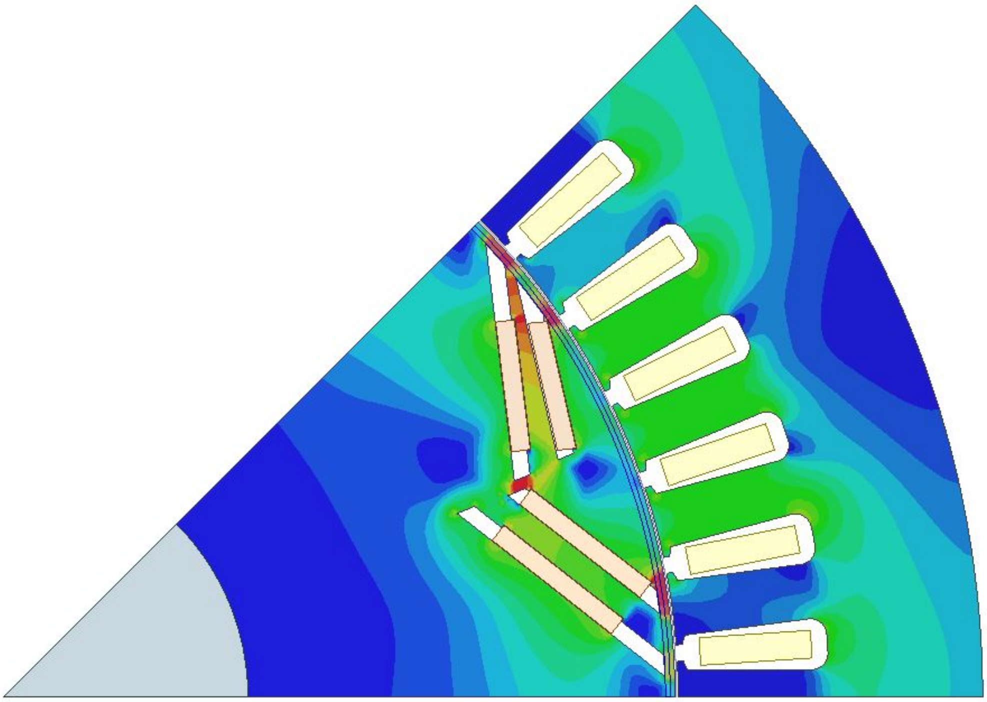

# Analysis of asymmetrical features of an electric machine

*Master of Scinecee Thesis*


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Cover: Magentic field of a modified rotor for an IPMSM at no-load conditions.

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# Abstract

This study was conducted to analyze the impact of asymmetrical features on the performance of an electric machine used for electric vehicles. The asymmetrical features were implemented through stator and rotor geometrical modifications. The performance of the asymmetrical features were compared to that of a similar symmetrical 2 layer interior permanent magnet synchronous machine. This reference machine was designed by finding the optimum combination of stator slot opening width, stator slot height, V-angle of the magnets and distance between the magnets that resulted in high torque and low torque ripple.

Stator modifications include modifying the stator slot shape and changing the stator slot opening position. A rectangular stator slot was used to assess the effect of the stator slot shape. To study the impact of the stator slot opening position, it was moved sequentially to the left and right side of the stator slot, and then the slot opening position was altered between the adjacent stator slots.

Rotor modifications comprises of intra-polar asymmetry, asymmetry between the flux barriers and adding air slots or gaps in the rotor. Intra-polar asymmetry includes placing the magnets close to the rotor surface one at a time and increasing the concentration of magnets in one side of the barriers. Asymmetry between the flux barriers comprises of having two different V-angles for each layer and designing the flux barriers so that no two flux barrier end face the stator at the same location.Additionally, rectangular air slots were added near the rotor surface.

The results indicate that moving the stator slot opening position to the right in motor mode and introducing rectangular air slots in the rotor improve the performance of the machine when compared to the optimized reference machine but only to a limited extent. In order to achieve a desirable performance from such asymmetrical features, further geometrical optimization and a control strategy is required.

Keywords: Electric Machine, IPMSM, geometrical modifications, EV, asymmetrical electric machine.

# Acknowledgements

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Tamanna Zahangir, Gothenburg, October, 2018

# List of Abbreviations

| | |
|---|---|
| EV | Electric Vehicle |
| FEA | Finite Element Analysis |
| IPMSM | Interior permanent magnet synchronous machine |
| MTPA | Maximum torque per ampere |
| SPMSM | Surface mounted permanent magnet synchronous machine |
| SynRM | Synchronous reluctance machines |

# Contents

# Chapter 1

# Introduction

With the acceptance of electric vehicles(EV) as the key player in the future of transportation, a lot of research is carried out into making them more cost efficient. Most EVs convert 59% to 62% electrical energy from the grid to propel the wheels [?]. However, EVs require system-wise optimization to be cost-competitive compared to conventional internal combustion engine cars. Electrical machines play a key role in making EVs more cost effective. The machine converts the electrical energy of the battery to the mechanical energy that propels the wheel. At the same time, it acts as a generator during regenerative braking [5]. In a nutshell, the electric machine is the heart of the propulsion system.

In this project, the effects of asymmetrical features on the performance of an electric machine are analyzed. The analysis was carried out by comparing the torque and torque ripple of a machine with asymmetrical features to that of a similar symmetrical reference machine. A two layered interior permanent magnet synchronous machine (IPMSM) was used as the reference machine. The asymmetrical features were implemented through geometrical modifications. The reference machine and the subsequent asymmetrical features were modeled and analyzed with ANSYS Maxwell.

## 1.1 Background

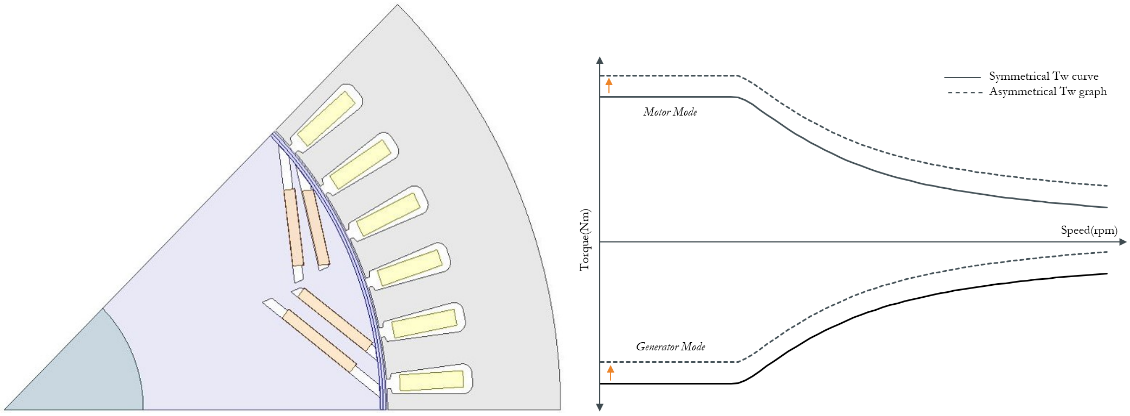
Unlike industrial electric machines, electric machines for EV have to meet specific requirements. The later must have high torque and power densities, increased field weakening capabilities, high efficiency in low to medium torque ranges, reliability, good noise, vibration and harness, mass manufacturing capabilities and most importantly, low cost solutions [7]. No single type of electric machine alone can meet all these specifications. Additionally, optimizing for one characteristic often adversely affects the other. This is why it is important to be strategic in the selection and design an electric machine for an EV.

The selection of an electric machine is based on the performance requirement of a vehicle such as mean torque, torque ripple, efficiency of the machine, vs the system cost. As described in [2], the cheapest and most reliable option would be to use induction machines(IM). The ability to control the rotor flux makes them competitive for high speed region application. However, current through the rotor means high losses. The alternative is to opt for synchronous machines. These include, electrically magnetized synchronous machines, synchronous reluctance machines(SynRM), permanent magnet synchronous machines(PMSM), axial flux machines and transverse flux machines. Among these, SynRMs and PMSMs are popular choices to be used in EVs. SynRMs produce torque through the reluctance effect of machine avoiding the use of permanent magnets or windings in the rotor. These machines have high torque ripple. Additionally, the design of a SynRM require high precision. The other option is to use a PMSM where torque is primarily produced from the permanent magnets in the rotor. Based on the location of the magnets, PMSMs can be divided in two categories: Surface mounted permanent magnet synchronous machine (SPMSM) and Interior permanent magnet synchronous machine(IPMSM). As the name suggests, SPMSM have magnets mounted on the surface on the rotor. This configuration utilizes the magnets most efficiently as they are placed close to the airgap. However, they require high current for field weakening which can permanently demagnetize the magnets. IPMSMs have the magnets inserted inside the rotor. This configuration allows them to utilize torque from both the permanent magnets and reluctance of the machine. IPMSMs offer high reliability, overload capability and a wide field weakening region. The combination of all these factors makes IPMSM the most common electric machine for EV.

A major drawback for an IPMSM is high torque ripple which is a result of non-uniformity of the developed torque. As the rotor advances during rotation, the torque changes causing deviation from the sinusoidal flux distribution in the air gap [6]. This non-sinosodial distribution is due to the interaction of rotor and stator flux in the airgap.

The torque ripple in an IPMSM is addressed in two ways, either through improved control methods or through modified machine designs [10]. An improved control algorithm is the most efficient way to reduce torque ripple. They usually reduce torque ripple by compensating for the parasitic phenomenon [13]. However, implementing such control algorithms adds cost and complexity to the system. On the other hand, the design of an IPMSM can be modified to reduce torque ripple. Such design modifications include skewing the rotor, finding the optimal slot/pole ratio, reshaping the rotor surface and so on. However, each of the design modifications is aimed at optimizing one certain factor. Optimizing the design of IPMSM to reduce torque ripple can lead to a decrease in mean torque. Therefore, the design of an IPMSM has to balance between high mean torque and low torque ripple along with low losses.

