Welcome to

Electric Machines & Drives

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Session 4:
Efficiency &
3 Ph Induction Mach.

Fall 2011

Session 4

- **Chapter 6 – Efficiency and Heating of Electrical machines**
- **Chapter 13 – Three Phase Induction Machines**

Chapter 6 – Efficiency and Heating of Electrical Machines

Chapter 6

Losses consist of –
-Bearing friction
-Brush friction
-Windage
-I^2R losses (copper losses)
-Brush Losses
-Iron Losses

Chapter 6

I^2R Losses
R depends on –
Appendix AX2 - values of
ρ_O & α
Armaure, series field, commutating poles, compensating winding.

Chapter 6

$R = \rho\, L / A$
$\rho = \rho_O (1 + \alpha\, t)$

R = Resistance of conductor (Ω)
L = Length of conductor (m)
A = Cross section of conductor (m^2)
ρ = resistivity of conductor at temperature t (Ω m)
ρ_O = resistivity of conductor at 0^OC (Ω m)
α = temperature coefficient of resistance at 0^OC ($1/^O$C)
T = temperature of conductor (^{O}C)

Chapter 6

Power loss per Kg material expressed as:

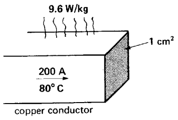
$P_c = 1000\, J^2 \rho / \zeta$

P_c = specific conductor power loss (W/kg)

J = current density (A/mm2)

ρ = resistivity of the conductor Ω m)

ζ = density of the conductor (kg/m^3)



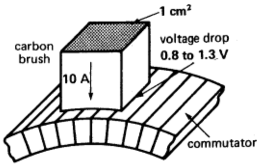
Chapter 6

Brush Loss - I2R small –

Brush Contact Loss V 1-2 Vdc

Iron Loss – Hysteresis, Eddy currents

Losses higher in teeth at higher B



Example 6-1

A dc machine turning at 875 rpm carries an armature winding whose total weight is 40 kg. The current density is 5A/mm^2 and the operating temperature is 80^{O}C. The total iron losses in the armature amount to 1100W. Calculate

a. The copper losses
b. The mechanical drag (Nm) due to the iron losses

Chapter 6

Windage, friction, & iron loss not based on load

I^{2}R loss based on load

Efficiency not same as load changes

η = (Po/Pi)*100% where Pi = Po + losses

η = efficiency (%)

Po = output power (W)

Pi = input power (W)

Example 6-2

A dc compound motor having a rating of 10kW, 1150 rpm, 230V, 50A, has the following losses at full load;

bearing friction loss	40 W
brush friction loss	50 W
windage loss	200 W
total mechanical loss	290 W
iron loss	420 W
copper loss in shunt field	120 W
copper loss at full load	
a. In the armature	500 W
b. In the series field	25 W
c. In the commutating winding	70 W
total copper loss in the armature ckt at full load	595 W

Example 6-2

Calculate the losses and efficiency at no load and at 25%, 50%, 75% and 150% of the nominal rating of the machine.

LOSSES	FULL LOAD	NO LOAD	25% LOAD	50% LOAD	75% LOAD	150% LOAD
bearing friction loss	40 W	40 W	40 W	40 W	40 W	40 W
brush friction loss	50 W	50 W	50 W	50 W	50 W	50 W
windage loss	200 W	200 W	200 W	200 W	200 W	200 W
total mechanical loss	290 W	290 W	290 W	290 W	290 W	290 W
iron loss	420 W	420 W	420 W	420 W	420 W	420 W
copper loss in shunt field	120 W	120 W	120 W	120 W	120 W	120 W
copper loss at full load						
a. In the armature	500 W	0 W	31.25 W	125 W	281.25 W	1125 W
b. In the series field	25 W	0 W	1.5625 W	6.25 W	14.0625 W	56.25 W
c. In the commutating winding	70 W	0 W	4.375 W	17.5 W	39.375 W	157.5 W
total copper loss in the armature ckt at full load	1425 W	830 W	867.1875 W	978.75 W	1164.6875 W	2168.75 W
motor load	10000	0	2500	5000	7500	15000
efficiency (%)	94.38	0	74.25	83.63	86.56	87.37

Chapter 6

Temperature Rise –based on 40OC
½ life for every 10OC above rated (approx)

