EE564 First Project III: BMW i3 - Synchronous Reluctance 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 a synchronous reluctance motor that might be used in **BMW i3** will be considered.

- **Maximum Power:** 125 kW
- **Maximum Torque:** 250 Nm
- **Top Speed:** 150 km/h
- **Number of poles:** 4
- Maximum RPM value of our motor is 16000 RPM. This value is calculated by considering BMW i3 has 19' (48.26 cm) tires and 9.7 reduction ratio.

If we assume average speed is 85 km/h. Then rated RPM value of motor will be 9000 RPM.

```
In this case supply frequency will be 300 Hz.
```

- **Number of phases:** 3
- **Nominal battery voltage:** 360 V

- **Rated Power:** 75 kW

In synchronous reluctance motor and induction motor comprasion it is possible to say that for same power rating, size of synchronous reluctance motor might be half of the induction machine. Instead rest of the stator design is for induction motor but by taking same power rating, our advantage will be better efficiecny.

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 96 %.

Power factor is taken as 0.8 .

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:

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

Airgap power is calculated as 94.7 KVA.

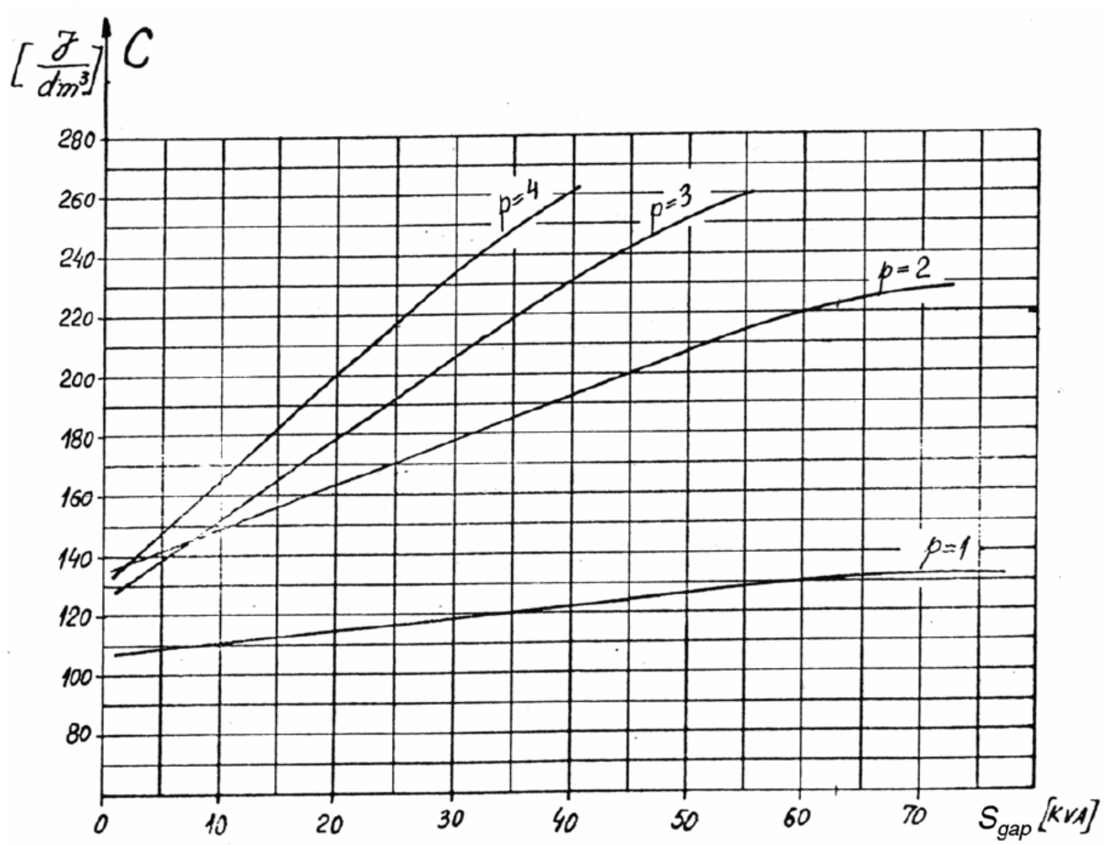
After this calculation, missing parameters are stack aspect ratio and Esson's constant Co. Stack aspect ratio is selected from table below:

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 13.072 cm.

For realistic dimensions it is going to be taken as 13.1 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 15.43 cm.

For being realistic it is going to be taken as 15.5 cm.

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

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

Pole pitch is 10.29 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 21.475 cm.

S#nce this value isn't good enough for a acceptable back-core flux density, 5 cm will is added to the calculated value.

For realistic dimensions it is going to be taken as 26.5 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 0.6604 mm.

For being realistic it is going to be taken as 0.67 mm.

The Stator Winding

Following James Hendershot's lecture notes, for 4 poles and 75 kW of rated power Stator slot number will be selected. Our rated power is nearly 67 HP and from table below, it is advised to choose 47 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. So Ns can be taken as 36.

```
Number of slots per pole per phase is 3 .
```

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 0.349 radian means 20 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 .

