EM564 SECOND PROJECT:TRAIN MOTOR DESIGN

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Specification and Design Parameter

This project is relevant to design is a traction asynchronous squirrel cage induction motor with the following specifications:

*Rated Power Output: 1280 kW

*Line-to-line voltage: 1350 V

*Number of poles: 6

*Rated Speed: 1520 rpm (72 km/h) (driven with 78 Hz inverter)

*Rated Motor Torque: 7843 Nm

*Cooling: Forced Air Cooling

*Insulating Class: 200

*Train Wheel Diameter: 1210 mm

*Maximum Speed: 140 km/h

*Gear Ratio: 4.821

The main idea of design motor is to obtain the dimensions of all parts of the motor in order to supply these data to the manufacturer. The outcome of the project are like this:

*Material Properties, Frame size etc.

*Magnetic Circuit Details (flux density calculations at various points: air-gap, teeth, back-core etc, magnetic loading)

*Electric Circuit (Winding selection, electric loading, fill factor, phase resistance, winding factors (for fundamentalsn and for harmonics))

*Rough thermal calculations (cooling method, operating temperature, ways to improve cooling)

*Efficiency, current, torque characteristics

*Mass Calculations (structural mass, copper mass, steel mass etc)

```
P=1280000;
V=1350;
Vph=V/sqrt(3);
 pole=6;
 pole_p=pole/2;
 m=3; % phase number
 q=4;
 Nr=1520;
 f=78;
 Nsyn=f/(pole/2); % synchronous rotor speed in hertz
 Tr=7843;
 Ns=120*f/(pole);
s=(Ns-Nr)/Ns;
power_factor=0.85;
efficiency=0.91;
```

Since January 1, 2015: The legally specified minimum efficiency IE3 must be maintained for power ratings from 7.5 kW to 375 kW or an IE2 motor plus frequency inverter.

```
eff = imread('efficiency_table.png');
figure;
imshow(eff);
title('Efficiency Table','FontSize',18,'FontWeight','Bold');
```

Efficiency Table

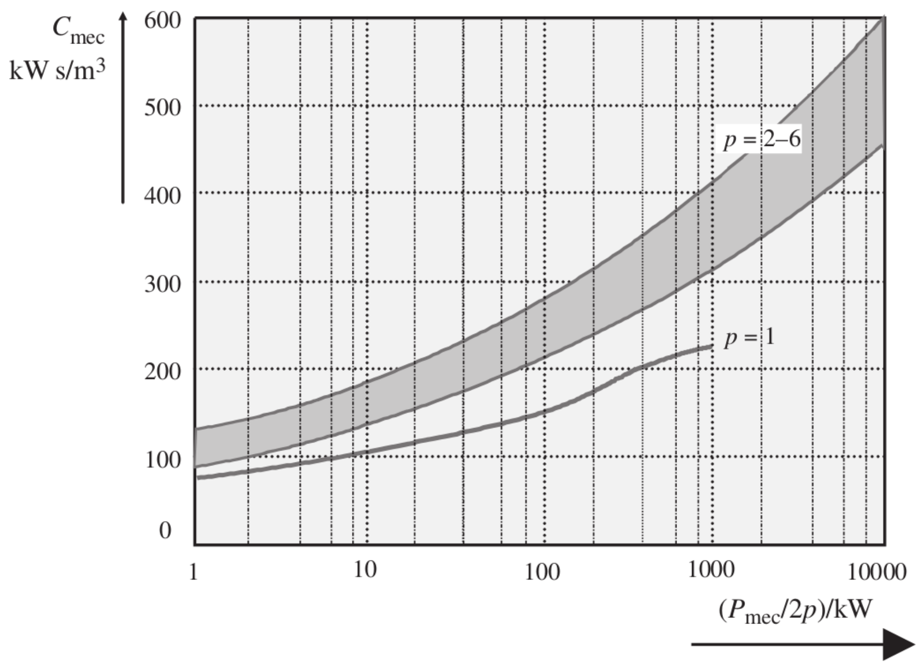
Minimum 50 Hz efficiency values defined in IEC/EN 60034-30-1:2014 (based on test methods specified in IEC 60034-2-1:2014)