There are many papers and journals published on design optimization of an IPMSM, however, almost all of them have been evaluated from a symmetrical point of view. Very little research is carried out into investigating the asymmetrical




(a) (b)

**Figure 1.1:** Asymmetrical features (a)Design asymmetry and (b)T-$\omega$ asymmetry

aspects of an IPMSM. In this project, asymmetry is realized by making design modifications that would lead to asymmetrical behavior in the torque-T-$\omega$ characteristic of an IPMSM. The intention is to analyze whether introducing asymmetry into the machine allows some sort of design freedom in the design of an IPMSM.

Figure 1.1(a) demonstrates an example of a design asymmetry in IPMSM whereas figure 1.1(b) demonstrates the asymmetrical nature of the torque-speed characteristic of a PMSM. Generally, an IPMSM is designed to have similar geometry for all the poles of the machine. The torque-speed characteristic is symmetrical around the speed axis. In this project, the design medications that can lead to asymmetrical T-$\omega$ characteristic will be analyzed. It can be implemented where modifying a symmetrical design or by design asymmetry. Design asymmetry can be implemented in one of two ways, inter-polar asymmetry and intra-polar asymmetry. Inter-polar asymmetry implies that there is asymmetry within the same pole. Inter-polar asymmetry means that the poles of the machines are not identical to one another. Asymmetry in torque-speed characteristic is related to torque being asymmetrical around the speed axis. An electric machine designed for EV spends most of time in motor mode and less in generator mode. Therefore, it is worth investigating whether any geometrical change would shift the torque-speed characteristic to favor the motor mode. This would make the torque-speed characteristic asymmetrical around the speed axis.

There are many possible ways to implement the above mentioned asymmetry in the design of an IPMSM. In this project, the changes are limited to stator modifications and rotor modifications. The modifications were made to a reference machine. The reference machine used in the case is a two-layer IPMSM. The average torque and torque ripple from the each of the modified designs were compared to that of the reference machine.

## 1.2 Purpose and Task

The purpose of the project is to study and analyze the effects of different asymmetrical features on torque and torque ripple of an IPMSM. The performance of such modified design can be analyzed by:

1. Modeling and verifying a typical IPMSM used for EV in FEA software, ANSYS Maxwell. This machine is known as reference machine.
2. Optimizing the design of the reference machine so that it produces high mean torque and low torque ripple.
3. Finalizing the design modifications to be implemented on the reference machine and would lead to asymmetrical features.
4. Modelling and verifying each of the modified designs in ANSYS Maxwell.
5. Optimizing each of the modified design so that it produces high mean torque and low torque ripple. This is done by finding current angle corresponding to the MTPA curve for each of the design.
6. Comparing the torque and torque ripple of each of the modified design to that of the optimized reference machine.

## 1.3 Scope

The scope of the project is limited to comparing torque and torque ripple of the reference machine and the subsequent modified designs at 1000 rpm. The aim is to understand the impact of asymmetrical features on the performance of an electric machine rather than optimizing the design of an asymmetrical electric machine.

The reference machine chosen is a 2-layered IPMSM intended for EV with distributed windings. The effect of winding distribution and number of flux barrier were not included in the study.

Owing to time constraints, the design modifications were only limited to intra-polar asymmetry. This implies that the same asymmetrical feature would be applied to all the poles.

The performance analysis will not include the impact of design modifications on the losses of the machine. This is because at 1000 rpm, copper loss is substantially higher than core losses. The reference machine and the subsequent modified machines have the same amount of copper and hence, similar copper losses. In order to understand the effect of geometrical modifications on losses, the machine needs to be simulated for every speed between 0-14000 rpm. This was not feasible within the time frame of the project.

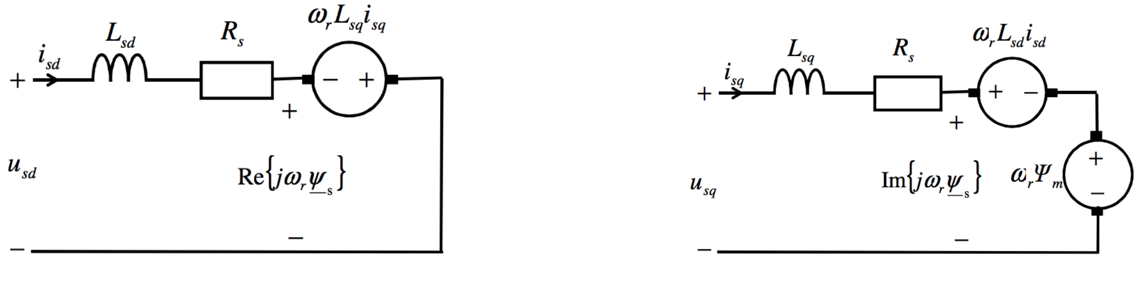
# Chapter 2

# Theory

The design modifications made in this project are not based on any one theory. The results of the analysis can be understood by speculations. The aim of this chapter is to provide provide knowledge to interpret the results of the analysis.

## 2.1 Circuit model of an IPMSM

The equivalent circuit model of an IPMSM can be represented in figure 2.1 where $u_{sd}$ and $u_{sq}$ are stator voltages in dq frame, $i_{sd}$ and $i_{sq}$ are the current in dq frame, $L_{sd}$ and $L_{sq}$ are inductance in d and q direction respectively, $R_s$ is the stator resistance, $\omega_r$ is the electrical rotor speed, $\Psi_m$ is the flux linkage among the magnets.




(a) (b)

**Figure 2.1:** Equivalent circuit model of an IPMSM in (a)d-frame and (b) q-frame[12]

Based on the circuit, the stator equations can be derived as

$$L_{sd}\frac{di_{sd}}{dt} = u_{sd} - R_s i_{sd} + \omega_r L_{sq} i_{sq} \tag{2.1}$$

$$L_{sq}\frac{di_{sq}}{dt} = u_{sq} - R_s i_{sq} - \omega_r (L_{sd} i_{sd} + \Psi_m) \tag{2.2}$$

Flux linkage, current and inductance are related as

$$\Psi_d = L_{sd} i_{sd} + \Psi_m \tag{2.3}$$

$$\Psi_q = L_{sq} \tag{2.4}$$

$$|\Psi_s| = \sqrt{{\Psi_d}^2 + {\Psi_q}^2} \tag{2.5}$$

where $\Psi_d$ and $\Psi_q$ are flux linkage in d and q direction respectively. Therefore, electromagnetic torque can be derived as

$$T_e = \frac{3n_p}{2}(\Psi_m i_{sq} + (L_{sd} - L_{sq})i_{sd}i_{sd}) \tag{2.6}$$

where $n_p$ is the number of pole pairs.

## 2.2 Maximum Torque Per Ampere

As described in [4], maximum torque per ampere (MTPA) is a control method that results in maximum torque while minimizing the current. As torque is a function of $i_{sd}$ and $i_{sq}$, different combinations of $i_{sd}$ and $i_{sq}$ can be used to produce the same amount of torque while minimizing the losses.

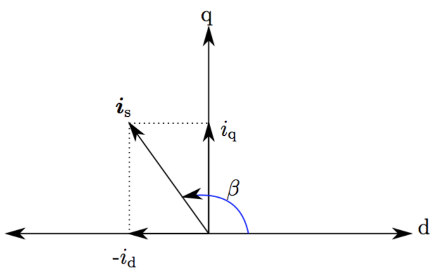



**Figure 2.2:** Current Angle[14]

From figure 2.2, the following equation can be derived:

$$i_{sd} = |i_s| cos\beta \tag{2.7}$$

$$i_{sq} = |i_s| sin\beta \tag{2.8}$$

where $\beta$ is the current angle. Substituting (2.7) and (2.8) in (2.6), the following can be concluded:

$$cos\beta = -\frac{\Psi_m}{4(L_{sd} - L_{sq})|i_s|} - \sqrt{\frac{1}{2} + (\frac{\Psi_m}{4(L_{sd} - L_{sq})|i_s|})^2} \tag{2.9}$$

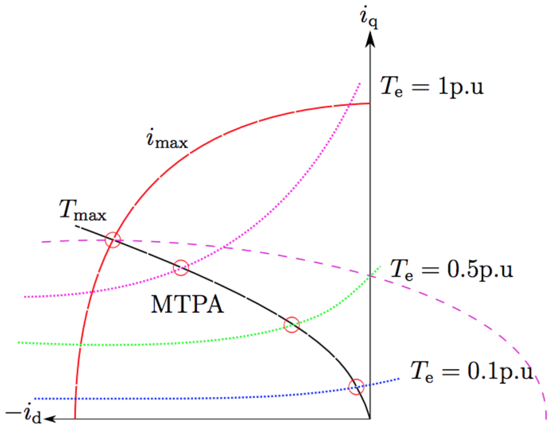



**Figure 2.3:** MTPA[14]

Figure 2.2 shows the constant torque lines plotted with current limit. The current angle can be found by finding point where constant torque lines intersect the current limit. As mention in [1], 2.9 accounts for non-linear current dependencies of $L_{sd}$,$L_{sq}$ and $\Psi_m$ on $i_sd$ and $i_sq$.

# Chapter 3

# Case set-up

This chapter includes the methodology for modelling and optimizing the reference machine and subsequent modified designs in ANSYS Maxwell. The analysis setup for ANSYS Maxwell is discussed as well. It also includes a description of all the design modifications.

