Welcome to

# Energy Production Systems Engineering

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Session 7:
Electrical Systems

Spring 2012

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## Session 7: Electrical Systems

- Electrical Systems

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## Electrical Systems

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## Electrical Systems

Load Determination
Lighting loads – safety normal & emergency
CRI – Color Rendering Index
Do not connect to station battery
Indoor & Outdoor
Aesthetics

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## Electrical Systems

Power Loads – proper planning –
Demand Factor / Diversity Factor / Load Factor
NEC exempt for utility (Use NESC)
Covers installation safety –

Still justify when not follow NEC
Bad Idea – Citing precedent based on another jurisdiction
Good Idea – Citing precedent based on previous installation or previous experience

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## Electrical Systems

Power Loads / Motor Loads

Other engineering disciplines determine loads, electrical system support those loads.

Static loads – heating, cooling, process handling, etc

Motor loads – conveyors, fans, pumps, etc

## Electrical Systems

Motor starting:  LRA, LRT

Minimize voltage drop

Load shedding on feeder trip – why?

## Electrical Systems

Voltage Selection:

| Typically | Motor | Static |
|---|---|---|
| 480V | (1-200HP) | (1-200KVA) |
| 4160V | (250 – 2000 HP) | (250-2000KVA) |
| 13.8KV | (2000 – 20,000 HP) | (>2MVA) |

LV system solid or impedance gnd
480Y/277 or isolation xfmr for single phase load

MV system impedance grounded

## Electrical Systems

System Configuration:
Three most common
Radial
Secondary Selective
Primary Selective

UAT (SST) vs. SAT (RSST)
Dependence on location of generator breaker
Decreased reliability with RSST

## Electrical Systems

Radial system – low install cost, low reliability, simple protection

Primary selective system – increased cost added feeder, but xfmr size not effected, interlock to prevent double fed bus (higher interrupt currents),
Xfmr still single point of failure.

Closed vs. Open transition

## Electrical Systems

Secondary Selective system:
Double ended substation with tie breaker
Size of xfmr
Typically, redundant loads on each bus to improve reliability
Large motors may required delay to reclose
27 function relay

## Electrical Systems

Battery Systems:
Arguably the most critical piece of equipment
IEEE 485 – Recommended Practice for Sizing Large Lead Storage Batteries for Generating Stations and Substations

IEEE 484 – Recommended Practice for Installation Design and Installation of Large Lead Storage Batteries for Generating Stations and Substations

## Electrical Systems

IEEE 450 – Recommended Practice for Maintenance, Testing, and Replacement of Large Lead Storage Batteries for Generating Stations and Substations

## Electrical Systems

Battery Systems:

Battery is group of "electro-chemical" cells
Stores electricity – not generate
Lead Acid – 2 volts / cell
Series connection – higher voltage, same ampacity
Parallel connection – same voltage, higher ampacity

## Electrical Systems

Lead Acid –
Reaction between lead (-) and lead oxide (+) with $H_2SO_4$ electrolyte produces voltage

Discharge current flows from (+) to (-)

Charging current flows from (-) to (+)

## Electrical Systems

Recommended battery temperatures

| Calcium | Antimony | T avg (a) | T cell max(m) |
|---|---|---|---|
| 1.215 | 1.215 | 77.5F | 90F |
| 1.250 | 1.250 | 72F | 85F |

Adequate air circulation for cooling

Two types of lead acid
Flooded Wet Cells – VRLA

## Electrical Systems

Flooded cell:
Positive plates brown to black, Negative plates gray
One more negative than positive plate.
Sulfation – positive plates take on color of negative plates (gray) – limit capacity of cell
Hydration – white bands across plates – from severe discharge of cells, cause shorted plates.

Equalizing when cell voltage < 2.13V to equalize cell voltage across cell.

## Electrical Systems

Relationship of temperature to battery life:

| T avg (F) | Anitomy (yr) | Calcium (yr) |
|---|---|---|
| 107 F | 6 yrs | 5 yrs |
| 92 F | 12 yrs | 10 yrs |
| 77 F | 20 yrs | 20 yrs |
| 62 F | 22 yrs | 22 yrs |
| 47 F | 25 yrs | 25 yrs |

## Electrical Systems

Battery charging – float vs. equalizing

| Nom SG | Antimony | Calcium |
|---|---|---|
| 1.250 | 2.17 – 2.30 | 2.21 – 2.30 |
| 1.215 | 2.15 – 2.20 | 2.17 – 2.26 |

## Electrical Systems

IEEE Maintenance recommendations:
Cleaning – water only – disconnect battery
Clean corrosion with sodium bicarbonate & water
Rinse with water
Grease bolted connection with oxidization inhibit compound

## Electrical Systems

Monthly PM (flooded cell)-
Check / record float voltage
Check / record appearance
Check / record electrolyte levels
Check / record leaks
Check / record terminal condition
Check / record ambient temperature

## Electrical Systems

Quarterly PM (flooded cell)-
All monthly procedures plus –
Check / record specific gravity of each cell
Check / record Voltage of each cell & total battery voltage
Check / record Temperature of electrolyte in representative cells

## Electrical Systems

Annual PM (flooded cell)-
All monthly & quarterly procedures plus –
Check / record detailed visual inspection of each cell
Check / record cell to cell connection resistance – compare with baseline

## Electrical Systems

Battery capacitance test:
Acceptance – at factory and after installation
Performance – first two years service (warranty period), then every 5 years, (if battery has reached 85% of service life, annual test).

Replace battery when below 80% nominal capacity or plate changes or failure to hold charge (voltage or SG)

## Electrical Systems

Battery Charger –
Provide normal load current (DC load and inverter load)
Provide float voltage
Antimony 2.15 – 2.19 V / cell
Calcium 2.17 – 2.26 V / cell
Provide equalizing voltage
Antimony 2.24 – 2.36 V / cell
Calcium 2.30 – 2.48 V / cell
Dependent on SG
(note for some electrical loads, max # cells 58 instead of 60 cells)
SCR based typical – need battery for DC filter

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## Electrical Systems

AC Motors and Their Applications:

Stator armature – rotor field (squirrel cage) with shorting rings on end of field conductors

Applied AC in armature induces alternating magnetic field. Relative motion between rotor field conductor and alternating field induces current in field winding – no relative motion (synch speed), no current, no torque.

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stator

## Electrical Systems

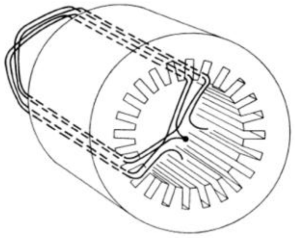

FIGURE 4.5.1 Stator core showing two two-turn coils in slots. Complete winding would fill all the slots.

