EE564 First Project II: TESLA Model S Induction Motor

Table of Contents

ID

NAME : Mehmet Kaan Mutlu

STUDENT NUMBER : 2121408

E-mail : kaan.mutlu@metu.edu.tr

Specifications

In this project, design of the induction motor that is used in **Tesla Model S**. Normally it has different variations, to keep things simple; **RWD 85 Model** will be used that has the following specs:

- **Maximum Power:** 270 kW
- **Maximum Torque:** 441 Nm
- **Top Speed:** 225 km/h

Except for these given specs, these are also found from internet:

- **Number of poles:** 4
- Maximum RPM value of our motor is 21848 RPM. This value is calculated by considering Tesla Model S has 21' tires and 9.73 to 1 gear ratio.

If we assume average speed is 85 km/h. Then rated RPM value of motor will be 7960 RPM.

```
In this case supply frequency will be 265 Hz.
```

- **Number of phases:** 3
- **Line supply voltage:** 400 V
- **Rated Power:** 185 kW

Main Dimensions of Stator Core

Boldea's The Induction Machine Handbook is going to be used to determine parameters and dimensions of motor. In Chapter 15, it is explained that $D_{is}^2 L$ output constant concept will be used. For internal stator diameter formula below will be used:

$$D_{is}^3 = \frac{2pp_1 S_{gap}}{\pi \lambda f C_0}$$

To be able to calculate D_{is}, airgap power is needed.

At this point targeted efficiency is taken as 95 %.

Power factor is taken as 0.89

Another required parameter to be able to calculate airgap power is Ke that is defined as E1 to Vin ratio in equation 14.8.

$$K_E \approx 0.98 - 0.005 p_1$$

Now everything is ready for airgap apparent power:

$$S_{gap} = \frac{K_E P_n}{\eta_n \cos \Phi}$$

Airgap power is calculated as 212.2 KVA.

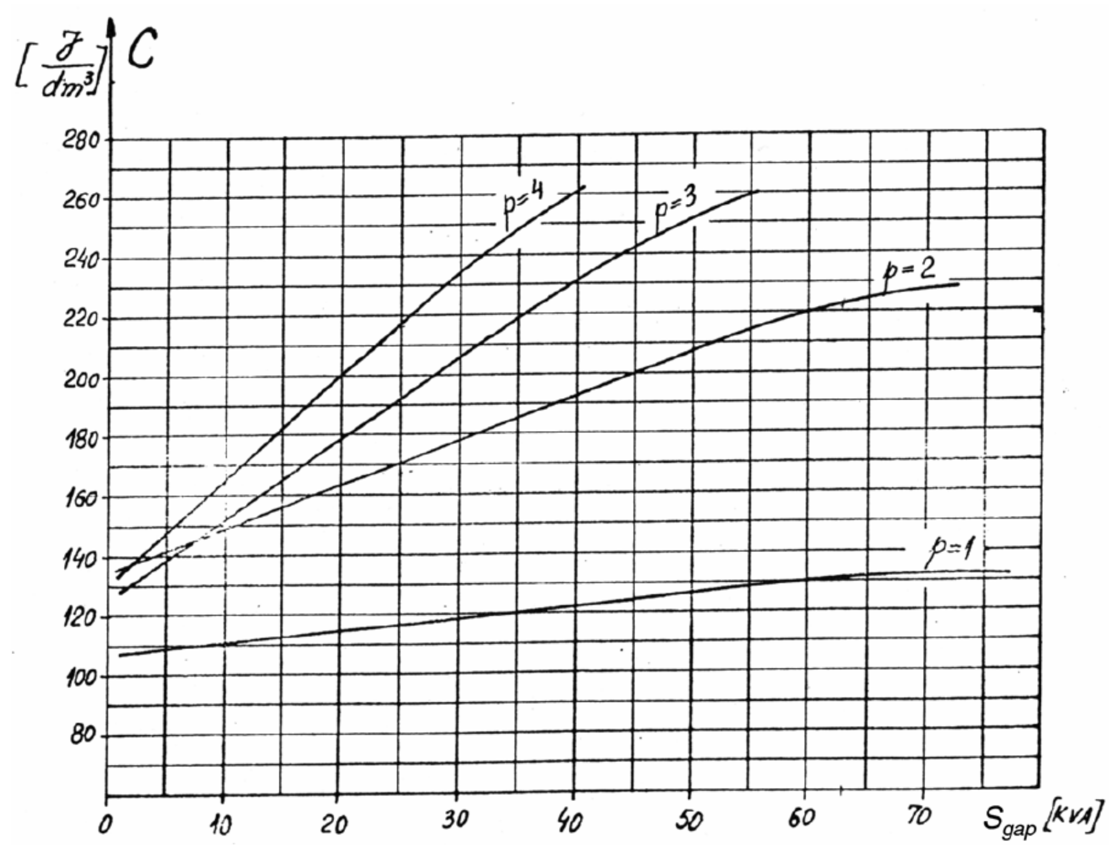
After this calculation, missing parameters are stack aspect ratio and Esson's constant Co. Stack aspect ratio is selected from table below:

