Resistors



Wound Rotor

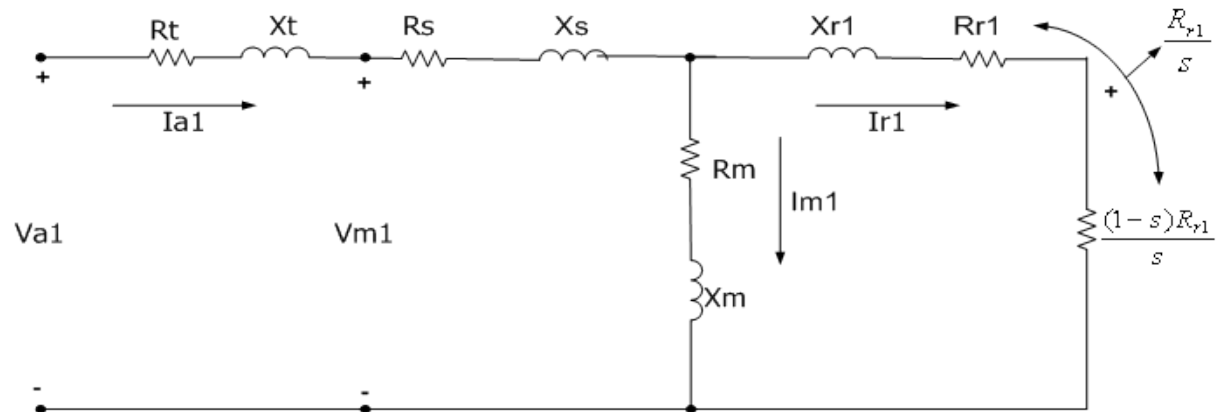


Squirrel Cage Rotor

Induction Motor Equivalent Circuit

- R_s and X_s are Stator resistance and Reactance
- R_t and X_t are equivalent source resistance and Reactance
- R_m represent losses due to eddy current and hysteresis
- X_m is the magnetizing reactance
- R_r and X_r are rotor resistance and reactance

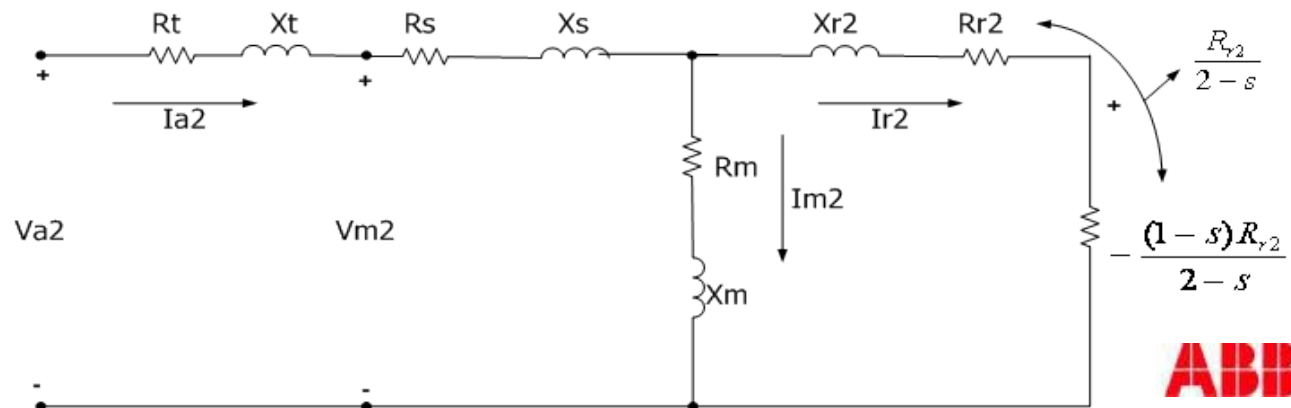
Induction Motor Positive Sequence Equivalent Circuit



$$\frac{R_{r1}}{s} = R_{r1} + \frac{(1-s)}{s} R_{r1}$$

$$I_R^2 \times \frac{R_{r1}}{s} = I_R^2 \times R_{r1} + I_R^2 \frac{(1-s)}{s} R_{r1}$$

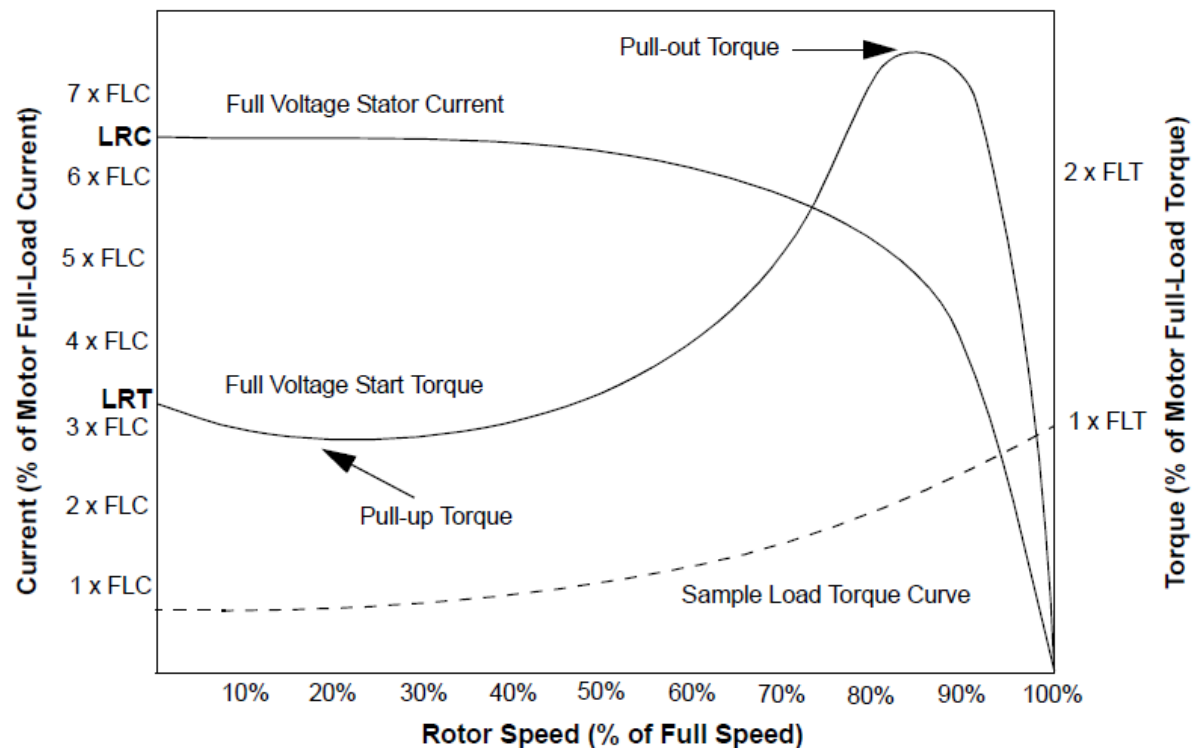
Induction Motor Negative Sequence Equivalent Circuit



