Motor Protection Fundamentals

IEEE SF Power and Energy Society
May 29, 2015

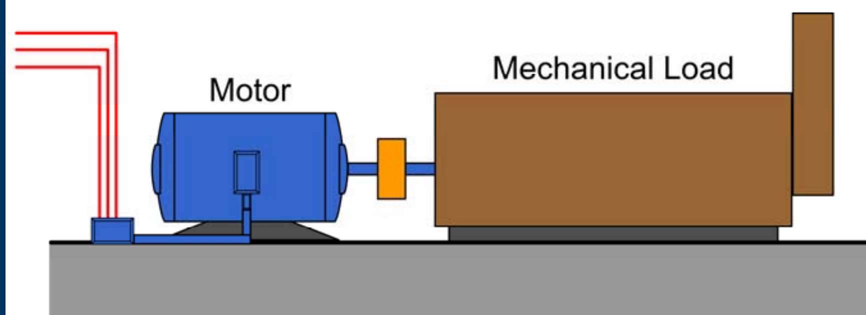
Ali Kazemi, PE
Regional Technical Manager
Schweitzer Engineering Laboratories
Irvine, CA

Motor Protection - Agenda

- Motor Basics
- Protection Requirements
  - Thermal
  - Short circuit
- Special Consideration
  - High Inertia Motor Starting
  - VFD Application

A Motor Is an Electromechanical Energy Converter

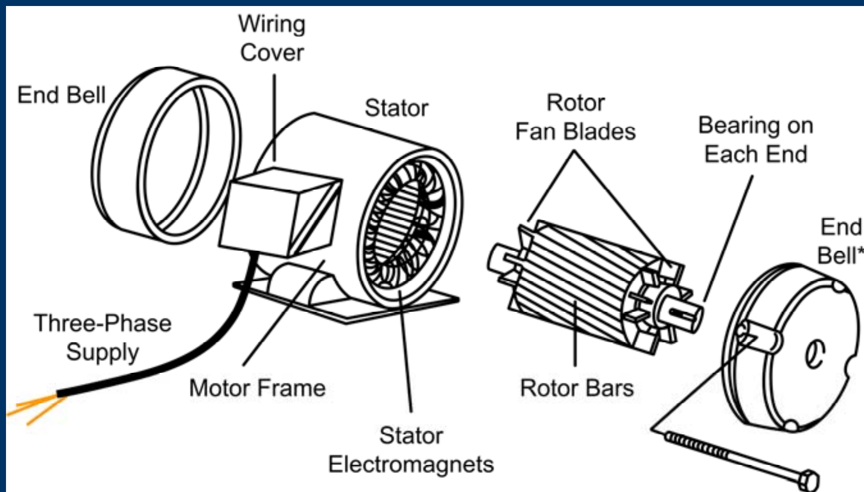
Electric Energy Input = Mechanical Energy Output + Magnetizing Energy + Losses



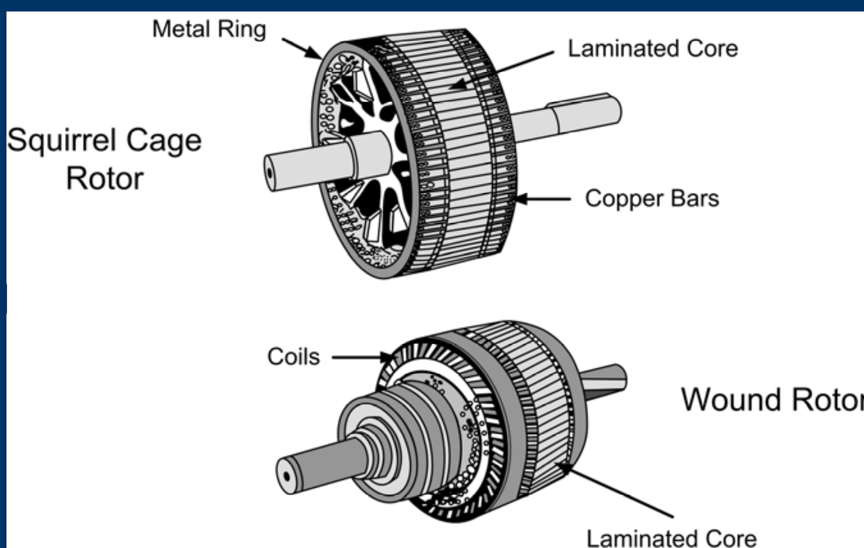
Motor Types

- Induction motors
  - Squirrel cage rotor
  - Wound rotor
- Synchronous motor
  - Salient-pole rotor
  - Round rotor (high speed)

