

# Motor Protection Principles



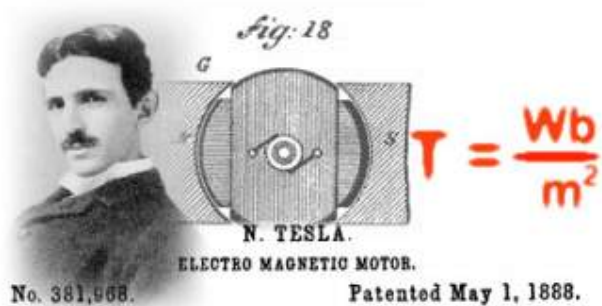
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# Motor History & Facts

- The first U.S. patent for a motor was issued to Thomas Davenport in 1837.



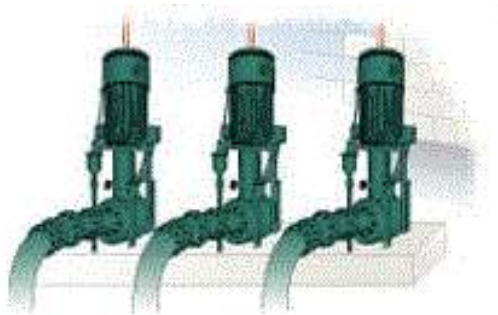
- In 1888, Nikola Tesla patented the first AC poly-phase motor.



- Today in North America, more than 1 billion motors are in service.
- Motors consume 25% of electricity in North America.
- Electricity consumption by motors in manufacturing sector is 70%. In oil, gas and mining industries around 90%.
- Three phase squirrel-cage induction motors account for over 90% of the installed motor capacity.

# Various Industry Motor Applications

- Fans, Blowers
- Pumps, Compressors
- Grinders, Chippers
- Conveyors, Shredders
- Crushers, Mixers
- Cranes, Extruders
- Refiners, Chillers



# Motor Failure Rates and Cost

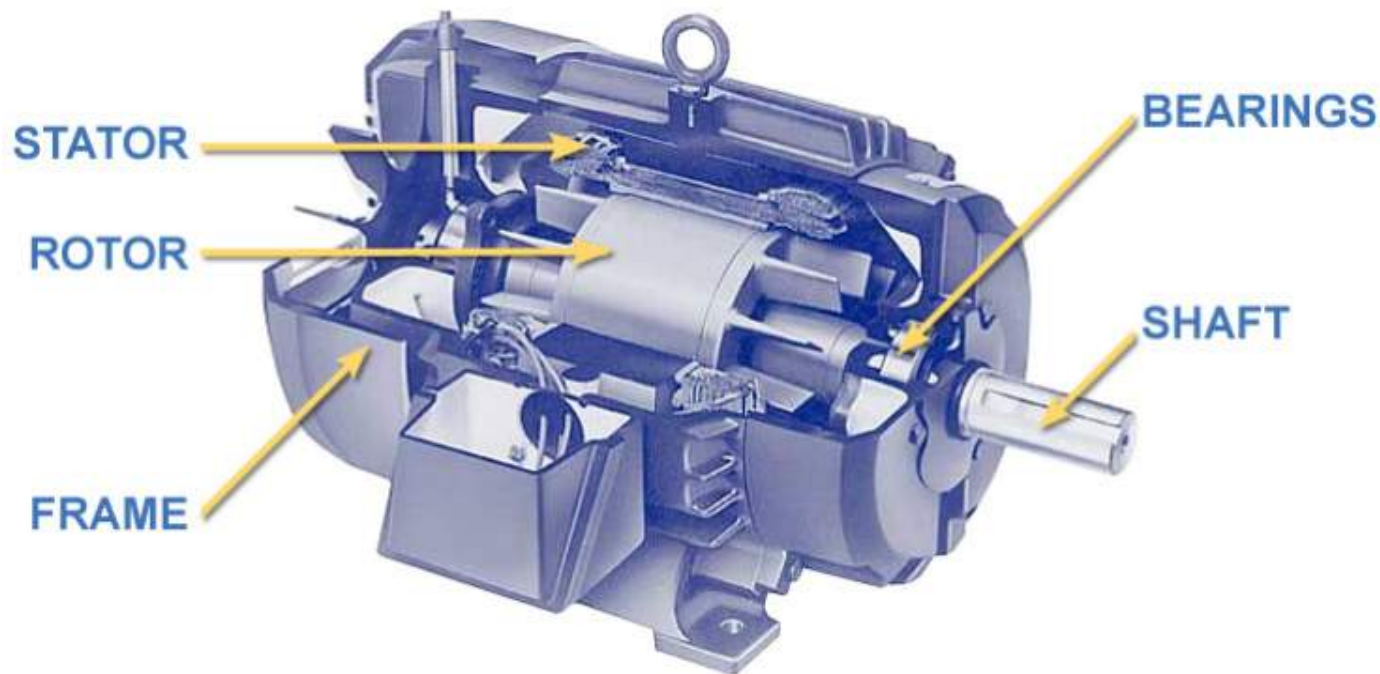
- Motor failure rate is conservatively estimated as 3-5% per year
  - In Mining, Pulp and Paper industry, motor failure rate can be as high as 12%.
- Motor failures divided in 3 groups:
  - Electrical (33%)
  - Mechanical (31%)
  - Environmental, Maintenance, & Other (36%)
- Motor failure cost contributors:
  - Repair or Replacement
  - Removal and Installation
  - Loss of Production

IEEE STUDY		EPRI STUDY		AVERAGE
FAILURE CONTRIBUTOR	%	FAILED COMPONENT	%	%
Persistent Overload	4.20%	Stator Ground Insulation	23.00	Electrical Related Failures  <b>33%</b>
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%	
High Vibration	15.50%	Sleeve Bearings	16.00	Mechanical Related Failures  <b>31%</b>
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%	
High Ambient Temp.	3	Bearing Seals	6.00	Environmental, Maintenance & Other Reasons Related Failures  <b>36%</b>
Abnormal Moisture	5.8	Oil Leakege	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 Related & Other Reasons: Total	38.70%	Maintenance Related & Other Parts: Total	32.00%	

**Harsh Conformal Coating Can Reduce Environmental Failures**

# Thermal Stress Causes Motor Failure

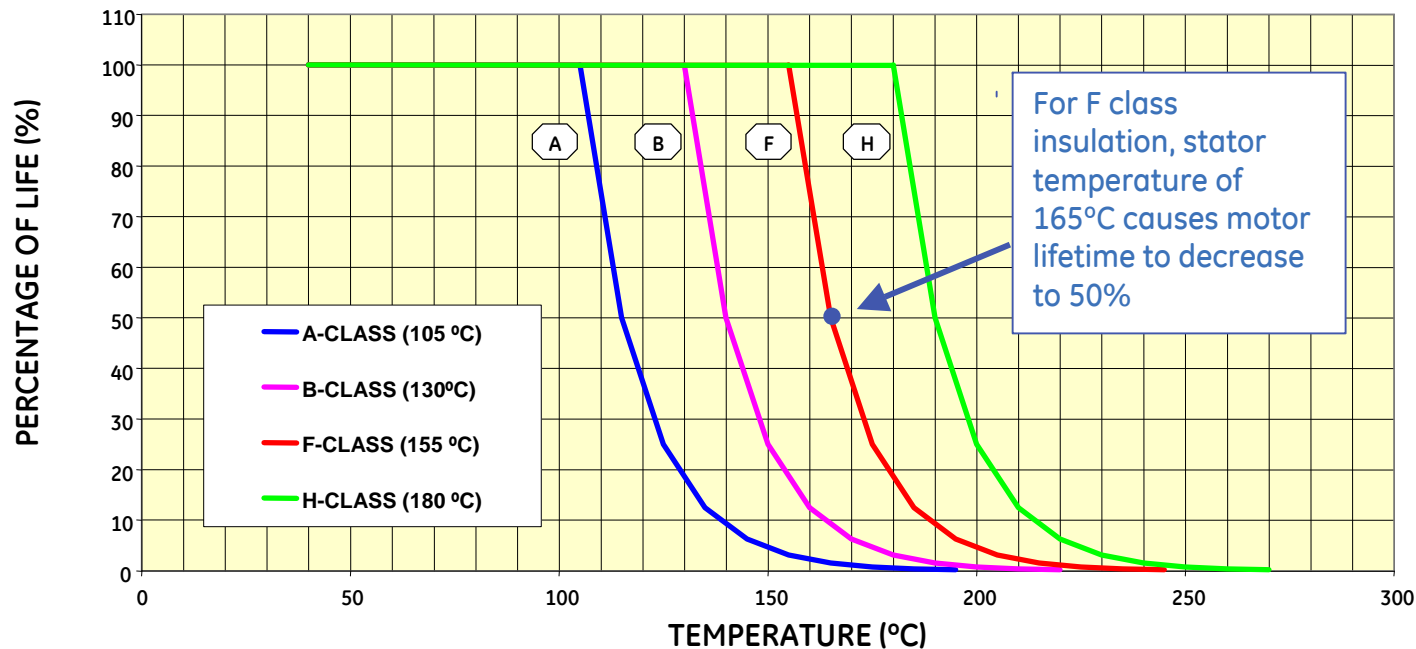
- Most of the motor failure contributors and failed motor components are related to motor overheating.
- Thermal stress potentially can cause the failure of all the major motor parts: Stator, Rotor, Bearings, Shaft and Frame.



