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Some Design Calculations for a 60kW, 6000 rpm, 4/6 SRM

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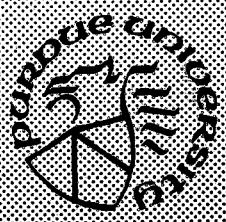

Some Design Calculations for a 60kW, 6000 rpm, 4/6 SRM

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SUMMARY

This report contains results from a finite element study of the SR machine whose dimensions were provided by Mr Lewis Unnewehr of Sullair Corporation. The objective of the study is to determine the static and steady-state operational characteristics of a given machine design to see if it meets certain design specifications.

The study made use of a two-dimension, finite element program that has been developed and described in [1-3]. The same set of references also contained information on the simulation methods and types of control used in this study. Part I of this report presents the basic input data used in this study. The iron parts, including that of the shaft, are assumed to have the magnetic characteristics of M19 steel. The current distribution in the stator coils is assumed to be uniform.

Part II contains the results from the FEM calculations: included in here are static characteristics of the flux distribution at several rotor positions, and computed profiles of the flux linkages, the induced emf, and the static torque as a function of rotor position for a range of current excitation. These static characteristics are for the base case design given in Table 1 and are obtained with only one stator phase energized at a time.

Part III of the report contains results from sensitivity studies to determine the effects of variations in the airgap, in the relative width of the stator to rotor poles, in the shape of rotor poles, and in the skewing of the rotor poles. Unless otherwise stated the curves and data presented in this report are for the base case dimensions given in Table 1. Sensitivity analysis on airgap length, pole shape, and pole width have been obtained by making the appropriate changes on the rotor pole, the stator dimensions remained the same as those given in Table 1. Also presented are a set of static characteristics for a machine with a smaller airgap length of 0.5 mm.

Finally, Part IV of report contains steady-state operational characteristics of the stator current and shaft torque of the machine operating in the current- and angle-control modes as predicted from a steady state simulation assuming a constant input dc voltage. In the steady state simulation the electrical condition of the machine and its torque output are modeled by the appropriate flux linkage, induced emf, and developed torque profiles given in Part II.

At the end of the report is a brief discussion on some of the effects that we have studied, and the conclusion that the basic design, with standard angle and current controls, appears to be capable of delivering the desired torque.

ACKNOWLEDGEMENT

The authors are grateful to Sullair Corporation for the grant that made this project possible and would like to thank Mr. Lewis Unnewehr for the input data of the machine and for his expert guidance throughout the project.

Part I Input data

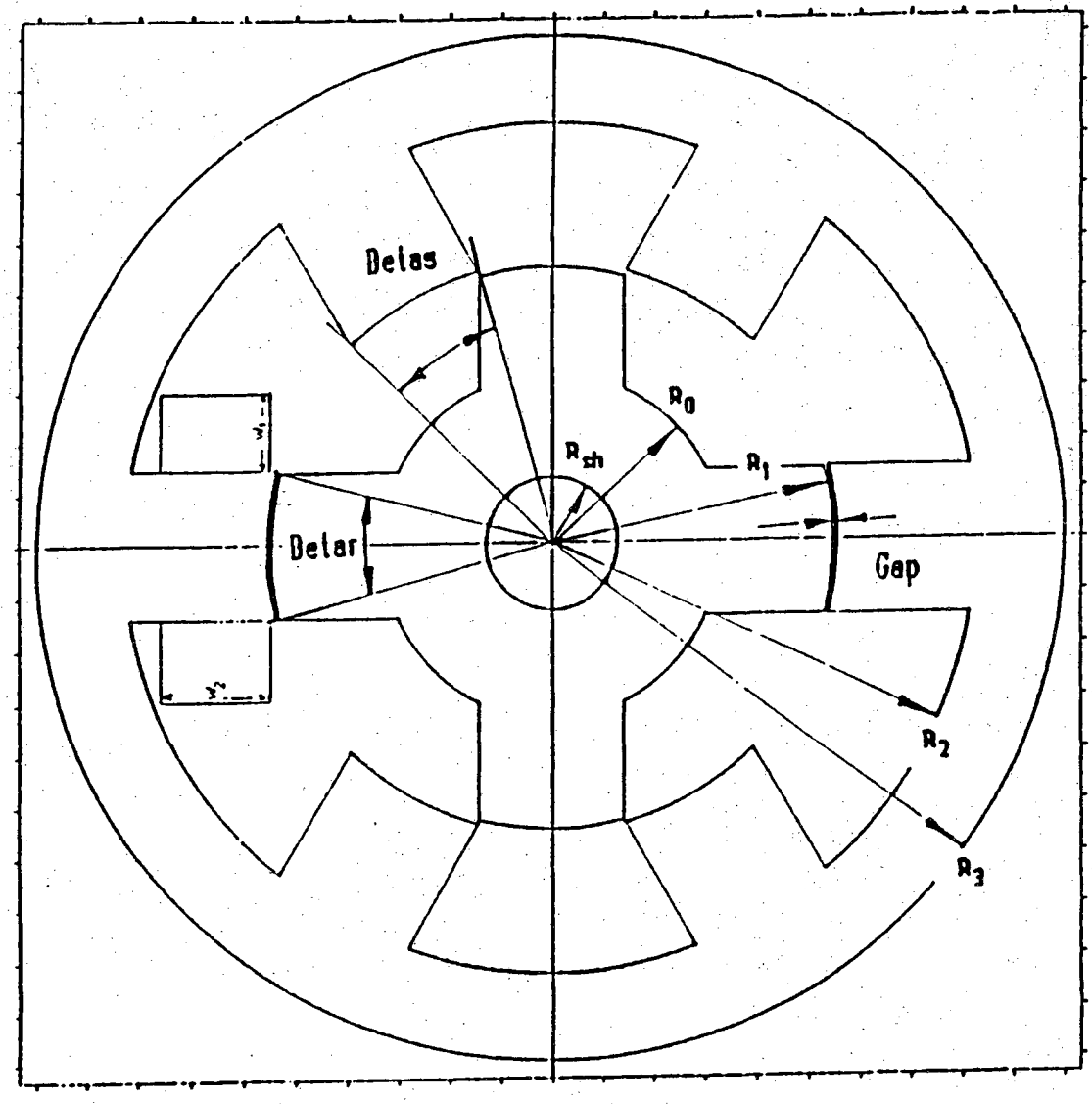

Figure 1. Cross sectional view of the SR motor

Table 1. Geometric data of the SR motor

All dimensions in millimeters

R_{sh}:	18.0
R_o:	40.0
R_1:	70.0
R_2:	102.0
R_3:	135.0
Gap :	1.
LStk :	140
$Beta_R$:	28.0°
$Beta_S$:	28.0°
N :	24 turns
N_s:	8
N_r:	6
W_1:	21
W_2:	25

Table 2. Finite element data

Number of nodes:	4297
Number of elements:	8496
Number of nodes in aigap:	360
Number of elements in airgap:	720
Number of layers:	30
Radius of outer boundary:	150 mm

Table 3. Motor lamination B-H data

B (Tesla)	H (At/m)
0.0	0.0
0.5	54.
0.55	60.5
0.6	67.6
0.65	74.8
0.7	83.5
0.75	93.5
0.8	104.4
0.85	116.9
0.9	131.3
0.95	148.2
1.0	167.1
1.05	187.8
1.1	214.9
1.15	250.7
1.2	298.4
1.25	374.
1.3	485.5
1.35	652.6
1.4	1010.6
1.45	1551.8
1.5	2308.
1.55	3342.
1.6	4775.
1.65	6366.
1.7	8356.
1.75	10743.
1.8	14165.
1.85	18303.
1.9	23874.
1.95	30240.
2.0	44565.
2.05	79580.
2.06	87537.7