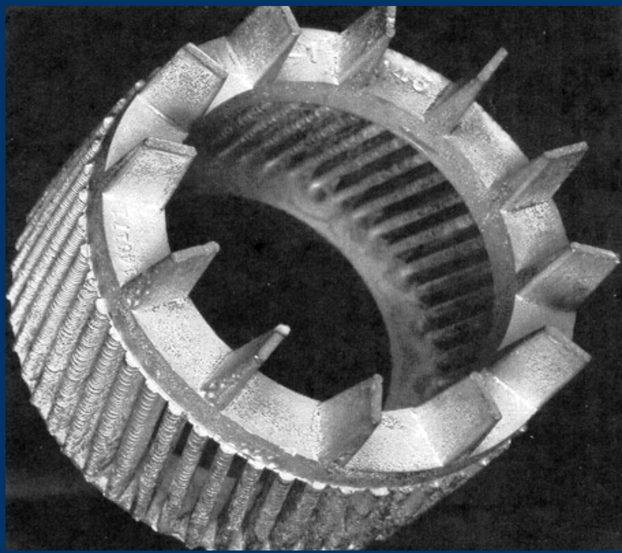
Main Parts of an Induction Motor



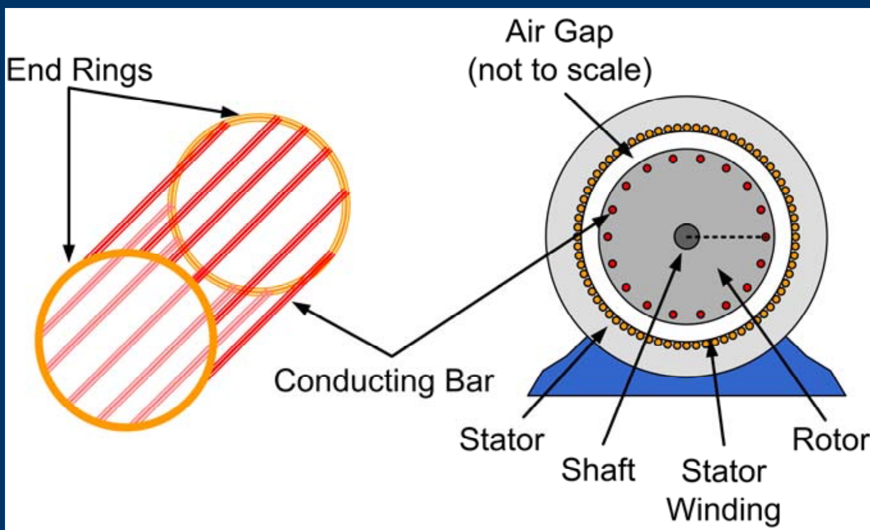
The Rotor



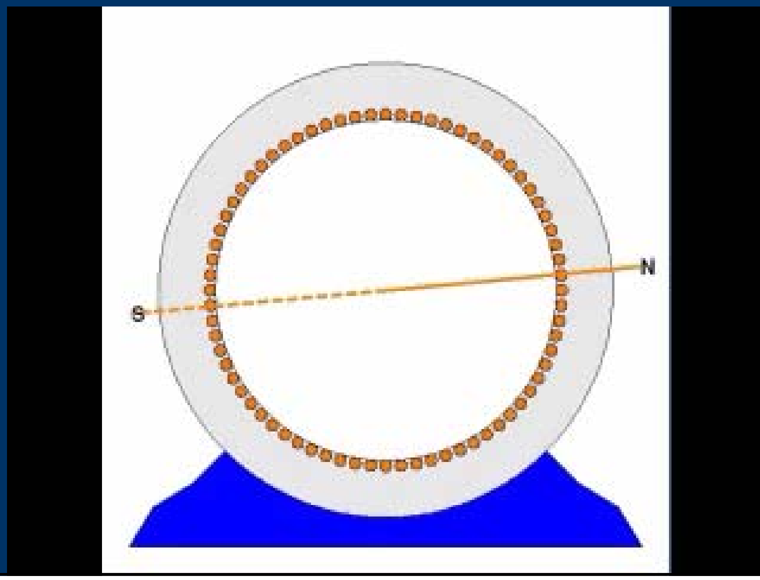
Squirrel Cage Example



Squirrel Cage Rotor Schematics

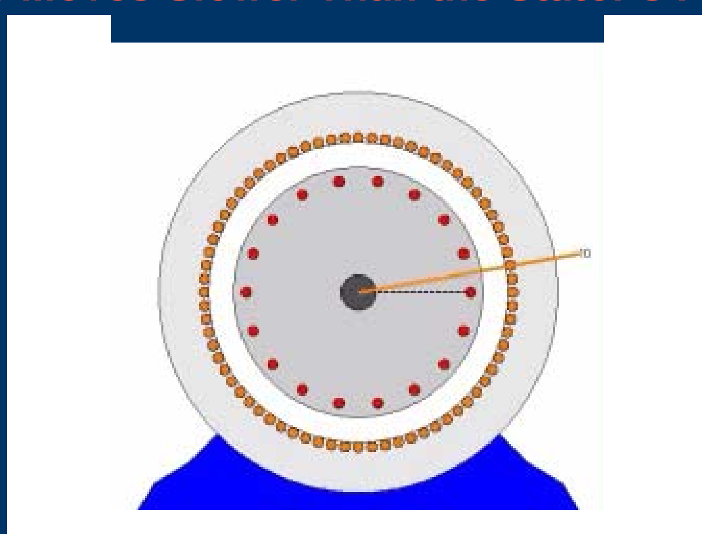


Stator Magnetic Field Rotates at Synchronous Speed



What Is Slip?

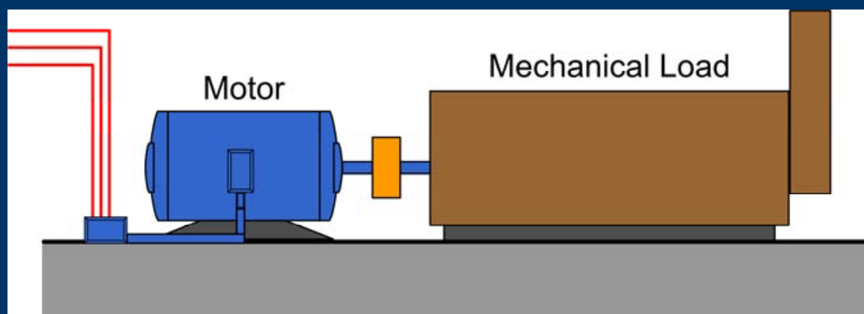
Rotor Moves Slower Than the Stator's Field



Calculation of Slip

A 6-pole, 60 Hz induction motor runs at 1180 rpm

- What is the synchronous speed in rpm?
- What is the slip when it runs at 1180 rpm?



