

DC Stator Modelling

by Derek Lockhart

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DC Motor Stator Modelling Pt 2

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1. Abstract

A finite element method analysis of a DC Motor Stator given variations in stator design, including maximum flux density, maximum useable flux and flux leakage factor analysis for variations in stator body width, pole width and pole face width.  1

2. Introduction

This paper shall use the finite element method to establish a simulation of the flux characteristics of a given DC motor stator and thereby calculate its Flux Leakage Factor (FLF), maximum generated flux and maximum useable flux. Analysis of the results shall be used to investigate which specification changes to the stator dimensions have the most effect on improving these metrics.

2.1 Previous work

Assignment 1 of this module was used to define the Flux Leakage Factor (FLF) of a given stator. The stator used is shown in Fig 1.



Figure 1 Given DC Motor Stator

The DC Stator was modelled using the FEMM software package and the maximum generated flux was found to be 2.38636×10^{-4} Webers as shown in

Figure 2. This is the flux generated for the given dimensions of a stator made from 'Carpenter Silicon Core Iron 'A' 1066C Anneal' with two 500 turn coils carrying 1A.

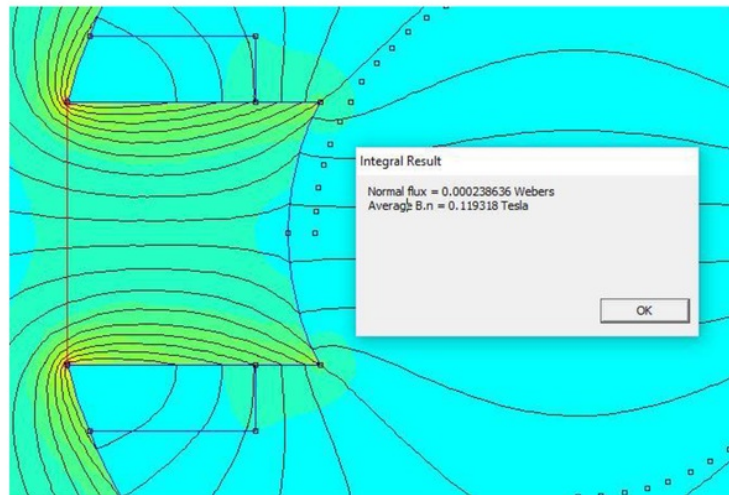


Figure 2 Max flux density

For the given design the maximum usable flux was found to be 8.52×10^{-5} Webers, this proved to be indicative of a FLF of 0.643 (64.3%). It is this metric that design changes will attempt to improve.

3. Method

The factors that have effect on the flux in a DC stator shall be considered in turn, a selection of these will be used in this paper, these are:

Stator Material

Free space material

Electrical current

Electrical turns

Rotor design (Turns/diameter)

Airgap (Armature to pole face)

Stator inner radius

Pole width

Pole face radius

3.1 Stator Material

The 'Carpenter Silicon Core Iron 'A' 1066C Anneal' core, has a BH curve shown in Figure 3[1].

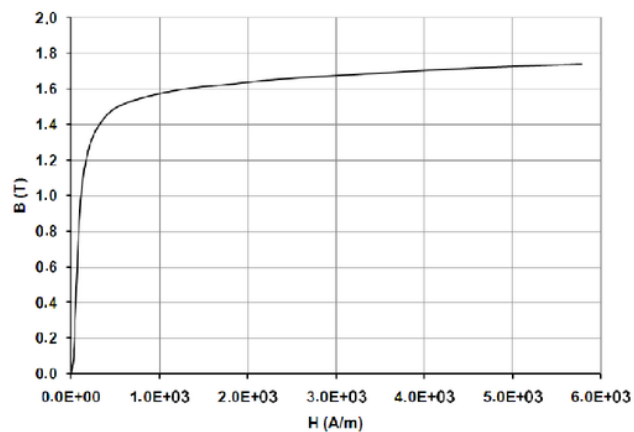


Figure 3 BH Curve of Carpenter Silicon Core Iron 'A' 1066C Anneal

The BH curve of a material characterises the flux density (B) a given material is capable of supporting for a given magnetizing force (H)[2], therefore, the BH curve relates to the permeability of a material when exposed to a DC generated magnetic force. When exposed to an AC generated magnetic force the BH curve would become a four quadrant depiction that would expose such factors as the retentivity and coercivity of the material[3]. Changing the stator material may produce a better BH response and thereby improve flux. The given stator material has a relative permeability (μ_r) of 4500[4], that is 4500 times more permeable than a vacuum. A change of material shall not be further considered.

3.2 Free space material

Air has a relative permeability of 1.000000374[5], therefore, for the scope of this investigation, can be treated as having effectively the same permeability as a vacuum (μ_0)[6]. A change of the free space material will not be considered further.

3.3 Electrical current and turns

The electrical current is the source of the magnetomotive force (mmf) produced by the magnetic field and increases as a factor of the number of turns in the coil, as per $F=NI$ [7]. These variables are fixed in the task and shall not be considered further.

3.4 Rotor Design

No specifications for the rotor design are given, changes could be made to the electrical configuration of the rotor (turns/series/shunt/compound)[8]. These characteristics would not in any case affect the max flux generated nor the max usable flux and shall not be considered further.

3.5 Airgap

The magnitude of the airgap between the armature face and the pole face would affect the flux intersected by the armature and therefore the maximum usable flux and therefore the FLF[9]. To limit the number of variables in this investigation, the airgap shall not be considered further.

3.6 Stator Inner Radius

To increase the maximum useable flux, the design shall be modified such that the flux is offered a path with the lowest overall reluctance to complete the magnetic circuit. This path includes traveling across the radius of the armature, as shown in Figure 4 (High reluctance=Dark Blue, low reluctance=Light Blue). The air offers a relatively short though path to complete the magnetic circuit, though this path includes high reluctance through the air, it can also be seen that the poles offer a path of low reluctance at the cost of a longer path[10]. In a ideal design, all flux would bridge through the armature radius.

A design modifying the inner radius of the stator will affect the maximum usable flux such that if the inner radius were to be smaller, it would reduce the gap from the pole edge to the inner radius face and thereby reduce the size of the air gap, this would reduce the length of the high reluctance path through the air. Conversely, increasing this distance would increase the reluctance of this air path and consequently encourage the flux to bridge the gap between pole faces and become useable[10].

