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MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

EE 568 Project #2

Motor Winding Design & Analysis

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Introduction

In this report, the electric machine winding design and analysis are studied. In electrical machines, windings play an essential role because they define the critical machine performance indicators such as current density, fill factor or winding factor, etc. In the winding design, the number of slots per pole per phase determines the winding type. There are two types of winding designs, integral slot winding, and fractional slot winding. If the number of slots per pole per phase is an integer, the winding is integral slot winding. In the first question of the report, integral slot winding design is conducted, and it is analyzed. The main parameter that defines a winding is winding factor, and it defines how much of the available voltage can be induced. It is determined by distribution and pitch factors. Integral slot winding design is analyzed by calculating these winding factors. Also, each harmonic has a different winding factor and in the analysis, the winding factor for the third and fifth harmonics are considered. In the second question, the fractional slot windings are studied, where the number of slots per pole per phase is fractional. In the design, the winding diagram is obtained for 20-pole 30 slots and 20-pole 24-slots machines. Their winding factors are compared with their harmonics. The comparison study is conducted. The report is ended with the third question, where the winding analysis of 20-pole 24-slots machine is verified with computer tools. I the analysis, RMXprt tool of Ansys Maxwell is preferred. The obtained results are compared with analytical results and the report is concluded.

Question I: Integral-Slot Winding Design

We have 20-pole 120 slot 3-phase winding. I preferred to design a full pitched winding configuration. The number of slots per pole per phase is 2. Let's assume that we have a double winding configuration. The winding diagram under one pole pair is as follows.

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

pitch factor: $k_p(n) = \sin\left(n * \frac{cs}{2}\right)$

distribution factor: $k_d(n) = \frac{\sin\left(\frac{q\alpha n}{2}\right)}{q\sin\left(\frac{\alpha n}{2}\right)}$

winding factor: $k_w(n) = k_p(n) * k_d(n)$

where n is harmonics number, cs is coil span, q is the number of slots per phase per pole, α is the electrical angle between two adjacent slots. In our case, q is 2, α is 30° and cs is 180°. Since we had full pitched design, our pitch factor is one. Considering this, we got the following results.

	Fundamental	**3rd**	**5th**	**7th**
Pitch factor	1	-1	1	-1
Distribution factor	0,9659	0,7071	0,2588	-0,2588
Winding factor	0,9659	-0,7071	0,2588	0,2588

The results show that the winding factor for the harmonics can be negative. Pitch factor for the third harmonic is negative. This design has a high winding factor for the third harmonic component. Therefore, the coil pitch selection may be revisited. There is also considerable winding factor for higher harmonics in the design.