Slip

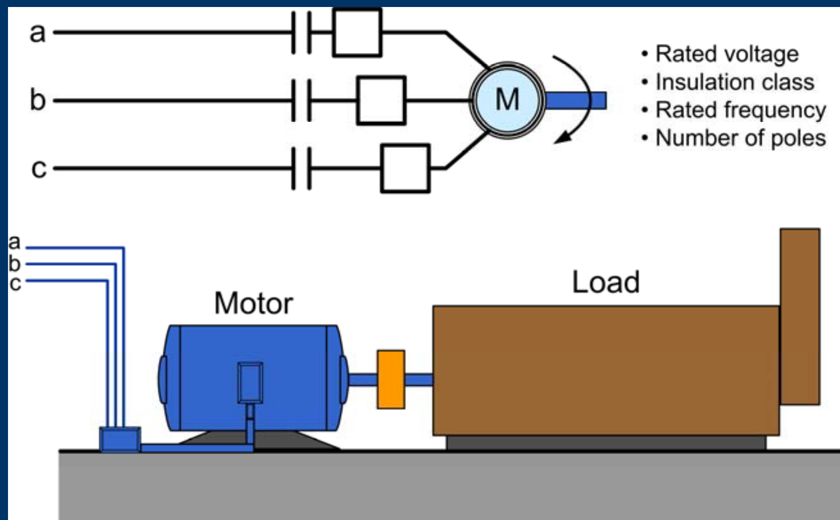
$n_s = 120 \cdot f / p = 120 \cdot 60 / 6 \text{ rpm} = 1200 \text{ rpm}$

$s = 1 - n_r / n_s = 1 - 1180 / 1200 = 0.0166$

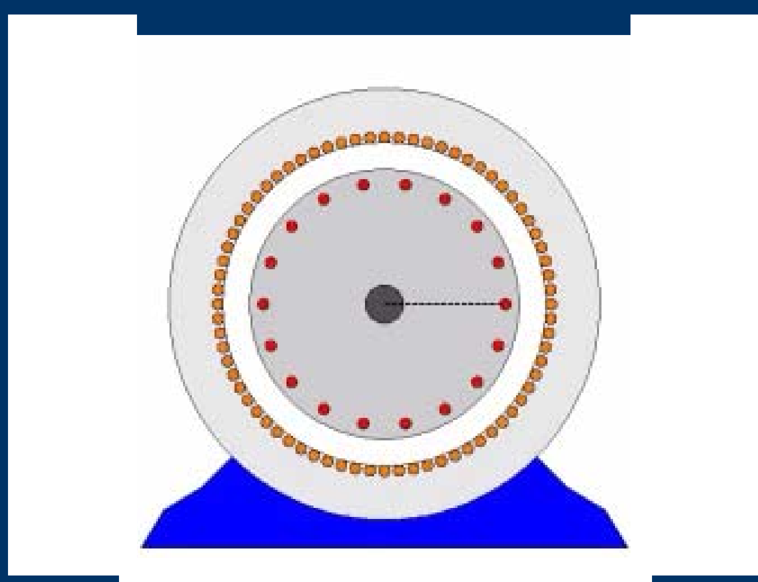
or

1.6%

AC Induction Motor Basic Ratings and Characteristics

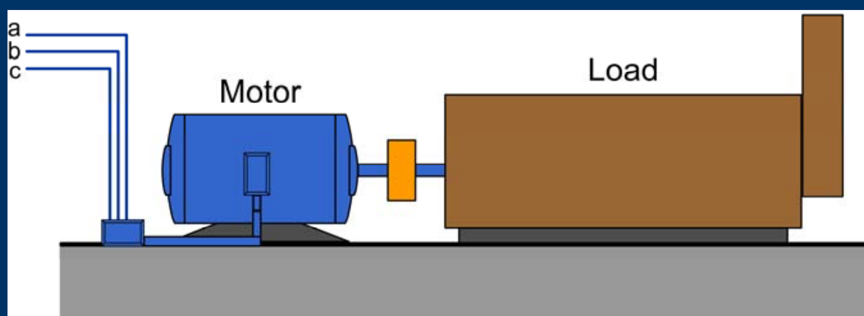


Torque



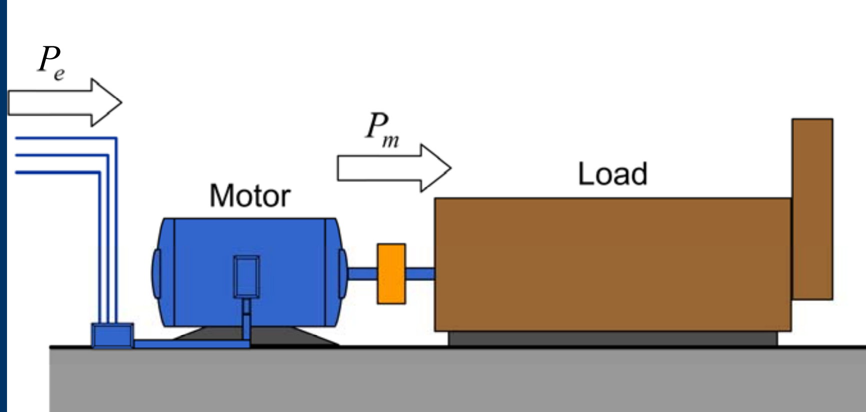
Rated Power

Rated mechanical power, P_m (hp or kW)
Full-load speed, n_r (rpm or rad/s)
Full-load torque, FLT (lbf • ft or N • m)