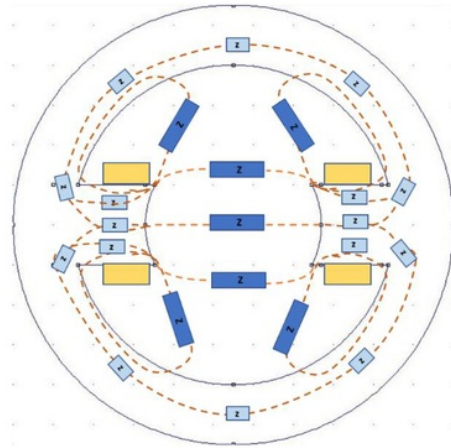


Figure 4 Illustration of relative reluctance

3.7 Pole Widths

Increasing the pole widths increases the length of the low reluctance path toward the other coil thereby increasing the likelihood of flux bridging the gap between poles rather than to the stator body and thereby increase the useable flux[11].

3.8 Pole face

Increasing the pole face widths reduces the overall reluctance between the poles whilst maintaining the reluctance toward the stator body[11].

3.9 Proposed alterations

This paper shall therefore use variations in the stator thickness, pole width and pole face to ascertain a design that will improve the useable flux and therefore reduce the flux leakage factor.

The original dimensions and proposed test dimensions are given in Table 1.

	Original Size	Size 1	Size2
Stator Body	15	10	5
Pole Width	20	15	10
Pole Face	20	25	30

Table 1 Proposed Dimension Alterations

3.10 Test methodology

Given the number of variables, it would take a large number of tests, in this case $3^3=27$ tests, to examine every variation and determine a preferred design. Orthogonal Array Testing (OATs) is a statistical method of reducing the quantity of tests completed to procure a valid result[12][13][14]. Therefore, a series of indicative tests, $3^2=9$, shall be completed using the OATs method to determine important stator design factors.

3.11 Stator Dimensions

The following stator dimensions shall be used to determine optimal design.

Model	Rotation			Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
A	1	1	3	15	20	30
B	1	2	2	15	15	25
C	1	3	1	15	10	20
D	2	1	2	10	20	25
E	2	2	1	10	15	20
F	2	3	3	10	10	30
G	3	1	1	5	20	20
H	3	2	3	5	15	30
I	3	3	2	5	10	25

Table 2 Proposed alternative dimensions

4. Results

The shown dimensions were used, and the following models were produced using the FEMM software and the maximum flux, useable flux and FLF estimated.

4.1 Model A

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
A	15	20	30

Table 3 Model A Dimensions

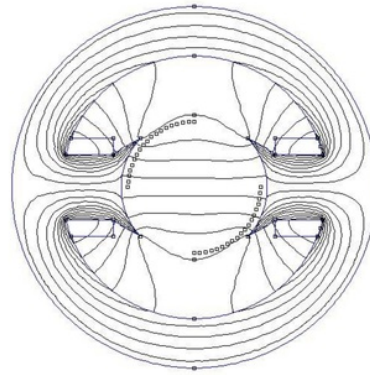


Figure 5 Model A Flu

A	μWb
Max flux	314.69
0	0.05
5	8.31
10	17.34
15	26.32
20	35.37
25	46.08
30	57.02
35	69.95
40	85.06
45	97.68
50	105.45
55	108.60
60	109.16
65	109.22
70	108.94
75	108.58
80	108.30
85	107.97
90	107.97
Useable	109.22
Max Gen	314.69
FLF	0.6529
%	65.3%
Avg	74.59722

Table 4 Model A Flux by Angle

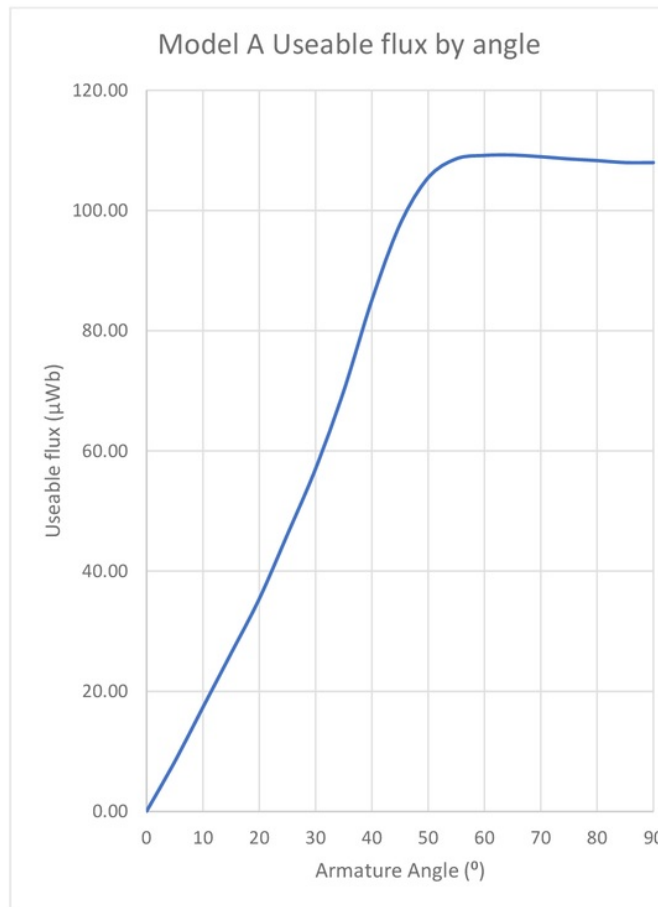


Figure 6 Model A Flux by Angle

4.2 Model B

B	15	15	25
Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)

Table 5 Model B Dimensions

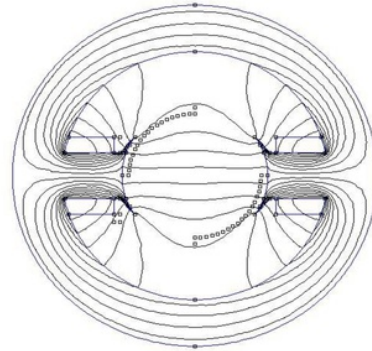


Figure 7 Model B Flux

B	μWb
Max flux	277.15
0	0.09
5	9.17
10	19.24
15	29.43
20	39.92
25	52.76
30	66.31
35	88.40
40	92.97
45	93.75
50	95.51
55	95.74
60	95.03
65	94.52
70	93.78
75	93.22
80	92.82
85	92.46
90	92.40
Useable	95.74
Max Gen	277.15
FLF	0.6546
%	65.5%
Avg	70.39589