# Risks for an Overheated Motor

- Stator Windings Insulation Degradation (for stator limited motors)

Insulation lifetime decreases by half if motor operating temperature exceeds thermal limit by 10°C for any period of time



- Rotor Conductors Deforming or Melting (for rotor limited - thermal limit is defined by motor stall time)

# Motor Electrical Protection

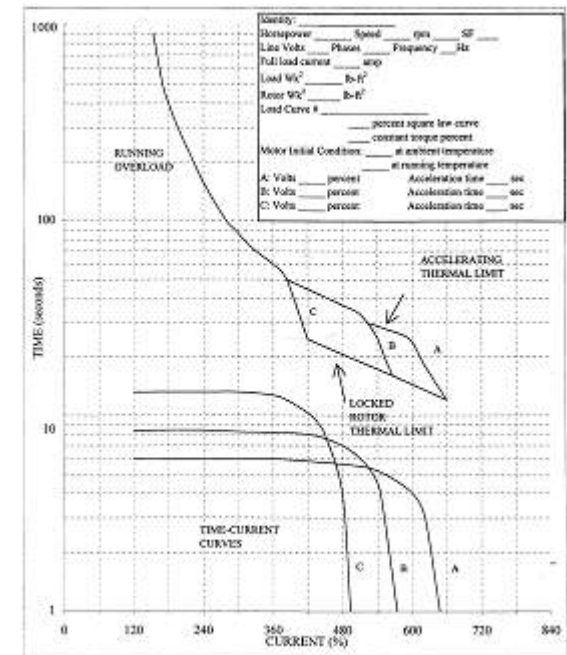
- Thermal Overload
  - Process Caused (Excessive load)
  - High Ambient Conditions (Hot, Blocked Ventilation)
  - Power Supply Issues (Voltage/Current Unbalance, Harmonics)
- Phase Fault
- Ground Fault
- Abnormal Operating Conditions
  - Over & Under Voltage
  - Underfrequency
  - Voltage and Current Unbalance
  - Load Loss
  - Jamming
  - Jogging

# Overload Protection - Thermal Model

A motor can run overloaded without a fault in motor or supply

A primary motor protective element of the motor protection relay is the **thermal overload element** and this is accomplished through motor thermal image modeling. This model must account for thermal process in the motor while motor is starting, running at normal load, running overloaded and stopped. Algorithm of the thermal model integrates both stator and rotor heating into a single model.

- Main Factors and Elements Comprising the Thermal Model are:
  - Overload Pickup Level
  - Overload Curve
  - Running & Stopped Cooling Time Constants
  - Hot/Cold Stall Time Ratio
  - RTD & Unbalance Biasing
  - Motor State Machine





# Thermal Model - Motor States

- **Motor Stopped:**

Current < “0” threshold & contactor/breaker is open.

- **Motor Starting:**

Previous state is “Stopped” & Current > “0” threshold. Motor current must increase to the level higher than overload pickup within seconds.

- **Motor Running:**

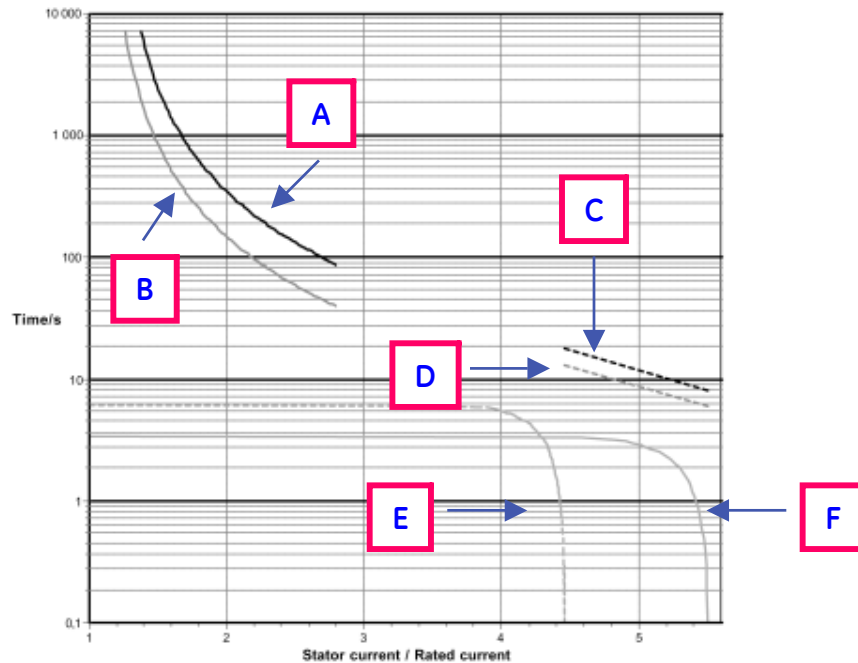
Previous state is “Starting” or “Overloading” & Current drops below overload pickup level.

- **Motor Overloading:**

Previous state is “Running” & Current raises above overload pickup level. Thermal Capacity Used (TCU) begins to accumulate during overload.

# Motor Thermal Limit Curves

- Thermal Limit of the model is dictated by overload curve constructed in the motor protection device in reference to thermal damage curves normally supplied by motor manufacturer.
- Motor protection device is equipped with set of standard curves and capable to construct customized curves for any motor application.



## Thermal Limit Curves:

- A. Cold Running Overload
- B. Hot Running Overload
- C. Cold Locked Rotor Curve
- D. Hot Locked Rotor Curve
- E. Acceleration curve @ 80% rated voltage
- F. Acceleration curve @ 100% voltage

# Thermal Overload Pickup

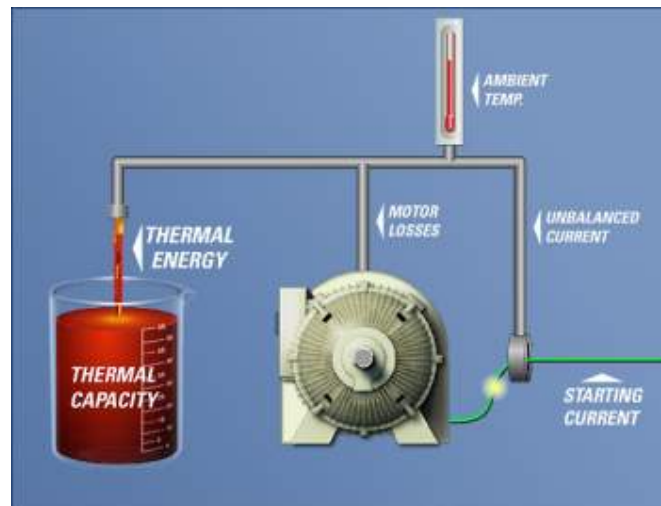
- Set to the maximum allowed by the service factor of the motor.
- Set slightly above the motor service factor by 8-10% to account for measuring errors
- If RTD Biasing of Thermal Model is used, thermal overload setting can be set higher
- Note: motor feeder cables are normally sized at 1.25 times motor's full load current rating, which would limit the motor overload pickup setting to a maximum of 125%.