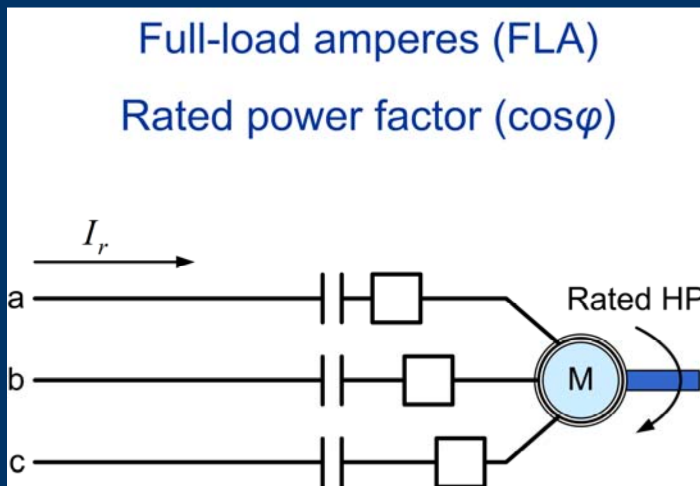


Efficiency and Electrical Power

Efficiency = $\eta = P_m / P_e$



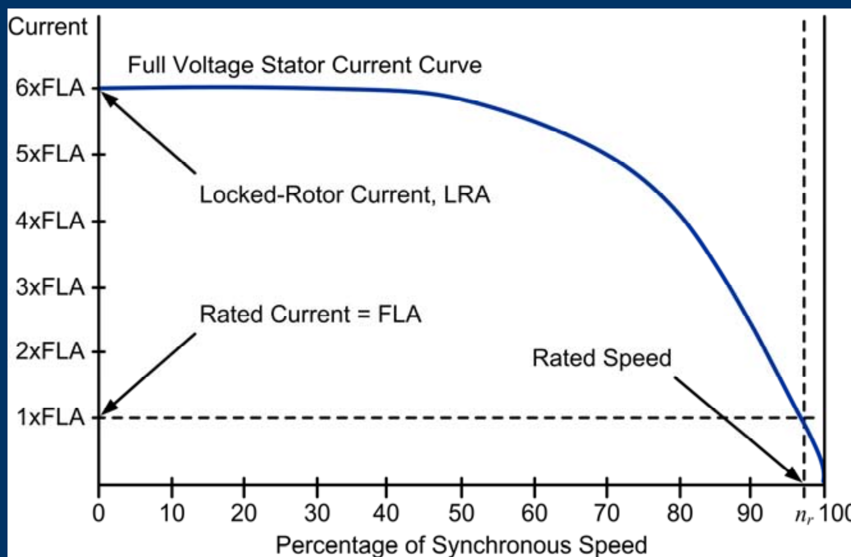
Current Rating



Service Factor (SF)

- Measure of the steady-state overload capability of a motor
- A motor with a service factor = 1.15 can be overloaded by 1.15 • FLA
- A motor with a service factor = 1.0 should not be overloaded

Stator Current vs. Speed Curve



Locked-Rotor Amperes

- Current drawn when a motor is energized with rated voltage and the rotor is stationary
- May be 3 to 7 times or more of rated full-load amperes
- Sometimes given as a KVA code

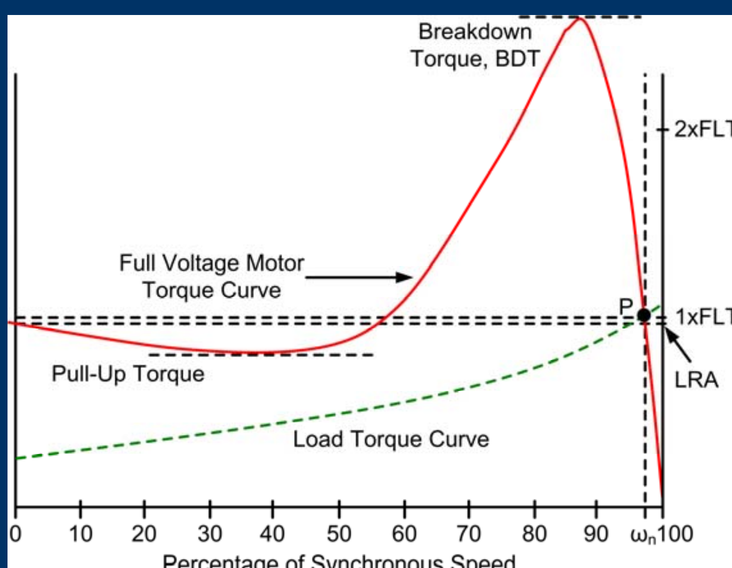
Locked-Rotor KVA Codes

Locked-rotor current calculations from a KVA code:

$I = (CL \cdot 1000 \cdot HP) / (V \cdot 1.73)$

- CL = KVA / HP multiplier (for KVA code letter value: See notes)
- V = Rated motor voltage in volts
- HP = Rated motor horsepower

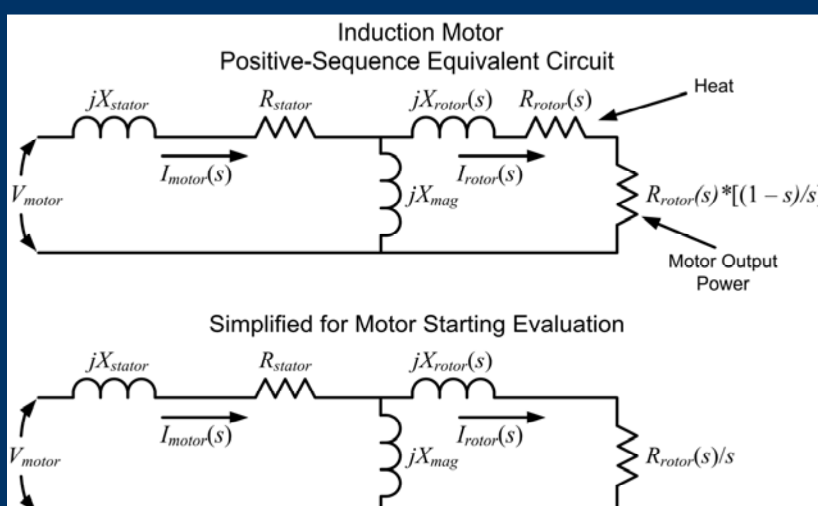
Torque vs. Speed Curves



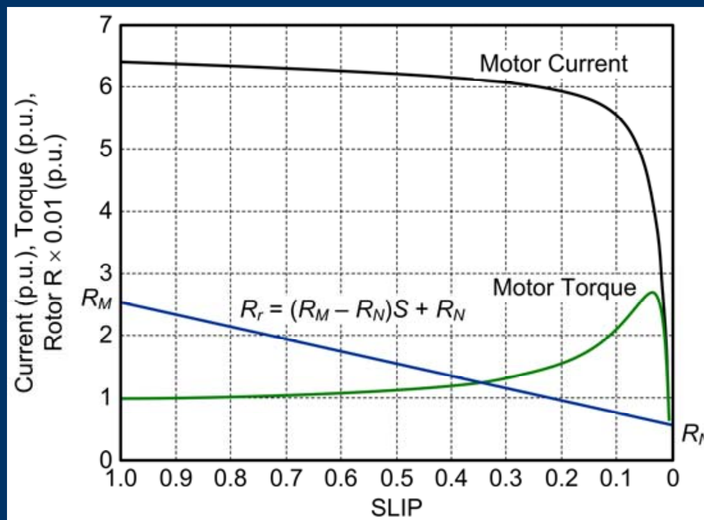
Example: Motor Data Sheet

Motor Data	
Rated output:	5000 hp
Rated speed:	3583 rpm
Rated voltage:	4000 volts
Rated frequency:	60 hertz
Rated current:	608 amperes
Locked-rotor current:	600 percent
Hot stall time:	7 seconds at 100 percent voltage
Cold overload time:	800 seconds at 2 per-unit current
Service factor:	1.15
Locked-rotor torque:	55 percent
Insulation class:	F