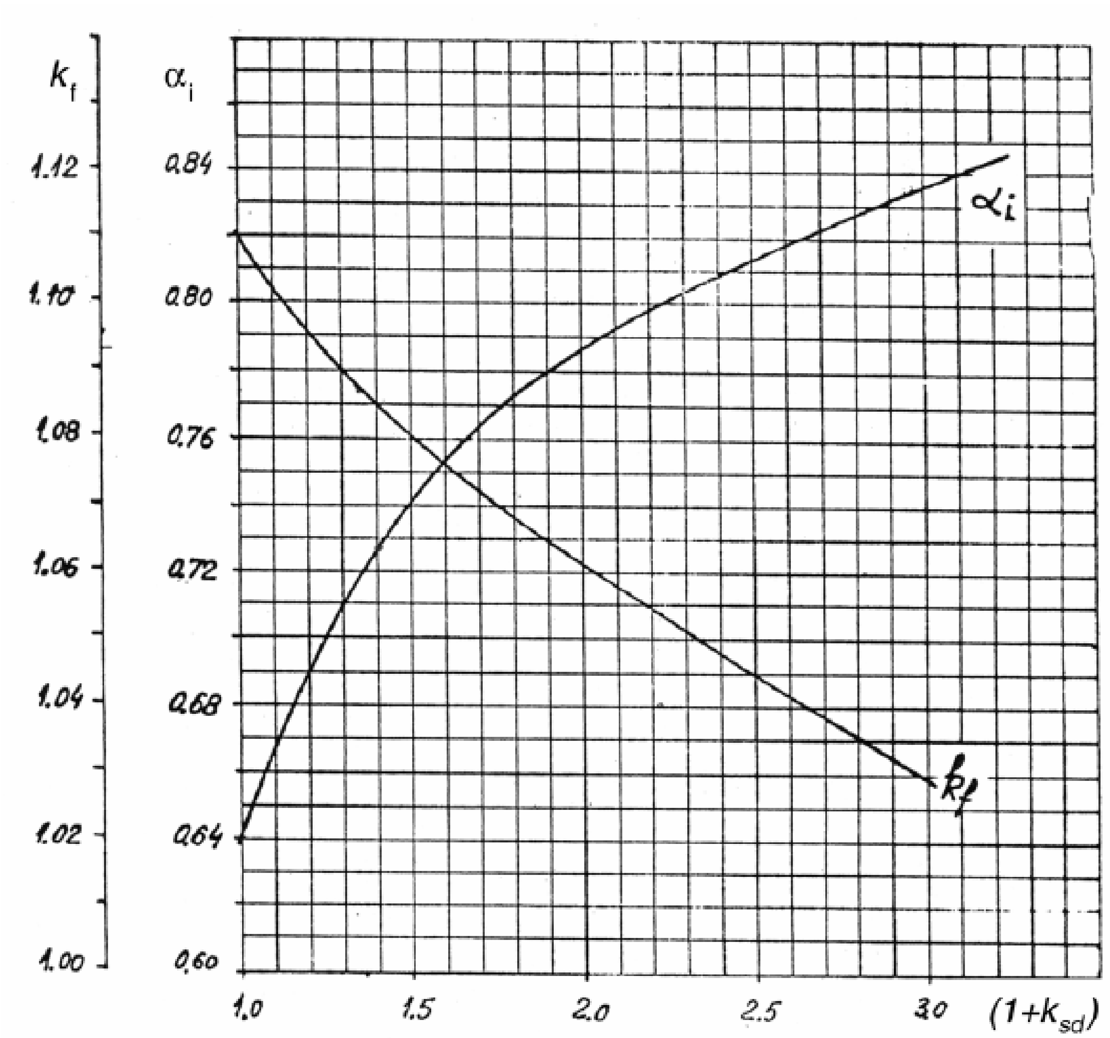
Multiplicaiton of distribution and pitch factors are called as winding factor.

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.

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 7.557 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 27 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 4.50 .
```

It should be an even number as there are two distinct coils per slot in a double layer winding. So ns is selected as 4.

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

```
Recalculated airgap flux density is 0.731 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 221.5 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 36.91 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 6.86 mm.
```

Because this diameter is not small, 20 conductors will be paralleled to decrase the diameter of each conductor.

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

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

```
Insulated wire gauge diameter is 1.60 mm.
```

Stator Slot Sizing

Since we know wire diameter, number of conductors in parallel and number of turns per slot, it is possible for us to calculate the slot area. Only missing parameter is fill factor selection. For round wire and at our rated power level it is advised to be taken between 0.4 and 0.44. So it is selected as 0.44. For useful area calculation formula (15.21) will be used:

$$A_{su} = \frac{\pi d_{co}^2 a_p n_s}{4K_{fill}}$$

```
Calculated useful slot area is 335.589 mm^2.
```

There are two recommended stator slot shapes in the book as follows:

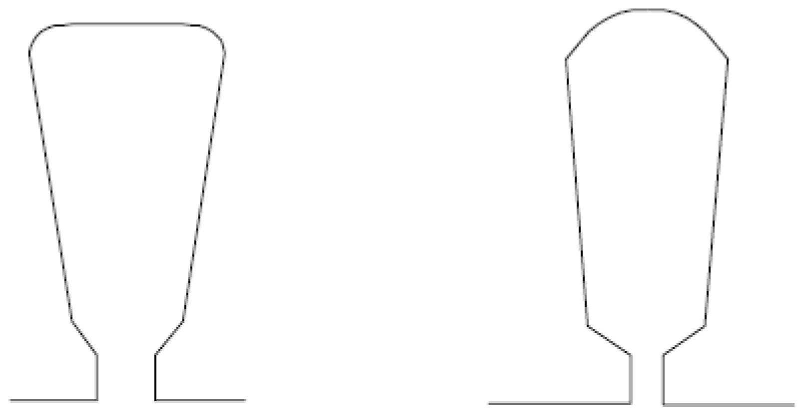


Figure 15.4 Recommended stator slot shapes

For ease of calculation and to be able to use explained slot geometry, left-hand side of stator slot shape is selected.

For this shape, explained lengths and are as in the figure below:

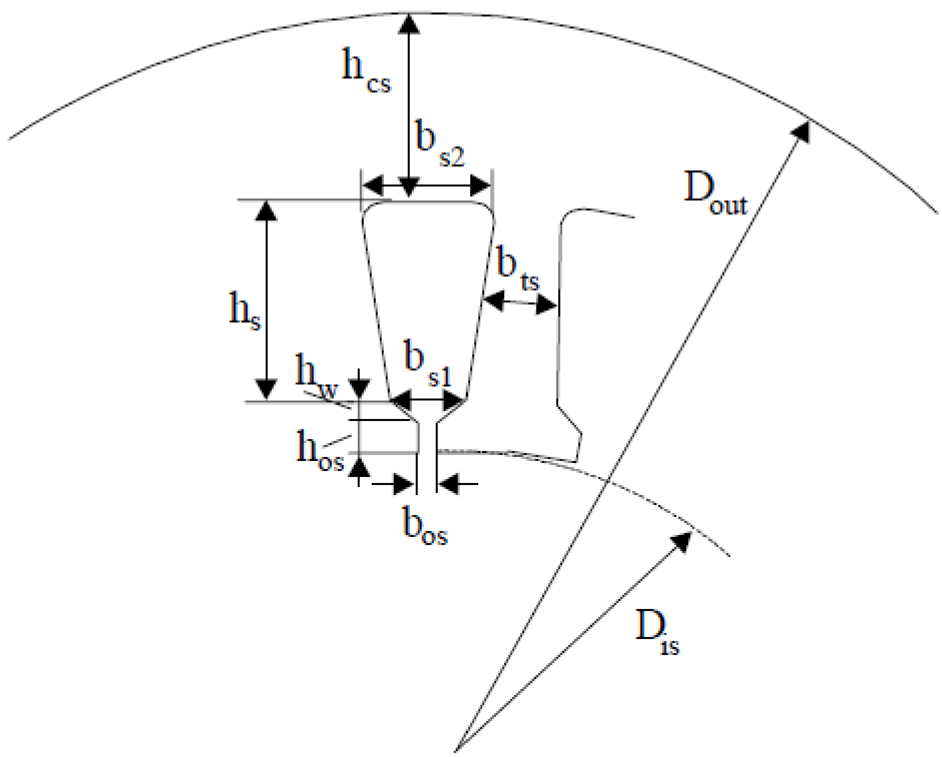


Figure 15.5 Stator slot geometry

Here, some parameters will be selected via following books' suggestions and some of them will be calculated.

Suggested variables are bos, hos and hw. bos can be defined as slot opening length and it is selected as 2 mm. hos is the height of slot opening and it is taken as 1 mm. hw is wedge height and it is selected as 3 mm.

Assuming that all the airgap flux passes through stator teeth:

$$B_g \tau_s L \approx B_{ts} b_{ts} L K_{Fe}$$

Here, Kfe is a constant to include lamination insulation's effect and suggested to be defined as 0.96. It is suggested to have a tooth flux density between 1.5 and 1.6 T. Let us take it as 1.6 T and determine bts:

Slot pitch isn't calculated yet, it is possible to use equation (15.3) for it.

$$\tau_s = \frac{\tau}{3q}$$