Induction Motors

STARTING CHARACTERISTIC

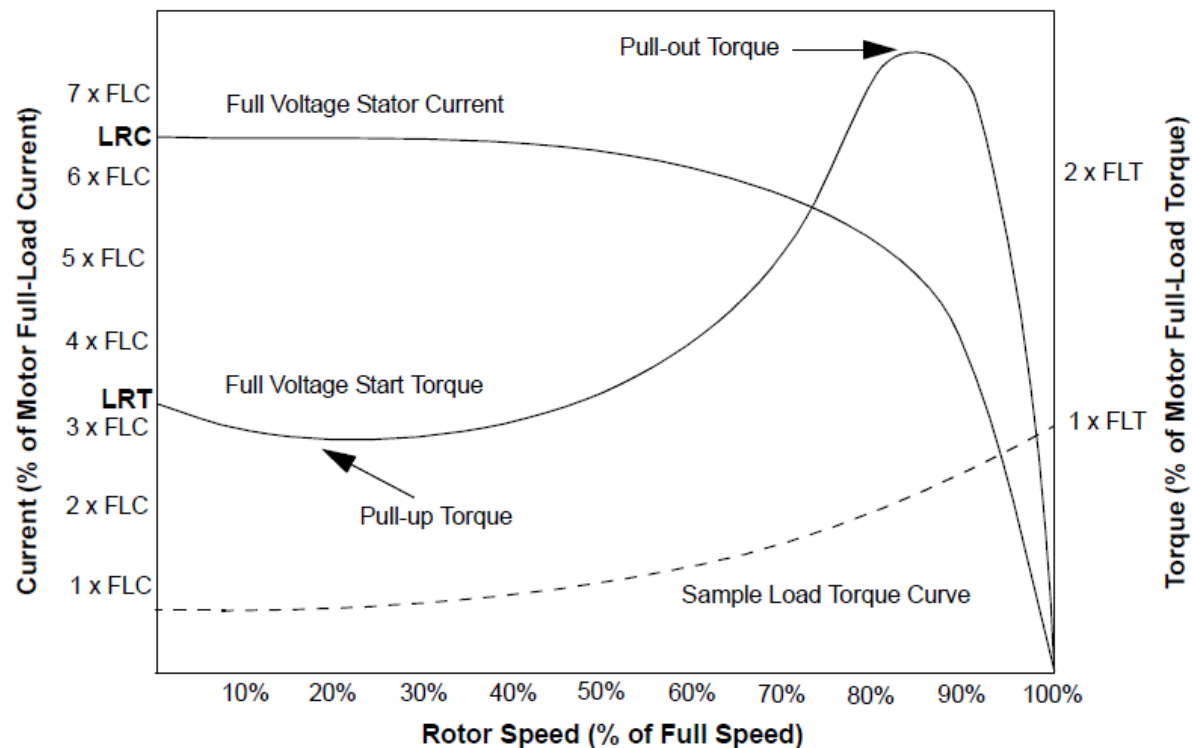
Induction motors, at rest, appear just like a short circuited transformer and if connected to the full supply voltage, draw a very high current known as the “Locked Rotor Current.” They also produce torque which is known as the “Locked Rotor Torque”.



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.



Glossary

- **Synchronous Speed:**
 - Speed at which motor's magnetic field rotates
- **Rated Speed:**
 - Speed at which motor runs when fully loaded and supplied 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

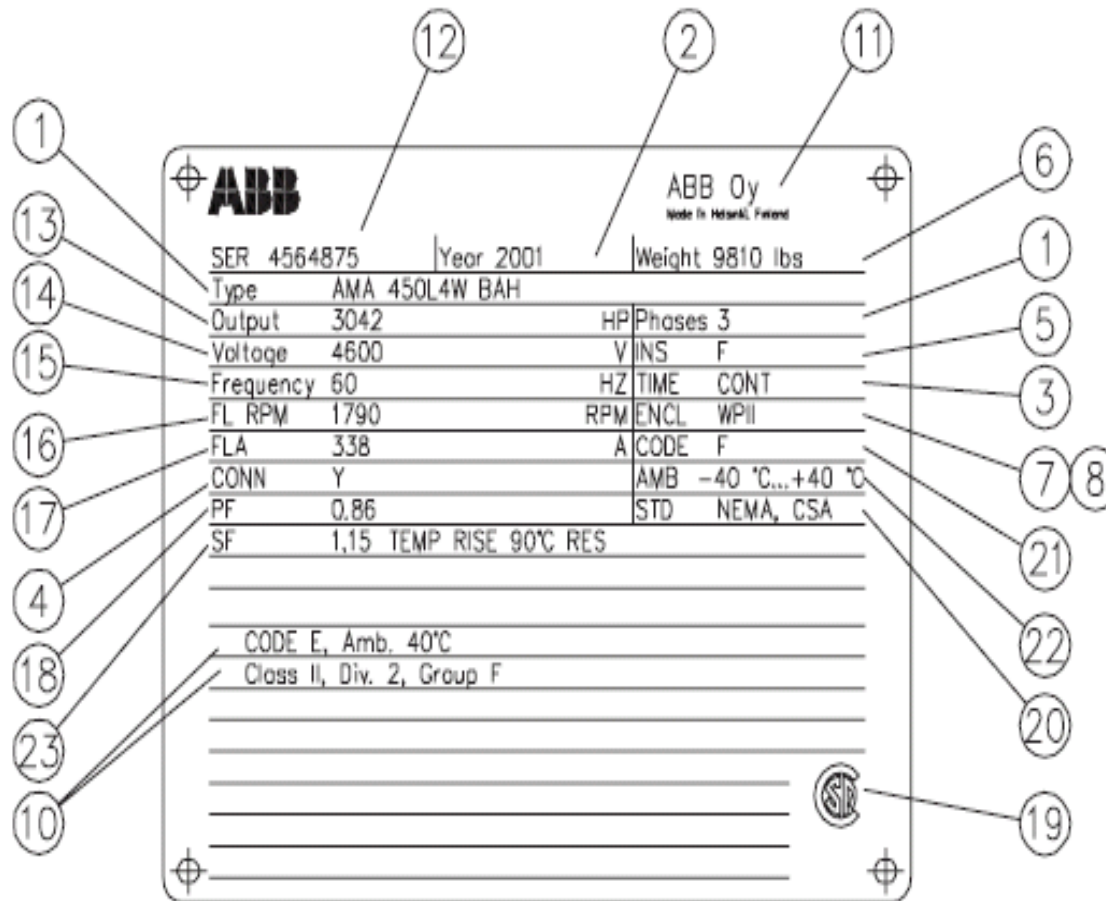
- **Starting Torque:**
 - The rated motor torque capability during start at rated voltage and frequency
- **Pull Up Torque:**
 - The minimum torque developed by the motor during the period of acceleration from rest to the speed at which breakdown torque occurs
- **Breakdown Torque:**
 - The maximum torque 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)

Figure 1-3 Rating plate for direct on line machines manufactured according to NEMA

▪ Motor Nameplate

▪ Class of Insulation System

Class of Insulation System	Temperature, Degrees C
A	75
B	95
F	115
H	130

▪ Service Factor

- The service factor is a multiplier when applied to the rated horsepower, indicates a permissible horsepower loading which may be carried under the conditions specified for the service factor at the rated voltage and frequency.
- The service factor helps in estimating horsepower needs and actual running horsepower requirements. It also allows for cooler winding temperatures at rated load, protects against intermittent heat rises, and helps to offset low or unbalanced line voltages.