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## Electrical Systems

Synch speed = 120 * F / P

Where F is applied armature frequency
P is number of poles in stator circuit.

Percentage of slip =

[(Synch speed – FL speed)/Synch speed] * 100%

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## Electrical Systems

Example 1:

For a 6 pole motor with 60 hz applied to stator, what is synchronous speed?

Synch speed = 120 * F / P

= 120 * 60 / 6 = 1200 RPM

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## Electrical Systems

Example 2:

For a 6 pole motor with 60 hz applied to stator, runs at full load at 1125 RPM, what is the percent slip of the motor at full load?

Percentage of slip =

[(Synch speed – FL speed)/Synch speed] * 100%

[(1200 RPM – 1125 RPM)/1200 RPM] * 100%

= 6.25 % slip

## Electrical Systems

Torque Characteristics
Rotor frequency varies as slip changes -> torque available dependent on slip
Different rotor bar shapes and depths result in different torque / speed characteristics.

Locked rotor / breakdown / pull up torque

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## Electrical Systems

Rotor Bar Design

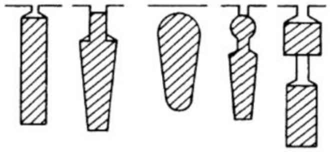

**FIGURE 4.5.3** Typical rotor bar and slot shapes for squirrel-cage rotors. Double cage, at right, uses two separate conductors in each slot.

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## Electrical Systems

Lagging vs. leading

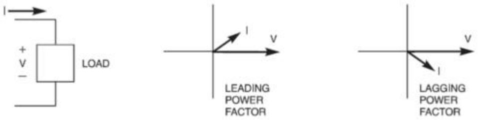

**Figure 8-3—Phasor diagrams showing leading and lagging currents and power factors**

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## Electrical Systems

Power Factor Correction

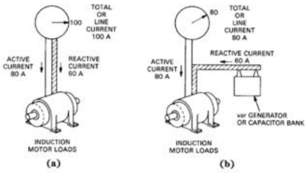

**Figure 8-5—Schematic arrangement showing how capacitors reduce total line current by supplying reactive power requirements locally**

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## Electrical Systems

Motors.
partly loaded induction motor PF is poor
Hermetic and wound-rotor type motors have a lower PF

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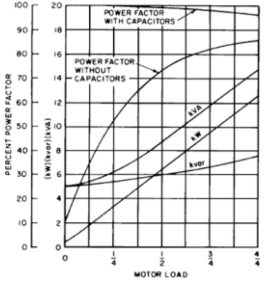
## Electrical Systems



## Electrical Systems

*AC to DC power converters*
*- Diode type with no phase control*
Small single-phase units = about 50% distortion PF
Large multiphase units may have a 95% distortion PF
*- Static converter drives.*
PF = ratio of dc output voltage to rated voltage
Partial loads, the power factor is poor.
*Electric furnaces.*
Arc furnaces 70-85%
Induction 30-70%

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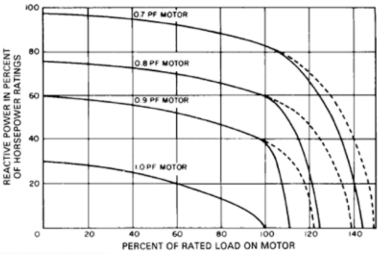
## Electrical Systems

Synchronous Motor Reactive Power Capability



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## Electrical Systems

*Capacitive VAR Calculation*

*Example 3.*
Using table 8-2, find the capacitor rating required to improve the power factor of a
500 kW load from 0.76 to 0.93:
Kvar = kW * multiplier
= 500 * 0.46
= 230 kvar

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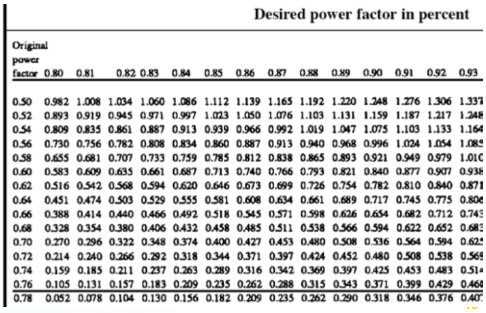

Desired power factor in percent

| Original power factor | 0.80 | 0.81 | 0.82 | 0.83 | 0.84 | 0.85 | 0.86 | 0.87 | 0.88 | 0.89 | 0.90 | 0.91 | 0.92 | 0.93 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 0.50 | 0.982 | 1.008 | 1.034 | 1.060 | 1.086 | 1.112 | 1.139 | 1.165 | 1.192 | 1.220 | 1.248 | 1.276 | 1.306 | 1.337 |
| 0.52 | 0.893 | 0.919 | 0.945 | 0.971 | 0.997 | 1.023 | 1.050 | 1.076 | 1.103 | 1.131 | 1.159 | 1.187 | 1.217 | 1.248 |
| 0.54 | 0.809 | 0.835 | 0.861 | 0.887 | 0.913 | 0.939 | 0.966 | 0.992 | 1.019 | 1.047 | 1.075 | 1.103 | 1.133 | 1.164 |
| 0.56 | 0.730 | 0.756 | 0.782 | 0.808 | 0.834 | 0.860 | 0.887 | 0.913 | 0.940 | 0.968 | 0.996 | 1.024 | 1.054 | 1.08 |
| 0.58 | 0.655 | 0.681 | 0.707 | 0.733 | 0.759 | 0.785 | 0.812 | 0.838 | 0.865 | 0.893 | 0.921 | 0.949 | 0.979 | 1.01 |
| 0.60 | 0.583 | 0.609 | 0.635 | 0.661 | 0.687 | 0.713 | 0.740 | 0.766 | 0.793 | 0.821 | 0.840 | 0.877 | 0.907 | 0.93 |
| 0.62 | 0.516 | 0.542 | 0.568 | 0.594 | 0.620 | 0.646 | 0.673 | 0.699 | 0.726 | 0.754 | 0.782 | 0.810 | 0.840 | 0.871 |
| 0.64 | 0.451 | 0.474 | 0.503 | 0.529 | 0.555 | 0.581 | 0.608 | 0.634 | 0.661 | 0.689 | 0.717 | 0.745 | 0.775 | 0.80 |
| 0.66 | 0.388 | 0.414 | 0.440 | 0.466 | 0.492 | 0.518 | 0.545 | 0.571 | 0.598 | 0.626 | 0.654 | 0.682 | 0.712 | 0.74 |
| 0.68 | 0.328 | 0.354 | 0.380 | 0.406 | 0.432 | 0.458 | 0.485 | 0.511 | 0.538 | 0.566 | 0.594 | 0.622 | 0.652 | 0.68 |
| 0.70 | 0.270 | 0.296 | 0.322 | 0.348 | 0.374 | 0.400 | 0.427 | 0.453 | 0.480 | 0.508 | 0.536 | 0.564 | 0.594 | 0.62 |
| 0.72 | 0.214 | 0.240 | 0.266 | 0.292 | 0.318 | 0.344 | 0.371 | 0.397 | 0.424 | 0.452 | 0.480 | 0.508 | 0.538 | 0.56 |
| 0.74 | 0.159 | 0.185 | 0.211 | 0.237 | 0.263 | 0.289 | 0.316 | 0.342 | 0.369 | 0.397 | 0.425 | 0.453 | 0.483 | 0.51 |
| 0.76 | 0.105 | 0.131 | 0.157 | 0.183 | 0.209 | 0.235 | 0.262 | 0.288 | 0.315 | 0.343 | 0.371 | 0.399 | 0.429 | 0.46 |
| 0.78 | 0.052 | 0.078 | 0.104 | 0.130 | 0.156 | 0.182 | 0.209 | 0.235 | 0.262 | 0.290 | 0.318 | 0.346 | 0.376 | 0.40 |