```
Slot pitch is 11.432 mm.

Tooth width is 5.442 mm.

It is better to take it as 5.4 mm.
```

For this value let us recalculate flux density of tooth:

```
Recalculated tooth-flux density is 1.61 Tesla.
```

This value is nearly inside the suggested range so acceptable.

With the variables we know, using equation (15.23) it is possible to calculate the slot lower width:

$$b_{s1} = \frac{\pi(D_{is} + 2h_{os} + 2h_w)}{N_s} - b_{ts}$$

```
Lower slot width is 6.7 mm.
```

At this point missing variables are slot height and upper slow width. If slot area's round corners are ignored and area is taken as a trapezoid, its are would be;

$$A_{su} = h_s \frac{b_{s1} + b_{s2}}{2}$$

Also, we have(15.25) formula as follows:

$$b_{s2} \approx b_{s1} + 2h_s tan\frac{\pi}{N_s}$$

From these 2 equations;

$$b_{s2} = \sqrt{4A_{su} tan\frac{\pi}{N_s} + b_{s1}^2}$$

```
Upper slot width is 12.7 mm.
```

$$h_s = \frac{2A_{su}}{b_{s1}+b_{s2}}$$

Slot height is 34.6 mm.

Now we can proceed in calculating mmf of airgap and teeth. The airgap mmf is:

$$F_{mg} \approx K_c * g * \frac{B_g}{\mu_0}$$

Here, Kc is the Carter's cofficient and it helps us to consider airgap surface as smooth and make our calculations directly. It is expected that it is greater but close to 1; its formula is:

$$K_c = \frac{\tau_s}{\tau_s - b_e}$$

$$b_e = K b_{os}$$

$$K = \frac{\frac{b_{os}}{g}}{5+\frac{b_{os}}{g}}$$

Carter coefficient is calculated as 1.07 .

Now airgap mmf may be calculated:

The airgap mmf is 417.163 Aturns.

Using tooth flux density and tooth's related heights we may calculate also mmf of stator tooth. Its formula is given with (15.30) and as follows:

$$F_{mts} = H_{ts}(h_s + h_{os} + h_w)$$

Only missing parameter is H of stator tooth and its value will be taken from table 15.4 of lamination magnetization curve.

H of stator tooth is selected as 2960 A/m for 1.61 Tesla.

So the stator tooth mmf is 114.256 Aturns.

Only missing dimension for stator side is its back core and this value may be calculated with the formula below (15.32):

$$h_{cs} = \frac{D_{out} - (D_{is} + 2(h_s + h_{os} + h_w))}{2}$$

Back core is calculated as 2.8 cm.

Here, we should take a look at to the flux density to avoid a saturation.

$$B_{cs} = \frac{\phi}{2Lh_{cs}}$$

Back core flux density is 0.86 Tesla.

This is an acceptable value, therefore outer diameter is OK with additional 5 cm.

Stator Resistance

For stator phase resistance formula (15.63) will be used.

$$R_s = \rho_{Co} \frac{l_c N_{ph}}{A_{co} a_1}$$

Here coil length includes the active part 2L and the end connection part 2lend

$$l_c = 2(L + l_{end})$$

End connection length depends on the coil span, number of poles, shape of coils and number of layers in the winding. For its calculation formula (15.65) will be used.

$$l_{end} = 2y - 0.02$$

Here, y is the coil span and can be calculated as

$$y = \beta\tau$$

In coil span formula, beta is chording factor and it is already selected as 5/6.

The end connection length is 15.1 cm

So the coil length is 61.3 cm

Another consideration for stator resistance is the copper resistivity. At room temperature its value is $1.7810^{-8}\Omega m$ and at 115 degree it increases 37%. Because we don't know the rated temperature yet and this value will be taken for 50 degrees.

The stator resistance is 8.857 mohm

Losses and Efficiency

Efficiency is the rate of output power to the input power. It is possible to describe input power as ouput +losses. So calculation the losses will hep us to calculate efficiency.

Let us start with stator winding losses. $P_{co} = 3R_s I_{in}^2$

Stator winding losses are calculated as 1.30 kW

Mechanical and ventilation losses are considered as 1.2% of rated power.

Mechanical losses are taken as 0.90 kW

For stray losses 1% of rated power will be taken as standard value.

Stray losses are taken as 0.75 kW

Remaining losses are core losses made of fundamental and additional (harmonic) iron losses. The fundamental core losses occur only in the teeth and back iron of the stator as the rotor frequency is low. Stator teeth fundamental losses are going to be calculated using formula (15.98)

```
Stator tooth weight is 8.71 kg

Stator teeth fundamental lose is 795.50 W
```

In a similar way, using (15.100) stator back iron fundamental losses are going to be calculated.

```
Yoke weight is 24.50 kg

Stator back core fundamental lose is 776.33 W

So the fundamental iron losses is 1571.84 W

Total iron loss is 1.66 kW

Total loss of the motor is 4.62 kW

Neglecting rotor losses, calculated efficiency is 94.20 %.
```

Thermal Design

First, the temperature difference between the conductors in slots and the slot wall is calculated.

http://www.engineeringtoolbox.com/overall-heat-transfer-coefficients-d_284.html

Once this website is checked, it is seen that for forced air cooling, convection coefficient is betweeen 100 and 200 depending on flow rate of the air and surface shape. Therefore this coefficient may be taken as 150 W/m^2K.

Another required coefficient is about conductivity. Following equation (15.24) it is taken as 822 W/m^2K.

Let us calculate the stator slot lateral area

$$A_{ls} \approx (2h_s + b_{s2})LN_s$$

```
It is calculated as 0.457 m^2.
```

If we take finn constant from equation (15.126) as 3;

```
Frame area calculated as 0.644 m^2.
```

Now we may calculate the temperature difference between conductors and slow wall:

```
This temperature change is 3.47 degree.
```

Supposing the ambient temperature as 30 degree, now we may calculate the winding temperature:

```
Winding temperature change is 47.80 degree.