■ Motor Nameplate

■ Locked-Rotor Letter

Letter Designation	kVA per Horsepower*	Letter Designation	kVA per Horsepower*
A	0-3.15	K	8.0-9.0
B	3.15-3.55	L	9.0-10.0
C	3.55-4.0	M	10.0-11.2
D	4.0-4.5	N	11.2-12.5
E	4.5-5.0	P	12.5-14.0
F	5.0-5.6	R	14.0-16.0
G	5.6-6.3	S	16.0-18.0
H	6.3-7.1	T	18.0-20.0
J	7.1-8.0	U	20.0-22.4
		V	22.4-and up

Locked rotor letter defines low and high voltage inrush values on dual voltage motors. These values can be used for sizing starters.

▪ Motor Nameplate

- According with the nameplate:

Locked Rotor letter is F, this is 5 to 5.6 kVA / HP so, the Starting current will be:

$$I_{LR} = \frac{\text{kVA/HP} \times \text{HP} \times 1000}{\sqrt{3} \times V}$$

$$I_{LR} = \frac{5.6 \times 3042 \times 1000}{\sqrt{3} \times 4600}$$

$$I_{LR} = 2141 \text{ A}$$

$$I_{LR} = \frac{2141 \text{ A}}{338 \text{ A}} = 6.33$$

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)

Motor Protection

Bearings

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

Motor Protection Failure Statistics

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

IEEE Study		EPRI Study		Average
Failure Contributor	%	Failed Component	%	%
Persistent Overload	4.2%	Stator Ground Insulation	23.00	Electrical Related Failures
Normal Deterioration	26.40%	Turn Insulation	4.00	
		Bracing	3.00	
		Core	1.00	
		Cage	5.00	
Electrical Related Total	30.60%	Electrical Related Total	36.00%	33%
High Vibration	15.50%	Sleeve Bearings	16.00	Mechanical Related Failures
Poor Lubrication	15.20%	Antifriction Bearings	8.00	
		Trust Bearings	5.00	
		Rotor Shaft	2.00	
		Rotor Core	1.00	
Mechanical Related Total	30.70%	Mechanical Related Total	32.00%	31%
High Ambient Temp.	3	Bearing Seals	6.00	Environmental Maintenance & Other Reasons Related Failures
Abnormal Moisture	5.8	Oil Leakage	3.00	
Abnormal Voltage	1.5	Frame	1.00	
Abnormal Frequency	0.6	Wedges	1.00	
Abrasive Chemicals	4.2			
Poor Ventilation Cooling	3.9			
Other Reasons	19.7	Other Components	21.00	
Environmental Reasons & Other Reasons Total	38.70%	Maintenance Related & Other Parts Total	32.00%	35%

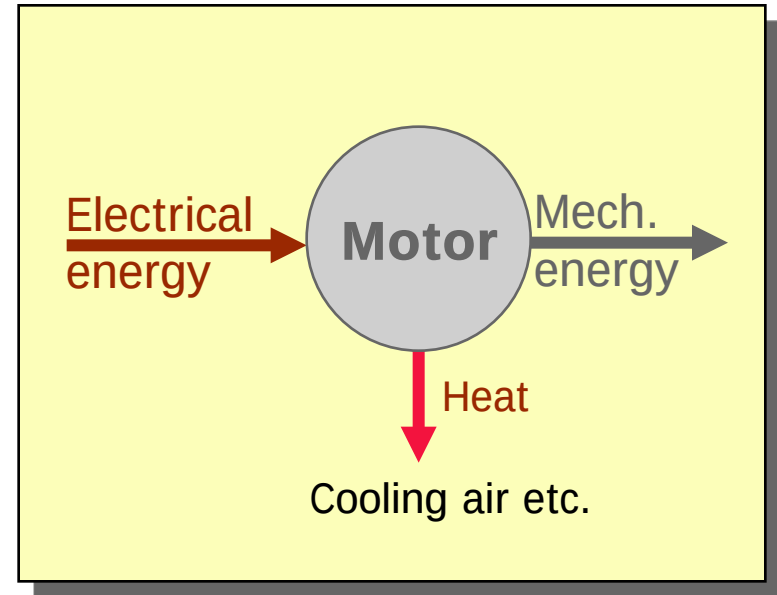
Thermal Protection



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

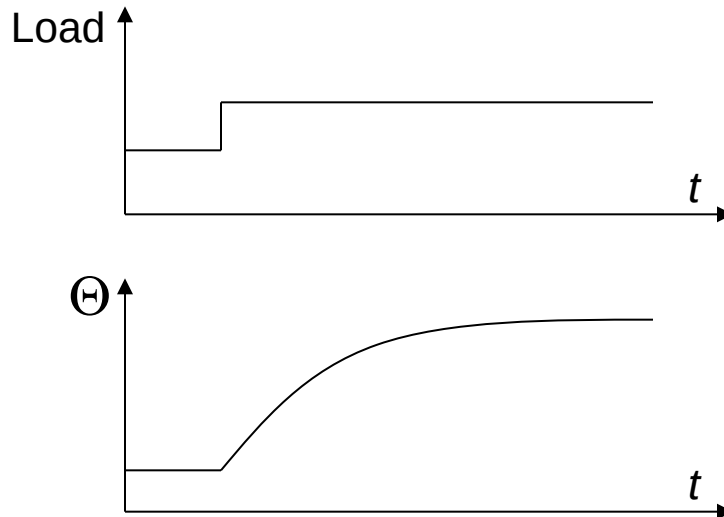


Motor Thermal Characteristics

Heating follows an exponential curve

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

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

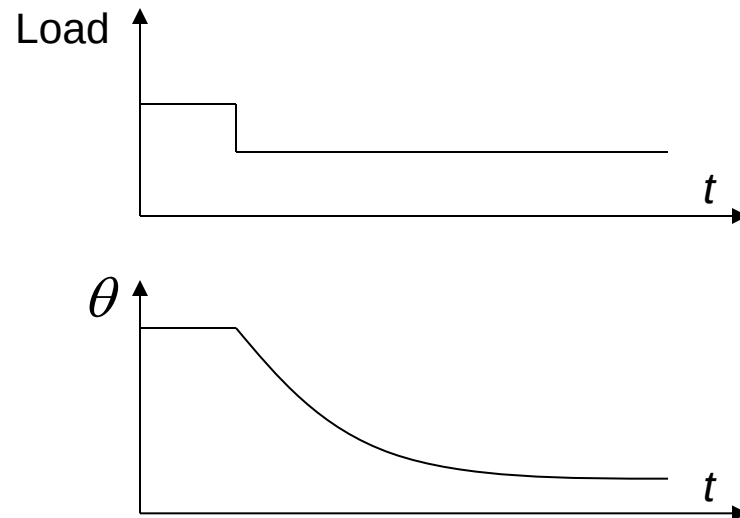


K = constant
 t = time
 τ = time constant
 I = highest phase current
 I_{FLC} = Full Load Current