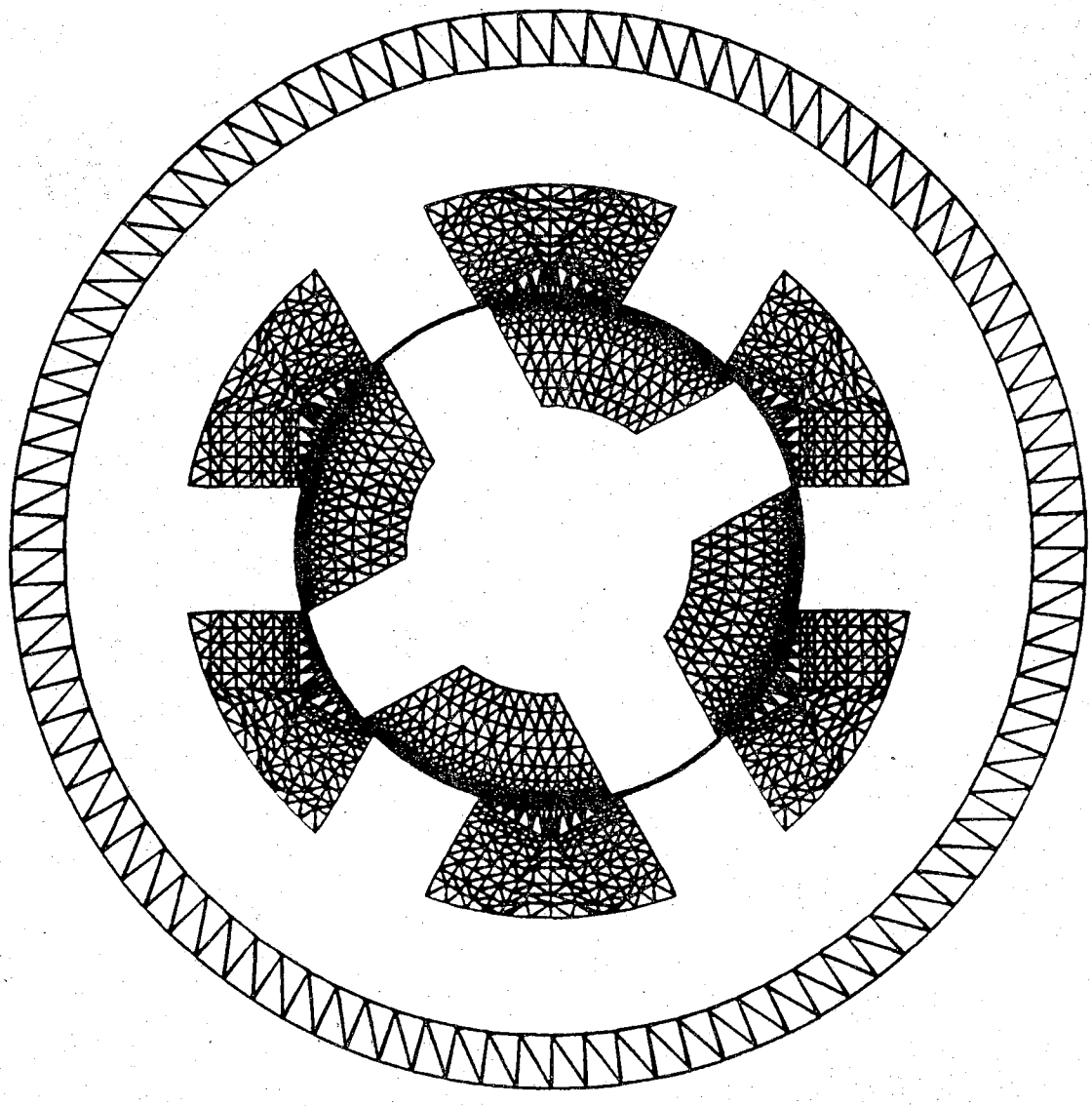

Figure 2. Air mesh

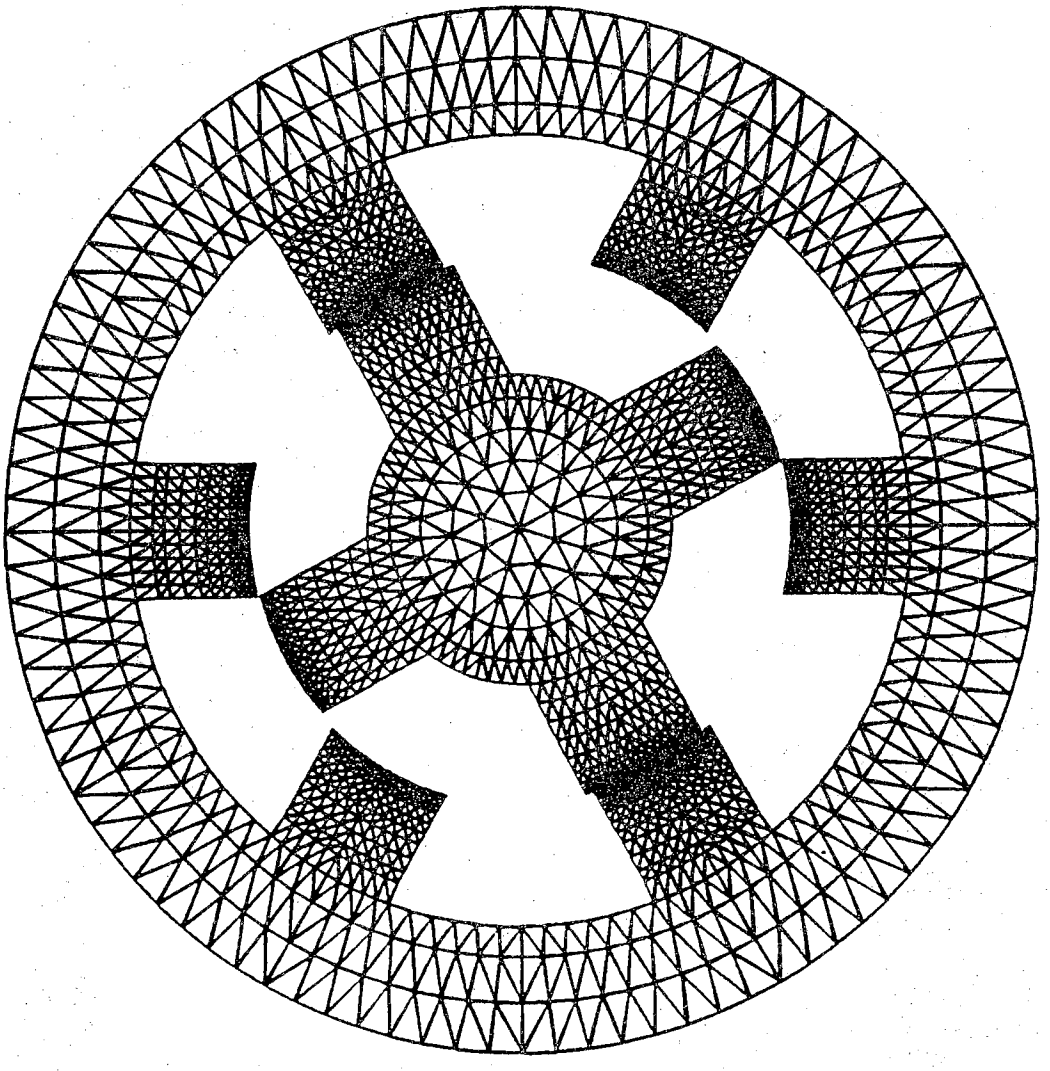

Figure 3. Iron mesh

Part II Static Characteristics

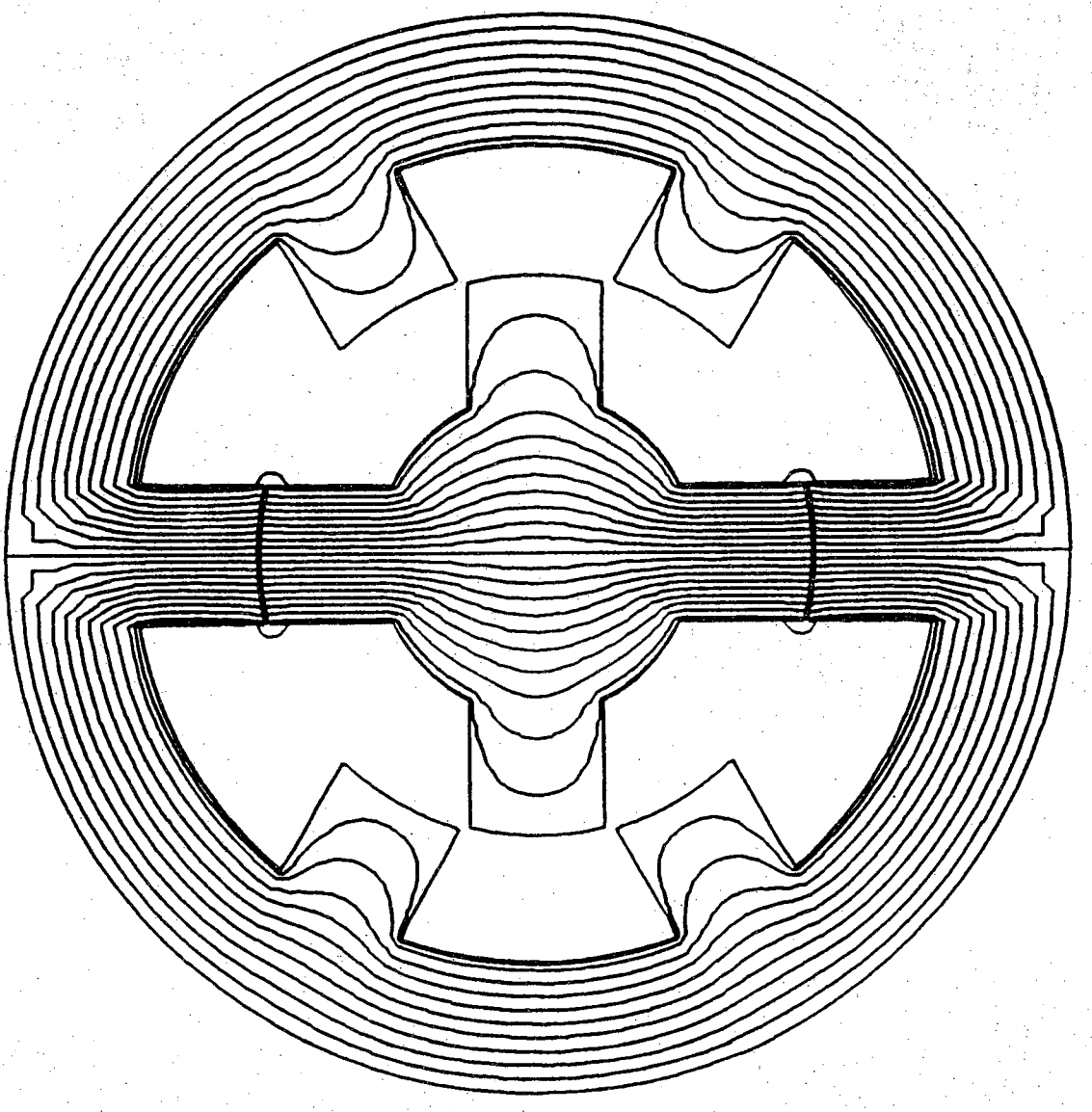

Figure 4. Flux lines at aligned position

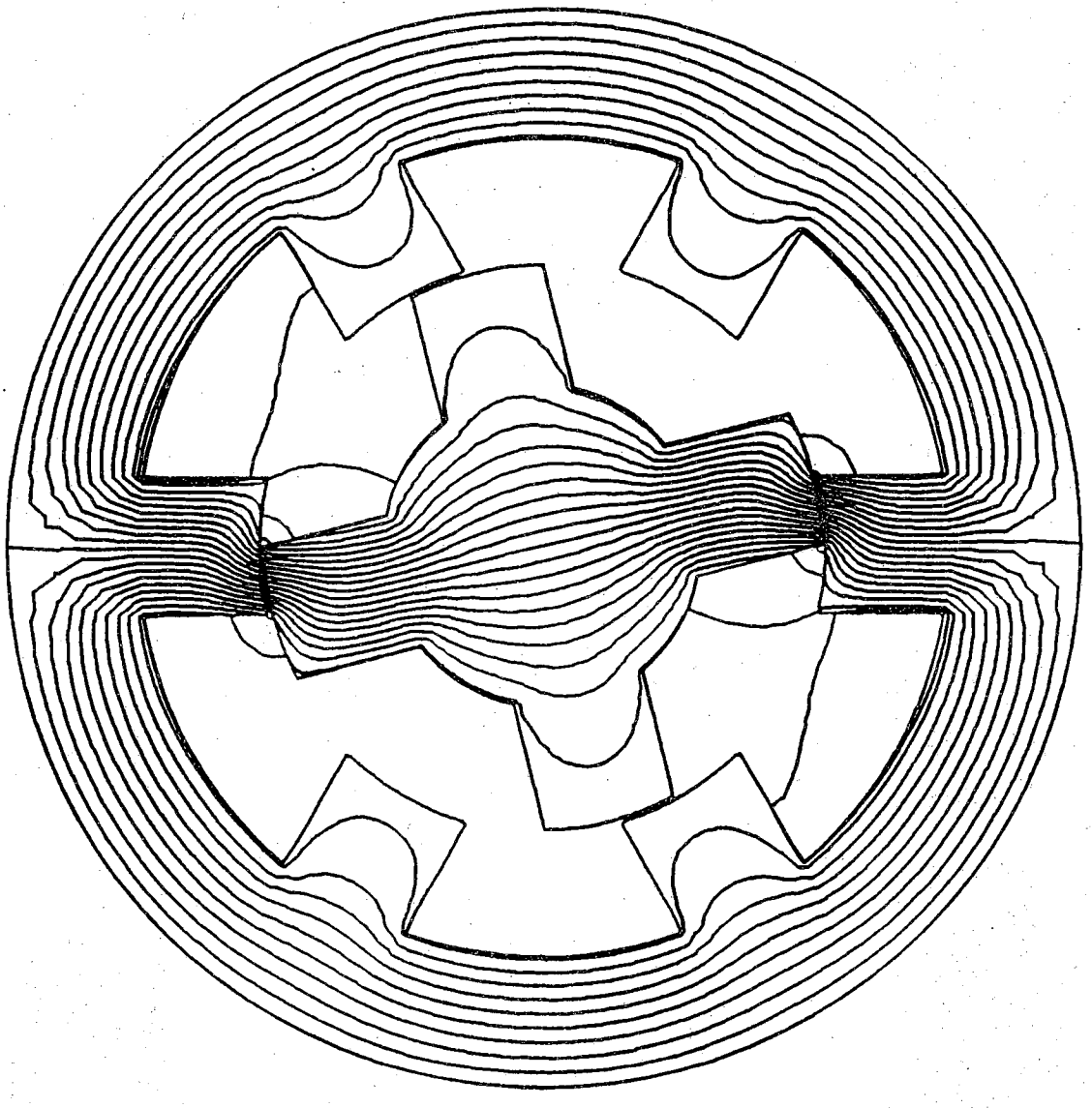

Figure 5. Flux lines at 14 deg. position

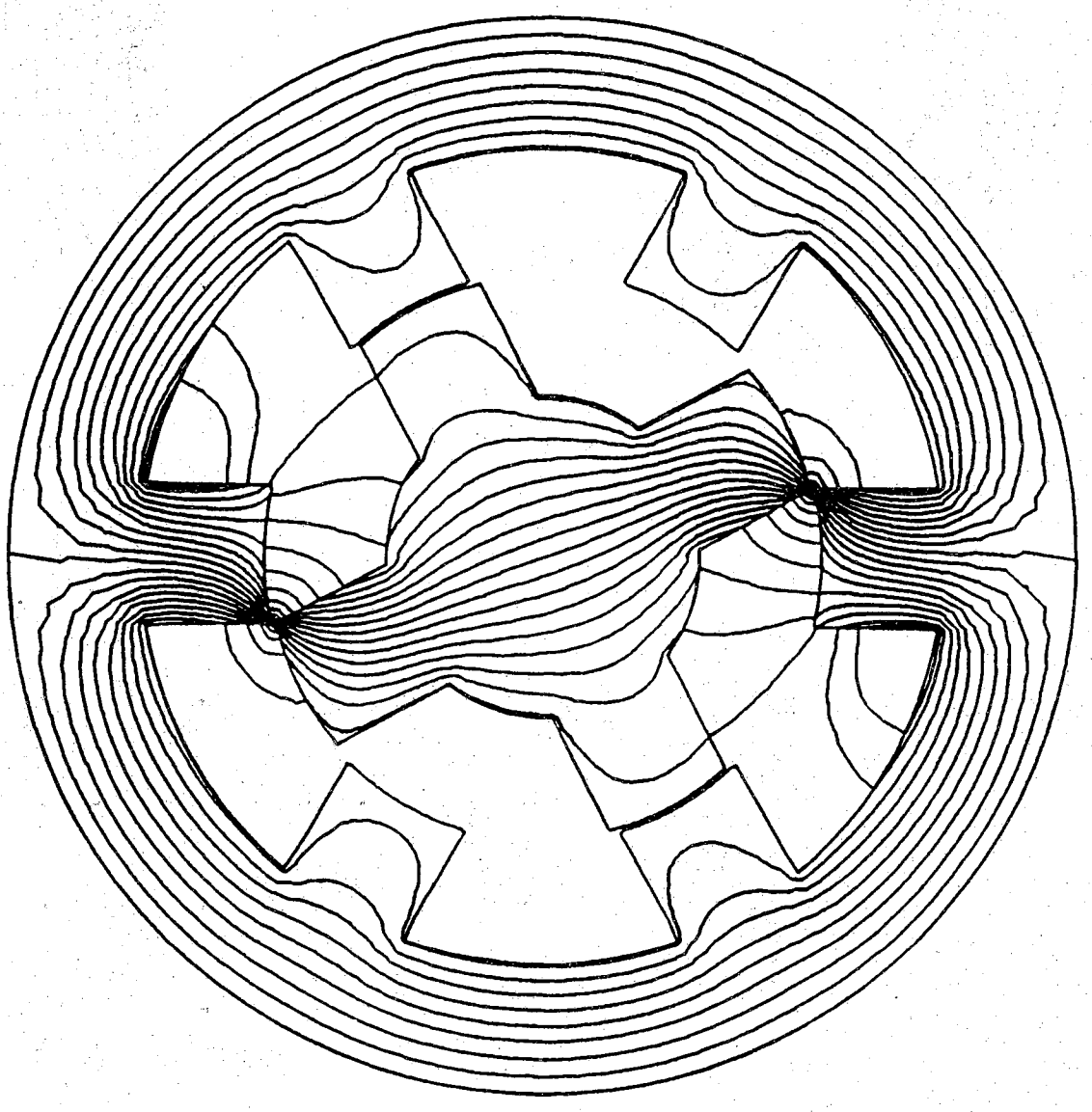

Figure 6. Flux lines at 28 deg. position

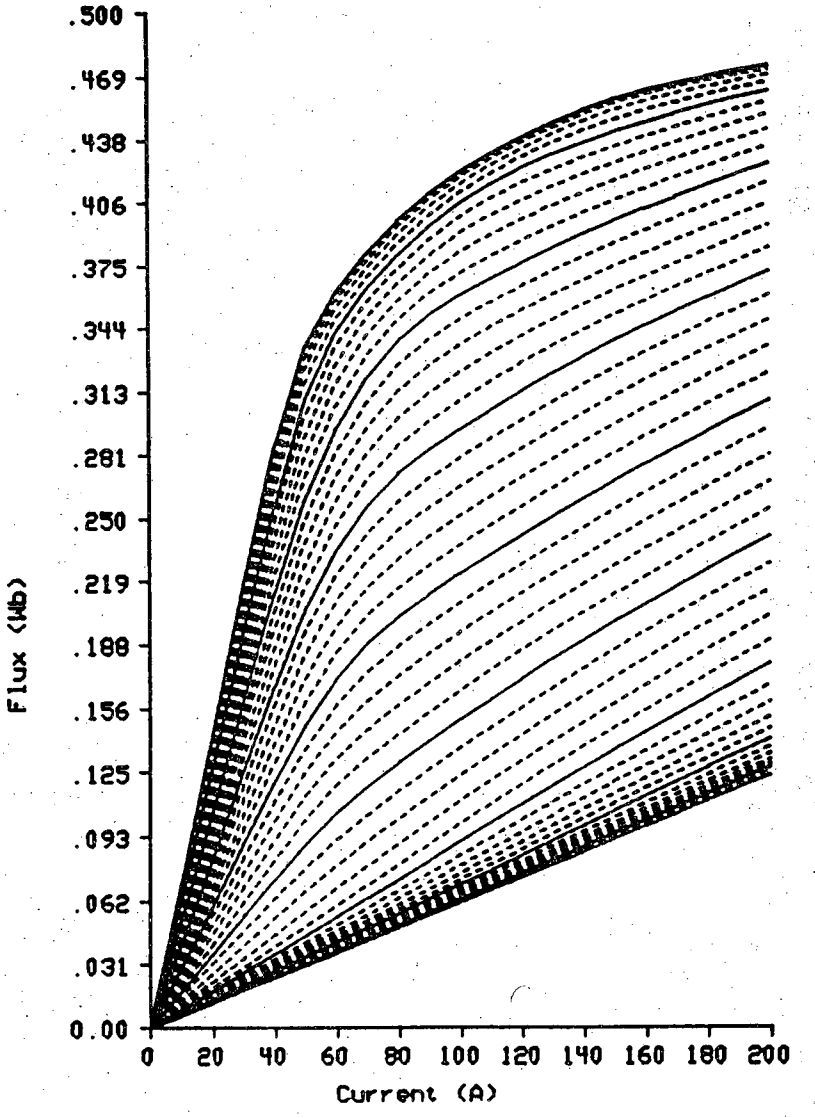

Figure 7. Flux linkage curves, 0-45° in 1° intervals

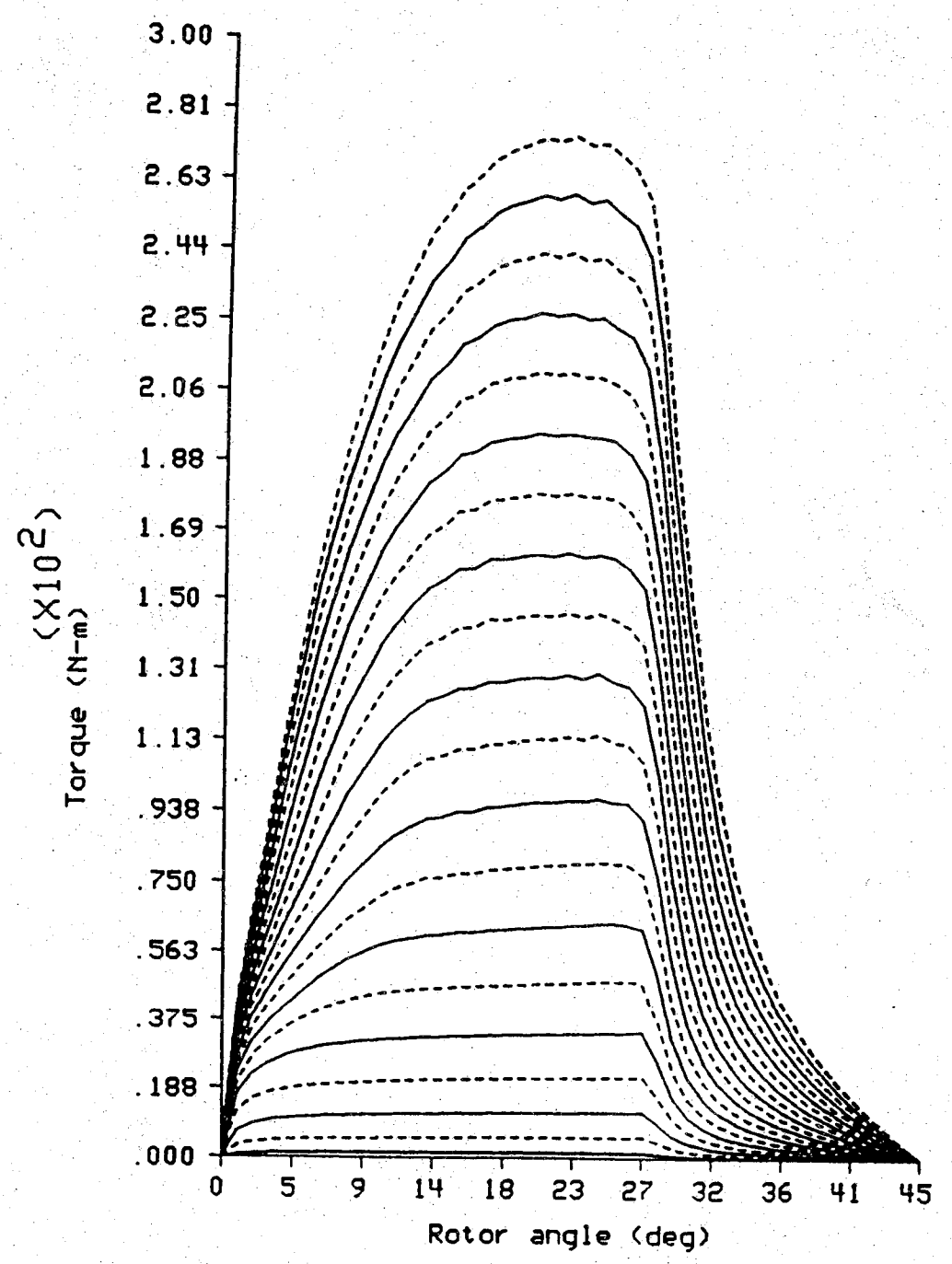

Figure 8. Static torque curves, 10-200A in 10 A intervals

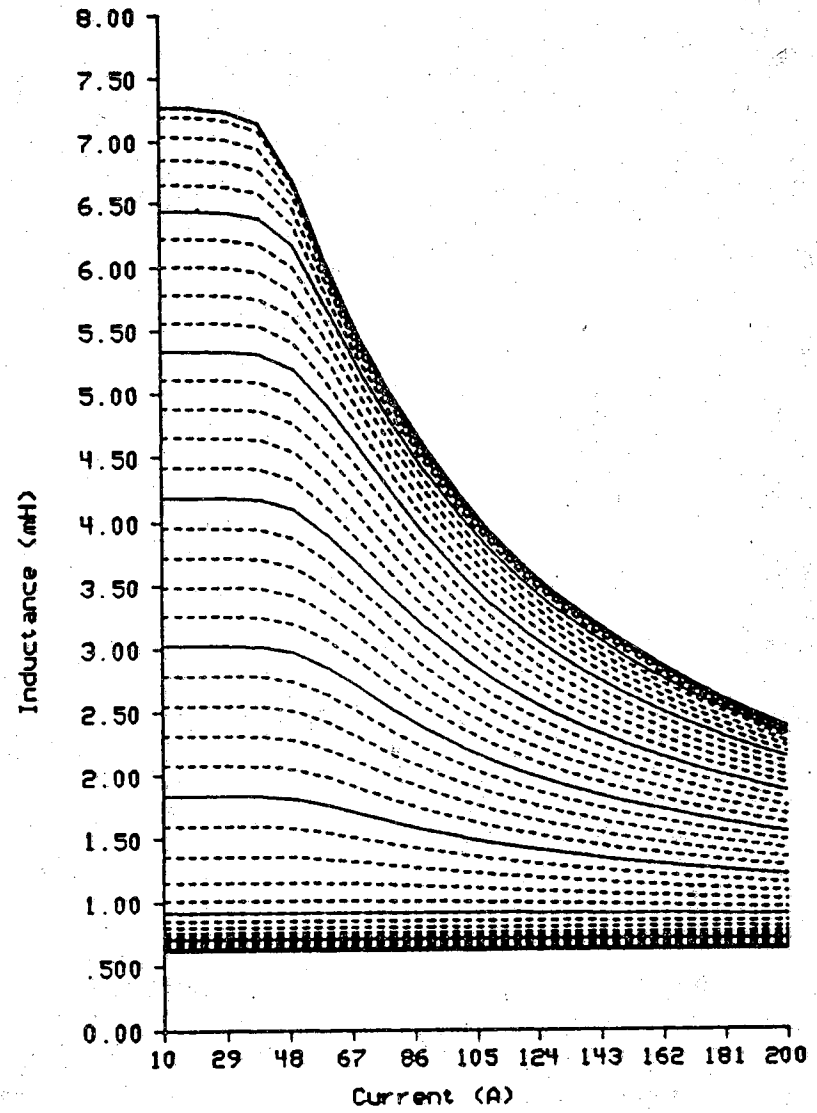

Figure 9. Inductance curves, 0-45° in 1° intervals

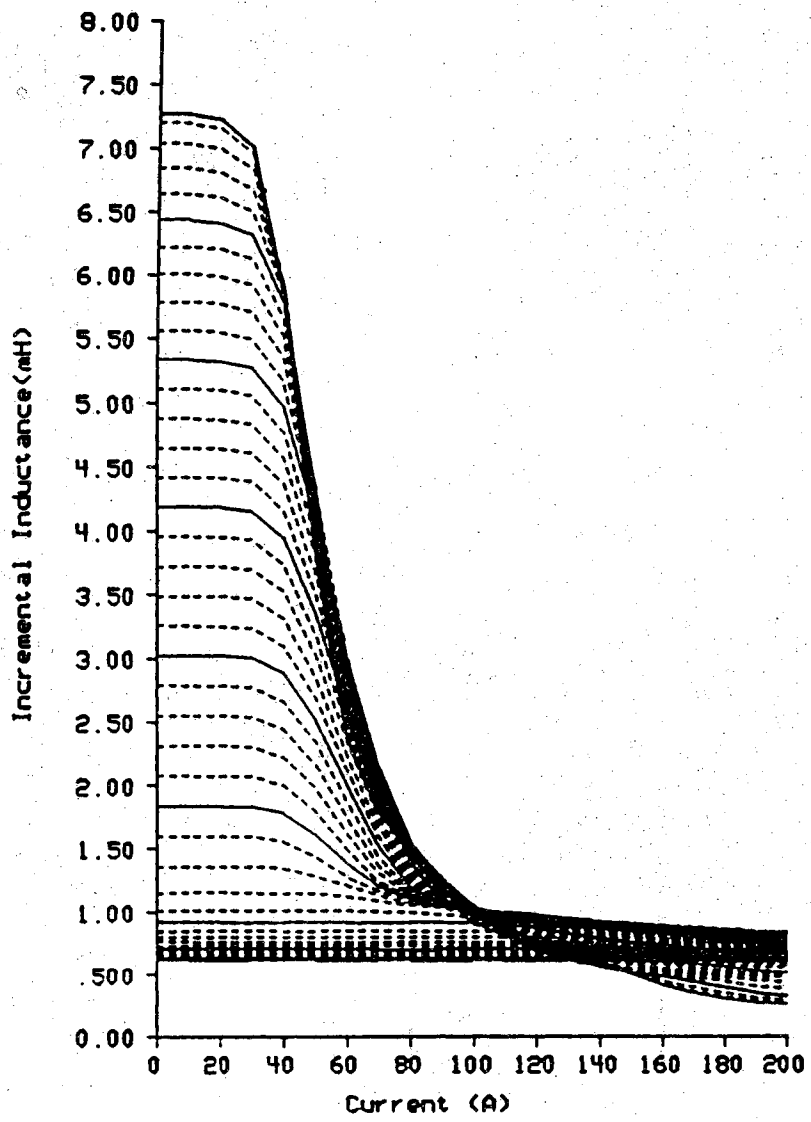

