EM564 SECOND PROJECT:TRAIN MOTOR DESIGN

Table of Contents

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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 outcomea 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;
 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;
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.
power_factor=0.85;

% eff = imread('efficiency_table.png');
% figure;
% imshow(eff);

% Define the magnetic loading and electric loading
%
% Define the Diameter and axial length
%
% Define the Airgap
%
% Winding Type and number of coils
%
% Determination of other dimensions (slot, tooth etc.)
%
% Calculation of machine performance
%
% Lots of iteration/optimization
```

Main Dimension of Stator Core

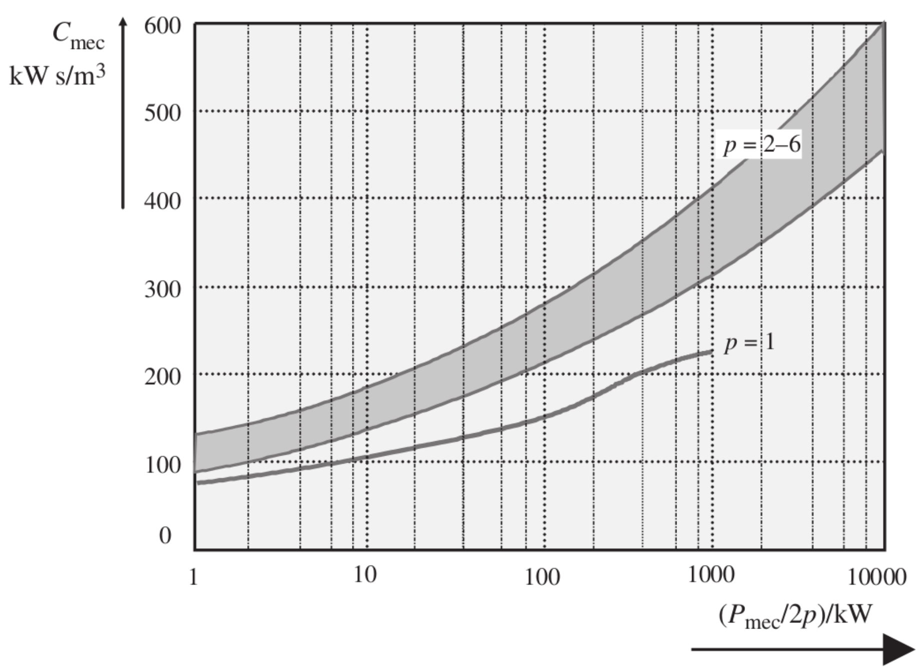
```
cmec = imread('Cmech.png');
figure;
imshow(cmec);

Cmec=400;
x=(pi*(pole_p^(1/3)))/pole;
Din=((P/1000)/(Cmec*Nsyn*x))^(1/3); %m
L=x*Din;  %m

ratio = imread('Do_Di_ratio.png');
figure;
imshow(ratio);

Dout=1.78*Din;
Qs=q*m*pole;
Ftan=Tr/(Din/2);
surface_area=pi*Din*L; %m^2
sheer_stress=Ftan/surface_area; %N/m^2
B=0.8; %Magneticloading
electric_loading=sheer_stress/B;
% airgap=1.6*(0.1+0.012*(P^(1/3)))/1000; %m

% For converter driven motors airgap can be increased by 60 % to
 reduce rotor surface losses. (from the leture notes)
airgap=1.6*(0.18+0.006*P^(0.4));
```



N Poles	2	4	6	8	10	12
Do/Di	2	1.88	1.78	1.66	1.54	1.43

Stator Winding

```
% slot_number = imread('stator and rotor slot number.png');
% figure;
% imshow(slot_number);

Qs=q*m*pole;

