ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

EE 568

Selected Topics on Electrical Machines

Project 2

Motor Winding Design & Analysis

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Introduction

In this project, electrical machines winding diagrams are investigated for integral slot windings and fractional slot windings with design examples. As integral slot winding, 20 poles, 120 slots machine winding diagram is designed and its parameters are presented. On the other hand, as an example of fractional slot winding 20 poles 24 slots machine diagram is designed. This design is analysed with Maxwell which is one of the Finite Element Analysis tool.

Q1) Integral Slot Winding

In this part, 20 poles, 120 slots, 3-phase machines winding diagram is designed. Distribution factor, pitch factor, winding factor is calculated for fundamental, 3rd and 5th components.

Q(number of slots) = 120, p(pole pairs) = 10, m(number of phases) = 3;

$q = \frac{Q}{2*p*m} = 2$ slots per pole per phase $\alpha = \frac{360°}{(Q/p)} = 30°$ slot angle

Double layer, 5/6 short pitched design is selected. Suggested winding diagram can be found in Table 1.

Table 1: 20 pole 120 slot machine winding diagram

120	1	2	3	4	5	6	7	8	9	10	11	12
	A1	A2	-C1	-C2	B1	B2	-A3	-A4	C3	C4	-B3	-B4
A3	A4	-C3	-C4	B3	B4	-A1	-A2	C1	C2	-B1	-B2	

λ (coil pitch) = 150°

- Fundamental component;

Distribution factor $k_{d1} = \frac{\sin(q*n*\frac{\alpha}{2})}{q*\sin(n*\frac{\alpha}{2})} = \frac{\sin(30°)}{2*\sin(15°)} = 0.966$

Pitch factor $k_{p1} = \sin\left(n*\frac{\lambda}{2}\right) = \sin(\frac{150°}{2}) = 0.966$

Winding factor $k_{w1} = k_{d1} * k_{p1} = 0.933$

- 3rd harmonic component;

Distribution factor $k_{d3} = \frac{\sin(90°)}{2*\sin(45°)} = 0.707$

Pitch factor $k_{p3} = \sin(3*\frac{150}{2}) = -0.707$

Winding factor $k_{w3} = k_{d3} * k_{p3} = -0.499$

- 5th harmonic component;

Distribution factor $k_{d5} = \frac{\sin(150°)}{2*\sin(75°)} = 0.259$

Pitch factor $k_{p5} = \sin(5 * \frac{150}{2}) = 0.259$

Winding factor $k_{w5} = k_{d5} * k_{p5} = 0.067$

As double layer and 5/6 short pitched configuration is chosen, 5th harmonic component is found very small and induced voltage magnitude will be very small compared to 1st harmonic. 3rd harmonic component is respectively high but it can be eliminated with connection type of the phases.

Q2) Fractional Slot Winding Design

In this part, Emetor Winding Design is used for initial design. According to tool, maximum possible fundamental winding factor is achieved with 20 pole numbers and 24 slots which is 0.966. In order to achieve maximum winding factor for fundamental component, 20 pole numbers and 24 slots configuration is selected. Winding diagram of the design can be found in Table 2.

$q = \frac{Q}{2*p*m} = \frac{24}{2*10*3} = 0.4$ slots per pole per phase $\alpha = \frac{360°}{(Q/p)} = 150°$ slot angle

Table 2: 24 slot 20 pole machine design

Slot number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
Electrical angle (degree)	0	150	300	90	240	30	180	330	120	270	60	210
3rd harmonic angle	0	90	180	270	0	90	180	270	0	90	180	270
5th harmonic angle	0	30	60	90	120	150	180	210	240	270	300	330
Coil distribution	A1	-A2	-B1	B2	C1	-C2	-A1	A2	B1	-B2	-C1	C2
Slot number	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**
Electrical angle (degree)	0	150	300	90	240	30	180	330	120	270	60	210
3rd harmonic angle	0	90	180	270	0	90	180	270	0	90	180	270
5th harmonic angle	0	30	60	90	120	150	180	210	240	270	300	330
Coil distribution	A3	-A4	-B3	B4	C3	-C4	-A3	A4	B3	-B4	-C3	C4

Phasor diagram of the Phase A fundamental component according to proposed design can be found in Figure 1.

