MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRONICS AND ELECTRICAL ENGINEERING

Selected Topics on Electrical Machines (EE 568)
Project 2 Report

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GitHub link

Q1- Integral-Slot Winding Design

Assume you have a 6-pole, 72 slot, 3-phase machine with double-layer winding configuration. Design the following windings for this machine:

- Full-pitched winding
- 11/12 short-pitched winding

For these winding configurations:

a) Show the winding diagram layout (just one pole-pair is enough)
b) Calculate the distribution factor, pitch factor and the winding factor for the fundamental component
c) Repeat the same for the 3rd and the 5th harmonics d) Comment on the results

Full pitch winding

- Winding diagram

72 slot, 6 pole, q=4

AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B	AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B
AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B	AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B

- Calculation of winding factors for fundamental, 3rd and 5th harmonics

To calculate winding factor an excel file was written which is available in Github

the results are as below

	Harmonic number	kd	kp	kw	Lambda Coil pitch ED	Alpha Slot pitch ED	Qs	P	q	m	coil span
Full pitch	1	0.95766	1	0.95766	180	15	72	6	4	3	12
	3	0.65328	-1	-0.6533	180	15	72	6	4	3	12
	5	0.20533	1	0.20533	180	15	72	6	4	3	12

11/12 short-pitched winding

- Winding diagram

72 slot, 6 pole, q=4

AAA-C	-C-C-CB	BBB-A	-A-A-AC	CCC-B	-B-B-BA	AAA-C	-C-C-CB	BBB-A	-A-A-AC	CCC-B	-B-B-B-A
AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B	AAAA	-C-C-C-C	BBBB	-A-A-A-A	CCCC	-B-B-B-B

- Calculation of winding factors for fundamental, 3rd and 5th harmonics

To calculate winding factor an excel file was written which is available in GitHub repository

the results are as below

	Harmonic number	kd	kp	kw	Lambda Coil pitch ED	Alpha Slot pitch ED	Qs	P	q	m	coil span
Short pitch 11/12	1	0.95766	1	0.94947	165	15	72	6	4	3	11
	3	0.65328	-1	-0.6036	165	15	72	6	4	3	11
	5	0.20533	1	0.1629	165	15	72	6	4	3	11

Comment on results:

	Harmonic number	kd	kp	kw	Lambda Coil pitch ED	Alpha Slot pitch ED	Qs	P	q	m	coil span
Full pitch	1	0.95766	1	0.95766	180	15	72	6	4	3	12
	3	0.65328	-1	-0.6533	180	15	72	6	4	3	12
	5	0.20533	1	0.20533	180	15	72	6	4	3	12
	7	-0.1576	-1	0.15756	180	15	72	6	4	3	12
	11	-0.1261	-1	0.12608	180	15	72	6	4	3	12
Short pitch 11/12	1	0.95766	1	0.94947	165	15	72	6	4	3	11
	3	0.65328	-1	-0.6036	165	15	72	6	4	3	11
	5	0.20533	1	0.1629	165	15	72	6	4	3	11
	7	-0.1576	-1	0.09592	165	15	72	6	4	3	11
	11	-0.1261	-0	0.01646	165	15	72	6	4	3	11

By looking at the winding factors it can be inferred that short pitch causes the 5th, 7th and 11th harmonics winding factor to decrease (more than 10 times decrease for 11th harmonic). And only 0.8 % decrease in fundamental winding factor. Therefore, the short pitched winding arrangement will have a lower torque ripple.

Q2- Fractional-Slot Winding Design

In this part, you are going to analyze a 3-phase permanent-magnet synchronous machine with a fractional-slot winding.

Choose a pole number of either 20 or 22. For this pole number, choose a slot number between 20 and 30. You can use Emetor Winding Design for an initial design.

- Calculate the phase angle of the induced voltage in each slot, and present them with a table.
- Draw the phasor diagram for one phase, and calculate the winding factor.
- Repeat the same procedure for the 3rd and 5th harmonics and comment on the results.

