Synchronous Machine for Unidirectional Application

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Synchronous Machine for Unidirectional Application

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Abstract

This master thesis investigates the possibilities for performance improvements of synchronous machines with unidirectional application.

The literature review part presents theories and applications of asymmetrical machine. Four categories regarding asymmetrical machine, namely mixed pole, saturation mitigation, pole shifting and asymmetrical pole shaping, are summarized. It is shown that asymmetrical concept offers characteristic improvement in one or both rotational directions.

A field winding synchronous model was used in FEM simulation (FLUX 2D). Armature reaction effect on this machine is investigated. It is found that armature reaction has different effects with varying current angle.

Two ideas regarding asymmetrical pole shaping are investigated. First of all, pole shoe cutting idea is investigated. It leads to increased airgap length and less output torque. Secondly, progressive airgap idea shows reduced armature reaction effect and improved power factor, but higher torque ripple. Furthermore, an improved idea is suggested to reduce the torque ripple.

Performance improvement by assisted permanent magnet is also studied. Four ideas of this field are investigated. It is found that permanent magnet can be used to reduce saturation, improve power factor and output torque. The reasons for limited improvements are analyzed.

Key words

Asymmetrical machine, unidirectional rotation, mixed pole, saturation mitigation, pole shifting, asymmetrical pole shaping, progressive airgap, assisted permanent magnet, armature reaction, power factor improvement.
Sammanfattning

Detta examensarbete undersöker möjligheter att förbättra prestanda hos synkrona maskiner med drift endast i en rotationsriktning.

Litteraturstudien sammanfattar teorin om samt tillämpning av asymmetriska elmaskiner. Fyra kategorier av asymmetriska maskiner är presenterade i arbetet: blandade poler, dämpade mättning, skiftade poler och formade asymmetriska poler. Det har visats att det asymmetriska konceptet förbättrar prestanda hos elmaskiner i en eller båda rotationsriktningar.

Modellen av en fältlindad synkronmaskin används i FEM beräkningar (FLUX2D). Ankarreaktionens effekt på denna maskin har undersömts. Det harvisats att effekten av ankarreaktionen på maskinen varierar med strömvingeln.


Två olika sätt att förbättra prestanda genom att använda assisterande permanentmagneter har studerats. Det har visats att assisterande permanentmagneter kan användas för att minska mättningen, förbättra effektfaktorn och öka momentet. Orsakerna bakom dessa förbättringar analyseras.

Nyckelord

Asymmetriska maskiner, enkelriktad rotationsriktning, blandade poler, dämpade mättning, skiftad poler, formade asymmetriska poler, progressiv luftgapslängd, assisterande permanentmagneter, ankarreaktion, effektfaktorförbättring.
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Yang Yu

Västerås, One day before middle summer holiday, 2012
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List of abbreviations

PM: Permanent magnet
PMSM: Permanent magnet synchronous machine
Syn RM: Synchronous reluctance machine
IPM interior PM-motor
P.F: Power factor
FEM: Finite element modeling
MTPA: Maximum torque per ampere
SMPM: Surface mounted permanent magnet
List of symbols

- **U**: terminal voltage \([V]\)
- **U_{\text{rated}}**: terminal voltage at rated condition \([V]\)
- **E**: back EMF \([V]\)
- **I_s**: stator current \([A]\)
- **I_a**: a phase stator current \([A]\)
- **I_b**: b phase stator current \([A]\)
- **I_c**: c phase stator current \([A]\)
- **I_{fw}**: field winding current \([A]\)
- **I_{\text{rated}}**: stator current at rated condition \([A]\)
- **I_d**: d-axis component of stator current \([A]\)
- **I_q**: q-axis component of stator current \([A]\)
- **X_d**: d-axis inductance \([H]\)
- **X_q**: q-axis inductance \([H]\)
- **T**: magnetic torque \([N.m]\)
- **T_{\text{rated}}**: rated torque at rated condition \([N.m]\)
- **T_{\text{cog}}**: cogging torque \([N.m]\)
- **\beta**: current angle \([\text{degree}]\)
- **\delta**: load angle \([\text{degree}]\)
- **\phi**: power factor angle \([\text{degree}]\)
- **\omega_1**: synchronous electrical angular speed \([\text{rad/s}]\)
- **\omega**: rotational speed \([\text{rad/s}]\)
- **B**: flux density \([\text{Tesla}]\)
- **B_1**: fundamental flux density in the airgap \([\text{Tesla}]\)
- **B_{fw}**: flux density from field winding current \([\text{Tesla}]\)
- **B_s**: airgap flux density \([\text{Tesla}]\)
- **B_{arm}**: flux density from armature reaction \([\text{Tesla}]\)
- **B_{sat}**: flux density in the airgap that could cause saturation \([\text{Tesla}]\)
- **B_r**: remanence flux density \([\text{Tesla}]\)
- **\Psi_r**: rotor flux linkage \([\text{Wb}]\)
- **P_{\text{iron}}**: iron losses \([\text{Kw}]\)
- **\eta**: efficiency
- **\sigma_{\text{iron}}**: iron conductivity \([\text{s/m}]\)
- **d_{\text{lam}}**: lamination thickness \([\text{mm}]\)
- **\rho**: resistivity \([\Omega.\text{m}]\)
- **\Delta T**: temperature rise \([\text{oC}]\)
- **P_{\text{copper_stator}}**: stator copper losses \([\text{Kw}]\)
- **P_{\text{copper_fieldwinding}}**: field winding copper losses \([\text{Kw}]\)
- **P_2**: output power \([\text{Kw}]\)
- **P_{\text{losses}}**: total losses \([\text{Kw}]\)
- **\tau_s**: stator slot pitch \([\text{mm}]\)
- **p**: number of poles
- **N_s**: number of slot
- **K_{\text{f}}**: stacking factor
- **K_{\text{hyst}}**: hysteresis loss coefficient
- **K_{\text{exc}}**: excess loss coefficient
1 Introduction

Nearly all electrical machines are designed symmetrically to have the same performance in both rotational directions. However, in many applications such as pumps, fans, and electric cars, their shafts rotate always or mainly in one direction. This means that machine’s characteristic in one rotational direction is much less important than that in its dominant rotational direction.

If a machine is designed symmetrically to achieve equal performance in both rotational directions, it is reasonable to suggest that unequal characteristic could be achieved by asymmetrical design. The concept of asymmetrical machine is created under this assumption. The goal of this topic is to investigate the possibility of performance improvement in one rotational direction of the machine.

Subjects of this report have been divided into the following parts:

1—Summary of asymmetrical machine principles, chapter 2
2—Original machine and armature reaction study, chapter 3
3—Asymmetrical rotor pole study, chapter 4
4—PM assisted machine study, chapter 5
5—Conclusion and future work, chapter 6

Torque, efficiency, and power factor are the main focus of the investigation. Totally 6 ideas regarding asymmetrical machine study have been proposed and analyzed in this report.
2 Literature review

In this chapter, ideas of asymmetrical machine are summarized and presented. Four categories of asymmetrical machine theories are introduced respectively. Firstly, mixed pole principle offers the possibility of saving permanent magnet material in surface-mounted synchronous machine. Secondly, saturation mitigation principle can be used to reduce saturation level of the machine in one rotational direction. Furthermore, pole shifting principle is an effective method to reduce cogging torque. Lastly, asymmetrical pole shape idea is presented. A summary table is shown at the end of this chapter.

2.1 Mixed pole

2.1.1 Introduction

The concept and principle of mixed pole have been suggested in [1] and [2], which aims to save half of the PM material used in a surface-mounted PMSM. The mixed pole is a combination of half permanent magnetic pole and half soft magnetic pole. It has the same advantage as PMSM in terms of loss-free rotor and high power density; it can even achieve better field weakening capability than PMSM [1]. The application of mixed pole would be ship propulsion and traction [1]. Figure 2.1 shows the structure of the mixed pole.

