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## Appendix B. MATLAB Code: Basic Sizing Method

Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pmlbasic

"% Program performs basic sizing and parameter calculations

"% for generators.

"% Definition of variables

"% Name Variable

"% General variables

"% Pwr Required power

"% rpm Speed (RPM)

"% psi Power factor angle

"% f Electrical frequency (Hz)

"% omega Electrical frequency (rad/sec)

"% vtip Tip speed (m/s)

"% LovD L/D ratio

"% stress Gap shear stress (psi)

"% Rotor variables

% R Rotor radius (m)

% D Rotor diameter (m)

% Lst Rotor stack length (m)

% p Number of pole pairs

"% Bg Expected air gap flux density (T)

"% Stator variables

"% Kz Surface current density (A/m)

"% Jz Current density (A/m2)

"% hs Slot height (m)

clear;

# % Constants & conversion factors

hs = .015; % Assume slot depth of 15 mm

lams = 0.5; % Assume slot fill fraction

convI = 9.81; % 9.81 W per Nm/s

conv2 = 703.0696; % 703.0696 N/m2 per psi

% INPUTS

Pwr = 16e6; % Required power

vtip = 200; % Max tip speed (m/s)

LovD = 2.85 1; % Wound rotor usually 0.5-1.0, PM 1.0-3.0

# "% Shear stress usually 1-10 psi small machines, 10-20 large liquid

"% liquid cooled machines

stress = 15;

p = 3; % Pole pairs

Bg = 0.8; % Tesla

"% Calculations

"% Size

% Initially use Pwr = 2\*pi\*R\*Lst\*stress\*vtip

% Lst =2\*LovD\*R

hscm =hs\* 100;

R = sqrt(Pwr/(2\*pi\*(LovD\*2)\*vtip\*stress\*convl \*conv2));

D = 2\*R;

Lst = LovD\*D;

% Speed

omega = (p\*vtip)/R;

f = omega/(2"'pi);

rpm = (60\*f)/p;

% Current densities

Kz = (stress\*conv2)/(Bg\* 100);

Ja = 1O\*KzJ(hscm\*lams);

# % Output

fprintf('Basic Machine Design\n');

fprintf('lnput Parameters:\n');

fprintfQ'Power = %1O.lf kW Shear Stress =%10.lf psi\n',Pwr/1e3,stress);

fprintf('L/D Ratio = %10.2f Tip Speed = %lO.lf m/s\n',LovD,vtip);

fprintf('Pole Pairs = %1O.lf Air Gap Bg = %10.lfl~hi,p,Bg);

fprintf('Output:\n');

fprintfQ'Rotor Radius = %10.3f m Stack Length = %10.3f m\n',R,Lst);

fprintfC'Speed = %10.0fRPM Frequency = %10.lfHz\n',rpm,f);

fprintfQ'Ja =%10.2f A/cm2\n',Ja);

## Appendix D. MATLAB Code: Sizing Method 1

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pmlinput

"% Program used as input file for pmlcalc

"% All necessary input parameters entered here.

clear;

"% Definition & Entry of variables

# "% General variables

Pwr = 16e6; % Required power (W)

rpm = 13000; % Speed (RPM)

psi = 0; % Power factor angle

# % Rotor variables

R = 0.147; % Rotor radius (m)

hm = 0.025; % Magnet thickness (m)

Lst = 0.838; % Rotor stack length (m)

p = 3; % Number of pole pairs

Br = 1.2; % Magnet remnant flux density (T)

thm = 50; % Magnet physical angle (deg)

thsk = 10; % Magnet skew angle (actual deg)

# % Stator variables

q = 3; % Number of phases

Ns = 36; % Number of slots

Nsp = 1; % Number of slots short pitched

g = .004; % Air gap (m)

tfrac = 0.5; % Peripheral tooth fraction

hs = .025; % Slot depth (m)

hd = .0005; % Slot depression depth (m)

wd = le-6; % Slot depression width (m)

syrat = 0.7; % Stator back iron ratio (yoke thick/rotor radius)

Nc = 1; % Turns per coil

lams = 0.5; % Slot fill fraction

sigst = 6.0e+7; % Stator winding conductivity

# % Densities

rhos = 7700; % Steel density (kg/m3)

rhom = 7400; % Magnet density (kg/m3)

rhoc = 8900; % Conductor density (kg/m3)

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pmlcalc

"% Program performs sizing and parameter calculations

"% for permanent magnet machines with surface magnets and

"% slotted stators.

"% Program developed from J.L. Kirtley script with permission

"% MUST RUN pmlinput PRIOR TO RUNNING pmlcalc

Definition of variables

% Name Variable

"% General variables

"% Pwr Required power (W)

"% rpm Speed (RPM)

"% psi Power factor angle

"% f Electrical frequency (Hz)

"% omega Electrical frequency (rad/sec)

"% vtip Tip speed (m/s)

"% lambda Flux linkage

% Ea RMS Internal voltage (V)

% Rotor variables

% R Rotor radius (in)

% hm Magnet thickness (in)

% Lst Rotor stack length (in)

% p Number of pole pairs

"% Br Magnet remnant flux density (T)

"% thin Magnet physical angle (deg)

"% thsk Magnet skew angle (actual deg)

"% Stator variables

% q Number of phases

% m Slots per pole per phase

"% Ns Number of slots

"% Nsp Number of slots short pitched

% g Air gap (in)

% ge Effective air gap (in)

"% tfrac Peripheral tooth fraction

"% hs Slot depth (in)

"% hd Slot depression depth (in)

"% wd Slot depression width (in)

"% syrat Stator back iron ratio (yoke thick/rotor radius)

% Nc Turns per coil

"% lams Slot fill fraction

"% sigst Stator conductivity

% Kc Carter coefficient

"% Loss Models

"% P0 Base power for core losses

"% FO Base frequency for core loss

"% BO Base flux density

"% epsb Flux density exponent

"% epsf Frequency exponent

"% rhos Steel density

"% rhom Magnet density

% rhoc Conductor density

% Constants to be used

mu0 = 4\*pi\*le-7; % Free space permeability

tol = I e-2; % Tolerance factor

cpair = 1005.7; % Specific heat capacity of air (J/kg\*C)

rhoair = 1.205; % Density of air at 20 C (kg/m3)

nuair = 1.5e-5; % Kinematic viscosity of air at 20 C (m2/s)

