Tesla Model S Induction Motor

RWD 85 Model

Hüseyin YÜRÜK

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Chapter 1. Introduction

The specs of the induction motor are as follows:

```
% Input Parameters of the
% Tesla Model S Induction Motor
power_max = 270;                 % [kW] from project2
torque_max = 440;                % [Nm] from project2
speed_max = 225;                 % [km/sa] from project2
m = 3;                           % [-] three phases
p1 = 2;                          % [-] pole pair from Hendershot-FIU-Lecture
power_rated = 288 * 0.746 ;      % [kW] from Hendershot-FIU-Lecture
tire_diameter = 27.7 * 25.4;     % [mm] from
                                 % https://tiresize.com/tires/Tesla/Model-S/
                                 % https://tiresize.com/tiresizes/245-45R19.htm
gear = 9.73;                     % [-] 9.73:1 (transmission) from
                                 % https://en.wikipedia.org/wiki/Tesla_Model_S
speed_rpm_max = (speed_max*10^3/3600)/(tire_diameter*10^-3/2)*(60/2*pi())*gear; %
speed_rpm_rated = 6000;          % [rpm] from Hendershot-FIU-Lecture
                                 % approx. knee of the torque-speed curve
f1 = speed_rpm_rated*2*p1/120;   % [Hz] frequency of the driver unit
Vd = 400;                        % [V] nominal bus voltage 85kWh from
                                 % http://teslatap.com/undocumented/
u0 = 4*pi*10^-7;                 % [-]
```

Chapter 2. Main Dimensions of Stator Core

Dis^2 * L output constant concept is used to determine parameters.

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
neff = 0.96;               % [-] targetted efficiency (IE3)
pwr_factor = 0.88;         % [-] typ. power factor for induction motors
                           % at full load varies between 0.85-0.90
Ke = 0.98 - 0.005*p1;      % [-] Ke defined as E1 / V1n (eq. 14.8)
                           % and approx. given as eq. 14.10
Sgap = Ke * power_rated * 10^3 / (neff * pwr_factor);  % [VA] (eq. 15.2)
stack_aspect = 1.25;        % [-] stack aspect ratio define as
                           % stack length to pole pitch ratio (eq. 14.19)
                           % (table 15.1)
Co = 250*10^3;             % [J/m^3] extracted from figure 14.14
Dis = ((2*p1*p1*Sgap)/(pi()*stack_aspect*f1*Co))^(1/3); %[m] (eq. 15.1)
pole_pitch = pi()*Dis/(2*p1);   % [m] pole pitch (eq. 15.2)
L = stack_aspect * pole_pitch;  % [m] stack length (eq. 15.2)
Ftan_max = torque_max / (Dis/2);% [N] tangential force
Sr = pi()*Dis*L;                % [m^2] surface area
shear_stress_max = Ftan_max / Sr; % [N/m^2], [Pascal] tangential shear stress
Cmech = power_max / (Dis^2*L*f1/p1); % [kWs/m^3] specific machine constant
max_stator_num = round(pi()*Dis/0.007); % [-] max. stator number from
                                        % ee564_basic_machine_design2, 8/23
min_stator_num = ceil(pi()*Dis/0.045);  % [-] min. stator number