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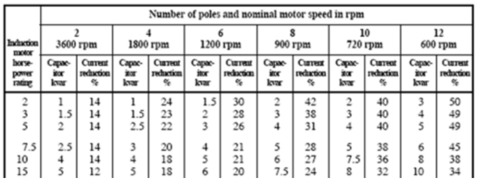
## Electrical Systems

Table 8-4—Suggested maximum capacitor ratings—
"T-frame" NEMA Design B motors



| Induction motor horse-power rating | Number of poles and nominal motor speed in rpm | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2<br>3600 rpm | | 4<br>1800 rpm | | 6<br>1200 rpm | | 8<br>900 rpm | | 10<br>720 rpm | | 12<br>600 rpm | |
| | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % |
| 2 | 1 | 14 | 1 | 24 | 1.5 | 30 | 2 | 42 | 2 | 40 | 3 | 50 |
| 3 | 1.5 | 14 | 1.5 | 23 | 2 | 28 | 3 | 38 | 3 | 40 | 4 | 49 |
| 5 | 2 | 14 | 2.5 | 22 | 3 | 26 | 4 | 31 | 4 | 40 | 5 | 49 |
| 7.5 | 2.5 | 14 | 3 | 20 | 4 | 21 | 5 | 28 | 5 | 38 | 6 | 45 |
| 10 | 4 | 14 | 4 | 18 | 5 | 21 | 6 | 27 | 7.5 | 36 | 8 | 38 |
| 15 | 5 | 12 | 5 | 18 | 6 | 20 | 7.5 | 24 | 8 | 32 | 10 | 34 |

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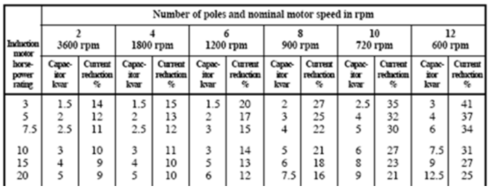
## Electrical Systems

Table 8-3—Suggested maximum capacitor ratings—used for
high-efficiency motors and older design (pre-"T-frame") motors



| Induction motor horse-power rating | Number of poles and nominal motor speed in rpm | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2<br>3600 rpm | | 4<br>1800 rpm | | 6<br>1200 rpm | | 8<br>900 rpm | | 10<br>720 rpm | | 12<br>600 rpm | |
| | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % | Capacitor kvar | Current reduction % |
| 3 | 1.5 | 14 | 1.5 | 15 | 1.5 | 20 | 2 | 27 | 2.5 | 35 | 3 | 41 |
| 5 | 2 | 12 | 2 | 13 | 2 | 17 | 3 | 25 | 4 | 32 | 4 | 37 |
| 7.5 | 2.5 | 11 | 2.5 | 12 | 3 | 15 | 4 | 22 | 5 | 30 | 6 | 34 |
| 10 | 3 | 10 | 3 | 11 | 3 | 14 | 5 | 21 | 6 | 27 | 7.5 | 31 |
| 15 | 4 | 9 | 4 | 10 | 5 | 13 | 6 | 18 | 8 | 23 | 9 | 27 |
| 20 | 5 | 9 | 5 | 10 | 6 | 12 | 7.5 | 16 | 9 | 21 | 12.5 | 25 |

## Electrical Systems

Effect PFCC has
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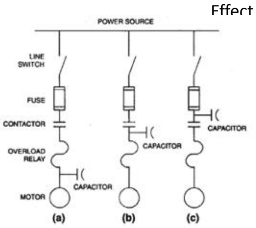

Figure 8-12—Electrical location of capacitors when used with induction motors for power factor improvement

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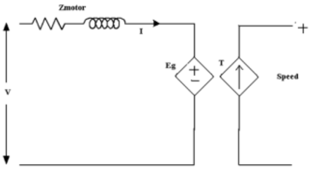
## Electrical Systems

Simplified induction motor circuit model
Power = Eg * I = T * Speed



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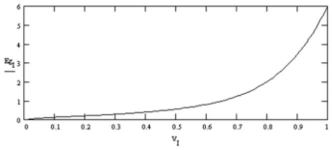
## Electrical Systems

Eg = Irotor * Rr (1-S)/S



How does Eg vary as motor accelerates to full speed?
At low speed, Eg changes little = constant impedance device.
At high speed, Eg changes greatly = constant HP device

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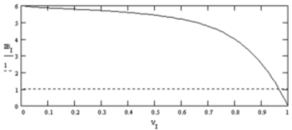
## Electrical Systems

MOTOR CURRENT DURING ACCEL



Irunning = (V - Eg) / Zmotor
At locked rotor, Eg = 0
Istarting = V / Zmotor
As motor increases speed, Eg increases
Motor current decays as Eg increases

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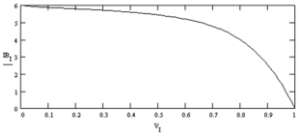
## Electrical Systems

MOTOR KVA DURING ACCEL



KVA = V motor * I motor * 1.73
Since Vmotor constant in ATL starting, KVA curve appears as current curve

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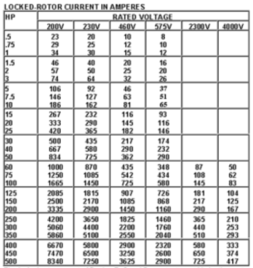
## Electrical Systems

MAXIMUM LRA
(NEMA B-D)