P0 = 36.79; % Base Power Losss, W/lb

FO = 1000; % Base freuency, 60 Hz

B0 = 1.0; % Base flux density, 1.0 T

epsb = 2.12;

epsf= 1.68;

# "% Generate geometry of machine

"% Number of slots/pole/phase

m = Ns/(2\*p\*q);

% Number of armature turns (each slot has 2 half coils)

Na = 2\*p\*m\*Nc;

% Tooth width

wt = 2\*pi\*(R+g+hm+hd)\*tfrac/Ns;

% Slot top width (at air gap)

wst = 2\*pi\*(R+g+hm+hd)\*(1-tfrac)/Ns;

% Slot bottom width

wsb = wst\*(R+g+hd+hs)/(R+g+hm+hd);

% Stator core back iron depth (as p increases, dc decreases)

dc = syrat\*R/p;

% Full-pitch coil throw

Nsfp = floor(Ns/(2\*p));

% Actual coil throw

Nsct = Nsfp - Nsp;

"% Estimate end turn length

"% End turn travel (one end)

laz = pi\*(R+g+hm+hd+0.5\*hs)\*Nsct/Ns;

% End length (half coil)

le2 = pi\*laz;

% End length (axial direction)

lel = 2\*le2/(2\*pi);

# % Calculate electrical frequency & surface speed

f = p\*rpm/60;

omega = 2\*pi\*f;

vtip = R\*omega/p;

# % Winding & skew factors

gama = 2\*pi\*p/Ns;

alfa = pi\*Nsct/Nsfp;

kp = sin(pi/2)\*sin(alfa/2);

kb = sin(m\*gama/2)/(m\*sin(gama/2));

kw = kp\*kb;

ths = ((p\*thsk)+le-6)\*(pi/180); % skew angle (elec rad)

ks = sin(ths/2)/(ths/2);

# % Calculate magnetic gap factor

Rs = R+hm+g;

Ri = R;

R1 = R;

R2 = R+hm;

kg = ((RiA(p-1))/(Rs^(2\*p)-RiA(2\*p)))\*((p/(p+l))\*(R2A(p+l)-R1A(p+l))...

+(p\*RsA(2\*p)/(p-1))\*(R1 A(1-p)-R2A(1-p)));

# "% Calculate air gap magnetic flux density

"% Account for slots, reluctance, and leakage

ws = (wst+wsb)/2; % Average slot width

taus = ws + wt; % Width of slot and tooth

Kc = 1/(1-(1/((taus/ws)\*((5\*g/ws)+l))));

ge = Kc\*g;

Cphi = (p\*thm)/180; % Flux concentration factor

KI = 0.95; % Leakage factor

Kr = 1.05; % Reluctance factor

murec = 1.05; % Recoil permeability

PC = hm/(ge\*Cphi); % Permeance coefficient

Bg = ((Kl\*Cphi)/(1+(Kr\*murec/PC)))\*Br;

# % Calculate magnetic flux and internal voltage

thmrad = thm\*(pi/180);

B I = (4/pi)\*Bg\*kg\*sin(p\*thmrad/2);

lambda = 2\*Rs\*Lst\*Na\*kw\*ks\*B l/p;

Ea = omega\*lambda/sqrt(2); % RMS back voltage

# "% Calculation of inductances/reactances

"% Air-gap inductance

Lag = (q/2)\*(4/pi)\*(muo\*Na^2\*kwA2\*Lst\*Rs)/(pA2\*(g+hm));

% Slot leakage inductance

perm = mu0\*((1/3)\*(hs/wst) + hd/wst);

Las = 2\*p\*Lst\*perm\*(4\*NcA2\*(m-Nsp)+2\*Nsp\*NcA2);

Lam = 2\*p\*Lst\*Nsp\*NcA2\*perm;

if q == 3

Lslot = Las + 2\*Lam\*cos(2\*pi/q); % 3 phase equation

else

Lslot = Las - 2\*Lam\*cos(2\*pi/q); % multiple phases

End

% End-turn inductance (Hanselman)

As = ws\*hs; % Slot area

Le = ((Nc\*muO\*(taus)\*Na^2)/2)\*log(wt\*sqrt(pi)/sqrt(2\*As));

% Total inductance and reactance

Ls = Lag+Lslot+Le;

Xs = omega\*Ls;

% Lengths, Volumes, and Weights

% Armature conductor length

Lac = 2\*Na\*(Lst+2\*le2);

% Armature conductor area (assumes form wound)

Aac = As\*lams/(2\*Nc);

% Mass of armature conductor

Mac = q\*Lac\*Aac\*rhoc;

% Overall machine length

Lmach = Lst+2\*lel;

% Core inside radius

Rci = R+hm+g+hd+hs;

% Core outside radius

Rco = Rci+dc;

% Overall diameter

Dmach = 2\*Rco;

% Core mass

Mcb = rhos\*pi\*(RcoA2-RciA2)\*Lst; % Back iron

Mct = rhos\*Lst\*(Ns\*wt\*hs+2\*pi\*R\*hd-Ns\*hd\*wd); % Teeth

Mc = Mcb + Mct;

% Magnet mass

Mm = O.5\*(p\*thmriad)\*((R+hM)A2-RA2)\*Lst\*rhom;

% Shaft mass

Ms = pi\*R A2\*Lst\*rhos;

% 15% service fraction

Mser = 0. 15 \*(Mc+Ms+Mm+Mac);

% Total mass

Mtot = Mser+Mc+Ms+Mm+Mac;

% Stator resistance

Ra = Lac/(sigst\*Aac);

"%C ore Loss Calculations

"%T ooth Flux Density

Bt = Bg/tfrac;

% Back iron flux density (Hanselman)

Bb = Bg\*RI(p\*dc);

% Core back iron loss

Pcb = Mcb\*PO\*abs(BbIBO)A epsb\*abs(fIFO)A epsf;

% Teeth Loss

Pct = Mct\*PO\*abs(BtIBO)A epsb\*abs(ffFO)A epsf;

% Total core loss

Pc = Pcb + Pct;

# % Start loop to determine terminal voltage and current

notdone = 1;

1 =0;

la = Pwr/(q\*Ea);

while notdone ==I1

i = i+1;

xa = Xs\*IaIEa;

% Conductor losses

Pa = q\*IaA2\*Ra;