Motor Thermal Characteristics

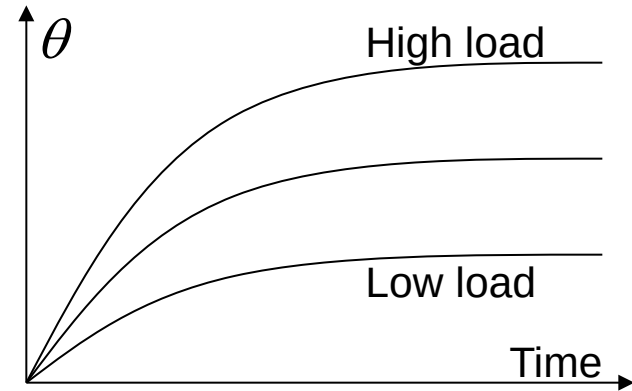
Cooling also follows an exponential curve

- Rate of temperature drop depends on cooling time constant (Can be different when the motor is stopped)

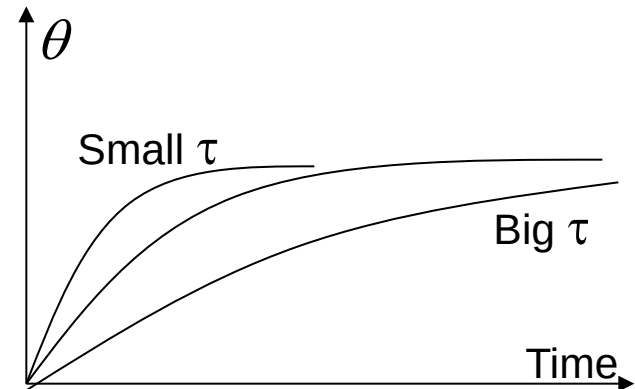


Motor Thermal Characteristics

- Heating with different loads

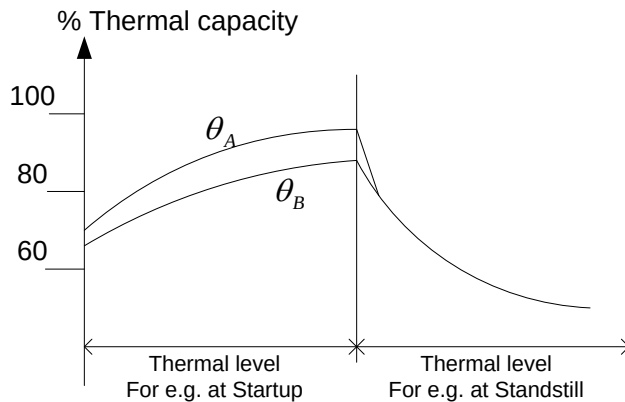


- Heating with different time constants



Motor Protection

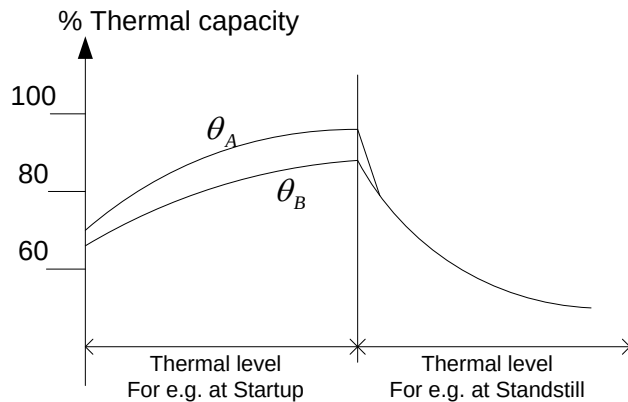
Thermal Overload Protection



- 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

Motor Protection

Thermal Overload Protection

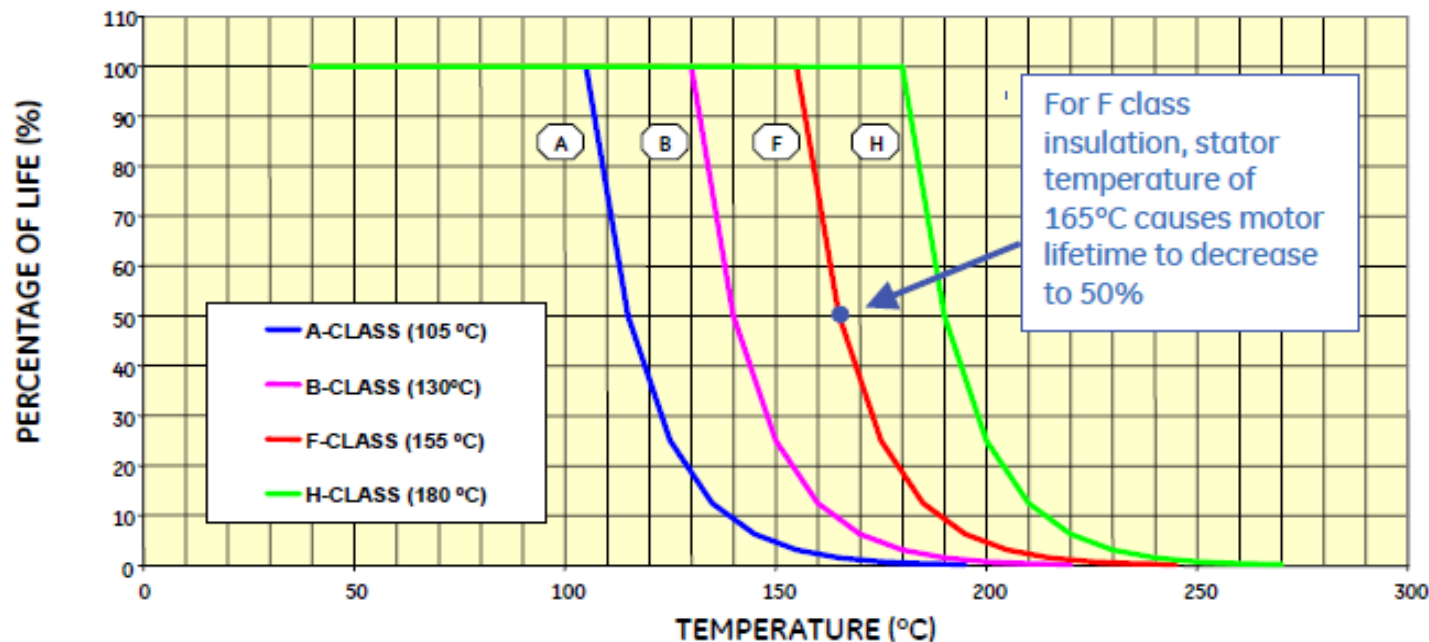


- Abnormal conditions that can result in overheating include:
 - Overload
 - Stalling
 - Failure to start
 - High ambient temperature
 - Restricted motor ventilation
 - Reduced speed operation