Question II: Fractional-Slot Winding Design

Design I: 20-pole 30-slots

Pole number	20
Slot number	30
Number of layers	2
Coil span	1 slot

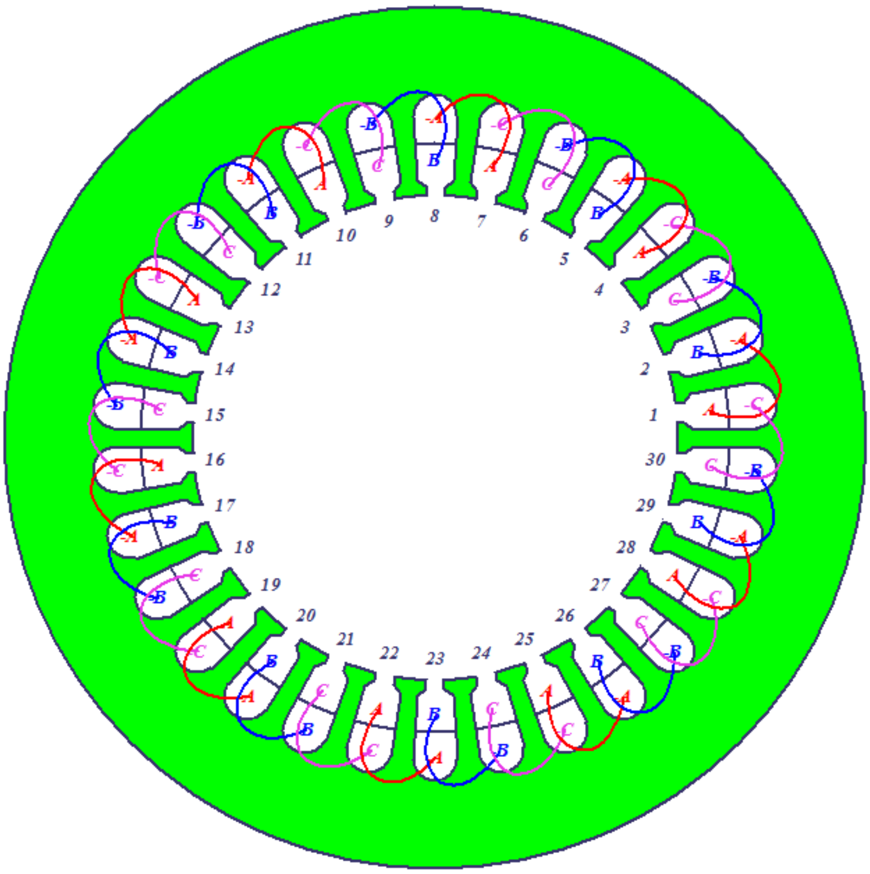

Figure 1: Winding diagram for the stator windings

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
First	0	120	240	0	120	240	0	120	240	0	120	240	0	120	240
Third	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fifth	0	240	120	0	240	120	0	240	120	0	240	120	0	240	120
	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C

16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
0	120	240	0	120	240	0	120	240	0	120	240	0	120	240
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	240	120	0	240	120	0	240	120	0	240	120	0	240	120
A	B	C	A	B	C	A	B	C	A	B	C	A	B	C

Note that we have a coil span of 1 slot in our double-layer design. The two adjacent slots have electrical phase difference of 120°. Therefore, A, B and C phases are wound on the adjacent teeth of the stator slots. Therefore, this design enjoys the advantage of the short end winding connections. Now, let's observe the phasor diagrams.

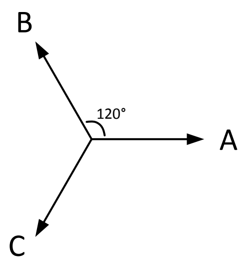

Figure 2: Phasor diagram for fundamental components

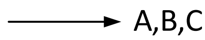

Figure 3: Phasor diagram for the third harmonics

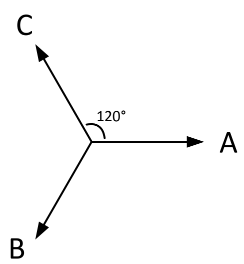

Figure 4: Phasor diagram for the fifth harmonic

Now, let's calculate the winding factor for fundamental and harmonic components. The winding factor is the product of distribution and pitch factors. The distribution factor for fractional pitch windings can be found as follows.

$$k_d = \frac{mag(vector\ sum\ of\ the\ phase\ vectors)}{scalar\ sum}$$

In our case, the vector sum is equal to the scalar sum because there is no phase difference between coils in a phase as shown in Figure 2, Figure 3 and Figure 4. Therefore, one can conclude that

$$k_d(1) = k_d(3) = k_d(5) = 1$$

Now, let's find the pitch factor for the fundamental and harmonics. The pitch factor can be defined as follows.

$$k_p = \sin\left(\frac{cs * n}{2} \right)$$

where cs is the coil span and n is the harmonic component number. In our case, the coil span for fundamental harmonic is 120°; for the third harmonic, it is zero, and for the fifth harmonic, it is 240°. Therefore, one can find the pitch factors as follows.

$$k_p(1) = \sin\left(\frac{120°}{2} \right) = 0.866$$

$$k_p(3) = \sin(0°) = 0$$

$$k_p(5) = \sin\left(\frac{120° * 5}{2} \right) = -0.866$$

	Fundamental	**3rd**	**5th**
Pitch factor	0,866	0	-0,866
Distribution factor	1	1	1
Winding factor	0,866	0	-0,866