"%G ap friction losses

"%R eynold's number in air gap

omegam = omega/p;

Rey = omegam\*R\*g/nuair;

% Friction coefficient

Cf = .0725/ReyA.2;

% Windage losses

Pwind = Cf\*pi\*rhoair\*omegamA3\*RA4\*Lst;

# % Get terminal voltage

Va = sqrt(EaA2-((Xs+Ra)\*Ia\*COS(pSi))A2)-(Xs+Ra)\*Ia\*sin(psi);

Ptemp, = q\*Va\*Ia\*cos(psi)..Pwind;

error = PwrlPtemp;

err(i) = error;

if abs(eff or- 1) < tol

notdone = 0;

else

Ia = Ia\*error;

end

end

"%R emaining performance parameters

"%C urrent density

Ja = IaIAac;

% Power and efficiency

Pin =Pwr+Pc+Pa+Pwind;

eff =Pwr/Pin;

pf = cos(psi);

fprintff'pmlcalc complete: Ready\n');

"%Jo nathan Rucker, MIT Thesis

"%M ay 2005

% Program: pmloutput

"%Pr ogram outputs values from pmlcalc.

"%P rogram developed from J.L. Kirtley script with permission

"%M UST RUN pmlinput and pmlcalc PRIOR TO RUNNING pmloutput

"%V ariables for output display

Pout = Pwr/le3;

Jao =Ja/le4;

Pco =Pc/le3;

Pwindo = Pwind/1e3;

Pao = PaIl e3;

wso = ws\* 1000;

hso = hs\* 1000;

wto = wt\* 1000;

dco = dc\* 1000;

Lso =Ls\* 1000;

hmo =hm\* 1000;

go = g\*1000;

# % Output Section:

fprintfC'\nPM Machine Design, Version 1: Surface Magnet, Slotted Stator\n');

fprintf('Machine Size:\n');

fprintf('Machine Diameter = %8.3f m Machine Length = %8.3f m\n',Dmach,Lmach);

fprintf('Rotor radius = %8.3f m Active length =%8.3f m\n',R,Lst);

fprintfQ'Slot Avg Width =%8.3f mm Slot Height = %8.3f mm\n',wso,hso);

fprintfQ'Back Iron Thick =%8.3f mm Tooth Width =%8.3f mm\n',dco,wto);

fprintf('Machine Ratings:\n');

fprintf('Power Rating = %8.If kW Speed = %8.Of RPM\n', Pout,rpm);

fprintfQ'Va (RMS) = %8.Of V Current = %8.lfA\n', Va,Ia);

fprintfQ'Ea (RMS) = %8.Of V Arm Resistance = %8.5f ohm\n',Ea,Ra);

fprintf(QSynch Reactance = %8.3f ohm Synch Induct =%8.3f mH\.n',Xs,Lso);

fprintf('Stator Cur Den = %8.lf A/cm2 Tip Speed =%8.Of m/s\n', Jao,vtip);

fprintfQ'Efficiency = %8.3f Power Factor =%8.3f\n', eff~pf;

fprintf('Phases = %8.Of Frequency = %8.lf Hz\n',q,f);

fprintfC'Stator Parameters:\n');

fprintf('Number of Slots = %8.Of Num Arm Turns = %8.Of \n',Ns,Na);

fprintfQ'Breadth Factor = %8.3f Pitch Factor =%8.3f nW, kb,kp);

fprintfQ'Tooth Flux Den =%8.2f T Back Iron =%8.2f T\n', Bt,Bb);

fprintf('Slotsfpole/phase =%8.21\n',m);

fprintf(QRotor Parameters:\n');

fprintf(QMagnet Height = %8.2f mm Magnet Angle = %8.lf degm\n',hmo,thm);

fprintf('Air gap = %8.2f mm Pole Pairs = %8.Of \n',go,p);

fprintf('Magnet Remanence = %8.2f T Aig Gap Bg = %8.2f TWn,Br,Bg);

fprintfQ'Magnet Factor = %8.3f Skew Factor =%8.3f \n',kg,ks);

fprintf('Machine Losses:\n');

fprintf('Core Loss = %8.lf kW Armature Loss = %8.If kW~n', Pco,Pao);

fprintfQ'Windage Loss = %8.lf kW Rotor Loss = TBD kWfn', Pwindo);

fprintf('Machine Weights:\n');

fprintfQ'Core = %8.2f kg Shaft = %8.2f kg\n',Mc,Ms);

fprintfQ'Magnet = %8.2f kg Armature = %8.2f kg\n',Mm,Mac);

fprintf('Services = %8.2f kg Total = %8.2f kg\n',Mser,Mtot);

## Appendix E. MATLAB Code: Sizing Method 2

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pm2input

"% Program used as input file for pm2calc

"% All necessary input parameters entered here.

clear;

% Definition & Entry of variables

# % General variables

Pwr = 16e6; % Required power (W)

rpm = 13000; % Speed (RPM)

psi = 0; % Power factor angle

Bsat = 1.65; % Stator saturation flux density

# % Rotor variables

vtip = 200; % Tip speed limit (m/s)

p = 3; % Number of pole pairs

Br = 1.2; % Magnet remnant flux density (T)

thsk = 10; % Magnet skew angle (elec deg)

PC = 5.74; % Permeance coefficient for magnets

# % Stator variables

Ja = 2200; % Initial current density (A/cm2)

q = 3; % Number of phases

m = 2; % Slots/pole/phase

Nsp = 1; % Number of slots short pitched

g = .004; % Air gap (in)

hs = .025; % Slot depth (in)

hd = .0005; % Slot depression depth (in)

wd = le-6; % Slot depression width (in)

ws = .016; % Avg slot width (in)

Nc = 1; % Turns per coil

lams = 0.5; % Slot fill fraction

sigst = 6.0e+7; % Stator winding conductivity

# % Densities

rhos = 7700; % Steel density (kg/m3)

rhom = 7400; % Magnet density (kg/m3)

rhoc = 8900; % Conductor density (kg/m3)

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pm2calc

"% Program performs sizing and parameter calculations

"% for permanent magnet machines with surface magnets and

"% slotted stators.