 - Frequent starting or jogging
 - High or low line voltage or frequency
 - Mechanical failure of the driven load, improper installation, and unbalanced line voltage or single phasing

Motor Protection

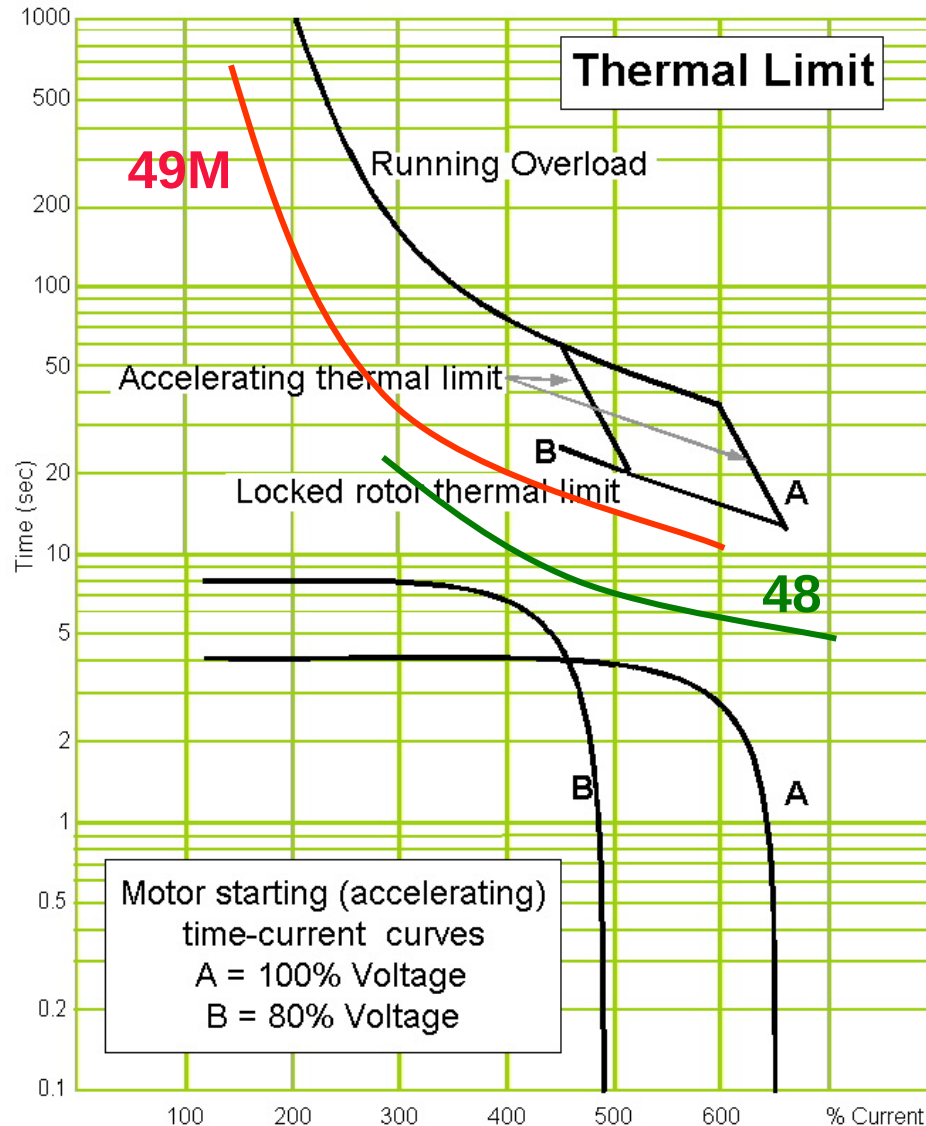
Thermal Overload Protection

- Rule of thumb developed from tests and experience indicate that the life of an insulation system is approximately,
 - halved for each 10 °C incremental increase of winding temperature
 - doubled for each 10 °C decrease (the range of 7 °C–12 °C is indicated for modern insulation systems)



Motor Protection

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

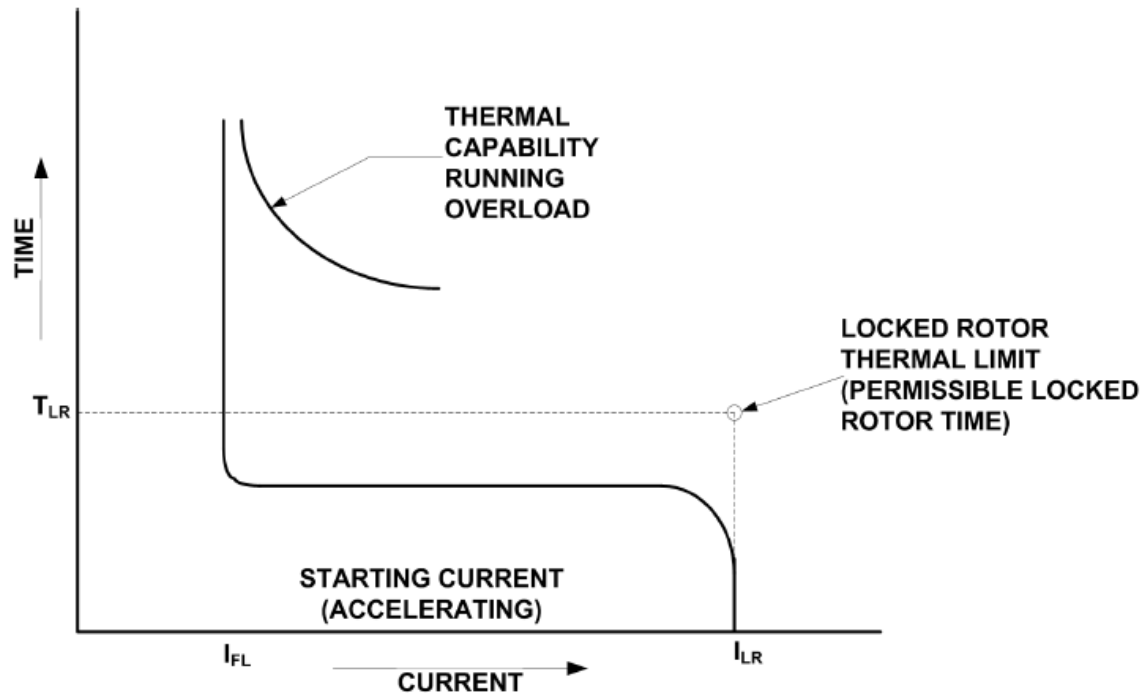
Emergency start:

- 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

Motor Startup Supervision 66/51LRS



- 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.