## 3.1 FEA Software-Ansys Maxwell

In ANSYS Maxwell, the reference machine and the modified designs were modelled for 1/8th of the original machine. This is because Maxwell can be made to assume symmetry and repeats the same behavior for the rest of the machine.

An appropriate mesh size was needed for proper electromagnetic calculation. For the stator and rotor, 2 mm mesh was used. However, the magnetic saturation is high near the surface of the rotor where the magnets end. Therefore, a mesh of 1 mm was used near the surface of the rotor to get an accurate representation of the saturation.

For ensuring an accurate data representation, the data sampling rate needed to be determined. This was done by sampling the torque from the reference machine at 600 samples per line period, 120 samples per line period and 60 samples per line period.

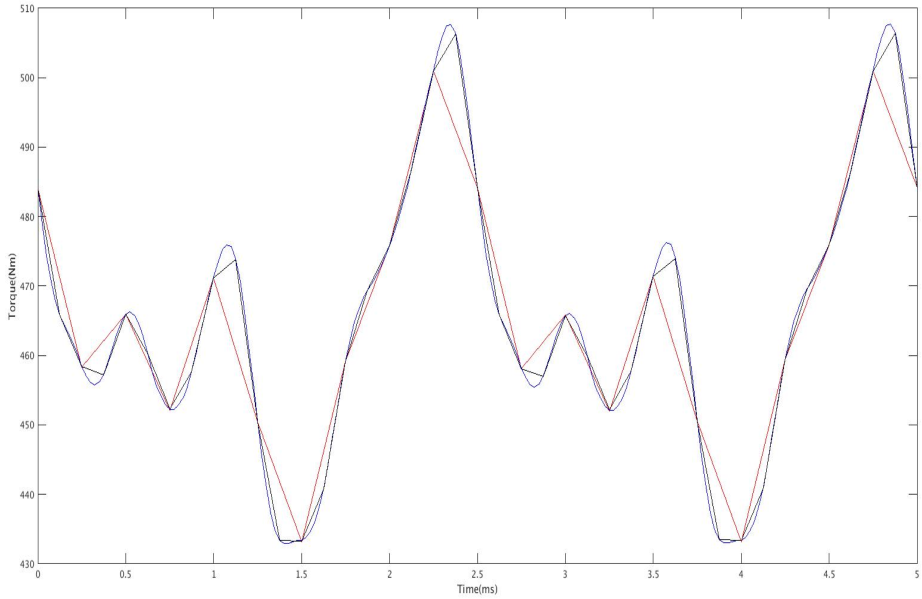



**Figure 3.1:** Torque from reference machine sampled at 60 samples per line period (red), 600 samples per line period(blue) and 120 samples per line period(green)

As it can be seen from figure 3.1, 600 samples per line period produces the most accurate data. However, sampling at such high rate slows down the simulation time. On the other hand, simulating at 60 samples per line period takes comparatively shorter time. However, this sampling rate is not enough as it misses peak torque data points. At 120 samples per line period, the simulation run time is fast enough and captures most of the key data points. Therefore, a sampling resolution of 120 samples per line period is selected.

## 3.2 Method

To compare the torque and torque ripple of asymmetrical features, a reference machine suited for EV application was selected. The reference machine was modelled and evaluated in ANSYS Maxwell. The electromagnetic properties of the reference machine were verified.

The design of the reference machine was then optimized. This included finding the optimal V-angle, the distance between the two flux barriers, the stator slot height and the stator slot opening width that would result in high mean torque and low torque ripple. By means of Maximum Torque Per Ampere(MTPA),the current angle for the reference machine was determined. The torque and torque ripple of the reference machine was then obtained from ANSYS Maxwell.

Asymmetrical design changes were made to the reference machine. These design changes were implemented through a python script that made those geometrical changes in ANSYS Maxwell. Each design was then optimized by finding the current angle for the corresponding MTPA curve. The resultant torque and torque ripple from each of the modified designs was then compared to that of the optimized reference machine.

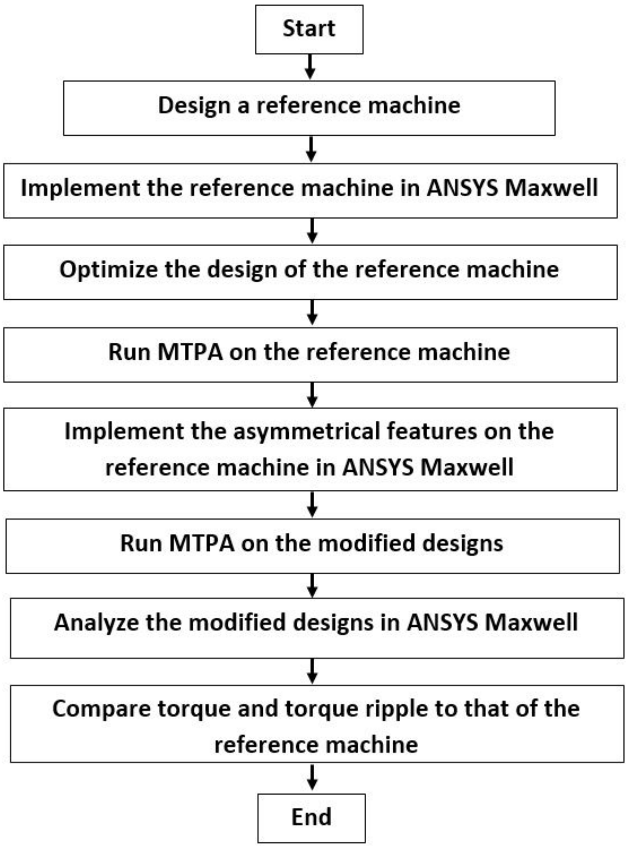



**Figure 3.2:** Method for analyzing asymmetrical feature of an IPMSM

Figure 3.2 describes the methodology used to analyze the impact of asymmetrical designs on the performance of the machine. These design changes can be categorized in two ways, stator modifications and rotor modifications.When stator modifications were made, the rotor that was used in the design was that of the reference machine's rotor and vice versa. Certain parameters, namely the outer diameter, active length, no. of poles, no of flux barriers, maximum voltage and current to be supplied to the windings, and airgap length were held the same between the reference machine and subsequent modified designs.

## 3.3 Reference machine

The reference machine is inspired from a typical electric machines used for EV and the parameters can be found in table3.1. The reference machine design was optimized by finding the optimal V-angle between the flux barriers,the distance between the flux barriers, stator slot height and stator slot opening width. The current angle corresponding to the MTPA was found and the reference machine was implemented and evaluated using ANSYS Maxwell. The performance of the optimized reference machine is presented in table 3.2. The torque ripple is described both in % and peak to peak to get an accurate representation of torque ripple.

**Table 3.1:** Parameters of the reference motor

| Parameter | Value |
|---|---|
| Voltage | 350V |
| Current(RMS) | 600A |
| Outer Diameter | 545mm |
| Length | 164.4mm |
| No of Pole Pair | 4 |
| Stator Slots | 48 |
| Maximum Speed | 14000rpm |

**Table 3.2:** Performance of the reference motor

| Parameter | Value |
|---|---|
| Torque | 470.64 Nm |
| Torque Ripple(%) | 13.64 % |
| Torque Ripple (p2p) | 64.31 Nm |

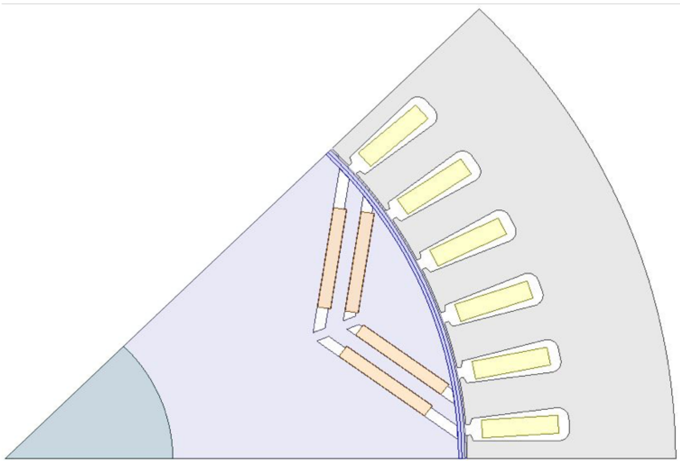


**Figure 3.3:** Reference Machine

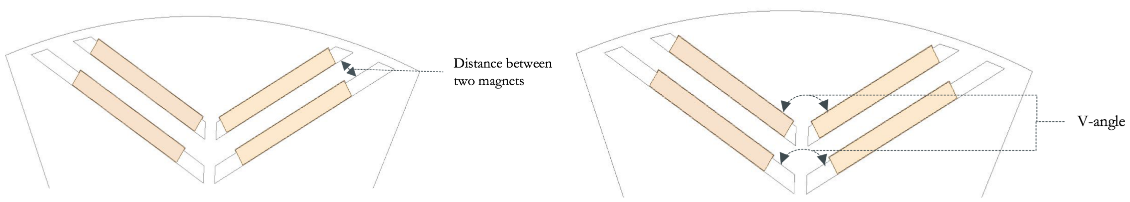
Figure 3.3 represents the optimized reference machine. It is modelled for 1/8 of the size in ANSYS Maxwell. The torque and torque ripple achieved from Maxwell is used as a reference point to compare the performance of asymmetrical features.

### 3.3.1 Optimization

The design of the reference machine includes an optimized stator and rotor. The rotor was optimized by finding the most favorable distance between the layers of flux barriers and the V-angl. The stator was optimized by finding the right stator slot opening width and stator slot height. For each of the optimization,the optimal parameter was determined by comparing torque and torque ripple at different values.