Slip-Dependent Motor Impedance: Steinmetz Model

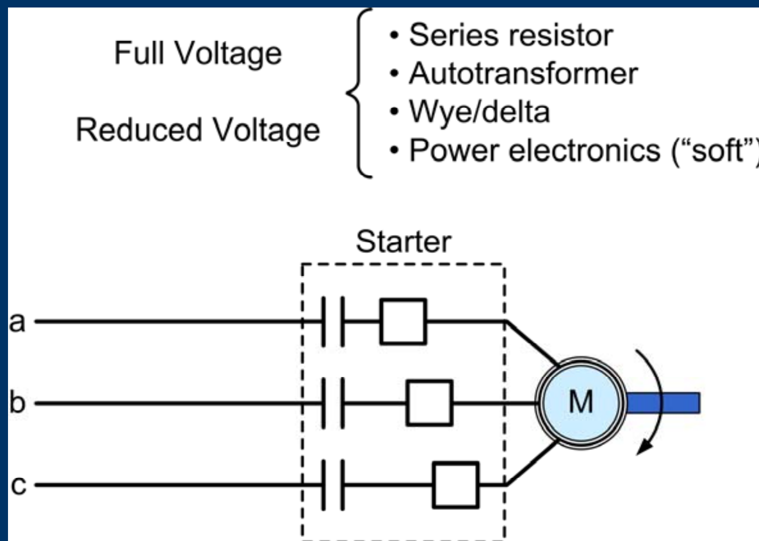


Motor Current, Torque, and Rotor (R) Plotted vs. Slip

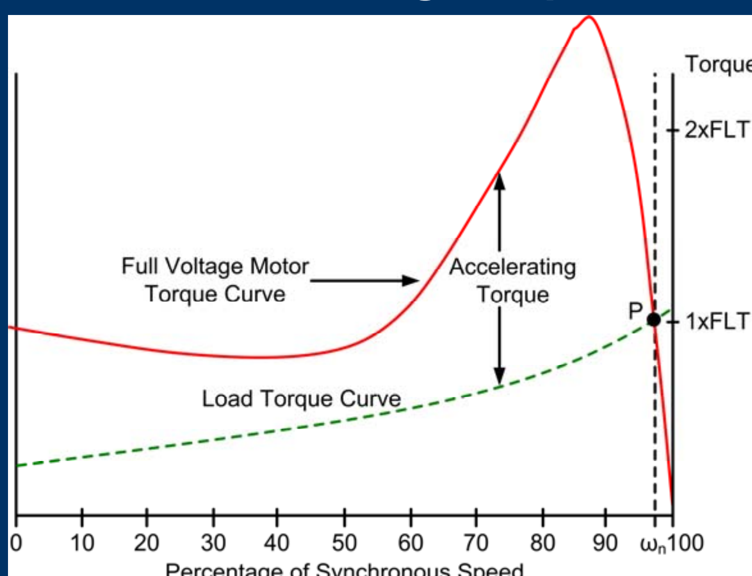


AC Motor Starting

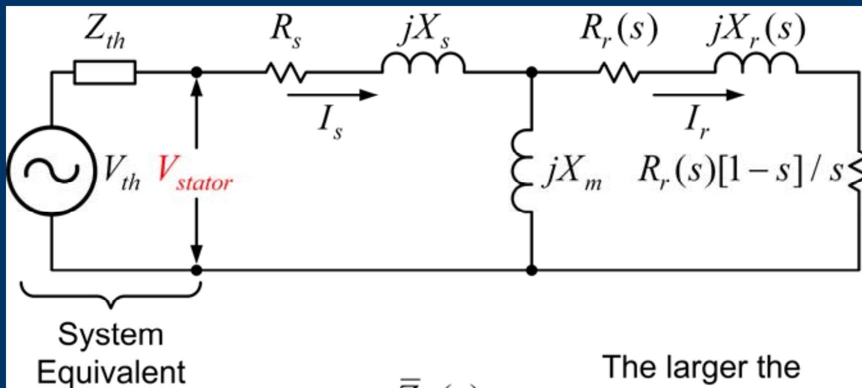
Starters



Accelerating Torque



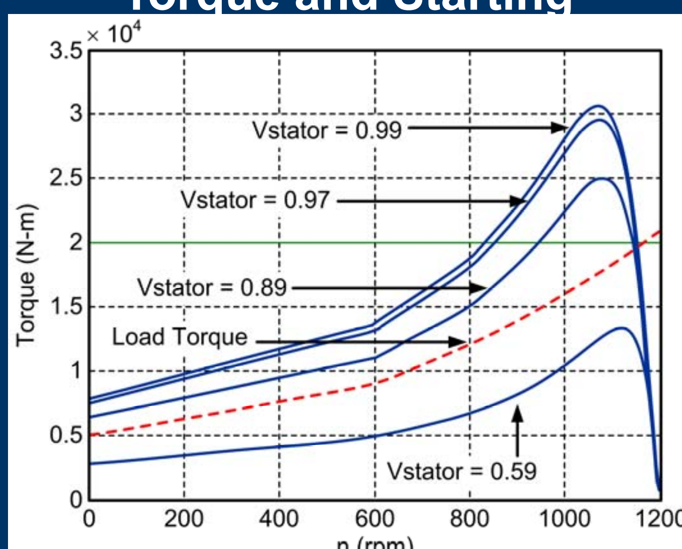
Impact of Source Impedance on Starting Voltage