"% MUST RUN pm2input PRIOR TO RUNNING pm2calc

% Definition of variables

% Name Variable

% General variables

% Pwr Required power (W)

% rpm Speed (RPM)

% psi Power factor angle

% f Electrical frequency (Hz)

% omega Electrical frequency (rad/sec)

% vtip Tip speed (m/s)

% lambda Flux linkage

% Ea RMS Internal voltage (V)

% Rotor variables

% R Rotor radius (m)

% hm Magnet thickness (m)

% Lst Rotor stack length (m)

% p Number of pole pairs

% Br Magnet remnant flux density (T)

% thm Magnet physical angle (deg)

% thsk Magnet skew angle (actual deg)

% Stator variables

% q Number of phases

% m Slots per pole per phase

% Ns Number of slots

% Nsp Number of slots short pitched

% g Air gap (m)

% ge Effective air gap (m)

% tfrac Peripheral tooth fraction

% hs Slot depth (m)

% hd Slot depression depth (m)

% wd Slot depression width (m)

% syrat Stator back iron ratio (yoke thick/rotor radius)

"% Nc Turns per coil

"% lams Slot fill fraction

"% sigst Stator conductivity

% Kc Carter coefficient

"% Loss Models

"% P0 Base power for core losses

"% FO Base frequency for core loss

"% BO Base flux density

"% epsb Flux density exponent

"% epsf Frequency exponent

"% rhos Steel density

"% rhom Magnet density

"% rhoc Conductor density

# % Constants to be used

muO = 4\*pi\*le-7; % Free space permeability

tol = le-2; % Tolerance factor

cpair = 1005.7; % Specific heat capacity of air (J/kg\*C)

rhoair = 1.205; % Density of air at 20 C (kg/m3)

nuair = 1.5e-5; % Kinematic viscosity of air at 20 C (m2/s)

P0 = 36.79; % Base Power Losss, W/lb

FO = 1000; % Base freuency, 60 Hz

BO = 1.0; % Base flux density, 1.0 T

epsb = 2.12;

epsf= 1.68;

# % Calculate electrical frequency & rotor radius

f = p\*rprn/60;

omega = 2\*pi\*f;

R = p\*vtip/omega;

% Winding & skew factors

Ns = floor(2\*q\*p\*m); % Number of slots

gama = 2\*pi\*p/Ns;

Nsfp = floor(Ns/(2\*p));

Nsct = Nsfp - Nsp;

alfa = pi\*Nsct/Nsfp;

kp = sin(pi/2)\*sin(alfa/2);

kb = sin(m\*gama/2)/(m\*sin(gama/2));

kw = kp\*kb;

ths = ((p\*thsk)+le-6)\*(pi/180); % skew angle (elec rad)

ks = sin(ths/2)/(ths/2);

# % Calculate magnet dimensions, tooth width, & air gap flux density

thme = 1; % Initial Magnet angle (deg e)

notdone = 1;

ge = g; % Initial effective air gap

while notdone == 1

alpham = thme/1 80; % Pitch coverage coefficient

Cphi = (2\*alpham)/(l+alpham); % Flux concentration factor

hm = ge\*Cphi\*PC; % Magnet height

Ds = 2\*(R+hm+g); % Inner stator/air gap diameter

K1 = 0.95; % Leakage factor

Kr = 1.05; % Reluctance factor

murec = 1.05; % Recoil permeability

Bg = ((Kl\*Cphi)/(1+(Kr\*murec/PC)))\*Br;

wt = ((pi\*Ds)/Ns)\*(Bg/Bsat); % Tooth width

taus = ws + wt; % Width of slot and tooth

Kc = 1/(1-(1/((taus/ws)\*((5\*g/ws)+1)))); % Carter's coefficient

ge = Kc\*g;

eratio = ws/wt;

if abs(eratio - 1) < tol

notdone = 0;

else

thme = thme + 1;

end

end

# % Set final values

thm = thme/p; % Magnet physical angle

thmrad = thm\*(pi/1 80);

hm = ge\*Cphi\*PC; % Magnet height

Ds = 2\*(R+hm+g); % Inner stator/air gap diameter

"% Generate geometry of machine

"% Peripheral tooth fraction

tfrac = wt/(wt+ws);

% Slot top width (at air gap)

wst = 2\*pi\*(R+g+hm+hd)\*tfrac/Ns;

% Slot bottom width

wsb = wst\*(R+g+hm+hd+hs)/(R+g+hm+hd);

% Stator core back iron depth

dc = (pi\*Ds\*thmradl(4\*p))\*(BglB sat);

% Core inside radius

Rci = R+hm+g+hd+hs;

% Core outside radius

Rco = Rci+dc;

% Slot area

As = ws\*hs;

"%E stimate end turn length

"%E nd turn travel (one end)

laz = pi\*(R+g+hm+hd+0.5\*hs)\*NsctlNs;

% End length (half coil)

1e2 = pi\*laz;

% End length (axial direction)

lel = 2\*1e2/(2\*pi);

# % Calculate magnetic gap factor

Rs = R+hm+g;

Ri = R

RI = R;

R2 =R+hm;

kg = ((RiA(p~1 ))/(RSA (2\*p)-RiA (2\*p)))\*((p/(p+l1))\*(R2A(p+ 1)-Ri A(p+ 1))...

+(p\*RSA (2\*p)I(p- 1))\*(R JA( I -p)-R2A( 1p)));

% Core loss calculations (per length)

% Core mass per length

Mcbperl = rhos\*pi\*(RcOA 2-RciA 2); % Back iron

MctperL =rhos \*(Ns\*wt\*hs+2\*pi\*R\*hd-Ns\*hd\*wd); % Teeth

Mcperl = McbperL + MctperL;

% Tooth Flux Density

Bt = Bg/tfrac;

% Back iron flux density (Hanselman)

Bb = Bg\*R/(p\*dc);

% Core back iron loss per length

PcbperL = McbperL\*PO\*abs(Bb/BO0)A epsb\*abs(f/FO)A epsf,

% Teeth Loss per length

PctperL = MctperL\*PO\*abs(Bt!BO)A epsb\*abs(f/FO)A epsf;

% Total core loss per length

PcperL = PcbperL + PctperL;

% Current and surface current density

% Armature turns (each slot has 2 half coils)

Na = 2\*p\*m\*Nc;

% Arm cond area (assumes form wound)

Aac = (As\*lams)/(2\*Nc);

% Power & Current waveform factors (Lipo)

ke 0.52;

ki =sqrt(2);