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

Winding Factor

Total winding factor (kw) consist of distribution factor (kd) and pitch factor (kp). To eliminate 9.harmonik chording factor is selected 7/9

```
chording_factor=7/9;
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);

matris=[];

for Bg=0.7:0.01:0.9

% the lengthening of the machine caused by the edge field can be
 approximated by the equation l' ? l + 2?.
Le=L+(2*airgap)/1000;
area_of_one_pole=pi*Din*Le/pole;  %m^2

%inductionmotors, 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
% ?i takes notably higher values than the value corresponding to a
 sinusoidal distribution. The
% factor ?i (2/pi)has to be iterated gradually to the correct value
 during the design process. The value
% ?i = 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.

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

format rat
alfa_u_rad=alfa_u/pi;
format short

%from the E=4.44*f*N*kw*magnetic_flux we can find turn number
Kf=1.085;
N=(V/sqrt(3))/(4.44*Kf*Kw*f*fundamental_magnetic_flux);


a1=1;  %number of current path in parallel
conductor_per_slot=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*pole_p*q;

Bg_new=Bg*(N/N_new);
    matris=[matris Bg_new];

if Bg_new>0.7
    break;
end

end

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

% 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)); % after recalculated
 diameter of the wire
% awg#11 is enough for size

awg_size=[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_size/d_copper_new);% oran dizisi
[M,I]=min(prop(prop>1));

d_co_new=awg_size(I);
```

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
```

Stator Slot Sizing

```
Kfill=0.44;  % above 10kW Kfill=0.4-0.44
slot_area=pi*d_co_new^2*parallel_branch*number_of_conductor_per_slot/
(4*Kfill); %mm^2

Bts=1.6;
Kfe=0.96; % stator stackinf factor
bts=Bg_new*slot_pitch/(Bts*Kfe);   %tooth width
bos=0.0025;  %m
hos=0.0013; %m
hw=0.002;  %m

bs1=(pi*(Din+2*hos+2*hw)/Qs)-bts;  %slot lower width m
%bs2=sqrt(4*slot_area*10^-6*tan(pi/Qs)+((bs1*10^3)^2)); %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
Hts=2460;  %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

%  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 (Equation 15.1) 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.
```

Rotor Slot

From the common combination Qr =88 is selected

```
Qr=88;
hor=0.0005; %m
bor=0.0015;  %m

%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 = 6; % A/mm^2;  %rotordaki ak#m yo#unlu#u
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)); % A

%The current density in the end ring Jer = (0.75 – 0.8)Jb. The higher
 valuescorrespond 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 = 1.65; % T
H_tr=3460;
btr = Bg_new*T_rotor_slot/(Kfe*B_rotor_tooth); % m

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

hor = 0.001; % m
bor = 0.003; % m
d1 = (pi*(D_r-2*hor)-Qr*btr)/(pi+Qr); % m
d2 = d1/4; % mm
hr = (d1-d2)/(2*tan(pi/Qr)); % m
rotor_slot_area = ((pi/8)*(d1^2+d2^2))+((d1+d2)*hr/2); % m^2
Bcr = 1.65; % T
hcr = fundamental_magnetic_flux/(2*L*Bcr); % m
MMF_rotor_teeth=H_tr*(hr+hor+(d1+d2)/2);  %Aturns

Dshaftmax = Din-(2*airgap*(10^-3))-2*(hor+hr+hcr+(d1+d2)/2); % mm

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

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

Der=D_r-3.5*10^-3;
b=1.0*(hr+hor+(d1+d2)/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:

Hcs=760; %Stator back core flux intensity in A/m Bcs=1.4 olarak
 dü#ünüldü
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

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 (Chapter 9),
(Equation9.1), 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*(d1+d2))+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
```

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.

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+(d1+d2)/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;
```