Table 15.1. Stack aspect ratio λ

$2p_1$	2	4	6	8
λ	0.6 – 1.0	1.2 – 1.8	1.6 – 2.2	2 -3

It is selected as 1.5.

Esson's constant is selected using Figure 14.14.



Because our calculated airgap power is out of figure's range it isn't possible to read a certain value but for two pole-pairs after 60 kVA Esson's constant starts to saturate and for our airgap apparent power this value is taken as 240 J/dm^3.

Now we are ready to calculate internal stator diameter:

Internal diameter of stator is calculated as 17.827 cm.

For realistic dimensions it is going to be taken as 17.9 cm.

Now we can calculate stack length, deriving its formula from equation 15.2:

$$L = \frac{\lambda \pi D_{is}}{2p}$$

Stack length L is 21.09 cm.

For being realistic it is going to be taken as 21.1 cm.

By using equation 14.14 it is possible to calculate the pole pitch:

$$\tau = \frac{\pi D_{is}}{2p}$$

Pole pitch is 14.06 cm.

Next step is deciding external stator diameter. For its calculation, table below will be used.

Table 15.2. Inner/outer stator diameter ratio

$2p_1$	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

It gives us information about ratio of internal and external stator diameters. For 4 poles this ratio will be taken as 0.61.

External diameter of stator is calculated as 29.344 cm.

For realistic dimensions it is going to be taken as 29.4 cm.

For suitable airgap calculation book's equation of 14.38 may be used as well as the equation defined during the EE564 lecture of 6th April. Here it is important to remind that the minimum airgap is 0.2 mm.

Formula discussed in the lecture is as follows:

$$airgap = 0.18 + 0.006P^{0.4}mm$$

Book equation of 14.38 is

$$airgap = 0.1 + 0.012P^{\frac{1}{3}}mm$$

As known, too small airgap would produces large space airgap field harmonics and additional losses while a too large one would reduce the power factor and efficiency. Therefore, average of these two calculated airgap values will be used as actual airgap value.

Airgap is calculated as 0.8656 mm.

For being realistic it is going to be taken as 0.87 mm.

The Stator Winding

Following James Hendershot's lecture notes, for 4 poles and 185 kW of rated power Stator slot number will be selected. Our rated power is nearly 250 HP and from table below, it is advised to choose 58 stator slots for our case.

HP	2 POLE			4 POLE		
	STD	EM	XE	STD	EM	XE
1	32/24	32/24	32/24	28/36	45/36	45/36
1.5	32/24	32/24	32/24	28/36	45/36	45/36
2	32/24	32/24	32/24	28/36	45/36	45/36
3	32/24	32/24	32/2	28/36	45/36	45/36
5	32/24	32/24	32/24	28/36	45/36	45/36
7.5	28/36	28/36	28/36	28/36	45/36	45/36
10	28/36	28/36	28/36	28/36	45/36	45/36
15	28/36	28/36	28/36	40/48	40/48	40/48
20	28/36	20/36	28/36	40/48	40/48	40/48
25	28/36	28/36	28/36	40/48	40/48	40/48
30	28/36	28/36	28/36	40/48	40/48	40/48
40	28/36	28/36	28/36	40/48	40/48	40/48
50	28/36	28/36	28/36	40/48	40/48	40/48
60	38 or 40/48	38 or 40/48	38 or 40/48	47/60	47/60	47/60
75	38 or 40/48	38 or 40/48	38 or 40/48	47/60	47/60	47/60
100	38 or 40/48	38 or 40/48	38 or 40/48	73/60	47/60	47/60
125	38 or 40/48	38 or 40/48	38 or 40/48	58/72	58/72	58/72
150	38 or 40/48	38 or 40/48	38 or 40/48	58/72	58/72	58/72
200	38 or 40/48	38 or 40/48	38 or 40/48	58/72	58/72	56or58/72
250	38 or 40/48	38 or 40/48	38 or 40/48	56or58/72	56or58/72	56or58/72