% Initial terminal current

la = Ns\*lams\*As\*Ja\* 1 e4/(2\*q\*Na);

notfin = 1;

Lst =0. 1; % Initial stack length

= 1

% Start loop to determine Lst, Ea, Va, and Ia

notdone = 1;

k = 0;

while notdone == 1

k=k+ 1;

% Surface current density

A = 2\*q\*Na\*Ia/(pi\*Ds);

% Calculate stack length of machine

% Loop to get stack length

while notfin == 1

% Gap power

Pgap = 4\*pi\*ke\*ki\*kw\*ks\*kg\*sin(thmrad)\*(f/p)\*A\*Bg\*(Ds^2)\*Lst;

% Length of conductor

Lac = 2\*Na\*(Lst+2\*le2);

% Stator resistance

Ra = Lac/(sigst\*Aac);

% Copper Loss

Pa = q\*IaA2\*Ra;

% Core losses

Pc = PcperL\*Lst;

% Iterate to get length

Ptempl = Pgap-Pa-Pc;

error = Pwr/Ptemp 1;

err(i) = error;

if abs(error-1) < tol

notfin = 0;

else

Lst = Lst\*error;

i=i+ 1;

end

end

# % Calculate magnetic flux and internal voltage

thmrad = thm\*(pi/180);

B 1 = (4/pi)\*Bg\*kg\*sin(p\*thmrad/2);

lambda = 2\*Rs\*Lst\*Na\*kw\*ks\*B I/p;

Ea = omega\*lambda/sqrt(2); % RMS back voltage

# "% Calculation of inductances/reactances

"% Air-gap inductance

Lag = (q/2)\*(4/pi)\*(muO\*NaA2\*kwA2\*Lst\*Rs)/(pA2\*(g+hm));

% Slot leakage inductance

perm = muO\*((1/3)\*(hs/wst) + hd/wst);

Las = 2\*p\*Lst\*perm\*(4\*NcA2\*(m-Nsp)+2\*Nsp\*NcA2);

Lam = 2\*p\*Lst\*Nsp\*NcA2\*perm;

if q == 3

Lslot = Las + 2\*Lam\*cos(2\*pi/q); % 3 phase equation

else

Lslot = Las - 2\*Lam\*cos(2\*pi/q); % multiple phases

End

% End-turn inductance (Hanselman)

taus = ws + wt; % Width of slot and tooth

Le = ((Nc\*muO\*(taus)\*NaA2)/2)\*log(wt\*sqrt(pi)/sqrt(2\*As));

% Total inductance and reactance

Ls = Lag+Lslot+Le;

Xs = omega\*Ls;

"% Lengths, Volumes, and Weights

"% Armature conductor length

Lac = 2\*Na\*(Lst+2\*le2);

% Mass of armature conductor

Mac = q\*Lac\*Aac\*rhoc;

% Overall machine length

Lmach = Lst+2\*lel;

% Overall diameter

Dmach = 2\*Rco;

% Core mass

Mc = McperL\*Lst;

% Magnet mass

Mm = 0.5\*(p\*thmrad)\*((R+hm)A2-RA2)\*Lst\*rhom;

% Shaft mass

Ms = pi\*RA2\*Lst\*rhos;

% 15% service fraction

Mser = 0.15\*(Mc+Ms+Mm+Mac);

% Total mass

Mtot = Mser+Mc+Ms+Mm+Mac;

"% Gap friction losses

"% Reynold's number in air gap

omegam = omega/p;

Rey = omegam\*R\*g/nuair;

% Friction coefficient

Cf = .0725/ReyA.2;

% Windage losses

Pwind = Cf\*pi\*rhoair\*omegamA3\*RA4\*Lst;

% Get terminal voltage

xa = Xs\*Ia/Ea;

Va = sqrt(EaA2-((Xs+Ra)\*Ia\*cos(psi))A2)-(Xs+Ra)\*Ia\*sin(psi);

Ptemp = q\*Va\*Ia\*cos(psi)-Pwind;

Perror = Pwr/Ptemp;

Perr(k) = Perror;

if abs(Perror-1) < tol

notdone = 0;

else

Ia = Ia\*Perror;

end

end

% Remaining performance parameters

% Current density

Ja = Ia/Aac;

% Power and efficiency

Pin = Pwr+Pc+Pa+Pwind;

eff = Pwr/Pin;

pf = cos(psi);

156

fprintf('pm2calc complete: Ready.\n');

"%Jo nathan Rucker, MIT Thesis

"%M ay 2005

"%P rogram: pm2output

"%P rogram outputs values from pm2calc.

"%Pr ogram developed from J.L. Kirtley script with permission

"%M UST RUN pm2input and pm2calc PRIOR TO RUNNING pm2output

"%V ariables for output display

Pout =Pwr/1e3;

Jao =Ja/l e4;

Pco =Pc/1e3;

Pwindo = Pwind/1e3;

Pao =Pa/le3;

wso = ws\*'1000;

hso = hs\* 1000;

wto = wt\* 1000;

dco = dc\* 1000;

Lso =Ls\* 1000;

hmo hm\* 1000;

go = g\*1000;

# % Output Section:

fprintf('\nPM Machine Design, Version 2: Surface Magnet, Slotted Stator\n');

fprintfQ'Machine Size:\n');

fprintfC'Machine Diameter = %8.3f m Machine Length = %8.3f m\n',Dmach,Lmach);

fprintf('Rotor radius = %8.3f m Active length = %8.3f mn~n',R,Lst);

fprintf(QSlot Avg Width =%8.3f mm Slot Height = %8.3f mm\n',wso,hso);

fprintf('Back Iron Thick =%8.3f mm. Tooth Width = %8.3f mm\n',dco,wto);

fprintf('Machine Ratings:\n');

fprintf('Power Rating = %8.if kW Speed = %8.Of RPM\n', Pout,rpm);

fprintf('Va (RMS) = %8.Of V Current = %8.If A\n', VaIa);

fprintf('Ea (RMS) = %8.Of V Arm Resistance = %8.5f ohm\n',Ea,Ra);

fprintf('Synch Reactance = %8.3f ohm Synch Induct =%8.3f mH\n',Xs,Lso);

fprintf('Stator Cur Den = %8.lf A/cm2 Tip Speed = %8.Of mls\n', Jao,vtip);

fprintf('Efficiency = %8.3f Power Factor =%8.3f\n', eff~pf);