Kd = 0.63;                  % [-] for 2p1 pole number (Table 15.2)
Dout = Dis / Kd;            % [m] outer diameter of the stator (eq. 15.4)
g1 = 0.1+0.012*(power_rated*10^3)^(1/3); %[mm] airgap (eq. 15.5)
g2 = 0.18+0.006*(power_rated*10^3)^(0.4);%[mm] airgap from
                                         % ee564_basic_machine_design 16/18
if (g1 > g2)
    g = g1;
else
    g = g2;
end;
g = g * 1.2;                         % [mm] to add safety factor
```

Chapter 3. The Stator Winding

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
Ns = 2*p1*m*4;          % [-] number of stator slots
q = Ns/(2*p1*m);        % [-] slots per pole per phase
pitch_factor = 5/6;     % [-] to minimize 5th and 7th harmonics
pitch_angle = 5/6*180;  % [°] pitch angle
slot_angle_alpha = 180/(Ns/(2*p1)); % [°] slot angle (eq. 15.7)
Kp1 = sind(pitch_angle/2); % [-] fundamental pitch factor (eq. 15.9)
Kd1 = sind(q*slot_angle_alpha/2)/(q*sind(slot_angle_alpha/2));
                        % [-] fundamental distribution factor (eq. 15.8)
Kw1 = Kp1*Kd1;          % [-] fundamental winding factor
Bg = 0.65;              % [Tesla] (e.q. 15.11)
Kst = 0.4;              % [-] so 1+Kst = 1.4
den_shape = 0.729;      % [-] density shape factor fig.14.13, where 1+Kst=1.4
Kf = 1.085;             % [-] form factor fig.14.13
flux_airgap = den_shape*pole_pitch*L*Bg; %[Wb] airgap flux (eq. 15.10)
Vph_rms = 4/pi()*Vd/2*(1/sqrt(2)); %[V] (eq. 8.56 Mohan) rms phase voltage
N_per_ph = Ke*Vph_rms/(4*Kf*Kw1*f1*flux_airgap); % [turns/phase] (eq. 15.12)
a1 = 1;                 % [-] the number of current path in parallel
ns = a1*N_per_ph/(p1*q);% [*] the number of conductors per slot
% to get even number conductors because of double layer winding
if ns<=2
    ns = 2;
else
    ns = ceil(ns);
    if 1 == mod(ns,2)
        ns = ns +1;
    end
end
N_per_ph_req = p1*q*ns;         % [turns/phase] required turns/phase
Bg_req = Bg * N_per_ph/N_per_ph_req; % [Tesla] required Bg
Vll_rms = Vph_rms * sqrt(3);    % [V] line-line rms voltage
Iph_rated_rms = power_rated*10^3/(neff*pwr_factor*sqrt(3)*Vll_rms);
                                % [A] rated phase current (eq. 15.16)
Jcos = 5.5;            % [A/mm^2] current density for 2p1=2,4 (eq. 15.17)
Aco = Iph_rated_rms/(Jcos*a1);  % [mm^2] stator wire cross section
dco = sqrt(4*Aco/pi);  % [mm] wire gauge diameter (eq. 15.19)
ap = 4;                % [-] number of conductor in parallel
dcop = sqrt(4*Aco/(pi*ap)); % [mm] wire gauge diameter (eq. 15.20)
dcop_sta = 5.189;      % [mm] AWG4 size is chosen by regarding above value
```

```
The number of stator slots (Ns) should be multiple of 12.
By referring the suggested stator slot pitch for induction machines
(7-45mm), Ns should be between 16-97.
Let's choose Ns as 48.
To reduce harmonic frequency components let's use fractional pitch.
5/6 fraction is used to reduce 5th and 7th harmonics.
Note that
5/6 pitch will
minimize the 5th harmonic but not eliminate it as will 4/5 pitch
```