Here we should remember that the total number of slots per stator should be divisible by the number of phases. So it should be a number that is multiple of 3.

$$q = \frac{N_s}{2pm}$$

If we think about its formula above (taken from book; 4.7), it is possible to see that choosing Ns/m integer doesn't guarantee that q is an integer. In fact it doesn't have to be an integer and may be selected as a fraction. But in most induction machines, q is an integer to provide complete (pole to pole) symmetry for the winding. So in our case Ns must be multiple of 2pm=12. Advised number is 58, so Ns would be taken as 60. It was tried and seen that number of conductors, flux density and other parameteres don't meet the expectations. So it is going to be taken as 48.

```
Number of slots per pole per phase is 4 .
```

Now we should decide pitch factor. It can be selected as 5/6 to reduce 5th harmonic and reduce 7th harmonics. So two layered winding with chorded coils will be used.

```
Selected pitch angle is 150 degree .
```

It is possible to calculate the electrical angle between emfs in neighboring slots α_{ec}

$$\alpha_{ec} = \frac{2\pi p}{N_s}$$

It is 0.262 radian means 15 degree.

Now we can calculate pitch factor. Due to chorded coils of stator,induced voltage will drop but by means of harmonics we will have better results.

$$k_p = sin(\frac{\lambda}{2})$$

Pitch factor is calculated as 0.97 .

Using formula below it is possible to calculate distribution factor.

$$k_d = \frac{sin(q\frac{\alpha}{2})}{qsin\frac{\alpha}{2}}$$

Distribution factor is calculated as 0.96 .

Multiplicaiton of distribution and pitch factors are called as winding factor.

Winding factor is calculated as 0.93 .

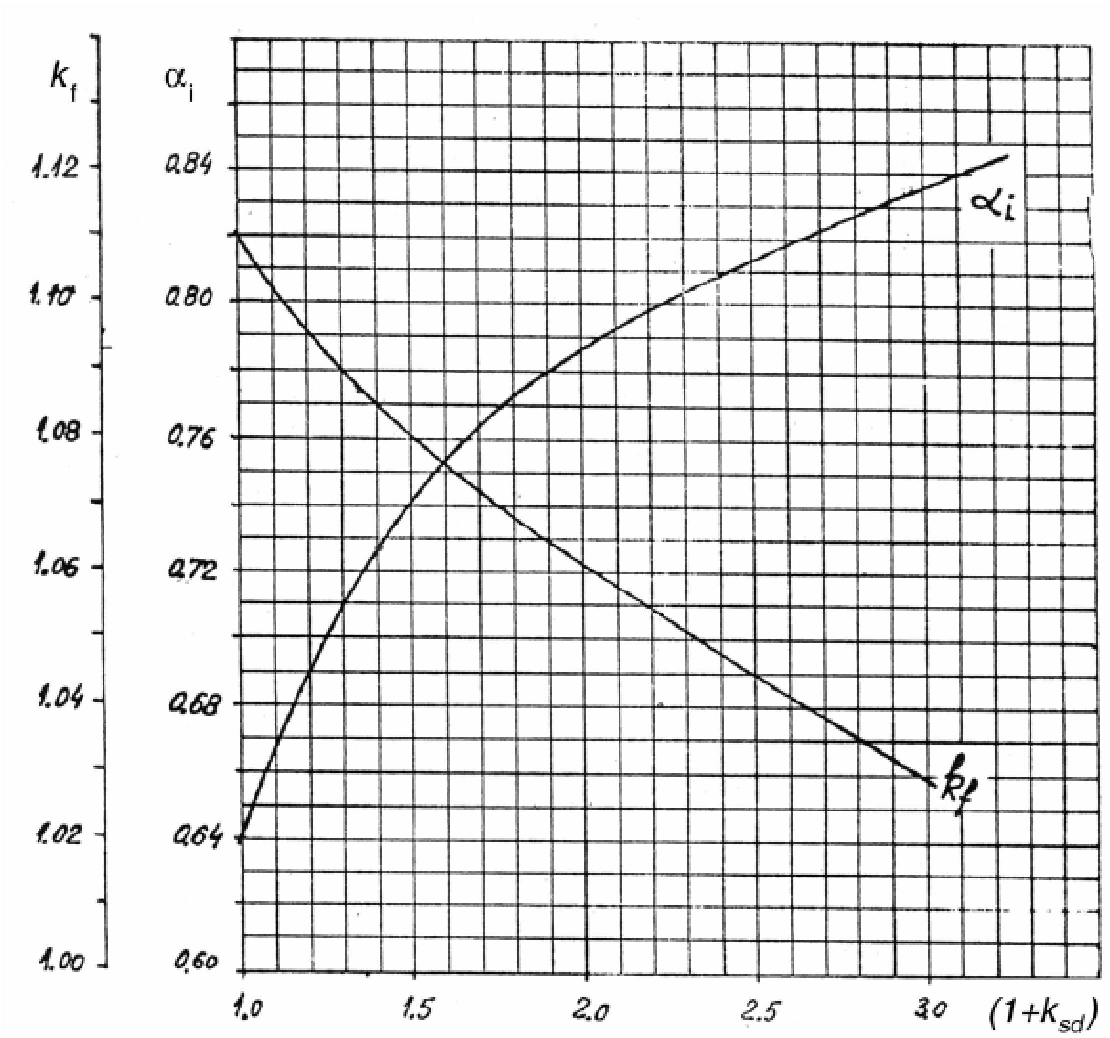
Using recommended intervals given in 15.11, it is possible to select the airgap flux density. For 4 poles suggested interval is 0.65 to 0.78 Tesla. To decrease iron losses minimum of this interval will be taken as airgap flux density.

```
Bg =

    0.7000
```