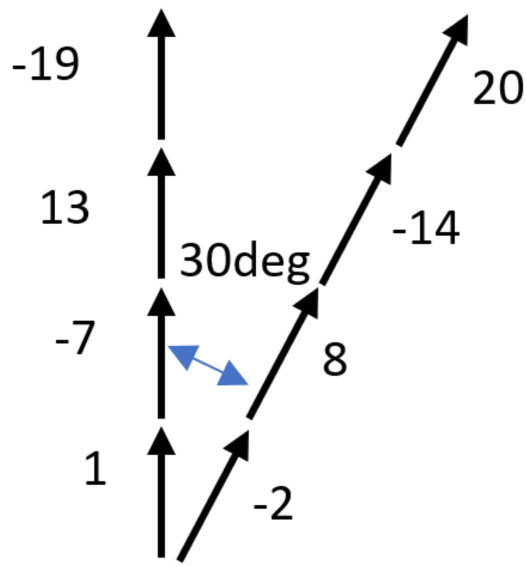
Now for the same pole number you had chosen, choose a different slot number. This choice would not be as good as the first one, but still should be a viable one.

- Repeat the same analysis with the previous one.
- Compare the results of the two designs and comment in detail.

For the first analysis 20 pole , 24 slot was chosen with single layer winding. The voltage phasor angles and winding factors for fundamental, 3rd and 5th harmonics are calculated in an excel file which is available in GitHub repository. Results are as follows:

20p/24s fundamental harmonic

slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	150	-A
3	300	-C
4	90	C
5	240	B
6	30	-B
7	180	-A
8	330	A
9	120	C
10	270	-C
11	60	-B
12	210	B
13	0	A
14	150	-A
15	300	-C
16	90	C
17	240	B
18	30	-B
19	180	-A
20	330	A
21	120	-C
22	270	C
23	60	B
24	210	-B

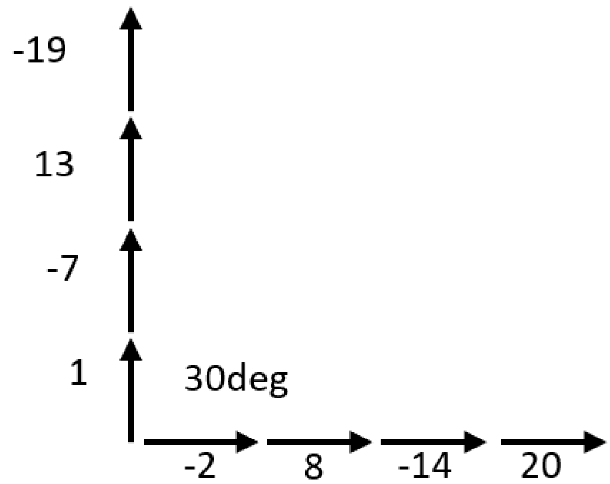


to calculate winding factor, vectorial summation the vectors and division to 8X which is the maximum possible value (each vector has an amplitude of X)

Winding factor for fundamental= 2*cos(15)*4X/8X = cos(15) = 0.9659

20p/24s 3rd harmonic

slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	90	-A
3	180	-C
4	270	C
5	0	B
6	90	-B
7	180	-A
8	270	A
9	0	C
10	90	-C
11	180	-B
12	270	B
13	0	A
14	90	-A
15	180	-C
16	270	C
17	0	B
18	90	-B
19	180	-A
20	270	A
21	0	-C
22	90	C
23	180	B
24	270	-B