In this case maximum temperature is 81.27 degree.
```

This value is acceptable since design is made for 80 degree maximum.

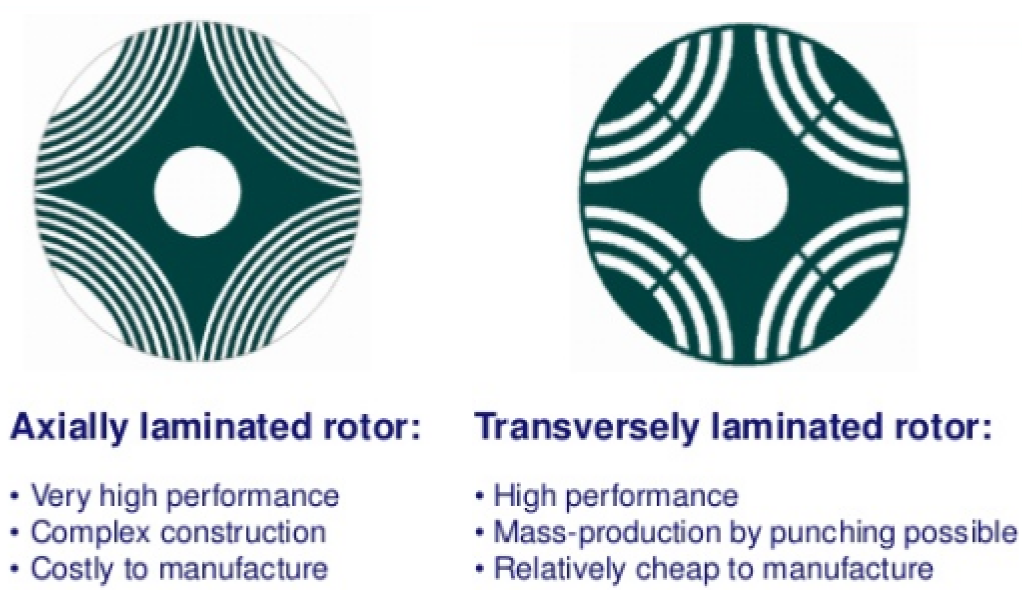
Syre Design and Simulations

After stator design and other calculations are completed using induction motor design guide, this stator is combined with a synchronous reluctance rotor, using Syre tool. Thanks to following three Master and Phd thessis from Sweden, lots of useful information are gathered:

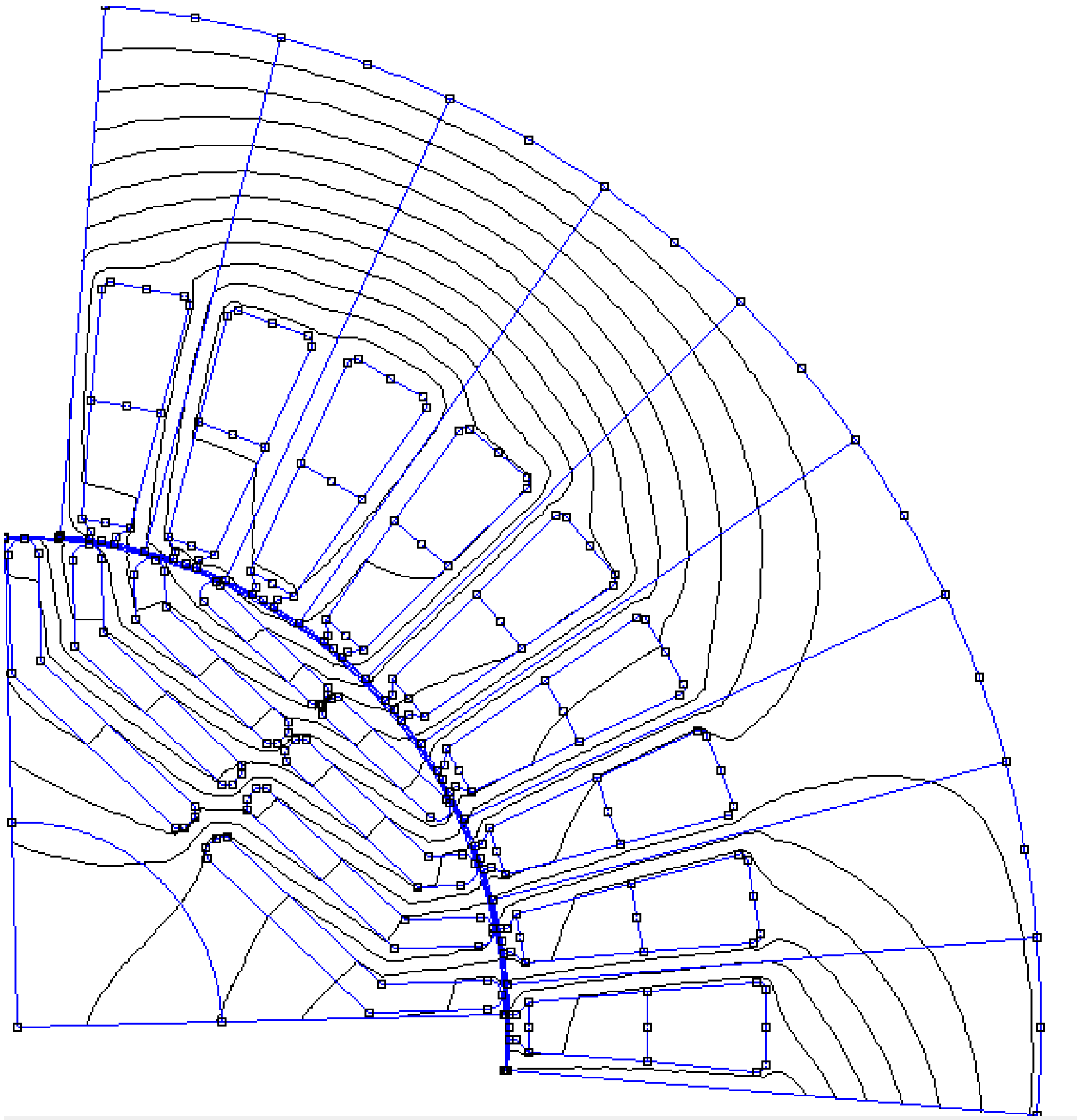
- Design of a Permanent-Magnet Assisted Synchronous Reluctance Machine for a Plug-In Hybrid Electric Vehicle
- Synchronous Reluctance Machine (SynRM) in Variable Speed Drives (VSD) Applications
- Synchronous Reluctance Machine(SynRM) Design