The pole coefficient α_i and form factor Kf depend on the tooth saturation factor 1+Kst. If 1+Kst is taken as 1.4 than Kst is 0.4.

Using this value and graph below, it is possible to select form factor and flux density shape factor.



Form factor is selected as 1.085 .

Flux density shape factor is selected as 0.729 .

Using these coefficients it is possible to calculate pole flux.

$$\phi = \alpha_i \tau L B_g$$

Pole flux is calculated as 15.137 mWb.

The number of per phase can be calculated using formula below given with (15.12).

$$N_{ph} = \frac{K_E V_{ph}}{4 K_f K_w f \phi}$$

The number of turns per phase is calculated as 17.0 turns/phase.

The number of conductors per slot ns can be calculated using formula below:

$$n_s = \frac{a_1 N_{ph}}{p_1 q}$$

Here a1 ise the number of current paths in parallel and will be taken as 1 for our case.

```
It is calculated as 2.13 .
```

It should be an even number as there are two distinct coils per slot in a double layer winding. So ns is selected as 2.

If we turn back and recalculate the actual airgap flux density:

```
Recalculated airgap flux density is 0.745 T .
```

Now we can calculate rated current. 15.16 formula will be used:

$$I_{in} = \frac{P_n}{\eta cos\phi_n \sqrt{3} V_1}$$

```
Rated phase current is calculated as 315.8 A .
```

To be able to calculate wire cross section, current density will be selected first. Here, recommendation 15.17 will be followed and for 4 poles current density will be taken as 6 A/mm^2.

$$A_{co} = \frac{I_{in}}{J_{cos}}$$

```
Magnetic cross section area is calculated as 52.64 mm^2.
```

Using cross-sectional wire area information it is possible to calculate the diameter wire gauge.

$$d_{co} = \sqrt{\frac{4A_{co}}{\pi}}$$

```
Wire gauge diameter is 8.19 mm.
```

Because this diameter is not small, 30 conductors will be paralleled to decrase the diameter of each conductor.

```
New wire gauge diameter is 1.49 mm.
```

By using table 15.3, it is possible to jump from wire diameter to insulated wire diameter.

```
Insulated wire gauge diameter is 1.53 mm.
```

Stator Slot Sizing

Published with MATLAB® R2013a