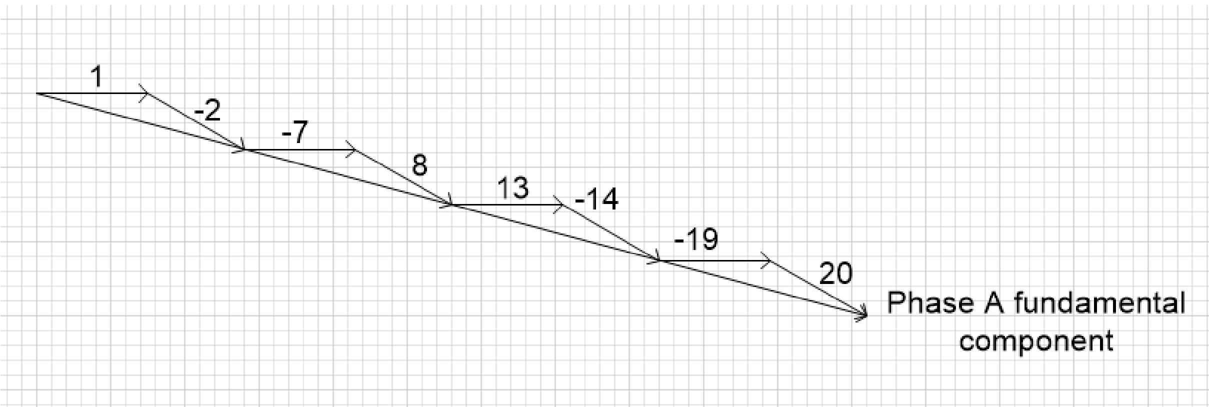

Figure 1: Phasor diagram of fundamental component of Phase A

Distribution factor can be calculated by defining a z variable as follows [1];

$z = \frac{Q/2}{\mathrm{gcd}(\frac{Q}{2},2p*m)}$ where gcd is greatest common divisor,

Winding factor is defined according to z is; $k_{dn} = \frac{\sin(n*\frac{\alpha}{2})}{z*\sin(n*\frac{\alpha}{2*z})}$

For this design; $z = \frac{Q/2}{\mathrm{gcd}(\frac{Q}{2},2p*m)} = \frac{12}{12} = 1$; All of the harmonics distribution factors are 1.

Distribution factor $k_{d1} = 1$

Pitch factor $k_{p1} = \sin\left(n * \frac{\lambda}{2}\right) = \sin(\frac{150°}{2}) = 0.966$

Winding factor $k_{w1} = k_{d1} * k_{p1} = 0.966$

Phasor diagram of the Phase A 3rd harmonic component according to proposed design can be found in Figure 2.