Output	IE1				IE2				IE3				IE4			
kW	2 pole	4 pole	6 pole	8 pole	2 pole	4 pole	6 pole	8 pole	2 pole	4 pole	6 pole	8 pole	2 pole	4 pole	6 pole	8 pole
0.12	45.0	50.0	38.3	31.0	53.6	59.1	50.6	39.8	60.8	64.8	57.7	50.7	66.5	69.8	64.9	62.3
0.18	52.8	57.0	45.5	38.0	60.4	64.7	56.6	45.9	65.9	69.9	63.9	58.7	70.8	74.7	70.1	67.2
0.20	54.6	58.5	47.6	39.7	61.9	65.9	58.2	47.4	67.2	71.1	65.4	60.6	71.9	75.8	71.4	68.4
0.25	58.2	61.5	52.1	43.4	64.8	68.5	61.6	50.6	69.7	73.5	68.6	64.1	74.3	77.9	74.1	70.8
0.37	63.9	66.0	59.7	49.7	69.5	72.7	67.6	56.1	73.8	77.3	73.5	69.3	78.1	81.1	78.0	74.3
0.40	64.9	66.8	61.1	50.9	70.4	73.5	68.8	57.2	74.6	78.0	74.4	70.1	78.9	81.7	78.7	74.9
0.55	69.0	70.0	65.8	56.1	74.1	77.1	73.1	61.7	77.8	80.8	77.2	73.0	81.5	83.9	80.9	77.0
075	72.1	72.1	70.0	61.2	77.4	79.6	75.9	66.2	80.7	82.5	78.9	75.0	83.5	85.7	82.7	78.4
1.1	75.0	75.0	72.9	66.5	79.6	81.4	78.1	70.8	82.7	84.1	81.0	77.7	85.2	87.2	84.5	80.8
1.5	77.2	77.2	75.2	70.2	81.3	82.8	79.8	74.1	84.2	85.3	82.5	79.7	86.5	88.2	85.9	82.6
2.2	79.7	79.7	77.7	74.2	83.2	84.3	81.8	77.6	85.9	86.7	84.3	81.9	88.0	89.5	87.4	84.5
3	81.5	81.5	79.7	77.0	84.6	85.5	83.3	80.0	87.1	87.7	85.6	83.5	89.1	90.4	88.6	85.9
4	83.1	83.1	81.4	79.2	85.8	86.6	84.6	81.9	88.1	88.6	86.8	84.8	90.0	91.1	89.5	87.1
5.5	84.7	84.7	93.1	81.4	87.0	87.7	86.0	83.8	89.2	89.6	88.0	86.2	90.9	91.9	90.5	88.3
7.5	86.0	86.0	84.7	83.1	88.1	88.7	87.2	85.3	90.1	90.4	89.1	87.3	91.7	92.6	91.3	89.3
11	87.6	87.6	86.4	85.0	89.4	89.8	88.7	86.9	91.2	91.4	90.3	88.6	92.6	93.3	92.3	90.4
15	88.7	88.7	87.7	86.2	90.3	90.6	89.7	88.0	91.9	92.1	91.2	89.6	93.3	93.9	92.9	91.2
18.5	89.3	89.3	88.6	86.9	90.9	91.2	90.4	88.6	82.4	92.6	91.7	90.1	93.7	94.2	93.4	91.7
22	89.9	89.9	89.2	87.4	91.3	91.6	90.9	89.1	92.7	93.0	92.2	90.6	94.0	94.5	93.7	92.1
30	90.7	90.7	90.2	88.3	92.0	92.3	91.7	89.8	93.3	93.6	92.9	91.3	94.5	94.9	94.2	92.7
37	91.2	91.2	90.8	88.8	92.5	92.7	92.2	90.3	93.7	93.9	93.3	91.8	94.8	95.2	94.5	93.1
45	91.7	91.7	91.4	89.2	92.9	93.1	92.7	90.7	94.0	94.2	93.7	92.2	95.0	95.4	94.8	93.4
55	92.1	92.1	91.9	89.7	93.2	93.5	93.1	91.0	94.3	94.6	94.1	92.5	95.3	95.7	95.1	93.7
75	92.7	92.7	92.6	90.3	93.8	94.0	93.7	91.6	94.7	95.0	94.6	93.1	95.6	96.0	95.4	94.2
90	93.0	93.0	92.9	90.7	94.1	94.2	94.0	91.9	95.0	95.2	94.9	93.4	95.8	96.1	95.6	94.4
110	93.3	93.3	93.3	91.1	94.3	94.5	94.3	92.3	95.2	95.4	95.1	93.7	96.0	96.3	95.8	94.7
132	93.5	93.5	93.5	91.5	94.6	94.7	94.6	92.6	95.4	95.6	95.4	94.0	96.2	96.4	96.0	94.9
160	93.8	93.8	93.8	91.9	94.8	94.9	94.8	93.0	95.6	95.8	95.6	94.3	96.3	96.6	96.2	95.1
200	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.3	95.4
250	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.5	95.4
315	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.6	95.4
355	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.6	95.4
400	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.6	95.4
450	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.6	95.4
500-1000	94.0	94.0	94.0	92.5	95.0	95.1	95.0	93.5	95.8	96.0	95.8	94.6	96.5	96.7	96.6	95.4

Main Dimension of Stator Core

```
cmec = imread('Cmech.png');
figure;
imshow(cmec);
title('Motor constant:Cmec','FontSize',18,'FontWeight','Bold');

Cmec=280;
x=(pi*(pole_p^(1/3)))/pole;
Din=((P/1000)/(Cmec*Nsyn*x))^(1/3); %m
L=x*Din;  %m

ratio = imread('Do-Di value.png');
figure;
imshow(ratio);
title('Inner and outer diameter
 proportion','FontSize',14,'FontWeight','Bold');

Dout=Din/0.7;
Qs=q*m*pole;

Ftan=Tr/(Din/2);
surface_area=pi*Din*L; %m^2
sheer_stress=Ftan*10^-3/surface_area; %kPa
magnetic_loading=0.85; %Magnetic loading
electric_loading=(sheer_stress/magnetic_loading);

airgap=(0.18+0.006*P^(0.4));
```

Motor constant:Cmec



Inner and outer diameter proportion

$2p_1$	2	4	6	8
$\frac{D_{is}}{D_{out}}$	0.54 – 0.58	0.61 – 0.63	0.68 – 0.71	0.72 – 0.74

Stator Winding

```
slot_number = imread('stator and rotor slot number.png');
figure;
imshow(slot_number);
title('Commen stator rotor slot combination
 ','FontSize',18,'FontWeight','Bold');

Qs=q*m*pole;

electrical_angle=(2*pi*pole_p)/Qs;
format rat
electrical_angle_rad=electrical_angle/pi;
format short
```

Commen stator rotor slot combination

p	Q_s	Q_r
1	24	28, 16, 22
	36	24, 28, 48, 16
	48	40, 52
	60	48
2	36	24, 40, 42, 60, 30, 44
	48	60, 84, 56, 44
	60	72, 48, 84, 44
3	36	42, 48, 54, 30
	54	72, 88, 48
	72	96, 90, 84, 54
4	36	48
	48	72, 60
	72	96, 84

Total winding factor (kw) consist of distribution factor (kd) and pitch factor (kp). To eliminate 5.harmonik chording factor is selected 5/6 under pitch

```
chording_factor=5/6;
Kd=sin(pi/(2*m))/(q*sin(pi/(2*m*q)));
Kp=sin((pi/2)*chording_factor);
Kw=Kd*Kp;

pole_pitch=pi*Din/pole; %m
slot_pitch=pole_pitch/(3*q);

mag_flux= imread('magnetic_flux_value.png');
figure;
imshow(mag_flux);
title('Magnetic flux value for the different part of the motor
 ','FontSize',14,'FontWeight','Bold');

Bg=0.7;  % for p=6 Bg=0.7-0.82

Le=L+(2*airgap)/1000;
area_of_one_pole=pi*Din*Le/pole;  %m^2
```

Magnetic flux value for the different part of the motor

	Asynchronous machines
Air gap	0.7–0.90 ($\hat{B}_{\delta 1}$)
Stator yoke	1.4–1.7 (2)
Tooth (apparent maximum value)	1.4–2.1 (stator) 1.5–2.2 (rotor)
Rotor yoke	1–1.6 (1.9)
Pole core	—
Commutating poles	—

Induction motors, both the stator and rotor teeth are saturated at the peak value of the flux density. This leads to a higher reluctance of these teeth when compared with other teeth, and thus ai takes notably higher values than the value corresponding to a sinusoidal distribution. The factor ai (2/pi)has to be iterated gradually to the correct value during the design process. The value ai = 0.64 of an unsaturated machine can be employed as an initial value, unless it is known at the very beginning of the design process that the aim is to design a strongly saturating machine, in which case a higher initial value can be selected.