POWER	:8000 HP	TYPE	:K
POLES	:4	FRAME	:8713Z
VOLTAGE	:13200 V	ENCLOSURE	:WPII
FREQUENCY	:60 Hz	PHASES	:3
		SERVICE FACTOR	:1.00
		INSULATION CLASS	:F (POLYESTER)
TEMPERATURE RISE:80 C /RTD @ SF 1.0			
-----			
DRIVEN LOAD	:FAN CLOSED VALVE		
MAX. ALTITUDE	:3300 Ft		
LOAD WK2 REF. TO MOTOR SHAFT	: 49249 Lbft2		
-----			
		Calculated Performance	
RATED RPM	:1780	NEMA STARTING CODE	:F
RATED CURRENT	: 297 A	LOCKED ROTOR CURRENT	:540 %
RATED TORQUE	:23571 lbft	LOCKED ROTOR TORQUE	:77 %
RATED KVA	:6790	PULL UP TORQUE	:77 %
STATOR CONNECTION	:Y	BREAKDOWN TORQUE	:245 %
MIN. STG. VOLTAGE	:70% V	COUPLING TYPE	:DIRECT
TIME RATING	:CONTINUOUS	ARRANGEMENT	:F1
AMB. TEMP. (MIN/MAX)	:-18/40 C	ROTATION	:DUAL
TOTAL WEIGHT (calc.)	:53700 lb	MAX. BRG.VIBR. (PK-PK)	:0.0016 in
ROTOR WK2 (calculated)	:10422 Lbft2	BEARING TYPE	:SLEEVE
		BEARING LUBRICATION	:OIL
		END PLAY	:0.50 in
NOISE LEVEL (dBA)	: 85.0 @ 3.3 ft	LOCKED ROTOR TIME	
MAX CAPACITOR KVAR	:1000	COLD	:35 Sec
STATOR RESIST. @ 25C	:0.1910 Ohms L-L	HOT	:30 Sec
X/R RATIO	: 33.960	NUMBER OF STARTS (NEMA MG1-20.43)	
OPEN CIRC. CONSTANT	:1.5680 S	COLD	:2
ACCELERATION TIME	:15 Sec	OR HOT	:1

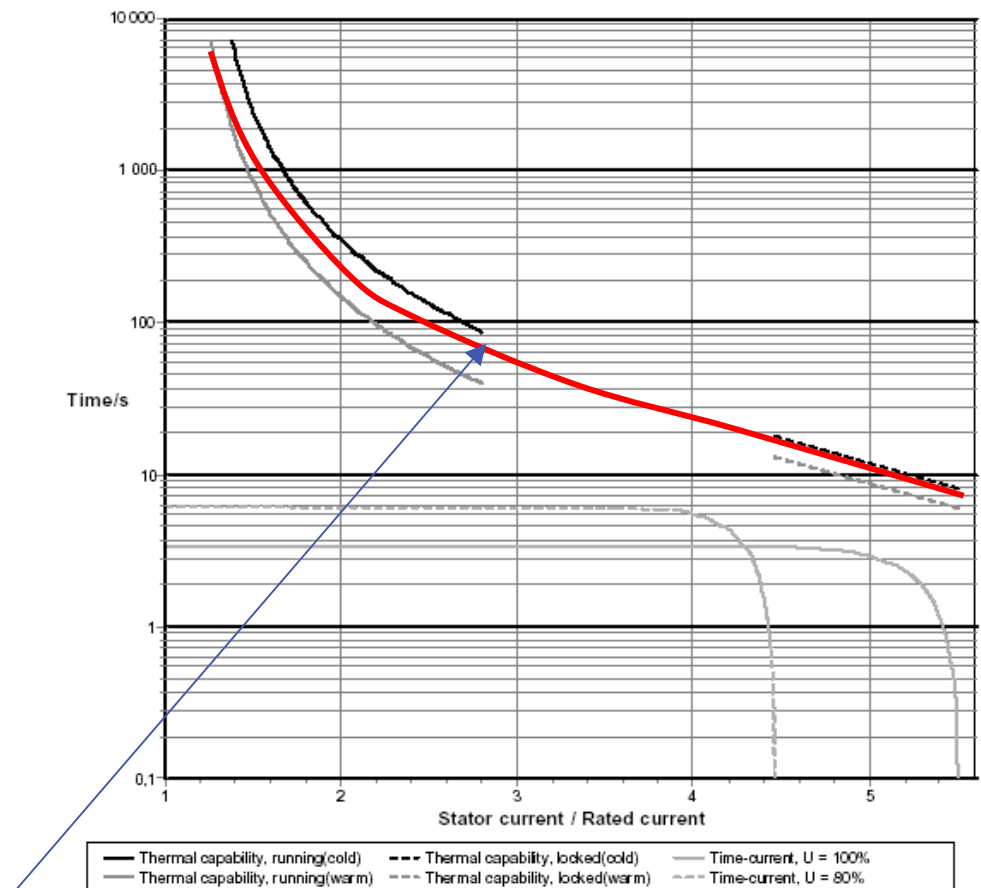
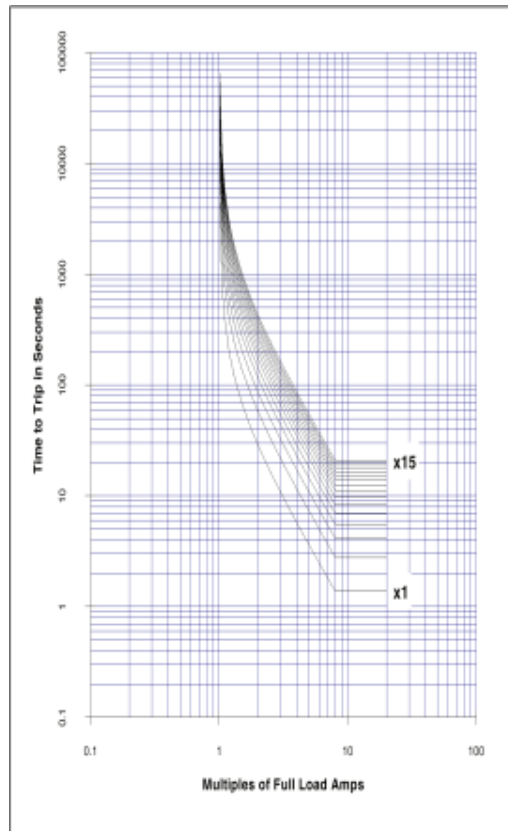
<u>SF</u>	<u>Thermal Overload Pickup</u>
1.0	1.1
1.15	1.25

# Thermal Model – Thermal Capacity Used

- Thermal Capacity Used (TCU) is a criterion selected in thermal model to evaluate thermal condition of the motor.
- TCU is defined as percentage of motor thermal limit utilized during motor operation.
- A running motor will have some level of thermal capacity used due to Motor Losses.
- Thermal Overload Trip when Thermal Capacity Used equals 100%