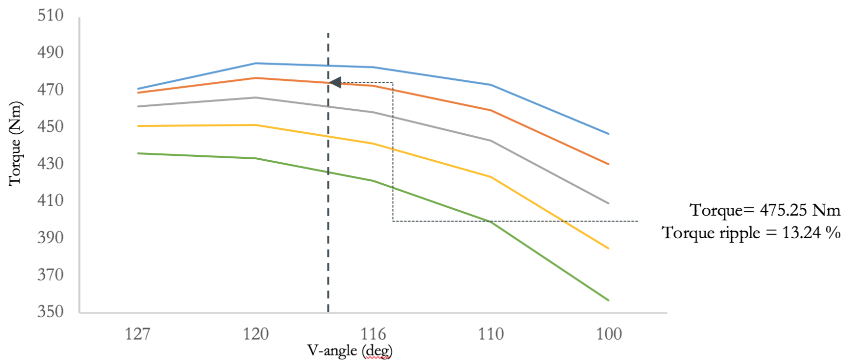
### 3.3.2 Rotor Optimization

The rotor was optimized by finding the V-angle and the distance between the flux barrier where torque is sufficiently high and torque ripple is low. Both the flux barrier layers are designed to have the same V-angle. The distance between the flux barrier were swept from 2 mm to 6 mm at an increment of 1 mm and the V-angle were swept from 100 deg to 127 deg.

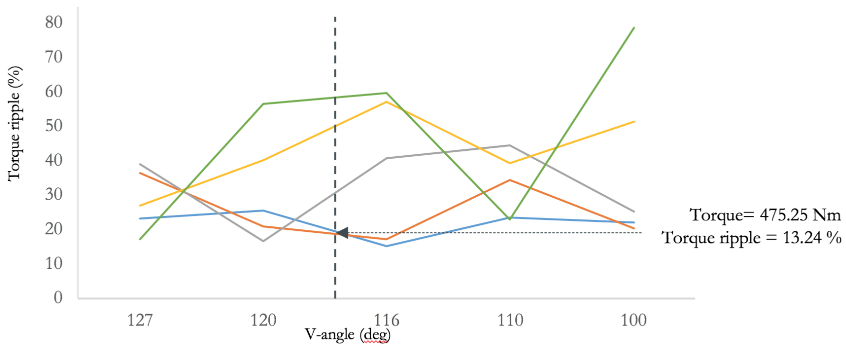



(a) (b)

**Figure 3.4:** Rotor Parameter (a)Distance between two magnets in reference machine and (b)V-angle in reference machine




**(a)** Torque




**(b)** Torque ripple

**Figure 3.5:** Torque and Torque Ripple different V-angle and magnet distance. The distance between the magnets are 2 mm(blue), 3 mm(red), 4 mm(grey), 5 mm(amber), 6mm(green)

Figure 3.4 identifies the V-angle and the distance between the magnets whereas figure 3.5 shows the torque and torque ripple as a function of V-angle and distance between the magnets. As it can be seen from figure 3.5(a), torque is directly proportional to the distance between layers of the magnets. Therefore, torque is highest at the smallest distance which is 2 mm. This is expected as closer layers would mean concentrated flux towards the ends of the magnets resulting in higher torque. As a function of V-angle, torque is highest at 118 deg. This angle is determined by the position at which the ends of each flux barrier would meet the stator slot opening.

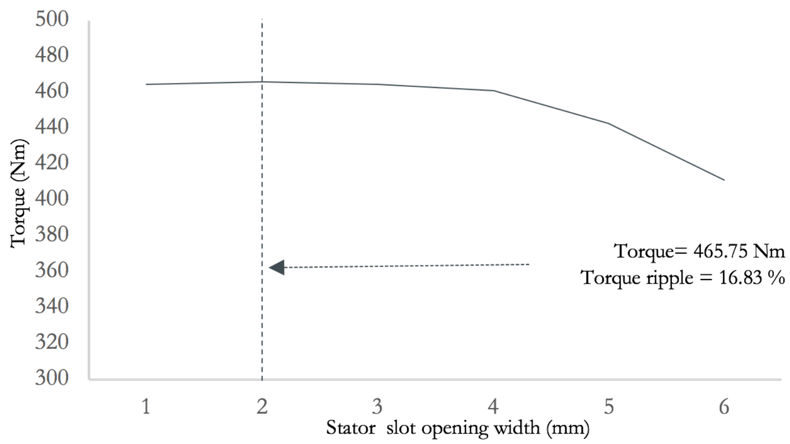
Figure 3.5(b) shows that torque ripple as a function of the same V-angle and distance between the magnetic layers. In order to get the lowest torque ripple, the distance of 3 mm between the magnets and a V-angle of 118 deg were chosen. At these points, the torque is at 475.25 Nm and torque ripple is at 13.24%.

### 3.3.3 Stator Optimization

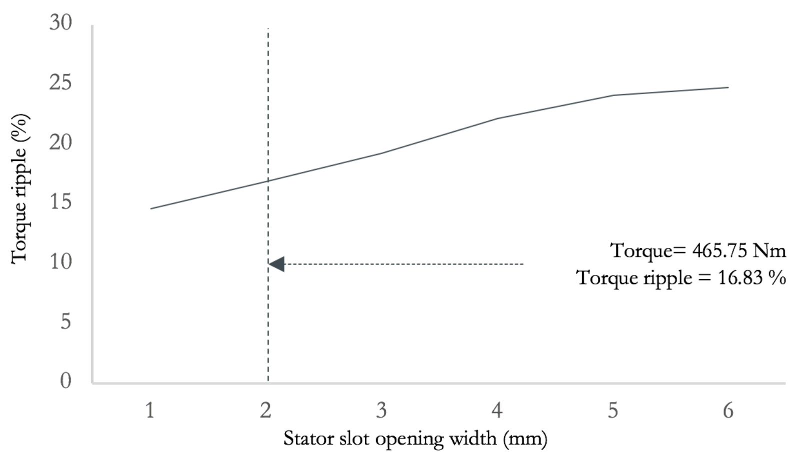
The stator was optimized by finding the optimal stator slot height and stator slot opening width. Similar to rotor optimization, the optimal parameter is at which the torque is sufficiently high and torque ripple is low. The stator slot opening width is swept between 1 mm to 6 mm with an increment of 1 mm and the stator slot height is swept between 5 mm to 25 mm with an increment of 5 mm.

**(a)** **(b)**

**Figure 3.6:** Stator Parameter (a) Stator slot opening width and (b) Stator slot height

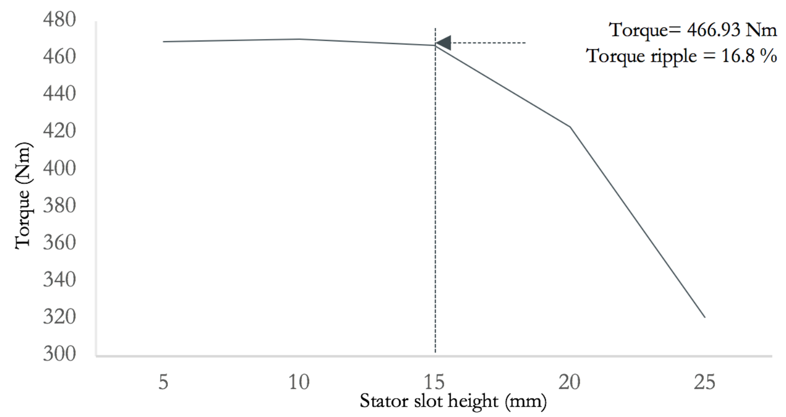



**(a)** Torque

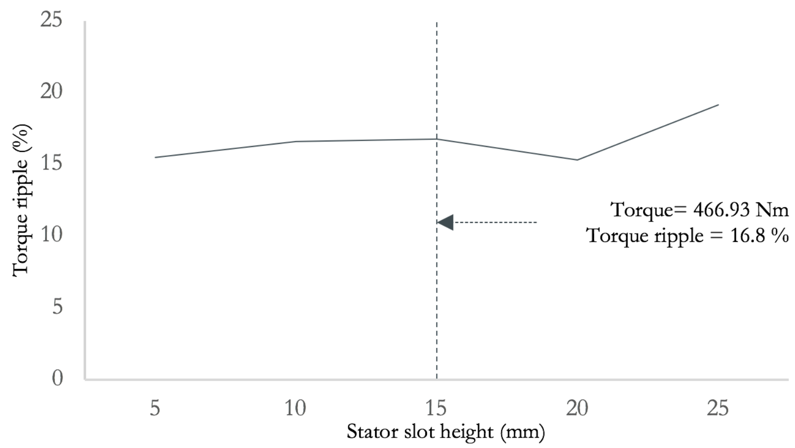



**(b)** Torque ripple

**Figure 3.7:** Torque and Torque Ripple as a function of stator slot opening width




(a) Torque




(b) Torque ripple

**Figure 3.8:** Torque and Torque Ripple as a function of stator slot height

Figure 3.6 identifies the stator slot opening width and stator slot height. Figure 3.7 illustrates the torque and torque ripple as a function of stator slot opening width. Torque is almost constant between 1 mm to 4 mm and starts dropping as the slot width widens. This is expected because a wider slot opening means less area for the flux from the rotor to travel to the stator and return back to the rotor. This is also reflected figure 3.7(b) in terms of torque ripple. The torque ripple increases with the stator slot opening width. However, a slot opening width of 2 mm is chosen as its slot opening width of 1 mm is difficult to implement. At this point, the torque is 465.75 Nm and the torque ripple is 16.83%.