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+(d1+d2)/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.
```

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)
fprintf('Rotor diameter: %d m\n',D_r)
fprintf('Airgap: %d mm\n',airgap)
```

```
Stator bore diameter: 0.546235 m
Stack length: 0.412495 m
Pole pitch: 0.286008 m
Slot pitch: 0.023834 m
Outer diameter: 0.972298 m
Rotor diameter: 5.403352e-01 m
Airgap: 2.949676e+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('Airgap flux density:%f T\n',Bg_new)
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 \n',d_co_new)
```

```
Number of stator slot: 72
Distribution factor:0.957662
Pitch factor:0.939693
Winding factor:0.899908
Pole flux:0.053326  Wb
Airgap flux density:0.840469 T
```

```
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:4.170000
```

Stator Slot Sizing

```
fprintf('Slot area:%f \n',slot_area)
fprintf('Stacking factor:%f\n',Kfe)
fprintf('Bts:%f T\n',Bts)
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('Airgap mmf:%f Aturns\n',MMF_airgap)
fprintf('Bcs:%f T\n',Bcs)
```

```
Slot area:1117.408101
Stacking factor:0.960000
Bts:1.600000 T
hos:1.300000 mm
bos:2.500000 mm
bts:13.041490 mm
bs1:11.080469 mm
bs2:17.830456 mm
bcs:132.431432 mm
Airgap mmf:2367.377872 Aturns
Bcs:0.488092 T
```

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('Rotor tooth flux density:%f T\n',B_rotor_tooth)
fprintf('hor:%f mm\n',hor*1000)
fprintf('bor:%f mm\n',bor*1000)
fprintf('btr:%f mm\n',btr*1000)
fprintf('d1:%f mm\n',bs1*1000)
fprintf('d2:%f mm\n',bs2*1000)
fprintf('hcr:%f mm\n',hcr*1000)
fprintf('Maximum diameter of the shaft:%f mm\n',Dshaftmax*1000)
```

```
Number of stator slot: 88.000000
Rated rotor bar current:1375.647514 A
Rotor slot area:0.000229 m^2
End ring cross section:0.001375 m^2
Rotor slot pitch:19.289923 mm
Rotor tooth flux density:1.650000 T
hor:1.000000 mm
```

```
bor:3.000000 mm
btr:10.235220 mm
d1:11.080469 mm
d2:17.830456 mm
hcr:39.175015 mm
Maximum diameter of the shaft:267.000498 mm
```

End Ring Cross Section

```
fprintf('a:%f mm\n',a)
fprintf('b:%f mm\n',b)
```

```
a:0.014103 mm
b:0.097492 mm
```

Magnetization Current

```
fprintf('Magnetization current:%f A\n',Imu)
fprintf('Magnetization mmf:%f Aturns\n',MMF_magnetization)
fprintf('Carter coefficient:%f \n',Kc)
```

```
Magnetization current:207.397315 A
Magnetization mmf:6049.213476 Aturns
Carter coefficient:1.042852
```

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 \n',Xm)
```

```
Stator phase reactance:0.183836 ohm
Stator phase resistance:0.011198 ohm
Rotor leakage reactance:0.241617 ohm
Rotor phase resistance:0.007142 ohm
Magnetization:1.749711
```

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('Stray losses:%f W\n',Pstray)
fprintf('Efficiency:%f  \n',efficiency_new*100)
```

```
Stator winding losses:16825.711423  W
Rotor cage losses:8310.091660 W
Mechanical/ventilation losses:10240.000000  W
Stray losses:12800.000000 W
Total losses:66905.654917 W
Stray losses:12800.000000 W
Efficiency:95.032640
```

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)
```

```
Starting torque:595.730958  Nm
Breakdown torque:36207.502461 Nm
rated shaft torque:7885.289754 Nm
Stray losses:12800.000000 W
```

Cost

```
fprintf('Rotor iron weight:%f  kg\n',Gr)
fprintf('Total motor weight:%f  kg\n',Gtotal)
fprintf('Shaft weight:%f  kg\n',Gshaft)
```

```
Rotor iron weight:384.835364  kg
Total motor weight:2389.954112  kg
Shaft weight:436.725575  kg
```

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