Table 6 Model B Flux by Angle

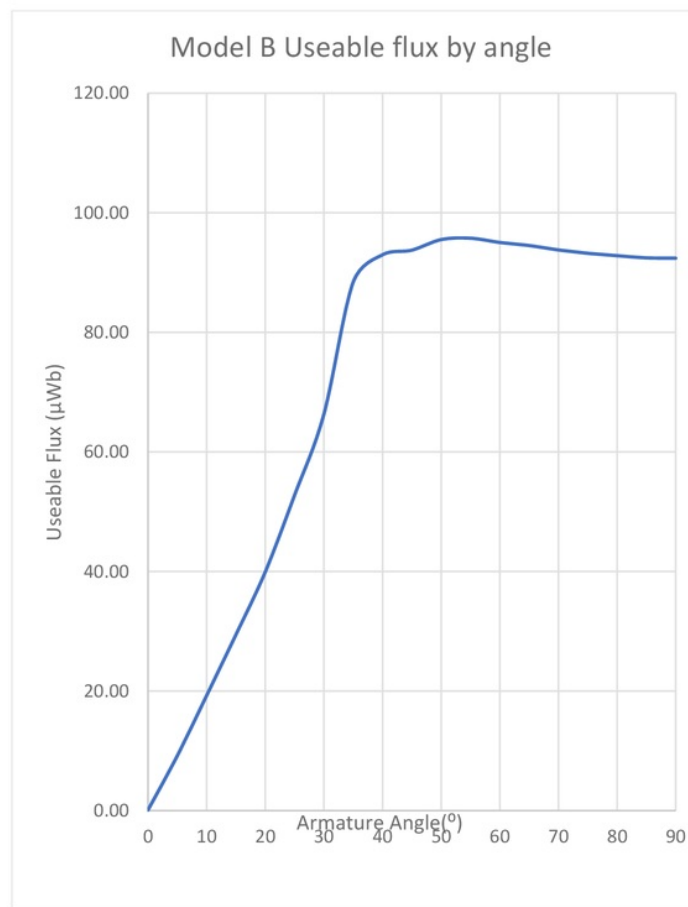


Figure 8 Model B Flux by Angle

4.3 Model C

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
C	15	10	20

Table 7 Model C Dimensions

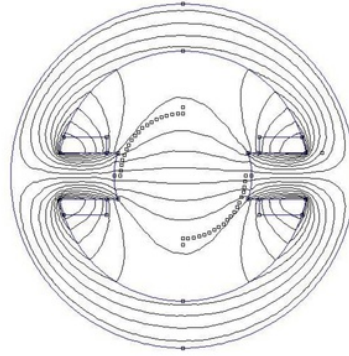


Figure 9 Model C Flux

C	μWb
Max flux	247.74
0	0.08
5	10.46
10	22.06
15	34.05
20	46.84
25	62.54
30	74.67
35	81.23
40	83.49
45	83.64
50	83.86
55	83.22
60	82.25
65	81.46
70	80.69
75	80.10
80	79.68
85	79.32
90	79.25
Useable	83.86
Max Gen	247.74
FLF	0.6615
%	66.2%
Avg	64.67812

Table 8 Model C Flux by Angle

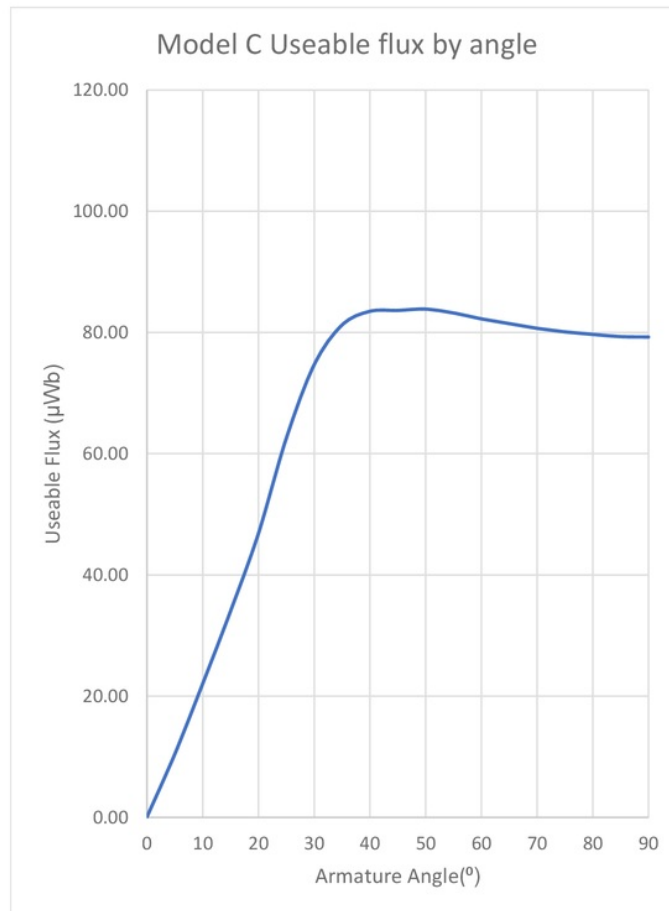


Figure 10 Model C Flux by Angle

4.4 Model D

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
D	10	20	25

Table 9 Model D Dimensions

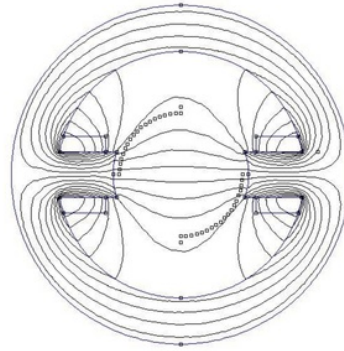


Figure 11 Model D Flux

D	μWb
Max flux	231.75
0	0.09
5	9.07
10	19.04
15	29.11
20	39.46
25	52.12
30	65.47
35	80.10
40	89.54
45	93.24
50	95.47
55	96.24
60	96.15
65	95.95
70	95.66
75	95.38
80	95.20
85	94.95
90	94.96
Useable	96.24
Max Gen	231.75
FLF	0.5847
%	58.5%
Avg	70.37863

