MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

EE568 Selected Topics on Electrical Machines

PROJECT 1

MOTOR Winding Design and Analysis

Enes AYAZ 2093318

Introduction

In this report, motor winding design will be investigated. Firstly, integral slot winding is designed and the effect of distribution factor and pitch angle on the coil voltages will be analyzed. Also, harmonic elimination by using under-pitch coil is made. Secondly, a fractional slot winding will be analyzed for chosen slot and pole number. The voltages of the coils considering 3^{rd} and 5^{th} harmonics will be calculated by using phasors. Then, effect of changing slot number at the same pole number will be investigated and the two results are compared. Finally, finite element analysis will be made for fractional slot windings. Induced emf and airgap flux distribution will be observed and the analytical calculation will be compared.

Integral Slot Winding Design

We have a 20-pole,120 slot, 3-phase machine. For distributed coils, algebraic sum of the coil voltages is not equal to vector sum of the coil voltages. The differences can be formulated with respect to coil numbers q, electrical angle α between two coils and harmonic numbers h.

$$k_d = \frac{\sin\left(h\frac{q\alpha}{2}\right)}{q sin(h\frac{\alpha}{2})} \qquad (1)$$

Also, the voltage of two coils are summed arithmetically, if the electrical angle between two coils are 180°, so full-pitched. The angle between two coils are bigger than 180°, named as over-pitch coils or smaller than 180°, named as under-pitch coil. It can be formulated with respect to electrical pitch angle λ between two coils and harmonic numbers h . Also, the pitch angle can be used to eliminate the harmonics.

$$k_p = \sin(\frac{h\lambda}{2}) \qquad (2)$$

Design is chosen as 120° pitch angle to eliminate 3rd harmonics.

- First of all, number of slots per pole per phase is calculated as $\frac{120\ slot}{20\ pole*3\ phase} = 6$

In this part, design is shown for only a pole-pair (2 pole).

A1	A2	-B1	-B2	C1	C2	-A3	-A4	B3	B4	-C3	-C4
B3	B4	C3	C4	-A1	-A2	-B1	-B2	-C1	-C2	A3	A4

- By using formula 1 and 2, and taken the variables as:

$$\lambda = 150° \; h = 1 \; q = 2 \; \alpha = 30°$$

$$k_d = \frac{\sin\left(h\frac{q\alpha}{2}\right)}{q sin(h\frac{\alpha}{2})} = \frac{\sin(30)}{2*\sin(15)} = 0.9659$$

$$k_p = \sin\left(\frac{h\lambda}{2}\right) = \sin(120) = 0.8660$$

Winding factor is calculated by multiplying distribution and pitch factor.

$$k_w = \mathrm{k_d} * k_p = 0.9659 * 0.8660 = 0.8364$$

For third and fifth harmonics winding factor can be calculated by using the same formulation.

- $\lambda = 150° \; h = 3 \; q = 2 \; \alpha = 30°$

$$k_d = \frac{\sin\left(h\frac{q\alpha}{2}\right)}{q sin(h\frac{\alpha}{2})} = \frac{\sin(90)}{2 * \sin(45)} = 0.7071$$

$$k_p = \sin\left(\frac{h\lambda}{2}\right) = \sin(360) = 0$$

$$k_w = \mathrm{k_d} * k_p = 0.7071 * 0 = 0$$

- $\lambda = 150° \; h = 5 \; q = 2 \; \alpha = 30°$

$$k_d = \frac{\sin\left(h\frac{q\alpha}{2}\right)}{q sin(h\frac{\alpha}{2})} = \frac{\sin(150)}{2 * \sin(75)} = 0.7071$$

$$k_p = \sin\left(\frac{h\lambda}{2}\right) = \sin(240) = 0.8660$$

$$k_w = \mathrm{k_d} * k_p = 0.7071 * 0.8660 = 0.6123$$

- Distributed winding causes a small voltage drops due to vector sum of the voltages. The voltage decrease is formulated as distribution factor. The distribution winding factor is smaller if the harmonic number increases. Thus, distribution of windings attenuates the harmonics respectively increasing order. Also, coil pitch can be adjusted to eliminate a harmonic. In this part, it is chosen as 120 degree to eliminate 3^{rd} harmonic. Thus, there is no voltage contribution from 3^{rd} harmonic.

Fractional Slot Winding Design

In this part, 3-phase permanent-magnet synchronous machine with fractional-slot winding will be analyzed. Firstly, pole number and slot number are chosen by using Emetor. Pole number is chosen as 20 and slot number is chosen as 24 because the configuration brings high winding factor as 0.966. The machine is shown figure 1.