As mentioned by [2], the idea of the mixed pole is based on following observations:

Firstly, assume a soft magnetic material has the same saturation flux density as the remanence flux density of a PM. When the external magnetizing field acts in the direction of the intrinsic polarization of the PM, the soft magnetic material and PM would have very similar magnetic properties. Secondly, in a PMSM motor only half volume of each PM is exposed to a demagnetizing field, while the other half is exposed to a magnetic field in the direction of the intrinsic polarization. Hence the last mentioned part of the PM can be substituted by a soft-magnetic material. Figure 2.2 shows the airgap flux density distribution in a surface-mounted SMPM.
2.1.2 Sparsely laminated pole

As indicated by [1], reluctance pole made of saturable SL (sparsely laminated) layers is the key component in a mixed pole motor. A saturable SL pole approximately has the same saturation flux density as the remanence flux density of a PM. It behaves like a PM pole at flux density above its saturation polarization. Figure 2.3 a) shows the flux density along the air gap for mixed pole with half PM and half SL. Figure 2.3 b) shows for flux density distribution along the air gap for a conventional surface-mounted PMSM.

According to [1] and [2], sparsely laminated pole is made of electrical steel lamination with shortened every second lamination of the pole body. The effect of SL pole is to reduce the average value of iron saturation flux density. The un-solid surface layers of the rotor pole appears as a homogenous ferromagnetic body with a reduced saturation flux density [3]. Figure 2.4 shows the sparsely laminated electrical steel.

There are other methods to reduce the saturation flux density of the electrical steel [1]. One possibility is to use recesses, e.g. holes, in the soft-magnetic pole. The other possibility is to make the soft-magnetic pole sections with composites of soft-magnetic material and non-magnetic material.

2.1.3 Torque

One edge of a PM pole can be either pulled or pushed, while one edge of a reluctance pole can be pulled only. The mixed-pole can be optimized both for reversible and unidirectional torque production. In case of reversible torque production, SL pole is symmetrically located between two adjacent PM poles. Reference [1] suggests that mixed-pole optimized for unidirectional torque production can even save more PM material. Figure 2.5 shows the mixed-pole optimized for reversible rotation and unidirectional rotation, respectively.
Synchronous machine for unidirectional application

The torque from a mixed-pole shown in figure 2.6 can be roughly estimated by adding the torque from PM and soft-magnetic pole. Assume the PM pole and soft-magnetic pole both have 60 electrical degrees circumferential length. An example of the force acting on PM pole, SL pole and fully laminated iron pole can be found in [1] and is shown in figure 2.7.

Figure 2.6 Mixed-pole with 60 electrical degrees PM pole and soft-magnetic pole

Figure 2.7 Force acting on different poles [1]

Figure 2.8 a) shows the torque estimation for the mixed-pole with PM and SL pole, while figure 2.8 b) shows the torque estimation for the mixed-pole with PM and fully laminated iron pole.
Synchronous machine for unidirectional application

The maximum torque of the mixed pole is determined not only on the magnitudes of the torques from PM and SL pole, but also on the distance between the torque peaks.

It can be seen that mixed-pole with fully laminated iron pole and PM can achieve a maximum torque of 0.77 p.u. in one rotational direction. The maximum torque for mixed-pole with sparsely laminated pole can achieve is 0.92 p.u..
2.2. Saturation mitigation

2.2.1 Introduction

The armature reaction refers to the interaction between the magnetic field from the stator winding and magnetic field produced by the rotor. Due to iron saturation the addition of pole-flux at one edge is smaller than the subtraction at the other edge [5]. The net flux of a whole pole will be reduced consequently. Reference [5] shows the armature reaction can result in reduction of torque production. The flux saturation reduction due to armature reaction is explained in figure 2.9. Several methods, as reported by reference [4], [6] and [7], have been introduced to reduce the saturation level and utilize the iron in a more efficient way.

![Figure 2.9 Flux density along the airgap under loaded condition for a SM-PMSM](image)

2.2.2 Asymmetrical design to mitigate saturation

Reference [4] and [6] suggest three methods of asymmetrical rotor design. These ideas can be used to reduce the average saturation level and improve the output power of an interior permanent magnet motor. Reference [4] and [7] show the airgap length can be varied progressively to improve the output torque. These methods will be introduced respectively in this section.

2.2.2.1 Asymmetrical cooling hole displacement

Figure 2.10.a shows the flux distribution in an interior permanent magnet motor at loaded condition. The triangular holes are introduced for cooling or weight reduction purpose. However, their existence may change the magnetic flux flow width and local saturation around the holes. As a result, higher current is needed to produce the same torque and the efficiency of the motor goes down.

![Figure 2.10 Flux distribution with symmetrical cooling hole](image)
It can be seen from figure 2.10 a) that the placement of cooling holes causes low saturation and high saturation area around the cooling holes. An improvement to mitigate saturation level can be achieved by placing cooling hole asymmetrical as shown in figure 2.10.b). The advantage of the asymmetrical cooling hole displacement is explained in figure 2.11.

As shown in figure 2.10.b, the flux density in the low saturation area increases and it decrease in the high saturation area. Figure 2.11 shows the flux density and MMF changes in both low and high saturation areas. However, the MMF reduction in the high saturation area is greater than its increase in the low saturation area. Therefore, the stator current required to produce the rated torque could be reduced and the efficiency of the motor will be improved [6].
2.2.2.2 Asymmetrical air cavities displacement

The second method deals with reluctance torque enhanced rotor structure for IPM, which is shown in figure 2.12. Additional cavities are adopted along the d-axis.

![Diagram showing flux distribution with cavities and asymmetrical cavities.]

Figure 2.12 Flux distributions in an interior permanent magnet motor at loaded condition [6]

The principle of asymmetrical cavities displacement can be explained in the same way as the asymmetrical cooling holes.

Similar application can be found in other types of machine. Reference [4] suggests additional PM can be added on the rotor of a hybrid excitation machine to reduce the effect of armature reaction. Figure 2.13 shows the compensating magnets used in a hybrid excitation machine.
Figure 2.13 Compensation magnets in a hybrid excitation machine [4]

Figure 2.14 shows the rated torque with compensation magnets is 7% larger than the original motor. Moreover, the torque production with higher armature current is improved significantly as shown in figure 2.15. Thus the over-load capacity of the motor can be improved significantly.

Figure 2.14 Rated torque with and without compensating magnets [4]

Figure 2.15 Torque at different armature currents [4]
2.2.2.3 Asymmetrical magnets displacement

Figure 2.16 shows the principle of asymmetrical magnets displacement. It can be explained in the same way as asymmetrical cooling hole displacement (section 2.2.2.1). The magnets are asymmetrically displaced in order to mitigate the average saturation level of the rotor and optimize the usage of iron.

![Asymmetrical magnets displacement](image)

**Figure 2.16 Asymmetrical magnets displacement [6]**

2.2.2.4 Progressive air gap

As mentioned in reference [4] and [7], due to the fact that one side of the pole is more saturated than the other, the iron is underutilized. In order to improve the iron utilization, a variable air gap can be adopted to make the air gap flux density more homogenous. Figure 2.17 shows the structure of variable air gap in a field winding synchronous machine.

![Variable air gap length](image)

**Figure 2.17 Variable air gap length [7]**

The MMF and flux density distribution in a field winding synchronous machine is shown in figure 2.18. The air gap length changes progressively in order to keep quasi-rectangular air gap flux density at rated load.

![MMF and Flux density](image)

a). Flux density and MMF of the field  

b).MMF from armature current
The air gap taper should be determined between the ratio of field MMF and armature MMF. It is suggested in reference [7] that when the load changes, the field MMF must be changed in proportion to the armature current which can be achieved by series connection of the field and armature.

