Middle East Technical University

EE568 - Selected Topics on Electrical Machines

Electrical Electronics Engineering

PM Motor Comparison Analysis

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Project 4

http://keysan.me/ee568/

Introduction

In this report, Different electrical machines are designed, analyzed and compared. Roughly, technical specifications of machine are,
-Power rating: 125 kW
-Rated speed: 5000rpm
-Pole number: 4 poles
Generated files for analyses of FEA are uploaded to the GitHub repository. ANSYS Rmxprt are used for the analyses.

Question 1

Literature of review for permanent magnet assisted synchronous reluctance machine (PMASRM) is held in this part. Current status of machine type is researched, discussed and summarized.

There is an increasing demand for synchronous reluctance machine for some specific applications because there is higher requirement for power factor and also it is less dependent on rare earth permanent magnets like NdFeB or SmCo. It also has advantages like high efficiency compared to the induction machine, wide speed range at constant power, high torque-volume ratio, capable for detection of rotor position, cost-friendly manufacturing. Still, additional permanent magnet will help to increase flux linkage even with cheap and easily accessible ferrite magnets [1].

PMASRM is novel machine among interior permanent magnet (IPM) machine. Besides its advantages, it also has some disadvantages like relatively low power factor compared to synchronous machines, high torque ripple and higher price depending on the magnet material [2].

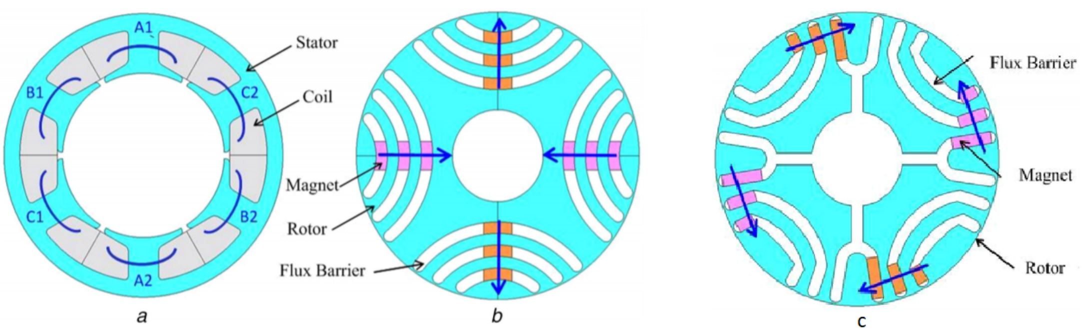

Figure 1: Cross section of machine part (a) Conventional stator model (b) Conventional rotor model of PMASRM (c) Rotor model with asymmetrically inserted permanent magnets[2]

Stator of PMASRM is very similar to synchronous machines as it is shown in Fig-1(a). Conventional rotor of PMASRM has permanent magnet placed into every single rotor flux barrier. Cross section of the conventional rotor with placed multiple parallel permanent magnets is given in Fig-1(b) [2]. Placing permanent magnets asymmetrically is also studied and shown in Fig-1(c). Purpose of this process is decreasing the rotor leakage. An experiment is carried on the machine which has 6 stator slot, 4 pole with 0.5mm air-gap, 88 mm as outer diameter of stator and 50 mm as outer diameter of rotor while stack length is 52 mm as specifications to prove the reducing rotor leakage flux. Rated speed of machine is 4800 rpm while number of turns for winding is 125 [2].

Additional permanent magnet will, of course, increase the total cost. Therefore, there should be notable improving effect on the machine. There are some studies to examine the effect and compare the performance of synchronous reluctance machine and PMASRM. There is a study which uses two types of machine which specifications are given in Table-I that shows the results of comparison. As it is obivious in the results, adding permanent magnets has increased efficiency 5% and reduced the rated current more than 20% for same size, speed and power rating [3].