After calculate magnetic flux using the below equation we can find turn number

E=4.44*f*N*kw*magnetic_flux

```
fundamental_magnetic_flux=(2/pi)*pole_pitch*Bg*L; %Wb
flux=pole_pitch*Le*Bg;
alfa_u=pole*pi/Qs;

format rat
alfa_u_rad=alfa_u/pi;
format short

Kf=1.085;
Ke=0.97;
N=(Ke*Vph)/(4*Kf*Kw*f*fundamental_magnetic_flux);


a1=1;  %number of current path in parallel
```

```
conductor_per_slot=a1*N/(pole_p*q);
number_of_conductor_per_slot=fix(conductor_per_slot); %(ns)
if mod(number_of_conductor_per_slot,2)==0
    number_of_conductor_per_slot_n=number_of_conductor_per_slot;
else
        number_of_conductor_per_slot_n=number_of_conductor_per_slot-1;
end

N_new=number_of_conductor_per_slot*Qs/pole;
```

Number of conductors per slot should be an even number as there are two distinct coils per slot in a double layer winding, Due to changing number of turns per phase we have to recalculate the actual airgap flux density Bg.

```
Bg_new=Bg*N/N_new

Irated=P/(efficiency*power_factor*V*sqrt(3));


Bg_new =

    0.7040
```

J=5-8 A/mm^2 for 2p=6,8

```
J=6.5;

Ac=Irated/J;
d_copper=sqrt(4*Ac/pi);

% because of the skin effect we use paralel conductors.
parallel_branch=12;

d_copper_new=sqrt(4*Ac/(pi*parallel_branch));

awg_area=[107,85,67.4,53.5
 42.4,33.6,26.7,21.2,16.8,13.3,10.6,8.37,6.63,5.26,4.17,3.31,2.63,2.08,1.65,1.31,1
prop=(awg_area*parallel_branch/Ac);
[M,I]=min(prop(prop>1));
awg_size=[11.684,10.405,9.266,8.251,7.348,6.544,5.827,5.189,4.621,4.115,3.665,3.26
wire_cross_section=awg_area(I);
d_co_new=awg_size(I);


awg_size =

  Columns 1 through 7

   11.6840   10.4050    9.2660    8.2510    7.3480    6.5440    5.8270

  Columns 8 through 14

    5.1890    4.6210    4.1150    3.6650    3.2640    2.9060    2.5880
```

```
  Columns 15 through 21

    2.3050    2.0530    1.8280    1.6280    1.4500    1.2910    1.1500

  Columns 22 through 28

    1.0240    0.9120    0.8120    0.7230    0.6440    0.5730    0.5110
```

Skin Effect

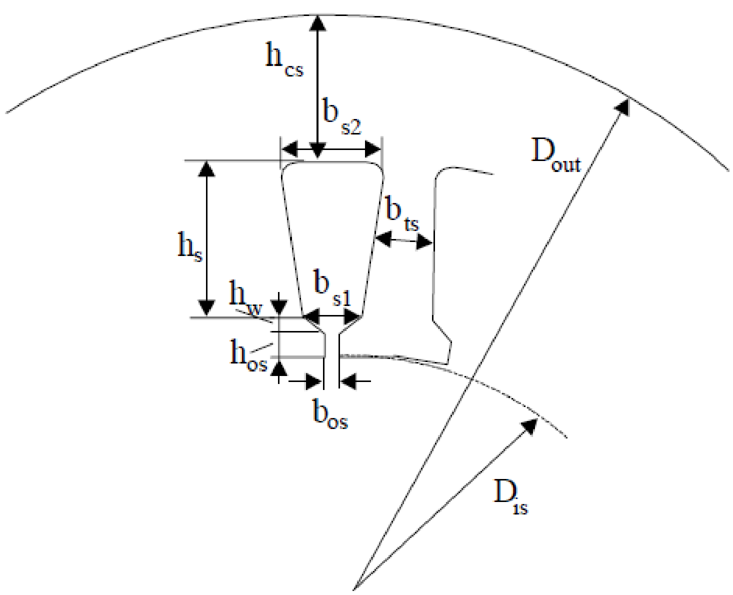
```
mu=4*pi*10^-7;
cop_mu=1.256629*10^-6;
cop_res=1.68*10^-8; % resistivity of the copper for 20C
w=2*pi*f/pole_p;
skin_dept=sqrt((2*cop_res)/(cop_mu*w))*1000; %mm
```

Skin depth is bigger than the wire size and frequency is not very high so we can ignore the skin effect.

Stator Slot Sizing

```
stator_slot= imread('stator_slot_geometry.png');
figure;
imshow(stator_slot);
title('Stator slot geometry','FontSize',18,'FontWeight','Bold');
```

Stator slot geometry



Above 10kW Kfill=0.4-0.44

```
Kfill=0.44;
slot_area=pi*d_co_new^2*parallel_branch*number_of_conductor_per_slot_n/
(4*Kfill); %mm^2

Bts=1.65;
Kfe=0.96; % stator stacking factor
bts=Bg_new*slot_pitch/(Bts*Kfe);   %tooth width
bos=0.0025;
hos=0.001;
hw=0.002;

bs1=(pi*(Din+2*hos+2*hw)/Qs)-bts;  %slot lower width m
bs2 = sqrt(4*slot_area*10^-6*tan(pi/Qs)+(bs1^2));
hs=2*slot_area*10^-6/(bs2+bs1); %m

MMF_airgap=(1.2*airgap*10^-3)*Bg_new/mu;  %airgap mmf
```

From the B-H curve table H values are selected

```
B_H= imread('magnetization_curve.png');
figure;
imshow(B_H);
title('B-H Magnetization curve','FontSize',18,'FontWeight','Bold');

Hts=3460;  %Bts=1.6T ya kar##l#k olarak tablodan seçilmi#tir
MMF_stator_tooth=Hts*(hs+hos+hw);
Kst=0.4;
Fmtr=Kst*MMF_airgap-MMF_stator_tooth;  % E#er Fmtr<<Fmts (yada
 negatif) olsayd# 1+Kst nin Bg de#erinden küçük olmas# gerekiyor.
bcs=(Dout-(Din+2*(hos+hw+hs)))/2; %stator back iron height
Bcs=fundamental_magnetic_flux/(2*L*bcs);  % back core flux density
```

B-H Magnetization curve

B[T]	H[A/m]	B[T]	H[A/m]
0.05	22.8	1.05	237
0.1	35	1.1	273
0.15	45	1.15	310
0.2	49	1.2	356
0.25	57	1.25	417
0.3	65	1.3	482
0.35	70	1.35	585
0.4	76	1.4	760
0.45	83	1.45	1050
0.5	90	1.5	1340
0.55	98	1.55	1760
0.6	106	1.6	2460
0.65	115	1.65	3460
0.7	124	1.7	4800
0.75	135	1.75	6160
0.8	148	1.8	8270
0.85	162	1.85	11170
0.9	177	1.9	15220
0.95	198	1.95	22000
1.0	220	2.0	34000