- slot= 24, pole=20, phase =3 ➔ $q=\frac{3}{10}$

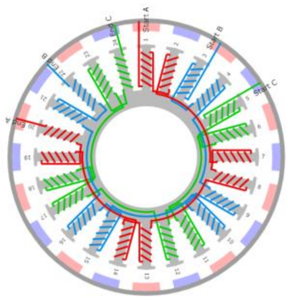

Figure 1 Fractional Slot Machine (24 Slot 20 Pole)

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Degree (Elec)	0	150	300	450	600	750	900	1050	1200	1350	1500	1650	1800	1950	2100	2250	2400	2550	2700	2850	3000	3150	3300	3450
Degree (Elec)	0	150	300	90	240	30	180	330	120	270	60	210	0	150	300	90	240	30	180	330	120	270	60	210
Phase	A1	-A1	-B1	B1	C1	-C1	-A2	A2	B2	-B2	-C2	C2	A3	-A3	-B3	B3	C3	+C3	-A4	A4	B4	-B4	-C4	C4

- The phasor diagram for only positive coils of phase A is shown figure 2.

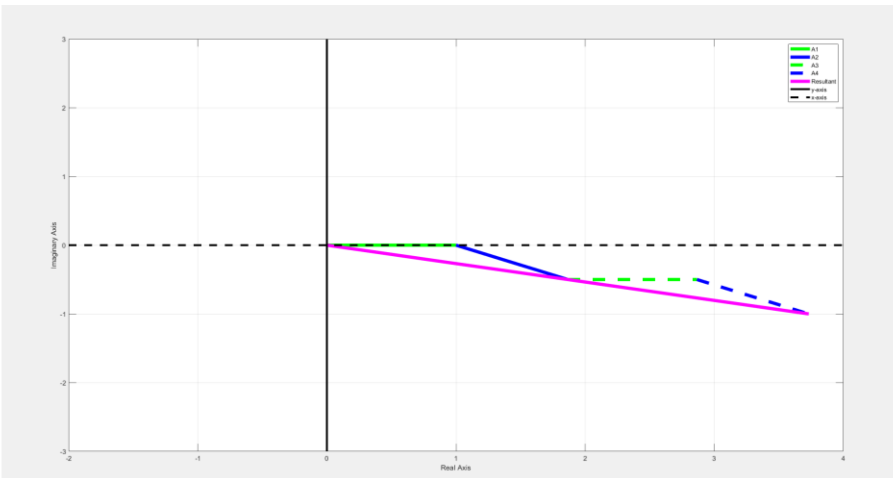

Figure 2 Phasor Diagram of phase A Voltages

For calculation of winding factor, only for A1 and A2 can be calculated thanks to A3 and A4 the same as A1 and A2 as shown figure 2. Also, pitch angle is 150 degree. Thus, we can calculate the windings factor like integral slot windings.

$$k_d = \frac{\sin\left(h\frac{q\alpha}{2}\right)}{q sin(h\frac{\alpha}{2})} = \frac{\sin(330)}{2 * \sin(165)} = 0.9659$$

$$k_p = \sin\left(\frac{h\lambda}{2}\right) = \sin(75) = 09659$$

$$k_w = \mathrm{k_d} * k_p = 0.9659 * 09659 = 0.9330$$

For 3rd and 5th harmonic winding factor is calculated as:

$$k_d = \frac{\sin\left(3\frac{q\alpha}{2}\right)}{q sin(3\frac{\alpha}{2})} = \frac{\sin(270)}{2 * \sin(135)} = 0.7071$$

$$k_p = \sin\left(\frac{3\lambda}{2}\right) = \sin(225) = -0.7071$$

$$k_w = 0.5 \text{ for } 3^{\mathrm{rd}}\ harmonics$$

$$k_d = \frac{\sin\left(5\frac{q\alpha}{2}\right)}{q sin(5\frac{\alpha}{2})} = \frac{\sin(90)}{2 * \sin(225)} = -0.7071$$

$$k_p = \sin\left(\frac{5\lambda}{2}\right) = \sin(15) = 0.258$$

$$k_w = 0.183 \text{ for } 5^{th}\ harmonics$$

- Slot number is changing with 21 and pole number is 20 as shown figure 3.