Design II: 20-pole 24-slots

Pole number	20
Slot number	24
Number of layers	2
Coil span	1 slot

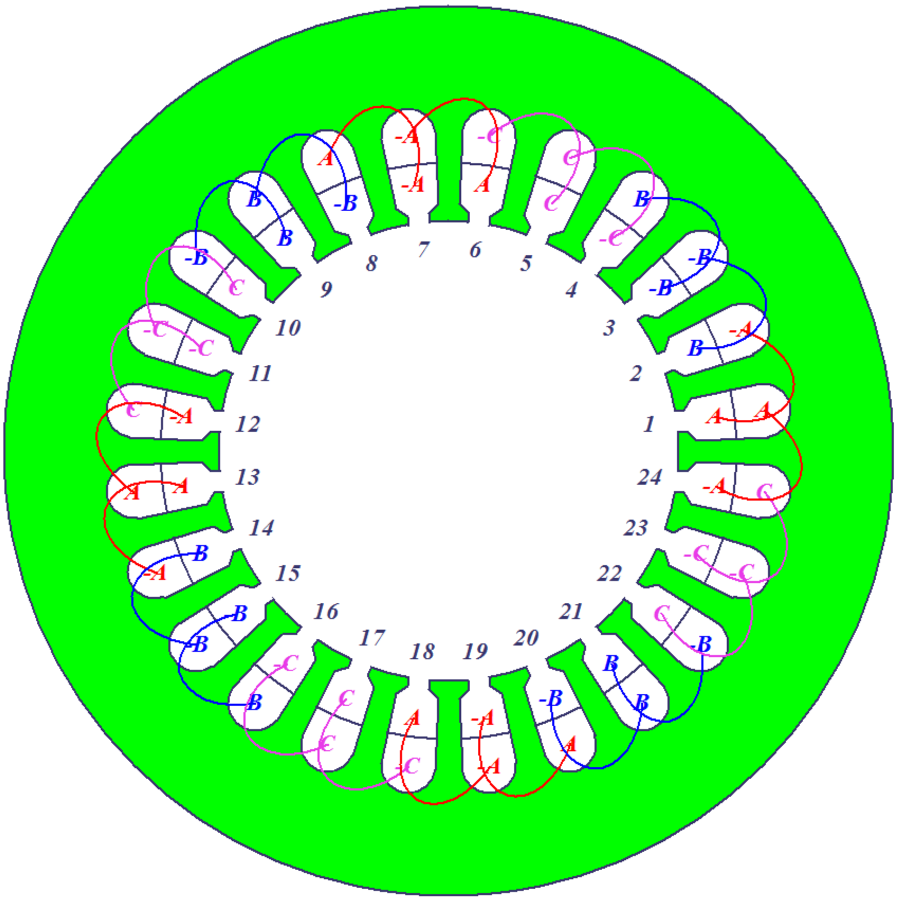

Figure 5: Winding diagram for the stator windings

	1	2	3	4	5	6	7	8	9	10	11	12
First	0	150	300	90	240	30	180	330	120	270	60	210
Third	0	90	180	270	0	90	180	270	0	90	180	270
Fifth	0	30	60	90	120	150	180	210	240	270	300	330
	A	B	-B	-C	C	A	-A	-B	B	C	-C	-A

13	14	15	16	17	18	19	20	21	22	23	24
0	150	300	90	240	30	180	330	120	270	60	210
0	90	180	270	0	90	180	270	0	90	180	270
0	30	60	90	120	150	180	210	240	270	300	330
A	B	-B	-C	C	A	-A	-B	B	C	-C	-A

Note that we have a coil span of 1 slot in our double-layer design. The two adjacent slots have electrical phase difference of 150° for the fundamental component. Therefore, A, B and C phases are wound on the adjacent teeth of the stator slots. Therefore, this design enjoys the advantage of the short end winding connections. Now, let's observe the phasor diagrams.