Figure 10. Incremental inductance curves, 0-45° in 1° intervals

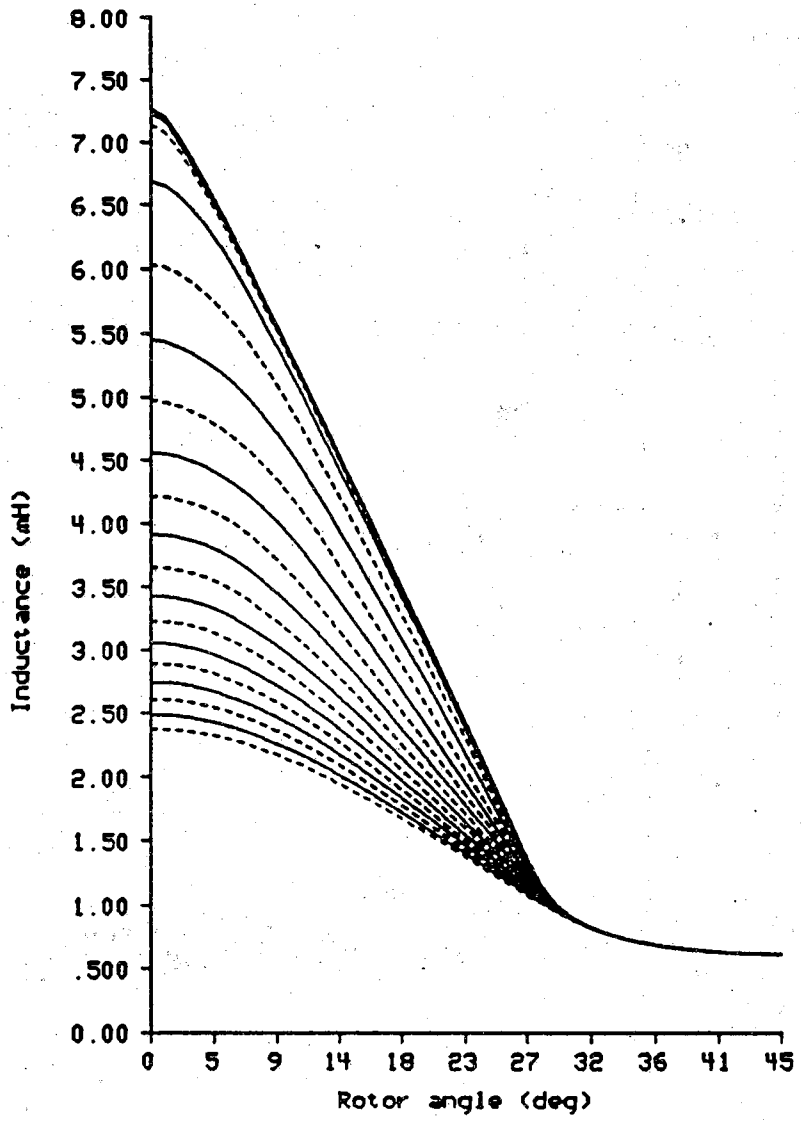

Figure 11. Inductance curves, 10-200 A, 10 A intervals

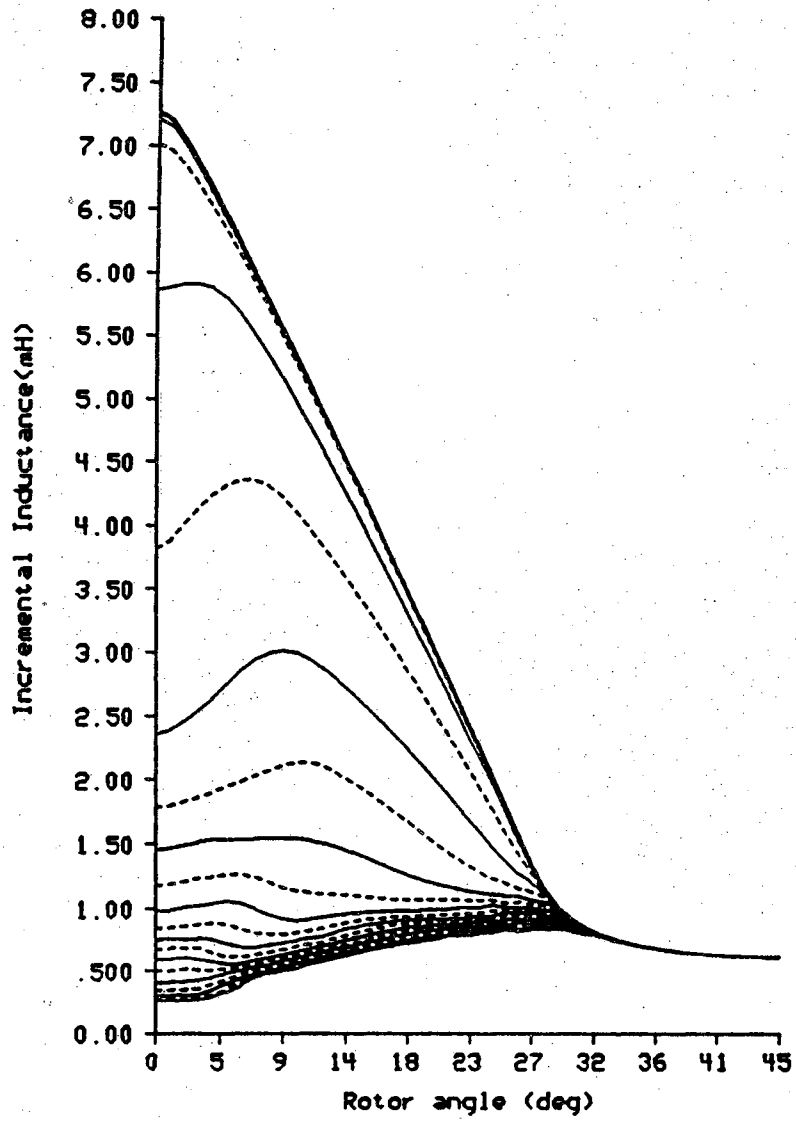

Figure 12. Incremental inductance curves, 10-200 A, 10 A intervals

$\frac{\partial \lambda}{\partial \theta}$

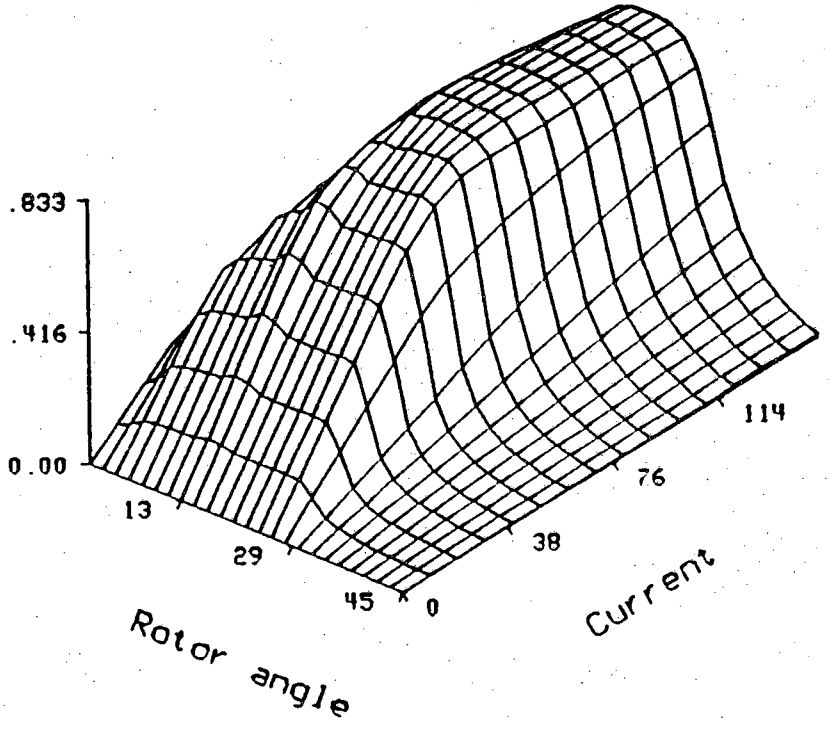

Figure 13. Back EMF coefficient profile

Part III Sensitivity Studies

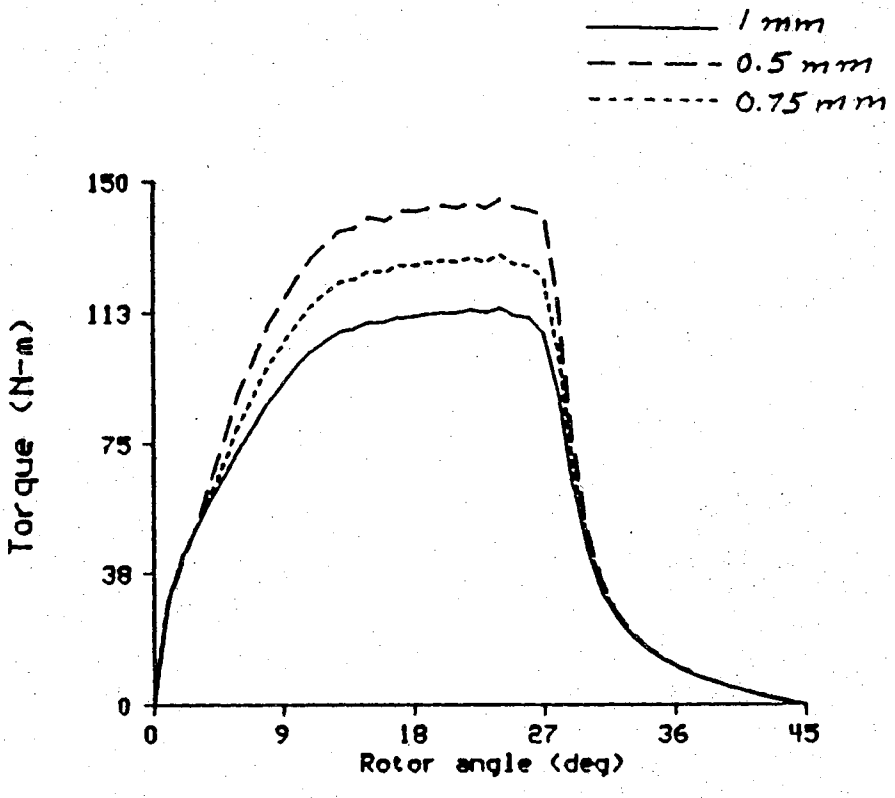

Figure 14. Effect of changing the airgap length

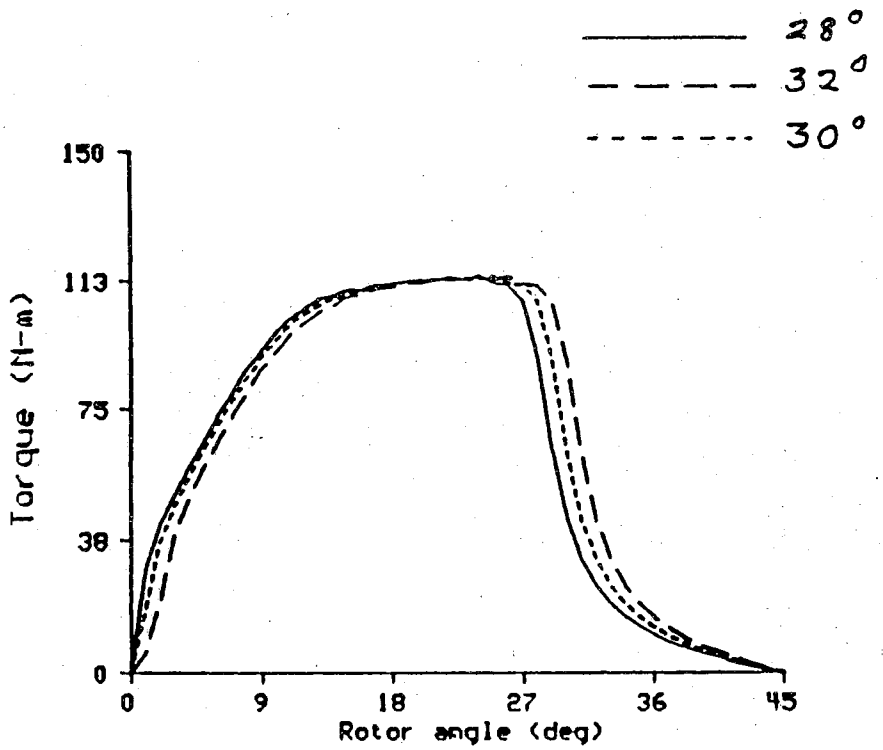

Figure 15. Effect of changing the rotor pole width

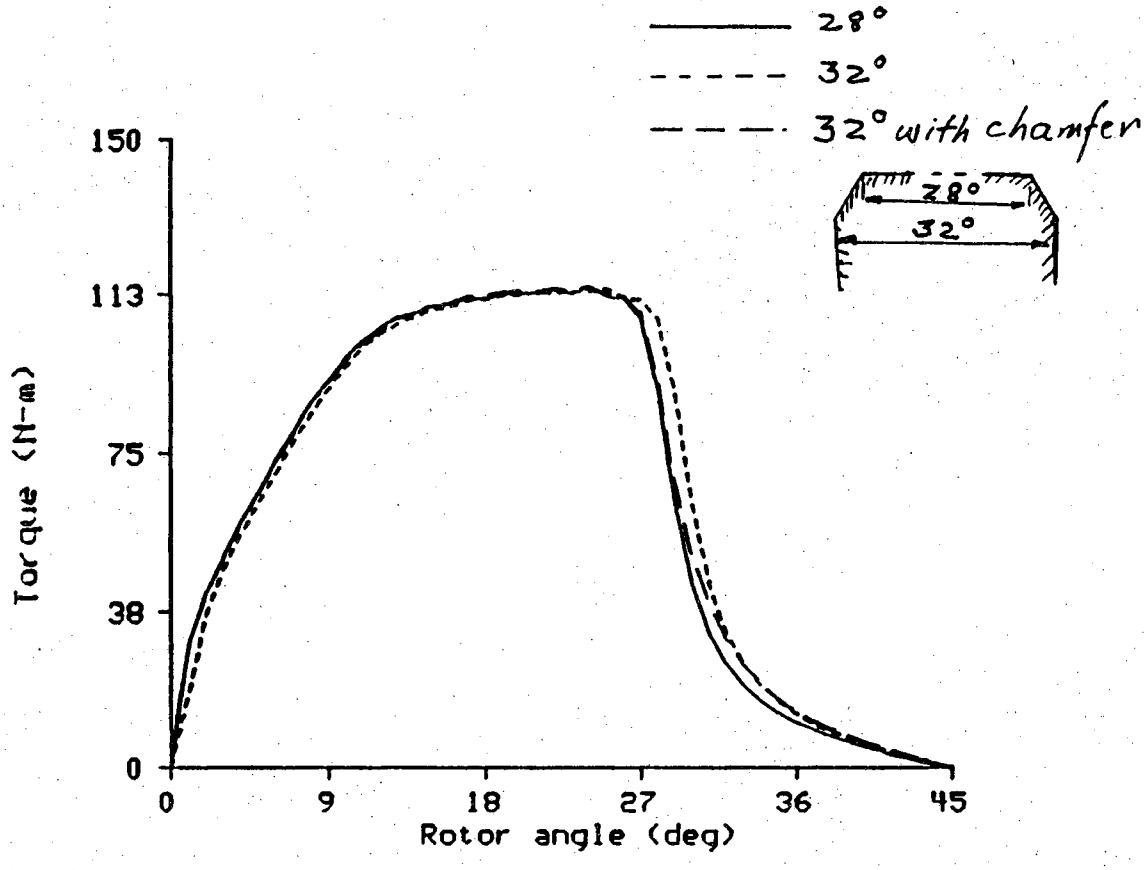

Figure 16. Effect of a 2° chamfer on both sides of the rotor pole face

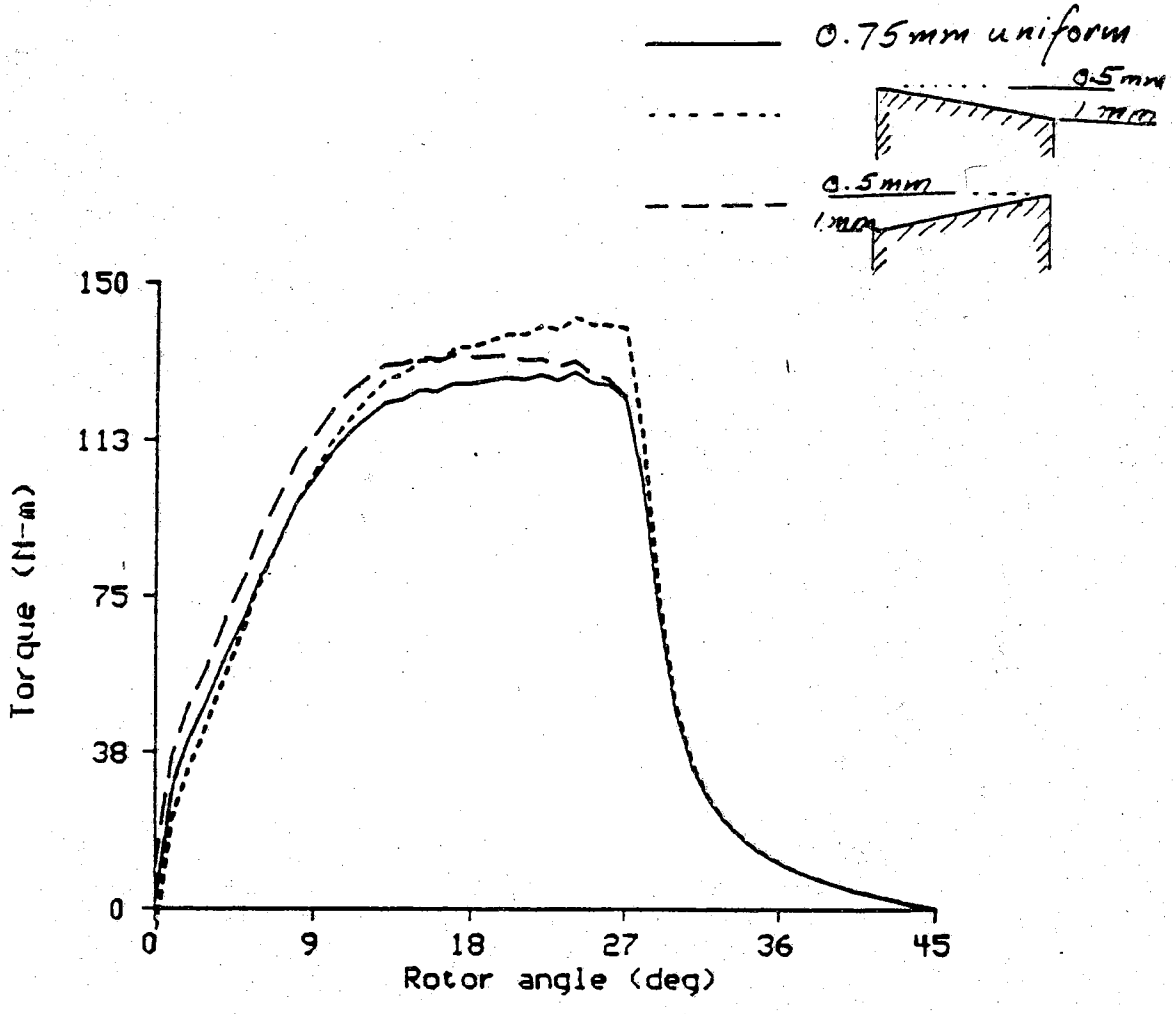