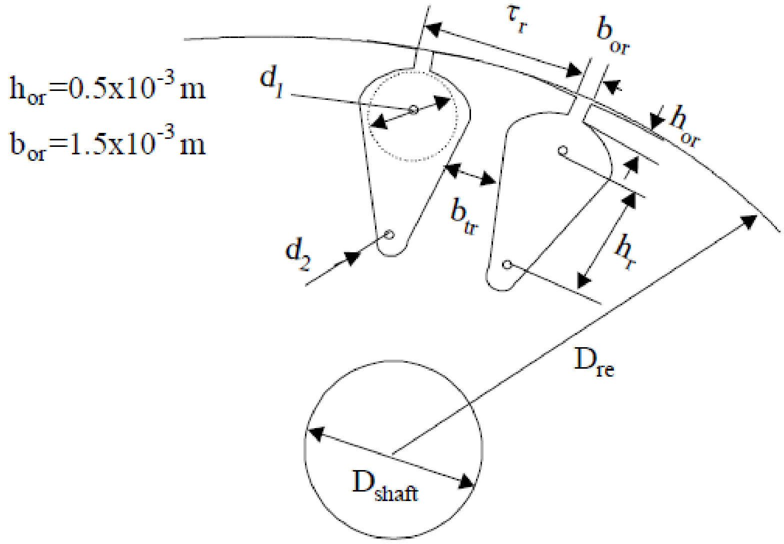
Evidently Bcs is too low. There are three main ways to solve this problem. One is to simply decrease the stator outer diameter until Bcs=1.4 to 1.7 T. The second solution consists in going back to the design start and introducing a minor stack aspect ratio which eventually would result in a bigger Dis, and, finally, a narrower back iron height bcs and thus a bigger Bcs. The third solution is to decrease current density and thus increase slot height hs. However, if high efficiency is the target, such a solution is to be used cautiously.

```
Dout_n=0.818;
bcs_n=(Dout_n-(Din+2*(hos+hw+hs)))/2;
Bcs_n=Bcs*bcs_n/(bcs_n+(Dout_n-Dout)/2);
```

Rotor Slot

```
rotor_slot= imread('rotor_slot_geometry.png');
figure;
imshow(rotor_slot);
title('Rotor slot geometry','FontSize',18,'FontWeight','Bold');

% From the common combination Qr =88 is selected
Qr=56;
hor=0.0005; %m
bor=0.0015;  %m
```

Rotor slot geometry



Ki= 1, the rotor and stator mmf would have equal magnitudes. In reality, the stator mmf is slightly larger.

```
Ki=0.8*power_factor+0.2;
I_rotor_bar=(Ki*2*m*N_new*Kw/Qr)*Irated;
J_r = 5; % A/mm^2;  %rotor current density
Ar=I_rotor_bar/(J_r*10^6);   %10^-6 m^2

rotor_slot_area =I_rotor_bar/J_r; % mm^2
I_end_ring=I_rotor_bar/(2*sin(pole_p*pi/Qr));
```

The current density in the end ring Jer = (0.75 – 0.8)Jb. The higher values correspond to end rings attached to the rotor stack as part of the heat is transferred directly to rotor core.

```
J_er = 0.78*J_r; % A/mm^2 end ring
A_end_ring = I_end_ring/(J_er*10^6); % mm^2
T_rotor_slot = pi*(Din-2*airgap*1e-3)/Qr; % m
B_rotor_tooth = 1.6;
H_tr=2460;
btr = Bg_new*T_rotor_slot/(Kfe*B_rotor_tooth); % m

D_r=Din-2*airgap*10^-3;  %rotor diameter

hw_r=0.003;
br1=(pi*(Din+2*hor+2*hw_r)/Qr)-btr;  %slot lower width m
br2 = sqrt(4*rotor_slot_area*10^-6*tan(pi/Qr)+br1^2);
hr=2*rotor_slot_area*10^-6/(br2+br1); %m

rotor_slot_area = ((pi/8)*(br1^2+br2^2))+((br1+br2)*hr/2); % m^2
Bcr = 1.65; % T
hcr = fundamental_magnetic_flux/(2*L*Bcr); % m
```

```
MMF_rotor_teeth=H_tr*(hr+hor+(br1+br2)/2);  %Aturns

Dshaftmax = Din-(2*airgap*(10^-3))-2*(hor+hr+hcr+(br1+br2)/2); % mm

Tar = 200*atan(2*(hw-hos)/(bs1-bos))/pi; % grad
```

The shaft diameter corresponds to the rated torque and is given in tables based on mechanical design and past experience. The rated torque is approximately

```
Ten=(P)/(2*pi*(f/pole_p)*(1-s));%rated torque Nm

Der=D_r-3.5*10^-3;
b=1.0*(hr+hor+(br1+br2)/2);
a=A_end_ring/b;
```

Magnetization Current

```
Y1=bos*bos/(5*airgap*10^-3+bos);
Y2=bor*bor/(5*airgap*10^-3+bor);
Kc1=slot_pitch/(slot_pitch-Y1);
Kc2=T_rotor_slot/(T_rotor_slot-Y2);
Kc=Kc1*Kc2; %Total Carter coefficient
```

Kc is close to 1.2 which is assumed initially when calculating Fmg. Back core mmfs Fmcs and Fmcr are calculated as follows:

Stator back core flux intensity in A/m Bcs=1.43 from the table # choose for the Bcs=1.45

```
Hcs=1050;
Hcr=3460; %Rotor back core flux intensity in A/m
Fmcs=0.88*exp(-0.4*Bcs^2)*(pi*(Dout-bcs)/(2*pole_p))*Hcs; %Stator back
 core mmf in Aturns
Fmcr=0.88*exp(-0.4*Bcr^2)*(pi*(Dshaftmax+hcr)/(2*pole_p))*Hcr; %Rotor
 back core mmf in Aturns


MMF_magnetization=2*(Kc*airgap*10^-3*Bg_new/mu+MMF_stator_tooth
+MMF_rotor_teeth+Fmcs+Fmcr); %Magnetization mmf in Aturns
Ks=MMF_magnetization/(2*MMF_airgap)-1; %Total saturation factor
```

The total saturation factor Ks takes like this

```
Ks = 0.97;

Imu=(pi*pole_p*MMF_magnetization/2)/
(3*sqrt(2)*N_new*Kw); %Magnetization current in A
i_mu=Imu/Irated; %Relative (p.u.) value of Iu
```

Resistances and Inductances

```
y=chording_factor*pole_pitch;    %Coil span in m
L_end=pi/2*y+0.018; %End connection length for 2*pole_p=6
```

```
L_coil=2*(L+L_end); %Coil length in m
resis_cu=1.78e-8; %Copper resistivity at 20 degrees
resis_cu_80=resis_cu*(1+1/273*(80-20)); %Copper resistivity at 80
 degrees
Rs=resis_cu_80*L_coil*N_new/(Ac*1e-6*a1);

L_er=pi*(Der-b)/Qr; %End ring segment length in m
Beta_s=sqrt(2*pi*f*mu/(2*resis_cu));
S=1;
eta=Beta_s*hr*sqrt(S);
```