The same method is used in [4], where the progressive air gap is adopted in a hybrid excitation machine. The constant air gap is replaced by a tangential air gap. The air gap of the more saturated side is enlarged while the other one reduced, but the average air gap length remains unchanged.

Figure 2.19 shows the progressive airgap used in a hybrid excitation machine. Figure 2.20 and figure 2.21 show the airgap flux density and torque with and without progressive airgap, respectively.

---

**Figure 2.18 MMF and flux density for a field winding synchronous machine [7]**

**Figure 2.19 Progressive airgap in a hybrid excitation machine**

**Figure 2.20 Airgap flux density with progressive airgap and constant airgap [4]**
Figure 2.20 shows the flux density with progressive airgap is more homogenous than the constant airgap. As mentioned by [4], the output torque is increased by 6% and the torque ripple becomes lower as shown in figure 2.21.
2.3 Pole shifting

2.3.1 Introduction

Permanent magnet machines are widely used in industrial applications. However, their torque ripple can be very harmful to their performance in speed or position control and wind turbine generators [9][10]. Torque ripple refers to the torque variation components superimposed on the average torque when the motor runs at a given speed. One great contributor of torque ripple is the cogging torque which is caused by permeance variation in the magnetic circuit. The source of cogging torque is the interaction between the stator geometry and the rotor magnet flux [16]. Cogging torque is independent of load current and can result in mechanical resonance [11].

Many methods have been reported to reduce cogging torque, such as optimal pole arc width, fractional winding, skewing, smoothing the magnet shape and etc [15].

• Optimal width of pole arc
  The magnet pole arc has a large effect on the magnitude of cogging torque. The optimal value for the pole arc that minimizes cogging can be found based on finite-element analysis [8].

• Fractional slot winding
  Cogging torque can be reduced in a fractional slot winding machine because the different stator slot pitch does not coincide with the rotor pole pitch.

• Skewing
  Skewing can be made either on the stator side or rotor side. The cogging torque can theoretically be reduced to zero by skewing the rotor magnet with an appropriate angle. The three-step skew scheme is shown in figure 2.22.

![Figure 2.22 Three-step magnet-skew scheme [15]](image)

• Smoothing the magnet shape
  The magnet shape has direct influence on the distribution of the air-gap magnetic field. Reshaping the permanent magnet can lead to harmonic reduction in the back EMF significantly. Figure 2.23 shows different magnet shapes of a surface-mounted PMSM. The loaf and petal shaped magnets are shown in figure 2.23 (b) and 2.23 (c).

![Figure 2.23 Different magnet shapes of a surface-mounted PMSM [15]](image)
A novel method, has been reported by reference [8]-[15], suggests that cogging torque of permanent magnet machine can be greatly reduced by pole shifting. The object of this report is to investigate the principle of cogging torque reduction by the usage of pole shifting.

### 2.3.2 Pole shifting principle

Several analytical methods to calculate pole shifting angles have been reported. Reference [11] and [13] suggest the shifting angles can be found based on the co-energy equation. However, this is complicated and would be time consuming. Reference [8] [14] and [10] presents the analytical equations to calculate cogging torque. This section is carried out based on the latter method.

#### 2.3.2.1 Pole shifting with integral number of slots per pole

The first harmonic frequency of cogging torque is determined by the least common multiple between the slot number $N_s$ and the pole number $p$ [8]. The cogging torque contribution from one pole can be expressed [8]:

$$ T_{cog} = \sum_{k=1}^{\infty} T_{PM} \sin(N_s k \theta) $$

Where $T_{PM}$ is a per magnet coefficient, $N_s$ is the number of slots and $k$ is the harmonic order. In a machine with integer number of slots per pole, the cogging torque from one pole is in phase with the others.

The highest cogging torque harmonics cancellation is provided in [8]. The pole shifting angle $\theta_0$ that each pole shifted relative to the others is given in equation 2.2.

$$ \theta_0 = \frac{\tau_s}{p} = \frac{2\pi}{N_s \cdot p} $$

Where $\tau_s$ is the slot pitch.

Figure 2.24 shows the pole shifting principle applied to a 4 pole machine.

![Figure 2.24 Pole shifting for 4 pole machine](image)

Cogging torque of the whole machine with pole shifting is determined by equation 3.

$$ T_{cog} = \sum_{h=0}^{p-1} \sum_{k=1}^{\infty} T_{PM} \sin(N_s k (\theta - h \theta_0)) $$

(2.3)
Figure 2.25 shows the phasor diagram of the cogging torque for a 4-pole machine with the pole shifting angles in equation 2.3. It can be found that all the harmonics except multiples of 4 are canceled. Then the first harmonic appears in the resulting cogging torque is the 4th harmonic.

\[ k=1,2,3 \]

\[ k=4 \]

Figure 2.25 Phasor diagram of cogging with pole shifting

2.3.2.2 Pole shifting with fractional number of slots per pole

In the case of fractional number of slots per pole, the above principle can be applied as well. The cogging torque of one pole with fractional number of slots per pole would be out of phase with the other. However, the sum of cogging torque from several adjacent poles (which we consider as a group) would be in phase with the other groups. Take a 6 pole 27 slots machine for example: cogging torque from 2 poles which share 9 slots would be in phase with the other 2 groups. Hence the shifting is made between the chosen pole groups instead of individual poles.

Figure 2.26 shows the cogging torque reduction for a 6 pole 27 slots brushless PM motor by the usage of pole shifting and resized magnets.

In both cases, the first cogging torque order after pole shifting would be \( N_s \cdot p \)-th harmonic. A summary of the cogging reduction by pole shifting method mentioned in reference [8]-[15] is shown in figure 2.27 and table 2.1.
### 2.3.3 Radial vibration problem

The pole shifting principle in section 2.3.2 would result in magnetic lateral force pull on the rotor which will cause eccentricity. This drawback can be avoided by placing the poles mechanically 180° against each other [12]. Figure 2.28 shows the principle of the pole shifting for an 8-pole machine.

### Table 2.1 Cogging Torque reduction by pole shifting [8][11][14][9]

<table>
<thead>
<tr>
<th>No.</th>
<th>Machine type</th>
<th>Poles/Slots (p/Qs)</th>
<th>Cogging Torque (original) [%]</th>
<th>Cogging Torque (pole-shifted) [%]</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3</td>
<td>Brushless PM motor</td>
<td>4/24</td>
<td>13.6</td>
<td>0.17</td>
<td>University of Wyoming USA [8]</td>
</tr>
<tr>
<td>4</td>
<td>Surface-mounted PM linear motor</td>
<td>6/18</td>
<td>66</td>
<td>5.2</td>
<td>University of Padova Italy [14]</td>
</tr>
<tr>
<td>5</td>
<td>Interior PM linear motor</td>
<td>6/18</td>
<td>25.6</td>
<td>4.4</td>
<td>University of Padova Italy [14]</td>
</tr>
<tr>
<td>6</td>
<td>PM synchronous generator</td>
<td>120/360</td>
<td>31</td>
<td>2.7</td>
<td>Lappeenranta University of Technology, Finland [9]</td>
</tr>
</tbody>
</table>

*Cogging Torque is calculated as the ratio of its peak-to-peak value to the average output torque in percentage
Figure 2.28 Pole shifting in an 8 pole machine ($\tau_s$ is the slot pitch)

It can be seen from figure 2.28 that the distance between the two diametrically opposed poles is kept the same as in the case of the uniform pole distribution. And the lateral force is cancelled out by the diametrically opposed poles. However, the lower frequency radial magnetic force variation result from the pole shifting still exists. But when it comes to machine with large number of poles, this problem can be less serious.

The pole shifting angle $\theta_0$ becomes:

$$\theta_0 = 2 \frac{2\pi}{N_s \cdot p}$$  \hspace{1cm} (2.4)

The resulting first order of cogging torque harmonic now becomes to the 4th harmonic, which is half value when the shifted angle shown in equation 2.2 is applied.