Table 10 Model D Flux by Angle

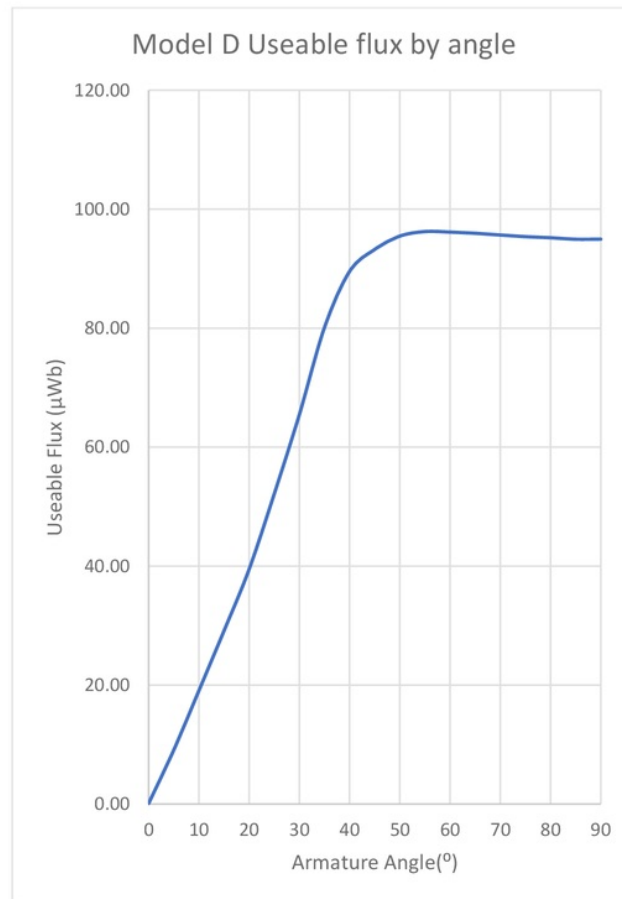


Figure 12 Model D Flux by angle

4.5 Model E

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
E	10	15	20

Table 11 Model E Dimensions

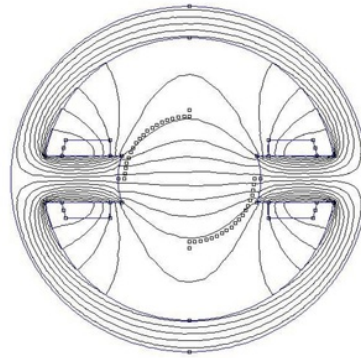


Figure 13 Model E Flux by Angle

E	μWb
Max flux	205.12
0	0.19
5	10.20
10	21.66
15	33.42
20	45.98
25	61.28
30	73.26
35	80.29
40	83.02
45	83.78
50	84.41
55	84.42
60	83.82
65	83.36
70	82.90
75	82.53
80	82.28
85	82.01
90	82.00
Useable	84.42
Max Gen	205.12
FLF	0.5884
%	58.8%
Avg	65.30622

Table 12 Model E Flux by Angle

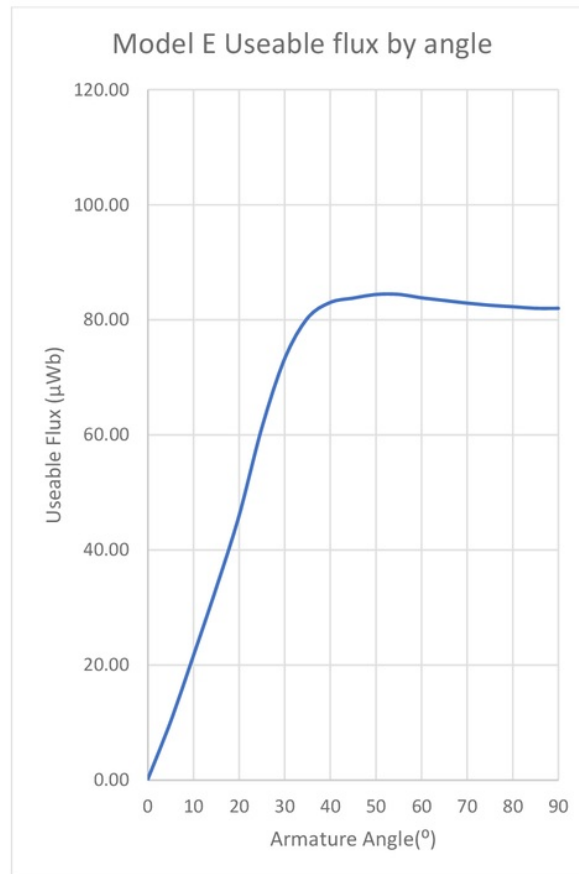


Figure 14 Model E Flux by Angle

4.6 Model F

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
F	10	10	30

Table 13 Model E Dimensions

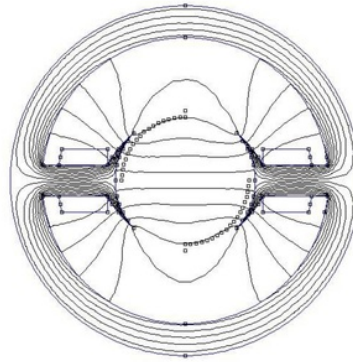


Figure 15 Model F Flux

F	μWb
Max flux	288.29
0	0.15
5	8.15
10	17.12
15	26.04
20	35.04
25	45.63
30	56.44
35	69.24
40	84.24
45	96.86
50	104.66
55	108.08
60	108.87
65	109.36
70	109.36
75	109.22
80	109.14
85	108.93
90	108.96
Useable	109.36
Max Gen	288.29
FLF	0.6207
%	62.1%
Avg	74.49994