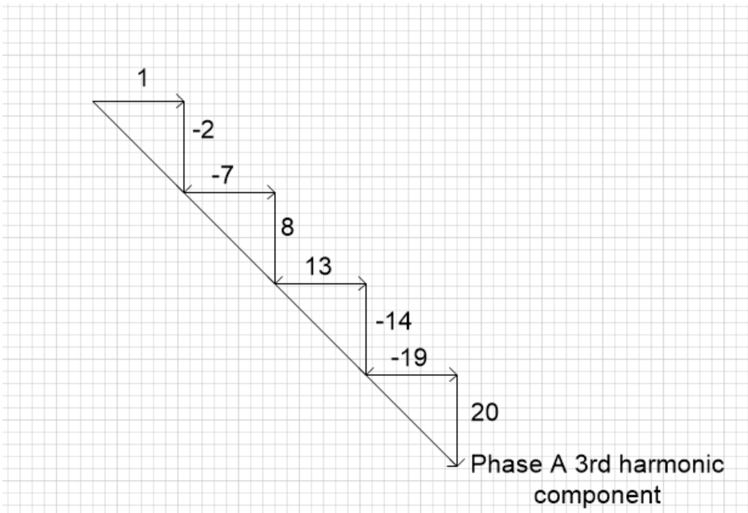

Figure 2: Phasor diagram of 3rd harmonic component of Phase A

Distribution factor $k_{d3} = 1$

Pitch factor $k_{p3} = \sin\left(n * \frac{\lambda}{2}\right) = \sin\left(\frac{450°}{2}\right) = -0.707$

Winding factor $k_{w3} = k_{d3} * k_{p3} = -0.707$

Phasor diagram of the Phase A 5th harmonic component according to proposed design can be found in Figure 3.

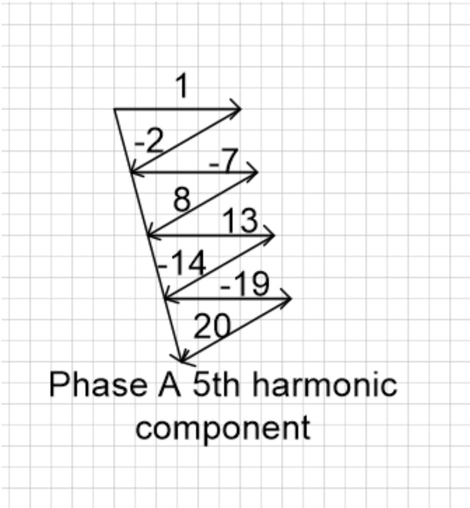

Figure 3: Phasor diagram of 5th harmonic component of Phase A

Distribution factor $k_{d5} = 1$

Pitch factor $k_{p5} = \sin\left(n * \frac{\lambda}{2}\right) = \sin\left(\frac{750°}{2}\right) = 0.259$

Winding factor $k_{w5} = k_{d5} * k_{p5} = 0.259$

As seen from Figure 1, one of the two adjacent vectors is subtracted from other one. Therefore, 30° degree between each adjacent vector is achieved. As a result of this, winding factor of fundamental component is calculated as 0.966 which can be considered as high. On the other hand, this angle increases to 90° for 3rd harmonic component and leading to 0.707 winding factor. Lastly, this angle even increases to 150° and leading 0.259 winding factor.

20 pole numbers, 30 slots are chosen for another design. Winding diagram of the design can be found in Table 3.

$q = \frac{Q}{2*p*m} = \frac{30}{2*10*3} = 0.5$ slots per pole per phase $\qquad \alpha = \frac{360°}{(Q/p)} = 120°$ slot angle

Table 3: 30 slot 20 pole machine design

Slot number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Electrical angle (degree)	0	120	240	0	120	240	0	120	240	0
3rd harmonic angle	0	0	0	0	0	0	0	0	0	0
5th harmonic angle	0	240	120	0	240	120	0	240	120	0
Coil distribution	A	-A	C	-C	B	-B	A	-A	C	-C
Slot number	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
Electrical angle (degree)	120	240	0	120	240	0	120	240	0	120
3rd harmonic angle	0	0	0	0	0	0	0	0	0	0
5th harmonic angle	240	120	0	240	120	0	240	120	0	240
Coil distribution	B	-B	A	-A	C	-C	B	-B	A	-A
Slot number	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Electrical angle (degree)	240	0	120	240	0	120	240	0	120	240
3rd harmonic angle	0	0	0	0	0	0	0	0	0	0
5th harmonic angle	120	0	240	120	0	240	120	0	240	120
Coil distribution	C	-C	B	-B	A	-A	C	-C	B	-B

Phasor diagram of the Phase A fundamental component according to second design can be found in Figure 4.