### 2.3.4 Conclusion

1. The pole shifting method can achieve as good effect as skewing in terms of cogging torque reduction. Stepwise skewing results in the cancellation of the low-order cogging torque harmonic [16]. The pole shifting method, as mentioned above, is also an effective way to suppress the low-order cogging torque harmonic.

2. The average output torque will go down slightly by the usage of pole shifting. Reference [9] shows the average output torque reduces 2.5% after the adoption of pole shifting.

3. Pole shifting will introduce lower frequency radial force vibration and additional noises. It would be less serious when the machine with large pole number is used.
2.4 Asymmetrical pole shaping

Synchronous machine with asymmetrical pole shaping can be found in reference [18], [19] and [20]. Figure 2.29 a) shows the asymmetrical pole shoe in an inserted permanent magnet motor. Figure 2.29 b) is a double stator hybrid motor with asymmetrical pole shoe. Figure 2.29 c) suggests a switched reluctance motor with asymmetrical rotor.

Reference [18] suggests the incisions on the rotor pole can reduce the reaction field in unidirectional rotation for inserted permanent magnet motor. Reference [19] implies that magnetic distribution is unbalanced with reference to the circumferential direction during motoring operation for hybrid double-stator motor. The asymmetrical rotor structure can lead to an increased torque. It is also implied in reference [20] that the asymmetrical rotor poles can provide starting torque at all the rotor positions in one direction of rotation.
## 2.5 Summary

<table>
<thead>
<tr>
<th>Method</th>
<th>Mixed pole</th>
<th>Saturation mitigation</th>
<th>Pole shifting</th>
<th>Asymmetrical pole shaping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine type</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Syn RM</td>
<td></td>
<td></td>
<td></td>
<td>![Increase output torque][19]</td>
</tr>
<tr>
<td>Surface-mounted PMSM</td>
<td>![Significant PM material save, Better field weakening capability][1]</td>
<td>![Reduction of cogging torque][11]</td>
<td>![Additional noise, low frequency radial force vibration, lower average torque][9]</td>
<td>![Unknown][1]</td>
</tr>
<tr>
<td>Interior PM</td>
<td>![Larger output torque][6]</td>
<td>![Reduction of cogging torque][11]</td>
<td>![Unknown][1]</td>
<td>![Unknown][1]</td>
</tr>
<tr>
<td>Field Winding</td>
<td>![Larger output torque][7]</td>
<td>![Unknown][1]</td>
<td>![Unknown][1]</td>
<td>![Unknown][1]</td>
</tr>
</tbody>
</table>

(The red boxed are investigated in chapter 4 and 5.)


3 Original machine study

In this chapter, the original machine is studied both analytically and by FEM simulation. It was found that FEM results are different to analytical curves. Further investigation showed it is because of saturation. In section 3.3, armature reaction effects are analyzed theoretically and compared with FEM results. Section 3.4 gives the motor losses calculation.

The original machine studied in chapter 3, 4 and 5 is a four pole field winding synchronous machine. Figure 3.1 shows the geometry of this type of machine.

![Figure 3.1 Four pole field winding synchronous machine](image)

3.1 Analytical analysis

The phasor diagram in steady-state is shown in figure 3.2. Three operation conditions regarding inductive, resistive and capacitive power factor are presented respectively.
The voltage equation for salient pole synchronous machine including voltage drop across the stator resistance can be expressed in equation 3.1.

$$U_s = E_f + jX_d \cdot I_d + jX_q \cdot I_q + (R_s I_s)$$  \hspace{1cm} (3.1)

where $U_s$ is the stator terminal voltage, $E_f$ is the back EMF, $I_s$ is the stator current, $X_d$ is the d-axis inductance, $X_q$ is the q-axis inductance, $I_d$ is the d-axis component of the stator current $I_s$, $I_q$ is the q-axis component of the stator current $I_s$.

For large machine where resistance is low, the last part of equation 3.1 can be omitted.

The relation between load angle $\delta$, power factor angle $\varphi$ and current angle $\beta$ can be derived from the phasor diagram and given in equation 3.2 and 3.3:

$$\tan \delta = \frac{x_q I_q}{E + x_d I_d} = \frac{x_q I_q \sin(\beta)}{\omega \psi_e + x_d I_s \cos(\beta)}$$  \hspace{1cm} (3.2)

$$\varphi = \delta + 90 - \beta$$  \hspace{1cm} (3.3)
Torque expression for field winding machine can be expressed in equation 3.4. It consists of two parts, one part comes from the field flux, and the other is the reluctance torque.

\[
T = \frac{3}{2} P \left( \psi_r I_q + (L_d - L_q) I_d I_q \right)
\]

Figure 3.3 show the torque and power factor variation as function of current angle ideally, assuming the stator current magnitude is constant.

![Figure 3.3 Analytical analysis of the original machine](image)

Figure 3.3a) shows the peak value of torque occurs before 90 degree, the reluctance torque contributes positively to the peak value of the torque. Figure 3.3b) shows the power factor is inductive when the current angle is small and become capacitive as the current angle increases.

### 3.2 Original machine simulation

The original machine is studied by FEM simulation in this section. The relation between simulation accuracy and simulation time steps is studied as well. A clear difference can be found between FEM simulation and analytical results. Further investigation shows the difference is mainly caused by armature reaction of the machine.

Figure 3.4 shows the machine geometry and mesh. Due to symmetry of the machine, only one pole is simulated for simplicity. The airgap mesh is divided into three layers in order to have enough accuracy to calculate torque ripple at no-load.
The relation between the number of simulation steps per period and accuracy is also investigated and shown in figure 3.5. Trade-off should be considered between accuracy and simulation time. Figure 3.5 shows how the simulation steps per period influences the power factor value. Four hundred steps per period was decided to use in the simulation to calculate power factor.

\[ I_a = I_{\text{rated}} \cdot \sin(2\pi ft) \]
\[ I_b = I_{\text{rated}} \cdot \sin(2\pi ft - \frac{2}{3}\pi) \]
\[ I_c = I_{\text{rated}} \cdot \sin(2\pi ft + \frac{2}{3}\pi) \]

(3.5)
The current angle is defined by the angle between d-axis and current vector. The d-axis of the machine is the middle line of rotor pole, and it is easy to change its position by setting rotor’s initial angle in FLUX 2D. Since the machine runs at steady state with constant speed, the angle difference between the current vector and d-axis is fixed during all the simulation period. Therefore, the current angle can be found by the angle difference between initial current vector and initial rotor position.

To fix the current vector at zero time instant, a DC current is used as the input. The DC current represents the sinusoidal current input at 0-time instant, which is shown below:

\[
I_a = I_{\text{rated}} \cdot \sin(0^\circ) = 0 \, A, \quad I_b = I_{\text{rated}} \cdot \sin(-\frac{2\pi}{3}) = -\frac{\sqrt{3}}{2} I_{\text{rated}}, \quad I_c = I_{\text{rated}} \cdot \sin(\frac{2\pi}{3}) = \frac{\sqrt{3}}{2} I_{\text{rated}}
\]

A straightforward explanation of how to find current angle is shown in figure 3.6. Set rotor initial angle to be zero. At t=0 instant, the d-axis is observed locating between C- and B+ winding. The current vector can be found locating in the middle of ‘A’-winding.

![Diagram showing current angle and rotor position](image)

The current angle which gives positive torque production is of interest to investigate. By fixing current vector at ‘A’-position while changing the initial position of d-axis, the output torque with different current angle can be found. Figure 3.7 shows the torque variations as function of rotor position. Per unit is used here, the rated torque is chosen to be the base value.
It is seen that when rotor position initiates between -37.5 to 52.5 mechanical degree, the torque is positive. The rotor locates between B+ and C- winding when d-axis initiates at 0 degree. Hence the current angle varies from 180 to 0 electrical degree if rotor position changes between -37.5 to 52.5 mechanical degree. Thus by changing the rotor initial position from -37.5 to 52.5 mechanical degree, the current angle is varied from 180 to 0 electrical degree correspondingly.