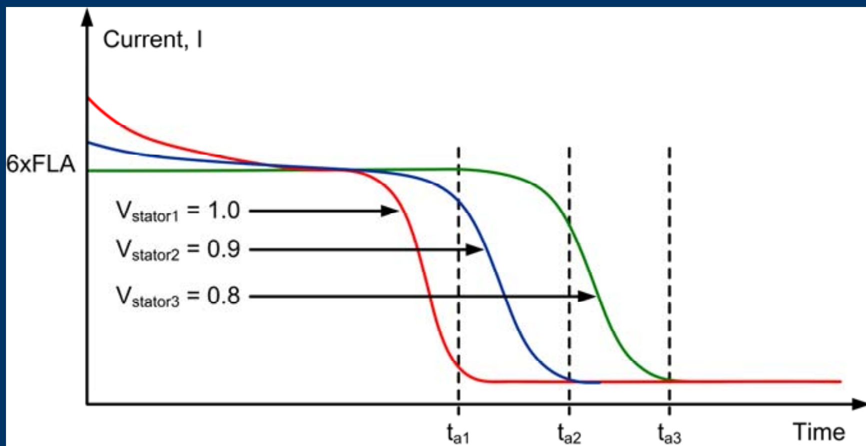
$$\overline{V}_{stator} = \frac{\overline{Z}_m(s)}{\overline{Z}_{th} + \overline{Z}_m(s)} \overline{V}_{th}$$

The larger the source equivalent impedance, the smaller V_{stator}

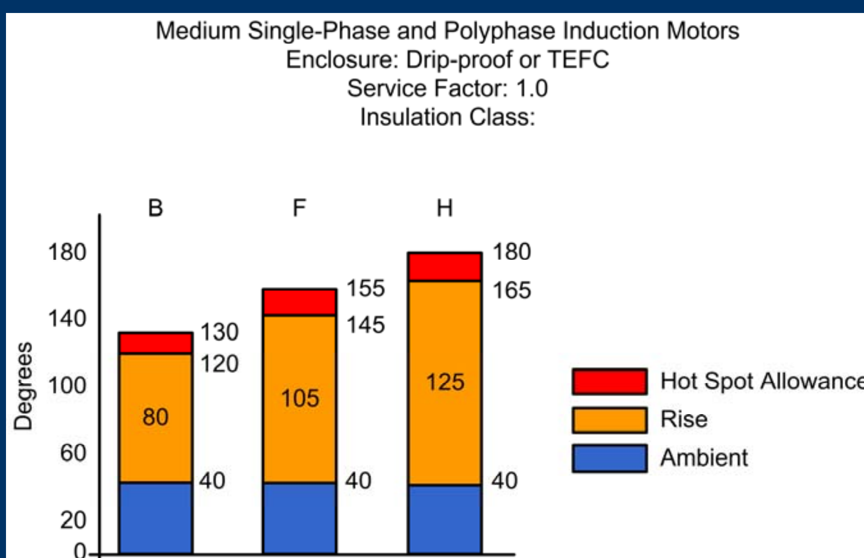
Impact of Voltage Drop on Motor Torque and Starting



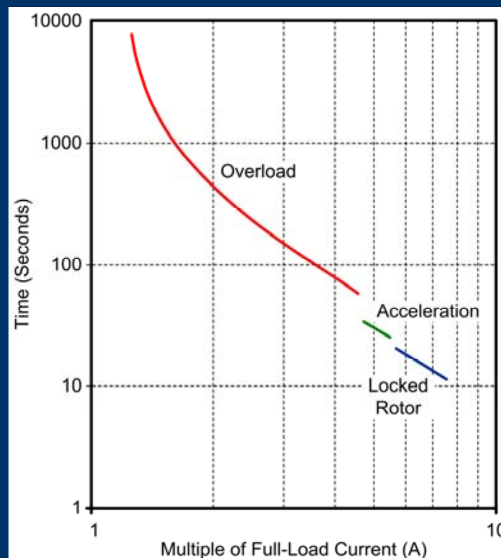
Impact of Reduced Voltage on Acceleration Time



Motor Thermal Limits



Induction Motor Damage Curves

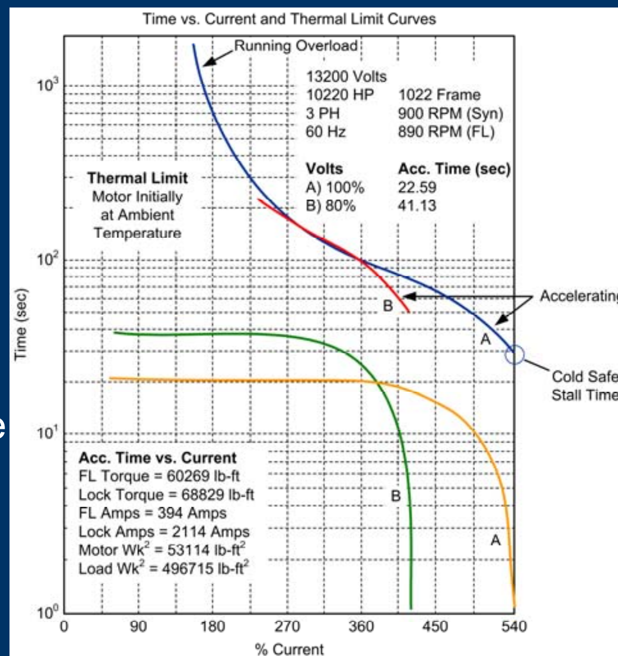


Motor Thermal Limit Curve

- IEEE 620, "IEEE Guide for the Presentation of Thermal Limit Curves for Squirrel Cage Induction Machines"
- Rotor temperature limits during starting
- Stator temperature limits during running