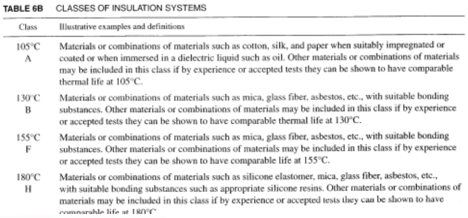


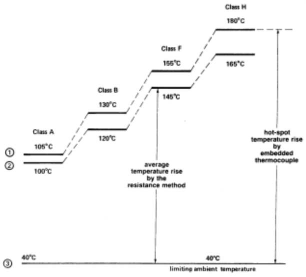
TABLE 6B CLASSES OF INSULATION SYSTEMS

Class	Illustrative examples and definitions
105°C A	Materials or combinations of materials such as cotton, silk, and paper when suitably impregnated or coated or when immersed in a dielectric liquid such as oil. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 105°C.
130°C B	Materials or combinations of materials such as mica, glass fiber, asbestos, etc., with suitable bonding substances. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable thermal life at 130°C.
155°C F	Materials or combinations of materials such as mica, glass fiber, asbestos, etc., with suitable bonding substances. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable life at 155°C.
180°C H	Materials or combinations of materials such as silicone elastomer, mica, glass fiber, asbestos, etc., with suitable bonding substances such as appropriate silicone resins. Other materials or combinations of materials may be included in this class if by experience or accepted tests they can be shown to have comparable life at 180°C.

Chapter 6

Typical limits of machines

1. Max temp of insulation for service life
2. Max temp using resistance calculation
3. Max ambient temp.



Example 6-3

A 75kW motor, class F insulation, opeates at full load in ambient temperature of 32^{O}C. If the not spot temperature is 125^{O}C, does the motor meet the temperature standards?

Chapter 6

Resistance Method – average value
For Aluminum, use 228 instead of 234

th = (Rh/Rc)(234 + tc) – 234

th = avg temp of winding when hot
Rh = hot resistance of winding
Rc = cold resistance of winding
tc = avg temp of winding when cold

Example 6-4

A dc motor is at ambient temperature of 19OC and has shunt field resistance of 22 Ω. At full load field resistance is 30 Ω. The corresponding ambient is 24^{O}C. If motor has class B insulation, calculate following;

a. Average temperature of the winding at full load.
b. Full load temperature rise by resistance method.
c. Whether motor meets class B rise standard.

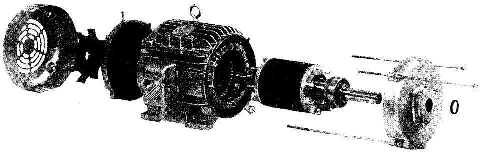
Chapter 13 – Three Phase Induction Machines

Chapter 13

Stator – laminated core, slots, 3phase winding
Rotor – laminated core, slots, 3phase winding or squirrel cage winding
Squirrel cage induction motor
Bare copper (aluminum) bars welded to copper (aluminum) end rings
Wound rotor induction motor
Three phase winding – three slip rings – external resistor

Chapter 13

Stator, rotor, end-bells, cooling fan, bearings, terminal box



Chapter 13

Faraday's Law:

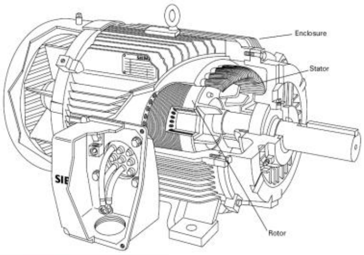
E = B l V = N ΔΦ/Δt

Lorentz Force:

F = B l i

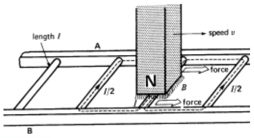
Chapter 13

Rotor, Stator, Enclosure



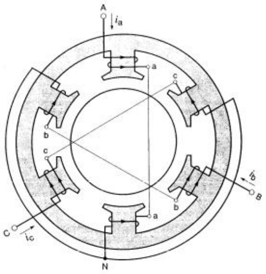
Magnet Moving Across Conductor

1. Voltage induced (E∝BlV) -> current induced
2. Forced induced (F∝Bli) -> direction with velocity
3. Ladder accel until equilibrium reached.