fprintf('Phases = %8.Of Frequency = %8. if Hz\n',q,t);

fprintfQ'Stator Paramteters:\n');

fprintfQ'Number of Slots =%8.Of Num Arm Turns = %8.Of \n',Ns,Na);

fprintf('Breadth Factor = %8.3f Pitch Factor =%8.3f W, kb,kp);

fprintf('Tooth Flux Den =%8.2f T Back Iron =%8.2f T\n', Bt,Bb);

fprintf('Slots/pole/phase =%8.2t\n',m);

fprintf('Rotor Parameters:\n');

fprintf('Magnet Height = %8.2f mm Magnet Angle = %8.l1f degm\n',hmo,thm);

fprintf('Air gap = %8.2f mm Pole Pairs = %8.Of \n',go,p);

fprintf('Magnet Remanence = %8.2f T Aig Gap Bg = %8.2f T\n',Br,Bg);

fprintfC'Magnet Factor = %8.3f Skew Factor = %8.3f \n',kg,ks);

fprintf('Machine Losses:\n');

fprintfQ'Core Loss = %8.lf kW Armature Loss = %8.lIf kW\n', Pco,Pao);

fprintfQ'Windage Loss = %8.If kW Rotor Loss = TBD kWV\n', Pwindo);

fprintf('Machine Weights:\n');

fprintfC'Core = %8.2f kg Shaft = %8.2f kg\n',Mc,Ms);

fprintf('Magnet = %8.2f kg Armature = %8.2f kg\n',Mm,Mac);

fprintfQ'Services = %8.2f kg Total = %8.2f kg\n',Mser,Mtot);

## Appendix F. MATLAB Code: Bode Plot

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: Buckfilter

"% Program calculates transfer function and outputs

"% Bode plot for buck converter input filter

clear;

# % Input parameters

R = 4.79e-3;

Cf= 2.84e-3;

Cb = 28.4e-3;

Lf= 1.415e-6;

# % Set up transfer function

num = [R\*Cb 1];

den = [Lf\*R\*Cf\*Cb Lf\*(Cf+Cb) R\*Cb 1];

H = tf(num,den);

bode(H)

## Appendix G. MATLAB Code: PM Generator Waveforms

% Jonathan Rucker, MIT Thesis

% May 2005

"% Program: pmwave

"% Program calculates and outputs different waveforms,

"% calculates THD, and computes the harmonic content

"% for permanent magnet machines with surface magnets and

% slotted stators.

% MUST RUN pmlinput and pmlcalc PRIOR TO RUNNING pmwave

Definition of variables

"% Name Variable

"% General variables

"% Pwr Required power (W)

"% rpm Speed (RPM)

"% psi Power factor angle

"% f Electrical frequency (Hz)

"% omega Electrical frequency (rad/sec)

"% vtip Tip speed (m/s)

"% lambda Flux linkage

"% Ea RMS Internal voltage (V)

"% Rotor variables

% R Rotor radius (in)

"% hm Magnet thickness (in)

"% Lst Rotor stack length (in)

% p Number of pole pairs

"% Br Magnet remnant flux density (T)

"% thin Magnet physical angle (deg)

"% thsk Magnet skew angle (actual deg)

"% Stator variables

% q Number of phases

%in Slots per pole per phase

% Ns Number of slots

% Nsp Number of slots short pitched

%g Air gap (m)

"% ge Effective air gap (in)

"% tfrac Peripheral tooth fraction

"% hs Slot depth (in)

"% hd Slot depression depth (in)

"% wd Slot depression width (in)

"% syrat Stator back iron ratio (yoke thick/rotor radius)

"% Nc Turns per coil

"% lams Slot fill fraction

"% sigst Stator conductivity

"% Kc Carter coefficient

# % Constants to be used

muO = 4\*pi\*le-7; % Free space permeability

tol = le-2; % Tolerance factor

# % Harmonics to be evaluated

n = 1:2:35;

np, = p .\* n; % Use in kgn equation

w = n .\* omega; % Harmonic angular frequencies

freq = w ./ (2\*pi); % Harmonic frequencies

# % Harmonic winding and skew factors

gama = 2\*pi\*p/Ns;

alfa = pi\*NsctlNsfp;

kpn = sin(n .~pi/2) .\* sin(n .~alfa/2);

kbn = sin(n .\*m\*gamal2) J1 (m\*sin(n A'gamal2));

kwn = kpn .\*kbn;

ths =((p\*thsk)+1e-6)\*(piI18O); % skew angle (elec rad)

ksn =sin(n A' ths/2) ./ (n A' ths/2);

% Calculate magnetic gap factor

Rs =R+hm+g;

Ri =R;

RI =R;

R2 =R+hm;

kgn = ((Ri.A(np 1 ))./(Rs.A (2. \*np)..Ri.A (2.\*np))).\*((np./(np+ 1))...

.\*(R2 A(np+ 1)-Ri.A(np+ 1))+(np.\*Rs.A(2.\*np)./(np- 1))...

# % Calculate magnetic flux and internal voltage

thmrad = thm\*(pi/I 80);

thmerad = P\*thmjrad;

Bn = Bg.\*((4/pi)./n). \*kgn.\*sin(n. \*thmerad/2).\*sin(n. \*pi/2);

lambdan = ((2\*Rs\*Lst\*Na). \*kwn.\*kn.\*Bn)./p;

Ean = (omega. \*Iambdan); % Peak back voltage

% Normalized values for plotting

Eanorm = abs(Ean) J1 Ean(1);

% Voltage THD

Eah=0;

for r =2:length(n)

Eah = Eah + Ean(r)A2;

end

THD = 100\*sqrt(Eah/(Ean(1)A2));

# "%G enerate waveforms

"%R otor physical angle goes from 0 to 2\*pi - electrical to 2\*p\*pi

ang = O:pi/lOO:2\*pi;

angp, = p\*ang;

Bout = zeros(size(angp));

Eaout = zeros(size(angp));

for i= 1:length(n)

Bout = Bout + Bn(i).\*sin(n(i).\*angp);

Eaout = Eaout + Ean(i).\*sin(n(i).\*angp);