Kr the skin effect resistance coefficient for the bar is approximately:

```
Kr=eta*(sinh(2*eta)+sin(2*eta))/(cosh(2*eta)-cos(2*eta));
R_be = resis_cu_80*(L/slot_area*Kr+L_er/(2*A_end_ring*(sin(pi*pole_p/
Qr))^2)); %Rotor bar/end ring segment equivalent resistance in Ohm
Rrc=(4*m/Qr)*(N_new*Kw)^2*R_be; %Rotor cage resistance reduced to the
 stator in Ohm

lambda_s=(2/3*hs/(bs1+bs2)+2*hw/(bos+bs1)+hos/
bos)*(1+3*chording_factor)/4; %Stator slot connection coefficient
Cs=1-0.033*bos*bos/(airgap*10^-3*slot_pitch);
phi=pi*(6*chording_factor-5.5);
gamma_ds=(0.14*sin(phi)+0.76)*1e-2;  % for q=4
lambda_ds=0.9*slot_pitch*q^2*Kw^2*Cs*gamma_ds/
(Kc*airgap*10^-3*(1.0+Kst)); %Stator differential connection
 coefficient
lambda_ec=0.34*q/L*(L_end-0.64*chording_factor*pole_pitch); %Stator
 end connection specific geometric permeance coefficient
Xsl=2*mu*2*pi*f*L*N_new^2/(pole_p*q)*(lambda_s+lambda_ds
+lambda_ec); %Stator phase reactance in Ohm

lambda_r=0.66+2*hr/(3*(br1+br2))+hor/bor; %Rotor slot connection
 coefficient
gamma_dr=9*((6*pole_p/Qr)^2)*1e-2;
lambda_dr=(0.9*T_rotor_slot*10^3*gamma_dr/
(Kc*airgap*10^-3))*10^-2*(Qr/(6*pole_p))^2; %Rotor differential
 connection coefficient
lambda_er=2.3*(Der-b)/(Qr*L*4*(sin(pi*pole_p/Qr))^2)*log10(4.7*(Der-
b)/(b+2*a));  %Stator end ring permeance coefficient
Kx=3/(2*eta)*(sinh(2*eta)-sin(2*eta))/(cosh(2*eta)-cos(2*eta)); %Skin
 effect coefficient for the leakage reactance
X_be=2*pi*f*mu*L*(lambda_r*Kx+lambda_dr+lambda_er); %Equivalent rotor
 bar leakage reactance in Ohm
Xrl=(4*m*(N_new*Kw)^2/Qr)*X_be; %Rotor leakage reactance in ohm
```

For zero speed (S = 1), both stator and rotor leakage reactances are reduced due to leakage flux path saturation. For the power levels of interest here, with semiclosed stator and rotor slots:

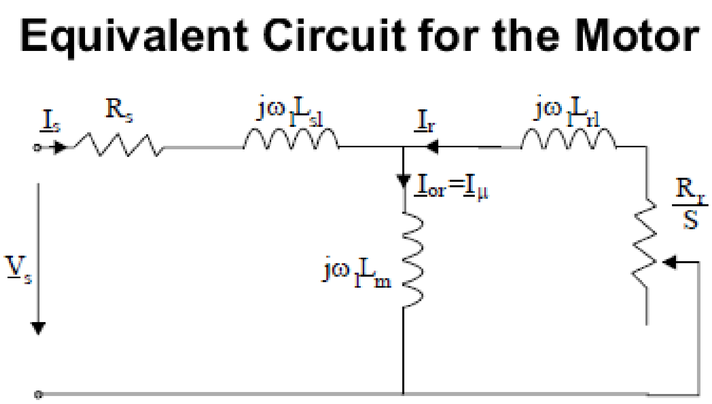
```
Xsl_sat=Xsl*0.75; %Stator leakage reactance at S=1 due to leakage flux
 path saturation
Xrl_sat=Xrl*0.65; %Rotor leakage reactance at S=1 due to leakage flux
 path saturation
```

For rated slip (speed), both skin and leakage saturation effects have to be eliminated (KR = Kx = 1)

```
Rbe_Sn=resis_cu_80*(L/Ar+L_er/(2*A_end_ring*(sin(pi*pole_p/Qr))^2)); %Rotor bar/end ring segment equivalent resistance at rated speed
Rrc_Sn=Rrc*Rbe_Sn/R_be; %Rotor cage resistance reduced to the stator at rated speed
Xbe_Sn=2*pi*f*mu*L*(lambda_r+lambda_dr+lambda_er); %Equivalent rotor bar leakage reactance at rated speed
Xrl_Sn=Xrl*Xbe_Sn/X_be; %Rotor leakage reactance at rated speed

Xm=sqrt(((V/sqrt(3))/Imu)-Rs^2)-Xsl; %Magnetization reactance
```

Skewing effect on reactances are considered in the design.

```
K_skew=sin(pi/(2*m*q))/(pi/(2*m*q)); %Skewing factor
Xm=Xm*K_skew; %Magnetization reactance including skewing
Xrl_skew=Xm*(1-(K_skew^2));
Xrl_sat_skew=Xrl_sat+Xrl_skew; %Final value of rotor leakage reactance at stand still, S=1
Xrl_Sn_skew=Xrl+Xrl_skew; %Final value of rotor leakage reactance at rated speed, S=Sn

equivalent= imread('equivalent_circuit.png');
figure;
imshow(equivalent);
title('Equivalent Circuit for the Motor','FontSize',18,'FontWeight','Bold');
```