Table 14 Model F Flux by angle

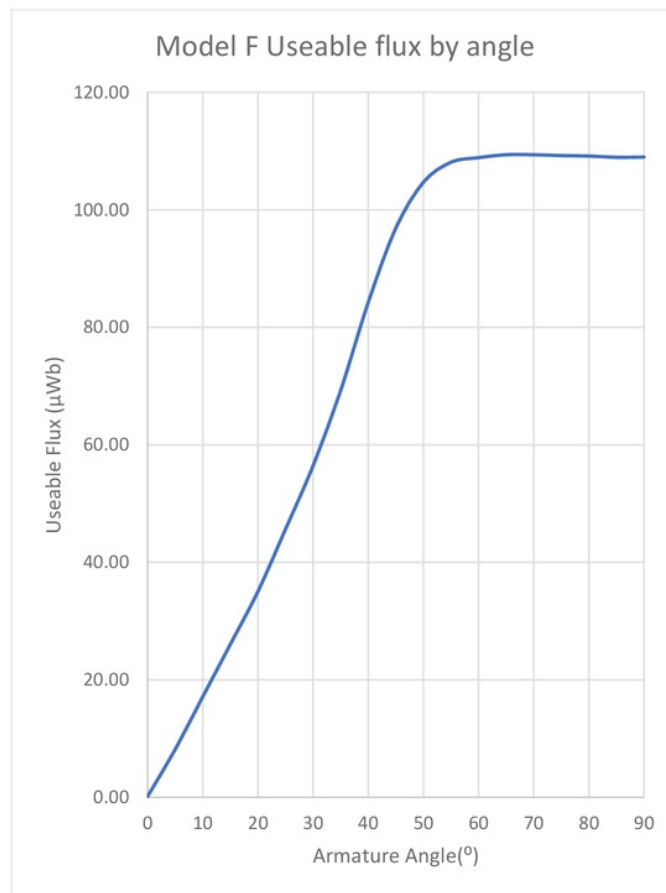


Figure 16 Model F Flux by angle

4.7 Model G

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
G	5	20	20

Table 15 Model E Dimensions

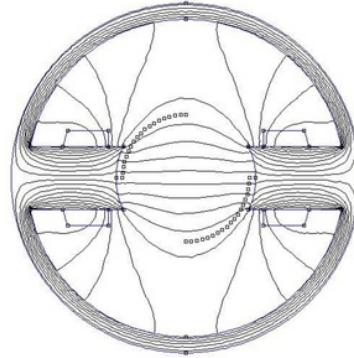


Figure 17 Model G Flux

G	μWb
Max flux	186.60
0	0.18
5	10.03
10	21.24
15	32.77
20	44.99
25	59.85
30	71.76
35	79.23
40	82.77
45	84.14
50	85.27
55	85.80
60	85.59
65	85.47
70	85.26
75	85.08
80	84.98
85	84.78
90	84.78
Useable	85.80
Max Gen	186.60
FLF	0.5402
%	54.0%
Avg	65.99847

Table 16 Model G Flux by angle

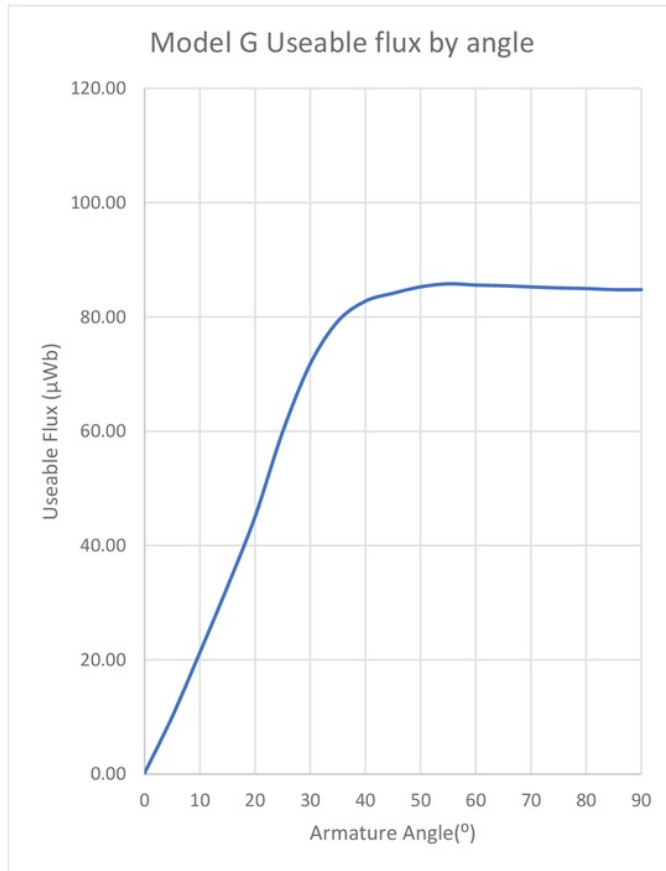


Figure 18 Model G by flux by angle

4.8 Model H

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
H	5	15	30

Table 17 Model E Dimensions

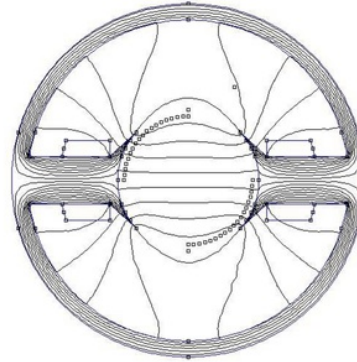


Figure 19 Model H Flux

H	Phi(Wb)
Max flux	242.31
0	0.08
5	8.34
10	17.44
15	26.51
20	35.68
25	46.55
30	57.72
35	71.08
40	86.09
45	97.30
50	103.46
55	106.88
60	106.72
65	107.02
70	106.98
75	106.88
80	106.86
85	106.66
90	106.68
Useable	107.02
Max Gen	242.31
FLF	0.5583
%	55.8%
Avg	73.9444