# Overload Curve Selection for Thermal Model

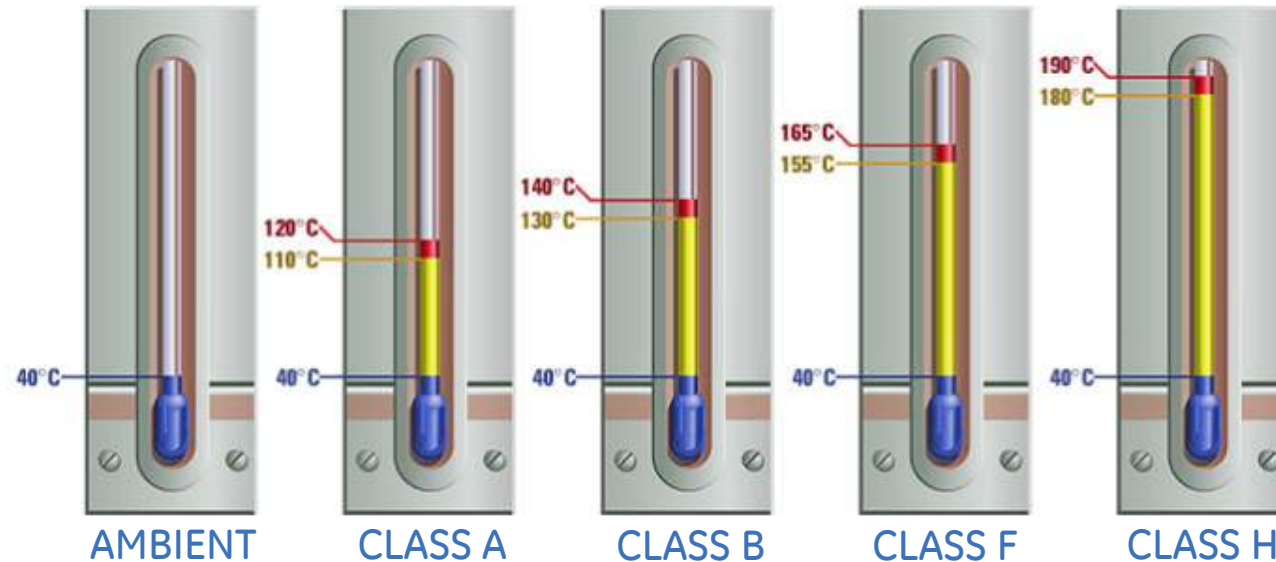


## Overload Curve

Set the overload curve below cold thermal limit and above hot thermal limit  
If only hot curve is provided by mfg, then must set at or below hot thermal limit

# Thermal Model–Hot/Cold Stall Time Ratio (HCR)

- Typically motor manufacturer provides the values of the locked rotor thermal limits for 2 motor conditions:
  - *COLD*: motor @ ambient temperature
  - *HOT*: motor @ rated temperature for specific class and service factor.
- NEMA standard temperature rises for motors up to 1500HP and Service Factors 1 and 1.15 respectively.



- When motor is running below overload pickup, the TCU will rise or fall to value based on average current and HCR. HCR is used to calculate level of TCU by relay, at which motor will settle for current below overload pickup.

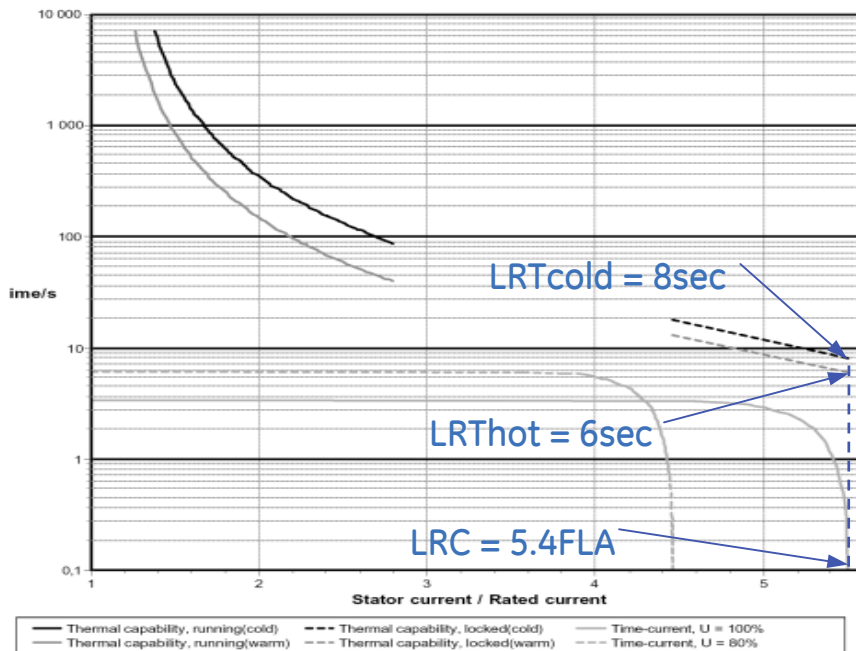
# Hot/Cold Safe Stall Ratio

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PHASES :3	INSULATION CLASS:F (POLYSEAL)
TEMPERATURE RISE:80 C /RTD @ SF 1.0	
-----	
DRIVEN LOAD :FAN CLOSED VALVE	
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Calculated Performance	
RATED RPM :1780	NEMA STARTING CODE :F
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TIME RATING :CONTINUOUS	ARRANGEMENT :F1
AMB. TEMP. (MIN/MAX) :-18/40 C	ROTATION :DUAL
TOTAL WEIGHT (calc.) :53700 lb	MAX. BRG. VIBR. (PK-PK) :0.0016 in
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NOISE LEVEL (dBA) :85.0 @ 3.3 ft	BEARING LUBRICATION :OIL
MAX CAPACITOR KVAR :1000	END PLAY :0.50 in
STATOR RESIST. @ 25C :0.1910 Ohms L-L	LOCKED ROTOR TIME :35 Sec
X/R RATIO :33.960	COLD :30 Sec
OPEN CIRC. CONSTANT :1.5680 S	HOT :30 Sec
ACCELERATION TIME :15 Sec	NUMBER OF STARTS (NEW) :20.457
	COLD :2
	OR HOT :1

$$HCR = \frac{LRT_{HOT}}{LRT_{COLD}}$$

Hot/Cold Ratio =  
30/35  
=> 0.86

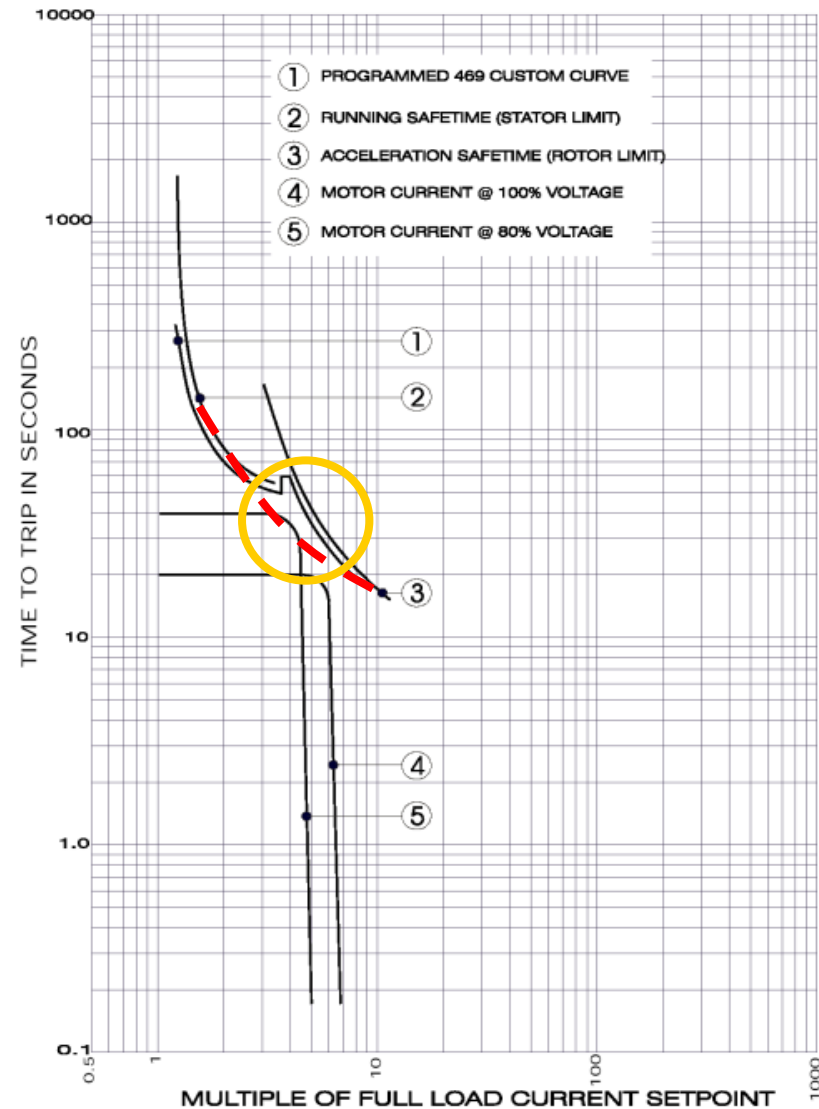
## Overload Curve Method



- If the thermal limits curves are being used to determine the HOT/COLD ratio proceed as follows:
- From the thermal limits curves run a line perpendicular to the current axis that intersects the hot and cold curves at the stall point or LRA
- The Hot/cold ratio can now be calculated as follows:  
= 6s/8s = 0.75
- If hot and cold times are not provided and only one curve is given verify with the manufacturer that it is the hot curve ( which is the worst case), then the Hot/ Cold ratio should be set to 1.0