TABLE I. THE STUDIED MACHINES' DESIGN AND MEASURED PARAMETERS

Parameter \ Machine	SynRM	PMSynRM
Frame size	132 MA	132 MA
Rated Power (kW)	10.5	10.5
Number of poles	2	2
Rated Speed (rpm)	1500	1500
Moment of inertia (kgm^2)	0.02	0.04
R_s (Ω)	0.72	0.72
L_d (H)	0.08	0.09
L_q (H)	0.02	0.01
cos(ϕ)	0.6	0.8
Rated current (A)	25.3	18.9
Efficiency	85.2%	90.6%

DC and AC copper losses for PMASRM and iron losses are investigated to observe parametric effect on efficiency. Experimental machine has 8 pole and 9 slot while torque is 0.874 Nm and maximum speed is 14000 rpm. Magnet material is NdFeB and outer diameter of stator is 117 mm. DC copper loss is 18 W while AC skin/proximity loss is 2 W average value depending on the speed since it is related to frequency. Iron loss is determined as 13 W for a PMASRM which has 750 W power rating. The results are verified with finite element analysis (FEM) with 2.71% difference [4].

Permanent magnets can be demagnetized for high performance operating conditions. Temperature, operating point of magnet, current magnitude or combined some of these conditions can cause demagnetizing. Relatively demagnetization will end up low flux density. In order to observe the condition of permanent magnets, a parameter called 'demagnetization ratio' is presented in a study [5].

There is also studies about bearingless PMASRM that compares single winding and double winding machines. Single winding machine is proposed depending on simplicity of stator windings and compactness of complete machine. Results show that suspension force is increases 18.71% by using bearingless single winding PMASRM compared to double winding PMASRM while having better performance [6]. It was pointed out that demagnetization of magnet has a negative effect on machine. Therefore, distributed and concentrated windings are compared by their performance of reluctance torque and anti-demagnetization capability. Results show that distributed winding has better performance than concentrated winding and it is verified by experimental study [7].

Question 2

Rough sizing of machine and analytical calculations are provided to determine design parameters in detail. Torque and output power is also calculated. For this part, The machine is specified machine type, PMASRM which is notified by mail. It has 125 kW power output, 5000 rpm speed and 4 poles.

Parameters are determined based on advantages and disadvantages. High number of slot has higher overload capacity while reducing pulsation but manufacturing is harder and magnetizing current is higher. There are some parameters which are estimated as;
Number of slots: 36
Number of poles: 4
Air gap clearance: 0,8 mm
Axial length: 100 mm
Outer diameter of rotor : 220 mm

There are some constants to ease to design depending on the experiences. Ratio of inner and outer diameter of stator is determined for 4 pole machines. Since airgap and rotor diameter is already defined, by this ratio, outer diameter of stator can be determined;
Rule of thumb for 4 pole: $D_o/ID = 1,88$
Inner diameter of stator ID: 220,8 mm
Outer diameter of stator D_o: 415 mm

Slot width can be calculated for parallel slot design which assumes teeth thickness and slot width are equal. For 36 slot machine, inner perimeter of stator needs to be divided to 72 pieces;
Teeth thickness: $\pi * 220,8/72 = 9,63mm$
Slot width: 9,63 mm

By determining slot ratio, back core thickness, slot height and slot area is calculated. There is an optimum point for slot ratio to obtain maximum torque. The ratio increases as the teeth gets thicker and decreases as the teeth gets thinner.
Slot ratio: $ID/OD = 0,6$
$OD = 368mm$
Back core thickness: 23,5 mm
Slot height: $(368 - 220,8)/2 = 73,6mm$
Slot area: $73,6 * 9,63 = 708mm^2$

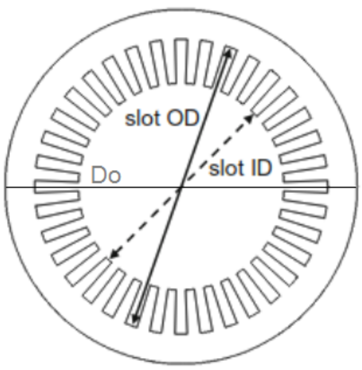

Figure 2: Notation of dimension

To determine number of turns, current, current density and fill factor need to be assumed There is certain number of turns for exact fill factor, current and current density since slot area is already determined. Power rating for one phase is 25 kW. DC link voltage is specified as 360 V in the paper which was notified over mail. Therefore, current is about 60 A. AWG 14 is used which has 2 mm^2 cross section area and paralleled 5 times to reach 10 mm^2 to be able to carry 60 A current with 6 A/mm^2 current density.
Current density: 6 A/mm^2
Current: 200 A
Wire size: AWG 14 ($2mm^2$)
Maximum number of turns: 708/33 = 21
Number of turns: 3