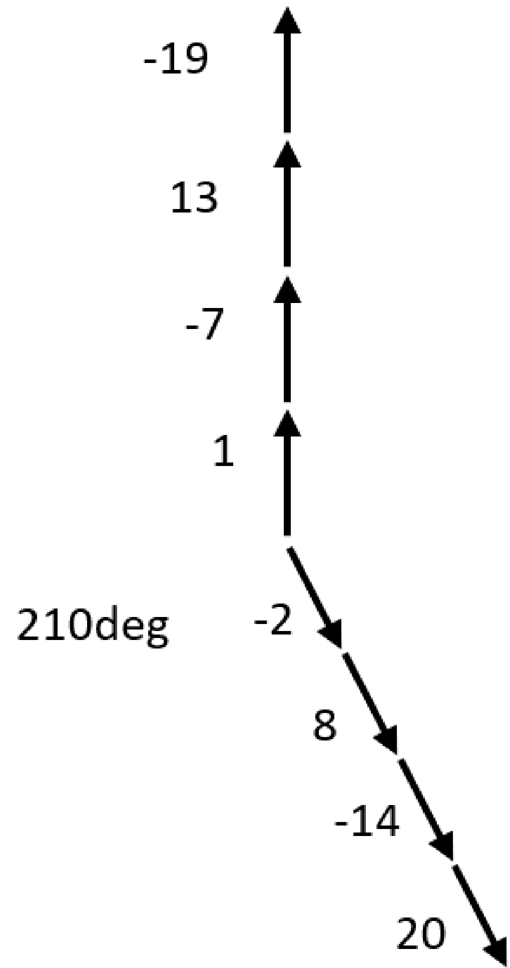


to calculate winding factor, vectorial summation the vectors and division to 8X which is the maximum possible value (each vector has an amplitude of X)

Winding factor for 3rd harmonic= 2*cos(90/2)*4X/8X = cos(45) = 0.707

20p/24s 5th harmonic

slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	30	-A
3	60	-C
4	90	C
5	120	B
6	150	-B
7	180	-A
8	210	A
9	240	C
10	270	-C
11	300	-B
12	330	B
13	0	A
14	30	-A
15	60	-C
16	90	C
17	120	B
18	150	-B
19	180	-A
20	210	A
21	240	-C
22	270	C
23	300	B
24	330	-B

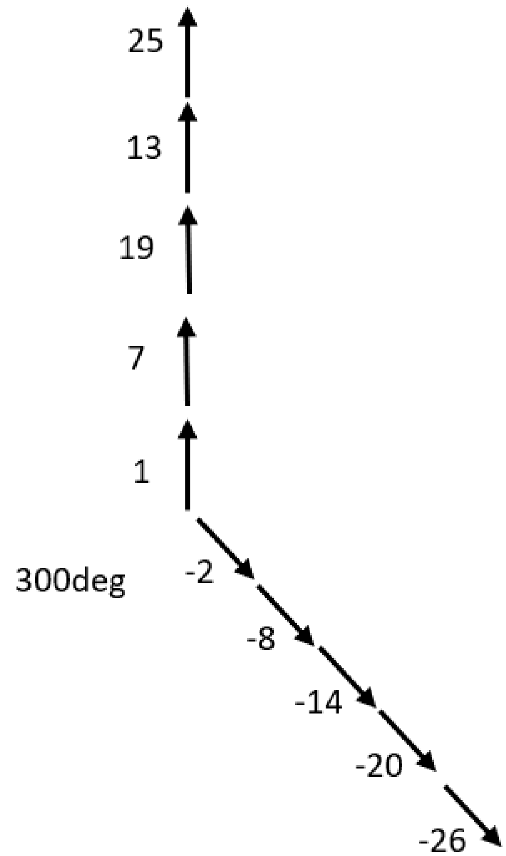


to calculate winding factor, vectorial summation the vectors and division to 8X which is the maximum possible value (each vector has an amplitude of X)

Winding factor for 5th harmonic= 2*cos(150/2)*4X/8X = cos(75) = 0.2588

Second selected slot/pole combination is 20 pole, 30 slot

	20p/30s fundamental harmonic	
slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	120	-A
3	240	-C
4	0	C
5	120	B
6	240	-B
7	0	A
8	120	-A
9	240	-C
10	0	C
11	120	B
12	240	-B
13	0	A
14	120	-A
15	240	-C
16	0	C
17	120	B
18	240	-B
19	0	A
20	120	-A
21	240	-C
22	0	C
23	120	B
24	240	-B
25	0	A
26	120	-A
27	240	-C
28	0	C
29	120	B
30	240	-B