LOCKED-ROTOR CURRENT IN AMPERES

| HP | RATED VOLTAGE | | | | | |
|---|---|---|---|---|---|---|
| | 200V | 230V | 460V | 575V | 2300V | 4000V |
| .5 | 23 | 20 | 10 | 8 | | |
| .75 | 29 | 25 | 12 | 10 | | |
| 1 | 34 | 30 | 15 | 12 | | |
| 1.5 | 46 | 40 | 20 | 16 | | |
| 2 | 57 | 50 | 25 | 20 | | |
| 3 | 74 | 64 | 32 | 26 | | |
| 5 | 106 | 92 | 46 | 37 | | |
| 7.5 | 146 | 127 | 63 | 51 | | |
| 10 | 186 | 162 | 81 | 65 | | |
| 15 | 267 | 232 | 116 | 93 | | |
| 20 | 333 | 290 | 145 | 116 | | |
| 25 | 420 | 365 | 182 | 146 | | |
| 30 | 500 | 435 | 217 | 174 | | |
| 40 | 667 | 580 | 290 | 232 | | |
| 50 | 834 | 725 | 362 | 290 | | |
| 60 | 1000 | 870 | 435 | 348 | 87 | 50 |
| 75 | 1250 | 1085 | 542 | 434 | 108 | 62 |
| 100 | 1665 | 1450 | 725 | 580 | 145 | 83 |
| 125 | 2085 | 1815 | 907 | 726 | 181 | 104 |
| 150 | 2500 | 2170 | 1085 | 868 | 217 | 125 |
| 200 | 3335 | 2900 | 1450 | 1160 | 290 | 167 |
| 250 | 4200 | 3650 | 1825 | 1460 | 365 | 210 |
| 300 | 5060 | 4400 | 2200 | 1760 | 440 | 253 |
| 350 | 5860 | 5100 | 2550 | 2040 | 510 | 293 |
| 400 | 6670 | 5800 | 2900 | 2320 | 580 | 333 |
| 450 | 7470 | 6500 | 3250 | 2600 | 650 | 374 |
| 500 | 8340 | 7250 | 3625 | 2900 | 725 | 417 |

The locked-rotor current of Design B, C and D constant-speed induction motors, when measured with rated voltage and frequency impressed and with rotor locked, shall not exceed the above values.
Reference: NEMA Standards MG 1-12.35.

## Electrical Systems

MAXIMUM LRA
(NEMA E)

**MAXIMUM LOCKED-ROTOR CURRENTS**
THREE-PHASE SQUIRREL CAGE MOTORS
NEMA DESIGN E

LOCKED-ROTOR CURRENT IN AMPERES

| HP | RATED VOLTAGE | | | | | |
|---|---|---|---|---|---|---|
| | **200V** | **230V** | **460V** | **575V** | **2300V** | **4000V** |
| .5 | 23 | 20 | 10 | 8 | | |
| .75 | 29 | 25 | 13 | 10 | | |
| 1 | 35 | 30 | 15 | 12 | | |
| 1.5 | 46 | 40 | 20 | 16 | | |
| 2 | 58 | 50 | 25 | 20 | | |
| 3 | 84 | 73 | 37 | 29 | | |
| 5 | 1140 | 122 | 61 | 49 | | |
| 7.5 | 210 | 183 | 92 | 73 | | |
| 10 | 259 | 225 | 113 | 90 | | |
| 15 | 388 | 337 | 169 | 135 | | |
| 20 | 516 | 449 | 225 | 180 | | |
| 25 | 646 | 562 | 281 | 225 | | |
| 30 | 775 | 674 | 337 | 270 | | |
| 40 | 948 | 824 | 412 | 330 | | |
| 50 | 1185 | 1030 | 515 | 412 | | |
| 60 | 1421 | 1236 | 618 | 494 | 124 | 71 |
| 75 | 1777 | 1545 | 773 | 618 | 155 | 89 |
| 100 | 2154 | 1873 | 937 | 749 | 187 | 108 |
| 125 | 2692 | 2341 | 1171 | 936 | 234 | 135 |
| 150 | 3230 | 2809 | 1405 | 1124 | 281 | 162 |
| 200 | 4307 | 3745 | 1873 | 1498 | 375 | 215 |
| 250 | 5391 | 4688 | 2344 | 1875 | 469 | 270 |
| 300 | 6461 | 5618 | 2809 | 2247 | 562 | 323 |
| 350 | 7537 | 6554 | 3277 | 2622 | 655 | 377 |
| 400 | 8614 | 7490 | 3745 | 2996 | 749 | 431 |
| 450 | 9691 | 8427 | 4214 | 3371 | 843 | 485 |
| 500 | 10767 | 9363 | 4682 | 3745 | 936 | 538 |

The locked-rotor current of Design E constant-speed induction motors, when measured with rated voltage and frequency impressed and with rotor locked, shall not exceed the above values.
Reference: NEMA Standards MG 1-12.35A.

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## Electrical Systems

NEMA E is “energy efficient”
To achieve “energy efficient”, Zmotor is reduced.
Since Istarting = V / Zmotor, as Zmotor is reduced, Istarting is increased.

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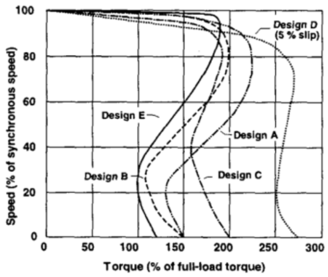
## Electrical Systems



MOTOR
TORQUE
DURING
ACCEL

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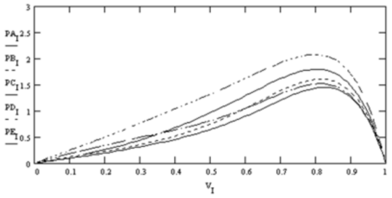
## Electrical Systems

MOTOR POWER DURING ACCEL



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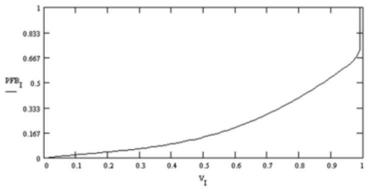
## Electrical Systems

MOTOR PF DURING ACCEL



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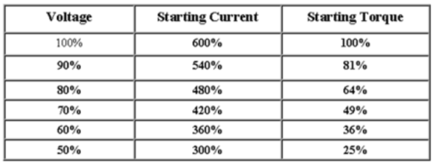
## Electrical Systems

REDUCED VOLTAGE STARTING



| Voltage | Starting Current | Starting Torque |
|---|---|---|
| 100% | 600% | 100% |
| 90% | 540% | 81% |
| 80% | 480% | 64% |
| 70% | 420% | 49% |
| 60% | 360% | 36% |
| 50% | 300% | 25% |

Reduction of current proportional to reduction of voltage.
Reduction of torque approximately proportional to square of reduction of voltage (actually slightly lower).