▪ Locked rotor or failure to accelerate

- Using a typical locked-rotor current of six times the rated current and a locked-rotor resistance of three times the normal running value:

$I^2R \sim 6^2 \times 3$, or 108 times that at normal current.

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

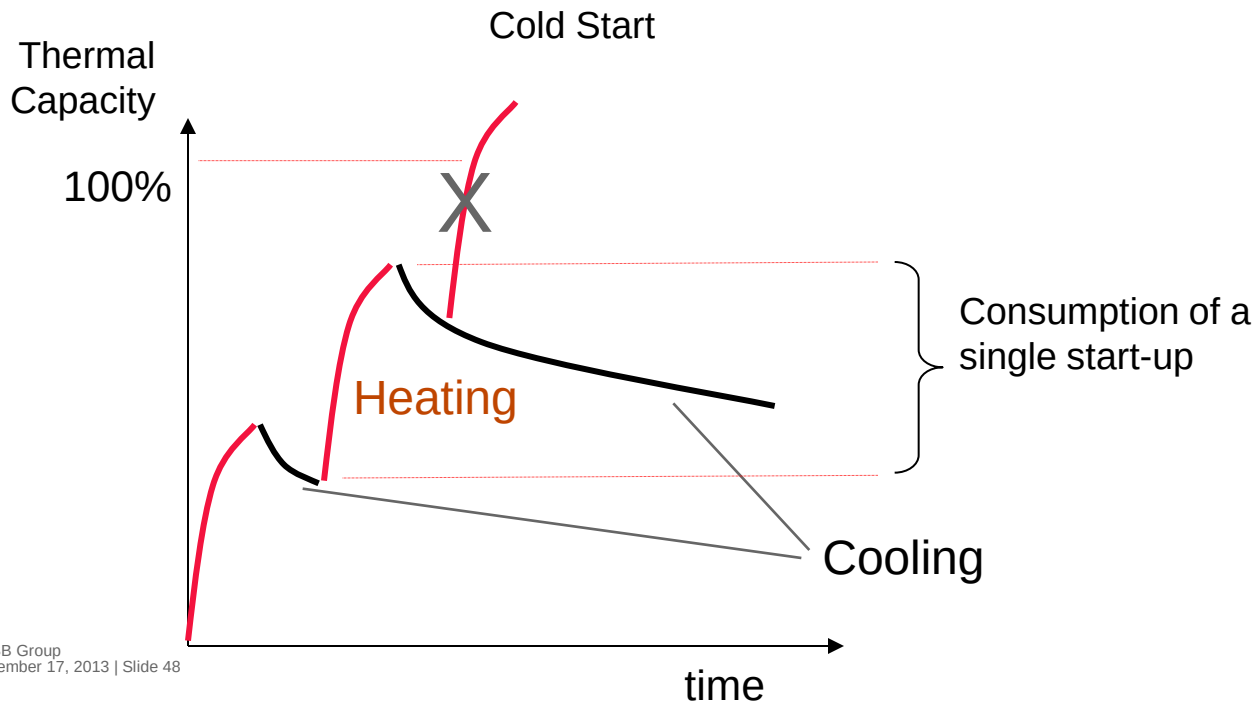
- Consequently, an extreme temperature must be tolerated for a limited time to start the motor.
- To provide locked-rotor or failure-to-accelerate protection, the protective device must be set to disconnect the motor before the stator insulation suffers thermal damage, or the rotor conductors melt or suffer damage from repeated stress and deformation.

▪ Frequent starting or intermittent operation

- 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

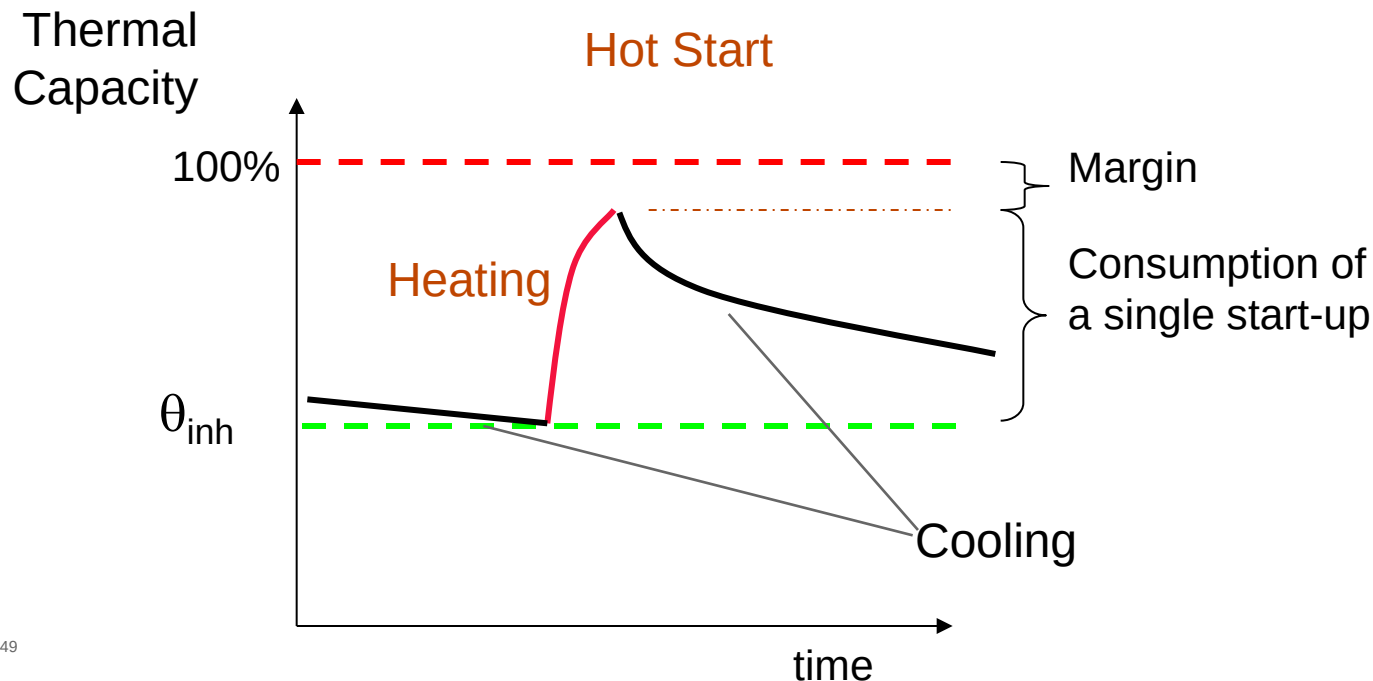
▪ Frequent starting or intermittent operation

- 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.