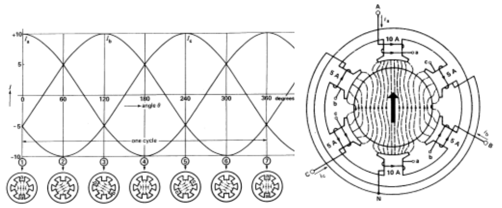
Chapter 13

Current displaced 120^O
Induce Magnetic Flux
Evaluate one cycle at 60^O increments



Chapter 13

Flux Pattern at instant 1



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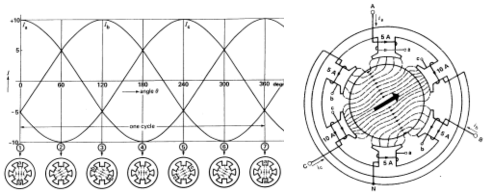
Chapter 13

Flux Pattern at instant 2



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Chapter 13

Flux Pattern at instant 3

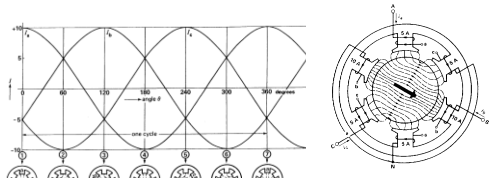

Figure 13.8c
Flux pattern at instant 3.

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Chapter 13

Flux Pattern at instant 4

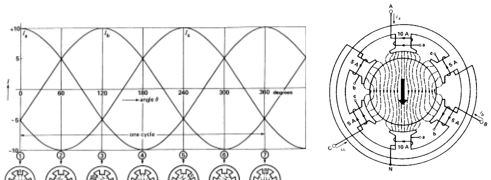

Figure 13.8d
Flux pattern at instant 4.

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Chapter 13

Flux Pattern at instant 5

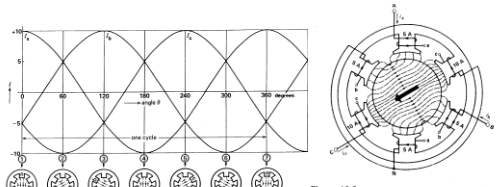

Figure 13.8e
Flux pattern at instant 5.

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Chapter 13

Flux Pattern at instant 6

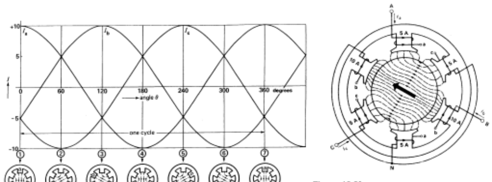

Figure 13.8f
Flux pattern at instant 6.

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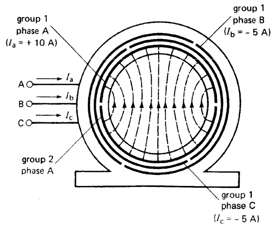
Chapter 13

Field speed = 120 * f / p
Salient Pole Stator -> Smooth Stator
Phase group -> group = #phase * #poles(*#winding)
Group = 3*2=6
#slot = #coils
Lap wound coil construction

Chapter 13

Phase B & C displaced by 120O
2 Pole machine shown



Chapter 13

N = 120*f/p
Speed is ½ 2pole

4 pole motor
Construction

Group=3*4=12

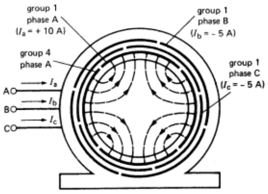


Figure 13.10b
Four-pole, full-pitch, lap-wound stator and resulting magnetic field when $I_a = +10$ A and $I_b = I_c = -5$ A.

Chapter 13

N = 120*f/p
Speed is 1/4 2pole

8 pole motor
Construction

Group=3*8=24

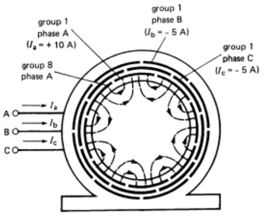
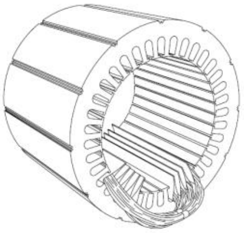


Figure 13.11
Eight-pole, full-pitch, lap-wound stator and resulting magnetic field when $I_a = +10$ A and $I_b = I_c = -5$ A.

Chapter 13

Stator construction



Chapter 13

During start, higher impedance – during run, lower impedance

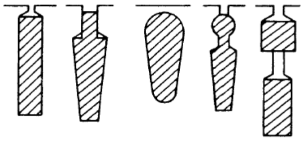


FIGURE 4.5.3 Typical rotor bar and slot shapes for squirrel-cage rotors. Double cage, at right, uses two separate conductors in each slot.