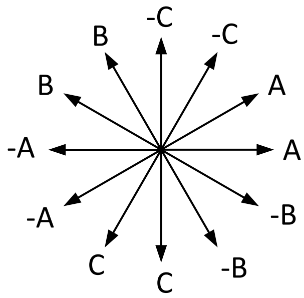

Figure 6: Phasor diagram for fundamental components of all phases

Now, let's draw phasor diagram for one phase to calculate the distribution factor.

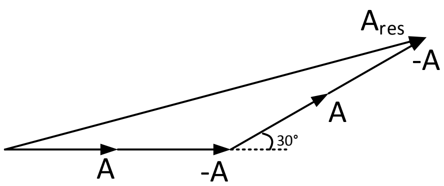

Figure 7: Phasor diagram for one phase for fundamental components

From Figure 7, the distribution factor can be calculated as

$$k_d = \frac{mag(vector\ sum\ of\ the\ phase\ vectors)}{scalar\ sum}$$

$$k_d(1) = \frac{3.8637}{4} = 0.9659$$

To find the distribution factor for the third harmonic, the following phasor diagram is considered.

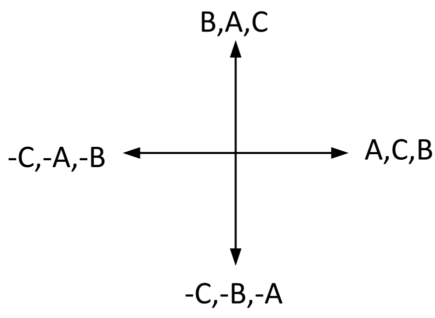

Figure 8: Phasor diagram for the third harmonics for all phases

Similar derivation is valid for the distribution factor for the third harmonics as follows.

$$k_d(3) = \frac{2\sqrt{2}}{4} = 0.7071$$

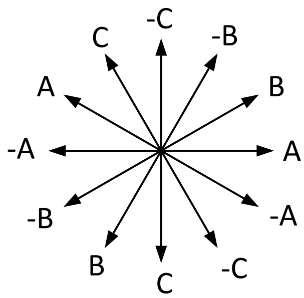

Figure 9:Phasor diagram for the fifth harmonics for all phases

$$k_d(5) = \frac{3.8637}{4} = 0.9659$$

Now, let’s calculate the pitch factors for the fundamental and harmonics. Remember that coil span for the fundamental component is 150°.

$$k_p(1) = \sin\left(\frac{150°}{2}\right) = 0.9659$$

$$k_p(3) = \sin\left(\frac{150° * 3}{2}\right) = -0.7071$$

$$k_p(5) = \sin\left(\frac{150° * 5}{2}\right) = 0.2588$$

	Fundamental	**3rd**	**5th**
Pitch factor	0.9659	-0.7071	0.2588
Distribution factor	0.9659	0.7071	0.9659
Winding factor	0.933	0.500	0.250

Question III: RMXprt Verification

In order to verify my results, I used Ansys Maxwell RMXprt tool that finds machine performance and parameters quickly. As a reference design, I used one of the example designs in RMXprt. It is a surface-mount permanent magnet synchronous machine with the rated parameters listed below. I converted this design into my 20-pole 24-slot design. It's 2D view and stator winding diagram is shown in Figure 10 and Figure 11.