Table 18 Model H by angle

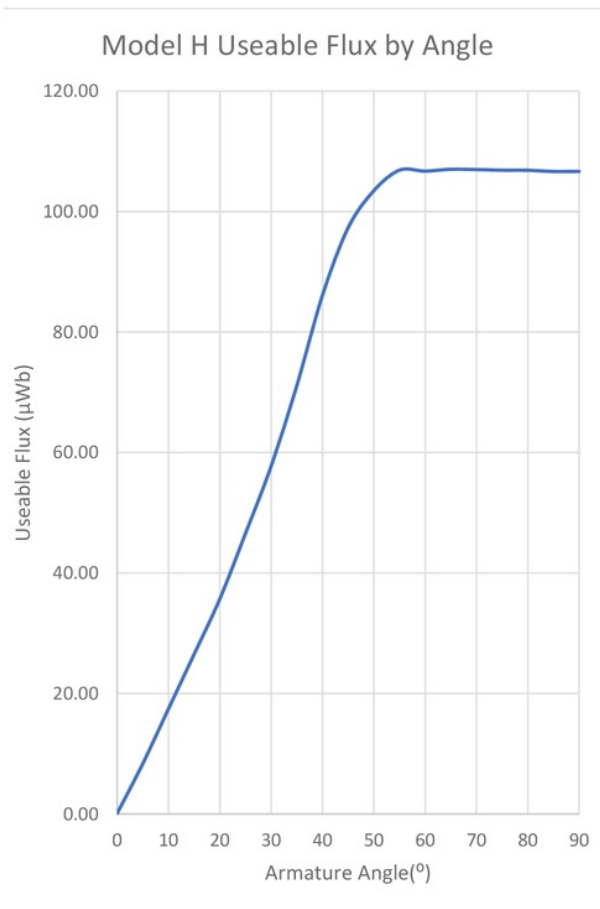


Figure 20 Model H by angle

4.9 Model I

Model	Stator Thickness(mm)	Pole Width(mm)	Pole Face(mm)
I	5	10	25

Table 19 Model E Dimensions

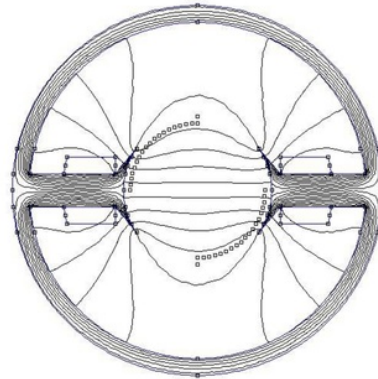


Figure 21 Model I flux

I	Phi(Wb)
Max flux	212.74
0	0.10
5	9.27
10	19.46
15	29.79
20	40.50
25	53.65
30	67.43
35	81.52
40	89.06
45	91.37
50	93.04
55	93.41
60	93.20
65	92.92
70	92.63
75	92.38
80	92.25
85	92.00
90	91.98
Useable	93.41
Max Gen	212.74
FLF	0.5609
%	56.1%
Avg	69.2612

Table 20 Model I Flux by angle

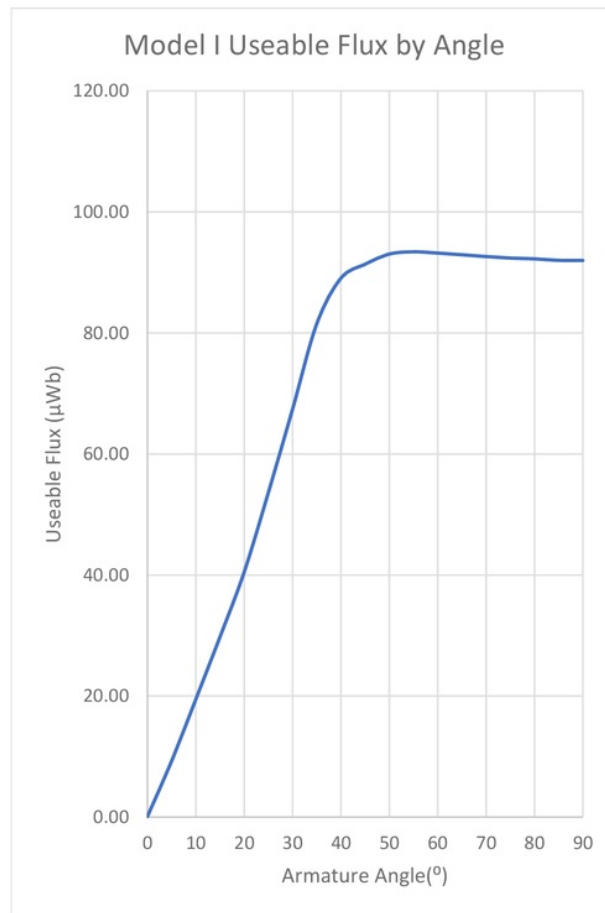


Figure 22 Model I Flux by angle

5. Analysis

From the results the following table was compiled.

Model	Variable			Max Useable Flux (μWb)	Max Generated Flux (μWb)	Flux Leakage Factor
	A	B	C			
A	1	1	3	109.220	314.687	0.653
B	1	2	2	95.739	277.153	0.655
C	1	3	1	83.217	82.248	0.662
D	2	1	2	96.238	231.745	0.585
E	2	2	1	84.425	205.122	0.588
F	2	3	3	109.361	288.287	0.621
G	3	1	1	85.803	186.599	0.540
H	3	2	3	107.024	242.306	0.558
I	3	3	2	93.412	212.735	0.561

Table 21 Model analysis

It can be seen that Model G provides the most efficient design in that it has the lowest FLF, however the most flux was generated by Model A and the maximum useable flux is generated by Model F. Therefore, it can be concluded that the variables used have a different effect on each of these metrics.

5.1 Flux leakage

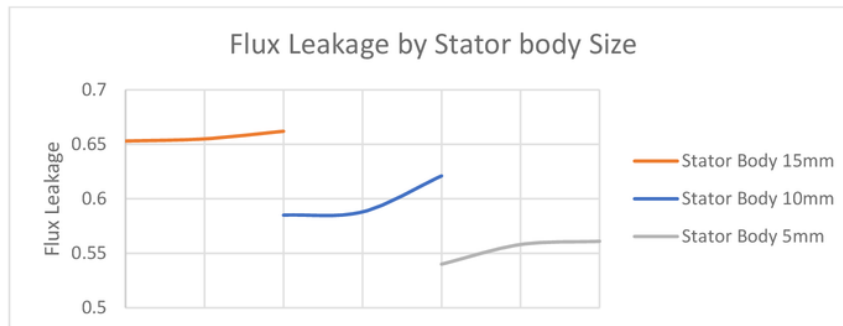


Figure 23 Flux Leakage by Stator Body Size

The Flux leakage metric by stator body size shows it as a distinct and important variable. The stator body thickness of 5mm gives the lowest flux leakage factor. It would seem to have a greater impact on flux leakage than

other factors combined. This significant result must be taken into account when analysing data from other variables.

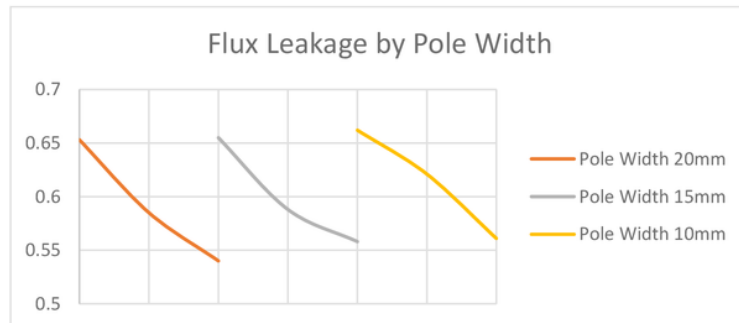


Figure 24 Flux Leakage by Pole Width

The FLF factor by pole width would seem less important than stator body thickness, although it shows that a pole width of 20mm has, by average, a lower FLF than other combinations.