Chapter 13

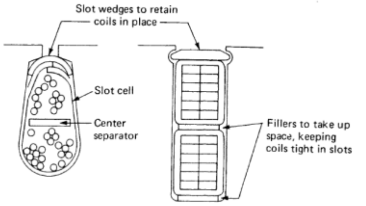


FIGURE 4.5.23 Cross section of random-wound stator slot, left, shows how round wires are randomly packed into areas occupied by top and bottom coil sides, with insulating separator plus slot *cell* or liner. At right, similar sectional view shows rectangular wires of *formed* and taped coils used for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

Chapter 13

Insulation System

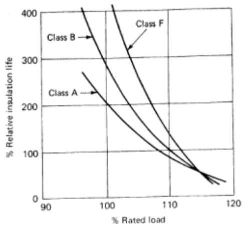


FIGURE 4.5.7 Insulation life versus load for three stan dard insulation systems, showing the effect of continuou motor operation at 1.15 service factor load.

Chapter 13

Motor efficiency –
Efficiency = Pout / Pin * 100%

For nominal efficiency, there is minimum efficiency per NEMA

May not pay back unless run time large.

NEMA MG10 – Payback period calculation

Chapter 13

NEMA nominal Efficiency Ranges

Nominal Efficiency (%)	Minimum Efficiency (%)
95	94.1
94.5	93.6
94.1	93
93.6	92.4
93	91.7
92.4	91

Chapter 13

Losses in System

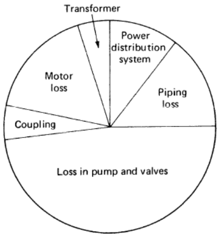


FIGURE 4.5.9 In a pump drive, power loss in the motor alone may be minor.

Chapter 13

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

Chapter 13

Synchronous speed vs. asynchronous speed

ns = 120 f / p

ns = synchronous speed (rpm)
f = frequency of the source (Hz)
p = number of poles

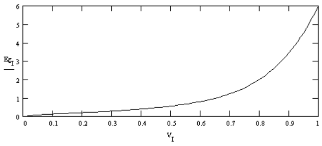
Example 13-1

Calculate the synchronous speed of a 3 pahse induction motor having 20 poles when connected to a 50 Hz source.

Chapter 13

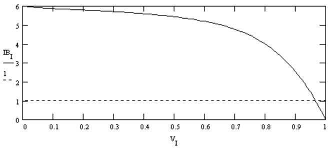
Starting Characteristics –
1.Revolving field set up by applied stator voltage
2.Field induced voltage (E_2) in rotor bars.
3.Induced voltage induces current in rotor bars.
4.Induced current in magnetic field induces force on conductors in direction of rotating magnetic field.
5.As rotor speed increases – rate at which rotor bars cut field reduces (reducing E_2)
6.Reduced E_2 -> reduced rotor current ->reduced force
7.When load torque = motor torque, steady state

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



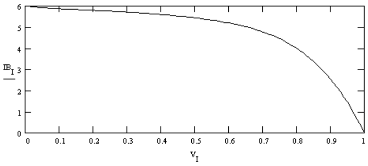
How does Eg vary as motor accelerates to full speed?
At low speed, Eg changes little = constant impedance device.
At high speed, Eg changes greatly = constant HP device.

Chapter 13



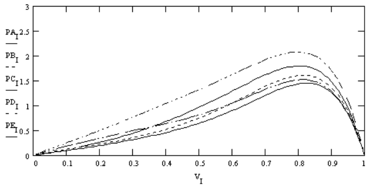
Irunning = (V - Eg) / Zmotor
At locked rotor, Eg = 0
Istarting = V / Zmotor
As motor increases speed, Eg increases
Motor current decays as Eg increases

KVA vs Speed



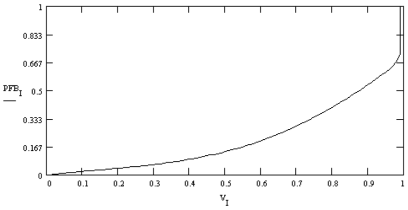
KVA = V motor * I motor * 1.73
Since Vmotor constant in ATL starting, KVA curve appears as current curve

Power vs speed

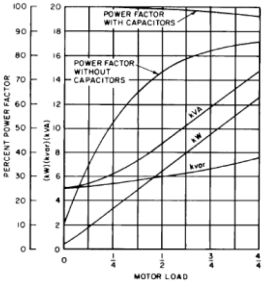


Motor Power vs Speed

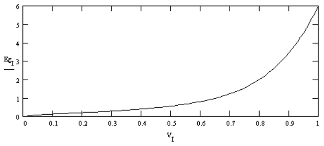
Power factor vs speed



Power & PF vs loading



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.