# Overload Curve Selection

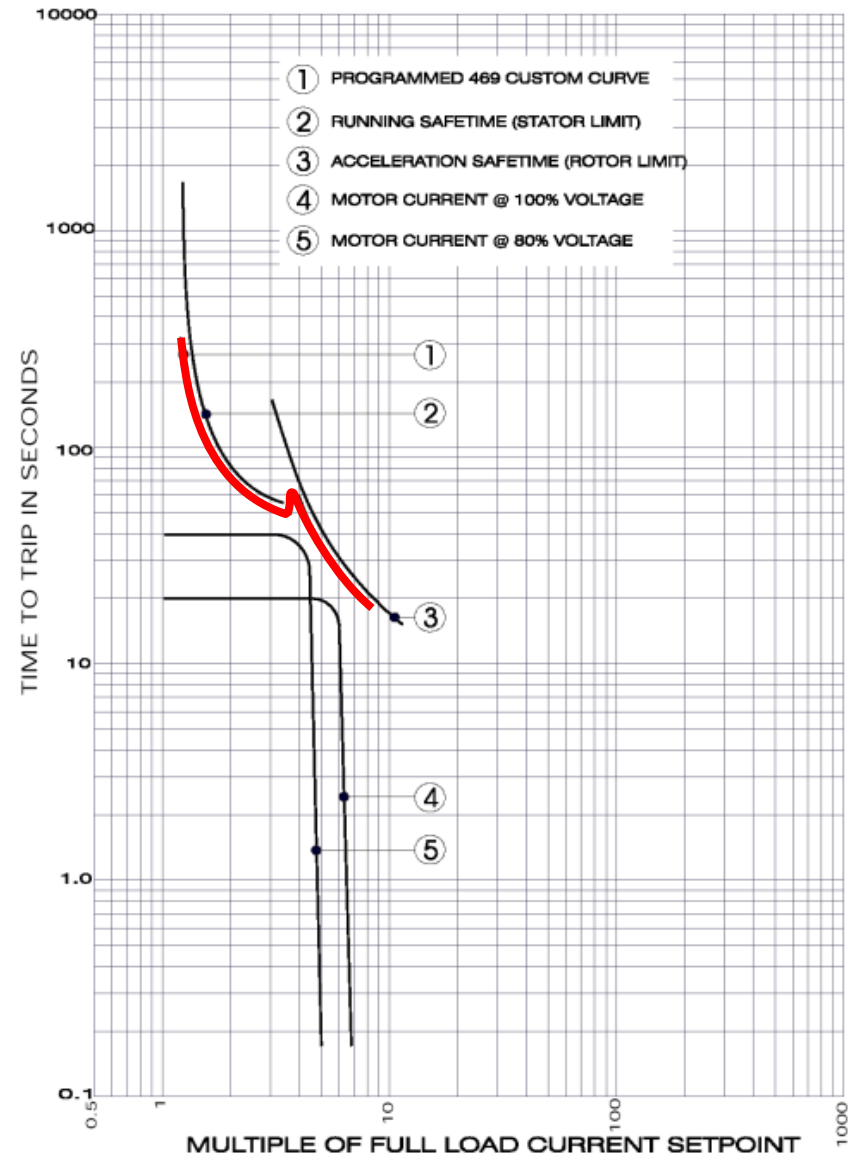
If the motor starting current begins to infringe on the thermal damage curves or if the motor is called upon to drive a high inertia load such that the acceleration time exceeds the safe stall time, **custom or voltage dependent overload curve** may be required.





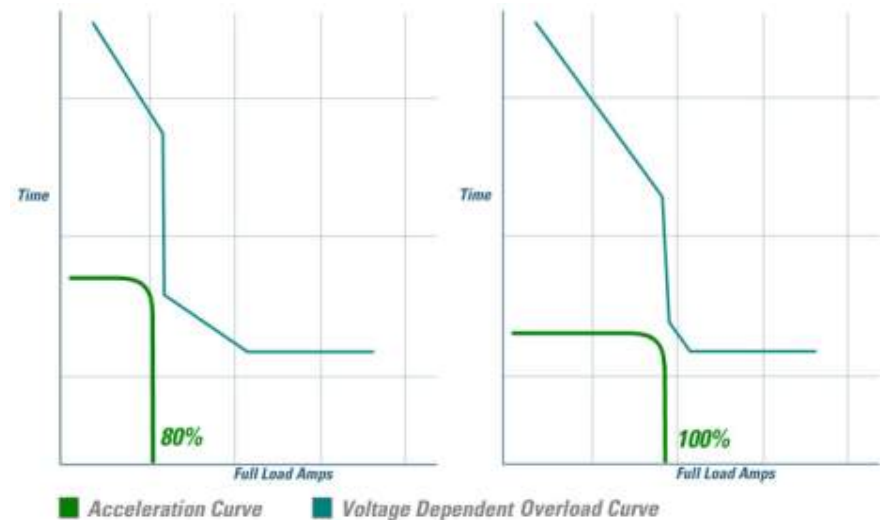
# Overload Curve Selection

A custom overload curve will allow the user to tailor the relay's thermal damage curve to the motor such that a successful start can occur without compromising protection while at the same time utilizing the motor to its full potential during the running condition.



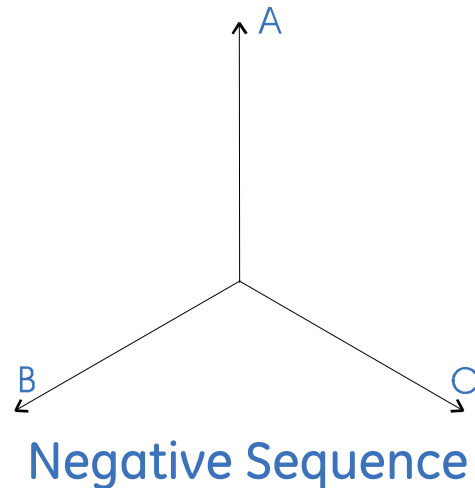
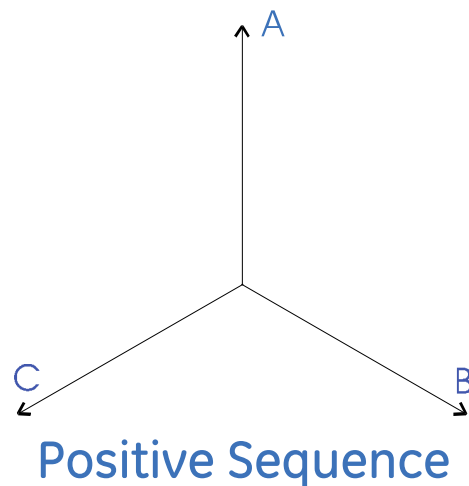
# Thermal Model Behavior - Long Starts

- Issue → Duration of a high inertia load start is longer than the allowed motor safe stall time.
  - For these starts, thermal model must account for the current change during acceleration and also use the acceleration thermal limits for TCU calculations.
  - Motor thermal limit is growing along with motor rotation speed during acceleration.
  - Starting current is proportional to system voltage during motor acceleration, thus voltage could be a good indication of the current level corresponding to the locked rotor conditions.
- Voltage dependant dynamic thermal limit curve is employed to enhance the thermal model algorithm.
- Motor relay will shift acceleration thermal limit curve linearly and constantly based on measured line voltage during a motor start.