One of the suggestions is for deciding number of flux barriers. It is indicated that increasing flux numbers increases average torque. But after more than four or five of them, increase is saturated. So three and four selections are tried and four flux barriers are selected as final decision. Flux barrier widths are generated by Syre as per-unit and because it looks good and close to the all reference figures, Syre's values are kept; 4mm!

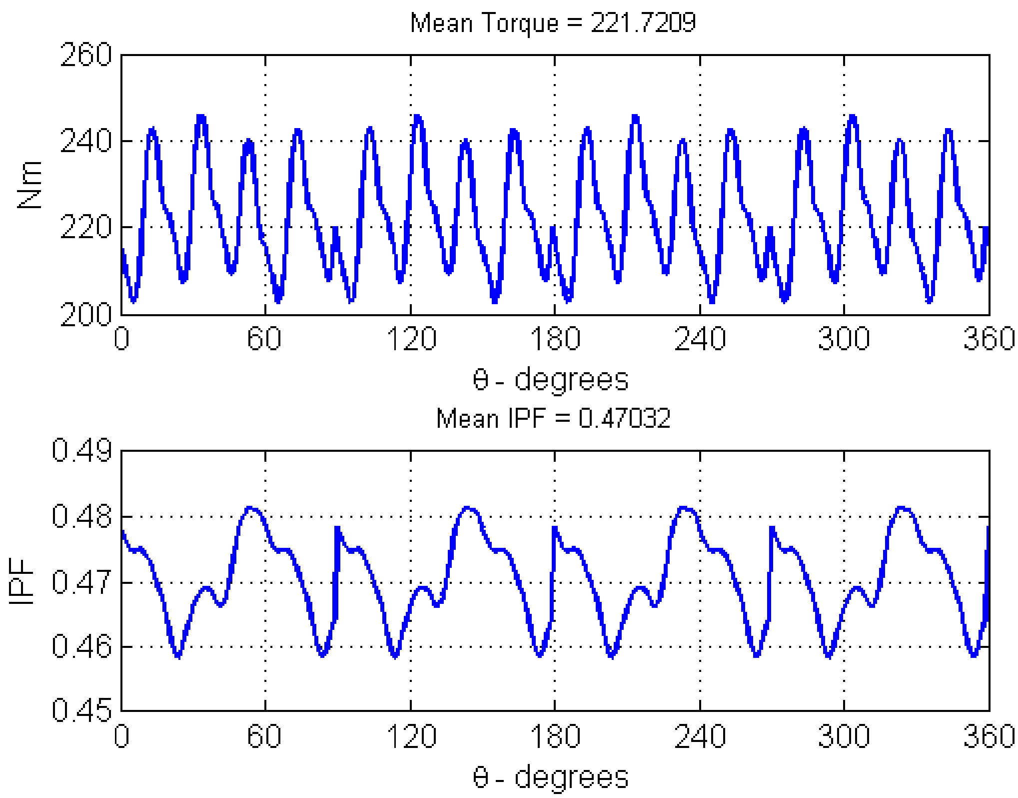
Other suggestion is about rotor's production method. Here are the two possible options and their comprasion:



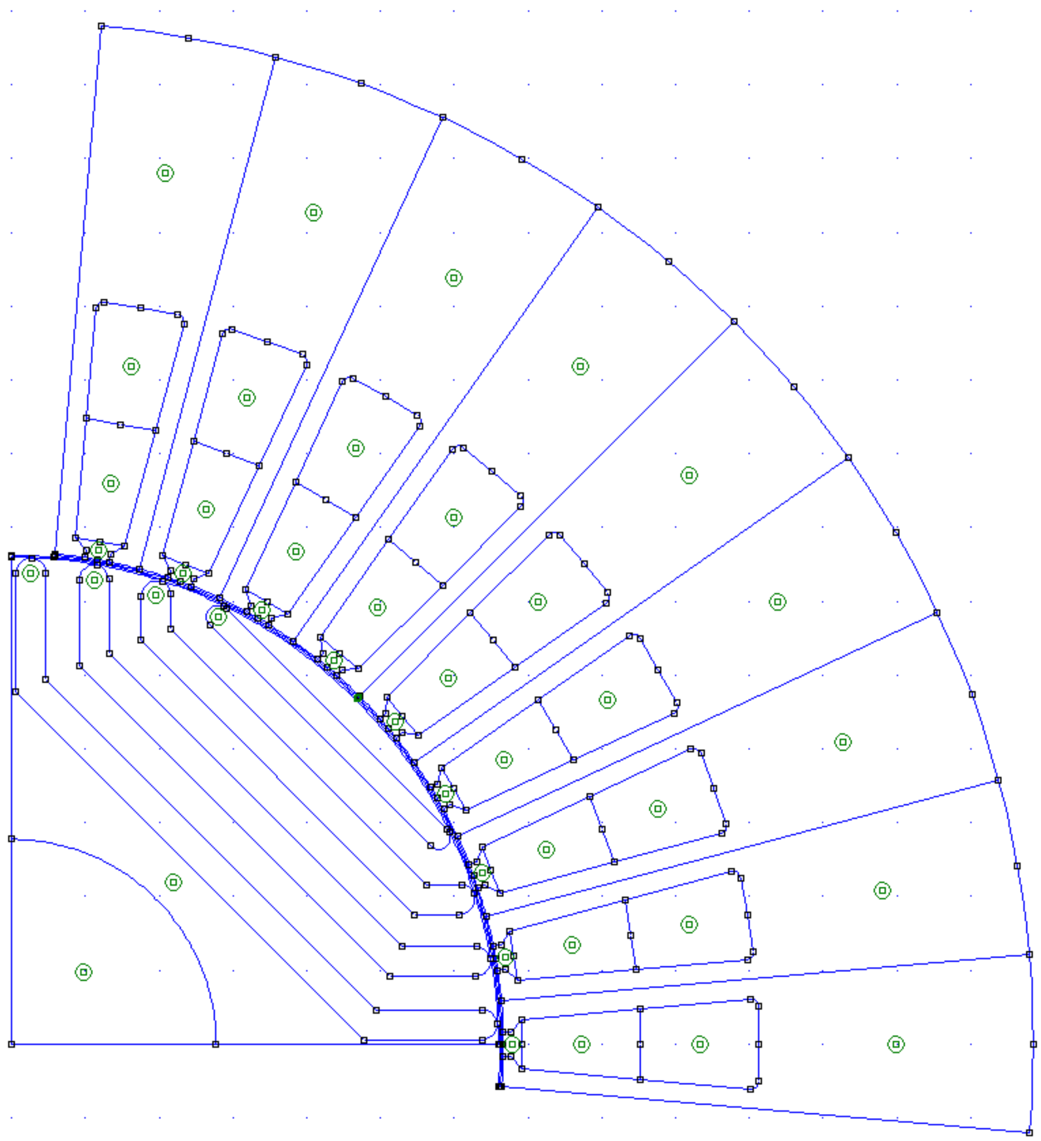
At this point, the problem about Syre tool is; after some size, it starts to create seperation in between flux barriers. So rotor behaves like it is transversely laminated. It is possible to understand it from machine's FEMM simulation results:



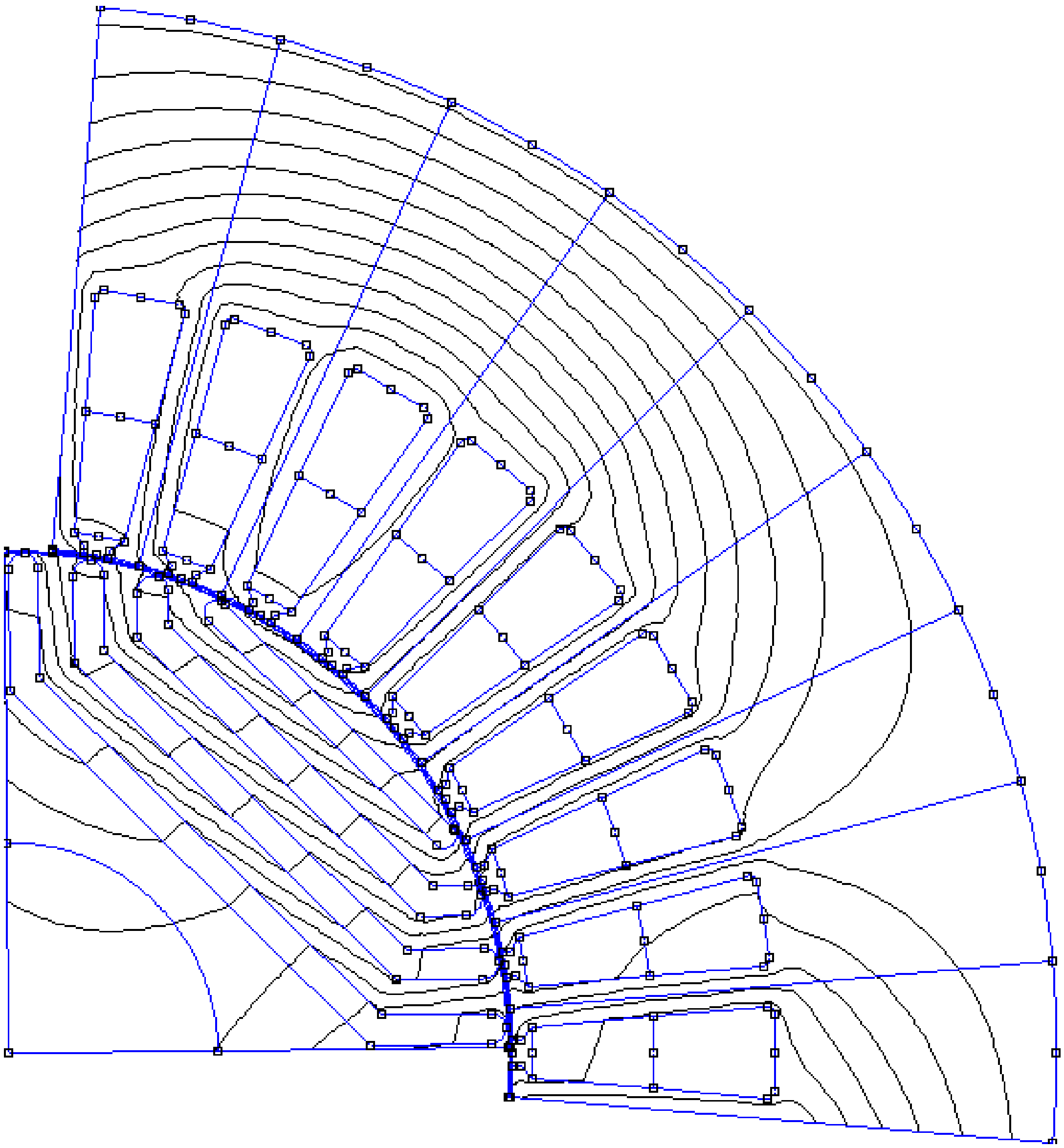