Similarly, figure 3.8 shows torque and torque ripple as a function of stator slot height. Torque is almost constant for heights between 5 mm to 15 mm and starts dropping on-wards. This behavior is expected because as the outer diameter is held constant, higher stator slot height means reduction of stator yoke. Therefore, the flux will not have much area to travel in the stator and this will result in low torque. On the other hand, torque ripple does not have a direct correlation to the stator slot height. Therefore, a stator slot height of 15 mm was chosen where the torque is 466.93 Nm and torque ripple is 16.8%.

The above mentioned parameters were implemented on the reference machine and it was evaluated at a current angle corresponding to the MTPA curve. The optimized reference machine produced a torque of 470.64 Nm and torque ripple of 13.64% or 64.31 Nm peak to peak.

## 3.4 Asymmetrical features

The asymmetrical design features can be divided into two categories, modifications made to the stator and modifications made to the rotor. These changes were made one at a time to the reference machine. Each design was then implemented in ANSYS Maxwell and the current angle corresponding to the MTPA curve was found. The torque and torque ripple for each of the designs was compared to that of the optimized reference machine.

### 3.4.1 Stator asymmetry

Asymmetry can be introduced to the stator in two forms, by modifying the shape of the stator slot and by moving the placement of the stator slot opening. The rotor in these analysis belongs to the rotor of the optimized reference machine.

**Stator slot shape-Rectangular**: The aim of changing the stator shape is to understand how it affects the torque and torque ripple of the machine. For the purposes of this study, the stator slot shape is limited to rectangular shape.

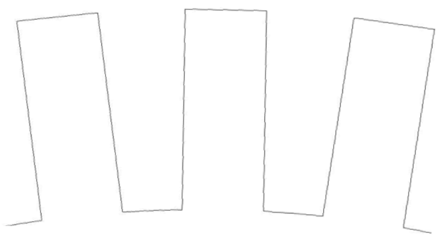
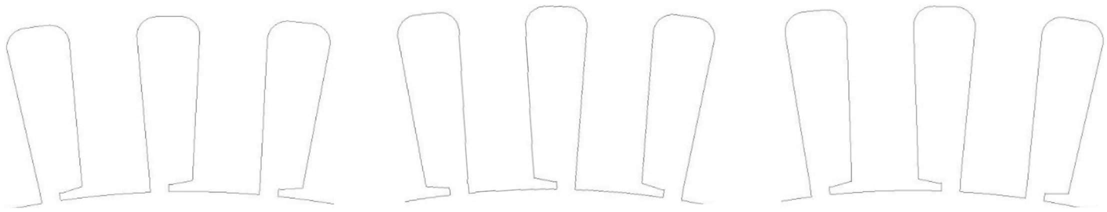


**Figure 3.9:** Stator slot shape- Rectangular

Figure 3.9 shows the rectangular stator slot used in the study. It is 6 mm wide and 15 mm in stator slot height. The stator height is kept similar to the optimized reference machine for comparison.

**Stator slot opening position**: The purpose of changing the stator opening position is to understand how it affects the torque and torque ripple of the machine. The stator slot opening position is moved to the left, right and then altered between the adjacent slots. The stator slot shape is kept similar to the reference machine.



**(a)** **(b)** **(c)**

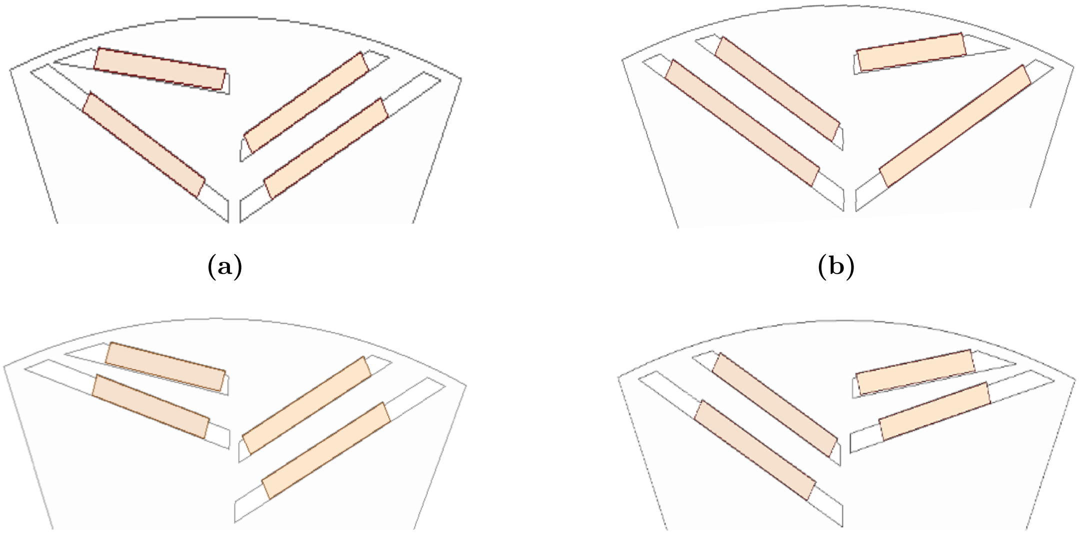
**Figure 3.10:** Stator slot opening position (a) Stator slot opening positing-Left, (b) Stator slot opening positing-Right and (c) Stator slot opening position-Alternate

Figure 3.10 shows the stator slot opening position used in the study. The stator slot height is 15 mm and stator slot width is 2 mm, which is similar to the stator slot height and stator slot opening width of the optimized reference machine.

### 3.4.2 Rotor asymmetry

For the purposes of this study, rotor asymmetry can be broadly categorized in three categories, intra-polar rotor asymmetry, asymmetry within the flux barriers and air slots within the rotor. The stator in each of these designs belongs to the stator of the optimized reference machine.

**Intra-polar rotor asymmetry**: Intra-polar asymmetry is achieved by playing with different magnet placements and concentration within the same pole. To start with, one magnet from the top layer is placed parallel to the rotor surface while the other magnet from the top layer remains in V-shape. The same design process is then repeated for the other side. Next, both the magnets from one side of V-shaped barriers are moved as parallel to the rotor surface as possible while the magnets from the other side remain in the V-shape. The same design procedure is repeated for the other side. The next step was to the change the magnet concentration in one side of the flux barrier. Therefore, it is designed so that one side of the V-shaped barrier have higher amount of magnet than the other side.



(a) (b) (c) (d)

**Figure 3.11:** Intra-polar asymmetry with magnet placement (a) Magnet placement-left,(b) Magnet placement-right,(c) Magnet placement-left both and (d) Magnet placement-left both

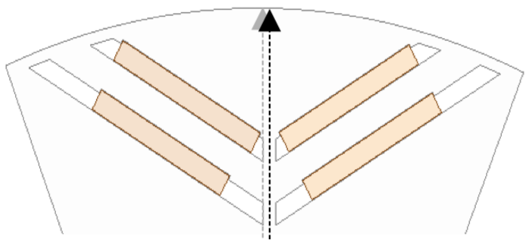
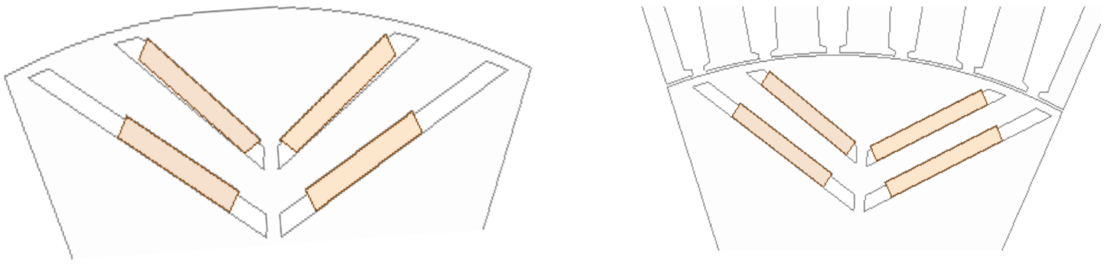


**Figure 3.12:** Intra-polar asymmetry with different magnet concentration around the mid-axis

Figure 3.11 shows intra-polar asymmetry with magnet placement. This was partially inspired by the design methodology suggested in [10]. In [10], an optimal rotor geometry is obtained by saturating the part of the rotor core where flux density is high, which in effect increases reluctance. The design optimization in the aforementioned paper was meant for a single layered IPMSM where the magnets were not buried in a V-shape. The aim of placing the magnets close to the rotor surface was to analyze whether or not a similar principal can be applied to the 2-layered IPMSM. While making the design modifications, the magnet concentration in each layer and each side is kept as close to that of the optimized reference machine as possible. Figure 3.12 shows intra-polar asymmetry that can be achieved by having different concentration of magnets at one side of the v-shaped barriers vs the other. In this particular study, the left of the barrier have slightly higher concentration of the magnet than the right.

**Asymmetry within the flux barriers**: Rotor asymmetry can also be achieved by playing with the placement of the flux barriers. It includes two cases, one where the top and bottom V-layer have different V-angles and second where the flux barrier endings are designed in a way that each of the flux barrier end meet the stator at a different location.



(a) (b)

**Figure 3.13:** Asymmetry within the flux barriers (a)Different V-angles and (b) Magnet ending

Figure 3.13 shows how rotor asymmetry can be designed with flux barriers. In figure 3.13(a), the top V-layer has a smaller V-angle than the bottom layer.In figure 3.13(b), no two flux barrier ending ever meet the stator at the same place. Torque ripple is at its worse if both the flux barrier ends coincide with the stator slot opening as it means no path for flux from the rotor to pass to the stator. This tries to deliberately avoid the coincident.

