MIDDLE EAST TECHNICAL UNIVERSITY
DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING
EE568 - SELECTED TOPICS ON ELECTRICAL MACHINES
PROJECT #2 REPORT
March 31, 2020

Motor Winding Design and Analysis

1 INTRODUCTION

In this project, different stator winding topologies will be discussed. The differences between integer and fractional slot windings will be investigated by means of winding factors for different harmonic components. Further, two different motors with fractional slot concentrated windings will be analyzed using finite element method. Their resultant magnetic aspects will be compared.

2 INTEGRAL-SLOT WINDING DESIGN

For the given number of slots, poles and phases, four different windings have been designed. These are:

- Single layer
- Double layer, full pitched
- Double layer, 5/6 pitched
- Double layer, 4/6 pitched

For all these designs, distribution, pitch and winding factors have been calculated using 2.1, 2.2 and 2.3, respectively where n is harmonic order, q is number of slots per pole per phase, α is electrical angle between two slots and λ is pitch angle of a coil, in radians.

$$k_d(n) = \frac{sin(\frac{nq\alpha}{2})}{q\,sin(\frac{n\alpha}{2})} \tag{2.1}$$

$$k_p(n) = sin(\frac{n\lambda}{2}) \tag{2.2}$$

$$k_w(n) = k_d(n) \times k_p(n) \tag{2.3}$$

2.1 Single Layer

Winding diagram for one pole pair is given below.

Slot	1	2	3	4	5	6	7	8	9	10	11	12
Layer 1	A1+	A2+	C1-	C2-	B1+	B2+	A1-	A2-	C1+	C2+	B1-	B2-

Winding factors for this winding topology for first, third and fifth harmonics using 2.1-2.3 are presented on the table below.

	First	Third	Fifth
k_d	0.966	0.707	0.259
k_p	1.000	-1.000	1.000
k_w	0.966	-0.707	0.259

2.2 Double Layer, Full Pitched

Winding diagram of full-pitched double layer winding for one pole pair is given below.

Slot	1	2	3	4	5	6	7	8	9	10	11	12
Layer 1	A1+	A2+	C1-	C2-	B1+	B2+	A3-	A4-	C3+	C4+	B3-	B4-
Layer 2	A3+	A4+	C3-	C4-	B3+	B4+	A1-	A2-	C1+	C2+	B1-	B2-

Winding factors for this winding topology for first, third and fifth harmonics using 2.1-2.3 are presented on the table below.

	First	Third	Fifth
k_d	0.966	0.707	0.259
k_p	1.000	-1.000	1.000
k_w	0.966	-0.707	0.259

2.3 Double Layer, 5/6 Pitched

Winding diagram of 5/6-pitched double layer winding for one pole pair is given below.

Slot	1	2	3	4	5	6	7	8	9	10	11	12
Layer 1	A1+	A2+	C1-	C2-	B1+	B2+	A3-	A4-	C3+	C4+	B3-	B4-
Layer 2	A4+	C3-	C4-	B3+	B4+	A1-	A2-	C1+	C2+	B1-	B2-	A3+

Winding factors for this winding topology for first, third and fifth harmonics using 2.1-2.3 are presented on the table below.

	First	Third	Fifth
k_d	0.966	0.707	0.259
k_p	0.966	-0.707	0.259
k_w	0.933	-0.500	0.067

2.4 Double Layer, 4/6 Pitched

Winding diagram of 4/6-pitched double layer winding for one pole pair is given below.

Slot	1	2	3	4	5	6	7	8	9	10	11	12
Layer 1	A1+	A2+	C1-	C2-	B1+	B2+	A3-	A4-	C3+	C4+	B3-	B4-
Layer 2	C3-	C4-	B3+	B4+	A1-	A2-	C1+	C2+	B1-	B2-	A3+	A4+

Winding factors for this winding topology for first, third and fifth harmonics using 2.1-2.3 are presented on the table below.

	First	Third	Fifth
k_d	0.966	0.707	0.259
k_p	0.866	0.000	-0.866
k_w	0.837	0.000	-0.224

2.4.1 Comments

For the first two topologies, there is no difference in electromagnetic point of view, therefore their configurations and winding factors are identical. Short-pitched windings have poorer fundamental winding factor. However, third harmonic component of full-pitched topology is quite high, where in short-pitched equivalents, this is low.

4/6-pitched winding is the most feasible topology among all of them. Even if its fundamental winding factor is the lowest, no third order and very little fifth order harmonic voltage is induced in this topology.