Parameter	Value
Rated power	550 W
Rated speed	1500 rpm
Rated voltage	127 V

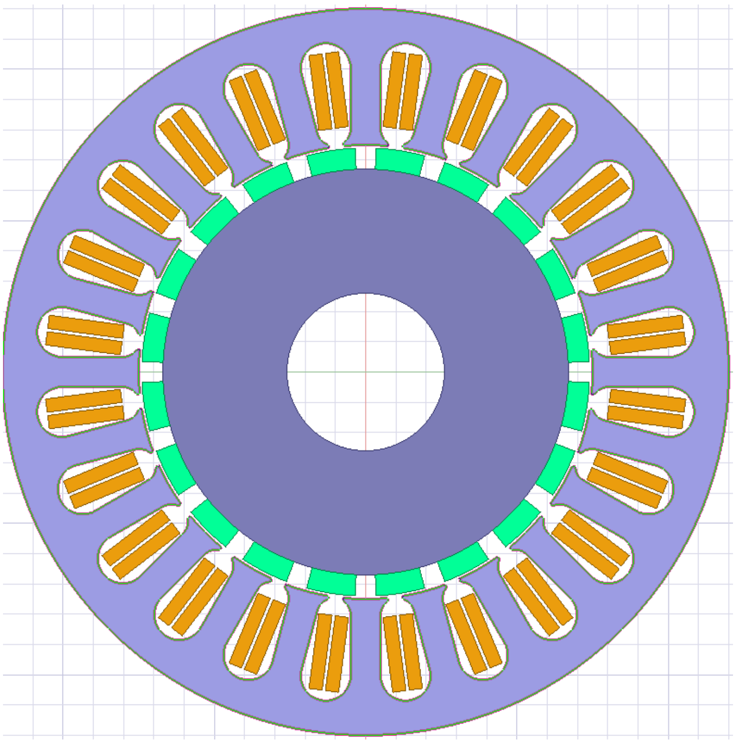

Figure 10: 20-pole 24-slot reference design

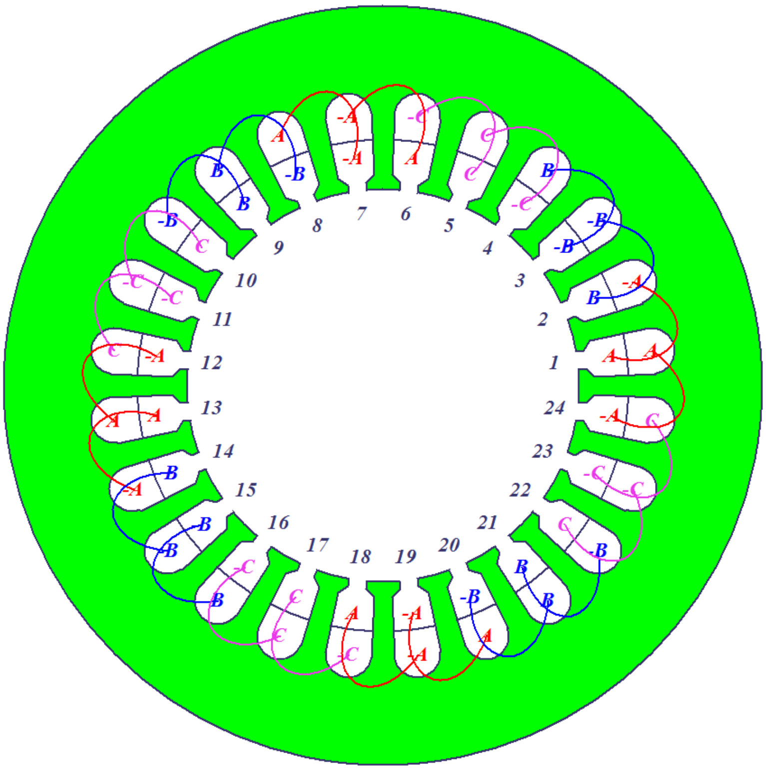

Figure 11: Winding diagram for 20-pole 24-slot machine

Data: Steady State Parameters

	Name	Value	Units	Description
1	Stator Winding Factor	0.933013		

As can be seen above, the winding factor of 0.933 is matching with my analytical winding factor derivation and my results are verified. Other rated parameters of the machine are listed in the following table.