Torque and power factor at every 10 electrical degrees are recorded and plotted in figure 3.8 and figure 3.9, respectively.

Reluctance torque can be calculated by setting the field winding current to be zero. Torque generated from field winding current is calculated by subtracting reluctance torque from the total torque. It can be found in figure 3.8 that the peak value of the field winding torque occurs around 115 degree, consequently the total torque peaks after 90 degree. Figure 3.9 shows the resistive power factor is reached at 109.3 degree.
Another investigation has been done to find how flux lines distribute at the maximum and minimum reluctance torque production points. Figure 3.10 shows flux lines distribution without field winding current at two current angles. It can be seen that rotor is pulled by the flux line when $\beta=45^\circ$. One the other hand, flux line pushes rotor when $\beta=135^\circ$.

A clear disagreement is found between analytical and FEM simulation results as shown in figure 3.11.
Synchronous machine for unidirectional application

It can be seen that the rated current angle $\beta$ has been shifted to a higher value. Reluctance torque contributes positively to the maximum torque theoretically; however, the FEM simulation indicates contribution of reluctance torque becomes negative.

### 3.3 Armature reaction investigation

Section 3.2 showed the difference between analytical and FEM results. The difference can be explained by saturation of the machine. This section investigates saturation influence from armature reaction. It is found that armature reaction effect varies with the varying current angle.

Figure 3.12 shows the flux density distribution along the air gap at three different operation points. The rated stator current and field winding current are used at all the operation points. Saturation can happen when airgap flux density is high. The dashed line represents the total flux density assuming neglectable saturation. The solid line represents saturation effect in the airgap introducing a limit to the peak value of airgap flux density. Both expected results and FEM results are compared in figure 3.12. The expected results disregard slotting effect on the airgap flux density.
Synchronous machine for unidirectional application

a) Flux density distribution along the air gap at $\beta=0^\circ$

b) Flux density distribution along the air gap at $\beta=90^\circ$
Figure 3.12 shows the different armature reaction effect at three current angles. When current angle $\beta=0^\circ$, the net flux in the airgap is reduced to the maximum extent. At $\beta=90^\circ$, the addition of the pole-flux at one edge is smaller than the subtraction at the other. This results in the reduction of the net airgap flux. However, armature reaction gives no saturation when $\beta=180^\circ$ because flux from stator current and field winding is 180 degrees phase different to each other. The rated current angle $\beta=144.6^\circ$, thus the saturation level is between $90^\circ$ and $180^\circ$ at rated condition.

Section 3.2 showed field winding torque is different to the analytical case. Field winding torque is directly related to the airgap flux density and airgap flux density is influenced by armature reaction. It is very interesting to see the field winding torque with reduced armature reaction effect.

Field winding torque with reduced stator current is calculated and shown in figure 3.13.
Figure 3.13 Torque generated by field winding current with different stator currents and field winding currents

It can be seen that lower stator current shifts the peak point of field winding torque towards 90° current angle. Saturation also depends on field winding current. When stator current has 25% rated value and field winding current has 50% rated value, the peak value of field winding torque almost reaches 90° current angle.

3.4 Losses calculation

3.4.1 Stator iron losses

The engineering method to determine iron losses is to separate it into three types, the hysteresis losses, eddy current losses as well as excess losses [21]. Iron loss density in FLUX 2D is calculated by equation 3.6 [24]:

\[
p_{iron} = k_{hyst} B^2 k_f f + \frac{1}{T} \int_0^T \left( \frac{\sigma_{iron} d_{lam} \left( \frac{dB(t)}{dt} \right)^2}{12} + k_{exc} \left( \frac{dB(t)}{dt} \right)^3 \right) k_f dt
\]

(3.6)

Where \( k_f \) is stacking factor, \( k_{hyst} \) is the hysteresis loss coefficient, \( k_{exc} \) is the excess loss coefficient, \( \sigma_{iron} \) is the conductivity of the iron lamination, \( d_{lam} \) is the lamination thickness.

The lamination used in the stator is M350-50A. Stator iron losses consist of three parts: stator teeth losses, stator yoke losses and stator teeth tip losses. Stator iron losses of each part at rated point are compared in table 3.1.

The losses are given in per unit, which can be calculated by using the physical value of losses divided by the rated power of the machine.
Table 3.1 Iron losses in stator teeth, stator yoke and stator teeth tip

<table>
<thead>
<tr>
<th>Stator</th>
<th>Iron losses [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stator teeth</td>
<td>0.0004</td>
</tr>
<tr>
<td>Stator yoke</td>
<td>0.0012</td>
</tr>
<tr>
<td>Stator teeth tip</td>
<td>0.000032</td>
</tr>
</tbody>
</table>

Table 3.1 shows iron losses in each part of the stator. It can be found that stator iron losses of original machine are 0.0017 p.u..

### 3.4.2 Rotor eddy current losses

The rotor eddy current losses are introduced by harmonics in the airgap. It is found that rotor eddy current introduces a long transient time. It takes around 2 seconds to reach steady state. Three seconds simulation time is used to ensure the machine already reaches its steady state.

![Eddy current losses](image)

DC component of rotor eddy current losses in steady state can be calculated by using Fourier analysis for the last several periods. It can be seen in figure 3.16 that DC component of rotor eddy current losses in steady state is 0.00035 p.u..

### 3.4.3 Efficiency calculation

Copper losses is calculated in equation 3.7:

\[
P_{copper} = P_{copper\_stator} + P_{copper\_fieldwinding} = 3 \cdot I_s^2 \cdot R_s + 4 \cdot I_{fw}^2 \cdot R_{fw} = 0.0155\text{ p.u.}
\]  

(3.7)

Since it is constant current supply, the copper losses for all the cases remains the same. The electrical magnetic efficiency is calculated by following equation:

\[
\eta = \frac{P_2}{P_2 + P_{losses}} = \frac{T_{rated} \cdot \omega}{T_{rated} \cdot \omega + P_{copper} + P_{iron}} = 97.93\%
\]

(3.8)

The real efficiency of the machine in a real world application is lower than the calculated value because of other losses such as friction losses.
3.5 Summary

1) Saturation reduces the maximum torque. It not only reduces the maximum value of field winding torque, but also shifts the peak value of field winding torque towards higher current angle where the reluctant torque is negative.

2) The rated point of the machine is shifted because of saturation. Hence, when the machine is analyzed by analytical calculation, a compensation value for the rated current angle should be considered.

3) Armature reaction effect of the machine varies with the varying current angle.
4 Asymmetrical rotor pole study

The original machine was studied both analytically and by FEM simulation. This chapter investigates asymmetrical rotor pole shape ideas. Two ideas, asymmetrical pole shoe and progressive airgap are suggested and studied. Firstly, pole shoe cutting is applied to investigate the influence of asymmetrical pole shape. Secondly, progressive airgap is investigated which shows power factor improvement in one rotational direction. Lastly, improved design of progressive airgap is suggested to reduce the torque ripple.

4.1 Pole shoe cutting (Idea 1)

To investigate how asymmetrical rotor shape influences pole machine’s characteristic, three cuts have been made as shown in figure 4.1. Idea 1a gives one quarter cutting on the rotor pole shoe, idea 1b and 1c cut half and three quarters of the rotor pole shoe, respectively.

![Figure 4.1 Asymmetrical pole shoe shape by cutting](image)
Figure 4.2 shows the airgap flux density distribution at no load for the original machine and idea 1.