Electrical loading;

$$A = \frac{N_{turn} I Q}{\pi D_i} \tag{1}$$

$$A = \frac{3.200.36}{\pi 0,22} \tag{2}$$

$$A = 31252 A/m \tag{3}$$

Magnet grade: N35H
Magnet thickness: 6 mm
B_r: 1.17 T
$\mu_r = 1,05$

$$\mathcal{R}_{gap} = \frac{0,8.g}{A.\mu_0} \tag{4}$$

$$\mathcal{R}_{magnet} = \frac{6.g}{1,05.A.\mu_0} \tag{5}$$

$$\mathcal{R}_{magnet} = 7,142.\mathcal{R}_{gap} \tag{6}$$

$$\mathcal{R}_{gap} = 1,026T \tag{7}$$

Magnet to pole pitch ratio: 0,9

$$B_{avg} = 1,026.0,9 = 0,923T \tag{8}$$

$$B_{fundamental} = 0,923.\frac{4}{\pi} = 1,17T \tag{9}$$

$$B_{fundamental} = 0,923.\frac{4}{\pi} = 1,17T \tag{10}$$

Magnetic loading;

$$B = \frac{2}{\pi}.1,17 = 0,74T \tag{11}$$

Machine constant;

$$C = \frac{\pi^2}{2} k_\omega AB \tag{12}$$

Winding factor is 0,9598;

$$C = \frac{\pi^2}{2}.0,9598.31252.0,74 \tag{13}$$

$$C = 109540 \tag{14}$$

Tangential stress;

$$\sigma_{tan} = \frac{A.B}{\sqrt{2}} \tag{15}$$

$$\sigma_{tan} = \frac{31252.0,74}{\sqrt{2}} = 16353 \tag{16}$$

Torque;

$$\mathcal{T} = \sigma_{tan}.S_r.D_r \tag{17}$$

$$\mathcal{T} = 16353.\pi.0,22.0,1.0,226 = 248,65Nm \tag{18}$$

Output power for 3000 rpm;

$$\mathcal{P}_{out} = \mathcal{T}.\omega \tag{19}$$

$$\mathcal{P}_{out} = 248,65.\frac{500}{3}.\pi = 130005W \tag{20}$$

To estimate one of electrical circuit parameters, induced phase voltage;

$$E_{ph} = \sqrt{2}.\pi.f.\phi.N.k_\omega \tag{21}$$

$$f = \frac{N.p}{120} \tag{22}$$

$$f = 167Hz \tag{23}$$

$$\phi = \frac{2}{\pi}B.\tau_p.l \tag{24}$$

Where τ_p is pole pitch in flux per pole equivalent;

$$\tau_p = \pi \frac{D_s}{p} \tag{25}$$

$$\tau_p = 325,9mm \tag{26}$$

Placing τ_p into flux per pole equivalent,

$$\phi = \frac{2}{\pi} 0,74.0,3259.0,1 = 0,0153Wb \tag{27}$$

Induced phase voltage;

$$E_{ph} = \sqrt{2}.\pi.167.0,0153.3.0,9598 = 326V \tag{28}$$

Phase inductance is;

$$L = \frac{\lambda}{I} \tag{29}$$

$$L = \frac{N.\phi}{I} \tag{30}$$

$$L = \frac{3.0,0153}{200} = 22,9uH \tag{31}$$

Question 3

FEA modelling of machine which designed for question 2 is carried out in this part. Machine model is two dimensional since Ansys Rmxprt is used.