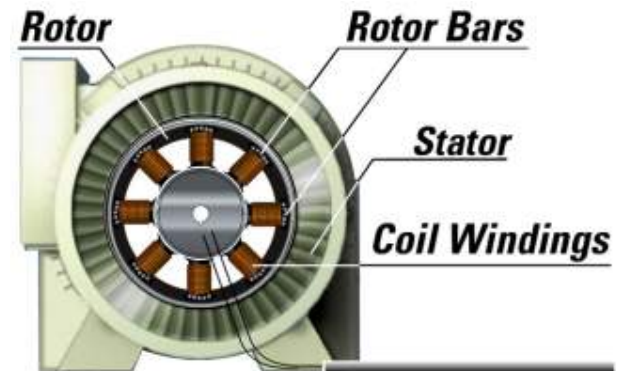


# Thermal Model - Current Unbalance Bias

Negative sequence currents (or unbalanced phase currents) will cause additional rotor heating that will be accounted for in Thermal Model.



- Main causes of current unbalance
  - Blown fuses
  - Loose connections
  - Stator turn-to-turn faults
  - System voltage distortion and unbalance
  - Faults



# Thermal Model - Current Unbalance Bias

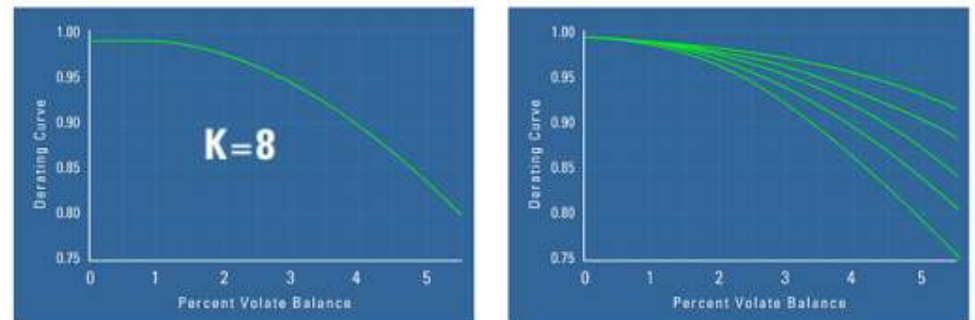
- **Equivalent heating motor current** is employed to bias thermal model in response to current unbalance.

$$I_{EQ} = \sqrt{I_M^2 \times (1 + K \times (I_2/I_1)^2)}$$

- $I_m$  - real motor current;  $K$  - unbalance bias factor;  $I_1$  &  $I_2$  - positive and negative sequence components of motor current.
- $K$  factor reflects the degree of extra heating caused by the negative sequence component of the motor current.
- IEEE guidelines for typical and conservative estimates of  $K$ .

$$K = 175/I_{LRC}^2 \quad \text{TYPICAL}$$

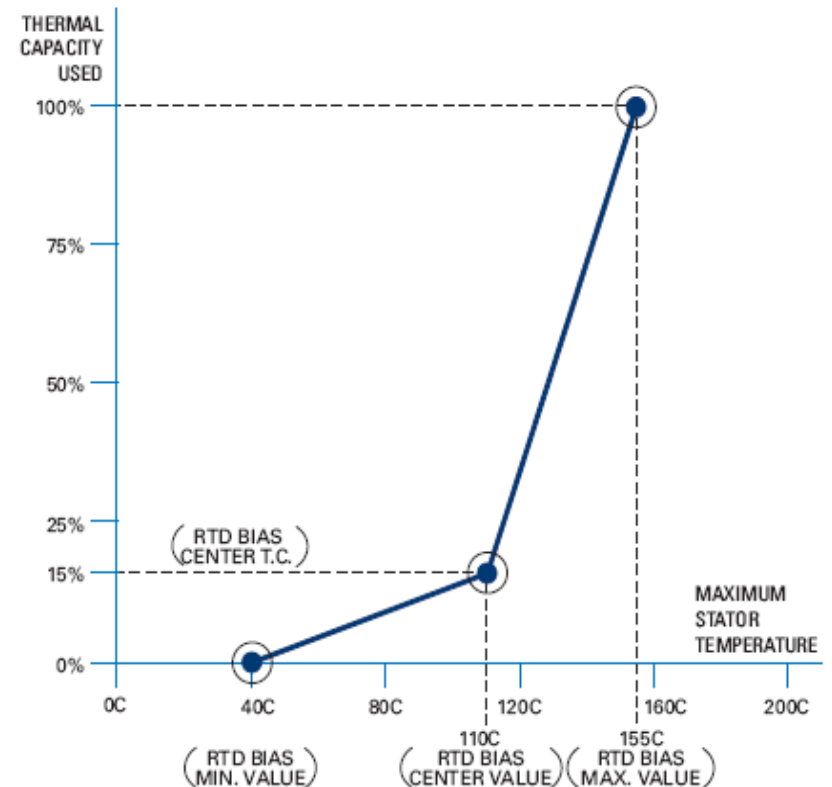
$$K = 230/I_{LRC}^2 \quad \text{CONSERVATIVE}$$



**NEMA**  
**Motor Derating Curves**

# Thermal Model – RTD Bias

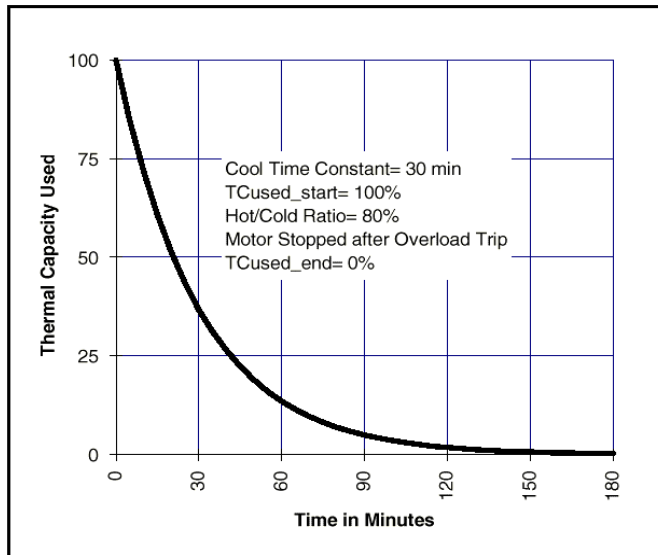
- Accelerate thermal trip for hot stator windings
- RTD bias model determines the Thermal Capacity Used based on the temperature of the Stator and is separate from the overload model for calculating Thermal Capacity Used.
- Motor relay will use the calculated thermal capacity unless the RTD thermal capacity is higher.
- This function will not trip the motor at the max point temp unless the average current is greater than the overload pickup setting
- RTD biasing is a back up protection element which accounts for such things as loss of cooling or unusually high ambient temperature.



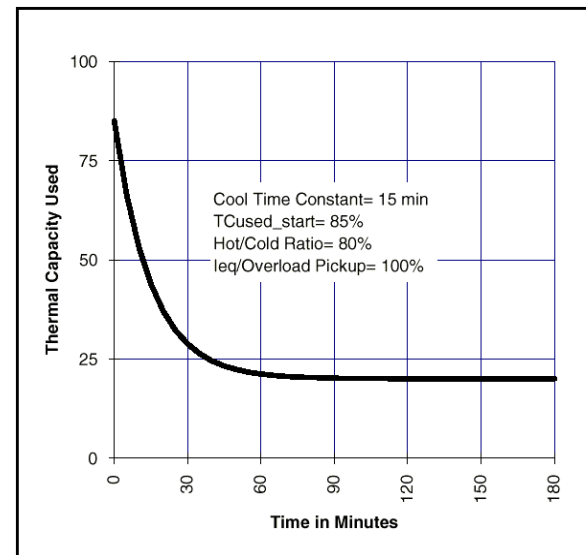
# Thermal Model - Motor Cooling

- Motor cooling is characterized by separate cooling time constants (CTC) for running and stopped motor states. Typical ratio of the stopped to running CTC is 2/1
- It takes the motor typically 5 time constants to cool.

## Thermal Model Cooling Motor Tripped



## Thermal Model Cooling 100% load - Running



# Overvoltage Protection

- The overall result of an overvoltage condition is a decrease in load current and poor power factor.
- Although old motors had robust design, new motors are designed close to saturation point for better utilization of core materials and increasing the V/Hz ratio cause saturation of air gap flux leading to motor heating.
- The overvoltage element should be set to 110% of the motors nameplate unless otherwise started in the data sheets.