3 Fractional-Slot Winding Design

3.1 24 Slots, 22 Poles

Winding diagram of 24 slot - 22 pole fractional slot concentrated winding is given below.

Slot	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Forward	0	165	330	135	300	105	270	75	240	45	210	15
Reverse	180	345	150	315	120	285	90	255	60	225	30	195
Third	0	135	270	45	180	315	90	225	0	135	270	45
Fifth	0	105	210	315	60	165	270	15	120	225	330	75
Phase	**A+**	**A-**	**A+**	**A-**	**C-**	**C+**	**C-**	**C+**	**B+**	**B-**	**B+**	**B-**
Slot	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Forward	180	345	150	315	120	285	90	255	60	225	30	195
Reverse	0	165	330	135	300	105	270	75	240	45	210	15
Third	180	315	90	225	0	135	270	45	180	315	90	225
Fifth	180	285	30	135	240	345	90	195	300	45	150	255
Phase	**A-**	**A+**	**A-**	**A+**	**C+**	**C-**	**C+**	**C-**	**B-**	**B+**	**B-**	**B+**

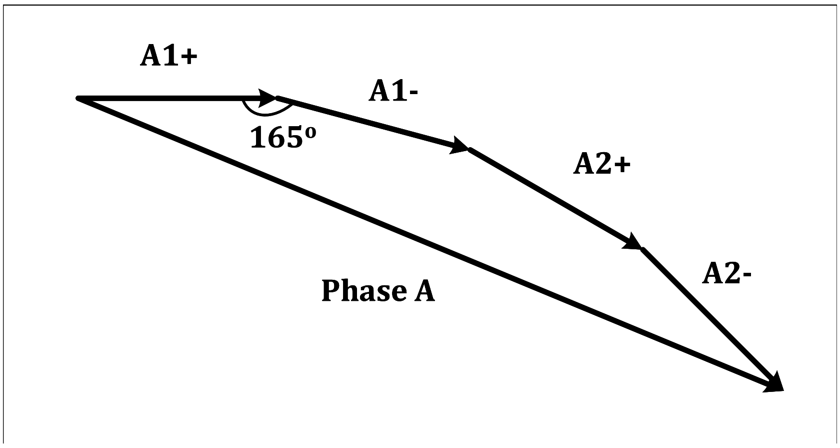

Figure 3.1: Phasor diagram of 24/22 winding (fundamental)

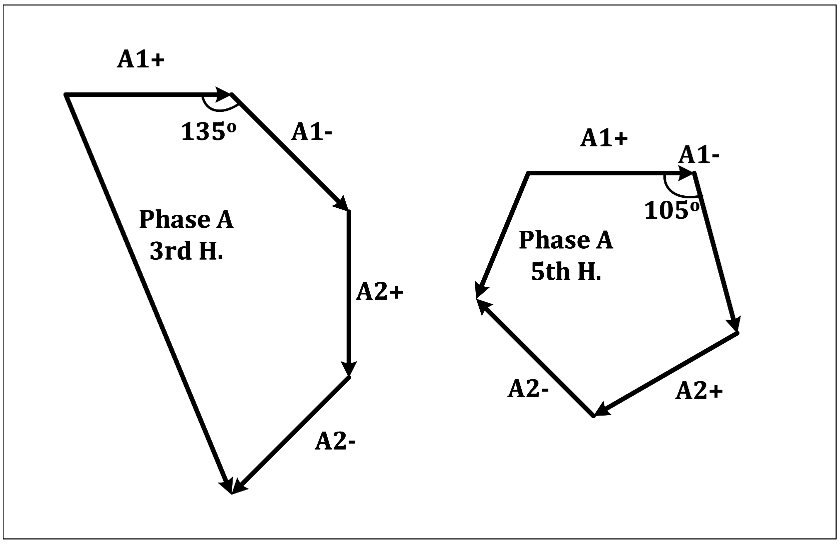

Figure 3.2: Phasor diagram of 24/22 winding (third and fifth)

Phasor diagrams of windings for fundamental, third and fifth order harmonics are given in Fig. 3.1 and 3.2

Following a geometrical approach, the distribution factor can be found as the ratio of the vectoral sum to arithmetic sum of the vectors.