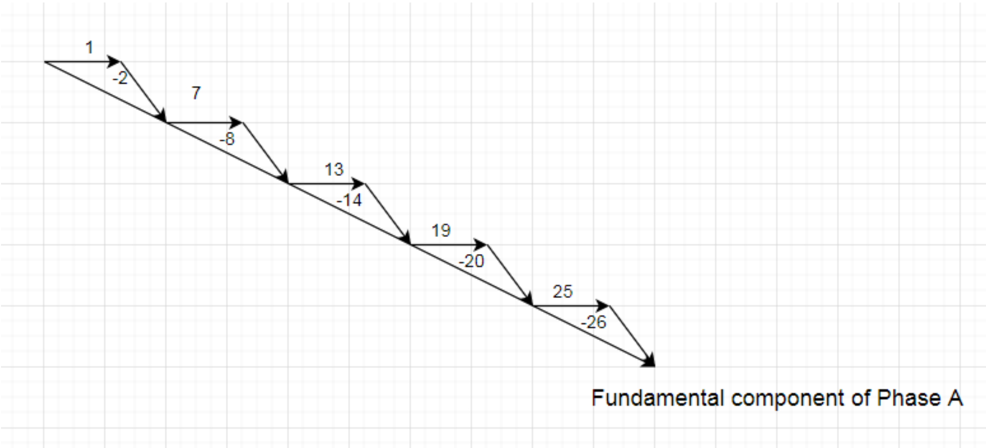

Figure 4: Phasor diagram of fundamental component of Phase A (second design)

For this design; $z = \frac{Q/2}{\gcd(\frac{Q}{2}, 2p*m)} = \frac{15}{15} = 1$; Same with previous design, all the harmonics distribution factor is 1.

Distribution factor $k_{d1} = 1$

Pitch factor $k_{p1} = \sin\left(n * \frac{\lambda}{2}\right) = \sin(\frac{120°}{2}) = 0.866$

Winding factor $k_{w1} = k_{d1} * k_{p1} = 0.866$

As all coils have same 3rd harmonic angle, they will cancel each other and no resultant phasor can be found.

Distribution factor $k_{d3} = 1$

Pitch factor $k_{p3} = \sin\left(n * \frac{\lambda}{2}\right) = \sin\left(\frac{360°}{2}\right) = 0$

Winding factor $k_{w3} = k_{d3} * k_{p3} = 0$; There will be no induced 3rd harmonic component for this design.

Phasor diagram of the Phase A 5th harmonic component according to second design can be found in Figure 5.

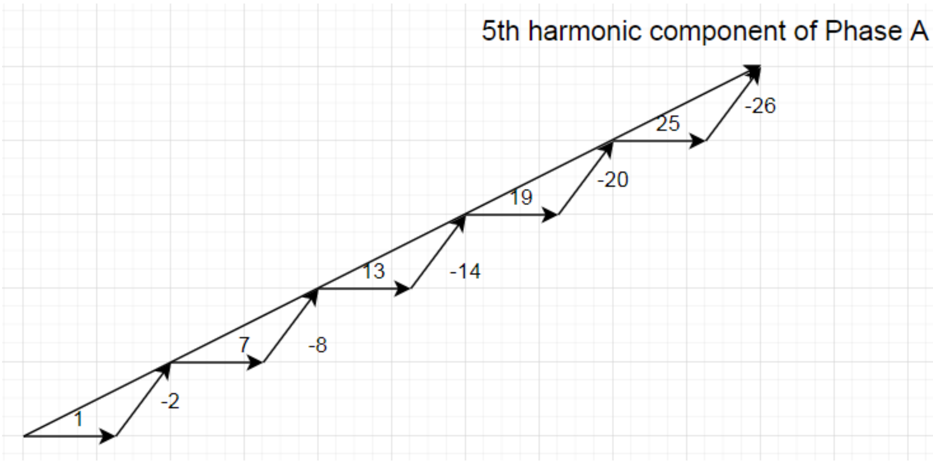

Figure 5: Phasor diagram of 5th harmonic component of Phase A (second design)

Distribution factor $k_{d5} = 1$

Pitch factor $k_{p5} = \sin\left(n * \frac{\lambda}{2}\right) = \sin\left(\frac{600°}{2}\right) = -0.866$

Winding factor $k_{w5} = k_{d5} * k_{p5} = -0.866$

Although this design has no 3rd harmonic component, 5th harmonic component is very high. This situation may be very problematic and design stages should be revisited.