Chapter 13

Percent difference between synch speed and actual speed = slip

s = (ns – n)/ns

s = slip
ns = synchronous speed (rpm)
n = rotor speed (rpm)

Example 13-2

A 0.5 hp, 6 pole induction motor is excited by a 3 phase, 60 Hz osurce. If the full load speed is 1140 rpm, calcuate the full load slip.

Chapter 13

Rotor Voltage (E_2) and frequency (f_2)
$f_2 = s f$

$E_2 = s$ Eoc (approx)

f_2 = frequency of rotor voltage / current (Hz)
f = frequency of stator voltage / current (Hz)
E_2 = voltage induced in rotor at slip s
Eoc = open circuit voltage induced in rotor at rest (V)

Example 13-3

The 6 pole, wound rotor induction motor of Example 13-2 is excited by a 3 phase, 60 Hz source. Calculate the frequency of the rotor current under the following conditions:

a. At standstill
b. Motor turning at 500 rpm in same direction as the revolving field
c. Motor turning at 500 rpm in the opposite direction to the revolving field
d. Motor turning at 2000 rpm in the same direction as the revolving field

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Chapter 13

Motor characteristics at NL, FL, LR

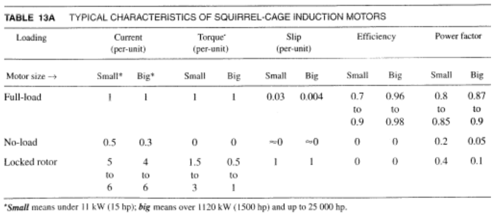

TABLE 13A TYPICAL CHARACTERISTICS OF SQUIRREL-CAGE INDUCTION MOTORS

Loading	Current (per-unit)		Torque' (per-unit)		Slip (per-unit)		Efficiency		Power factor	
Motor size →	Small*	Big*	Small	Big	Small	Big	Small	Big	Small	Big
Full-load	1	1	1	1	0.03	0.004	0.7 to 0.9	0.96 to 0.98	0.8 to 0.85	0.87 to 0.9
No-load	0.5	0.3	0	0	≈0	≈0	0	0	0.2	0.05
Locked rotor	5 to 6	4 to 6	1.5 to 3	0.5 to 1	1	1	0	0	0.4	0.1

*Small means under 11 kW (15 hp); *big* means over 1120 kW (1500 hp) and up to 25 000 hp.

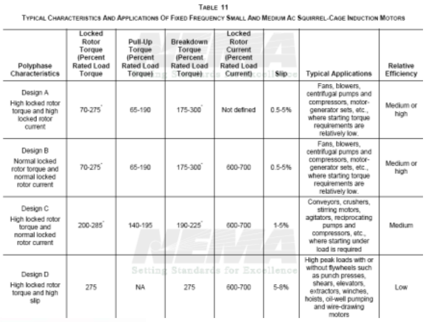

Table 11
Typical Characteristics And Applications Of Fixed Frequency Small And Medium Ac Squirrel-Cage Induction Motors

Polyphase Characteristics	Locked Rotor Torque (Percent Rated Load Torque	Pull-Up Torque (Percent Rated Load Torque)	Breakdown Torque (Percent Rated Load Torque)	Locked Rotor Current (Percent Rated Load Current)	Slip	Typical Applications	Relative Efficiency
Design A High locked rotor torque and high locked rotor current	70-275*	65-190	175-300*	Not defined	0.5-5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or high
Design B Normal locked rotor torque and normal locked rotor current	70-275*	65-190	175-300*	600-700	0.5-5%	Fans, blowers, centrifugal pumps and compressors, motor-generator sets, etc., where starting torque requirements are relatively low.	Medium or high
Design C High locked rotor torque and normal locked rotor current	200-285*	140-195	190-225*	600-700	1-5%	Conveyors, crushers, stirring motors, agitators, reciprocating pumps and compressors, etc., where starting under load is required	Medium
Design D High locked rotor torque and high slip	275	NA	275	600-700	5-8%	High peak loads with or without flywheels such as punch presses, shears, elevators, extractors, winches, hoists, oil-well pumping and wire-drawing motors	Low