$$k_d(1) = \frac{2cos(7.5) + 2cos(22.5)}{4} = 0.956$$

$$k_d(3) = \frac{2cos(22.5) + 2cos(67.5)}{4} = 0.653$$

$$k_d(5) = \frac{2cos(37.5) - 2cos(67.5)}{4} = 0.205$$

As each coil is wound in two consecutive slots, coil span becomes $\lambda = \frac{22\pi}{24}$. Therefore, pitch factors can be calculated as below:

$$k_p(1) = sin(\frac{22\pi}{48}) = 0.991$$

$$k_p(3) = sin(\frac{66\pi}{48}) = -0.924$$

$$k_p(5) = sin(\frac{110\pi}{48}) = 0.793$$

As a result, winding factors can be found as:

$$k_w(1) = k_d(1) \times k_p(1) = 0.947$$

$$k_w(3) = k_d(1) \times k_p(1) = -0.603$$

$$k_w(5) = k_d(1) \times k_p(1) = 0.163$$

3.2 30 Slots, 22 Poles

Winding diagram of 30 slot - 22 pole fractional slot concentrated winding is given below.

Slot	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
Forward	0	132	264	36	168	300	72	204	336	108	240	12	144	276	48
Reverse	180	312	84	216	348	120	252	24	156	288	60	192	324	96	228
Third	0	36	72	108	144	180	216	252	288	324	0	36	72	108	144
Fifth	0	300	240	180	120	60	0	300	240	180	120	60	0	300	240
Phase	**A+**	**A-**	**C-**	**B-**	**A-**	**C-**	**C+**	**B+**	**A+**	**C+**	**B+**	**B-**	**A-**	**C-**	**B-**
Slot	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Forward	180	312	84	216	348	120	252	24	156	288	60	192	324	96	228
Reverse	0	132	264	36	168	300	72	204	336	108	240	12	144	276	48
Third	180	216	252	288	324	0	36	72	108	144	180	216	252	288	324
Fifth	180	120	60	0	300	240	180	120	60	0	300	240	180	120	60
Phase	**A-**	**A+**	**C+**	**B+**	**A+**	**C+**	**C-**	**B-**	**A-**	**C-**	**B-**	**B+**	**A+**	**C+**	**B+**

Phasor diagrams of windings for fundamental, third and fifth order harmonics are given in Fig. 3.3 and 3.4

Following a geometrical approach, the distribution factor can be found as the ratio of the vectoral sum to arithmetic sum of the vectors.

$$k_d(1) = \frac{2cos(12) + 2cos(24) + 1}{5} = 0.957$$

$$k_d(3) = \frac{2cos(36) + 2cos(72) + 1}{5} = 0.647$$

$$k_d(5) = \frac{2cos(60) + 2cos(120) + 1}{5} = 0.2$$

The coil span becomes $\lambda = \pi$. Therefore, pitch factors can be calculated as below:

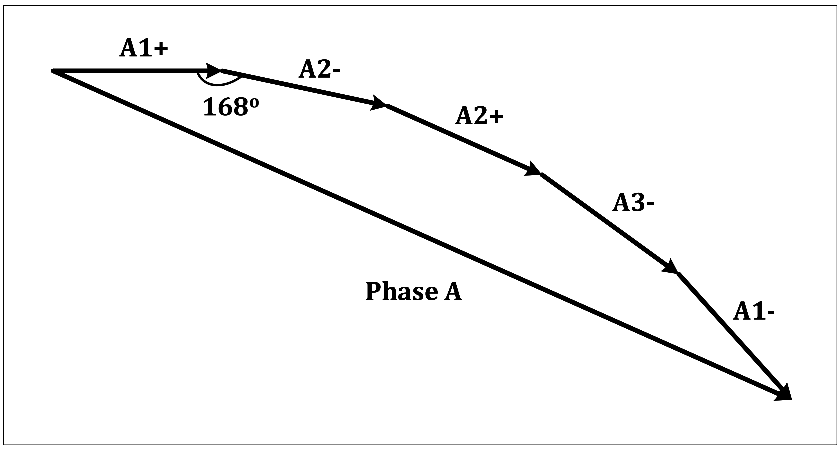

Figure 3.3: Phasor diagram of 30/22 winding (fundamental)