End

# % Plot waveforms

figure( 1)

plot(ang,Bout);

title('PM Generator: Flux Density');

ylabel(CB (Tesla)');

xlabelQ'Rotor Angle (rad)');

figure(2)

plot(ang,Eaout);

title(QPM Generator: Back EMF);

ylabel('Peak Voltage (V)');

xlabel(QRotor Angle (rad)');

figure(3)

hold on

title(['PM Generator: EMF Harmonics, THD = ,num2str(THD), %']);

ylabel('Normalized Back EMF');

xlabel('Harmonic Number');

text(20,O.7,'Dark: Above 10% of Fundamental','FontSize', 10);

text(20,0.65,'Light: Below 10% of Fundamental',FontSize', 10);

for z = 1 :Iength(Eanorm)

if Eanorm(z) < 0.10

bar(n(z),Eanorm(z),'c');

else

bar(n(z),Eanorm(z),'b');

end

end

hold off

## Appendix H. MATLAB Code: Retaining Sleeve Stress Calculations

"%Jo nathan Rucker, MIT Thesis

"%M ay 2005

% Program: pmcanstress

"%P rogram calculates and outputs retaining can stress

"%fo r permanent magnet machines with surface magnets and

"%sl otted stators.

"%M UST RUN pmiinput, pmicalc, and pmwave PRIOR TO RUNNING pmcanstress

# % Calculate retaining sleeve stresses

% Conversion

Patopsi = 1.45038e-4; % psi per Pa

% Material yield stresses (ksi)

Stain-str =90;

Alum-str =75;

Titan -str =110;

CarFib\_str =100;

Inconel-str =132;

% Safety factor

SF = 1.2;

"%F orce on magnets/sleeves is centrifugal force

"%M agnet tangential velocity

vmag = ((R+hm)\*omega)/p;

% Centrifugal force

Fm = (Mm\*vmagA2)/(R+hm);

% Outward pressure

Phoop = Fm/(2\*pi\*(R+hm)\*Lst);

# % Hoop Stress (in general, str = P\*R/t)

stop = 22;

for i= I: stop

t(i) = i\*.0005; % sleeve thickness t

slev(i) = t(i)\*1000;

Sthoop(i) = (Phoop\*(R+hm)/t(i))\*Patopsi/l 000;

SFHoop(i) = Sthoop(i)\*SF;

End

# % Output results

fprintf('Retaining Sleeve Stress:\n');

fprintf(QStress Limits:\n');

fprintf('Stainless Steel = %6.lf ksi Aluminum Alloy =%6.1f ksi~n',Stain-str,Alum-str);

fprintfQ'Titanium Alloy = %6. if ksi Carbon Fiber = %6. if ksi\n',Titan-StrCarFib str);.

fprintf('Inconel =%6. If ksi\n',Inconel-str);

fprintfQ'Actual Sleeve Stress:\n');

fprintf('Sleeve Thickness Actual Stress SF Stress\n');

for i = 1:stop

fprintf(Q %5.2f mm %6. if ksi %6. If ksi\n',...

slev(i),Sthoop(i),SFHoop(i));

end

## Appendix I. MATLAB Code: Rotor Losses from Winding Time and

Space Harmonics

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pmharmloss

"% Program performs rotor loss calculations caused by

"% winding time and space harmonics for permanent magnet

"% machines with surface magnets and slotted stators.

"% MUST RUN pmlinput, pmlcalc, pmloutput, and get harmonic

"% current data from PSIM prior to running pmharmloss

# "% Constants to be used

mu0 = 4\*pi\*le-7; % Free space permeability

tol = le-2; % Tolerance factor

% Retaining sleeve/magnet material resistivity (ohm-m)

Stainres = 0.72e-6;

Titan-res = 0.78e-6;

CarFibres = 9.25e-6;

Inconelres = 0.98e-6;

Magnetcres = 1.43e-6;

% Retaining sleeve thickness set at 0.5mm less than air gap

h\_sl = g - 0.0005; % Sleeve thickness

g\_act = g - hsl; % Actual air gap

% Retaining sleeve conductivities (S/m)

conds = 1/Stain res;

condt = 1/Titan res;

condc = l/CarFib-res;

cond-i = 1/Inconelres;

% Magnet & actual sleeve cond (S/m)

condm = 1/Magnet-res;

condsl = cond-s;

% Input time harmonic peak currents from PSIM

11 = 2895;

13 = 0;

15 = 209;

17 = 89.2;

19 = 0;

Il1 = 39.2;

113 = 27.6;

115 = 0;

117 = 17.0;

119 = 12.8;

121 = 0;

123 = 7.3;

125 = 6.3;

127 = 0;

167

129 =4.8;

131 = 3.9;

% Put currents in array

Iharm = [11 13 15 17 19 111113 115 117 119 121 123 125...

127 129 13 1];

# % Calculate current THD

lab = 0;

for r = 2:length(Iharm)

Iah = Iah + Iharm(r)A2;

end

THI~i = 100\*sqrt(Iah/(Iharm(1)A2));

% Calculate current densities

Iz = (1/sqrt(2)).\*Iharm;

Kz = ((q/2)\*(NaI(2\*pi\*Rs))).\*Iz;

Iz\_1 = (1/sqrt(2)).\*I1; % Fundamental RMS current

KzI = ((q/2)\*(Na/(2\*pi\*Rs))).\*Izj1; % Fundamental current density

# % Harmonics to be evaluated

n= 1:2:3 1;

w =n .\* omega; % Harmonic angular frequencies

freq = w I1 (2\*pi); % Harmonic frequencies

lam = (2\*(2\*pi/(2\*p)))./n;

k = (2\*pi)./lam; % Wavenumbers

# % Eta values

eta-m = sqrt((j\*muO\*cond m).\*w + (k.A2));

eta-s = sqrt((j\*muo\*cond~sl).\*w + (k.A2));

% Surface coefficient at top of magnet layer

alpha-m =j. \*(k./eta-m). \*coth(eta-m. \*hm);

% Surface coefficient at top of retaining sleeve

topI = (j.\*(k.fetas).\*sinh(etaS. \*h-sl)) + (alpha-m.\*cosh(eta-s.\*h-sl));

boti = (j \*(k./eta s).\*cosh(eta-s\*h sl)) + (alpha-m.\*sinh(eta-s.\*hLsl));

alpha-s = j. \*(k./eta s). \*(topl L/botl1);