Results of FEA are presented below for final design. Steady state parameters contain phase inductances and phase resistances for both d and q axis. Rotor diameter is 220 mm while axial lenght is 100 mm and outer diameter of stator is 415. Therefore, aspect ratio of the machine is0,1/0,415=0.23. Typical aspect ratio for synchronous machines is 0,39 which makes possible to see that final design has reasonable aspect ratio.

```
STEADY STATE PARAMETERS

Stator Winding Factor:        0.959795
D-Axis Reactive Inductance Lad (H):        0.00114443
Q-Axis Reactive Inductance Laq (H):        0.00114443
D-Axis Inductance L1+Lad (H):        0.00151062
Q-Axis Inductance L1+Laq (H):        0.00151062
Armature Leakage Inductance L1 (H):        0.000366189
Slot Leakage Inductance Ls1 (H):        0.000151216
End Leakage Inductance Le1 (H):        0.000208814
Harmonic Leakage Inductance Ld1 (H):        6.15951e-06
Zero-Sequence Inductance L0 (H):        0.000366189
Armature Phase Resistance R1 (H):        0.00755817
Armature Phase Resistance at 20C (ohm):        0.0062172

Armature Copper Weight (kg):        33.5838
Permanent Magnet Weight (kg):        2.72282
Armature Core Steel Weight (kg):        52.2988
Rotor Core Steel Weight (kg):        24.6262
Total Net Weight (kg):        113.232
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There is also material mass presented as steady state parameters. Weight of permanent magnets has 2.72 kg while total weight of steel is about 77 kg and total armature copper weight is about 33,5 kg. Overall net machine weight is about 113 kg.

```
NO-LOAD MAGNETIC DATA

Stator-Teeth Flux Density (Tesla):        0.911547
Stator-Yoke Flux Density (Tesla):        2.21398
Rotor-Yoke Flux Density (Tesla):        0.543212
Air-Gap Flux Density (Tesla):        0.616708
Magnet Flux Density (Tesla):        0.641394

Cogging Torque (N.m):        5.11985
```

Flux density in the part of machine is given above as teeth, back core, air gap and permanent magnet. More flux density expected in permanent magnet based on calculations, but core was neglected in the calculations. Therefore, it might be reasonable that magnet has less flux density than expected.

There are some losses neglected for the analysis such as semiconductor losses, while core losses and copper losses are presented below. Efficiency is very satisfying as it is %98. Rated torque was expected to be more close to 250 Nm to generate 125 kW output power, but it is determnined as 231 Nm. Therefore, generated output is about 121 kW for 5000 rpm.

```
FULL-LOAD DATA

Maximum Line Induced Voltage (V):        517.452
Input DC Current (A):        237.541
Root-Mean-Square Phase Current (A):        326.992
Armature Thermal Load (A^2/mm^3):        493.746
Specific Electric Loading (A/mm):        101.822
Armature Current Density (A/mm^2):        4.84911
Iron-Core Loss (W):        0.0349194
Armature Copper Loss (W):        2424.44
Transistor Loss (W):        0
Diode Loss (W):        0
Total Loss (W):        2424.47
Output Power (W):        121097
Input Power (W):        123521
Efficiency (Percent):        98.0372