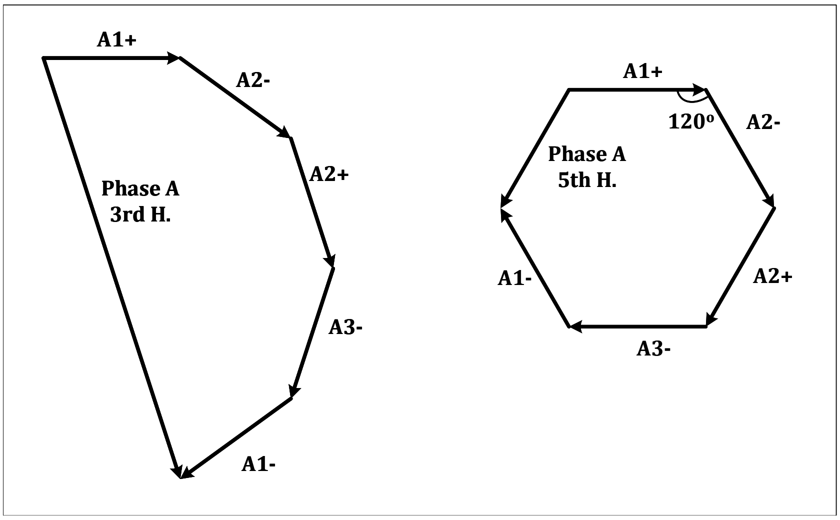

Figure 3.4: Phasor diagram of 30/22 winding (third and fifth)

$$k_p(1) = sin(\frac{\pi}{2}) = 1$$

$$k_p(3) = sin(\frac{3\pi}{2}) = -1$$

$$k_p(5) = sin(\frac{5\pi}{2}) = 1$$

As a result, winding factors can be found as:

$$k_w(1) = k_d(1) \times k_p(1) = 0.957$$

$$k_w(3) = k_d(1) \times k_p(1) = -0.647$$

$$k_w(5) = k_d(1) \times k_p(1) = 0.2$$

3.3 Comments

By means of winding factor, both designs are feasible. 30/22 has a larger fifth and smaller third harmonic winding factor. As these machines are 3-phase, third order induced voltages will be eliminated in wye connection. Therefore it can be said that the one with smaller higher order harmonic induced voltage components is more preferable. In this sense, 24/22 design is more advantageous than 30/22 design.

Also, distribution of the coils in 30/22 design is asymmetric. Each coil will have different span, in case they are placed in the nearest possible slots. If they are placed so that the coil span becomes π, mean turn length of each coil becomes too large and core loss will increase. Here also, 24/22 design is more advantageous due to symmetric and proper winding distribution and shorter end windings.

4 2D FEA Modelling

For 2D modelling of the two topologies, I took the design and dimensions of IMMD motor as reference, and modified the design as 24/22 and 30/22.

4.1 24 Slots, 22 Poles

The winding diagram of the design is given in Fig. 4.1.

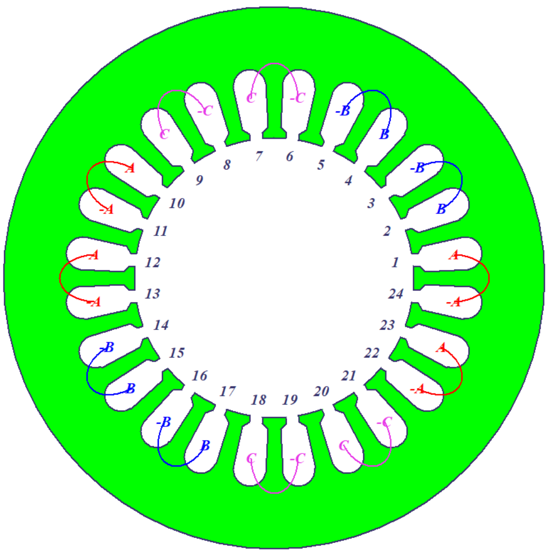

Figure 4.1: Winding Diagram

Air-gap flux density, back EMF and cogging torque waveforms over one electrical period are shown in Fig. 4.2, 4.3 and 4.4, respectively.