Figure 19. Effect of sloping the rotor pole face

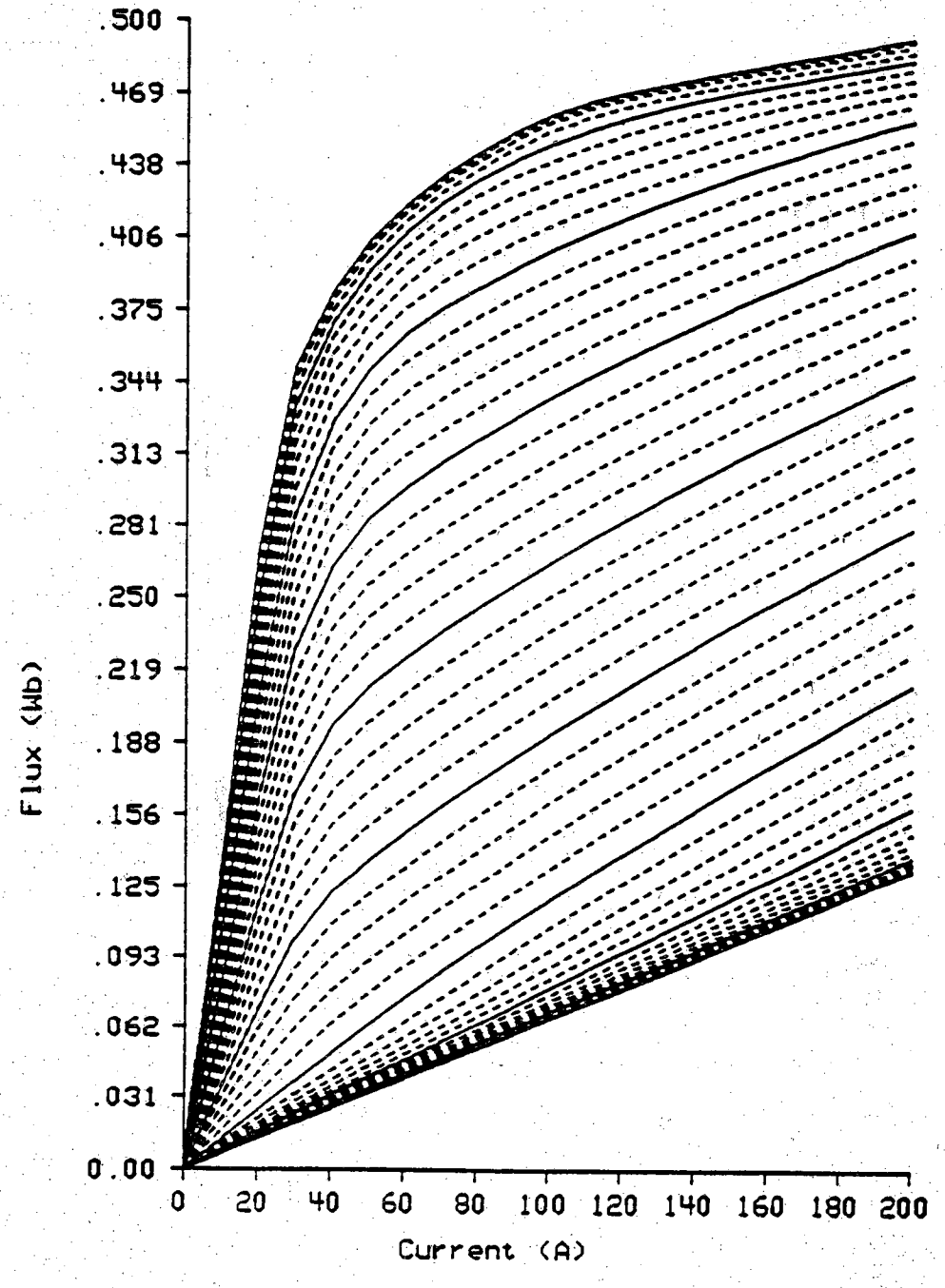

Figure 20. Flux linkage curves for 0.5 mm airgap case 0-45° in 1° intervals

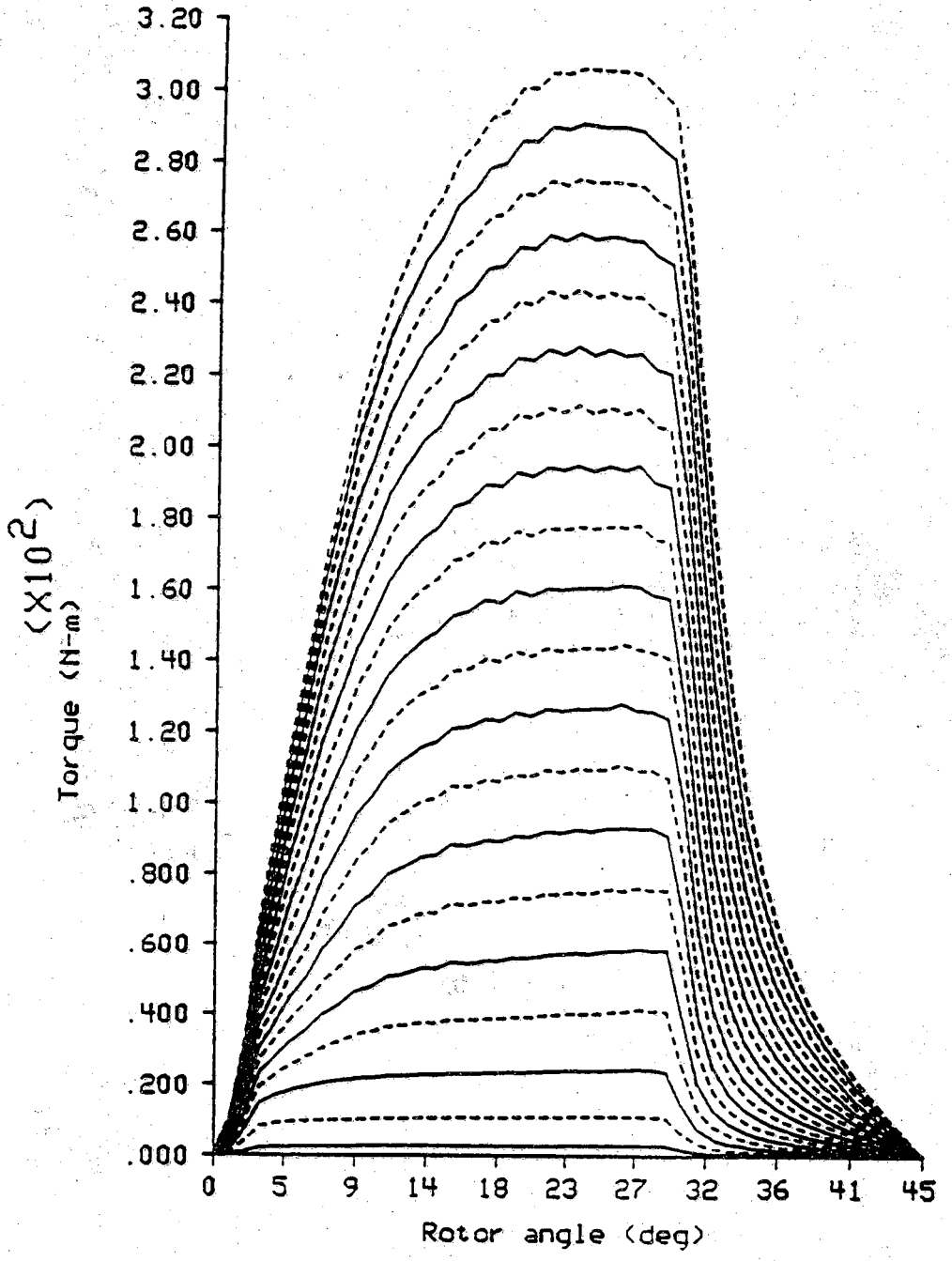

Figure 21. Static torque curves for 0.5 mm airgap case 10-200A in 10 A intervals

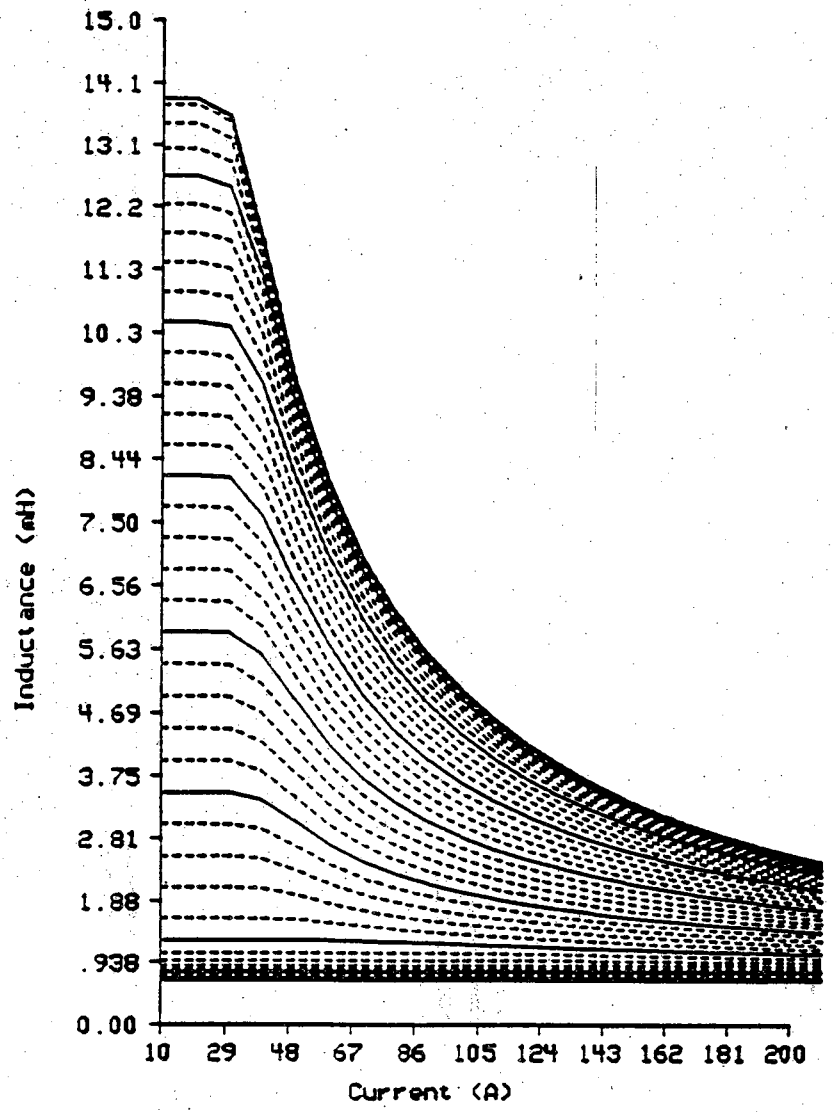

Figure 22. Inductance curves for 0.5 mm airgap case 0-45° in 1° intervals

Part IV Steady-State Waveforms

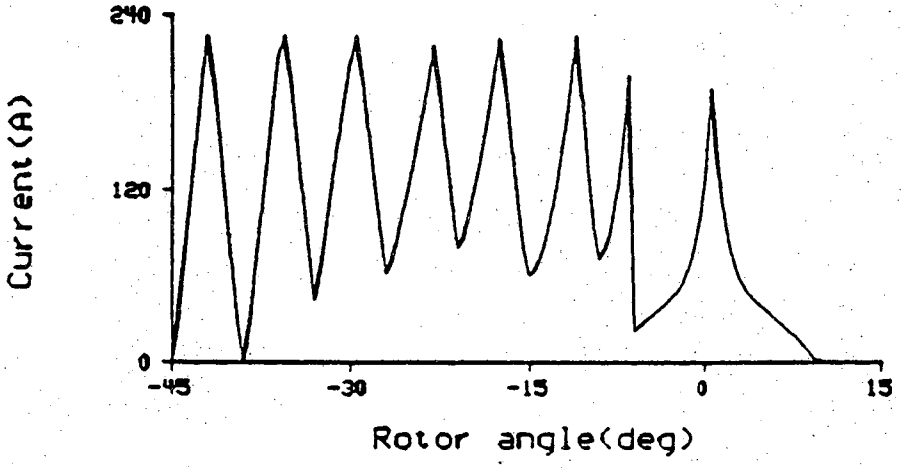

Figure 23. Current waveform at 1000 rpm, 1 msec off-time

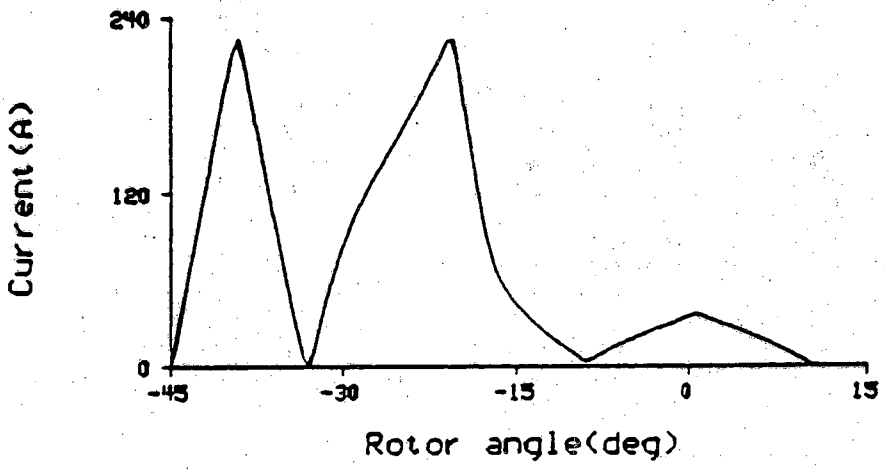

Figure 24. Current waveform at 2000 rpm, 1 msec off-time

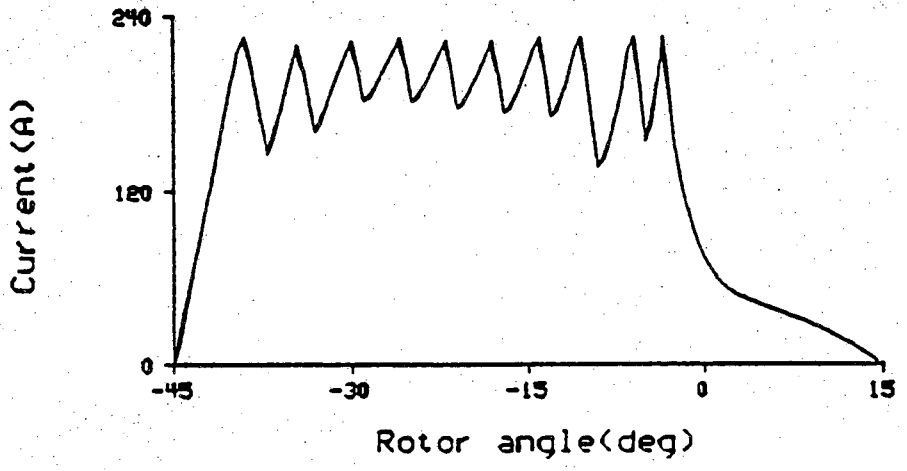

Figure 25. Current waveform at 1000 rpm, 0.3 msec off-time