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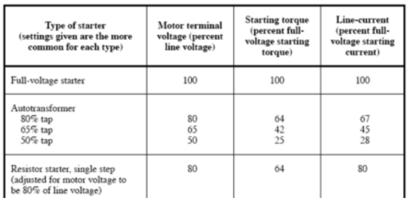
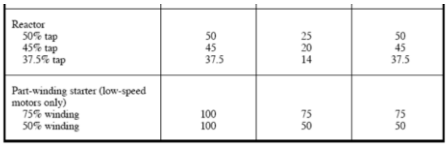
## Electrical Systems



| Type of starter (settings given are the more common for each type) | Motor terminal voltage (percent line voltage) | Starting torque (percent full-voltage starting torque) | Line-current (percent full-voltage starting current) |
|---|---|---|---|
| Full-voltage starter | 100 | 100 | 100 |
| Autotransformer |  |  |  |
| 80% tap | 80 | 64 | 67 |
| 65% tap | 65 | 42 | 45 |
| 50% tap | 50 | 25 | 28 |
| Resistor starter, single step (adjusted for motor voltage to be 80% of line voltage) | 80 | 64 | 80 |

## Electrical Systems



|  |  |  |  |
|---|---|---|---|
| Reactor |  |  |  |
| 50% tap | 50 | 25 | 50 |
| 45% tap | 45 | 20 | 45 |
| 37.5% tap | 37.5 | 14 | 37.5 |
| Part-winding starter (low-speed motors only) |  |  |  |
| 75% winding | 100 | 75 | 75 |
| 50% winding | 100 | 50 | 50 |

## Electrical Systems

Ensure sufficient motor available torque to start the motor.
Acceleration Time (Tacc) is defined as:

$$\text{Tacc} = \frac{\text{WK}^2 * \text{RPM}}{308 * \text{avg acc trq}}$$

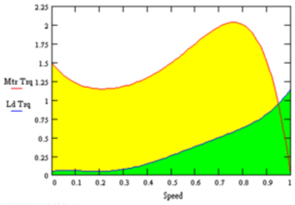
## Electrical Systems

Average Acceleration Torque (Avg Acc Trq) is defined as:
This definition does not account for load:

$$\text{Avg Acc Trq} = \frac{[(\text{FLT} + \text{BDT})/2] + \text{BDT} + \text{LRT}}{3}$$

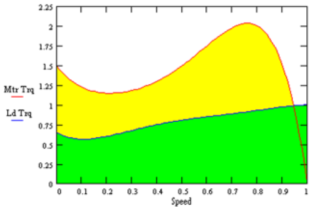
## Electrical Systems

MOTOR ATL TORQUE AND
VT LOAD CURVES



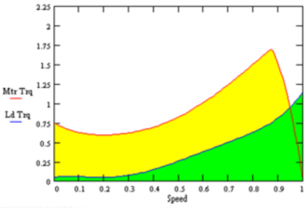
## Electrical Systems

MOTOR ATL TORQUE AND
CT LOAD CURVES



## Electrical Systems

MOTOR RVS TORQUE AND
VT LOAD CURVES



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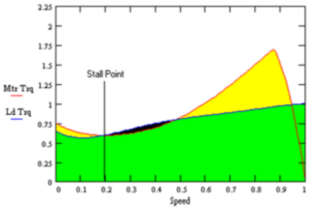
## Electrical Systems

MOTOR RVS TORQUE AND
CT LOAD CURVES



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---

## Electrical Systems

Trequired = Tmotor + Tload

Evaluate motor and load torque curves.

Ensure sufficient motor accelerating torque exists throughout acceleration curve.

API 841 recommends Tmotor >1.1*Tload throughout the speed range.

$$T_{\text{required}} = \frac{Wk^2 \times \text{ÄRPM}}{308 \times t} + T_{\text{load}}$$

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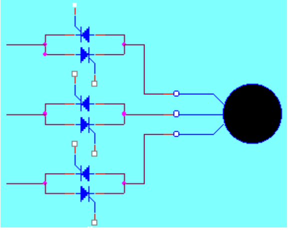
## Electrical Systems

SOFTSTART (2300V OR LESS)



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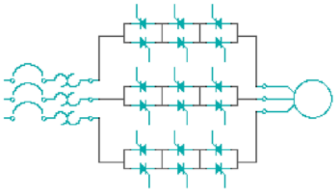
## Electrical Systems

SOFTSTART (4160 OR MORE)



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## Electrical Systems

WHERE AND WHEN ARE THEY USED

Pump Applications; prevent water hammer

Mech. transmission issues; reduce torque (electronic shear pin)

Weak distribution lines; limit voltage dip during start

Electronic braking; actively stop loads

Damp applications; motor heating

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## Electrical Systems

Standards for motors
1 – 250 HP – NEMA MG1 & IEEE 841
250HP – 500 HP – NEMA MG1 & IEEE API 546
500 HP – IEEE API 541
(for API, some items optional and specified by engineer)

## Electrical Systems

Standards address:
Dimensions
# of starts / hr
Standard HP and voltage rating
Enclosure definitions
Bearing construction
Noise, balance, vibration
Temperature rise

## Electrical Systems

Service factor –
For momentary overloads only! Only US motors have SF rating.
MG1-1.43 – “The service factor of an alternating current motor is a multiplier which, when applied to the rated HP, indicates a permissible HP loading which may be carried under conditions specified for service factor”
Do not depend on SF for design

## Electrical Systems

Insulation Class – Class defined by “hot spot”

| | | | |
|---|---|---|---|
| Class A | Class 105 | 105C | 221F |
| Class E | Class 120 | 120C | 248F |
| Class B | Class 130 | 130C | 266F |
| Class F | Class 155 | 155C | 311F |
| Class H | Class 180 | 180C | 356F |
| Class N | Class 200 | 200C | 392F |

## Electrical Systems

stator winding

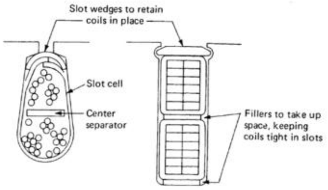

**FIGURE 4.5.23** Cross section of random-wound stator slot, left, shows how round wires are randomly packed into areas occupied by top and bottom coil sides, with insulating separator plus slot *cell* or liner. At right, similar sectional view shows rectangular wires of *formed* and taped coils used for higher voltages.

## Electrical Systems

Insulation Systems

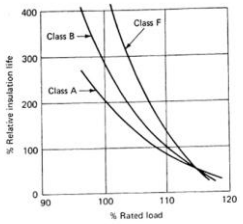

**FIGURE 4.5.7** Insulation life versus load for three standard insulation systems, showing the effect of continuou motor operation at 1.15 service factor load.