![Airgap flux density distribution over one pole at no load](image)

Table 4.1 shows fundamental airgap flux density at no load for original machine and idea 1. It can be seen that the fundamental airgap flux density is reduced by the increased airgap.

<table>
<thead>
<tr>
<th>Type</th>
<th>Original machine</th>
<th>Idea 1a</th>
<th>Idea 1b</th>
<th>Idea 1c</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deduction in no-load airgap flux density compare to the original machine in percentage [%]</td>
<td>0</td>
<td>0.6</td>
<td>4.2</td>
<td>12.7</td>
</tr>
</tbody>
</table>
Figure 4.3 shows the maximum torque goes down with pole shoe cutting. This can be explained by the fact that the fundamental flux density of the airgap decreases because of the increased airgap.

Reluctance torque can be found by calculating the torque without field winding current. It can be seen in figure 4.4 that reluctance torque is phase shifted by asymmetrical rotor pole shoe. Since the total torque is the summation of torque from field winding current and reluctance torque, the contribution from the reluctance torque to the total torque varies with varying current angles. Figure 4.4 shows original machine has largest reluctance torque between 0° to 50° and 155° to 180°, while idea 1c results in the most torque contribution between 85° to 155°.
Field winding torque can be calculated by subtracting the total torque from the reluctance torque, which is shown in figure 4.5.

Figure 4.5 shows the peak value of torque generated from field winding current goes down with pole shoe cutting. Power factor variation as function of current angle is shown in figure 4.6. It can be found that pole shoe cutting decreases the power factor value in the inductive power factor range, while increase its value in the capacitive power factor range. Compared to the original machine, pole shoe cutting gives worse power factor,
4.2 progressive airgap (Idea 2)

Reference [4] and [7] suggests progressive airgap can be used to reduce armature reaction effect. In order to investigate the principle of progressive airgap, two cases have been studied which are shown in figure 4.7. Both machines rotate in counter-clockwise direction.

Figure 4.7 shows airgap varies progressively while the average length of the airgap is kept constant.
Figure 4.8 Total torque comparison

Figure 4.8 shows the maximum torque with constant current can be improved slightly with Idea 2b, and the maximum torque of idea 2a goes down. Both the field winding torque and reluctance torque are calculated to investigate the torque change.

Figure 4.9 Field winding current torque comparison

Figure 4.9 shows the peak value of field winding torque of idea 2b is 3.8 % larger than the original machine. For idea 2a, the peak value of field winding torque is reduced. This can be explained by the
fact that armature reaction with asymmetrical pole shape of Idea 2b is reduced within positive torque range. For idea 2a, the armature reaction effect occurs oppositely.

It can be found that reluctance torque is shifted by asymmetrical rotor pole design, as shown in figure 4.10. When current angle varies between 0 to 50 degree and 125 to 180 degree, reluctance torque of Idea 2b contributes highest value to the total torque. Idea 2a has the highest reluctance torque production during 50 to 125 degree current angle.

The total torque consist both field winding torque and reluctance torque. The fielding winding torque of idea 2b has been improved by reduction of armature reaction; however, the reluctance torque of idea 2b at the current angle which gives the maximum total torque has the least value.

Figure 4.10 also shows that the positive and negative peak values of the reluctance torque become different when the rotor pole is asymmetrical.
Figure 4.11 shows the torque ripple of Idea 2b and Idea 2a has been increased, the way to lower the torque ripple is discussed later. Torque ripple is calculated by using the peak-to-peak value of torque variations divided by the rated torque.

Figure 4.12 shows the power factor variation as function of current angle. The change of power factor can be explained by the phasor diagram shown in figure 4.14. The location of d-axis is in the middle of the rotor pole. With progressive airgap, the iron distribution along the rotor pole shoe becomes asymmetrical. As illustrated in figure 4.13, the real d-axis for the asymmetrical motor is no longer the
middle line of the rotor pole. The phasor diagram of Idea 2b is analyzed and compared with the original machine in figure 4.14.

It can be seen in figure 4.14 that the d axis has shifted a certain angle to the right. As shown in figure 4.14 a), when the current stays in the first quadrant, the angle between stator voltage and current goes down, resulting in a higher inductive power factor. Figure 4.14 b) shows the power factor angle goes up when the stator current moves to the second quadrant, leading to an improved capacitive power factor.

4.3 Improvement of progressive airgap

The disadvantage of using Idea 2b is the higher torque ripple. A great contributor of the higher torque ripple is the torque ripple at no-load. Torque ripple at no-load of the original machine and Idea 2b are shown in figure 4.15.
Figure 4.15 shows the peak-to-peak value of the torque ripple at no-load of the original machine is 0.99 %, however, this value is increased to 3.14 % in Idea 2b.

Torque ripple at no-load of field winding synchronous machine can be explained in the same way as cogging torque in PM machine. Cogging torque can be regarded as interaction between PM edge and stator teeth as shown in figure 4.16.

The original machine has a low torque ripple at no-load thanks to the large airgap. However, the asymmetrical pole shape reduces distance between one corner of the rotor pole and stator teeth tip. As a result, torque ripple from that pole edge at no-load has been increased greatly.

Simply lowering one edge of Idea 2b can reduce torque ripple at no-load. However, the effective airgap length would be increased consequently. An improvement can be made to the asymmetrical design without changing the average airgap length. Figure 4.17 d) shows the improved rotor pole shape, i.e. Idea 2c, which has a lower right edge. The torque ripple at no-load generated from this edge is reduced. The average airgap length remains constant since the area A, B, C and D is equal.
Synchronous machine for unidirectional application

Rotors pole shoe shape of Idea 2c is shown in figure 4.18.

Figure 4.17 Asymmetrical pole designs with constant average airgap length

The torque ripple at no-load comparison between original machine, Idea 2b and Idea 2c is shown in figure 4.19. It can be found that torque ripple at no-load of Idea 2c has almost as low value as the original machine.
The peak-to-peak torque ripple at no-load value of Idea 2c is reduced to 1.28 %, a significant reduction compare to Idea 2b.

Table 4.2 Machine performance comparison at rated condition as well as maximum torque (Constant current)

<table>
<thead>
<tr>
<th></th>
<th>Efficiency [%]</th>
<th>Power factor</th>
<th>Torque ripple [%]</th>
<th>Torque ripple at no-load [%]</th>
<th>Stator iron losses [p.u.]</th>
<th>Rotor eddy current losses [p.u.]</th>
<th>Maximum torque with constant current [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original machine</td>
<td>97.93</td>
<td>0.794</td>
<td>2.87</td>
<td>0.99</td>
<td>0.00168</td>
<td>0.00035</td>
<td>1.58</td>
</tr>
<tr>
<td>Idea 2a</td>
<td>97.87</td>
<td>0.802</td>
<td>5.40</td>
<td>3.09</td>
<td>0.00166</td>
<td>0.00078</td>
<td>1.57</td>
</tr>
<tr>
<td>Idea 2b</td>
<td>97.93</td>
<td>0.782</td>
<td>4.66</td>
<td>3.14</td>
<td>0.00169</td>
<td>0.00029</td>
<td>1.59</td>
</tr>
<tr>
<td>Idea 2c</td>
<td>97.93</td>
<td>0.781</td>
<td>2.93</td>
<td>1.28</td>
<td>0.00171</td>
<td>0.00031</td>
<td>1.59</td>
</tr>
</tbody>
</table>

Table 4.2 shows the comparison between the original case, Idea 2a, Idea 2b and Idea 2c. It can be seen that the idea 2c has the same power factor improvement as idea 2b, but with much improved torque ripple.

An interesting investigation is done for Idea 2c. The stator current and power factor are kept the same value as the original machine at rated point, but the field winding current is changed to investigate how much rotor copper losses can be saved. This can be done by several iterations. It is found that the field winding current can be reduced 2.67% while keep the same power factor as the original machine. This means a 5.26% reduction for the rotor copper losses.
4.6 Summary

1) The asymmetrical pole shape can reduce armature reaction of the rotor in one rotational direction, but enlarge its effect in the other direction.