Losses and Efficiency

Total losses for the induction motor are copper losses on stator and rotor windings, core losses on the stator, mechanical/ventilation losses and stray losses. The mechanical/ventilation losses are considered as pmv = 0.03Pn for p1 = 1, 0.012Pn for p1 = 2, and 0.008Pn for p1 = 3,4. Here their standard value pstray = 0.01Pn is considered.

```
P_co_s=3*Irated^2*Rs;
Pcur=3*Rrc_Sn*Ki^2*Irated^2;
```

```
Pmv=0.008*P;
Pstray=0.01*P;

gamma_iron=7800; %Iron density in kg/m^3
Ky=1.7; %Influence of mechanical machining
Gt1=gamma_iron*Qs*bts*(hs+hw+hos)*L*Kfe; %Stator tooth weight in kg
Gy1=gamma_iron*pi/4*(Dout^2-(Dout-2*bcs)^2)*L*Kfe; %Yoke weight in kg

Kt=1.7; %Core loss augmentation due to mechanical machining
p10=2.5; %Specific losses (W/kg) at 1.0 T and 50 Hz
Pt1=Kt*p10*(f/50)^(1.3)*(Bts)^(1.7)*Gt1; %Stator teeth fundamental
 losses (W)
Py1=Ky*p10*(f/50)^(1.3)*(Bcs)^(1.7)*Gy1; %Stator back iron (yoke)
 fundamental losses  (W)
P1_iron=Pt1+Py1; %Fundamental iron losses (W)

Kps=1/(2.2-Bts);
Kpr=1/(2.2-B_rotor_tooth);
Bps=(Kc2-1)*Bg_new; %Stator pulse flux density  (T)
Bpr=(Kc1-1)*Bg_new; %Rotor pulse flux density  (T)

Gtr=gamma_iron*L*Kfe*Qr*(hr+(br1+br2)/2)*btr; %Rotor teeth weight (kg)

Gts=Gt1;
Ps_iron=0.5e-4*((Qr*(f/pole_p)*Kps*Bps)^2*Gts+(Ns*(f/
pole_p)*Kpr*Bpr)^2*Gtr); %Tooth flux pulsation core loss in W
Piron=P1_iron+Ps_iron; %Total iron losses W

Ploss= P_co_s+Pcur+Piron+Pmv+Pstray; %Total losses (W)

efficiency_new=P/(P+Ploss); %Efficiency
```

Operation Characteristics

The operation characteristics are defined as active no load current I0a, rated slip Sn, rated torque Tn, breakdown slip and torque Sk, Tbk, current Is and power factor versus slip, starting current, and torque ILR, TLR

```
I_noload=(Piron+Pmv+3*Imu*Imu*Rs)/(3*V/sqrt(3)); %No load active
 current A
s_rated=Pcur/(P+Pcur+Pmv+Pstray); %Rated slip
Tn=P/(2*pi*(f/pole_p)*(1-s_rated)); %Rated shaft torque in Nm

Cm=1+Xsl/Xm;
T_breakdown=(3*pole_p/(2*w))*((V/sqrt(3))^2)/(Rs+sqrt(Rs^2+(Xsl
+Cm*Xrl)^2));
I_starting=(V/sqrt(3))/(sqrt((Rs+Rrc)^2+(Xsl_sat+Xrl_sat)^2));
T_starting=(3*Rrc*I_starting^2/w)*pole_p;
power_factor_new=P/(3*(V/sqrt(3))*Irated*efficiency_new); % power
 factor

Te=(3*pole_p/w)*((V/sqrt(3))^2*Rrc_Sn/s)/((Rs+Cm*Rrc_Sn/s)^2+(Xsl
+Cm*Xrl_Sn_skew)^2); %Approximate torque vs. slip expression
```

```
tbk=T_breakdown/Tn;
tLR=T_starting/Ten;
iLR=I_starting/Irated;
```

Apparently the design does not need any iterations. This is pure coincidence “combined” with standard specifications. Higher breakdown or starting ratios tbk, tLR would, for example, need lower rotor leakage inductance and higher rotor resistance as influenced by skin effect. A larger stator bore diameter is again required. In general, it is not easy to make a few changes to get the desired operation characteristics.

Temperature Rise

```
lambda_ins=0.25; %Insulation thermal conductivity in W/mK
h_ins=0.3e-3; %Total insulation thickness from the slot middle to
 teeth wall in m
alpha_cond=lambda_ins/h_ins; %The slot insulation conductivity plus
 its thickness lumped in W/m^2K
alpha_conv=40; %For 6 pole IMs with selfventilators placed outside the
 motor in W/m^2K

A_stator_slot=(2*hs+bs2)*L*Qs; %Stator slot lateral area in m^2
theta_co=P_co_s/(alpha_cond*A_stator_slot); %Temperature differential
 between the conductors in slots and the slot wall

Kfin=3.0; %Finn coefficient
Aframe=pi*Dout*(L+pole_pitch)*Kfin; %Frame area in m^2
theta_frame=Ploss/(alpha_conv*Aframe); %Frame temperature rise with
 respect to ambient air in Celcius degrees

theta_amb=50; %Ambient temperature in Celcius degrees
theta_w=theta_amb+theta_co+theta_frame; %Winding temperature in
 Celcius degrees
```

Total Weight

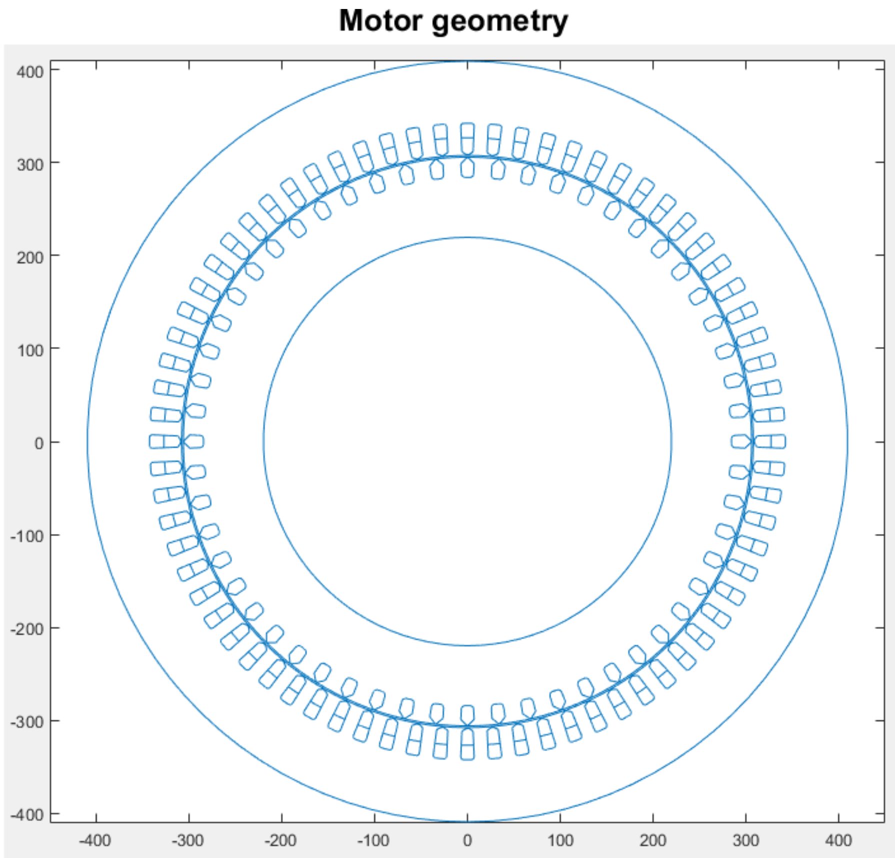
```
Gs=Gt1+Gy1; %Stator iron weight in kg
Gyr=gamma_iron*pi/4*((D_r-2*(hor+(br1+br2)/2+hr))^2-
(Dshaftmax)^2)*L*Kfe; %Rotor yoke weight
Gr=Gtr+Gyr; %Rotor iron weight in kg
Gcus=8940*L_coil*N_new*Ac*1e-6*m; %Stator copper weight in kg
Gcur=8940*(Ar*L+A_end_ring*L_er)*Qr; %Rotor copper weight in kg
Gshaft=gamma_iron*pi/4*Dshaftmax^2;%Shaft weight in kg
Gtotal=Gs+Gr+Gcus+Gcur+Gshaft; %Total motor weight excluding the
 enclosure, ventilation apparatus etc.
```