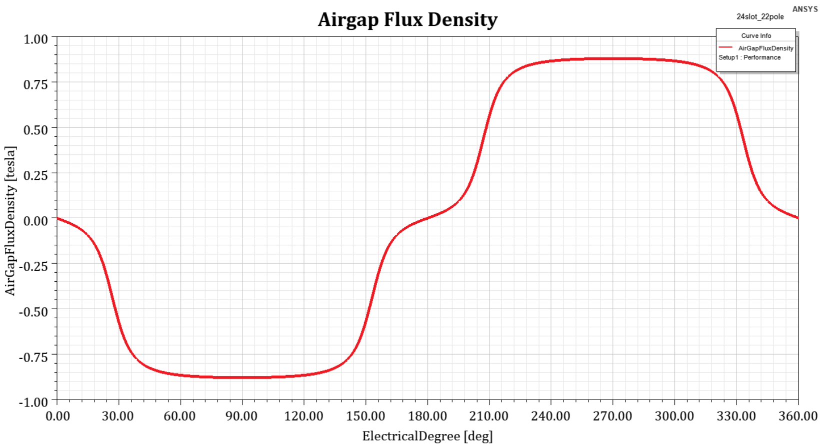

Figure 4.2: Air-Gap Flux Density

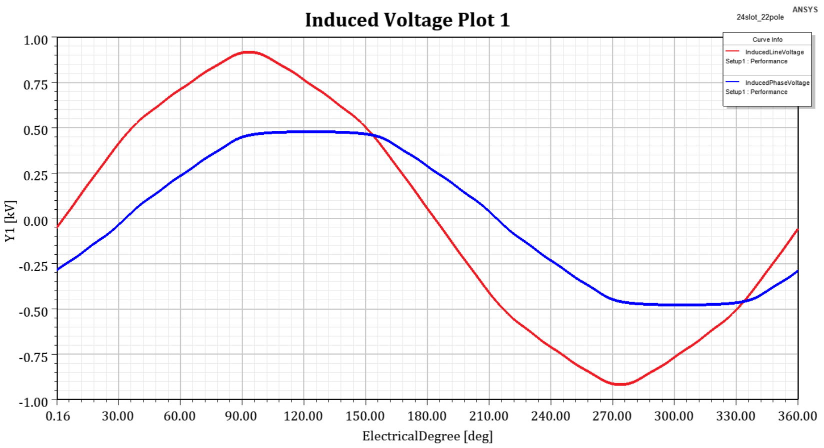

Figure 4.3: Induced Voltage

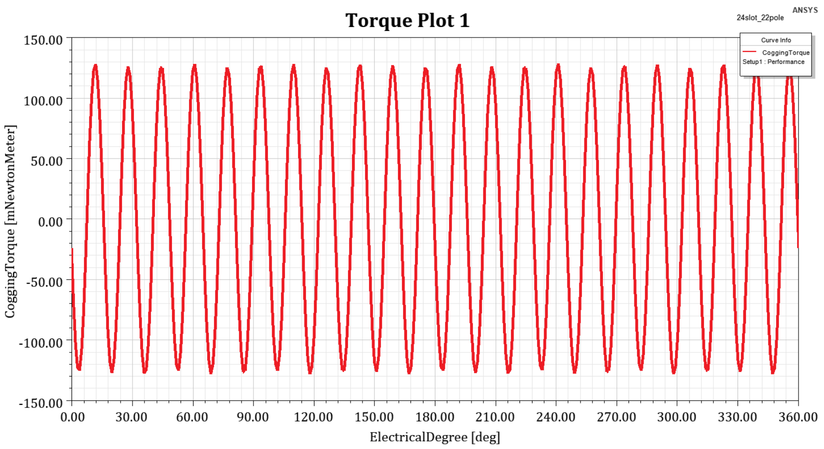

Figure 4.4: Cogging Torque

4.2 30 Slots, 22 Poles

The winding diagram of the design is given in Fig. 4.5.

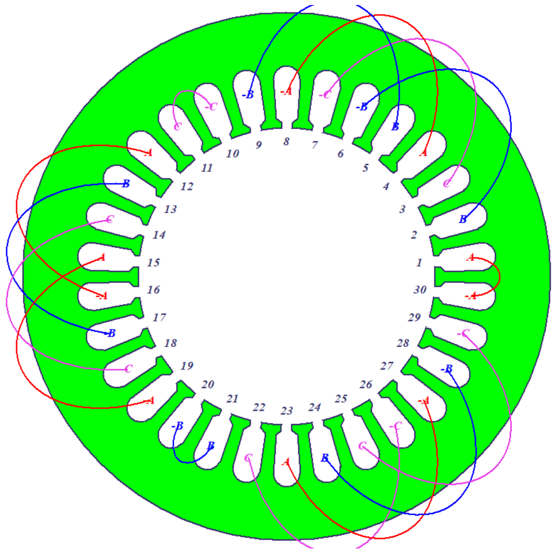

Figure 4.5: Winding Diagram

Air-gap flux density, back EMF and cogging torque waveforms over one electrical period are shown in Fig. 4.6, 4.7 and 4.8, respectively.