## Electrical Systems

Motor efficiency –
Efficiency = Pout / Pin * 100%

For nominal efficiency, there is minimum efficiency per NEMA

May not pay back unless run time large.

---

## Electrical Systems

Efficiency Ranges

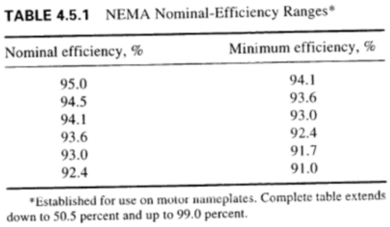

**TABLE 4.5.1** NEMA Nominal-Efficiency Ranges*

| Nominal efficiency, % | Minimum efficiency, % |
|---|---|
| 95.0 | 94.1 |
| 94.5 | 93.6 |
| 94.1 | 93.0 |
| 93.6 | 92.4 |
| 93.0 | 91.7 |
| 92.4 | 91.0 |

*Established for use on motor nameplates. Complete table extends down to 50.5 percent and up to 99.0 percent.

---

## Electrical Systems

Efficiency Ranges

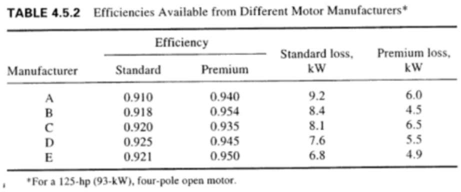

**TABLE 4.5.2** Efficiencies Available from Different Motor Manufacturers*

| Manufacturer | Efficiency | | Standard loss, kW | Premium loss, kW |
|---|---|---|---|---|
| | Standard | Premium | | |
| A | 0.910 | 0.940 | 9.2 | 6.0 |
| B | 0.918 | 0.954 | 8.4 | 4.5 |
| C | 0.920 | 0.935 | 8.1 | 6.5 |
| D | 0.925 | 0.945 | 7.6 | 5.5 |
| E | 0.921 | 0.950 | 6.8 | 4.9 |

*For a 125-hp (93-kW), four-pole open motor.

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## Electrical Systems

Power losses

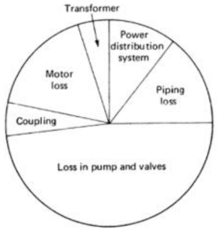

**FIGURE 4.5.9** In a pump drive, power loss in the motor alone may be minor.

---

## Electrical Systems

Motor enclosures
TENV – totally enclosed, non ventilated
TEFC – totally enclosed, fan cooled
TEBC – totally enclosed, blower cooled
TEWAC – totally enclosed, water to air cooled
TEAAC – totally enclosed, air to air cooled
WPII – Weather protected (two 90 degree turns in air path)
ODP – Open drip proof

---

## Electrical Systems

Overload protection – during start, LRA (I2T heating) + no cooling.
Time delay device long enough to allow start put quick enough to protect motor for thermal damage

Note must start with low voltage condition – Torque proportional to square (about 2.2 power) of Voltage reduction

## Electrical Systems

thermal limit

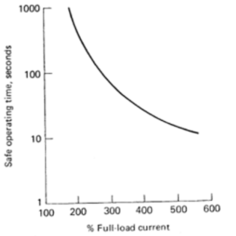

**FIGURE 4.5.10** Thermal damage curve for an induction motor.

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## Electrical Systems

thermal limit

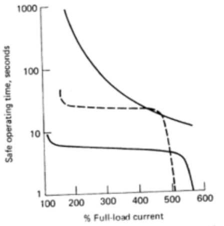

**FIGURE 4.5.11** Damage curve of Fig. 4.5.10 with actual time-current acceleration curves added. Solid curve is full-voltage acceleration; dashed curve is reduced voltage.

---

## Electrical Systems

Rotor Heating –

Heat = Tm / (Tm – Tl) for a given slip speed.

Protection –
External current sensor – Internal Temperature sensor

---

## Electrical Systems

Synchronous Motor –
DC energizes rotor field
May be brushes / slip rings or brushless exciter
Field discharge resistor for acceleration
Damper bars form squirrel cage for starting

Protection – Discharge resistor prevent OV of rotor winding
Loss of field relay – prevent induction operation

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## Electrical Systems

Synchronous Motor
Torque

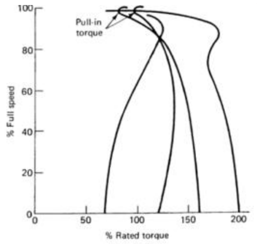

**FIGURE 4.5.16** Typical synchronous motor speed-torque curves. As with induction machines, rotor bar and slot design can provide wide variation in accelerating torque.

---

## Electrical Systems

Excitation System

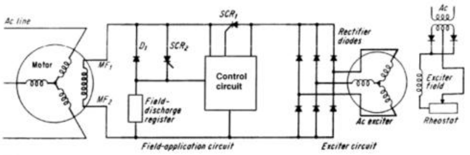

**FIGURE 4.5.15** Motor-mounted exciter gets its excitation from a small rectifier. Exciter ac output is fed to the rectifier diode assembly; output is controlled by the exciter field. The solid-state control circuit applies direct current to motor field through SCR1. Field discharge resistor is also shaft-mounted and is controlled by diode D1 and SCR2. Motor fields (MF1, MF2) are connected at the correct rotor speed.

## Electrical Systems

Synchronous motor more efficient, leading power factor, but more maintenance (possibly) and more costly initially
Risk of instability during transient

---

## Electrical Systems

Synchronous Field

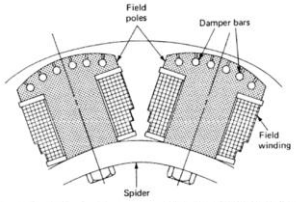

**FIGURE 4.5.14** Synchronous motor field poles (lower) inside stator which is slotted and wound as in Figs. 4.5.1 and 4.5.2.

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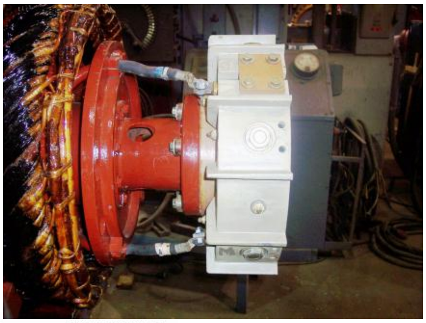

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## Electrical Systems

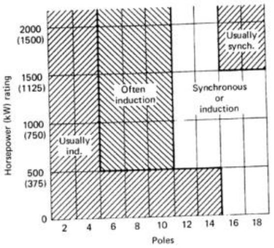


**FIGURE 4.5.17** Usual choice between induction and synchronous motors, depending on both horsepower and speed.

Choice of Synchronous or Induction

---

## Electrical Systems

Variable Frequency Drives –
Used on both induction and synchronous motors
Vary voltage / frequency = vary speed

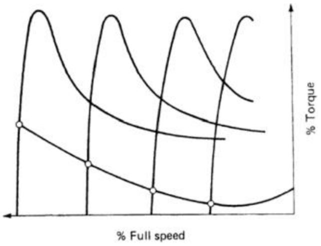
$N = 120 * F / P$

Three Types;
VSI
CSI (synchronous motors only)
PWM

---

## Electrical Systems

Torque / Speed with variable speed.