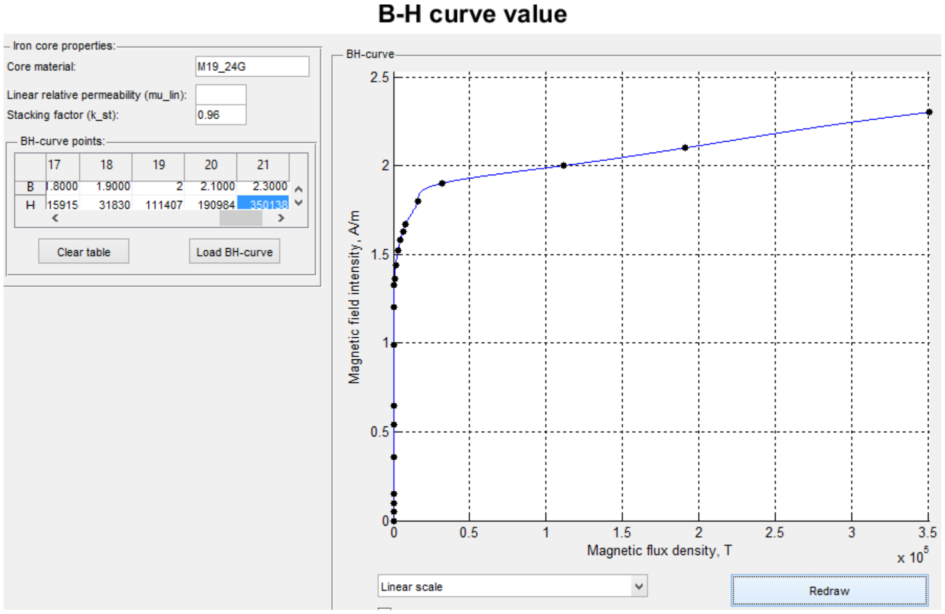
Motor Analysis

After finishing motor analytical design, geometry and winding type are tried to get simulation result by using motoranalysis software. It is got some visual design:

```
geometry= imread('motor_geometry_2nd.png');
```

```
figure;
imshow(geometry);
title('Motor geometry','FontSize',18,'FontWeight','Bold');

magn= imread('B-H_curve.png');
figure;
imshow(magn);
title('B-H curve value','FontSize',18,'FontWeight','Bold');
```





Conclusion

The increase of the rotor slot number has as an impact the stronger magnetization of the rotor parts close to the neutral zones of the magnetic field. On the other hand, the motor which has more rotor slot number presents greater magnetic flux density on the surface of the rotor core opposite to the neutral zones of the magnetic field, compared to the motor with lower slot number In order to sufficiently compare the starting behavior of the motors, the starting torque and stator current were extracted for each case, the motor with 56 rotor slots is characterized by the least starting torque, whereas the motor with 88 rotor slots has the greatest. The model with 88 rotor slots is also characterized by the least starting stator current amplitude. When we compare generally especially motor starting torque and breakdown torque are effected considerably. its value decrease by changing rotor slot number. In the first design Tstarting=304.317751 Nm and T_breakdown=24159.682886 Nm but now:

```
fprintf('T_starting: %f m\n',T_starting)
fprintf('T_breakdown: %f m\n',T_breakdown)
```

```
T_starting: 82.845630 m
T_breakdown: 12438.523633 m
```

Outputs

Main Dimension of Stator Core

```
fprintf('Stator bore diameter: %f m\n',Din)
fprintf('Stack length: %f m\n',L)
fprintf('Pole pitch: %f m\n',pole_pitch)
fprintf('Slot pitch: %f m\n',slot_pitch)
fprintf('Outer diameter: %f m\n',Dout_n)
fprintf('Rotor diameter: %d m\n',D_r)
fprintf('Airgap: %d mm\n',airgap)
```

```
Stator bore diameter: 0.615196 m
Stack length: 0.464571 m
Pole pitch: 0.322116 m
Slot pitch: 0.026843 m
Outer diameter: 0.818000 m
Rotor diameter: 6.115085e-01 m
Airgap: 1.843548e+00 mm
```

Stator Winding

```
fprintf('Number of stator slot: %d\n',Qs)
fprintf('Distribution factor:%f \n',Kd)
fprintf('Pitch factor:%f \n',Kp)
fprintf('Winding factor:%f \n',Kw)
fprintf('Pole flux:%f  Wb\n',fundamental_magnetic_flux)
fprintf('Number of turns per phase:%f turns/phase\n',N_new)
fprintf('Number of conductor per slot:%f
 \n',number_of_conductor_per_slot_n)
fprintf('Rated current:%f  A\n',Irated)
fprintf('Magnetic wire cross section:%f mm^2\n',Ac)
fprintf('Wire gauge diameter:%f mm\n',d_co_new)
```

```
Number of stator slot: 72
Distribution factor:0.957662
Pitch factor:0.965926
Winding factor:0.925031
Pole flux:0.066687  Wb
Number of turns per phase:36.000000 turns/phase
Number of conductor per slot:2.000000
Rated current:707.709875  A
Magnetic wire cross section:108.878442 mm^2
Wire gauge diameter:3.665000 mm
```

Stator Slot Sizing

```
fprintf('Slot area:%f mm^2\n',slot_area)
fprintf('Stacking factor:%f\n',Kfe)
fprintf('hos:%f mm\n',hos*1000)
fprintf('bos:%f mm\n',bos*1000)
fprintf('bts:%f mm\n',bts*1000)
fprintf('bs1:%f mm\n',bs1*1000)
fprintf('bs2:%f mm\n',bs2*1000)
fprintf('bcs:%f mm\n',bcs*1000)
fprintf('hs:%f mm\n',hs*1000)
fprintf('hw:%f mm\n',hw*1000)
```

```
Slot area:575.435173 mm^2
Stacking factor:0.960000
hos:1.000000 mm
bos:2.500000 mm
bts:11.929800 mm
bs1:15.174969 mm
bs2:18.187245 mm
bcs:94.331395 mm
hs:34.496222 mm
```

```
hw:2.000000 mm
```