minimize the 7th harmonic but not eliminate it as will 6/7 pitch

Chapter 4. Stator Slot Sizing

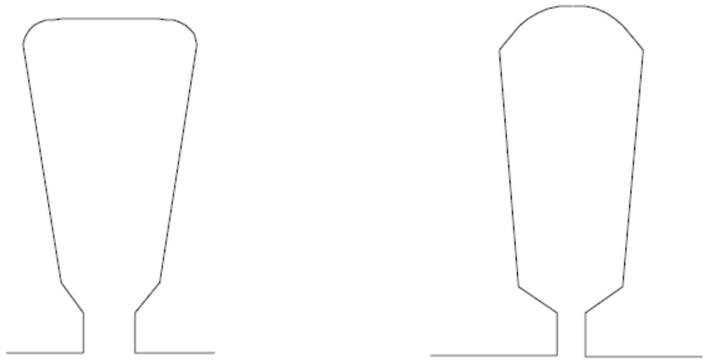

Figure 15.4 Recommended stator slot shapes

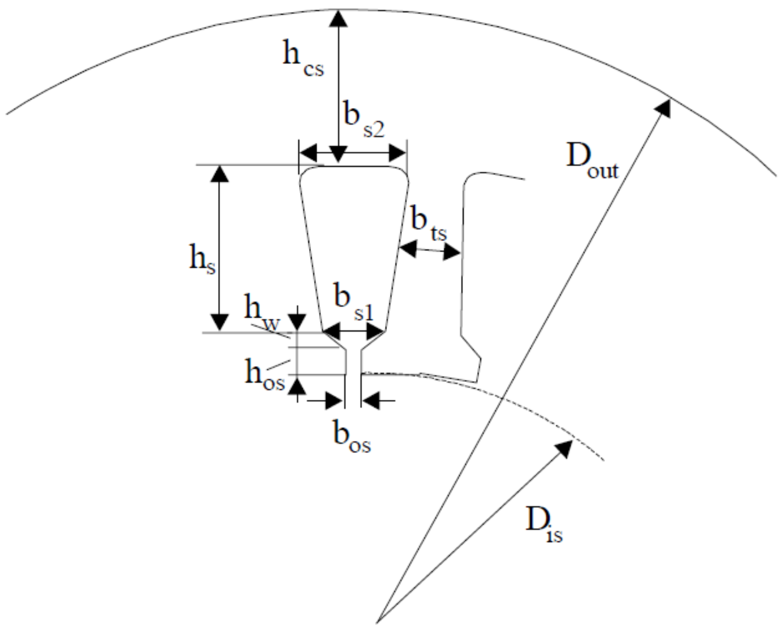

Figure 15.5 Stator slot geometry

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
% stator slot sizing will be determined
Kfill = 0.44;   % [-] slot fill factor for above 10kW
Asu = pi*dcop^2*ap*ns/(4*Kfill); % [mm^2] useful slot area (eq. 15.21)

% see figure stator slot geometry
bos = 2.5*10^-3;    % [m]
hos = 1*10^-3;      % [m]
hws = 4*10^-3;       % [m]
Kfe = 0.96;     % [-]
```

```
Bts = 1.625;     % [Tesla] stator tooth flux density
sta_slot_pitch = pole_pitch/(3*q);   % [m] stator slot pitch (eq. 15.3)
bts = Bg_req*sta_slot_pitch/(Bts*Kfe); % [m] tooth width  (eq. 15.22)
bs1 = (pi*(Dis+2*hos*+2*hws)/Ns)-bts;   % [m] slot lower witdh bs1 (eq. 15.23)
bs2 = sqrt(4*Asu*10^-6*tan(pi/Ns)+bs1^2);% [m] slot upper witdh bs1 (eq. 15.27)
hs = 2*Asu*10^-6/(bs1+bs2);             % [m] slot useful height (eq. 15.24)
Fmg = 1.2*g*10^-3*Bg_req/u0;            % [Aturns] airgap mmf (eq. 15.29)
                                        % note that carter coe. is taken 1.2
Hts = 3100;                             % [A/m] (table 15.4) interpolation
Fmts = Hts*(hs+hos+hws);                % [Aturns] stator tooth mmf (eq. 15.30)
Fmtr = Kst*Fmg - Fmts;                  % [Aturns] rotor tooth mmf (eq. 15.31)
hcs = (Dout-(Dis+2*(hos+hws+hs)))/2;   % [m] stator back iron height (eq. 15.32)
Bcs = flux_airgap/(2*L*hcs);            % [Tesla] back core flux density (15.33)
```

```
Stator slot geometry dimeonsions are shown in figure 15.5.
Asu = 389.0861 [mm^2]
bos = 0.0025  [mm]
hos = 1.0000e-03 [mm]
hws = 0.0040 [mm]
bts =  0.0047 [mm]
bs1 =  0.0094 [mm]
bs2 =  0.0138 [mm]
hs = 0.0335 [mm]
hcs = 0.0249 [mm]

Resultant mmfs
Fmg = 591.9621 [Aturns]
Fmts = 119.3143 [Aturns]
Fmtr = 117.4706 [Aturns]