For this design its rated torque is simulated as 222 Nm:



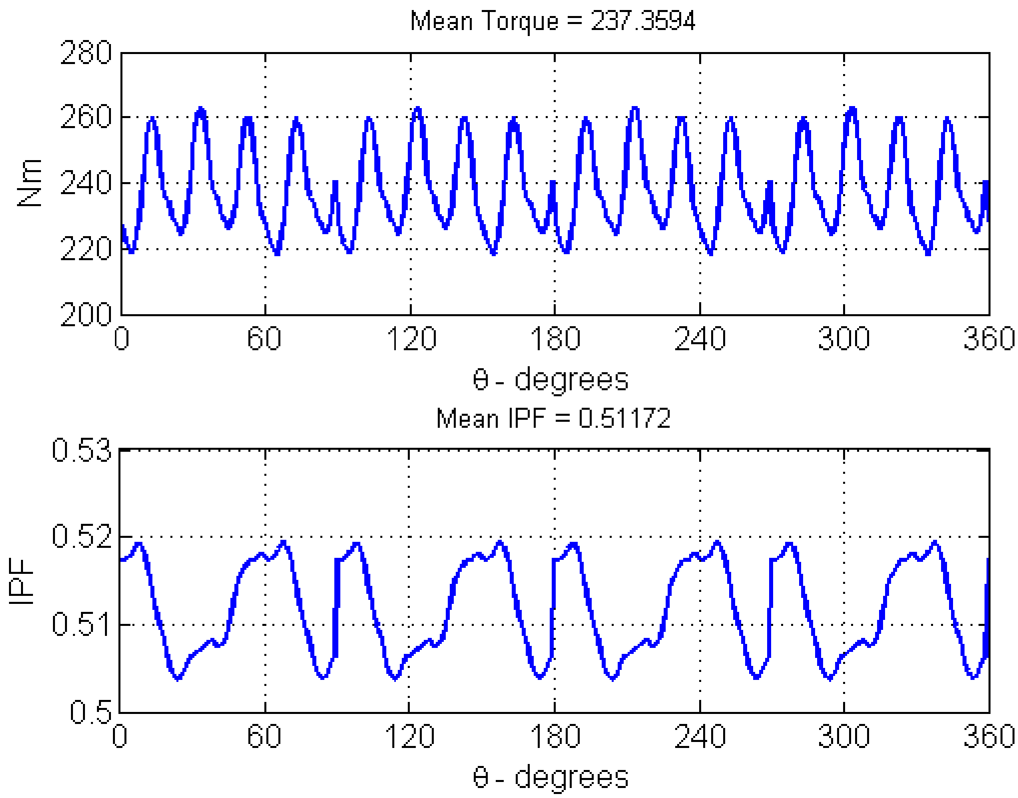
After a few tries, it is found out that if Syre's designed machine is saved and opened usign FEMM manually, it is possible to change it. So here, transversely laminated design is converted into axially laminated one to have better performance as it is promised.



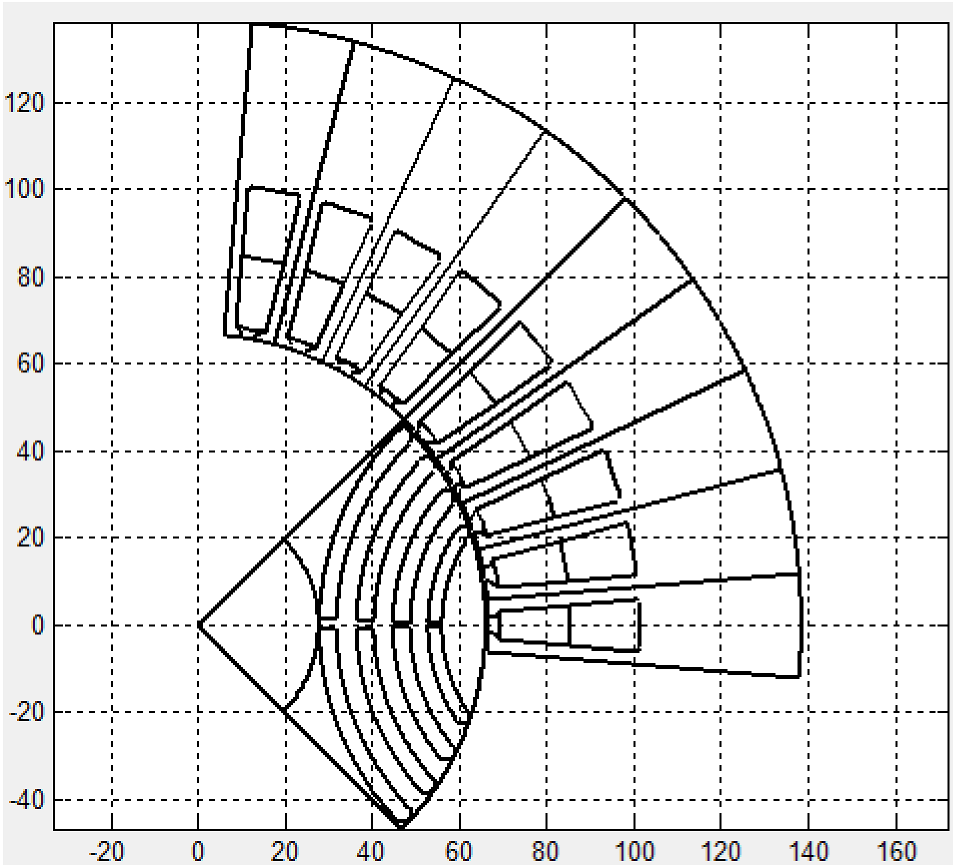
Once this design is saved over the Syre's design and simulation is re-run. This time flux path was different!



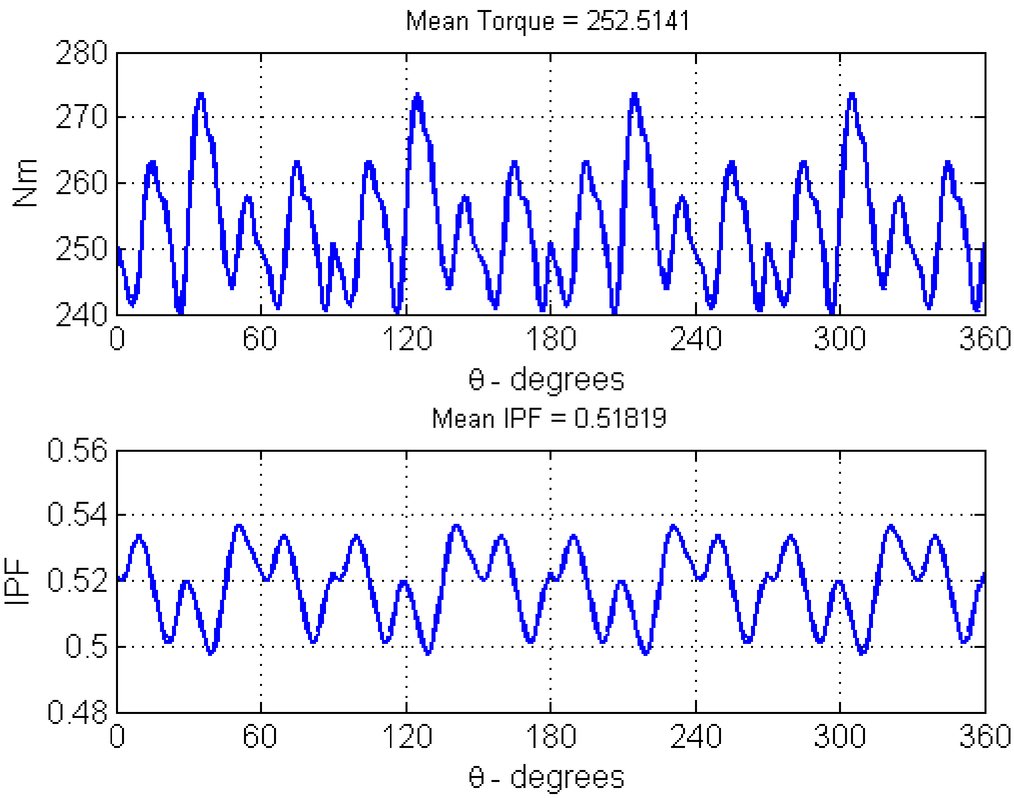
Performance is also better as it is promised and it is 237 Nm now.



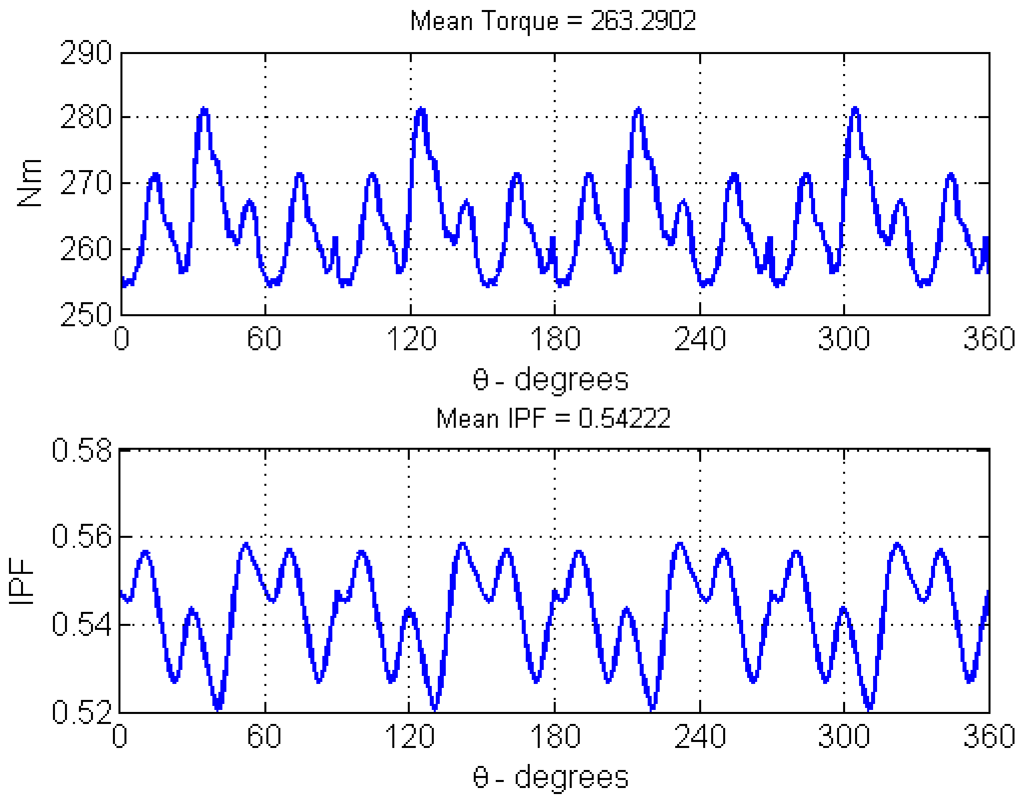
Since still it isn't sufficient enough to obtain desired torque, another suggestion is followed and design is converted from trapezoid flux barrier shape to circular shape.