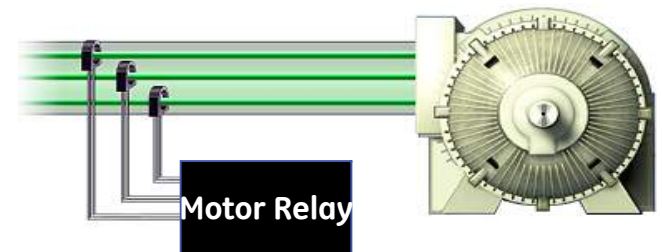
# Undervoltage Protection

- The overall result of an undervoltage condition is an increase in current and motor heating and a reduction in overall motor performance.
- The undervoltage protection element can be thought of as backup protection for the thermal overload element. In some cases, if an undervoltage condition exists it may be desirable to trip the motor faster than thermal overload element.
- The undervoltage trip should be set to 80-90% of nameplate unless otherwise stated on the motor data sheets.
- Motors that are connected to the same source/bus may experience a temporary undervoltage, when one of motors starts. To override this temporary voltage sags, a time delay setpoint should be set greater than the motor starting time.



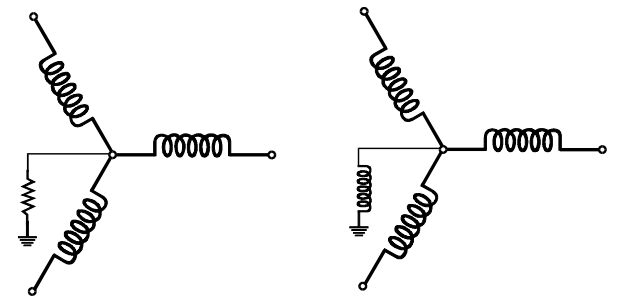
# Unbalance Protection

- Indication of unbalance → negative sequence current / voltage
- Unbalance causes motor stress and temperature rise
- Current unbalance in a motor is result of unequal line voltages
  - Unbalanced supply, blown fuse, single-phasing
- Current unbalance can also be present due to:
  - Loose or bad connections
  - Incorrect phase rotation connection
  - Stator turn-to-turn faults
- For a typical three-phase induction motor:
  - 1% voltage unbalance (V2) relates to 6% current unbalance (I2)
  - For small and medium sized motors, only current transformers (CTs) are available and no voltage transformers (VTs). Measure current unbalance and protect motor.
  - The heating effect caused by current unbalance will be protected by enabling the unbalance input to the thermal model
  - For example, a setting of 10-15% x FLA for the current unbalance alarm with a delay of 5-10 seconds and a trip level setting of 20-25% x FLA for the current unbalance trip with a delay of 2-5 seconds would be appropriate.

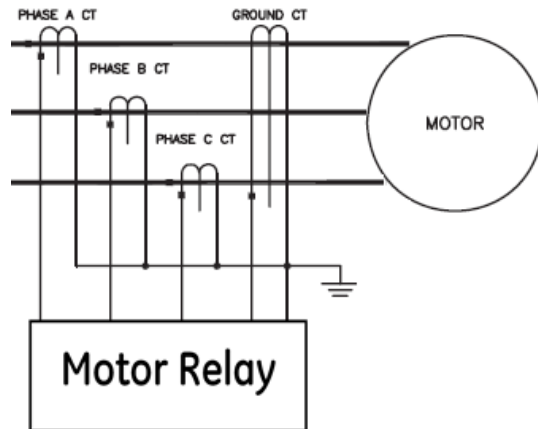


# Ground Fault Protection

- A ground fault is a fault that creates a path for current to flow from one of the phases directly to the neutral through the earth bypassing the load
- Ground faults in a motor occur:
  - When its phase conductor's insulation is damaged for example due to voltage stress, moisture or internal fault occurs between the conductor and ground
- To limit the level of the ground fault current connect an impedance between the supplies neutral and ground. This impedance can be in the form of a resistor or grounding transformer sized to ensure maximum ground fault current is limited.



# Ground Fault Protection

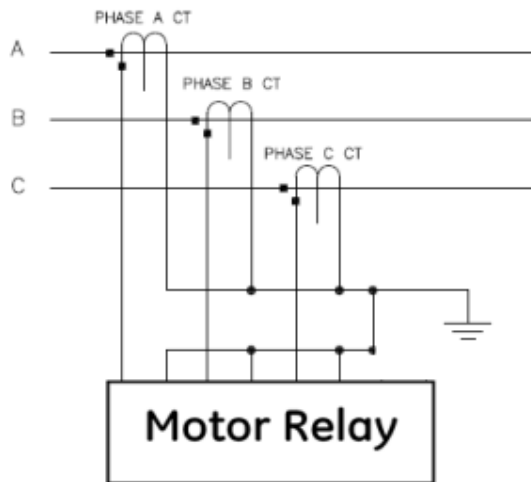


## Zero Sequence CT Connection

- Best method
- Most sensitive & inherent noise immunity

- All phase conductors are passed through the window of the same CT referred to as the zero sequence CT
- Under normal circumstances, the three phase currents will sum to zero resulting in an output of zero from the Zero Sequence CT's secondary.
- If one of the motors phases were to shorted to ground, the sum of the phase currents would no longer equal zero causing a current to flow in the secondary of the zero sequence. This current would be detected by the motor relay as a ground fault.

# Ground Fault Protection



## Residual Ground Fault Connection

- Less sensitive
- Drawbacks due to asymmetrical starting current and un-matched CTs

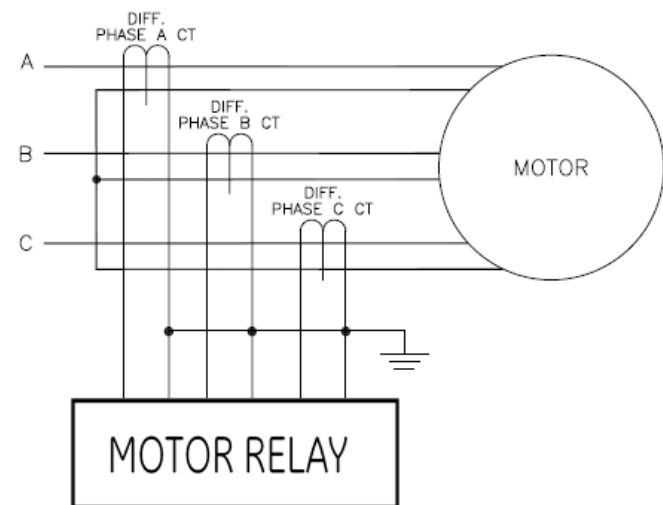
- For large cables that cannot be fit through the zero sequence CT's window, the residual ground fault configuration can be used.
- This configuration is inherently less sensitive than that of the zero sequence configuration owing to the fact that the CTs are not perfectly matched.
- During motor starting, the motor's phase currents typically rise to magnitudes excess of 6 times motors full load current and are asymmetrical.
- The combination of non perfectly matched CTs and relative large phase current magnitudes produce a false residual current. This current will be misinterpreted by the motor relay as a ground fault unless the ground fault element's pickup is set high enough to disregard this error during starting

# Differential Protection

- Differential protection may be considered the first line of protection for internal phase-to-phase or phase-to-ground faults. In the event of such faults, the quick response of the differential element may limit the damage that may have otherwise occurred to the motor.