Thermal Limit Curves

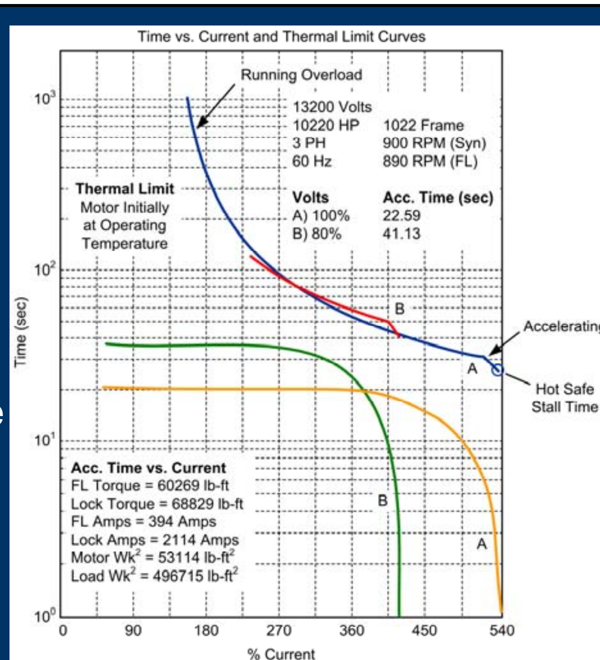
Motor Initially at Ambient Temperature



Hidden Slide for Full-Page Notes

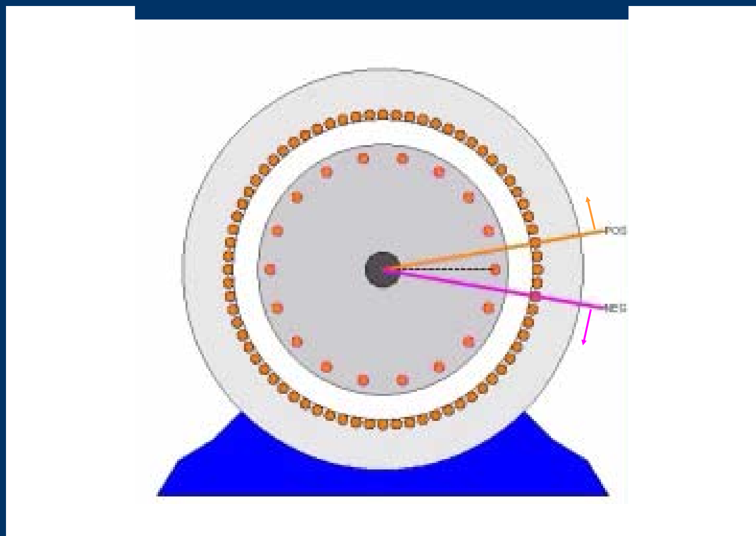
Thermal Limit Curves

Motor Initially at Operating Temperature

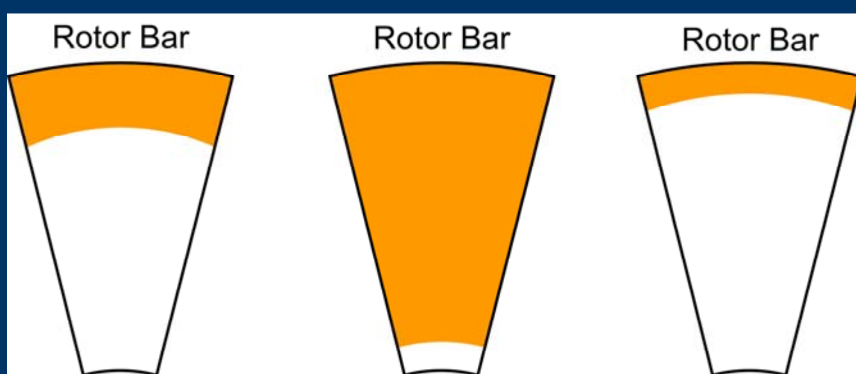


Hidden Slide for Full-Page Notes

Negative-Sequence Current Thermal Effect on the Rotor



Rotor Bar Current Distribution



Starting	Running	Unbalance
$s' = s = 1$	$s' = s = 0.01$	$s' = 2 - s$

s = Slip
s' = Rotor Current Frequency

Resistance Temperature Detectors (RTDs)

- Resistance temperature detectors are sometimes used to indicate the temperature of the stator and bearings
- RTDs are embedded in the stator winding; usually two RTDs are provided per phase
- One or two RTDs can be provided for each motor bearing
- RTDs can be connected to an external measuring device or relay
- Response of the RTDs to temperature change is slow

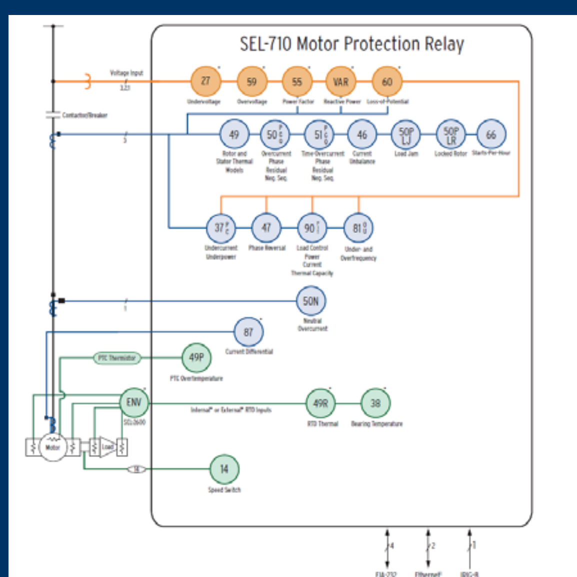
Motor Protection Requirements

- Phase fault protection
- Ground fault protection
- Locked-rotor protection
- Overload protection
- Phase rotation protection

Motor Protection - Optional

- Unbalance protection
- Phase differential protection
- Load-jam protection

Complete Motor Protection



Thermal Element - 49

- Provides starting and overload protection
- Based on motor nameplate rating
- Separate model for rotor and stator
- Takes into account negative-sequence heating effect

Short Circuit Protection Guideline (Instantaneous)