2) The asymmetrical pole shape can cause reluctance torque shifted in a certain direction. Idea 2b shows the reluctance torque has negative contribution to the maximum torque production due to shifting. Further investigation can be done to improve the contribution of reluctance torque to the maximum torque.

3) Asymmetrical pole shape provides possibility of friction reduction in one rotational direction.

4) The reluctance torque is calculated without field winding in this section. However, field winding current introduces saturation to the rotor which influences the reluctance torque. Thus the field winding torque curves could be a bit different if saturation influence on reluctance torque is considered.
5 PM-assisted machine study

This chapter studies the possibility of using additional permanent magnet to reinforce the machine’s characteristic. Four ideas regarding additional PM are applied to the original machine.

The permanent magnet material used in this chapter is Neorem 493a. Table 5.1 shows the nominal characteristics of Neorem 493a at 20°C [26]:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_r )</td>
<td>1.15 T</td>
</tr>
<tr>
<td>( B_H )</td>
<td>880 kA/m</td>
</tr>
<tr>
<td>( J_H )</td>
<td>2100 kA/m</td>
</tr>
<tr>
<td>((BH)_{max})</td>
<td>250 kJ/m³</td>
</tr>
</tbody>
</table>

Figure 5.1 shows magnetization curve of Neorem 493a at different temperatures. The working temperature of this machine is 95°C. It can be seen that the remanence flux density at 100°C is \( B_r = 1.06 \) T.

5.1 Hybrid pole with assisted PM (Idea 3)

The hybrid pole structure is shown in figure 5.2 b). PM material is added to the rotor pole. The rotor pole consist not only electrical steel but also PM material. Thus the total torque is a sum of torque generated from field winding current, PM and reluctance torque. Idea 1b (pole shoe cutting) is also presented in figure 5.2 a) to compare with the hybrid pole.
Synchronous machine for unidirectional application

Figure 5.2 Structure of Idea 1b and hybrid pole with assisted PM

Figure 5.3 shows flux density distribution of original machine and hybrid pole at no load.

Figure 5.3 Flux density distribution at no load comparison between original machine, Idea 1b and Idea 3

It can be found that the no-load fundamental flux density of Idea 3 has been improved by 0.17 % compared to the original machine in figure 5.3. The torque diagram is shown in figure 5.4.
Figure 5.4 Total torque comparisons among original machine, Idea 3 and idea 1b

Figure 5.4 shows torque improvement is neglectable compare to the original machine. Figure 5.5 shows the torque from PM increases as field winding current decreases. The torque from PM is calculated by using torque generation from hybrid pole (Idea 3) subtract torque from pole shoe cutting (Idea 1b). It can be found that the torque generated from PM is restricted by saturation.
Figure 5.6 shows the power factor of the hybrid pole and original machine. The power factor has no clear improvement to the power factor of original machine.

Table 5.2 shows the comparison between original machine and Idea 3. The eddy current losses on PM are neglected here, but in reality it introduces eddy current losses as well.

### Table 5.2 Comparison between original machine and Idea 3 at rated point as well as maximum torque

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum torque [p.u.]</th>
<th>Torque ripple [%]</th>
<th>Efficiency [%]</th>
<th>Power factor</th>
<th>Stator iron losses [p.u.]</th>
<th>Rotor eddy current losses [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original machine</td>
<td>1.58</td>
<td>2.87%</td>
<td>97.93</td>
<td>0.794</td>
<td>0.00168</td>
<td>0.00035</td>
</tr>
<tr>
<td>Hybrid pole</td>
<td>1.60</td>
<td>3.20%</td>
<td>97.94</td>
<td>0.767</td>
<td>0.00179</td>
<td>0.00017</td>
</tr>
</tbody>
</table>

### 5.2 PM slit (Idea 4)
Reference [4] shows adding a slit on the rotor can reduce armature reaction in a hybrid excitation machine. The slit has following functions [4]:

1) Set obstacles to eddy current in solid rotor machines
2) Reduce the armature reaction effect because the armature reaction has to bypass the slits.

This idea is applied to the original machine to investigate the possibility of performance improvement. Figure 5.7 shows the original machine with slit in the middle of the pole.
Torque increase of Idea 4 compared to the original machine is shown in figure 5.8.

The torque difference is calculated by using the torque generated from machine with slit subtracts the original machine’s torque. Figure 5.8 shows the slit’s influence on saturation is not dramatic. It’s effect varies as current angle changes. The maximum torque increase occurs at around 45 degree. It can be seen in figure 5.8 that if current angle varies between 0 to 83 degree, slit contributes positively to the total torque. Slit contribution becomes negative when current angle changes between 83 to 180 degree.

The comparison between original machine and Idea 4 can be found in table 5.3.
Table 5.3 Comparison between original machine and Idea 4 at rated point as well as maximum torque

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum torque [p.u.]</th>
<th>Torque ripple [%]</th>
<th>Efficiency [%]</th>
<th>Power factor</th>
<th>Stator iron losses [p.u.]</th>
<th>Rotor eddy current losses [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original machine</td>
<td>1.58</td>
<td>2.87%</td>
<td>97.93</td>
<td>0.794</td>
<td>0.00168</td>
<td>0.00035</td>
</tr>
<tr>
<td>Slit</td>
<td>1.58</td>
<td>2.79%</td>
<td>97.93</td>
<td>0.795</td>
<td>0.00167</td>
<td>0.00034</td>
</tr>
</tbody>
</table>

The reason that slit has very small influence on saturation reduction is due to the large airgap length. The permeance of the magnetic circuit for armature reaction is closely related to the airgap length. A large slit can increase the permeance of the magnetic circuit, but it increases the effective airgap length at the same time.

Reference [4] mentions slit provides the possibility to receive a compensation device, for example permanent magnets. The possibility to apply this method to field winding synchronous machine is investigated here. Figure 5.9 shows the permanent magnet is fixed inside slit as compensation device.

![Figure 5.9 Permament magnet used inside slit as compensation device](image)

Figure 5.9 b) shows PM is magnetically short-circuited inside the rotor pole. Consequently almost no flux from PM can pass the airgap. Two kinds of PM orientation, positive 45 degree and negative 45 degree, are studied respectively. The torque changes of these two cases are shown in figure 5.10.
Figure 5.10 shows the PM slit has no contribution to the maximum torque production of the machine. The flux of PM slit is restricted inside the rotor pole because of the large airgap length. But for electrical machine with small airgap length, the slit may has more effects on reducing aramture reaction.

### 5.3 Saturation mitigation by Additional PM (Idea 5a)

Reference [23] proposed the idea of using additional PM to reduce magnetic saturation of the rotor pole body, which is shown in figure 5.11 a). Figure 5.11 b) shows the additional PM is added to both side of the rotor by mechanical connection. Connection material is chosen to be non-magnetic material, e.g. stainless steel.
It can be seen in figure 5.12 that PM flux lines come into the rotor pole body. Flux density distribution at no load of original machine and machine with additional PM are presented and compared in figure 5.13. Two types of PM orientation are studied and compared.

Figure 5.13 a) shows one type of PM orientation (type I) where the flux line of PM goes opposite to the field winding flux; the other orientation (type II) generates flux with the same direction as field winding flux.

<table>
<thead>
<tr>
<th>Type of machine</th>
<th>Original</th>
<th>Additional (Type I)</th>
<th>Additional (Type II)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increase in no-load airgap flux density compare to the original machine in percentage [%]</td>
<td>0</td>
<td>1.18</td>
<td>-1.35</td>
</tr>
</tbody>
</table>
Area within the red lines shows how the flux from the outer edges of PM influence the airgap flux density. These flux lines of type I reduces the airgap flux density.