Winding factor for fundametal= 2*cos(60/2)*5X/10X = cos(30) = 0.866

20p/30s 3rd harmonic

slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	0	-A
3	0	-C
4	0	C
5	0	B
6	0	-B
7	0	A
8	0	-A
9	0	-C
10	0	C
11	0	B
12	0	-B
13	0	A
14	0	-A
15	0	-C
16	0	C
17	0	B
18	0	-B
19	0	A
20	0	-A
21	0	-C
22	0	C
23	0	B
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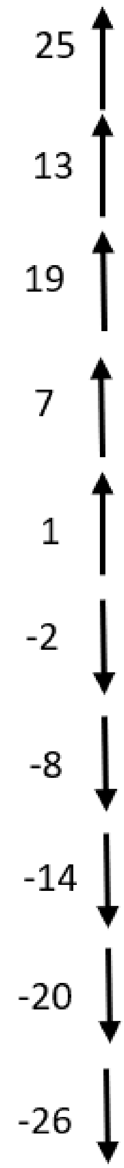
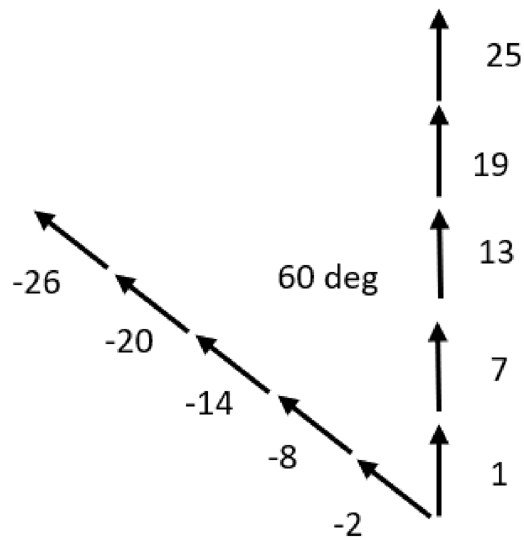
25	0	A
26	0	-A
27	0	-C
28	0	C
29	0	B
30	0	-B



Winding factor for 3rd harmonic= 2*cos(180/2)*4X/8X = cos(90) = 0

20p/30s 5th harmonic

slot number	Induced voltage phase angle2	Phase arrangement
1	0	A
2	240	-A
3	120	-C
4	0	C
5	240	B
6	120	-B
7	0	A
8	240	-A
9	120	-C
10	0	C
11	240	B
12	120	-B
13	0	A
14	240	-A
15	120	-C
16	0	C
17	240	B
18	120	-B
19	0	A
20	240	-A
21	120	-C
22	0	C
23	240	B
24	120	-B
25	0	A
26	240	-A
27	120	-C
28	0	C
29	240	B
30	120	-B



Winding factor for 5th harmonic= 2*cos(60/2)*5X/10X = cos(30) = 0.866

Q3- 2D FEA Modelling

Using a computer tool (some suggestions are presented in the course webpage), verify one of your designs with the fractional-slot winding. For reference you can use the same parameters given at the last section of your textbook (Hanselman). Alternatively you can use any other designs you found in the literature (but please give reference if you used someone else's design). Please don't try to optimize your design, a working design is enough.

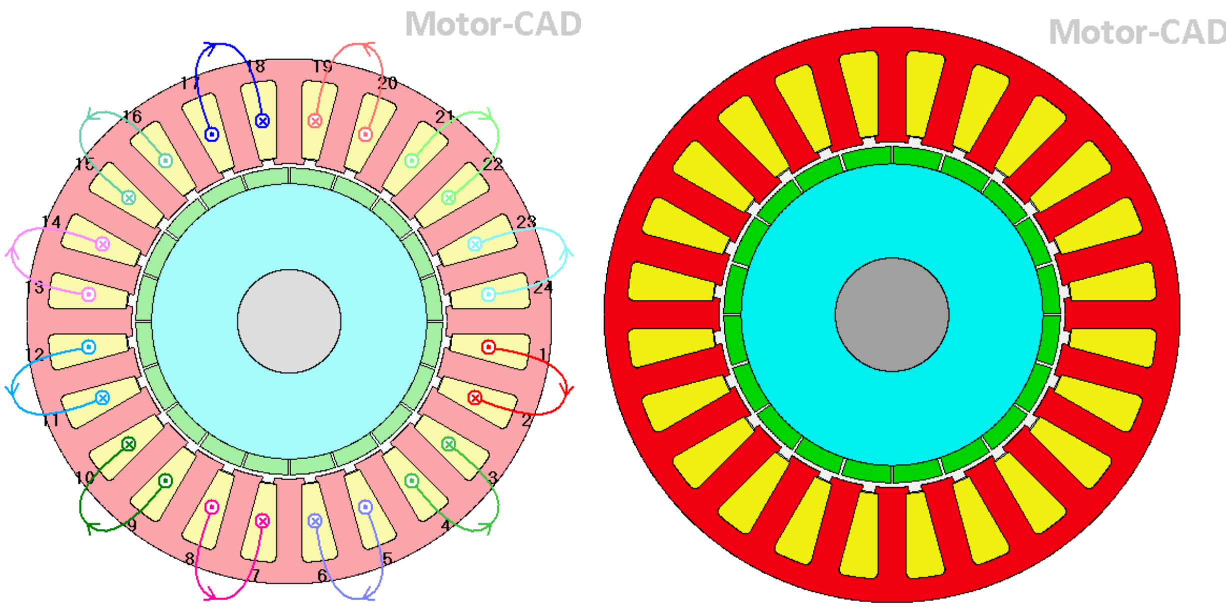
Try to obtain at least the following (you can present more results if you like).