- Phase
  - ♦ Set at 2 times ILR
  - ♦ Set at 1.2 times ILR, 10-15 cycle delay
- Ground
  - ♦ Set higher than maximum imbalance 1.1 times (ILR)
  - ♦ Set at 20% of IFL, 10-15 cycle delay

High-Inertia Start

- Acceleration time ≥ Rotor safe stall time
- Standard thermal/overcurrent element will time out and trip motor offline
- Motor will never start

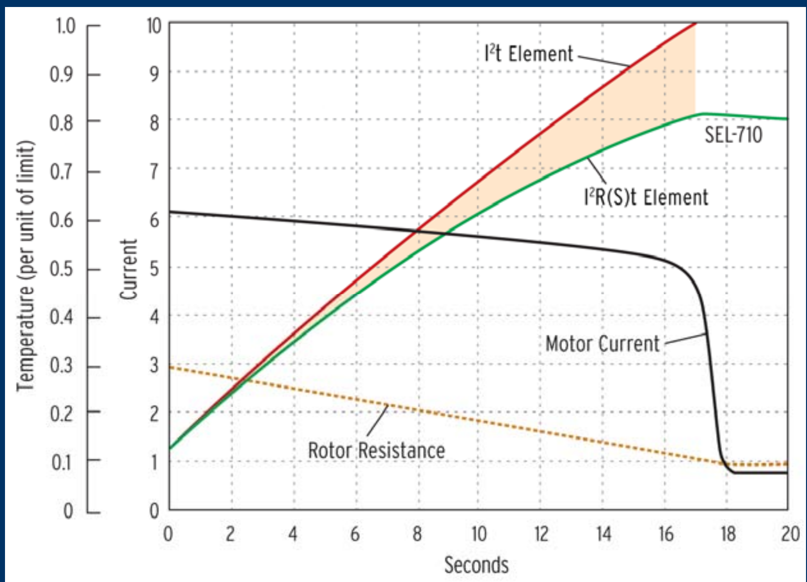
Traditional Solution – Speed Switch

- Examples of speed switches
  - Proximity probe – magnetic type
  - Rotating disc – laser type
- If shaft movement is NOT detected, starting is aborted.

Modern Protection Relay Solution

- Uses slip dependent thermal model
- Avoids potential complications associated with installation and operation of speed switches
- Offers high-inertia start protection without using speed switch

Comparing Starting Elements' Response



Synchronous Motor Consideration

- Field control – close field breaker
- Loss of field protection

VFD Application Consideration

- Motor starts at lower speed
- Lower speed = lower ventilation
- Derrating is required
- Conventional relays can not be applied!
- Requires thermal elements operating on RMS current

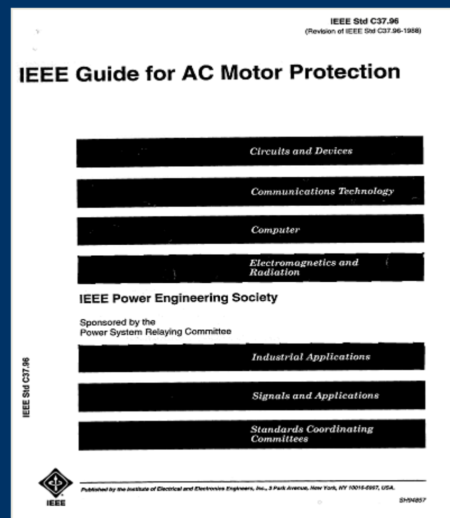
Summary

- Electrical, mechanical, and thermal motor characteristics define the frame needed for effective motor protection
- Running stage, starting stage, and locked-rotor conditions serve to determine the main motor parameters
- Motor heating and thermal damage motor characteristics depend on both positive- and negative-sequence current in the stator

Reference Material

Industry Guides

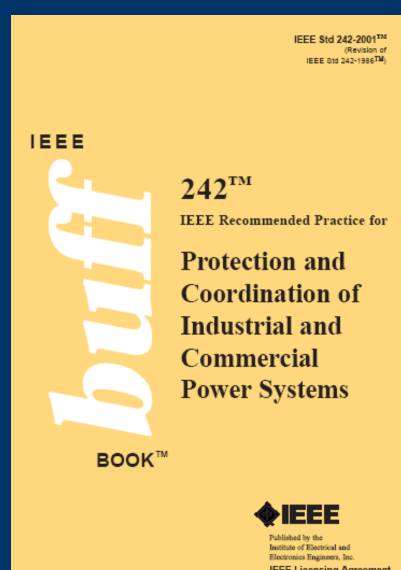
AC Motor Protection Guide: IEEE C37.96



IEEE Buff Book

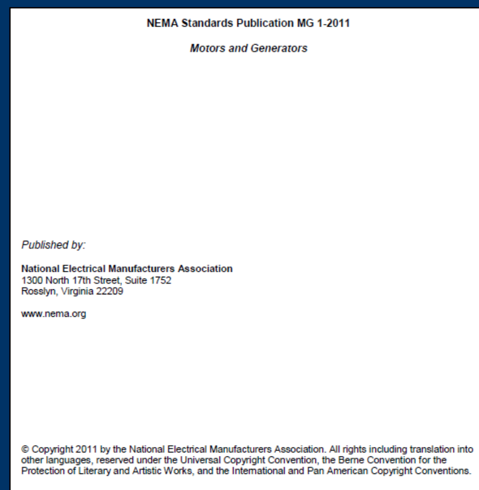
IEEE 242-2001

- Recommended protection practices
- Chapter 10: Motor protection



NEMA MG 1

National Electrical Manufacturers Association (NEMA) Standard MG 1: Provides construction and testing requirements for motors and generators



NEMA Standards Publication MG 1-2011

Motors and Generators

Published by:

National Electrical Manufacturers Association
1300 North 17th Street, Suite 1752
Rosslyn, Virginia 22209

www.nema.org

AC Motor Protection

By Stanley E. Zocholl

- Covers operation and protection of ac motors
- Optimizes motor protection relay thermal and fault protection settings