Rotor Slot

```
fprintf('Number of stator slot: %f\n',Qr)
fprintf('Rated rotor bar current:%f A \n',I_rotor_bar)
fprintf('Rotor slot area:%f m^2 \n',Ar)
fprintf('End ring cross section:%f m^2\n',A_end_ring)
fprintf('Rotor slot pitch:%f mm \n',T_rotor_slot*1000)
fprintf('hor:%f mm\n',hor*1000)
fprintf('bor:%f mm\n',bor*1000)
fprintf('btr:%f mm\n',btr*1000)
fprintf('br1:%f mm\n',br1*1000)
fprintf('br2:%f mm\n',br2*1000)
fprintf('hcr:%f mm\n',hcr*1000)
fprintf('hr:%f mm\n',hr*1000)
fprintf('hw_r:%f mm\n',hw_r*1000)
fprintf('Maximum diameter of the shaft:%f mm\n',Dshaftmax*1000)
```

```
Number of stator slot: 56.000000
Rated rotor bar current:2222.080430 A
Rotor slot area:0.000444 m^2
End ring cross section:0.001701 m^2
Rotor slot pitch:34.305544 mm
hor:0.500000 mm
bor:1.500000 mm
btr:15.722835 mm
br1:19.182253 mm
br2:21.628461 mm
hcr:43.498675 mm
hr:21.779383 mm
hw_r:3.000000 mm
Maximum diameter of the shaft:439.141622 mm
```

End Ring Cross Section

```
fprintf('End ring width:%f mm\n',a*1000)
fprintf('End ring heigth:%f mm\n',b*1000)
```

```
End ring width:39.843876 mm
End ring heigth:42.684740 mm
```

Magnetization Current

```
fprintf('Magnetization current:%f A\n',Imu)
fprintf('Airgap mmf:%f Aturns\n',MMF_airgap)
fprintf('Rotor teeth mmf:%f Aturns\n',MMF_rotor_teeth)
fprintf('Stator tooth mmf:%f Aturns\n',MMF_stator_tooth)
fprintf('Magnetization mmf:%f Aturns\n',MMF_magnetization)
fprintf('Carter coefficient:%f \n',Kc)
```

```
Magnetization current:123.742373 A
Airgap mmf:1239.320150 Aturns
Rotor teeth mmf:105.004460 Aturns
Stator tooth mmf:129.736929 Aturns
Magnetization mmf:3709.985269 Aturns
```

Carter coefficient:1.026555

Flux Density & Magnetical and Electrical Loading

```
fprintf('Bg:%f T\n',Bg_new)
fprintf('Bcs:%f T\n',Bcs_n)
fprintf('Bcr:%f T\n',Bcr)
fprintf('Brt:%f T\n',B_rotor_tooth)
fprintf('Bts:%f T\n',Bts)
fprintf('Magnetic loading:%f T\n',magnetic_loading)
fprintf('Electrical loading:%f \n',electric_loading)
```

```
Bg:0.703976 T
Bcs:1.452285 T
Bcr:1.650000 T
Brt:1.600000 T
Bts:1.650000 T
Magnetic loading:0.850000 T
Electrical loading:33.409103
```

Resistance and Inductance

```
fprintf('Stator phase reactance:%f ohm\n', Xsl)
fprintf('Stator phase resistance:%f ohm\n',Rs)
fprintf('Rotor leakage reactance:%f ohm\n', Xrl)
fprintf('Rotor phase resistance:%f ohm\n',Rrc_Sn)
fprintf('Magnetization:%f  ohm\n',Xm)
```

```
Stator phase reactance:0.167235 ohm
Stator phase resistance:0.012983 ohm
Rotor leakage reactance:1.087230 ohm
Rotor phase resistance:0.007108 ohm
Magnetization:2.335779  ohm
```

Current

```
fprintf('No load active current: %d m\n',I_noload)
fprintf('Rated current: %d m\n',Irated)
fprintf('Starting current: %d m\n',I_starting)
fprintf('End ring current: %d m\n',I_end_ring)
```

```
No load active current: 9.703483e+00 m
Rated current: 7.077099e+02 m
Starting current: 9.365180e+02 m
End ring current: 6.632829e+03 m
```

Losses & Efficiency

```
fprintf('Stator winding losses:%f  W\n',P_co_s)
fprintf('Rotor cage losses:%f W\n',Pcur)
fprintf('Mechanical/ventilation losses:%f  W\n',Pmv)
fprintf('Stray losses:%f W\n',Pstray)
fprintf('Total losses:%f W\n',Ploss)
fprintf('Efficiency:%f  \n',efficiency_new*100)
```

```
Stator winding losses:19507.329918  W
```

```
Rotor cage losses:8270.832781 W
Mechanical/ventilation losses:10240.000000  W
Stray losses:12800.000000 W
Total losses:62671.130113 W
Efficiency:95.332354
```

Operation Characteristic

```
fprintf('Starting torque:%f  Nm\n',T_starting)
fprintf('Breakdown torque:%f Nm\n',T_breakdown)
fprintf('Rated shaft torque:%f Nm\n',Tn)
fprintf('Stray losses:%f W\n',Pstray)
fprintf('Power factor:%f  \n',power_factor_new)
```

```
Starting torque:82.845630  Nm
Breakdown torque:12438.523633 Nm
Rated shaft torque:7885.053686 Nm
Stray losses:12800.000000 W
Power factor:0.811372
```

Mass

```
fprintf('Rotor iron weight:%f  kg\n',Gr)
fprintf('Shaft weight:%f  kg\n',Gshaft)
fprintf('Stator iron weight:%f  kg\n',Gs)
fprintf('Rotor yoke weight:%f  kg\n',Gyr)
fprintf('Stator copper weight:%f  kg\n',Gcus)
fprintf('Rotor copper weight:%f  kg\n',Gcur)
fprintf('Total motor weight:%f  kg\n',Gtotal)
```

```
Rotor iron weight:358.648027  kg
Shaft weight:1181.391078  kg
Stator iron weight:920.814796  kg
Rotor yoke weight:229.439158  kg
Stator copper weight:190.110912  kg
Rotor copper weight:130.367002  kg
Total motor weight:2781.331815  kg
```

References

*I.Boldea and S.A. Nasar "The Induction Machine Handbook"

*http://keysan.me/ee564

*J. Pyrhönen and T. Jokinen "Design of Rotating Electrical Machines"

*http://energy.gov/sites/prod/files/2014/04/f15/amo_motors_handbook_web.pdf

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