By comparing two designs, first design has relatively high fundamental winding factor. Although second design has no 3rd harmonic components in their induced voltage, 5th harmonic component is dramatically high. Therefore it can be thought as first design is more reliable design.

Q3) 2D FEA Modelling

In this part, proposed fractional slot machine is verified by using Maxwell. Proposed machine had 20 poles and 24 slots. While constructing FEA model, a tutorial which was published by Ansys Maxwell is followed. [2] Although tutorial consist an example of Interior Permanent Magnet Synchronous Machine, proposed model is constructed with Surface Mounted Permanent Magnet Synchronous Machine. Constructed model can be seen in Figure 6. Winding diagram of the constructed machine is exactly same with Table 2 which was previously proposed.

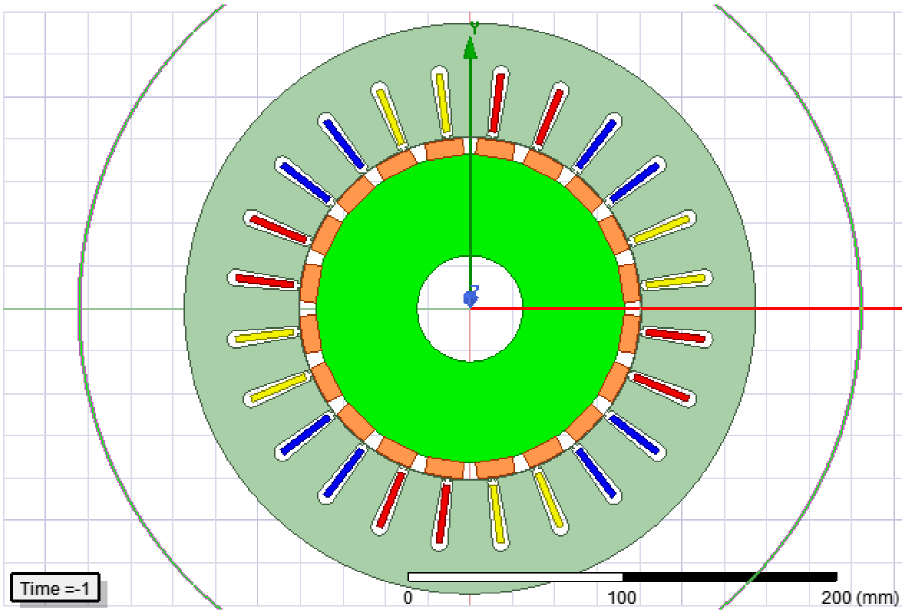

Figure 6: Constructed machine model

Flux density vectors of the design were evaluated in the Magnetostatic solver of Maxwell. Resultant figure can be seen in Figure 7. As design is fractional slot winding design, there is no symmetries for vectors.