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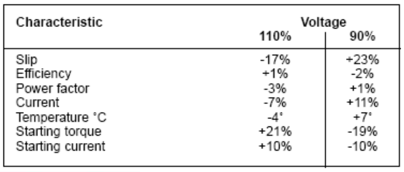
Chapter 13

Induction motors are designed to operate successfully with voltage variations of ±10%. Effects of a 10% variation on a typical design B induction motor at full load shown below.



Characteristic	Voltage 110%	90%
Slip	-17%	+23%
Efficiency	+1%	-2%
Power factor	-3%	+1%
Current	-7%	+11%
Temperature °C	-4°	+7°
Starting torque	+21%	-19%
Starting current	+10%	-10%

Chapter 13

Unbalanced voltage -> derate of motor capability

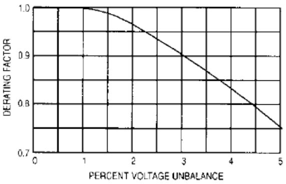


Figure 3.1
Polyphase Squirrel-Cage Induction Motors Derating Factor Due to Unbalanced Voltage

Chapter 13

Estimate of motor current

I = 6000 Ph / E

I = full load current (A)
Ph = output power (HP)
E = rated line voltage (V)

Chapter 13

Motor Full Load Current (NEMA design)

Motor Full Load Current (FLA) @ 60 Hz

Motor HP	200V	230V	460V	575V
5	15.2	13.2	6.6	5.28
7.5	22.2	19.3	9.7	7.72
10	29	25.2	12.6	10.1
15	43.8	38.1	19.1	15.2
20	58.1	50.5	25.3	20.2
25	72.1	62.7	31.3	25
30	83.7	72.8	36.4	29.2
40	112.7	98	49	39.2
50	139.2	121	60.5	48.4
60	164.5	143	71.5	57.2
75	204.7	178	89	71.2
100	268	233	116	93.2
125	332.4	289	144	115
150	397.9	346	173	138
200	529	460	230	184
250	657.8	572	286	229
300	787.8	685	342	274
400	-	-	455	364
500	-	-	578	462

MAXIMUM LOCKED-R0TOR 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.

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.

Chapter 13

Active power flow through motor

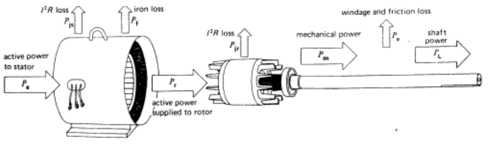


Figure 13.15
Active power flow in a 3-phase induction motor.

Chapter 13

Active power flow through motor
P_e – Active stator power input
P_{js} – I^2R loss in stator
P_f – Iron loss in stator
P_r – active power supplied to rotor
P_{jr} – I^2R loss in rotor
P_m – Mechanical power of rotor
P_v – windage / friction losses
P_L – power to load

Chapter 13

Efficiency = Pout to Pin

η = Pl / Pe

η = Pl / (Pl + P_{js} + P_f + P_{jr} + P_v)

P_{js} – I^2R loss in stator
P_f – Iron loss in stator
P_{jr} – I^2R loss in rotor
P_v – windage / friction losses

Chapter 13

Mechanical torque developed by shaft

Tm = 9.55 Pr / ns

Tm = torque developed by motor at any speed (Nm)
Pr = power transmitted to rotor (W)
Ns = synchronous speed (rpm)

Example 13-5

A 3 phase induction motor having a synchronous speed of 1200 rpm draws 80kW from a 3 phase feeder. The copper losses and iron losses in the stator amount to 5kW. If the motor runs at 1152 rpm, calculate;

a. The active power transmitted to the rotor
b. The rotor I^2R losses
c. The mechanical power developed.
d. The mechnical power delivered to the load, knowing that windage and friction losses are equal to 2kW
e. The efficiency of the motor

Chapters 13 continued and begin Chapter 14 and 15 all next session

Electric Machines & Drives

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End of Session 4:
Efficiency &
3 Ph Induction Mach.

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