- General 2D drawing and winding diagram of your design
- Airgap flux density distribution
- Induced voltage waveforms (for phase and line-to-line) at rated speed
- Cogging torque (i.e. torque when there is no current in the windings)

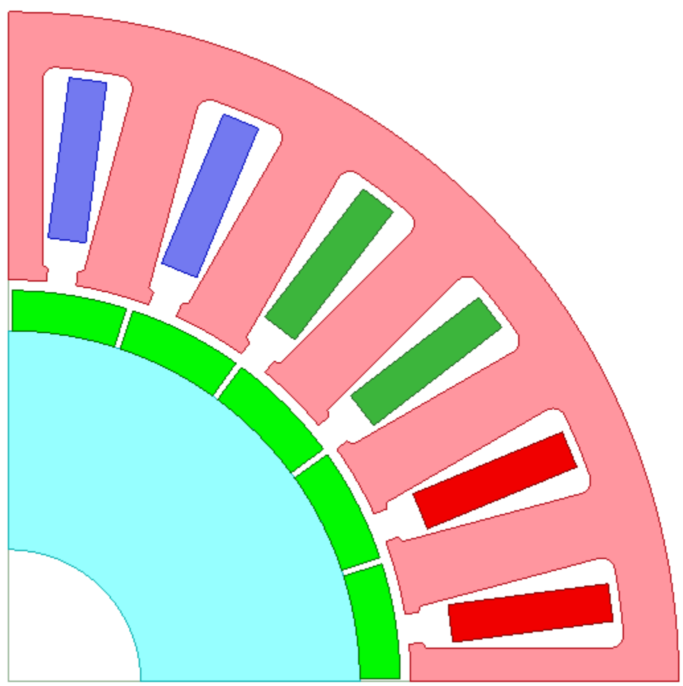
Due to low values of winding factor for the 5^{th} and 7^{th} harmonics and therefore lower torque ripple, I choose 20 pole/ 24 slot for the FEA analysis. The machine was designed in MotorCAD and further exported to Ansys Electronics to do some calculations.

The outer diameter of the machine was selected to be 100 mm because this machine is designed for high speeds and considered speed is 10000 rpm. The stack length is 60 mm which makes the machine volume 0.47 liter. DC bus voltage is 200 V and current density is 6 A/mm^2. It should be noted that this machine requires a liquid cooling system to operate.

Design Variables for 20 pole 24 slot machine	
Do [mm]	100
Di [mm]	60
Stack Length [mm]	60
Machine Volume [liter]	0.47
Machine Weight [kg]	3.48
Slot depth [mm]	16
Teeth Width [mm]	5
Airgap [mm]	0.8
Magnet Width [mm]	3
DC bus voltage [V]	200
Current Density [A/mm2]	6
Slot fill factor [%]	45
Slot Area [mm2]	75.5
Copper Area [mm2]	34
Machine speed [rpm]	10000
Turns per coil	4
Winding layers	1
Coil span	1
Winding arrangement	concentrated
Magnet Material	N48HM
Core Material	M250-35A