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## Electrical Systems

**TABLE 4.5.3** Strong Points (+) and Weaknesses (−) of Three Variable-Frequency Inverters

| Item | VSI* | CSI* | PWM* |
|---|---|---|---|
| Open-circuit protection | + | − | + |
| Short-circuit protection | − | + | − |
| Handle undersized motor | + | − | + |
| Handle oversized motor | − | + | − |
| Simplicity | + | + | − |
| Low cost | + | + | − |
| Regeneration capability | − | + | − |
| Stability | − | − | + |
| Efficiency at low speed | + | + | − |

*VSI = voltage-source inverter, CSI = current-source inverter, and PWM = pulse-width-modulated design.

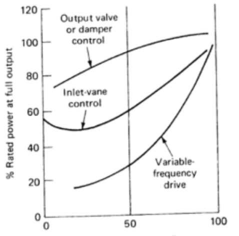

**FIGURE 4.5.18** How overall pump efficiency varies with the type of drive. Two upper curves apply with constant-frequency, single-speed drive motor.

## Electrical Systems

Potential for energy savings

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## Electrical Systems

Voltage Source Inverter

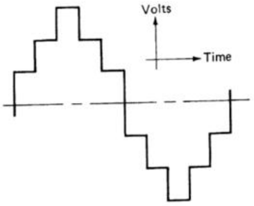

**FIGURE 4.5.20** "Stepped" voltage output of a VSI variable-frequency power supply.

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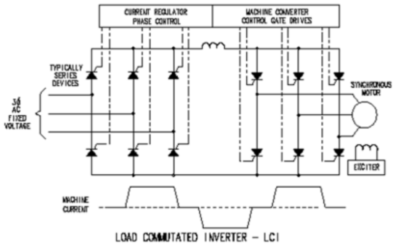
## Electrical Systems

CURRENT SOURCE INVERTER



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## Electrical Systems

Current Source Inverter –

SCR rectifier
L Filter
Synchronous Machines
Match motor to drive
PF reflected to line
Low speed cogging

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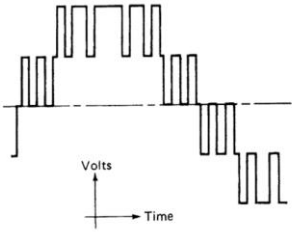
## Electrical Systems

PWM Inverter



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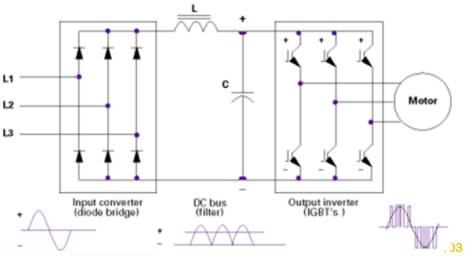
## Electrical Systems

PWM Inverter



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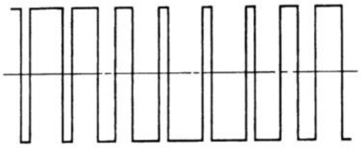
## Electrical Systems

PWM phase to DC bus



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## Electrical Systems

VFD Standards -

NEMA “Application Guide For AC Adjustable Speed Drive Systems”
Available at: http://www.nema.org/
IEEE Std P958 (in development) “Guide for Application of AC Adjustable-Speed Drives for Electric Power Generating Stations”
Available at: http://www.ieee.org/

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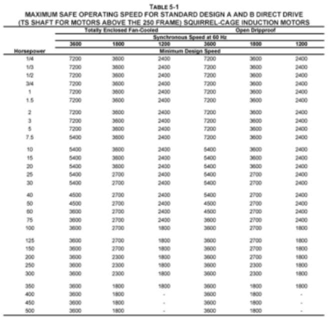

TABLE 5-1
MAXIMUM SAFE OPERATING SPEED FOR STANDARD DESIGN A AND B DIRECT DRIVE
(TS SHAFT FOR MOTORS ABOVE THE 250 FRAME) SQUIRREL-CAGE INDUCTION MOTORS

| | Totally Enclosed Fan-Cooled | | | Open Dripproof | | |
|---|---|---|---|---|---|---|
| | Synchronous Speed at 60 Hz | | | | | |
| | 3600 | 1800 | 1200 | 3600 | 1800 | 1200 |
| Horsepower | Minimum Design Speed | | | | | |
| 1/4 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 1/3 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 1/2 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 3/4 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 1 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 1.5 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 2 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 3 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 5 | 7200 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 7.5 | 5400 | 3600 | 2400 | 7200 | 3600 | 2400 |
| 10 | 5400 | 3600 | 2400 | 5400 | 3600 | 2400 |
| 15 | 5400 | 3600 | 2400 | 5400 | 3600 | 2400 |
| 20 | 5400 | 3600 | 2400 | 5400 | 3600 | 2400 |
| 25 | 5400 | 2700 | 2400 | 5400 | 2700 | 2400 |
| 30 | 5400 | 2700 | 2400 | 5400 | 2700 | 2400 |
| 40 | 4500 | 2700 | 2400 | 5400 | 2700 | 2400 |
| 50 | 4500 | 2700 | 2400 | 4500 | 2700 | 2400 |
| 60 | 3600 | 2700 | 2400 | 4500 | 2700 | 2400 |
| 75 | 3600 | 2700 | 2400 | 3600 | 2700 | 2400 |
| 100 | 3600 | 2700 | 1800 | 3600 | 2700 | 1800 |
| 125 | 3600 | 2700 | 1800 | 3600 | 2700 | 1800 |
| 150 | 3600 | 2700 | 1800 | 3600 | 2700 | 1800 |
| 200 | 3600 | 2300 | 1800 | 3600 | 2700 | 1800 |
| 250 | 3600 | 2300 | 1800 | 3600 | 2300 | 1800 |
| 300 | 3600 | 2300 | 1800 | 3600 | 2300 | 1800 |
| 350 | 3600 | 1800 | 1800 | 3600 | 1800 | 1800 |
| 400 | 3600 | 1800 | - | 3600 | 1800 | - |
| 450 | 3600 | 1800 | - | 3600 | 1800 | - |
| 500 | 3600 | 1800 | - | 3600 | 1800 | - |