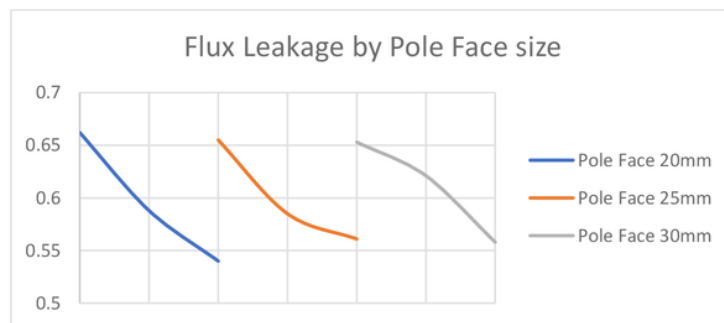


Figure 25 Flux Leakage by Pole Face Width

The FLF by Pole Face shows that a wider pole face gives a better FLF, this is stated whilst giving allowance for the lowest reading on the graph being for Model G which used the thinnest stator body, which has a significant effect.

5.2 Maximum Flux Generated

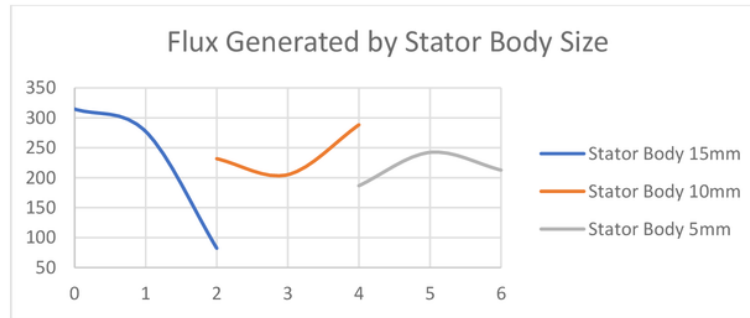


Figure 26 Flux Generated by Stator Body Size

It can be seen from the variation in responses that the stator body size has a lower effect on flux generated than other factors.

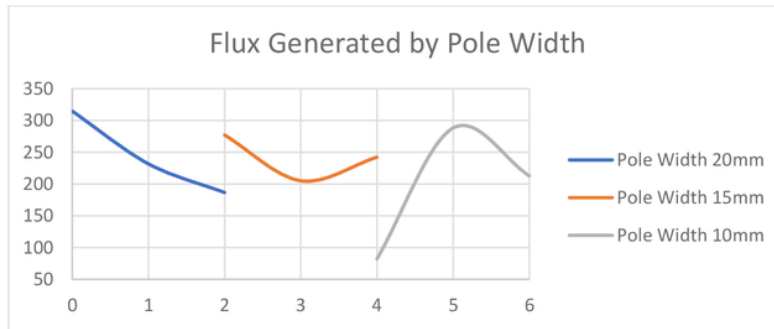


Figure 27 Flux Generated by Pole Width

Similarly, the pole width would seem to have a lesser effect on max flux generation than other factors, although the wider pole width gives a slight improvement.

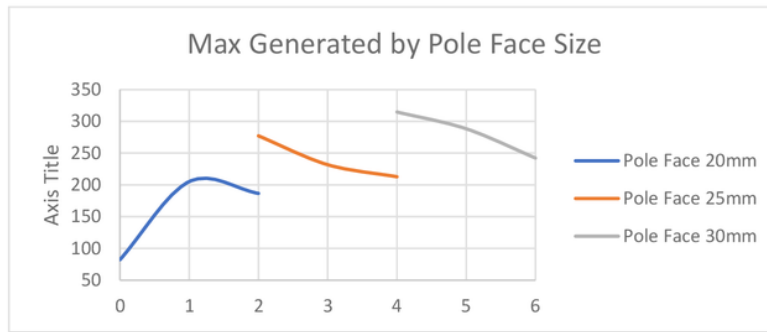


Figure 28 Max Flux Generated by Pole Face Size

The pole face size would seem to have a significant effect on the maximum flux, the wider pole face shows a significant improvement over the smaller models.

5.3 Maximum useable flux

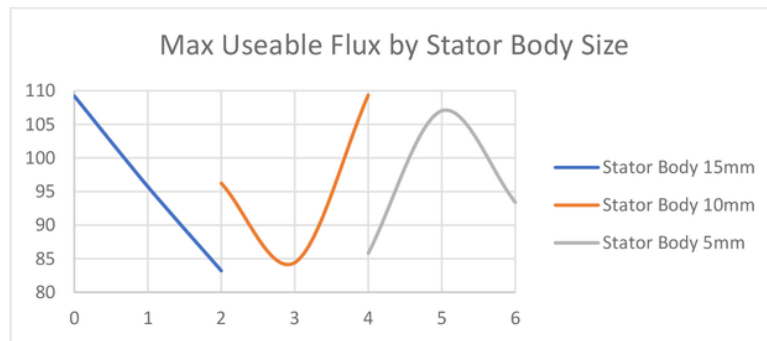


Figure 29 Max Useable Flux by Stator Body Size

Figure 29 shows that the stator body size has a smaller impact on useable flux than other factors.

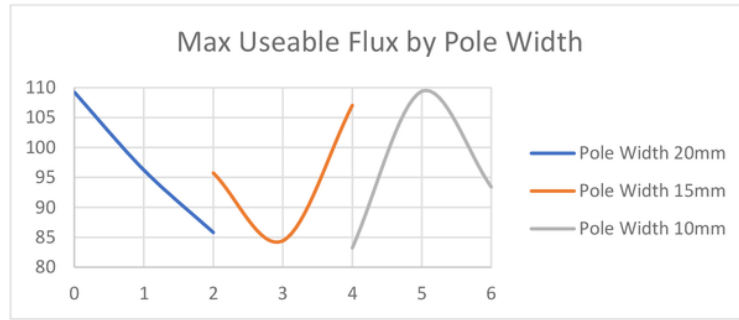


Figure 30 Maximum Useable Flux by Pole Width

Figure 30 similarly shows that pole width has a smaller effect on useable flux than other factors.