## Core balance method:

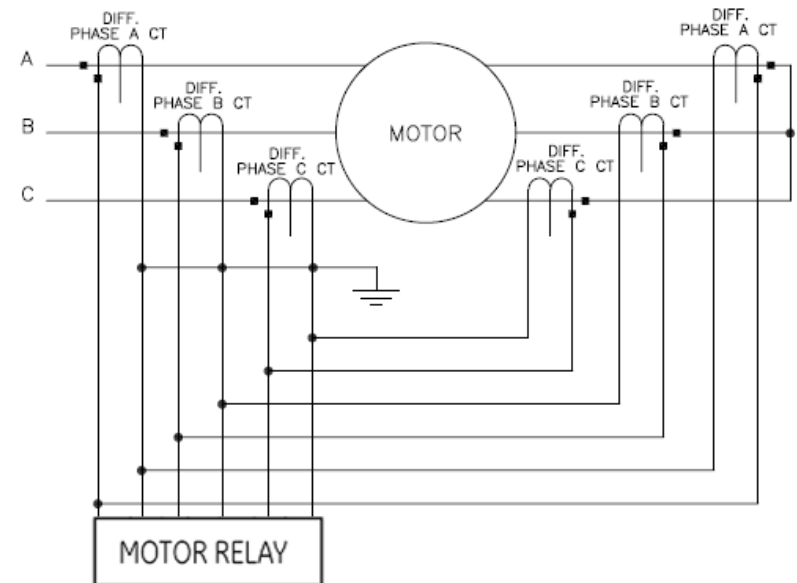
- Two sets of CT's, one at the beginning of the motor feeder, and the other at the neutral point
- Alternatively, one set of three core-balance CTs can also be used
- The differential element subtracts the current coming out of each phase from the current going into each phase and compares the result or difference with the differential pickup level.



# Differential Protection

## Summation method with six CTs:

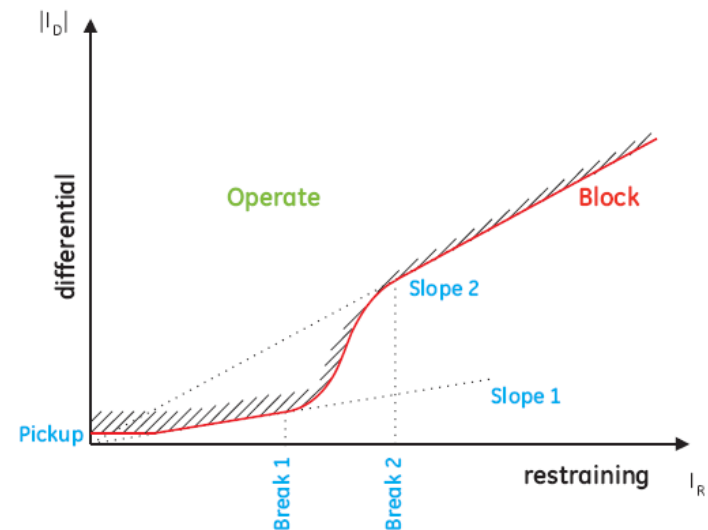
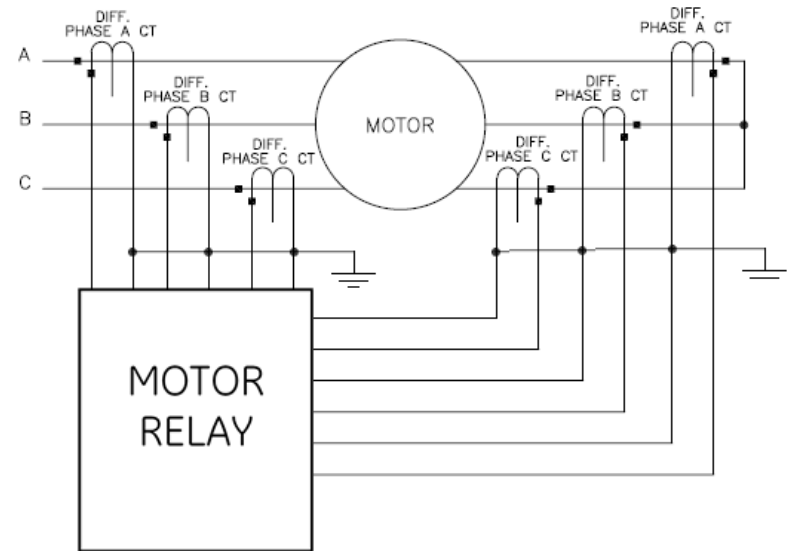
- If six CTs are used in a summing configuration, during motor starting, the values from the two CTs on each phase may not be equal as the CTs are not perfectly identical and asymmetrical currents may cause the CTs on each phase to have different outputs.
- To prevent nuisance tripping in this configuration, the differential level may have to be set less sensitive, or the differential time delay may have to be extended to ride through the problem period during motor starting.
- The running differential delay can then be fine tuned to an application such that it responds very fast and is sensitive to low differential current levels.



# Differential Protection

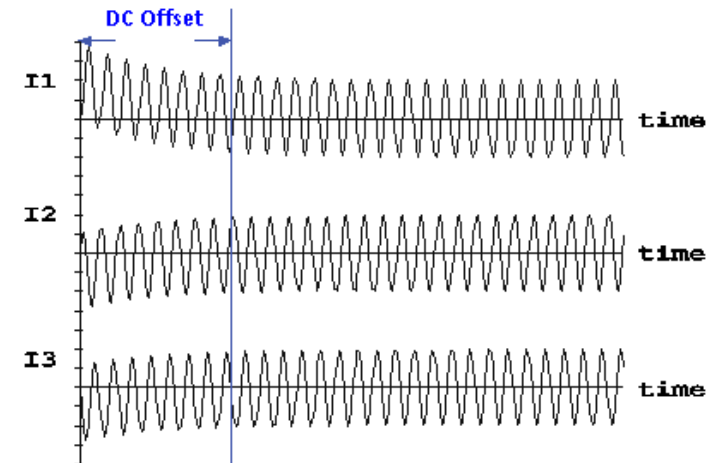
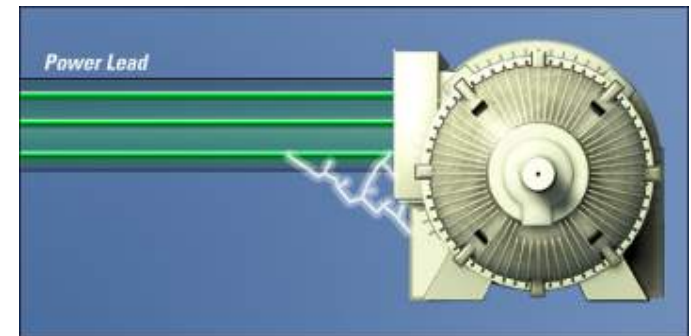
## Biased differential protection - six CTs:

- Biased differential protection method allows for different ratios for system/line and the neutral CT's.
- This method has a dual slope characteristic. Main purpose of the percent-slope characteristic is to prevent a mis-operation caused by unbalances between CTs during external faults. CT unbalances arise as a result of CT accuracy errors or CT saturation.
- Characteristic allows for very sensitive settings when the fault current is low and less sensitive settings when the fault current is high and CT performance may produce incorrect operating signals.



# Short Circuit Protection

- The short circuit element provides protection for excessively high overcurrent 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 the short circuit protection pick up to a value at least 1.7 times the maximum expected symmetrical starting current of motor.
- The breaker or contactor must have an interrupting capacity equal to or greater then the maximum available fault current or let an upstream protective device interrupt fault current.





# Stator RTD Protection

- 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  $155^{\circ}\text{C}$  could have the Stator RTD Trip level be set between  $140^{\circ}\text{C}$  to  $145^{\circ}\text{C}$ , with  $145^{\circ}\text{C}$  being the maximum ( $155^{\circ}\text{C} - 10^{\circ}\text{C}$  hot spot)
- The stator RTD alarm level could be set to a level to provide a warning that the motor temperature is rising



# Additional Protection Methods

- Start Inhibit

This function will limit starts when the motor is already hot.

- Starts/Hour

- Time Between Starts (Jogging)

- Bearing RTD Protection

- Acceleration Trip

Set higher than the maximum starting time to avoid nuisance tripping when the voltage is lower or for varying loads during acceleration.

# Conclusions

- Induction & synchronous motors are valuable assets to today's industrial facilities.
- The temperature rise of motor dictates its life
- When applied, thermal protection can prevent loss of motor life
- Additional protection elements such as overvoltage, undervoltage, unbalance, ground fault, differential, short circuit and stator RTD supplement the thermal model protection and provide complete motor protection.
- Harsh conformal coating of motor protection relays should be considered to avoid the environmental effects of harsh gaseous sulphides (H<sub>2</sub>S, etc.)