First design, again was transversely laminated but nevertheless it simulated, aand bingoo! Resulting torque was 252 Nm.



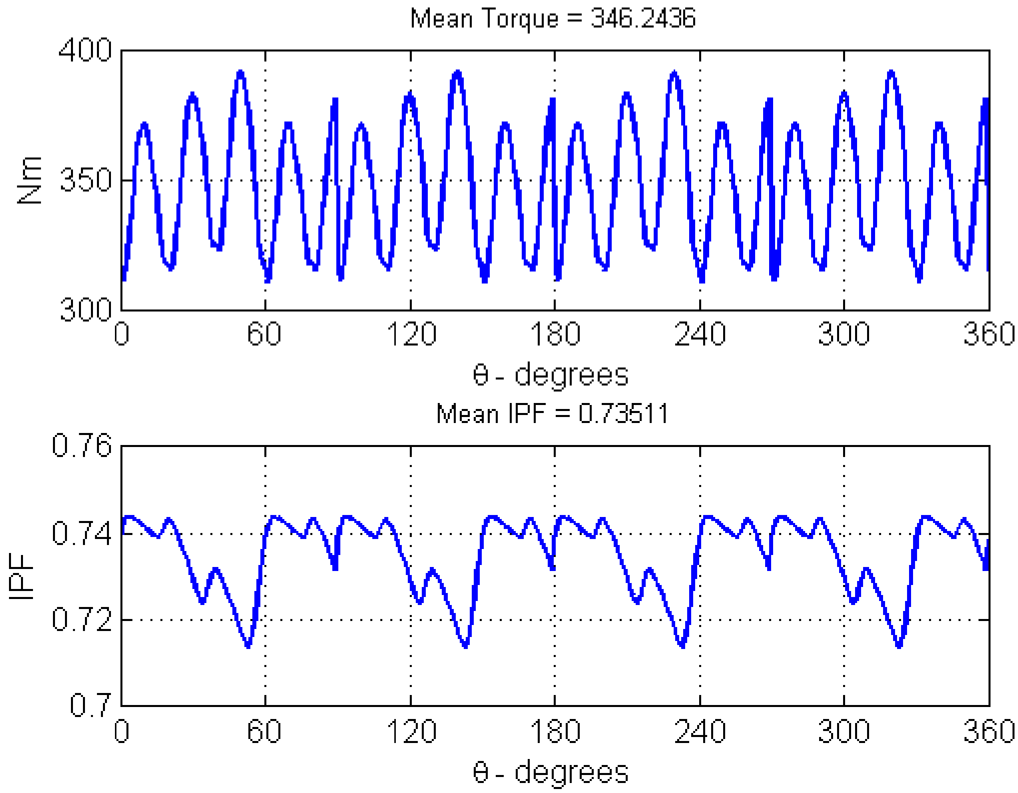
So here, it is possible to say that combining ease of production and better performance is possible with transversely-circullar lamination. Using same trick, design is converted into axially lamination and results are compared;



This time torque is increased to 263 Nm. Since this value is good enough for BMW i3 application another area; power factor is considered as Achilles heel. Until this point, all of the changes let power factor to increase but all of these values were below the desired level. So another suggestion is considered and permanent magnets are placed inside flux barriers. Since it wasn't possible to decide their lengths individually, 1/3 rate is accepted.

http://hyperphysics.phy-astr.gsu.edu/hbase/solids/magperm.html

In Syre's user guide, it is said that for permanent magnet placing purpose it is needed to enter magnet's remanence flux density value. For NdFeB magnet this value is 1.2 T but because not all of the barrier isn't replaced with magnet, remanence value is entered as 0.4 T.



With permanent magnet assisted synchronous reluctance motor torque is found as 346 Nm from simulation and this time power factor was also much more better. With this results, it is possible to say that having an even smaller motor is possible or better efficiency might be obtained from same sized motor. Since Nd and B are expensive elements, cheaper magnets with less remanence might be used to decrease the cost.

Published with MATLAB® R2013a