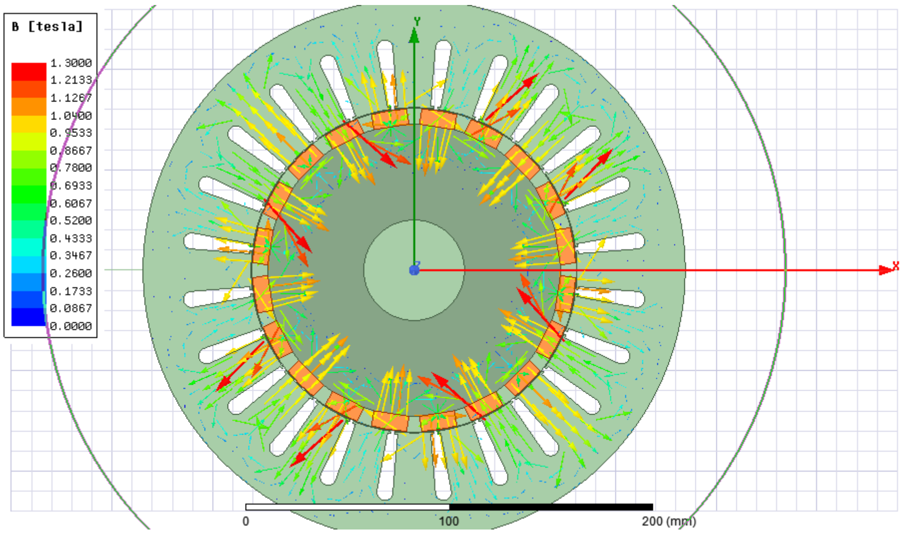

Figure 7: Flux density vectors

In order to reveal phase voltages and cogging torque, model is solved in Transient analysis. Rotor was rotated with 1000 rpm mechanical speed. Figure 8 shows induced phase voltages whereas Figure 9 shows induced phase to phase voltages. As design has effective 3rd and 5th harmonic components, their effect can be seen in these graphs. Phase to phase voltages has no 3rd harmonic component. Cogging torque can be seen in Figure 10. For one electrical cycle cogging torque has 12 cycles which is half of the slot number.