▪ Frequent starting or intermittent operation

- 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.
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Motor Protection

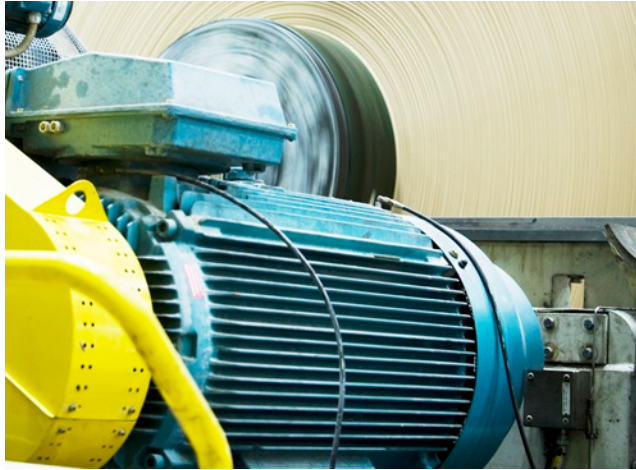
Loss of Load Supervision



- 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 healthy 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).

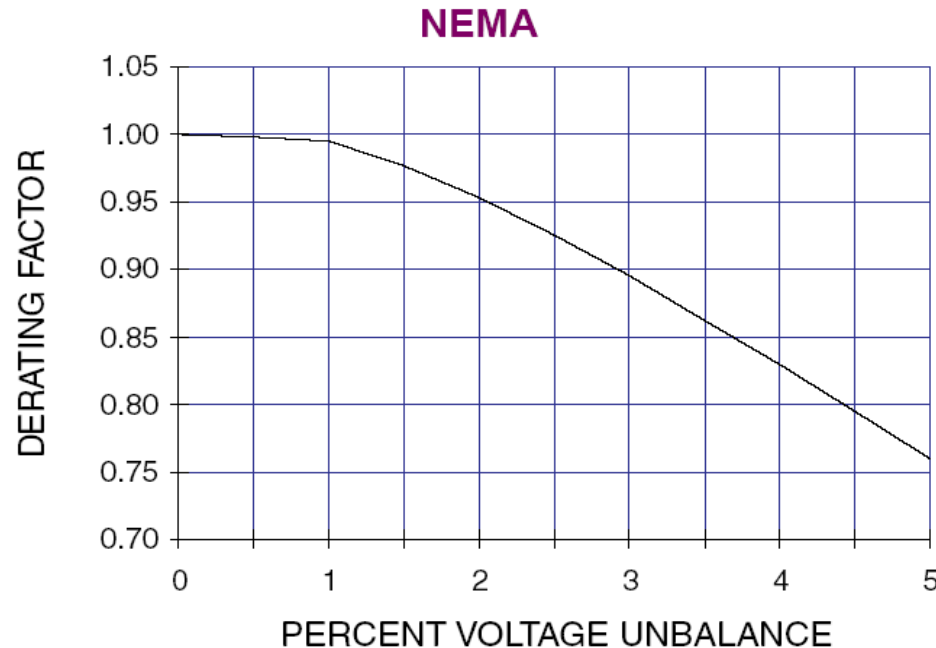
Motor Protection

Negative-Sequence Overcurrent Protection



- A small-voltage unbalance produces a large negative-sequence current flow in either a synchronous or induction motor.
- $Z_2 \sim 1/ILR$ pu
 - $ILR = 6$ pu, then $Z_2 \sim 0.167$ pu
 - Assume a $V_2 = 0.05$ pu is applied to the motor
 - From $V_2 = I_2 Z_2$, $I_2 = 0.30$ 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.

Negative Sequence Overcurrent Protection for Motors



Current Imbalance
Derates Thermal Capacity

Standing negative sequence (current imbalance) causes heating in both the stator and rotor

Negative Sequence Overcurrent Protection for Motors

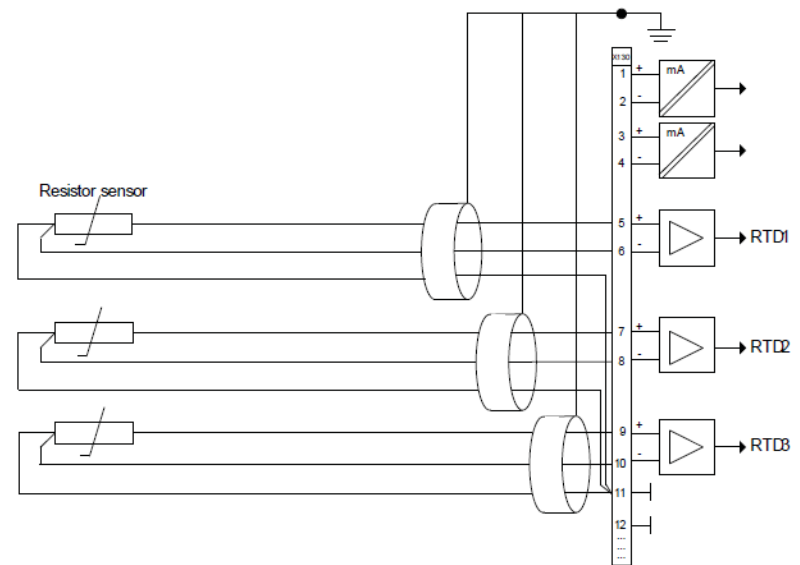
- Typical setting for the negative phase sequence voltage protection (47) is 5%
- Typical setting for the unbalance current protection (46) is 20% of nominal current
- Which protection, 46 or 47, should be applied for the unbalance protection?
 - Selective protection against voltage and current unbalance 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