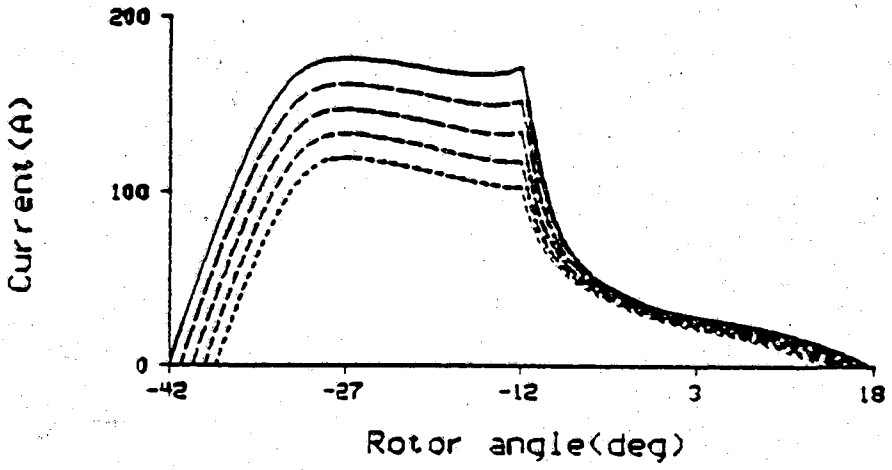

Figure 26. Current waveform at 4000 rpm, θ_{on} = -42 to -38, θ_{off} = -12 1° intervals

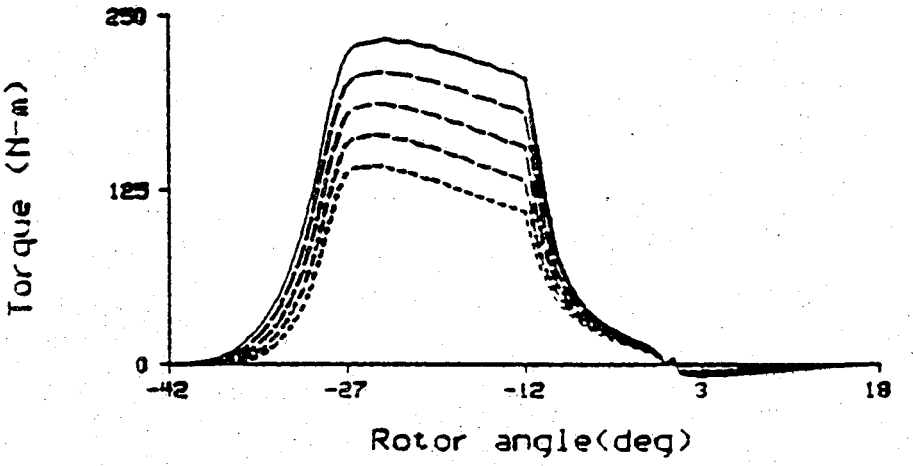

Figure 27. Phase torque at 4000 rpm, θ_{on} = -42 to -38, θ_{off} = -12 1° intervals

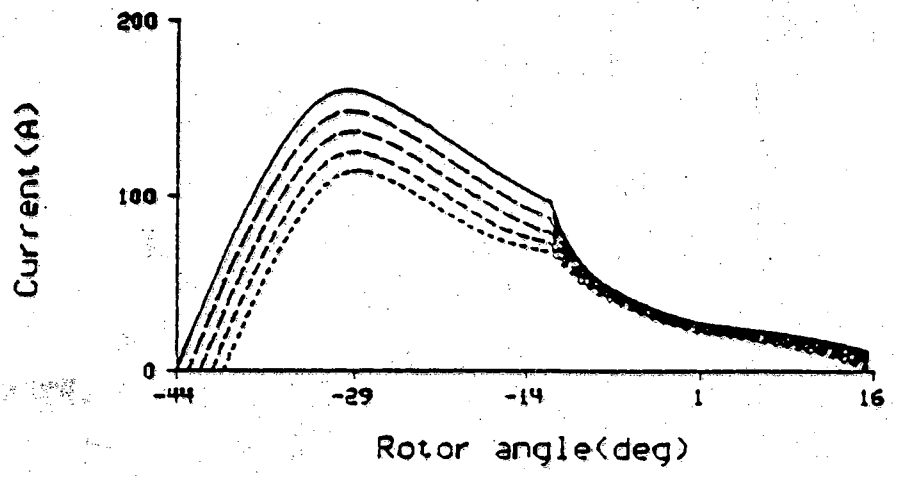

Figure 28. Current waveform at 5000 rpm, θ_{on} = -44 to -40, θ_{off} = -12
1° intervals

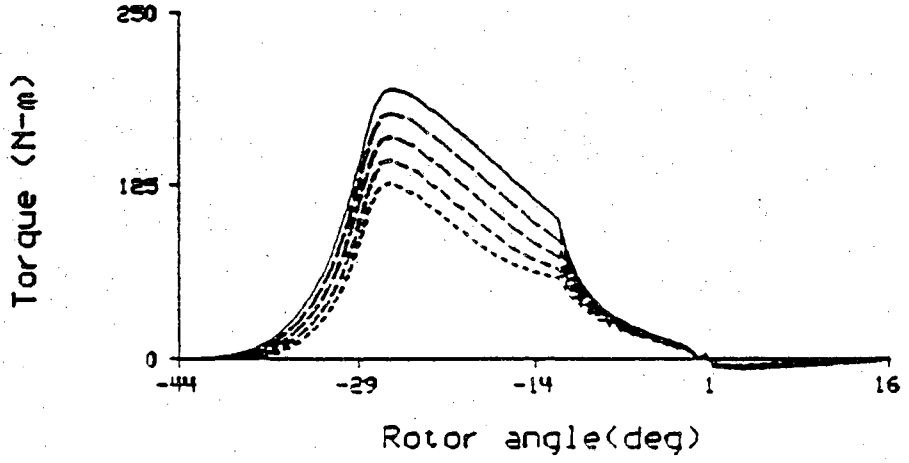

Figure 29. Phase torque at 5000 rpm, θ_{on} = -44 to -40, θ_{off} = -12 1° intervals

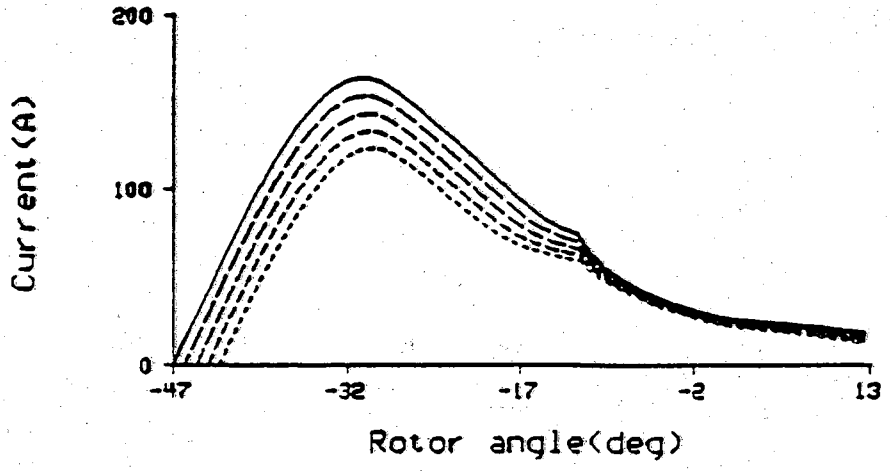

Figure 30. Current waveform at 6000 rpm, θ_{on}= -47 to -43, θ_{off}= -12

1° intervals

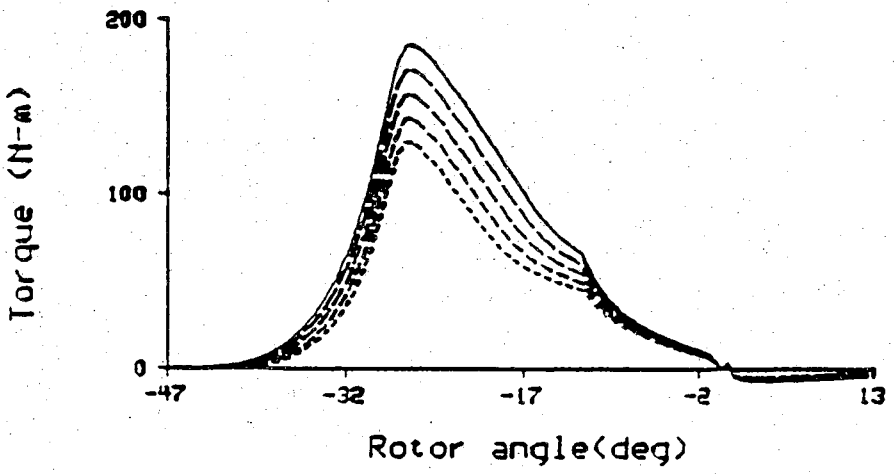

Figure 31. Phase torque at 6000 rpm, θ_{on}= -47 to -43, θ_{off}= -12 1° intervals