The back core flux density is calculated as 1.6138T where within 1.4-1.7T.
```

Chapter 5. Rotor Slots

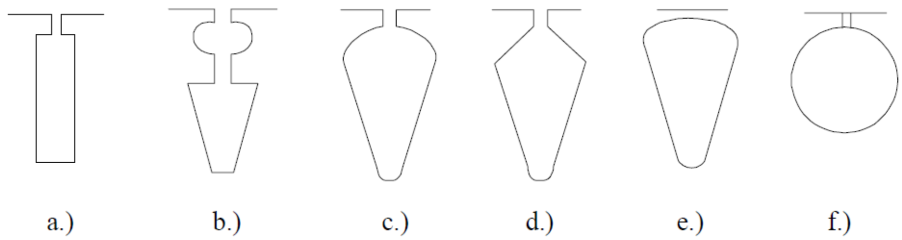

Figure 15.6 Typical rotor cage slots

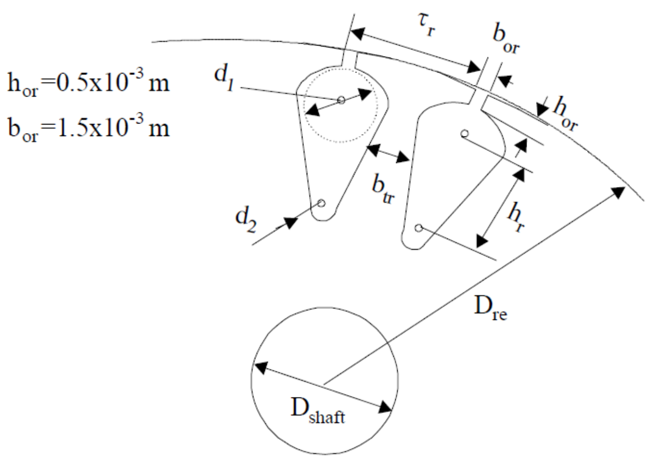

Figure 15.7 Rotor slot geometry

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
% rotor slot sizing will be determined
Nr = 60; % [-] rotor slot number
         % http://keysan.me/presentations/ee564_basic_machine_design2.html#32
         % 17/23 slayt table 7.5 most advantageous slot numbers for rotors
         % with slots skewed for a stator slot pitch 1-2
Ki = 0.8*pwr_factor+0.2; % [-] (eq. 15.35)
Ib = Ki*(2*m*N_per_ph_req*Kw1/Nr)*Iph_rated_rms;
                         % [A] rated rotor bar current (eq. 15.34)
Jb = 3.42; % [A/mm] current density in the rotor bar
Ab = Ib/(Jb*10^6);       % [m^2]rotor slot area (eq. 15.36)
Ier = Ib/(2*sin(pi*p1/Nr)); % [A] end ring current (eq. 15.37)
Jer = 0.75*Jb*10^6;  % [A/m^2] current density in the end ring
Aer = Ier / Jer;     % [m^2] end ring cross section (eq. 15.38)
hor = 1*10^-3;       % [m] refer to figure 15.7
hwr = 4*10^-3;       % [m] refer to figure 15.5
bor = 2.5*10^-3;     % [m] refer to figure 15.7
rot_slot_pitch = pi*(Dis-2*g*10^-3)/Nr; % [m] rotor slot pitch (eq. 15.39)
Btr = 1.675;           % [Tesla] rotor tooth flux density
btr = Bg_req*rot_slot_pitch/(Kfe*Btr); % [m] rotor tooth width (eq. 15.40)
% Let me calculate rotor slot dimensions like stator slot
```

```
br1 = pi*(Dis-2*hor-2*hwr)/Nr - btr; % [m] changed from (eq. 15.23)
br2 = sqrt(4*Ab*tan(pi/Nr)+br1^2);   % [m] changed from (eq. 15.27)
hr = 2*Ab/(br1+br2);                 % [m] changed from (eq. 15.24)
Htr = 4200;                          % [A/m] from table 15.4 interpolation
Fmtr_res = Htr*(hr+hor+hwr); % [Aturns] rotor teeth mmf changed from(eq. 15.30)
Bcr = 1.65;                  % [Tesla] rotor back core flux density
hcr = flux_airgap/(2*L*Bcr); % [m] rotor back core height (eq. 15.46)
Dshaft_max = Dis-2*g*10^-3-2*(hor+hwr+hr+hcr);
                             % [m] max. shaft diameter (eq. 15.47)
b = 1.0*(hr+hor+hwr);        % [m] end rind cross section b (eq. 15.50)
a = Aer/b;                   % [m] end rind cross section a (eq. 15.51)
```

```
Rotor slot geometry dimeonsions are shown in figure 15.7.
But rotor slot geometry type is assumed 15.6d.
And dimension calculations are computed like stator slot as in
figure 15.5.
But this time bs1 and bs2 are reversed.

Ib =  629.9058 [A]
Ab = 1.8418e-04 [m^2]
Ier = 3.0131e+03 [A]
Aer = 0.0012 [m^2]
bor = 0.0025  [mm]
hor = 1.0000e-03 [mm]
hwr = 0.0040 [mm]
btr =  0.0036 [mm]
br1 =  0.0072 [mm]
br2 =  0.0095 [mm]
hr = 0.0221 [mm]
hcr = 0.0243 [mm]

Resultant mmf
Fmtr_res = 113.9060 [Aturns]
so close to calculated as in stator siot sizing part Fmtr=117.4706.

The maximum diameter shaft 0.1105 [m].
```