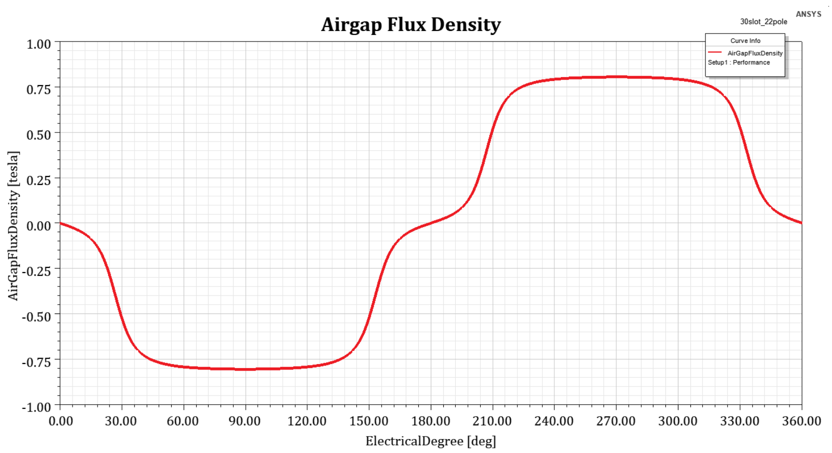

Figure 4.6: Air-Gap Flux Density

4.3 Comments

The designs are identical except for total number of turns, number of slots and stator tooth width. Each slot contains equal number of turns, therefore in total, 30/22 design has a larger number of turns. Resultantly, its induced voltage is also larger.

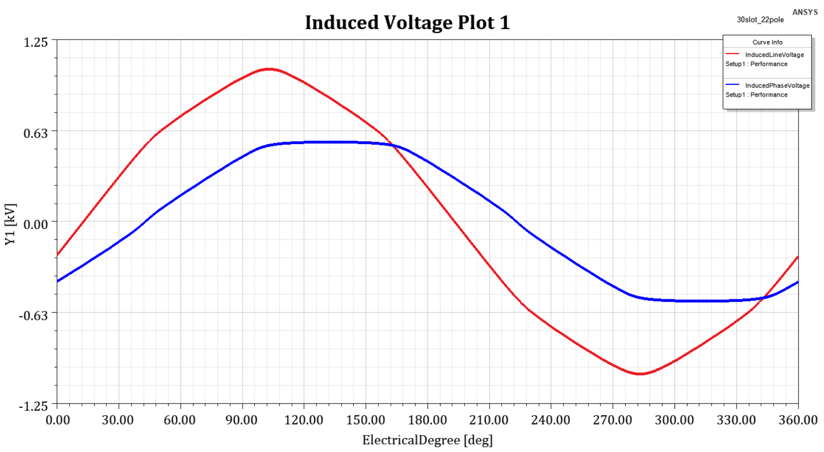

Figure 4.7: Induced Voltage

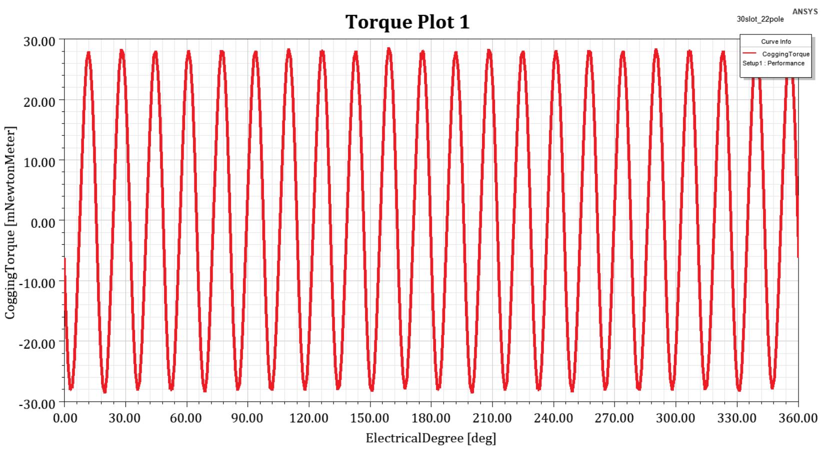

Figure 4.8: Cogging Torque

Cogging torque of 30/22 design is almost twice as that of 24/22 design. With lower cogging torque, 24/22 is a better solution.

5 Conclusion

In this project, differences between integer and fractional slot windings have been discussed by means of winding factors for different harmonic components. Two different motors with fractional slot concentrated windings have been analyzed using finite element method. Their performances have been compared. 24/22 is concluded to be a better topology than 30/22 due to its lower cogging torque, poorer higher order harmonic content of induced voltage, shorter end winding and lower copper loss.