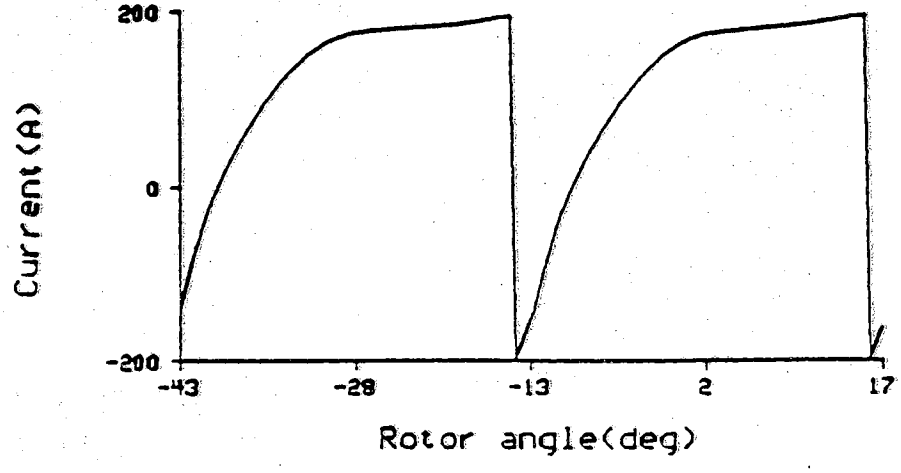

Figure 32. DC link current at 4000 rpm

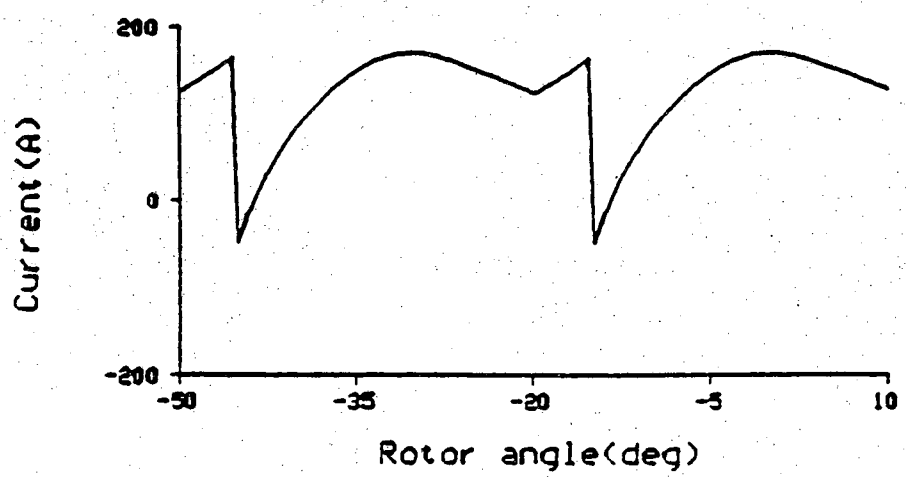

Figure 33. DC link current at 6000 rpm

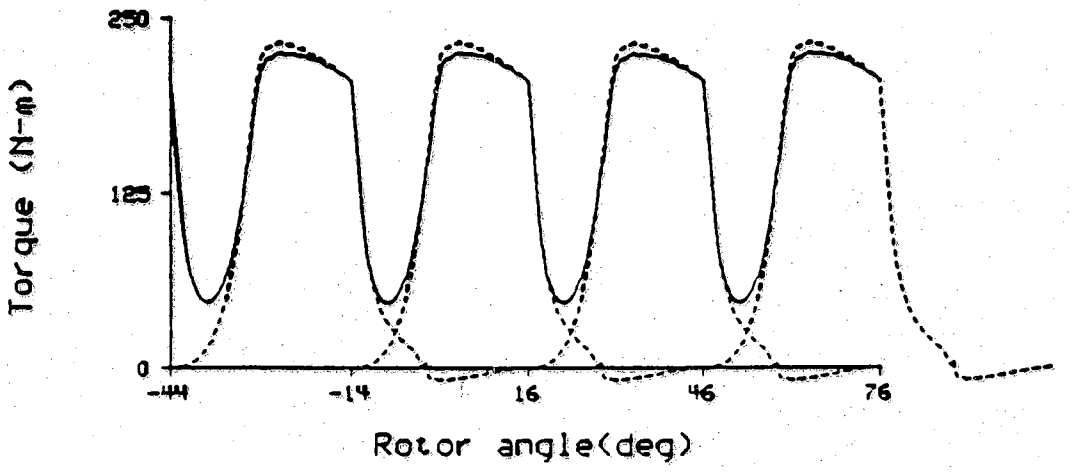

Figure 34. Shaft torque at 4000 rpm, θ_{on} = -43.5 θ_{off} = -15

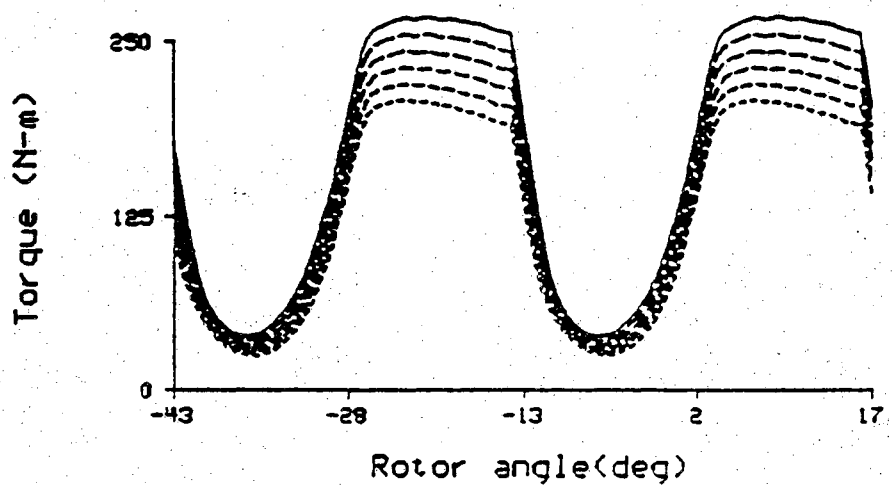

Figure 35. Shaft torque at 4000 rpm, θ_{on}= -43.5 to -41 θ_{off}= -15

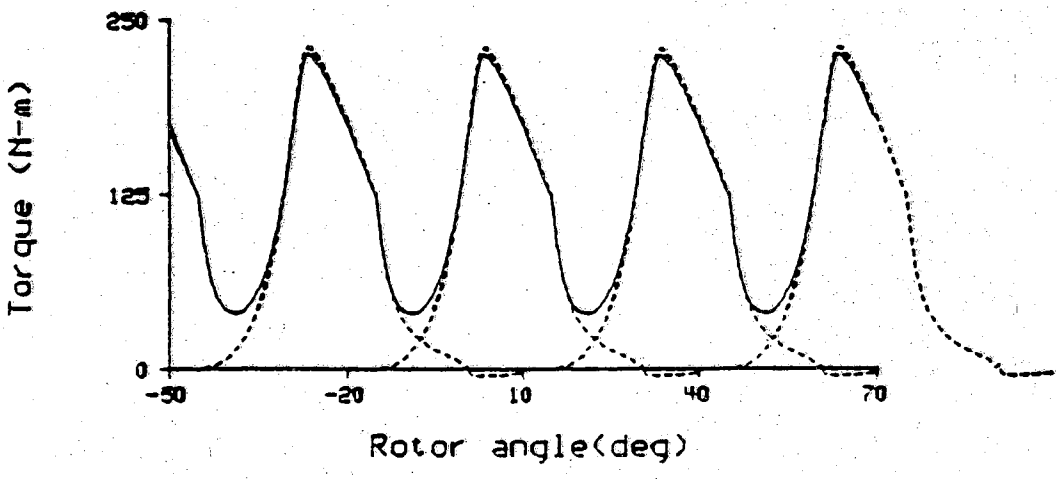

Figure 36. Shaft torque at 6000 rpm, θ_{on}= -50 θ_{off}= -15

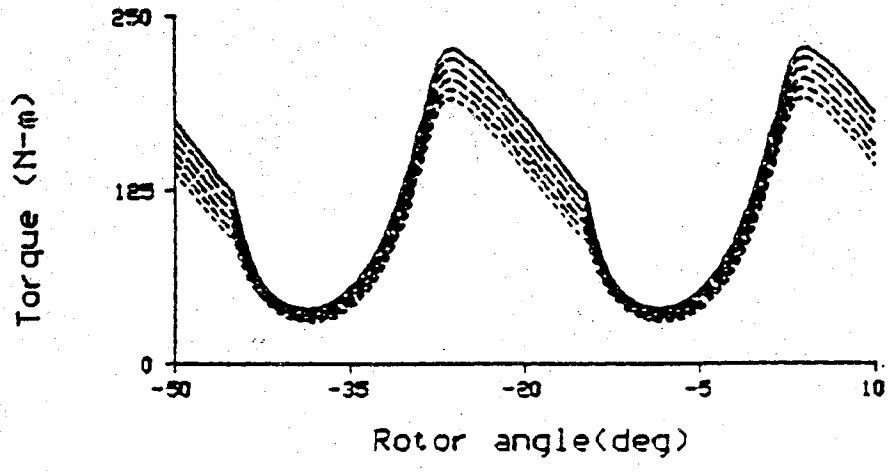

Figure 37. Shaft torque at 6000 rpm, θ_{on}= -50 to 47.5 θ_{off}= -15

Table 4. Steady-state data at 4000 rpm

Speed in rpm= 4000.00000000000

On	Off	Cond.	DC Link Ave.	DC Link Eff.	DC Link Max.	Phase Ave.	Phase Eff.	Switches Ave.	Switches Eff.	Diodes Ave.	Diodes Eff.
-47.0	-31.5	29.0	45.5	149.2	251.5	41.9	86.2	28.6	74.2	13.4	43.9
-46.5	-19.5	28.5	133.8	192.8	250.0	74.9	121.9	59.8	114.6	15.1	41.5
-46.0	-18.0	28.0	122.9	186.6	240.2	72.8	118.3	56.9	110.0	15.9	43.5
-45.5	-18.0	27.5	116.8	179.6	230.5	69.2	113.3	54.1	105.4	15.1	41.5
-45.0	-18.0	27.0	110.8	172.7	221.1	65.8	108.4	51.3	100.9	14.4	39.5
-44.5	-18.0	26.5	104.9	165.8	212.7	62.4	103.6	48.7	96.5	13.7	37.6
-44.0	-18.0	26.0	99.3	159.0	204.5	59.1	98.9	46.1	92.2	13.0	35.8
-43.5	-18.0	25.5	93.7	152.3	196.8	56.0	94.3	43.6	88.0	12.4	34.1
-43.0	-18.0	25.0	88.3	145.7	189.2	53.0	89.9	41.2	83.8	11.8	32.4
-42.5	-18.0	24.5	83.0	139.2	181.7	50.0	85.5	38.8	79.8	11.2	30.8

Speed in rpm= 4000.00000000000

On	Off	Cond.	Tpave	Tpmax	Tave(shaft)	Power	Trip
-47.0	-31.5	29.0	21.05	202.67	63.16	26458.28	3.20
-46.5	-19.5	28.5	64.74	345.65	194.22	81352.90	1.58
-46.0	-18.0	28.0	63.37	332.56	190.11	79634.13	1.55
-45.5	-18.0	27.5	60.26	319.46	180.79	75728.46	1.57
-45.0	-18.0	27.0	57.23	306.63	171.68	71913.53	1.60
-44.5	-18.0	26.5	54.25	293.85	162.75	68173.44	1.63
-44.0	-18.0	26.0	51.36	281.31	154.07	64537.58	1.65
-43.5	-18.0	25.5	48.54	269.20	145.62	60997.05	1.68
-43.0	-18.0	25.0	45.79	257.06	137.37	57543.09	1.71
-42.5	-18.0	24.5	43.11	245.07	129.32	54167.85	1.74

Table 5. Steady-state data at 5000 rpm

```
***************************************
*    Speed in rpm=    5000.00000000000    *
***************************************
```

On	Off	Cond.	DC Link Ave.	DC Link Eff.	DC Link Max.	Phase Ave.	Phase Eff.	Switches Ave.	Switches Eff.	Diodes Ave.	Diodes Eff.
-50.0	-18.0	32.0	140.3	173.9	217.5	76.1	117.0	61.4	111.2	14.7	36.3
-49.5	-18.0	31.5	134.3	168.1	210.4	72.9	112.8	58.8	107.3	14.1	34.8
-49.0	-18.0	31.0	128.5	162.7	204.7	69.8	108.7	56.3	103.4	13.5	33.5
-48.5	-18.0	30.5	122.8	157.5	199.0	66.8	104.7	53.9	99.6	12.9	32.1
-48.0	-18.0	30.0	117.1	152.6	193.4	63.9	100.7	51.5	95.9	12.4	30.9
-47.5	-18.0	29.5	111.6	147.7	187.7	61.0	96.8	49.1	92.2	11.9	29.6
-47.0	-18.0	29.0	106.2	142.7	182.2	58.2	93.0	46.8	88.6	11.4	28.4
-46.5	-18.0	28.5	100.9	137.8	176.7	55.5	89.3	44.6	85.0	10.9	27.3
-46.0	-18.0	28.0	95.8	132.8	171.3	52.9	85.6	42.4	81.5	10.5	26.2
-45.5	-18.0	27.5	90.7	127.8	165.9	50.3	82.0	40.3	78.1	10.0	25.1

```
***************************************
*    Speed in rpm=    5000.00000000000    *
***************************************
```

On	Off	Cond.	Tpave	Tpmax	Tave(shaft)	Power	Trip
-50.0	-18.0	32.0	57.26	304.27	171.77	89939.06	1.51
-49.5	-18.0	31.5	54.85	294.40	164.55	86156.08	1.54
-49.0	-18.0	31.0	52.49	284.73	157.48	82453.95	1.56
-48.5	-18.0	30.5	50.18	275.37	150.55	78828.05	1.59
-48.0	-18.0	30.0	47.91	266.19	143.73	75256.43	1.62
-47.5	-18.0	29.5	45.68	256.83	137.04	71755.67	1.64
-47.0	-18.0	29.0	43.50	247.53	130.50	68330.74	1.67
-46.5	-18.0	28.5	41.38	238.48	124.15	65003.65	1.70
-46.0	-18.0	28.0	39.30	229.24	117.89	61727.40	1.73
-45.5	-18.0	27.5	37.24	220.06	111.72	58496.50	1.76

Table 6. Steady-state data at 6000 rpm

Speed in rpm= 6000.00000000000											
			DC Link			Phase		Switches		Diodes	
On	Off	Cond.	Ave.	Eff.	Max.	Ave.	Eff.	Ave.	Eff.	Ave.	Eff.
-54.0	-18.0	36.0	157.9	178.1	236.4	81.3	119.3	67.0	114.9	14.3	32.2
-53.5	-18.0	35.5	152.2	172.1	225.0	78.4	115.7	64.5	111.4	13.8	31.2
-53.0	-18.0	35.0	146.5	166.3	213.6	75.5	112.1	62.2	108.0	13.3	30.1
-52.5	-18.0	34.5	140.9	160.6	202.3	72.7	108.6	59.8	104.6	12.9	29.1
-52.0	-18.0	34.0	135.4	155.1	196.2	69.9	105.1	57.5	101.2	12.4	28.1
-51.5	-18.0	33.5	130.0	149.8	191.4	67.2	101.6	55.3	97.9	12.0	27.2
-51.0	-18.0	33.0	124.6	144.7	186.6	64.6	98.2	53.1	94.6	11.5	26.2
-50.5	-18.0	32.5	119.4	139.7	181.8	62.0	94.8	50.9	91.4	11.1	25.3
-50.0	-18.0	32.0	114.2	135.0	177.1	59.5	91.6	48.8	88.2	10.7	24.5
-49.5	-18.0	31.5	109.2	130.5	172.4	57.0	88.3	46.7	85.1	10.3	23.6

Speed in rpm= 6000.00000000000							
On	Off	Cond.	Tpave	Tpmax	Tave(shaft)	Power	Trip
-54.0	-18.0	36.0	53.36	292.41	160.07	100572.36	1.53
-53.5	-18.0	35.5	51.42	284.45	154.27	96931.21	1.55
-53.0	-18.0	35.0	49.52	276.59	148.57	93348.43	1.57
-52.5	-18.0	34.5	47.65	268.90	142.96	89826.44	1.59
-52.0	-18.0	34.0	45.82	261.26	137.45	86362.30	1.62
-51.5	-18.0	33.5	44.00	253.55	132.01	82946.15	1.64
-51.0	-18.0	33.0	42.21	245.85	126.64	79569.57	1.67
-50.5	-18.0	32.5	40.45	238.23	121.35	76248.43	1.69
-50.0	-18.0	32.0	38.73	230.65	116.18	72995.89	1.72
-49.5	-18.0	31.5	37.04	223.08	111.11	69814.40	1.75

DISCUSSION AND CONCLUSION

The computed inductance and static torque curves for the machine dimensions considered show that both wider rotor width and a small rotor skew produce a shift of the positive slope of the inductance curve away from the aligned position. A shift of the positive slope towards the unaligned position has two advantages: One is that the phase inductance is at its maximum positive slope, hence maximum torque, when the phase is energized. Secondly, the flatter inductance profile near the aligned position when the phase current is to be commutated allow a faster drop off of the commutated current, thus smaller negative torque.