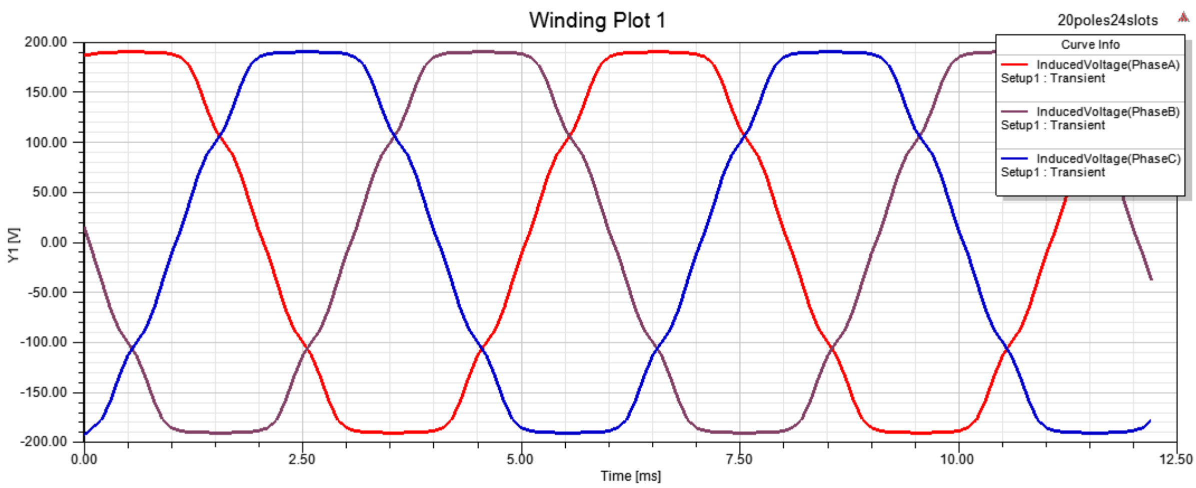

Figure 8: Induced phase voltages

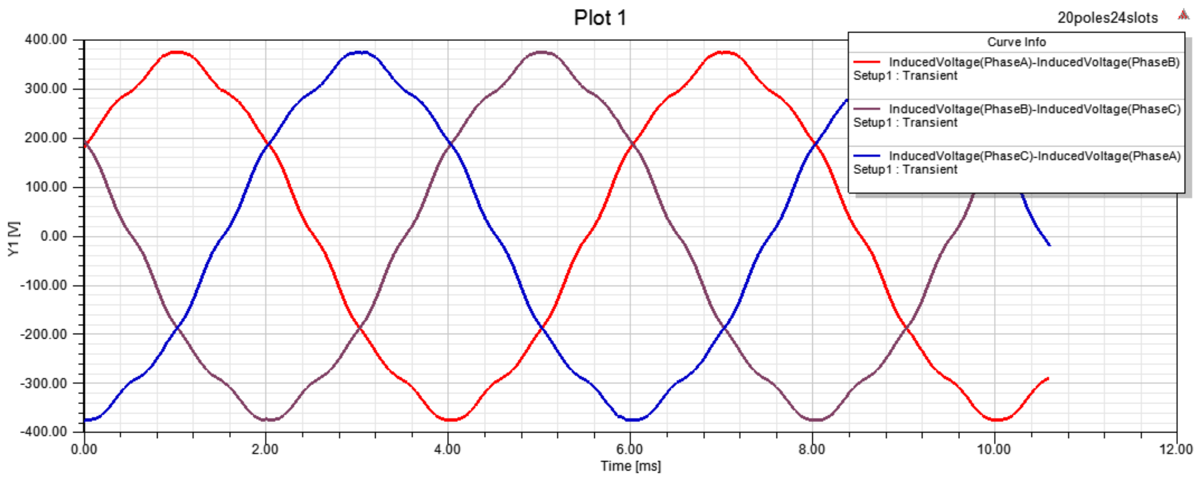

Figure 9: Induced phase to phase voltages

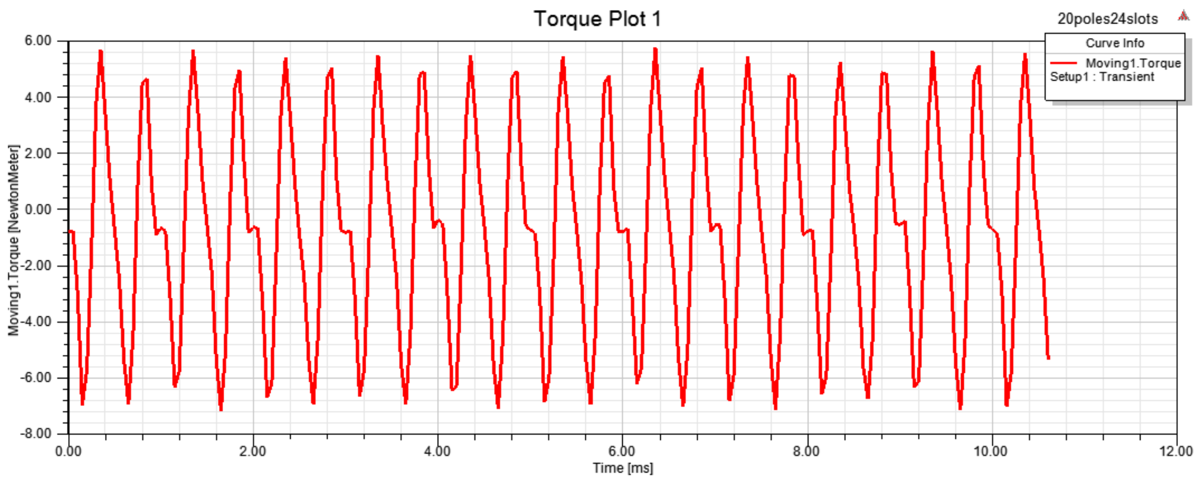

Figure 10: Cogging torque

Conclusion

In this project, different winding designs are evaluated for different slots and poles numbers. Proposed design is constructed in Maxwell and resultant outputs are presented.

References

[1] S. E. Skaar, O. Krovel, R. Nilssen, “Distribution, coil-span and winding factors for PM machines with concentrated windings”, 2006

[2] Ansys, Maxwell, “Study of a Permanent Magnet Motor with Maxwell 2D: Example of the 2004 Prius IPM Motor, 2013