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## Electrical Systems

Motor derating curve
Separately powered blower
Windings not randomly wound
Insulated bearings
Higher Vpeak

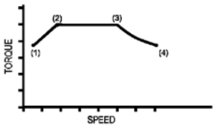

FIGURE 4-8
BASIS OF RATING

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## Electrical Systems

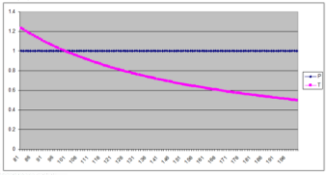
Load Characteristics

Constant HP
Constant Torque
Variable Torque

$$HP = \frac{\text{Torque (lb. ft) x RPM}}{5250}$$

## Electrical Systems

Constant Power –
Torque inverse to speed
Power independent of speed
V/F inverse to speed
High inertia applications



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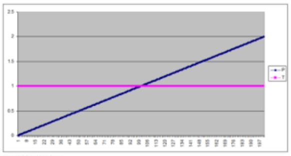
## Electrical Systems

Constant Torque –
Torque independent of speed
HP proportional to speed
V/F independent of speed
Conveyors, augers, etc.



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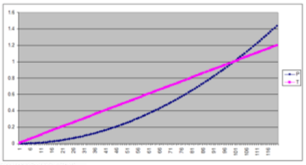
## Electrical Systems

Variable Torque (linear) –
Torque proportional to speed
Power proportional to square of speed
V/F proportional to speed
PD pump, mixer



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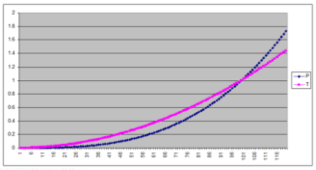
## Electrical Systems

Variable Torque (squared) –
Torque proportional to square of speed
Power proportional to cube of speed
V/F proportional to square of speed
Centrifugal pump, blower



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## Electrical Systems

Motor Bearings and Lubrication:
Antifriction bearings small motors (IEEE 841 specified)
Grease normal lubrication.
Larger motors sleeve or journal bearings.
Pressure lubricated / self lubricated via oil rings
Oil cooler possible
Vertical motor also have thrust bearing
Kingsbury thrust 1 type

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Thrust Bearing

## Electrical Systems

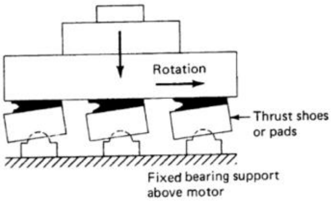

**FIGURE 4.5.22** Basic principle of a pivoted-pad thrust bearing in top end of vertical pump motor. Dark areas are oil-film wedges that sustain thrust. Heavy arrow shows direction of downward thrust load.

## Electrical Systems

Insulation system withstand
Voltage source PWM – switching transients

Surge withstand
Vl = rated motor KV
V1 = sqrt (2/3) & Vl KV
V2 = 2 * V1 KV
V3 = 1.25 * 1.414 * (2Vl + 1) KV

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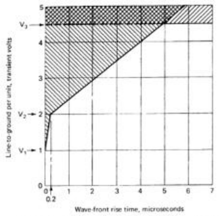

**FIGURE 4.5.24** Impulse or surge withstand capability of motor windings.

## Electrical Systems

insulation
surge
withstand

| Motor rating $V_L$ | Peak $V_1$ | Peak $V_2$ | Peak $V_3$ |
|---|---|---|---|
| 2.3 | 1.88 | 3.76 | 9.9 |
| 4.0 | 3.27 | 6.54 | 15.9 |
| 6.6 | 5.40 | 10.80 | 25.0 |

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## Electrical Systems

Applications
Car Dumper Drive – high torque (special rotor design) + Mechanical holding brake
Mills, Granulators, Pulverizes – lower speed
If try to start full, higher starting torque, (even with low voltage) – special rotor design for torque
Conveyors – high breakaway torque (constant torque)
BFP – high speed – vibration control –
Since motor has low starting torque, typically fluid clutch to decouple pump from motor during start

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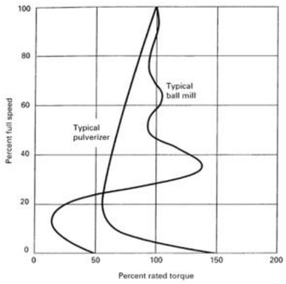

**FIGURE 4.5.26** Speed-torque curves for various types of coal mills are likely to require special high-torque motor designs for safe acceleration. These are only two examples.

## Electrical Systems

Accelerating
Torque

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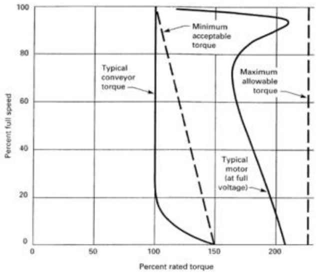

**FIGURE 4.5.27** Conveyor motors need high accelerating torque, but too much torque can overstress the conveyor belt. Keeping the motor accelerating torque within the band shown here by the dashed lines can be extremely difficult when voltage during acceleration undergoes wide excursions.

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## Electrical Systems

Applications
Fans – Centrifugal / Axial – 900 RPM typical - high inertia start – start with dampers closed
CWP – vertical low speed – 300 RPM typical – thrust load – also axial flow, so shut off increase load instead of decrease load
Avoid parallel hydraulic circuits to prevent starting on backflow.

## Electrical Systems

Acceleration Torque

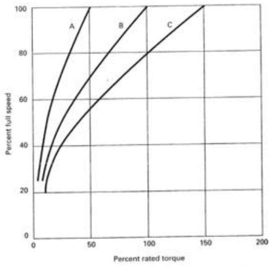

**FIGURE 4.5.28** Torque required by an accelerating pump is lowest for a centrifugal unit with closed discharge (curve *A*). With discharge open, the centrifugal pump follows curve *B*, as does an axial-flow pump. But the latter will demand much higher torque when its valve is closed—curve *C*.

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## Electrical Systems

Acceleration Torque

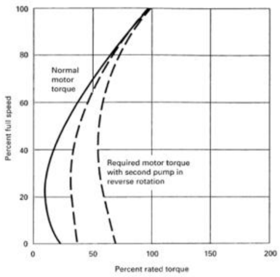

**FIGURE 4.5.29** The multiple-pump operation of a circulating water system can require unusually high motor-starting torque when one pump must be started against the backspin of another.

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## End of Electrical Systems

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# Energy Production Systems Engineering

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**End of Session 7:
Electrical Systems**

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