The broader torque-angle curve with a wider rotor pole width and skewing can be explained from the observation that torque reaches a maximum when the stator and rotor poles begin to overlap. At a low level of excitation current, the torque remains relatively flat until complete overlap when bulk saturation of the stator poles occurs. But with higher excitation current, bulk saturation of stator pole happens earlier and the torque peaks then. Thus, with a wider rotor pole width, initial overlap will happen earlier and complete overlapping of the stator pole will happen before the alignment of rotor and stator poles. A small skew of the rotor in the direction of rotation has the same effect. But with skewing, the neutral torque position is shifted away from the geometric aligned position; moreover, the maximum static torque could be smaller because of the smaller X_{min}/X_{max} ratio.

Toothed pole-face structure can bring about an increase in the torque by increasing the tangential component of the flux density. But on the basis of the same minimum airgap length, after adjusting for the increase in effective length of the airgap due to the teeth, toothed pole-face structure does not produce more torque. As shown in Figs. 14-20, the most effective way of increasing the torque capability of the machine is still to reduce the airgap length, subject to, of course, manufacturing costs and tolerances.

The predicted steady state results show that with proper angle and current control on the machine the basic design is capable of delivering the required shaft torque at the desired speed.

The aligned position is defined as the position where the axis of the excited phase pole coincides with that of the rotor pole.

REFERENCE

[1] M. Moallem and C. M. Ong, "Predicting the Torque of a Switched Reluctance Machine from its Finite Element Field Solution," IEEE, 1989 Power Engineering Society Summer Meeting, Paper No. 89 SM 617-2 EC, Long Beach, California, July 1989.

[2] M. Moallem and C. M. Ong, "Predicting the Steady-State Performance of a Switched Reluctance Machine," IEEE, 1989 Industry Applications Society Annual Meeting, Conference Record 89CH2792-0, San Diego, California, Oct. 1989, pp. 529 - 537.

[3] M. Moallem and C. M. Ong, "Performance Characteristics of Switched Reluctance Motor Drive," TR-EE 89-52, School of Electrical Engineering, Purdue University, West Lafayette, August 1989.

APPENDIX

Given in this Appendix are the numerical values of the flux linkage for the base case design. They correspond to the curves plotted in Fig. 7; they are repeated here in numeric form to facilitate future calculations requiring these numbers.

Table 7 Flux linkages

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	0.	0.0727	10.00	2.000	0.0704
20.00	0.	0.1453	20.00	2.000	0.1406
30.00	0.	0.2170	30.00	2.000	0.2102
40.00	0.	0.2855	40.00	2.000	0.2773
50.00	0.	0.3343	50.00	2.000	0.3284
60.00	0.	0.3619	60.00	2.000	0.3575
70.00	0.	0.3815	70.00	2.000	0.3776
80.00	0.	0.3976	80.00	2.000	0.3941
90.00	0.	0.4107	90.00	2.000	0.4075
100.00	0.	0.4213	100.00	2.000	0.4184
110.00	0.	0.4304	110.00	2.000	0.4277
120.00	0.	0.4383	120.00	2.000	0.4357
130.00	0.	0.4455	130.00	2.000	0.4430
140.00	0.	0.4520	140.00	2.000	0.4496
150.00	0.	0.4575	150.00	2.000	0.4553
160.00	0.	0.4620	160.00	2.000	0.4599
170.00	0.	0.4657	170.00	2.000	0.4637
180.00	0.	0.4689	180.00	2.000	0.4669
190.00	0.	0.4717	190.00	2.000	0.4697
200.00	0.	0.4743	200.00	2.000	0.4723
10.00	1.000	0.0720	10.00	3.000	0.0685
20.00	1.000	0.1438	20.00	3.000	0.1369
30.00	1.000	0.2149	30.00	3.000	0.2047
40.00	1.000	0.2829	40.00	3.000	0.2704
50.00	1.000	0.3326	50.00	3.000	0.3229
60.00	1.000	0.3606	60.00	3.000	0.3532
70.00	1.000	0.3804	70.00	3.000	0.3738
80.00	1.000	0.3966	80.00	3.000	0.3905
90.00	1.000	0.4098	90.00	3.000	0.4042
100.00	1.000	0.4205	100.00	3.000	0.4153
110.00	1.000	0.4296	110.00	3.000	0.4247
120.00	1.000	0.4376	120.00	3.000	0.4328
130.00	1.000	0.4449	130.00	3.000	0.4401
140.00	1.000	0.4514	140.00	3.000	0.4466
150.00	1.000	0.4569	150.00	3.000	0.4521
160.00	1.000	0.4615	160.00	3.000	0.4568
170.00	1.000	0.4652	170.00	3.000	0.4607
180.00	1.000	0.4684	180.00	3.000	0.4640
190.00	1.000	0.4713	190.00	3.000	0.4670
200.00	1.000	0.4739	200.00	3.000	0.4697

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	4.000	0.0665
20.00	4.000	0.1329
30.00	4.000	0.1988
40.00	4.000	0.2629
50.00	4.000	0.3163
60.00	4.000	0.3478
70.00	4.000	0.3691
80.00	4.000	0.3860
90.00	4.000	0.3998
100.00	4.000	0.4110
110.00	4.000	0.4206
120.00	4.000	0.4288
130.00	4.000	0.4358
140.00	4.000	0.4419
150.00	4.000	0.4473
160.00	4.000	0.4521
170.00	4.000	0.4563
180.00	4.000	0.4600
190.00	4.000	0.4633
200.00	4.000	0.4662
10.00	5.000	0.0644
20.00	5.000	0.1287
30.00	5.000	0.1926
40.00	5.000	0.2550
50.00	5.000	0.3085
60.00	5.000	0.3414
70.00	5.000	0.3635
80.00	5.000	0.3804
90.00	5.000	0.3942
100.00	5.000	0.4057
110.00	5.000	0.4153
120.00	5.000	0.4232
130.00	5.000	0.4298
140.00	5.000	0.4356
150.00	5.000	0.4410
160.00	5.000	0.4460
170.00	5.000	0.4507
180.00	5.000	0.4548
190.00	5.000	0.4586
200.00	5.000	0.4619

Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	6.000	0.0622
20.00	6.000	0.1244
30.00	6.000	0.1863
40.00	6.000	0.2468
50.00	6.000	0.2996
60.00	6.000	0.3340
70.00	6.000	0.3568
80.00	6.000	0.3737
90.00	6.000	0.3876
100.00	6.000	0.3991
110.00	6.000	0.4084
120.00	6.000	0.4159
130.00	6.000	0.4224
140.00	6.000	0.4283
150.00	6.000	0.4337
160.00	6.000	0.4390
170.00	6.000	0.4439
180.00	6.000	0.4485
190.00	6.000	0.4528
200.00	6.000	0.4566
10.00	7.000	0.0601
20.00	7.000	0.1201
30.00	7.000	0.1798
40.00	7.000	0.2384
50.00	7.000	0.2901
60.00	7.000	0.3255
70.00	7.000	0.3490
80.00	7.000	0.3662
90.00	7.000	0.3799
100.00	7.000	0.3911
110.00	7.000	0.3999
120.00	7.000	0.4073
130.00	7.000	0.4139
140.00	7.000	0.4201
150.00	7.000	0.4257
160.00	7.000	0.4311
170.00	7.000	0.4363
180.00	7.000	0.4412
190.00	7.000	0.4459
200.00	7.000	0.4503

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	8.000	0.0578	10.00	10.000	0.0534
20.00	8.000	0.1157	20.00	10.000	0.1067
30.00	8.000	0.1732	30.00	10.000	0.1598
40.00	8.000	0.2298	40.00	10.000	0.2122
50.00	8.000	0.2802	50.00	10.000	0.2593
60.00	8.000	0.3160	60.00	10.000	0.2943
70.00	8.000	0.3401	70.00	10.000	0.3193
80.00	8.000	0.3575	80.00	10.000	0.3371
90.00	8.000	0.3711	90.00	10.000	0.3502
100.00	8.000	0.3817	100.00	10.000	0.3599
110.00	8.000	0.3902	110.00	10.000	0.3684
120.00	8.000	0.3977	120.00	10.000	0.3762
130.00	8.000	0.4046	130.00	10.000	0.3835
140.00	8.000	0.4109	140.00	10.000	0.3904
150.00	8.000	0.4169	150.00	10.000	0.3969
160.00	8.000	0.4226	160.00	10.000	0.4032
170.00	8.000	0.4279	170.00	10.000	0.4091
180.00	8.000	0.4331	180.00	10.000	0.4149
190.00	8.000	0.4380	190.00	10.000	0.4204
200.00	8.000	0.4428	200.00	10.000	0.4256
10.00	9.000	0.0556	10.00	11.000	0.0511
20.00	9.000	0.1112	20.00	11.000	0.1022
30.00	9.000	0.1665	30.00	11.000	0.1531
40.00	9.000	0.2210	40.00	11.000	0.2033
50.00	9.000	0.2699	50.00	11.000	0.2486
60.00	9.000	0.3055	60.00	11.000	0.2827
70.00	9.000	0.3302	70.00	11.000	0.3075
80.00	9.000	0.3479	80.00	11.000	0.3254
90.00	9.000	0.3612	90.00	11.000	0.3381
100.00	9.000	0.3712	100.00	11.000	0.3479
110.00	9.000	0.3797	110.00	11.000	0.3565
120.00	9.000	0.3873	120.00	11.000	0.3645
130.00	9.000	0.3944	130.00	11.000	0.3720
140.00	9.000	0.4010	140.00	11.000	0.3791
150.00	9.000	0.4072	150.00	11.000	0.3859
160.00	9.000	0.4132	160.00	11.000	0.3925
170.00	9.000	0.4189	170.00	11.000	0.3988
180.00	9.000	0.4243	180.00	11.000	0.4048
190.00	9.000	0.4295	190.00	11.000	0.4105
200.00	9.000	0.4345	200.00	11.000	0.4161

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	12.000	0.0488	10.00	14.000	0.0442
20.00	12.000	0.0976	20.00	14.000	0.0884
30.00	12.000	0.1462	30.00	14.000	0.1325
40.00	12.000	0.1943	40.00	14.000	0.1761
50.00	12.000	0.2377	50.00	14.000	0.2157
60.00	12.000	0.2708	60.00	14.000	0.2465
70.00	12.000	0.2951	70.00	14.000	0.2693
80.00	12.000	0.3129	80.00	14.000	0.2861
90.00	12.000	0.3253	90.00	14.000	0.2981
100.00	12.000	0.3352	100.00	14.000	0.3082
110.00	12.000	0.3441	110.00	14.000	0.3175
120.00	12.000	0.3523	120.00	14.000	0.3263
130.00	12.000	0.3600	130.00	14.000	0.3346
140.00	12.000	0.3673	140.00	14.000	0.3425
150.00	12.000	0.3744	150.00	14.000	0.3500
160.00	12.000	0.3811	160.00	14.000	0.3572
170.00	12.000	0.3877	170.00	14.000	0.3642
180.00	12.000	0.3940	180.00	14.000	0.3710
190.00	12.000	0.4001	190.00	14.000	0.3776
200.00	12.000	0.4059	200.00	14.000	0.3840
10.00	13.000	0.0465	10.00	15.000	0.0419
20.00	13.000	0.0930	20.00	15.000	0.0838
30.00	13.000	0.1394	30.00	15.000	0.1256
40.00	13.000	0.1852	40.00	15.000	0.1669
50.00	13.000	0.2268	50.00	15.000	0.2046
60.00	13.000	0.2587	60.00	15.000	0.2341
70.00	13.000	0.2823	70.00	15.000	0.2561
80.00	13.000	0.2997	80.00	15.000	0.2723
90.00	13.000	0.3119	90.00	15.000	0.2840
100.00	13.000	0.3219	100.00	15.000	0.2941
110.00	13.000	0.3310	110.00	15.000	0.3036
120.00	13.000	0.3395	120.00	15.000	0.3126
130.00	13.000	0.3475	130.00	15.000	0.3212
140.00	13.000	0.3551	140.00	15.000	0.3293
150.00	13.000	0.3624	150.00	15.000	0.3371
160.00	13.000	0.3694	160.00	15.000	0.3446
170.00	13.000	0.3762	170.00	15.000	0.3519
180.00	13.000	0.3828	180.00	15.000	0.3588
190.00	13.000	0.3891	190.00	15.000	0.3656
200.00	13.000	0.3952	200.00	15.000	0.3723

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	16.000	0.0396
20.00	16.000	0.0791
30.00	16.000	0.1186
40.00	16.000	0.1577
50.00	16.000	0.1934
60.00	16.000	0.2216
70.00	16.000	0.2428
80.00	16.000	0.2583
90.00	16.000	0.2698
100.00	16.000	0.2800
110.00	16.000	0.2895
120.00	16.000	0.2986
130.00	16.000	0.3074
140.00	16.000	0.3157
150.00	16.000	0.3238
160.00	16.000	0.3315
170.00	16.000	0.3390
180.00	16.000	0.3463
190.00	16.000	0.3533
200.00	16.000	0.3602
10.00	17.000	0.0372
20.00	17.000	0.0745
30.00	17.000	0.1116
40.00	17.000	0.1484
50.00	17.000	0.1822
60.00	17.000	0.2091
70.00	17.000	0.2294
80.00	17.000	0.2442
90.00	17.000	0.2555
100.00	17.000	0.2656
110.00	17.000	0.2753
120.00	17.000	0.2845
130.00	17.000	0.2934
140.00	17.000	0.3020
150.00	17.000	0.3102
160.00	17.000	0.3182
170.00	17.000	0.3259
180.00	17.000	0.3333
190.00	17.000	0.3406
200.00	17.000	0.3477
10.00	18.000	0.0349
20.00	18.000	0.0698
30.00	18.000	0.1046
40.00	18.000	0.1392
50.00	18.000	0.1709
60.00	18.000	0.1964
70.00	18.000	0.2158
80.00	18.000	0.2299
90.00	18.000	0.2411
100.00	18.000	0.2513
110.00	18.000	0.2609
120.00	18.000	0.2701
130.00	18.000	0.2792
140.00	18.000	0.2879
150.00	18.000	0.2964
160.00	18.000	0.3046
170.00	18.000	0.3125
180.00	18.000	0.3201
190.00	18.000	0.3276
200.00	18.000	0.3349
10.00	19.000	0.0326
20.00	19.000	0.0651
30.00	19.000	0.0976
40.00	19.000	0.1298
50.00	19.000	0.1595
60.00	19.000	0.1836
70.00	19.000	0.2021
80.00	19.000	0.2155
90.00	19.000	0.2267
100.00	19.000	0.2369
110.00	19.000	0.2466
120.00	19.000	0.2559
130.00	19.000	0.2650
140.00	19.000	0.2738
150.00	19.000	0.2823
160.00	19.000	0.2907
170.00	19.000	0.2988
180.00	19.000	0.3067
190.00	19.000	0.3143
200.00	19.000	0.3218