	Name	Value	Units
1	RMS Line Current	2.6385	A
2	RMS Phase Current	1.5307	A
3	Armature Thermal Load	37.0694	A^2/mm^3
4	Specific Electric Loading	12473.1	A_per_meter
5	Armature Current Density	2971940	A_per_m2
6	Frictional and Windage Loss	12	W
7	Iron-Core Loss	25.635	W
8	Armature Copper Loss	2.0803	W
9	Total Loss	51.715	W
10	Output Power	550.27	W
11	Input Power	601.98	W
12	Efficiency	91.4092	%
13	Apparent Power	580.356	VA
14	Power Factor	0.948155	
15	Synchronous Speed	1500	rpm
16	Rated Torque	3.83234	NewtonMeter
17	Power Angle	8.17689	deg
18	Maximum Output Power	3334.6	W
19	Short Circuit Current	17.735	A

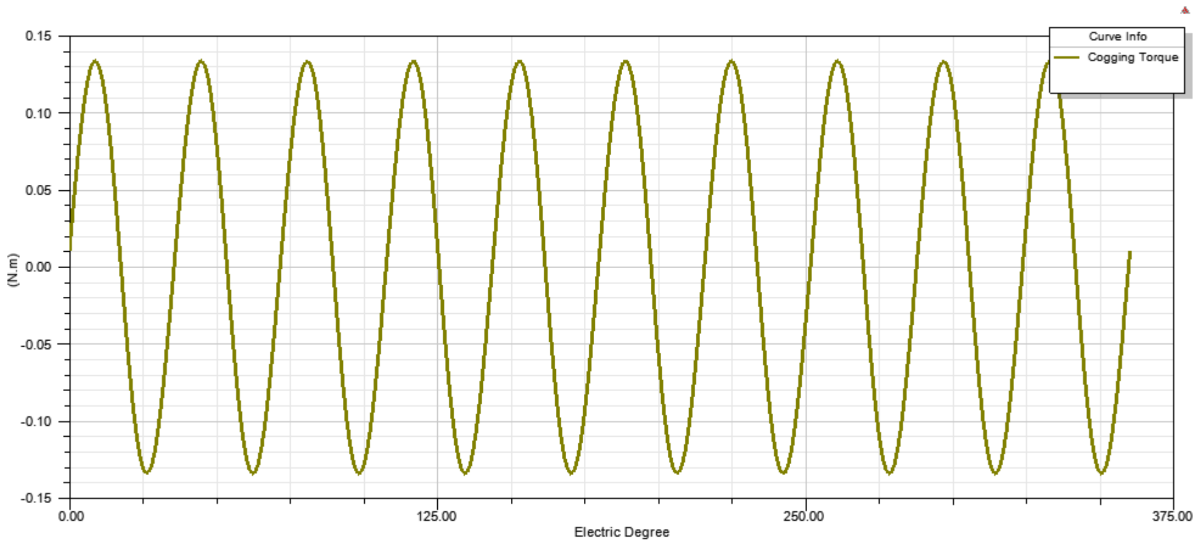

Figure 12: Cogging torque

In Figure 12, cogging torque of the motor is shown. It has a peak value of 133 mNm. Its period is 36 degrees electrically. It is equivalent to 3.6 degrees mechanically. It is interesting that cogging torque has 1/100 *360 deg mechanical period. I would expect this to be a combination of 20 and 24, which are pole and slot numbers.