% Surface coefficient at surface of stator

top2 = (j.\*sinh(k.\*g-act)) + (alpha-s.\*cosh(k.\*g-act));

bot2 = (j \*cosh(k.\*g-act)) + (alpha-s.\*sinh(k.\*g-act));

alpha-f = j.\*(top2./bot2);

% Surface impedance

Zs = (muO.\*wi/k).\*alpha-f;

"%C alculate losses due to time harmonics

"%U se only fundamental space harmonic factors

Kz -t =kw.\*Kz;

Syt = 0;

for i= 1:length(n)

Syjt(i) = 0.5\*(abs(Kz -t(i))A2)\*real(Zs(1));

Syt = Syt + Syjt(i);

end

# "%C alculate losses due to space harmonics

"%U se only fundamental time harmonic current

kpn = sin(n .~pi/2) .\* sin(n \*~ alfaI2);

kbn = sin(n .\*m\*gamal2) J1 (m. \*sin(n A'gama/2));

kwn = kpn .\*kbn;

Kz-s = kwn .\*Kzl I.J n;

Sys =0;

for i =1:length(n)

Sy-s(i) = 0.5\*(abs(Kz-s(i))A2)\*real(Zs(i));

Sys = Sys + Sy-s(i);

end

fprintf(AnRotor Losses Caused by Harmonics:\n');

fprintfQ'Time Harmonic Losses = %6.If kW~n',Syt/lOOO);

fprintf('Space Harmonic Losses = %6.lf kW\n',Sys/1000);

fprintf('Total Losses =%6.lf kW~n,(Syt-iSys)/1000);

fprintf('Current THD =%6.2f %%\n',THDi);

## Appendix J. MATLAB Code: Rotor Losses from Slot Effects

"% Jonathan Rucker, MIT Thesis

"% May 2005

"% Program: pmcanloss

"% Program calculates and outputs rotor losses caused by

"% stator slot effects for permanent magnet machines

"% with surface magnets and slotted stators.

"% MUST RUN pmlinput, pmlcalc, pmwave, and pmcanstress

"% PRIOR TO RUNNING pmcanloss

# % Calculate retaining sleeve losses

% Retaining sleeve/magnet material resistivity (ohm-m)

Stainres = 0.72e-6;

Titanres = 0.78e-6;

CarFibres = 9.25e-6;

Inconelres = 0.98e-6;

Magnet-res 1.43e-6;

# % Calculate Bd as function of wst and wt (max 10% of Bg)

Bd = (wst/wt)\*O.l\*Bg;

% Calculate flux variation parameters

beta = (wst/(2\*pi\*Rs))\*2\*pi;

lamB = 2\*pi/Ns;

B = (Bd/sqrt(2))\*sqrt(beta/lamB);

# "% Calculate geometry and can loss factor for different rings

"% k is number of rings

fork= 1:10

A(k) = pi\*2\*(R+hm)\*Lst/k;

Ks(k) = 1 - ((tanh(p\*Lst/(k\*2\*(R+hm))))/(p\*Lst/(k\*2\*(R+hm))));

End

% Input Stainless Steel sleeve thickness based on stress results

for i = 1:stop

if SFHoop(i) <= Stain str

t\_Stain = t(i);

break

elseif t(stop) > Stain-str

fprintf('Hoop Stress too high for Stainless Steel.A');

else

dummy = t(i);

end

end

% Input Titanium sleeve thickness based on stress results

for i = 1:stop

if SFHoop(i) <= Titan str

t\_Titan = t(i);

break

elseif t(stop) > Titan-str

fprintfQ'Hoop Stress too high for Titanium.\n');

else

dummy =ti)

end

end

% Input Carbon Fiber sleeve thickness based on stress results

for i= 1:stop

if SFHoop(i) <= CarFib-str

tCarFib t= )

break

elseif t(stop) > CarFib\_str

fprintfQ'Hoop Stress too high for Carbon Fiber.\n');

else

dummy =ti)

end

end

% Input Inconel sleeve thickness based on stress results

for i= l:stop,

if SFHoop(i) <= Inconel-str

tInconel =ti)

break

elseif t(stop) > Inconel-str

fprintf('Hoop Stress too high for Inconel.\n');

else

dummy =ti)

end

end

# % Calculate can losses

w\_Stain = (piA2/3600)\*((B \*rpm\*(R+hm))A2\*t -Stain)/Stain-res;

w\_Titan = (piA2/3600)\*((B \*ipm\*(R+hM))A2\*tTitan)/Titan-res;

wCarFib =(piA2/3600)\*((B \*rpm\*(R+hM))A2\*t -CarFib)/CarFib~res;

wInconel =(piA2/3600)\*((B\*rpm\*(R+hm))A2\*tjlnconel)/Inconel-res;

fork= 1:10

Pý\_Stain(k) = k\*wStain\*Ks(k)\*A(k)/1000;

PTitan(k) = k\*wTitan\*Ks(k)\*A(k)/1000;

P\_-CarFib(k) =k\*wCarFib\*Ks(k)\*A(k)/1000;

PInconel(k) =k\*w\_Inconel\*Ks(k)\*A(k)/1000;

End

# "%C alculate magnet losses (only with carbon steel)

"%C alculate geometry and can loss factor

Am = pj\*2\*R\*Lst;

Ksm = 1 - ((tanh(p\*LstI(2\*R)))/(p\*LstI(2\*R)));

"%C alculate magnet losses

"%A ssumes only 10% of magnet thickness sees effects

wMagnet =(piA2/3600)\*((B\*rpm\*R)A 2\*0. 1 \*hm)/Magnet-res;

P\_-Magnet =w-Magnet\*Ksm\*Am/lOOO;

# % Output Results

z=[15 510];

fprintfQ'Retaining Can Losses:\n');

for i=1:3

k = z(i);

fprintf'% 1 .Of Rings:\n',k)

fprintf('Material Thickness Can Loss\htO;

fprintfQ'Stainless Steel %5 .2f mm %6. if kW~n',t Stain\* 1000,P.Stain(k));

fprintf('Titanium %5.2f mm %6. if kW~n',t Titan\* 1000,PjTitan(k));

fprintfQ'Carbon Fiber %5.2f mm %6. if kW\n',t-CarFib\*1000,P-CarFib(k));

fprintf(Q Associated Magnet Loss %6. If kAWn',Magnet);

fprintf('lnconel %5 .2f mm %6. if kW~n\n',tjlnconel\* 1000,PjInconel(k));

end