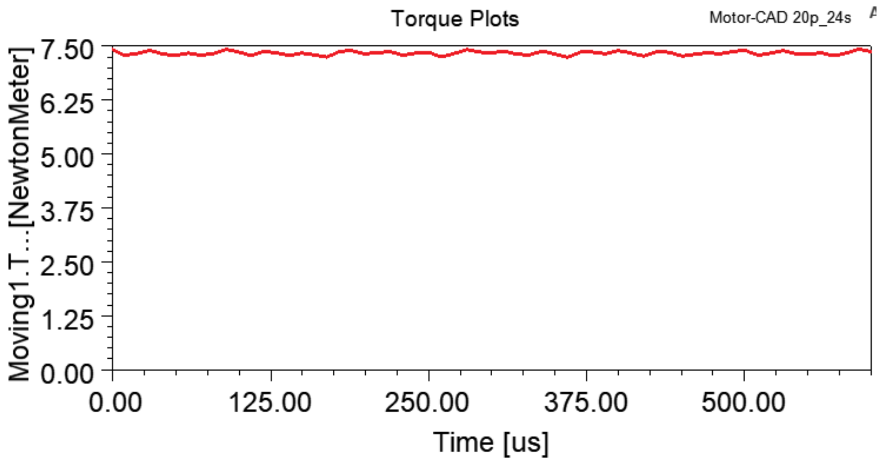


20 pole 24 slot machine and winding arrangement

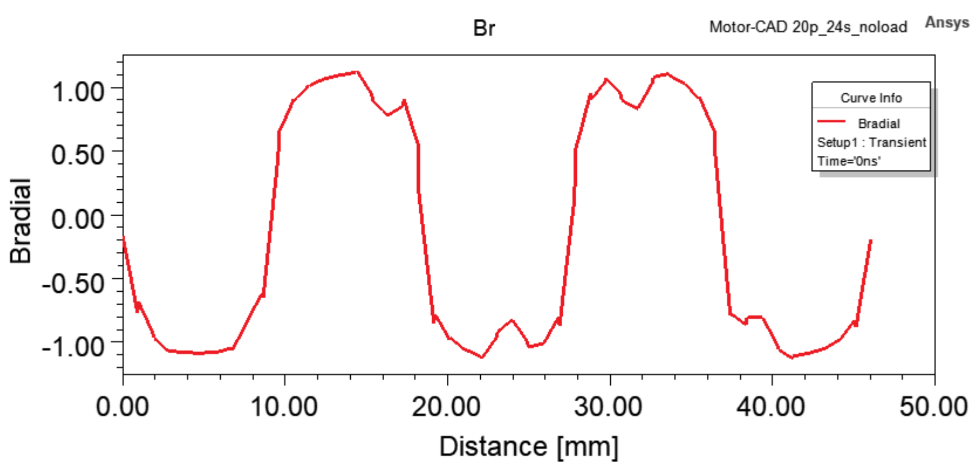


Exported model to Ansys to make further analysis

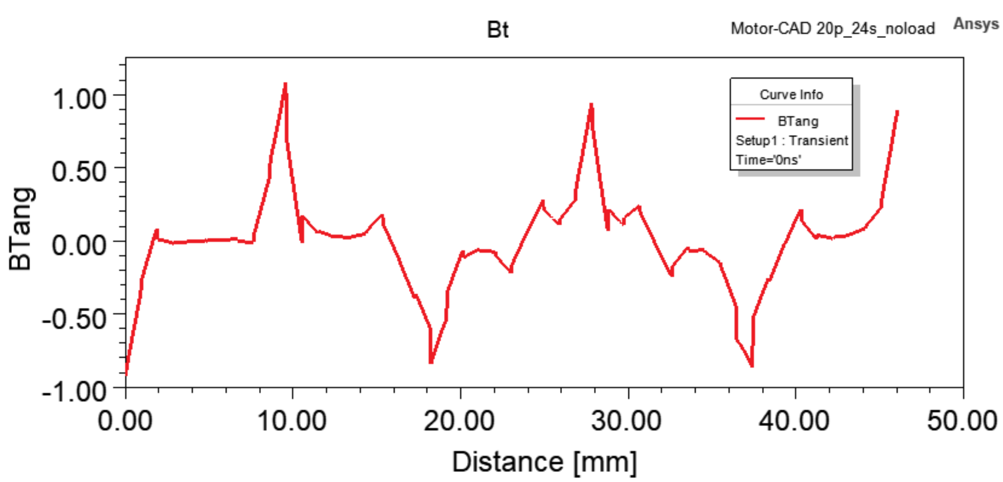
Performance of the designed machine is investigated in detail in the following pictures.