Synchronous Speed (rpm):        5000
Rated Torque (N.m):        231.278

Maximum Output Power (W):        121097
```

Air gap flux density distribution is demonstrated in Fig-3. There is a difference between FEA result and analytical calculations. It is because core reluctance is neglected during analytical calculations, but Ansys Rmxprt does not neglect it. Therefore, it might be the reason for difference.

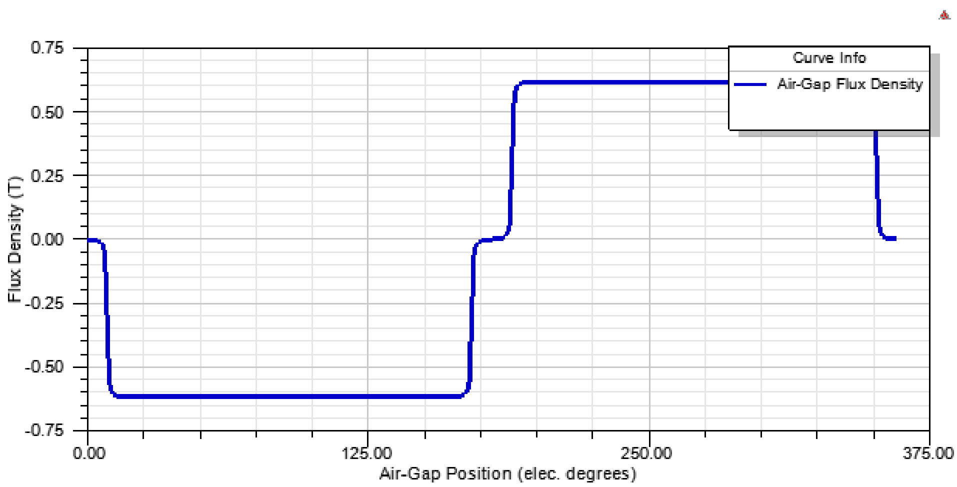

Figure 3: Air gap flux density distribution

Question 4

Based on the design of machine in question 2, some enhancements are applied. Size of machine is tried to be minimized. Electrical loading and magnetic loading are tried to be optimized and also some machine parameter are manipulated to improve machine for better performance. After all these changes, a final design is obtain. Other designs are obtained with the same way that has used for question 2. Finite element analysis of final is carried out to verify the design. Results are criticized.

First design iteration;

Electrical loading is around 31 KA/mm for machine in the question 2, but it can be increased up to 65 KA/mm based on the table which is presented on lecture notes. Therefore, machine size can get smaller and still generate same power output. Axial length is reduced from 100 mm to 80 mm and diameter of rotor is reduced from 220 mm to 180 mm. Such operation will cause the output power to drop, unless number of turn is increased from 3 to 5. Finally, a machine with smaller size and same output power is obtained.

Second design iteration;

Heat effects the machine performance by changing properties of magnetic materials like magnets. To ease cooling of the machine, current density is reduced from 6 A/mm^2 to 4 A/mm^2. This will force the cable size to get thicker as long as fill factor allows. Therefore, cable size is updated to AWG 12 from AWG 14.

It is still possible to reduce electrical loading since it is 63662 KA/mm which is very close to critical limit of 65 KA/mm after changes of first design iteration. For this purpose, magnet grade is changed with another magnet which has higher B_r value, so it will be possible to reduce number of turn from 5 to 4 and relatively this will cause electric loading to drop to 50930 KA/mm.

Final design;

As it is mentioned in the lecture notes, machine that has higher number of slot has higher overload capacity while reducing pulsation. To take advantage of these benefits, number of slot is increased from 36 to 48, but this change will increase electrical loading unnecessarily. Number of turn is reduced from 4 to 3 to diminish effect of increasing number of slot on electrical loading.

There are four different design which has different various specifications from magnet grade to slot dimension. A table of these specifications is prepared to make a clear comparison of these design and make possible to see effect of each change and evaluate the progress by changes. Mentioned Table-1 shows how the final design is reached step by step.

Table 1: Comparison of machine designs

	Q2 design	First	Second	Final Design
Number of slots	36	36	36	48
Number of poles	4	4	4	4
Air gap clearance	0,8 mm	0,8 mm	0,8 mm	0,8 mm
Axial length	100 mm	80 mm	80 mm	80 mm
Outer diameter of rotor	220 mm	180 mm	180 mm	180 mm
Rule of thumb for Do/Di	1,88	1,88	1,88	1,88
Inner diameter of stator	220,8 mm	180,8 mm	180,8 mm	180,8 mm
Outer diameter of stator	415 mm	340 mm	340 mm	340 mm
Teeth thickness	9,63 mm	7,88 mm	7,88 mm	7,88 mm
Slot width	9,63 mm	7,88 mm	7,88 mm	7,88 mm
Slot ratio	0,6	0,6	0,6	0,6
OD	368 mm	300 mm	300 mm	300 mm
Back core thickness	23,5 mm	20 mm	20 mm	20 mm
Slot height	73,6 mm	59,6 mm	59,6 mm	59,6 mm
Slot area	708 mm^2	470 mm^2	470 mm^2	470 mm^2
Current density	6 A/mm^2	6 A/mm^2	4 A/mm^2	4 A/mm^2
Current	200 A	200 A	200 A	200 A
Wire size	AWG 14	AWG 14	AWG 12	AWG 12
Maximum number of turns	21	12	7	7
Number of turns	3	5	4	3
Fill factor	0,1	0,41	0,6	0,42
Electrical loading	31252 A/m	63662 A/m	50930 A/m	50930 A/m
Lamination	50CS400	50CS400	50CS400	50CS400
Magnet grade	N35H	N35H	N42H	N42H
Magnet thickness	6 mm	6 mm	6 mm	6 mm
Br of magnet	1,17	1,17	1,28	1,28
μ_r **of magnet**	1,05	1,05	1,05	1,05
Magnetic loading	0,74 T	0,74 T	0,81 T	0,81 T
Winding factor	0,9598	0,9598	0,9598	0.9576
Machine constant	109540	223130	195390	194940
Torque	248,65 Nm	271,25 Nm	237,53 Nm	237,53 Nm
Output power for 5000 rpm	130005 W	141870 W	124230 W	124230 W

Results of FEA are presented below for final design. Steady state parameters contain phase inductances and phase resistances for both d and q axis. Rotor diameter is 180 mm while axial lenght is 80 mm and outer diameter of stator is 340. Therefore, aspect ratio of the machine is 0,08/0,34=0.23. Typical aspect ratio for synchronous machines is 0,39 which makes possible to see that final design has reasonable aspect ratio.