**Air slots/gaps within the rotor**: Another way to introduce asymmetry within rotor is to introduce air slots within the rotor geometry. This can either be done by introducing tiny rectangular air slots near the surface of the rotor.

**Figure 3.14:** Air slots near the rotor surface

Figure 3.14 shows small rectangular air slots that are introduced near the end of the rotor surface. This is to allow smother distribution of flux during rotation to achieve lower torque ripple.

# Chapter 4

# Results

The performance of each of the asymmetrical designs is compared to that of the optimized reference machine. Analysis of the performance of each of the designs is carried out in this chapter. The torque represented here is the mean torque calculated from the simulations. Torque ripple is represented both in % and in Peak to Peak and it is calculated as

$$\text{Torque Ripple}_{\%} = (\text{Max. Torque} - \text{Min. Torque})/\text{Avg Torque} \tag{4.1}$$

$$\text{Torque Ripple}_{p2p} = (\text{Max. Torque} - \text{Min. Torque}) \tag{4.2}$$

where data for Max. Torque, Min. Torque and Avg. Torque is collected from each of the designs form the ANSYS Maxwell simulations.

## 4.1 Analysis of stator modifications

Analysis of the performance of the stator slot shape and the stator slot opening position is carried out to understand if any of the modification will provide compatible performance to that of the optimized reference machine.

### 4.1.1 Stator slot shape-Rectangular

Table 4.1 compares the performance of the rectangular shaped stator slot to that of the optimized reference machine. It illustrates that a rectangular stator slot of similar dimensions causes torque to drop significantly to -65.26 Nm and the torque ripple to increase.

**Table 4.1:** Performance of stator slot shape- rectangular

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 405.38 Nm | 470.64 Nm | -65.26 Nm |
| Torque Ripple(%) | 21.15 % | 13.64 % | 7.51 % |
| Torque Ripple (p2p) | 85.75 Nm | 64.31 Nm | 21.43 Nm |

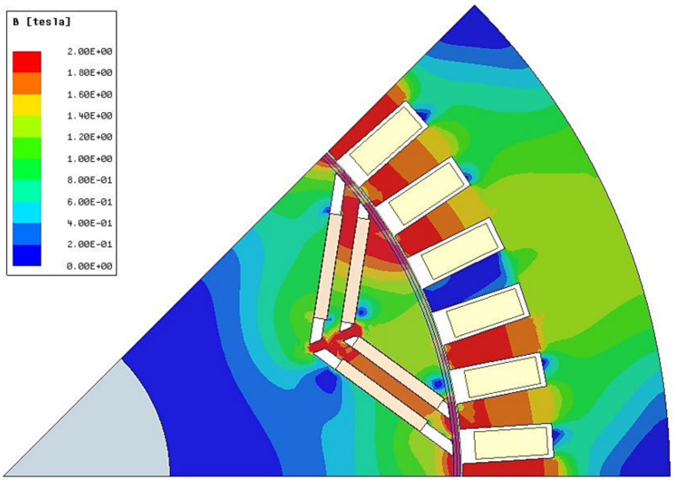



**Figure 4.1:** Magnetic flux density of stator slot shape- rectangular at load

The magnetic flux through the machine at load can be seen in the figure 4.1. It can be seen from the figure that a rectangular slot opening has increased the slot opening area. Therefore, as the rotor progresses, the flux barrier endings see more of air and not enough stator teeth material. Additionally, the rectangular stator slot deceased the total area of the stator core providing less path for the flux to flow through. These phenomena can explain the drop in torque and increase in torque ripple.

### 4.1.2 Analysis of various stator slot opening position

The stator slot opening position was placed to left, the right and then alternated between adjacent slots. This is to analyze the impact of slot opening position on the performance of the machine.

**Stator slot opening position-Left**: The table 4.2 compares the performance of the stator slot with opening to the left to that of the optimized reference machine. It shows that moving the slot opening to the left marginally improves the performance of the machine.

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 470.03 Nm | 470.64 Nm | -0.61 Nm |
| Torque Ripple(%) | 13.337 % | 13.637 % | -0.3 % |
| Torque Ripple (p2p) | 62.69 Nm | 64.312 Nm | -1.63 Nm |

**Table 4.2:** Performance of stator slot position- left

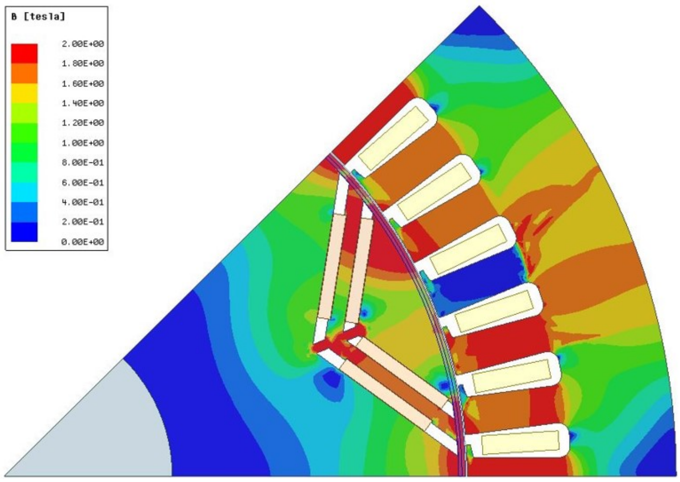



**Figure 4.2:** Magnetic flux density of stator slot position- left at load

The magnetic flux through the machine at load, and hence magnetic saturation can be seen from the figure 4.2.

**Stator slot opening position-Right**: As it can seen from figure 4.3, moving the stator slot opening to the right decreases the torque by almost 10 Nm. However, it also decreases peak to peak torque ripple by 8 Nm. This behavior was not observed when the stator slot opening was moved to the left. It can be attributed to the direction of rotation of the rotor.

**Table 4.3:** Performance of stator slot position- right

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 465.64 Nm | 470.64 Nm | -5 Nm |
| Torque Ripple(%) | 12.03 % | 13.64 % | -1.61 % |
| Torque Ripple (p2p) | 56 Nm | 64.31 Nm | -8.32 Nm |

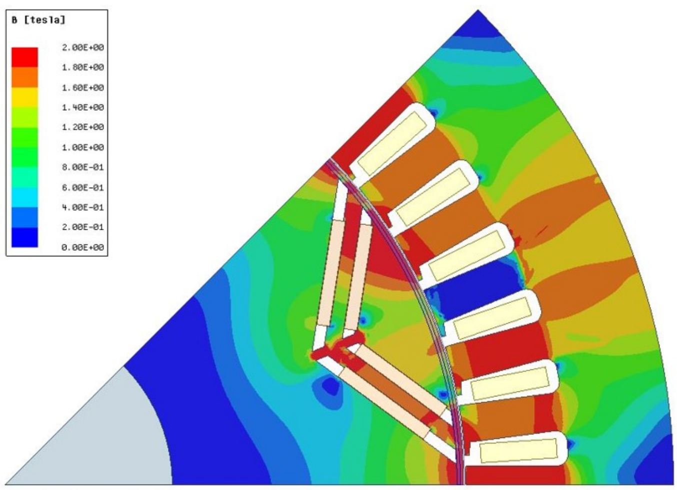



**Figure 4.3:** Magnetic flux density of stator slot position- right at load

The magnetic flux through the machine at load, and hence, magnetic saturation can be seen from figure 4.3.

**Stator slot opening position-Alternate**: Table 4.4 shows that alternating the position of the stator slot opening between the adjacent slots decreases the torque and increases torque ripple. Torque ripple peak to peak is increased by 26.576 Nm.

**Table 4.4:** Performance of stator slot position- alternate

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 461.54 Nm | 470.64 Nm | -9.1 Nm |
| Torque Ripple(%) | 19.69 % | 13.64 % | 6.06 % |
| Torque Ripple (p2p) | 90.88 Nm | 64.31 Nm | 26.58 Nm |

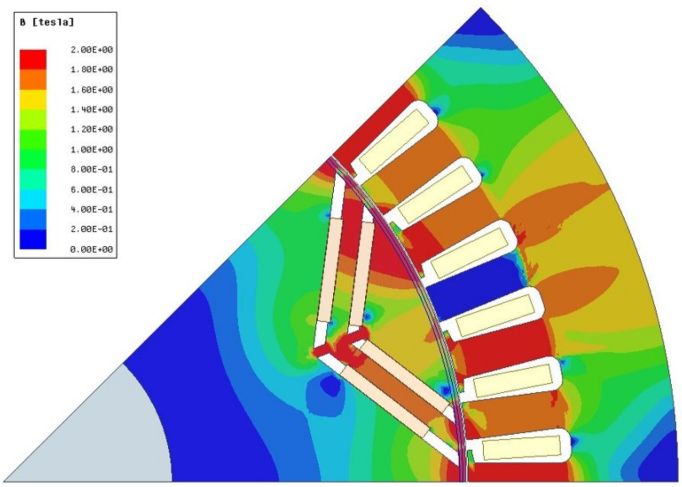



**Figure 4.4:** Magnetic flux density of stator slot position- Alternate at load

The magnetic flux through the machine at load can be seen from the figure 4.4. It can also be seen from the figure that the flux barrier ends almost coincides with the stator slot opening, which can explain the high torque ripple.

## 4.2 Rotor Modifications

Rotor modifications are carried out to understand the impact of intra-polar symmetry, asymmetry in the flux barriers and air slots in the rotor on the performance of the machine.