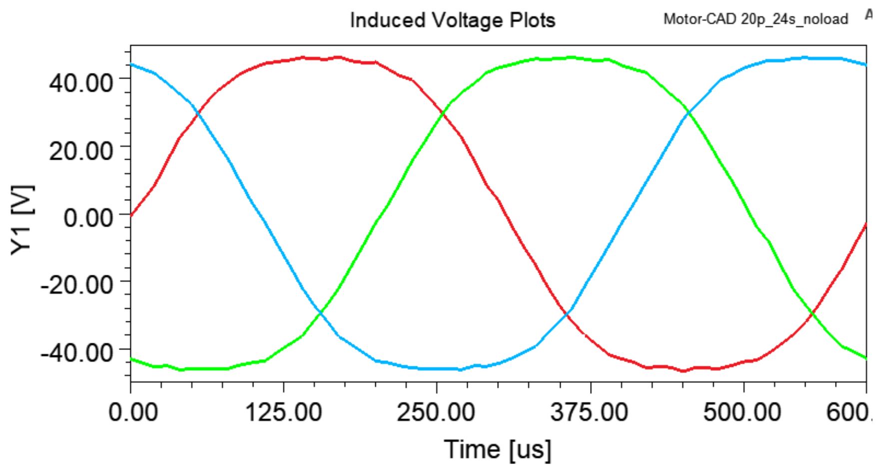
Torque waveform, average 7.4 Nm, torque ripple 2.5 % (from Ansys)



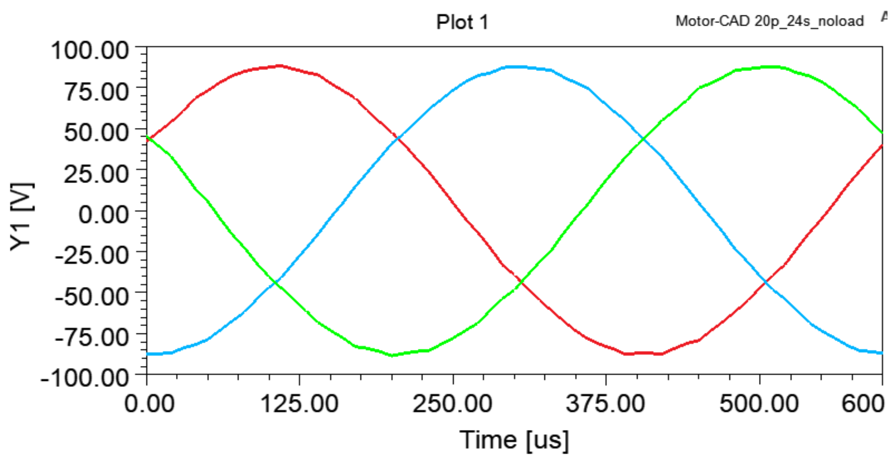
Radial component of airgap flux density at noload (from Ansys)



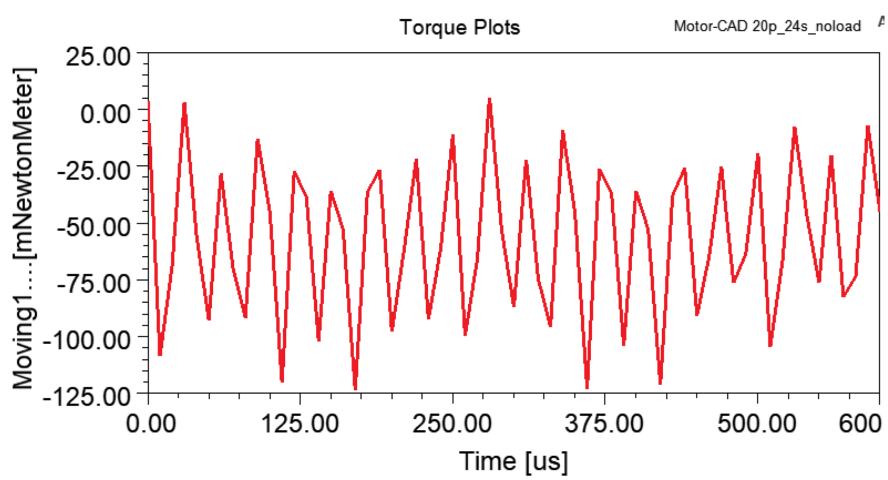
Tangential component of airgap flux density at noload (from Ansys)