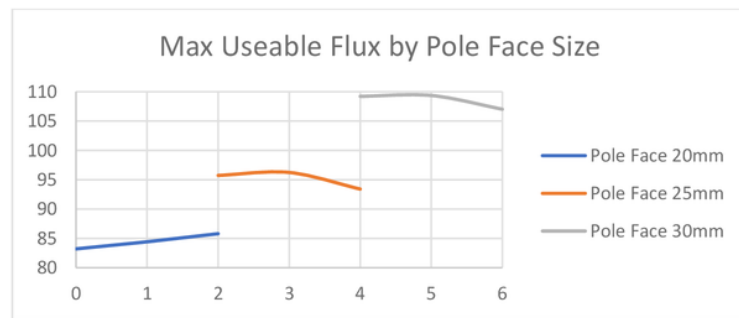


Figure 31 Max Useable Flux by Pole Face Size

Figure 31 shows that the overriding factor affecting useable flux is the pole face size, the larger pole face is a marked improvement over the smaller designs.

5.4 Maximum flux angle

The angle at which maximum useable flux was intersected and therefore maximum torque also changed dependant on each models' characteristics. These are shown in Table 13.

Model	A	B	C	D	E	F	G	H	I
Ø	65	55	50	55	55	65	55	65	55

Table 22 Maximum Useable Flux Angle

6. Conclusions

Of the factors investigated in this analysis it has been shown that the max generated flux is more a factor of pole width and pole face size than stator body width, the maximum useable flux is improved by pole face size more than other factors and the FLF is improved by stator body size more than other factors. Therefore, a best-case design for these factors would include the thinnest stator body and the widest pole widths and pole faces. Due to the OATs method used, this combination was not tested in this case but can be proved to be the better solution. This improved model is shown in Figure 32

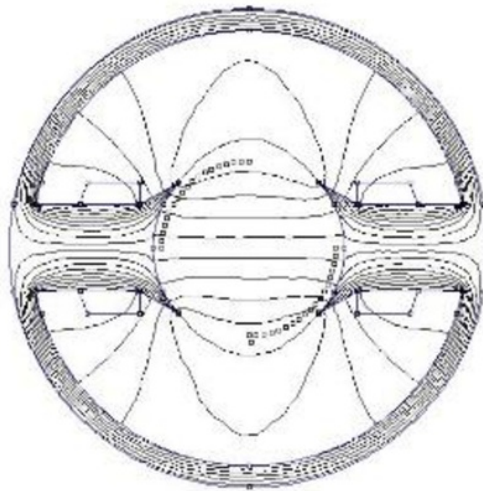


Figure 32 Maximised Model

Max Report	Phi(Wb)
Max flux	244.90
0	0.12
5	8.19
10	17.17
15	26.11
20	35.12
25	45.78
30	56.66
35	69.55
40	84.54
45	96.98
50	104.38
55	107.52
60	108.45
65	109.04
70	109.82
75	109.17
80	109.20
85	109.03
90	109.12
Max use	109.82
Max Gen	244.90
FLF	0.5540
%	55.4%
Avg	74.51

Table 23 Max model flux by angle

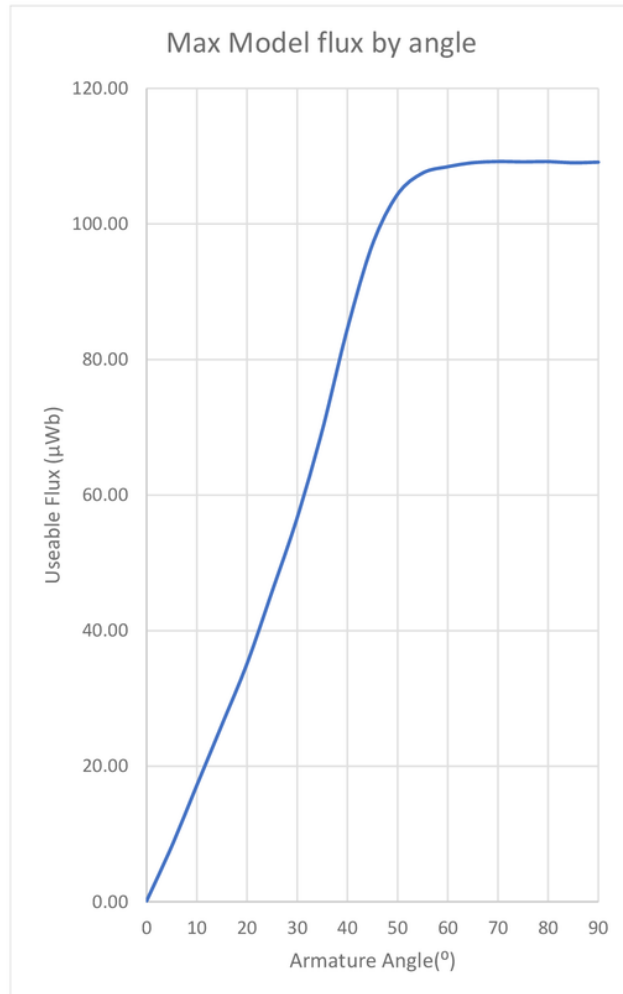


Figure 33 Max model flux by angle

It can be seen that this maximised model has the best overall performance of all the models, although it does not have the highest flux generated, due to the far lower flux leakage factor it has the most useable flux and a higher average flux.

7. References

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DC Stator Modelling

GRADEMARK REPORT

FINAL GRADE

GENERAL COMMENTS

81 / 100

Instructor

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Comment 1

Brief abstract. You should include more information on your results and conclusions, not just what you are going to do.

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Comment 2

should this say $3^2=9$

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DEREK LOCKHART

81.30

ENGAGEMENT WITH LITERATURE

including reading, referencing, academic conventions and academic



Outstanding knowledge of research-informed literature embedded in the work. Outstanding selection of relevant and credible sources. High-level referencing skills consistently and professionally applied.

9

KNOWLEDGE & UNDERSTANDING

Knowledge of the basic underlying concepts and principles of a subject.



Highly detailed knowledge and critical understanding of the main theories/concepts.

24

COGNITIVE & INTELLECTUAL

Evaluate underlying concepts and principles of a subject and interpret qualitative and quantitative data in order to develop lines of argument and make sound judgements.



Exceptional work; judiciously selected and evaluated evidence. Very high quality analysis. Ability to investigate contradictory information and identify reasons for contradictions. Highly persuasive conclusions

24.3

PRACTICAL APPLICATION SKILLS

Different approaches to solving problems in particular contexts.



Outstanding levels of application and deployment

skills. Assimilation and development of cutting edge processes and techniques.

16.2

TRANSFERABLE SKILLS

Communicate the results of their study/work accurately and reliably, and with structured and coherent arguments; the qualities needed for employment requiring the exercise of some personal responsibility within a structured and managed environment.



Can communicate professionally and, confidently in a suitable format. Work is coherent, very fluent and is presented professionally.

7.8