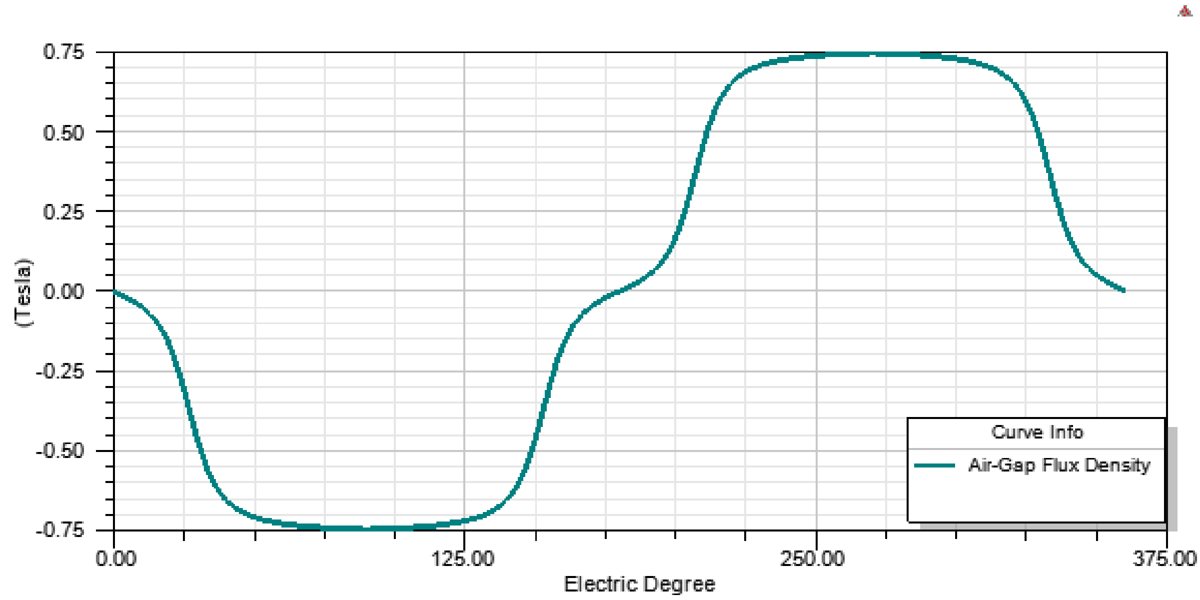

Figure 13: Air gap flux density

In air gap flux density distribution in Figure 13, it is seen that maximum flux density is around 0.75 T and there exists considerable amount of third harmonics. The induced phase voltage at rated speed is shown in Figure 14.

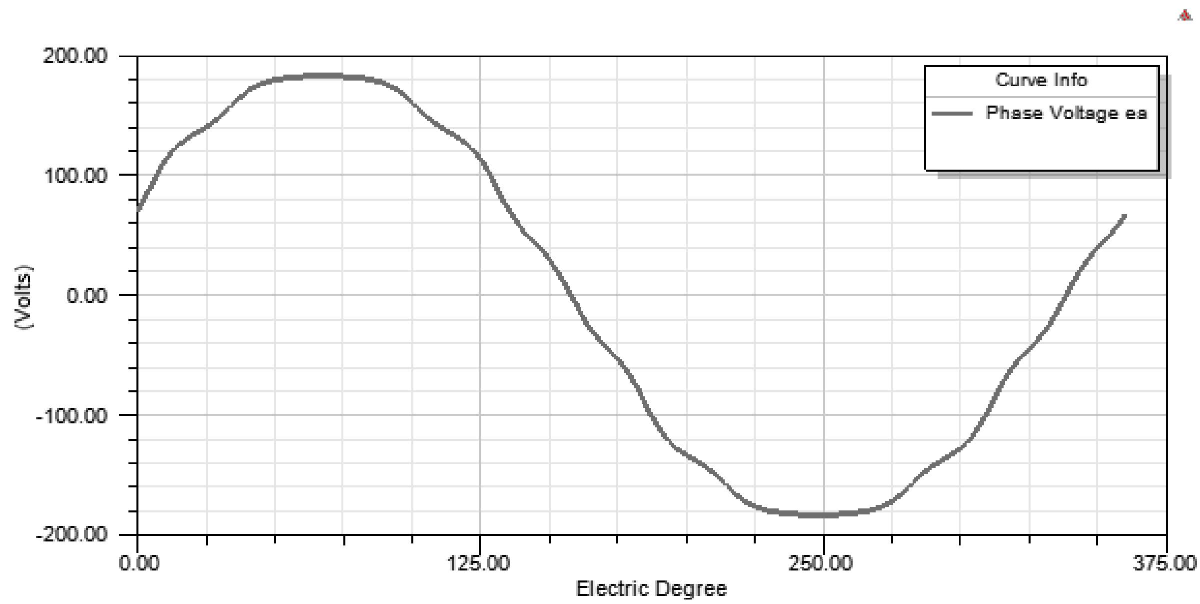

Figure 14: Induced phase voltage at rated speed