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	20.000	0.0302	10.00	22.000	0.0255
20.00	20.000	0.0604	20.00	22.000	0.0510
30.00	20.000	0.0906	30.00	22.000	0.0765
40.00	20.000	0.1205	40.00	22.000	0.1017
50.00	20.000	0.1482	50.00	22.000	0.1253
60.00	20.000	0.1708	60.00	22.000	0.1450
70.00	20.000	0.1882	70.00	22.000	0.1603
80.00	20.000	0.2011	80.00	22.000	0.1723
90.00	20.000	0.2122	90.00	22.000	0.1833
100.00	20.000	0.2225	100.00	22.000	0.1937
110.00	20.000	0.2322	110.00	22.000	0.2036
120.00	20.000	0.2416	120.00	22.000	0.2131
130.00	20.000	0.2507	130.00	22.000	0.2223
140.00	20.000	0.2596	140.00	22.000	0.2313
150.00	20.000	0.2683	150.00	22.000	0.2401
160.00	20.000	0.2768	160.00	22.000	0.2488
170.00	20.000	0.2850	170.00	22.000	0.2573
180.00	20.000	0.2930	180.00	22.000	0.2656
190.00	20.000	0.3009	190.00	22.000	0.2738
200.00	20.000	0.3085	200.00	22.000	0.2817
10.00	21.000	0.0279	10.00	23.000	0.0231
20.00	21.000	0.0557	20.00	23.000	0.0463
30.00	21.000	0.0835	30.00	23.000	0.0694
40.00	21.000	0.1111	40.00	23.000	0.0923
50.00	21.000	0.1367	50.00	23.000	0.1138
60.00	21.000	0.1580	60.00	23.000	0.1320
70.00	21.000	0.1743	70.00	23.000	0.1463
80.00	21.000	0.1867	80.00	23.000	0.1581
90.00	21.000	0.1978	90.00	23.000	0.1690
100.00	21.000	0.2081	100.00	23.000	0.1794
110.00	21.000	0.2179	110.00	23.000	0.1893
120.00	21.000	0.2273	120.00	23.000	0.1988
130.00	21.000	0.2365	130.00	23.000	0.2082
140.00	21.000	0.2454	140.00	23.000	0.2173
150.00	21.000	0.2542	150.00	23.000	0.2263
160.00	21.000	0.2628	160.00	23.000	0.2350
170.00	21.000	0.2712	170.00	23.000	0.2434
180.00	21.000	0.2793	180.00	23.000	0.2518
190.00	21.000	0.2872	190.00	23.000	0.2600
200.00	21.000	0.2951	200.00	23.000	0.2680

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	24.000	0.0208	10.00	26.000	0.0160
20.00	24.000	0.0415	20.00	26.000	0.0320
30.00	24.000	0.0623	30.00	26.000	0.0480
40.00	24.000	0.0829	40.00	26.000	0.0639
50.00	24.000	0.1023	50.00	26.000	0.0791
60.00	24.000	0.1189	60.00	26.000	0.0927
70.00	24.000	0.1322	70.00	26.000	0.1047
80.00	24.000	0.1437	80.00	26.000	0.1160
90.00	24.000	0.1546	90.00	26.000	0.1268
100.00	24.000	0.1652	100.00	26.000	0.1371
110.00	24.000	0.1753	110.00	26.000	0.1471
120.00	24.000	0.1849	120.00	26.000	0.1568
130.00	24.000	0.1942	130.00	26.000	0.1664
140.00	24.000	0.2033	140.00	26.000	0.1758
150.00	24.000	0.2122	150.00	26.000	0.1849
160.00	24.000	0.2210	160.00	26.000	0.1939
170.00	24.000	0.2297	170.00	26.000	0.2028
180.00	24.000	0.2382	180.00	26.000	0.2113
190.00	24.000	0.2466	190.00	26.000	0.2197
200.00	24.000	0.2547	200.00	26.000	0.2279
10.00	25.000	0.0184	10.00	27.000	0.0136
20.00	25.000	0.0368	20.00	27.000	0.0272
30.00	25.000	0.0551	30.00	27.000	0.0408
40.00	25.000	0.0734	40.00	27.000	0.0544
50.00	25.000	0.0907	50.00	27.000	0.0677
60.00	25.000	0.1057	60.00	27.000	0.0801
70.00	25.000	0.1184	70.00	27.000	0.0919
80.00	25.000	0.1298	80.00	27.000	0.1028
90.00	25.000	0.1405	90.00	27.000	0.1133
100.00	25.000	0.1508	100.00	27.000	0.1236
110.00	25.000	0.1608	110.00	27.000	0.1336
120.00	25.000	0.1707	120.00	27.000	0.1435
130.00	25.000	0.1804	130.00	27.000	0.1531
140.00	25.000	0.1897	140.00	27.000	0.1624
150.00	25.000	0.1987	150.00	27.000	0.1716
160.00	25.000	0.2074	160.00	27.000	0.1806
170.00	25.000	0.2160	170.00	27.000	0.1894
180.00	25.000	0.2245	180.00	27.000	0.1981
190.00	25.000	0.2329	190.00	27.000	0.2066
200.00	25.000	0.2412	200.00	27.000	0.2150

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	28.000	0.0115	10.00	30.000	0.0092
20.00	28.000	0.0231	20.00	30.000	0.0184
30.00	28.000	0.0346	30.00	30.000	0.0275
40.00	28.000	0.0461	40.00	30.000	0.0367
50.00	28.000	0.0576	50.00	30.000	0.0459
60.00	28.000	0.0690	60.00	30.000	0.0551
70.00	28.000	0.0801	70.00	30.000	0.0642
80.00	28.000	0.0908	80.00	30.000	0.0734
90.00	28.000	0.1012	90.00	30.000	0.0826
100.00	28.000	0.1114	100.00	30.000	0.0917
110.00	28.000	0.1211	110.00	30.000	0.1008
120.00	28.000	0.1307	120.00	30.000	0.1097
130.00	28.000	0.1402	130.00	30.000	0.1186
140.00	28.000	0.1494	140.00	30.000	0.1274
150.00	28.000	0.1586	150.00	30.000	0.1361
160.00	28.000	0.1676	160.00	30.000	0.1448
170.00	28.000	0.1765	170.00	30.000	0.1533
180.00	28.000	0.1852	180.00	30.000	0.1618
190.00	28.000	0.1938	190.00	30.000	0.1702
200.00	28.000	0.2022	200.00	30.000	0.1784
10.00	29.000	0.0101	10.00	31.000	0.0085
20.00	29.000	0.0202	20.00	31.000	0.0170
30.00	29.000	0.0303	30.00	31.000	0.0256
40.00	29.000	0.0404	40.00	31.000	0.0341
50.00	29.000	0.0505	50.00	31.000	0.0426
60.00	29.000	0.0606	60.00	31.000	0.0511
70.00	29.000	0.0707	70.00	31.000	0.0597
80.00	29.000	0.0807	80.00	31.000	0.0682
90.00	29.000	0.0907	90.00	31.000	0.0767
100.00	29.000	0.1003	100.00	31.000	0.0852
110.00	29.000	0.1099	110.00	31.000	0.0937
120.00	29.000	0.1193	120.00	31.000	0.1022
130.00	29.000	0.1286	130.00	31.000	0.1107
140.00	29.000	0.1378	140.00	31.000	0.1191
150.00	29.000	0.1468	150.00	31.000	0.1274
160.00	29.000	0.1556	160.00	31.000	0.1356
170.00	29.000	0.1643	170.00	31.000	0.1439
180.00	29.000	0.1729	180.00	31.000	0.1520
190.00	29.000	0.1814	190.00	31.000	0.1602
200.00	29.000	0.1898	200.00	31.000	0.1682

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	32.000	0.0080	10.00	34.000	0.0073
20.00	32.000	0.0161	20.00	34.000	0.0147
30.00	32.000	0.0241	30.00	34.000	0.0220
40.00	32.000	0.0321	40.00	34.000	0.0294
50.00	32.000	0.0402	50.00	34.000	0.0367
60.00	32.000	0.0482	60.00	34.000	0.0441
70.00	32.000	0.0562	70.00	34.000	0.0514
80.00	32.000	0.0643	80.00	34.000	0.0588
90.00	32.000	0.0723	90.00	34.000	0.0661
100.00	32.000	0.0803	100.00	34.000	0.0734
110.00	32.000	0.0884	110.00	34.000	0.0808
120.00	32.000	0.0964	120.00	34.000	0.0881
130.00	32.000	0.1044	130.00	34.000	0.0955
140.00	32.000	0.1124	140.00	34.000	0.1028
150.00	32.000	0.1204	150.00	34.000	0.1101
160.00	32.000	0.1283	160.00	34.000	0.1175
170.00	32.000	0.1362	170.00	34.000	0.1248
180.00	32.000	0.1440	180.00	34.000	0.1321
190.00	32.000	0.1518	190.00	34.000	0.1394
200.00	32.000	0.1596	200.00	34.000	0.1467
10.00	33.000	0.0077	10.00	35.000	0.0071
20.00	33.000	0.0153	20.00	35.000	0.0142
30.00	33.000	0.0230	30.00	35.000	0.0213
40.00	33.000	0.0306	40.00	35.000	0.0284
50.00	33.000	0.0383	50.00	35.000	0.0355
60.00	33.000	0.0459	60.00	35.000	0.0426
70.00	33.000	0.0536	70.00	35.000	0.0497
80.00	33.000	0.0612	80.00	35.000	0.0567
90.00	33.000	0.0689	90.00	35.000	0.0638
100.00	33.000	0.0765	100.00	35.000	0.0709
110.00	33.000	0.0842	110.00	35.000	0.0780
120.00	33.000	0.0918	120.00	35.000	0.0851
130.00	33.000	0.0995	130.00	35.000	0.0922
140.00	33.000	0.1071	140.00	35.000	0.0993
150.00	33.000	0.1147	150.00	35.000	0.1064
160.00	33.000	0.1223	160.00	35.000	0.1135
170.00	33.000	0.1299	170.00	35.000	0.1206
180.00	33.000	0.1375	180.00	35.000	0.1276
190.00	33.000	0.1450	190.00	35.000	0.1347
200.00	33.000	0.1525	200.00	35.000	0.1418

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	36.000	0.0069	10.00	38.000	0.0066
20.00	36.000	0.0138	20.00	38.000	0.0132
30.00	36.000	0.0207	30.00	38.000	0.0197
40.00	36.000	0.0275	40.00	38.000	0.0263
50.00	36.000	0.0344	50.00	38.000	0.0329
60.00	36.000	0.0413	60.00	38.000	0.0395
70.00	36.000	0.0482	70.00	38.000	0.0460
80.00	36.000	0.0551	80.00	38.000	0.0526
90.00	36.000	0.0620	90.00	38.000	0.0592
100.00	36.000	0.0689	100.00	38.000	0.0658
110.00	36.000	0.0758	110.00	38.000	0.0723
120.00	36.000	0.0826	120.00	38.000	0.0789
130.00	36.000	0.0895	130.00	38.000	0.0855
140.00	36.000	0.0964	140.00	38.000	0.0921
150.00	36.000	0.1033	150.00	38.000	0.0986
160.00	36.000	0.1102	160.00	38.000	0.1052
170.00	36.000	0.1171	170.00	38.000	0.1118
180.00	36.000	0.1239	180.00	38.000	0.1184
190.00	36.000	0.1308	190.00	38.000	0.1249
200.00	36.000	0.1377	200.00	38.000	0.1315
10.00	37.000	0.0067	10.00	39.000	0.0065
20.00	37.000	0.0134	20.00	39.000	0.0129
30.00	37.000	0.0201	30.00	39.000	0.0194
40.00	37.000	0.0269	40.00	39.000	0.0258
50.00	37.000	0.0336	50.00	39.000	0.0323
60.00	37.000	0.0403	60.00	39.000	0.0388
70.00	37.000	0.0470	70.00	39.000	0.0452
80.00	37.000	0.0537	80.00	39.000	0.0517
90.00	37.000	0.0604	90.00	39.000	0.0581
100.00	37.000	0.0672	100.00	39.000	0.0646
110.00	37.000	0.0739	110.00	39.000	0.0711
120.00	37.000	0.0806	120.00	39.000	0.0775
130.00	37.000	0.0873	130.00	39.000	0.0840
140.00	37.000	0.0940	140.00	39.000	0.0904
150.00	37.000	0.1007	150.00	39.000	0.0969
160.00	37.000	0.1075	160.00	39.000	0.1034
170.00	37.000	0.1142	170.00	39.000	0.1098
180.00	37.000	0.1209	180.00	39.000	0.1163
190.00	37.000	0.1276	190.00	39.000	0.1227
200.00	37.000	0.1343	200.00	39.000	0.1292

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	40.000	0.0064
20.00	40.000	0.0127
30.00	40.000	0.0191
40.00	40.000	0.0255
50.00	40.000	0.0318
60.00	40.000	0.0382
70.00	40.000	0.0446
80.00	40.000	0.0509
90.00	40.000	0.0573
100.00	40.000	0.0637
110.00	40.000	0.0700
120.00	40.000	0.0764
130.00	40.000	0.0828
140.00	40.000	0.0891
150.00	40.000	0.0955
160.00	40.000	0.1019
170.00	40.000	0.1082
180.00	40.000	0.1146
190.00	40.000	0.1210
200.00	40.000	0.1273
10.00	41.000	0.0063
20.00	41.000	0.0126
30.00	41.000	0.0189
40.00	41.000	0.0252
50.00	41.000	0.0315
60.00	41.000	0.0378
70.00	41.000	0.0441
80.00	41.000	0.0504
90.00	41.000	0.0566
100.00	41.000	0.0629
110.00	41.000	0.0692
120.00	41.000	0.0755
130.00	41.000	0.0818
140.00	41.000	0.0881
150.00	41.000	0.0944
160.00	41.000	0.1007
170.00	41.000	0.1070
180.00	41.000	0.1133
190.00	41.000	0.1196
200.00	41.000	0.1259
10.00	42.000	0.0062
20.00	42.000	0.0125
30.00	42.000	0.0187
40.00	42.000	0.0250
50.00	42.000	0.0312
60.00	42.000	0.0374
70.00	42.000	0.0437
80.00	42.000	0.0499
90.00	42.000	0.0561
100.00	42.000	0.0624
110.00	42.000	0.0686
120.00	42.000	0.0749
130.00	42.000	0.0811
140.00	42.000	0.0873
150.00	42.000	0.0936
160.00	42.000	0.0998
170.00	42.000	0.1061
180.00	42.000	0.1123
190.00	42.000	0.1185
200.00	42.000	0.1248
10.00	43.000	0.0062
20.00	43.000	0.0124
30.00	43.000	0.0186
40.00	43.000	0.0248
50.00	43.000	0.0310
60.00	43.000	0.0372
70.00	43.000	0.0434
80.00	43.000	0.0496
90.00	43.000	0.0558
100.00	43.000	0.0620
110.00	43.000	0.0682
120.00	43.000	0.0744
130.00	43.000	0.0806
140.00	43.000	0.0868
150.00	43.000	0.0930
160.00	43.000	0.0992
170.00	43.000	0.1054
180.00	43.000	0.1116
190.00	43.000	0.1178
200.00	43.000	0.1240

Table 7 Flux linkages (cont.)

Current (A)	Angle (deg)	Flux Linkage (Wb)	Current (A)	Angle (deg)	Flux Linkage (Wb)
10.00	44.000	0.0062	10.00	45.000	0.0062
20.00	44.000	0.0124	20.00	45.000	0.0123
30.00	44.000	0.0185	30.00	45.000	0.0185
40.00	44.000	0.0247	40.00	45.000	0.0247
50.00	44.000	0.0309	50.00	45.000	0.0309
60.00	44.000	0.0371	60.00	45.000	0.0370
70.00	44.000	0.0432	70.00	45.000	0.0432
80.00	44.000	0.0494	80.00	45.000	0.0494
90.00	44.000	0.0556	90.00	45.000	0.0555
100.00	44.000	0.0618	100.00	45.000	0.0617
110.00	44.000	0.0680	110.00	45.000	0.0679
120.00	44.000	0.0741	120.00	45.000	0.0740
130.00	44.000	0.0803	130.00	45.000	0.0802
140.00	44.000	0.0865	140.00	45.000	0.0864
150.00	44.000	0.0927	150.00	45.000	0.0926
160.00	44.000	0.0988	160.00	45.000	0.0987
170.00	44.000	0.1050	170.00	45.000	0.1049
180.00	44.000	0.1112	180.00	45.000	0.1111
190.00	44.000	0.1174	190.00	45.000	0.1172
200.00	44.000	0.1235	200.00	45.000	0.1234