Chapter 6. The Magnetizing Current

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
% magnetizing current will be determined
y1 = bos^2/(5*g*10^-3+bos);  % [m] (eq. 15.53)
y2 = bor^2/(5*g*10^-3+bor);  % [m] (eq. 15.53)
Kc1 = sta_slot_pitch/(sta_slot_pitch-y1); % [-] (eq. 15.55)
Kc2 = rot_slot_pitch/(rot_slot_pitch-y2); % [-] (eq. 15.56)
Kc = Kc1*Kc2;   % [-] total Carter coefficient Kc
Ccs = 0.88*exp(-0.4*Bcs^2); % [-] subunitary empirical coe. (eq 15.60)
Ccr = 0.88*exp(-0.4*Bcr^2); % [-] subunitary empirical coe. (eq 15.60)
Hcs = 2500;     % [A/m] Hcs value at Bcs (table 15.4)
Hcr = 3460;     % [A/m] Hcs value at Bcs (table 15.4)
Fmcs = Ccs*pi*(Dout-hcs)/(2*p1)*Hcs;
                % [Aturns] stator back core mmfs (eq. 15.58)

Fmcr = Ccr*pi*(Dshaft_max+hcr)/(2*p1)*Hcr;
                % [Aturns] rotor back core mmfs (eq. 15.59)
Flm = 2*(Fmg+Fmts+Fmtr+Fmcs+Fmcr); % [Aturns] magnetizing mmf (eq. 15.52)
Ks = Flm/(2*Fmg)-1; % [-] total saturation factor (eq. 15.61)
Im = pi*p1*(Flm/2)/(3*2^(0.5)*N_per_ph_req*Kw1); % [A] magnetizing current
                                                 % (eq. 15.62)
im = Im/Iph_rated_rms; % [-] relative (p.u) value of Im (eq. 15.62')
```

```
To find magnetizing current first of all magnetizing mmf
should be calculated.
Carter's coefficient is calculated and the result is 1.1297
which was taken 1.2 in eq. 15.29.
Back core mmfs are also calculated.
Fmcs = 193.6720 [Aturns]
Fmcr = 108.5249 [Aturns]
total magnetizing mmf
Flm = 2.2619e+03 [Aturns]
total saturation factor Ks is 0.9105
magnetizing current Im is 113.1641 [A]
relative p.u value of the Im is 0.2404.
```

Chapter 7. Resistance and Inductances

```
% Based on the The Induction Machine Handbook Chapter 14 & 15
% resistance and inductances refer to eq. circuit (figure 15.9)
y = pitch_factor*pole_pitch; % [m] coil span (eq. 15.67)
lend = 2*y-0.02;             % [m] coil end connection length (eq. 15.65)
lc = 2*(L+lend);             % [m] coil length (eq. 15.64)
pco_80deg = 2.1712*10^-8;    % [ohm.m] copper resistivity at @80° (eq. 15.69)
Rs = pco_80deg*(lc*N_per_ph_req)/(Aco*10^-6*a1); % [Ohm] stator resistance
                                                 % (eq. 15.63)
lambdaec = 0.34*(q/L)*(lend-0.64*pitch_factor*pole_pitch);
                             % [-] (eq. 15.79) two-layer, end connection
                             % specific geometric permeance coefficient
Lec = 2*u0*L*N_per_ph_req^2/(p1*q)*lambdaec; % [H] end winding inductance
                                             % derived from (eq. 15.75)
ler = pi*(Dis-(2*g*10^-3)-(3*10^-3)-b)/Nr;   % [m] end ring segment
                                             % (eq. 15.71 & Dre-Der~=3-4mm
pal_80deg = 3.1*10^-8*(1+(80-20)/273);       % [ohm.m] aluminium resistivity
Rer = pal_80deg*(ler/(2*Aer*sin(pi*p1/Nr)^2)); % [ohm] rotor end ring segment
                                               % derived from (eq. 15.70)
```

```
rotor resistance is calculated as 0.0039 Ohm.  (cupper at 80°)
End winding inductance Lec 1.8823e-05H
resistance of the end ring of the rotor is 1.4138e-05 (aliminium at 80°)
```