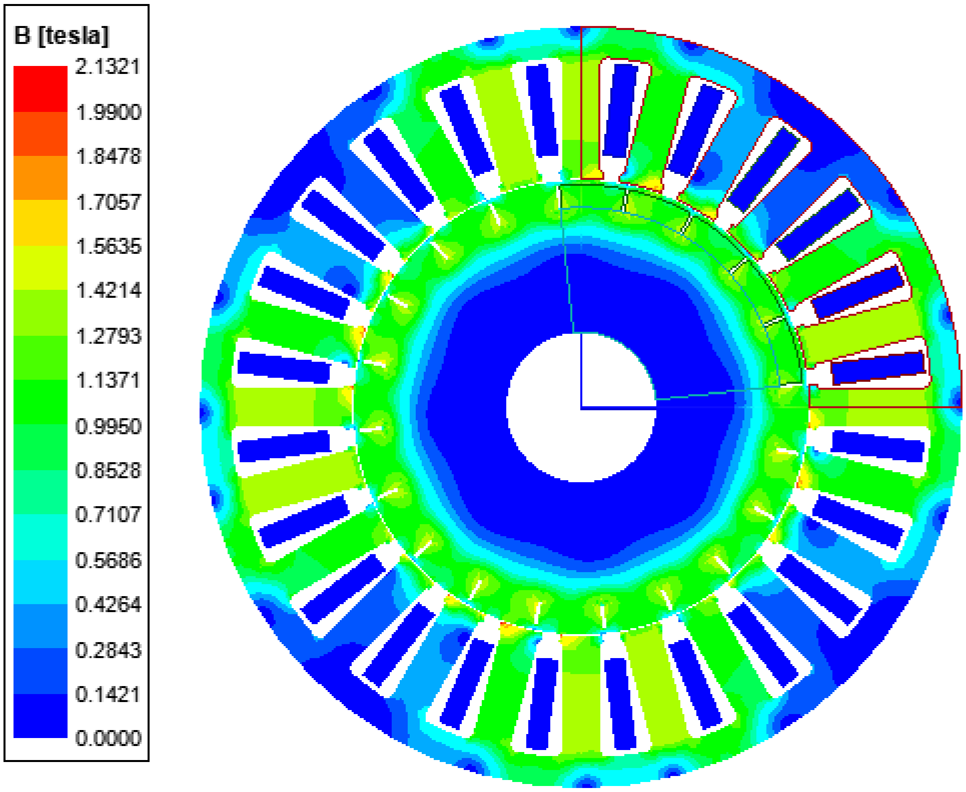
Induced phase voltage, 35.8 rms (from Ansys)



Induced line to line voltage, 61.77 rms (from Ansys)



Cogging torque [mNm]



Flux density in the machine at full load

Output results from MotorCAD	
Electromagnetic Torque [Nm]	6.9
Torque ripple [%]	1.7
Output Power [kW]	6.8
Power factor	0.94
Current Density [A/mm2]	6
Copper loss [W]	42.45
AC copper loss [W]	126
Iron loss [W]	414
Efficiency [%]	91.6
Base speed [rpm]	16227

It should be noted that mechanical losses have not been calculated here. Since machine speed is 10000 rpm, therefore, windage loss, bearing loss can decrease the efficiency 1-2 %.

Due to high fundamental frequency which 1667 Hz for 10000rpm, the Iron loss has a high value and AC copper loss (MotorCAD has a FEA solver to calculate AC copper loss) is much bigger than DC copper loss. Therefore, design of high-speed machines requires more attention to AC and mechanical losses.