It can be seen from table 5.4 that type I increases the fundamental component of airgap flux density. This is because of the reduction of saturation in the rotor body. While type II shows fundamental flux density goes down when saturation level increases.

Figure 5.14 shows the torque difference between Idea 5a and the original machine, it can be found that additional PM of type can improve the output torque by reducing rotor saturation. If more PM material can be added on both sides of the rotor pole, the effects of addition PM can be much greater.

The comparison between the original machine and idea 5a is listed in table 5.5. The maximum torque for idea 5a (type I) is 0.6 % higher than the original machine.

Another possible structure is also investigated by changing the position of PM and the connection. The connection should be magnetic conducting material to provide a path for the PM flux. Figure 5.15 shows the construction of this idea. Figure 5.16 shows the flux density distribution at no load.
5.4 Q-axis flux injection by Additional PM (Idea 5b)

The idea of q-axis flux injection can be explained by the phase diagram in figure 5.17. If an additional induced voltage in phase with d-axis can be added into the phasor diagram, the total induced voltage $E'$ will be phase shifted towards d axis.

Figure 5.16 shows the connection as well as rotor pole body are saturated at no-load condition. As a result, not all the PM flux would enter into steel path and additional PM has no effect to reduce saturation.
Figure 5.18 shows how the additional PM should be positioned and the flux lines from the PM.

The mechanical connection should be magnetic non-conducting material, which is neglected here for simplicity. The right figure shows the flux lines from the PM without field winding current and stator current.
The torque generated from PM is calculated by using the total torque of Idea 5b minus the torque of the original machine. The torque generated from PM is 90 degree phase shifted with respect to the original machine theoretically. Figure 5.19 b) shows the contribution to the maximum torque from PM is almost zero.

Figure 5.20 shows power factor of Idea 5b is improved. It can be seen in table 5.6 that torque ripple of Idea 5b becomes worse for Idea 5b because cogging torque from PM is added.
Table 5.6 Comparison between original machine and Idea 5b at rated point as well as maximum torque

<table>
<thead>
<tr>
<th>Type</th>
<th>Maximum torque [p.u.]</th>
<th>Torque ripple [%]</th>
<th>Efficiency</th>
<th>Power factor</th>
<th>Stator iron losses [p.u.]</th>
<th>Rotor eddy current losses [p.u.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original machine</td>
<td>1.58</td>
<td>2.87</td>
<td>97.3</td>
<td>0.794</td>
<td>0.00168</td>
<td>0.00035</td>
</tr>
<tr>
<td>Idea 5b</td>
<td>1.59</td>
<td>4.37</td>
<td>97.90</td>
<td>0.785</td>
<td>0.00192</td>
<td>0.00033</td>
</tr>
</tbody>
</table>

5.5 PM substitution (Idea 6)

It is interesting to investigate the possibility of substituting the rotor pole with permanent magnet. The rotor pole consists of two parts. In order to study this idea, 4 cases are proposed and simulated regarding different substituted part and field winding current which is shown in table 5.7. The PM flux has the same direction as the flux from field winding.

![Rotor pole structure](image)

**Figure 5.21 Rotor pole structure**

Table 5.7 Four types of PM substitution

<table>
<thead>
<tr>
<th>Type</th>
<th>Idea 6a</th>
<th>Idea 6b</th>
<th>Idea 6c</th>
<th>Idea 6d</th>
</tr>
</thead>
<tbody>
<tr>
<td>Part I/ Part II</td>
<td>PM/Iron</td>
<td>PM/Iron</td>
<td>PM/PM</td>
<td>PM/PM</td>
</tr>
<tr>
<td>I_f_w [p.u.]</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

No-load flux density distributions over the airgap of all the above cases as well as the original machine are shown in figure 5.22. It can be found that flux density distribution is reduced with PM substitution. This can be explained by the fact that the permanent magnet has as low permeability as air. Substitution PM would increase the effective airgap length.
Synchronous machine for unidirectional application

Figure 5.22 No-load flux density distribution over the airgap

Figure 5.23 shows the torque and power factor variation as function of different current angle.
It can be seen in figure 5.23 a) that torque with PM substitution goes down for all the 4 cases due to the reduction of no-load flux density.

Figure 5.23 b) shows the power factor variation as function of current angle for Idea 6. The power factor change of Idea 6 is not clear.

Larger effective airgap can reduce armature reaction, however, it reduces the flux density from field winding at the same time.
5.6 Summary

Four methods have been tried to improve the machine performance. However, it is found that the improvements of these ideas are not dramatic. The effects of these ideas and limited influences are summarized as following:

1) Hybrid pole (Idea 3): Torque from the PM is restricted by the strong field winding current.

2) Slit (Idea 4a): Slit has little influence to reduce the armature effect because the arigap length is much greater than the slit width.

3) Slit with PM (Idea 4b): PM inside slit is found to be short-circuited inside the rotor.

4) Additional PM (Idea 5a): Additional PM on both sides of the rotor can reduce saturation and increase the airgap flux density. More PM can be added when a machine with higher pole number is used.

5) Additional PM (Idea 5b): Additional PM can be used to improve power factor. But it introduces additional cogging torque at the same time.

6) PM substitution (Idea 6): Torque is reduced by PM substitution because the actual airgap length is increased (PM has a low permeability).
6 Conclusions and future work

The purpose of this thesis is to investigate the possibilities for performance improvements of synchronous machines with unidirectional rotation. Six ideas have been studied and presented in the report. The conclusions which are already known and the further work to be done in the future are shown in this chapter.

6.1 Conclusions

A summary table is presented with all the ideas investigated in this report and their corresponding effects.

<table>
<thead>
<tr>
<th>Idea</th>
<th>Pole shoe cutting (Idea 1)</th>
<th>Progressive airgap (Idea 2)</th>
<th>Hybrid pole (Idea 3)</th>
<th>Slit (Idea 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect</td>
<td>•Reduce output torque  &lt;br&gt; • Reduce power factor</td>
<td>•Improve P.F  &lt;br&gt; • Reduce armature reaction  &lt;br&gt; • Higher torque ripple can be solved by improved design</td>
<td>•Effect of PM is limited by saturation</td>
<td>•Influence armature reaction  &lt;br&gt; • Limited by large airgap  &lt;br&gt; • Slit with PM is short circuited inside the rotor pole</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Idea</th>
<th>Additional PM—reduce saturation (Idea 5a)</th>
<th>Additional PM—improve P.F. (Idea 5b)</th>
<th>PM substitution (Idea 6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect</td>
<td>•Reduce saturation level  &lt;br&gt; • Limited by the space, could have better effect in motor with higher pole numbers</td>
<td>•Improve P.F.  &lt;br&gt; • Additional cogging torque from PM</td>
<td>•Weaker airgap flux density</td>
</tr>
</tbody>
</table>
6.2 Future work

The studied topic is a very generous topic which can be applied to all types of machines. The following aspect is of interest to investigate in the future.

1) Mechanical requirements of all the ideas are disregarded; future work should take mechanical requirement into account.

2) Pole shifting to reduce cogging torque (section 2.3). It is interesting to see how the harmonic spectrum varies by pole shifting (The low-order harmonics are supposed to be canceled.)

3) Combination of asymmetrical pole shape and PM-assisted ideas could be an interesting investigation.

4) The original field winding synchronous machine is already optimized. It has large airgap, great input current, capacitive power factor working point and etc. All these could affect the asymmetrical machine’s performance. However, in other applications, e.g. machine with smaller airgap, larger pole numbers, asymmetrical ideas could lead to more positive result than what has been shown in this report.
7 References


Synchronous machine for unidirectional application


[21] Andreas Krings and Juliette Soulard, "Overview and comparison of iron loss models for electrical machines" March 2010, KTH


[24] FLUX 2D online documentation, iron losses calculation