### 4.2.1 Intra-polar rotor asymmetry

Intra-polar asymmetry can be implemented either by varying the magnet placement within a pole or having varying magnet concentration within the pole. When it comes to varying magnet placement, it was better to analyze the flux lines within the machine than magnetic flux density.

**Rotor magnet placement - left**: It can be seen from table 4.5 that placing the upper left magnet parallel to the rotor surface did not improve the performance of the machine. It resulted in a significant decrease in torque and increased ripple.

**Table 4.5:** Performance of rotor magnet placement - left

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 429.6 Nm | 470.64 Nm | -41.04 Nm |
| Torque Ripple(%) | 28.26 % | 13.64 % | 14.62 % |
| Torque Ripple (p2p) | 121.39 Nm | 64.31 Nm | 57.08 Nm |

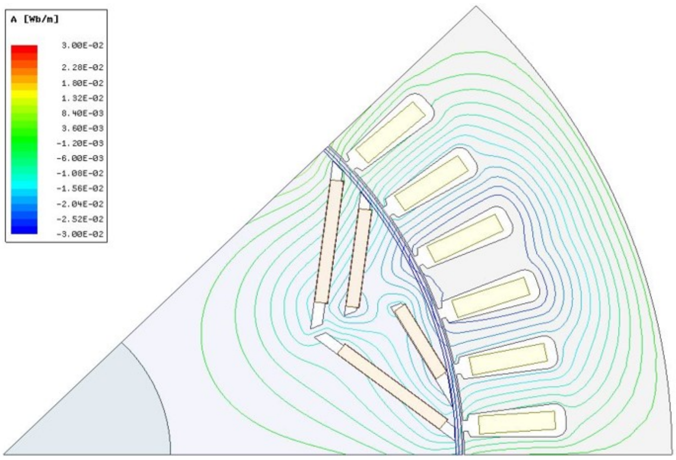



**Figure 4.5:** Magnetic flux lines at load with one left magnet placed parallel to the rotor surface

Figure 4.5 shows that flux line within the rotor. As it can be seen, most of the flux leaving the upper left magnet is attracted to the upper right magnet. Since the flux takes the least reluctance path, it stays within the rotor instead of travelling through the air gap to the stator.

**Rotor magnet placement - right**: Table 4.6 compares the performance of the machine when the upper right magnet is placed parallel to the rotor surface to that of the optimized reference machine. Similar to the previous case, the torque is reduced significantly and the ripple is increased. The performance is worse when the upper left magnet is placed parallel to the surface to when the upper right magnet is placed parallel to the surface. This can be attributed to the direction of the rotation of the rotor.

**Table 4.6:** Performance of rotor magnet placement - right

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 410.26 Nm | 470.64 Nm | -60.38 Nm |
| Torque Ripple(%) | 32.19 % | 13.64 % | 18.55 % |
| Torque Ripple (p2p) | 132.06 Nm | 64.31 Nm | 67.75 Nm |

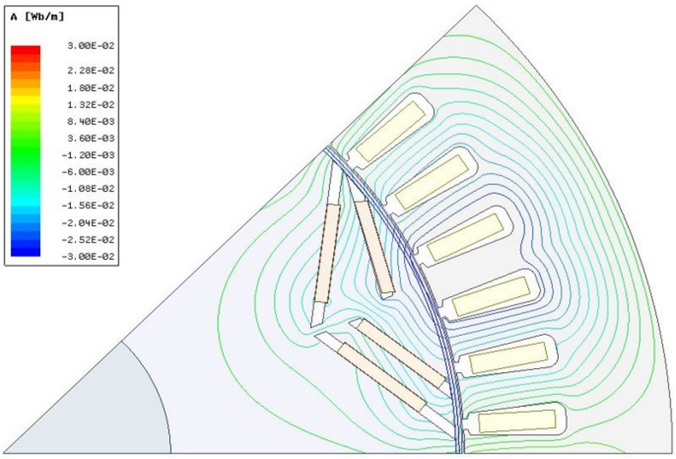



**Figure 4.6:** Magnetic flux lines at load with one right magnet placed parallel to the rotor surface

Figure 4.6 shows flux lines within the rotor. It shows similar characteristic to when the upper right magnet was places parallel to the surface.

**Rotor magnet placement - both left**: As is evident from table 4.7, placing both left magnets parallel to the rotor surface does not improve the performance of the machine. It worsened the performance of the machine when compared to placing upper left magnet parallel to the rotor surface.

**Table 4.7:** Performance of rotor magnet placement - both left

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 403.11 Nm | 470.64 Nm | -67.53 Nm |
| Torque Ripple(%) | 17.89 % | 13.64 % | 4.25 % |
| Torque Ripple (p2p) | 72.12 Nm | 64.31 Nm | 7.8 Nm |

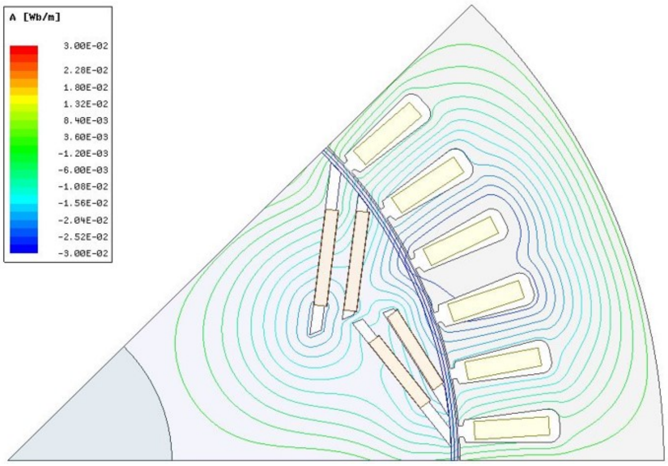



**Figure 4.7:** Magnetic flux lines at load with both left magnets placed parallel to the rotor surface

The flux lines within the rotor as seen from figure 4.5 shows that most of the flux leaving the left magnets is attracted to the adjacent magnets. Since flux takes the least reluctant path, it stays within the rotor instead of travelling through the air gap to the stator.

**Rotor magnet placement - both right**: Similar to placing the upper right rotor parallel to the surface, placing both the right magnet worsens the performance and it can be seen in table 4.8.

**Table 4.8:** Performance of rotor magnet placement - both right

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 357.45 Nm | 470.64 Nm | -113.19 Nm |
| Torque Ripple(%) | 19.902 % | 13.637 % | 6.254 % |
| Torque Ripple (p2p) | 71.139 Nm | 64.312 Nm | 6.8267 Nm |

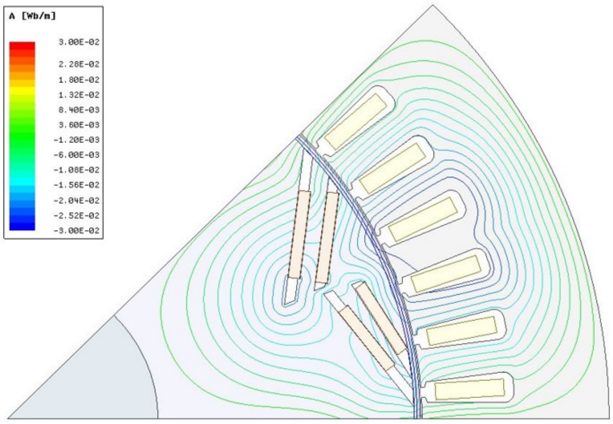



**Figure 4.8:** Magnetic flux lines at load with both right magnets placed parallel to the rotor surface

Figure 4.8 shows the flux lines within the rotor. It shows similar characteristic to when both the left magnets were placed parallel to the surface.

**Varying magnet concentration around the mid-axis**: The machine is designed so that the right side of the barriers have slightly higher magnet concentration than the left side. Table 4.9 shows that this design results in around 6.5 Nm of torque and increases torque ripple by 7.2 Nm peak to peak.

**Table 4.9:** Performance of rotor asymmetry-different magnet concentration around the mid-axis

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 464.15 Nm | 470.64 Nm | -6.5 Nm |
| Torque Ripple(%) | 15.42 % | 13.64 % | 1.79 % |
| Torque Ripple (p2p) | 71.58 Nm | 64.31 Nm | 7.27 Nm |

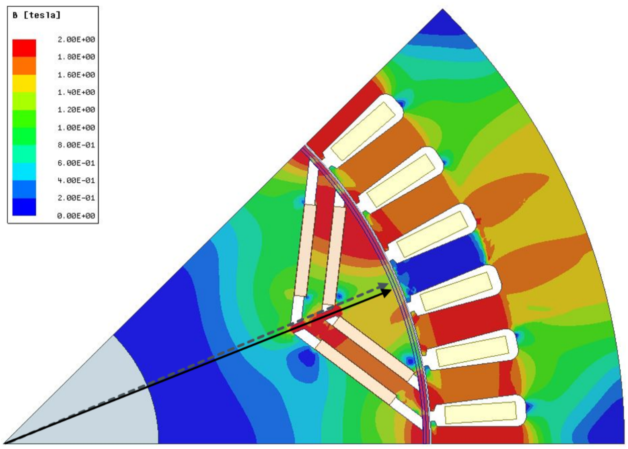



**Figure 4.9:** Magnetic flux density of rotor asymmetry-different magnet concentration around the mid-axis at load

Figure 4.9 shows the magnetic flux density distribution within the rotor. As expected, the side with more magnet concentration has more magnetic saturation.

### 4.2.2 Asymmetry within the flux barriers

Asymmetrical features can be achieved either when the flux barriers have different v-angle or the flux barriers are designed so that each barrier faces the stator at a different position.