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

Motor Protection

Short Circuit Protection

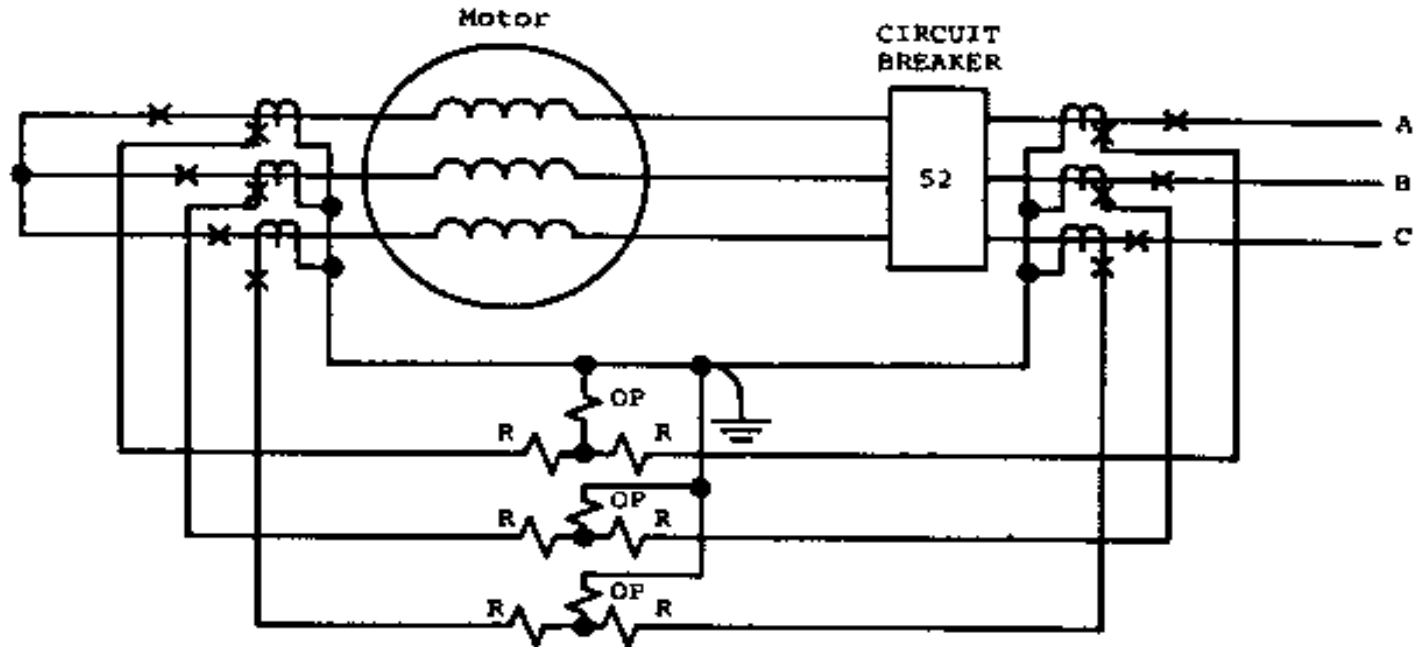
- The short circuit element provides protection for excessively high over current faults
- Phase-to-phase and phase-to-ground faults are common types of short circuits
- When a motor starts, the starting current (which is typically 6 times the Full Load Current) has asymmetrical components .
- These 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 motor.

Motor Protection

Short Circuit Protection

- 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.
- However, in case of high voltage motors (commonly called as “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, it is recommended to use percentage differential protection.

Differential Protection

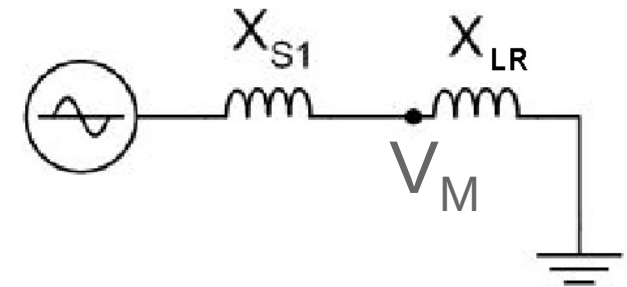
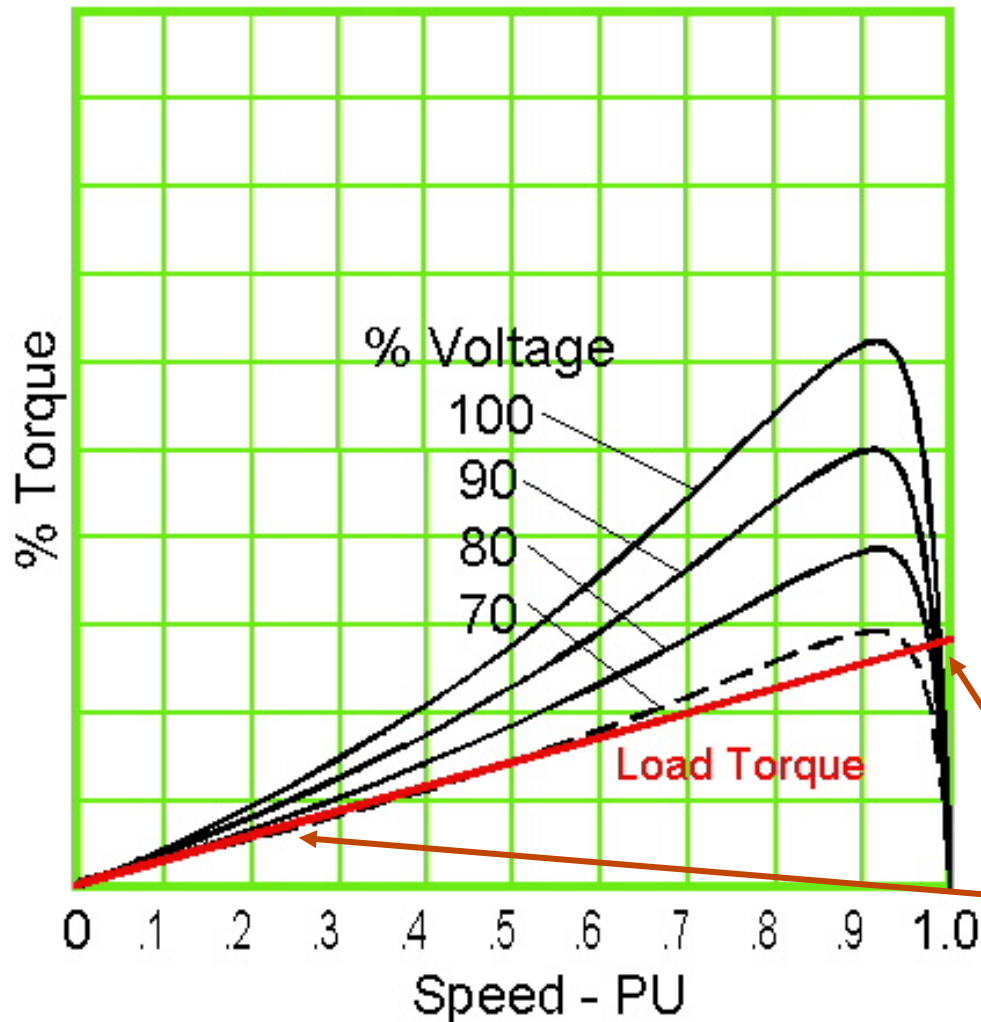


Differential protection with conventional type CT

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 cause 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
- Decrease in frequency without corresponding voltage reduction, the flux density is increased and consequently the losses and heating increased
- 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
- Power factor relay is a good solution for out of step operation since the power factor is very low during “pull out” operation

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