```
STEADY STATE PARAMETERS

Stator Winding Factor:        0.957662
D-Axis Reactive Inductance Lad (H):        0.000871067
Q-Axis Reactive Inductance Laq (H):        0.000871067
D-Axis Inductance L1+Lad (H):        0.00116002
Q-Axis Inductance L1+Laq (H):        0.00116002
Armature Leakage Inductance L1 (H):        0.00028895
Slot Leakage Inductance Ls1 (H):        0.000113531
End Leakage Inductance Le1 (H):        0.000172077
Harmonic Leakage Inductance Ld1 (H):        3.34176e-06
Zero-Sequence Inductance L0 (H):        0.00028895
Armature Phase Resistance R1 (H):        0.00883492
Armature Phase Resistance at 20C (ohm):        0.00726743

Armature Copper Weight (kg):          31.3637
Permanent Magnet Weight (kg):          1.7711
Armature Core Steel Weight (kg):          24.8546
Rotor Core Steel Weight (kg):          12.7883
Total Net Weight (kg):          70.7777
```

There is also material mass presented as steady state parameters. Weight of permanent magnets has 1.77 kg while total weight of steel is about 37,5 kg and total armature copper weight is about 31 kg. Overall net machine weight is 70 kg.

```
NO-LOAD MAGNETIC DATA

Stator-Teeth Flux Density (Tesla):        1.29923
Stator-Yoke Flux Density (Tesla):        2.27353
Rotor-Yoke Flux Density (Tesla):        0.60366
Air-Gap Flux Density (Tesla):        0.657624
Magnet Flux Density (Tesla):        0.690158

Cogging Torque (N.m):        6.44749
```

Flux density in the part of machine is given above as teeth, back core, air gap and permanent magnet. More flux density expected in permanent magnet based on calculations, but core was neglected in the calculations. Therefore, it might be reasonable that magnet has less than expected flux density.

There are some losses neglected for the analysis such as semiconductor losses, while core losses and copper losses are presented below. Efficiency is very satisfying as it is %97. Rated torque was expected to be more close to 250 Nm to generate 125 kW output power, but it is determnined as 232 Nm. Therefore, generated output is about 121 kW for 5000 rpm.

```
FULL-LOAD DATA

Maximum Line Induced Voltage (V):        402.417
Input DC Current (A):        239.912
Root-Mean-Square Phase Current (A):        349.727
Armature Thermal Load (A^2/mm^3):        966.304
Specific Electric Loading (A/mm):        147.772
Armature Current Density (A/mm^2):        6.53915
Iron-Core Loss (W):        0.0221791
Armature Copper Loss (W):        3241.77
Transistor Loss (W):        0
Diode Loss (W):        0
Total Loss (W):        3241.8
Output Power (W):        121512
Input Power (W):        124754
Efficiency (Percent):        97.4014

Synchronous Speed (rpm):        5000
Rated Torque (N.m):        232.071

Maximum Output Power (W):        121635
```

In this report, different machines are designed. It is observed how the each parameter effect the machine performance. An optimized solution is tried to be figured out. This report suppose to be subjected to permanent magnet assisted synchronous reluctance machine, however it would be hard to analyse the design of PMASRM on the ANSYS Rmxprt for the author of this report. Also, Surface mount rotor design is modelled for FEA. Therefore, there might be relatively higher percentage of error for finite element results. Relatively, obtaining FEA results of each design is becoming pointless. For this reason, only final design of FEA results are presented to compare with initial design which was prepared in question 2.

Reluctance variation will generate torque as well. Reluctance variation would be an issue to model analytically. To sustain simplicity, design equations which does not include effect of reluctance variation for standard permanent magnet synchronous machine in the lecture notes are used. Besides, designing, optimizing and analysing permanent magnet synchronous machine, PMASRM design should be criticized more in detail.

References

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