**Different V-angles between the flux barriers**: The machine is designed so that the top flux barrier has a smaller V-angle than the bottom layer. Table 4.10 shows that this design will result in around 4 Nm drop in torque, but increases the torque ripple to almost 32.63 Nm peak to peak. By allowing different V-angles, the flux barrier endings almost coincide with the stator slot opening which results in high torque ripple.

**Table 4.10:** Performance of rotor asymmetry-different V-angle between the top and the bottom magnet layer

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 466.62 Nm | 470.64 Nm | -4.02 Nm |
| Torque Ripple(%) | 20.78 % | 13.64 % | 7.14 % |
| Torque Ripple (p2p) | 96.94 Nm | 64.31 Nm | 32.63 Nm |

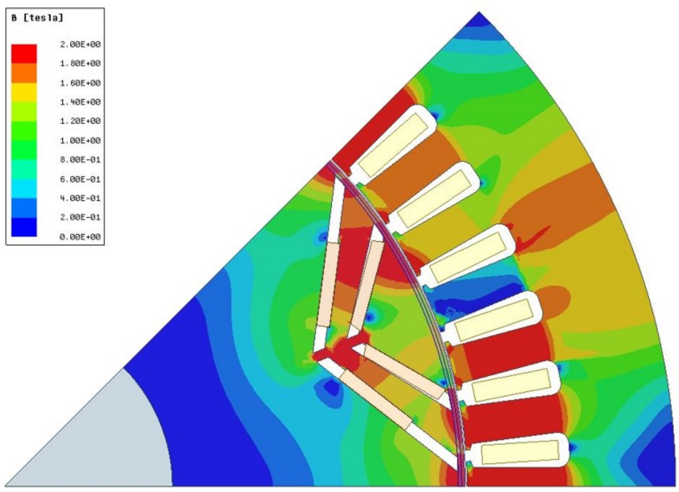



**Figure 4.10:** Magnetic flux density of rotor asymmetry-different V-angle between the top and the bottom magnet layer at load

Figure 4.10 depicts the magnetic flux density within the design and identifies the areas of saturation.

**Varying flux barrier endings**: As it can be seen from the previous analysis, the torque ripple is high when the two flux barrier endings coincide with the stator slot opening. This design is aimed to avoid such scenario. Each flux barrier faces the stator at a different position. Therefore, no two flux barrier would face the stator slot opening at the same time during rotation. However, table 4.11 shows that torque ripple did not decrease, rather increased by 32.6 Nm peak to peak. This concludes that though the torque ripple is high when flux barrier ending face the stator slot openings, it is not entirely caused by this event.

**Table 4.11:** Performance of rotor asymmetry- varying magnet ending

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 466.62 Nm | 470.64 Nm | -4.0198 Nm |
| Torque Ripple(%) | 20.775 % | 13.637 % | 7.1377 % |
| Torque Ripple (p2p) | 96.939 Nm | 64.312 Nm | 32.627 Nm |

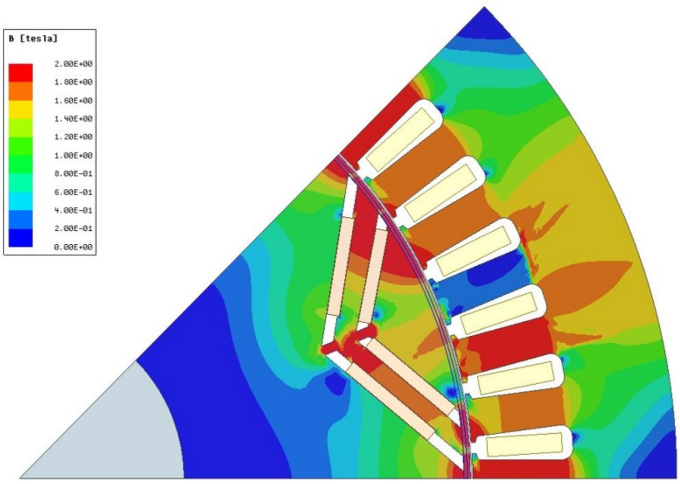



**Figure 4.11:** Magnetic flux density of rotor asymmetry- varying magnet ending at load

Figure 4.11 shows how the magnetic saturation changes when the flux barrier endings are modified.

### 4.2.3 Air slots within the rotor

The purpose of this design is to understand whether or not rectangular air slots near the surface of the rotor affect the performance of the machine and at what position of the rotor can these air slots be introduced.

**(a)** Position 1

**(b)** Position 2

**(c)** Position 3

**(d)** Position 4

**(e)** Position 5

**(f)** Position 6

**Figure 4.12:** : Rectangular air slot positions on rotor strip

Figure 4.12 shows various position along the rotor surface where the air slots were introduced. The first rectangular air slot were introduced at the edge of the rotor surface and incrementally moved inwards. Table 4.12 shows that only at position 3 is the performance compatible to the optimized reference machine. When the performance was compared in table 4.13, the increase in torque and decrease in torque ripple was marginal.

**Table 4.12:** Performance of rectangular air slot positions on rotor strip

| Design | Torque | Torque Ripple (%) | Torque Ripple (p2p) |
|---|---|---|---|
| Optimized reference machine | 470.64 Nm | 13.64 % | 64.31 Nm |
| Position 1 | 465.57 Nm | 15.77 % | 73.44 Nm |
| Position 2 | 465.54 Nm | 15.8 % | 73.57 Nm |
| Position 3 | 470.7 Nm | 13.51 % | 63.58 Nm |
| Position 4 | 471 Nm | 14.73 % | 69.38 Nm |
| Position 5 | 471 Nm | 14.73 % | 69.38 Nm |
| Position 6 | 465.62 Nm | 15.69 % | 73.06 Nm |

**Table 4.13:** Performance of rectangular air slot at position 3

| Parameter | Value(Unit) | Reference Machine | Difference |
|---|---|---|---|
| Torque | 470.7 Nm | 470.64 Nm | 0.06 Nm |
| Torque Ripple(%) | 13.51 % | 13.64 % | -0.13 % |
| Torque Ripple (p2p) | 63.58 Nm | 64.31 Nm | -0.78 Nm |

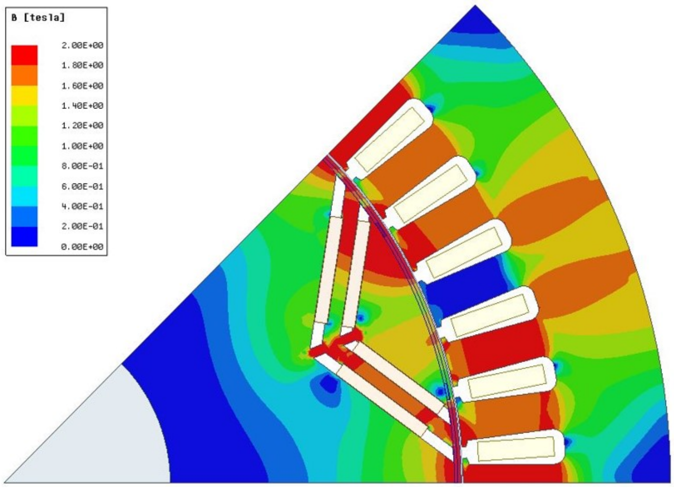



**Figure 4.13:** Magnetic flux density of rectangular air slot positions on rotor strip at load

As seen from figure 4.13, it is not possible to clearly see the effect of the rectangular air slots on the magnetic flux density of the machine.

# Chapter 5

# Conclusion

When the performance of each of the design modifications were compared, no single design showed significant improvement in the performance of the machine. It is worth noting that these designs were compared to an optimized reference machine. The modified designs were optimized by finding the current angle corresponding to the MTPA curve. However, the designs need to be further optimized to be properly comparable to an optimized reference machine. This would imply that for any stator modification, the rotor design needs to be optimized to fit the stator and vise versa. Designs that show performance improvement such as moving the stator slot opening to the right and introducing air slots on the rotor surface needs to improved and analyzed further.

## 5.1 Future Steps

This study was performed to broadly understand if asymmetrical features would have an impact on the performance of the machine. In order to further enhance the performance, geometrical modifications should be made in small increments. A right combination of stator and rotor modifications are needed to see a significant improvement on the performance. Investigation needs to be carried out to combine certain rotor and stator geometries so that harmonics from one modification can cancel out harmonics from the other.

For the purpose of this study, it was assumed that increasing or decreasing the torque in motor mode will impact the torque on the generator mode. This aspect of asymmetrical feature needs to be further investigated.

Owing to time restriction, the loss calculation was ignored. Each design needs to be simulated for every speed between 0-14000 rpm to get iron losses. Mechanical integrity of each of the designs needs to be verified as well.

In order to see a significant performance improve, a combination of geometrical changes and control strategies is required.

## 5.2 Conclusion

From an academic point of view, analyzing asymmetrical features is limited to developing a cost efficient electric machine. However, much attention needs to be paid whether these machines can be sourced and produced ethically and can contribute to a sustainable suture. It is important to analyze the environmental cost of producing EVs and what percentage of that cost could be attributed to the electrical machines. Different ways of recycling and reusing electric machines has to be identified. Otherwise, analysis needs to be carried out to increase the life-time of the machine.

The most costly part of an IPMSM is the permanent magnet which is a rare earth metal. As the trend in EV industry is to adapt IPMSM, it is worth looking into designs that would minimize the use of the permanent magnets. Lots of research is carried out into develop design that use as little permanent magnet as possible and still get the compatible performance. One such example is the use of PM assisted SynPMs. However, designing such machines is can be very costly and would increase the overall cost of EVs. More importantly, steps needs to be taken so not to permanently demagnetize them. This implies limiting high current, steps to minimize the losses at high speed ranges and so on.

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