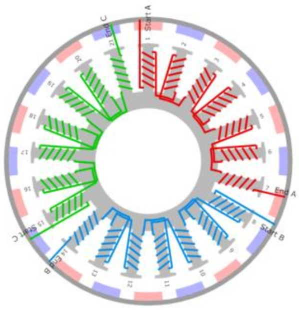

Figure 3 Fractional Slot Machine (21 Slot 20 Pole)

- slot= 21, pole=20, phase =3 ➔ q=0.35

Slot	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Degree (Elec)	0	171	342	513	684	855	1026	1197	1368	1539	1710	1881	2052	2223	2394	2565	2736	2907	3078	3249	3420
Degree (Elec)	0	171	342	153	324	135	306	117	288	99	270	81	252	63	234	45	216	27	198	9	180
Phase	A1	-A1	A2	-A2	A3	-A3	A4	B1	-B1	B2	-B2	B3	-B3	B4	C1	-C1	C2	-C2	C3	-C3	C4

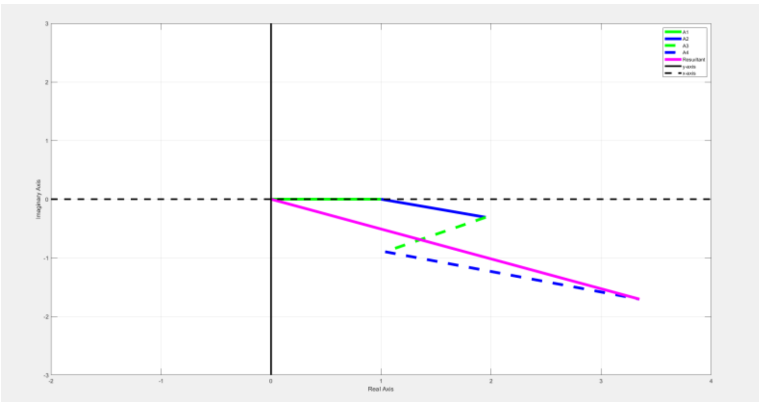

Figure 4 Phasor Diagram of phase A Voltages

The phasor diagram, figure 4, shows that the voltage difference between the coils are different from each other. Then, we cannot formulate the distribution factor. We can use the definition of the distribution factor which say that distribution factor is the ratio of vectoral sum and scalar sum of the coil voltages.

$$k_d = \frac{vectoral\ sum}{scalar\ sum} = \frac{3.7574}{4} = 0.939$$

$$k_p = \sin\left(\frac{h\lambda}{2}\right) = \sin(85.5) = 0997$$

$$k_w = \mathrm{k_d} * k_p = 0.939 * 0.997 = 0.936$$

For 3rd and 5th harmonic winding factor is found by using phasor diagram in figure 5.

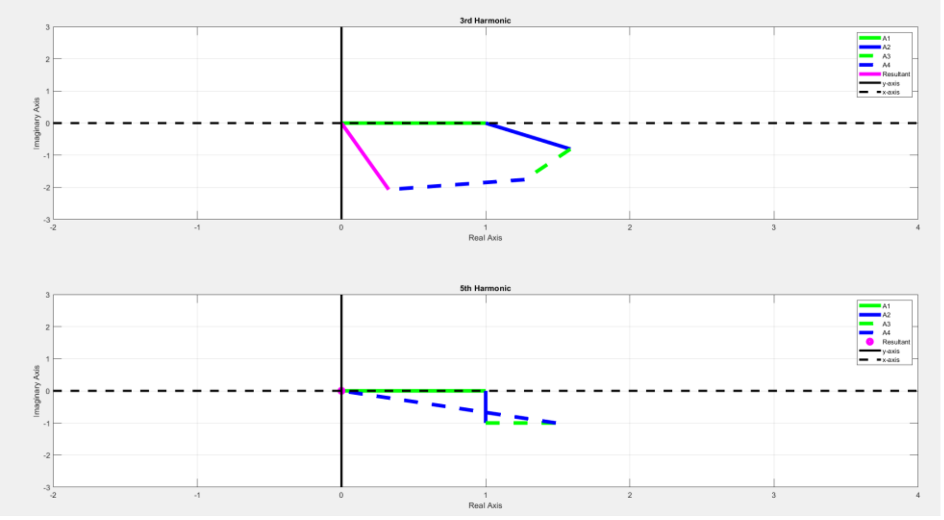

Figure 5 Phasor Diagram of phase A Voltages for 3rd and 5th harmonics

$$k_d = \frac{vectoral\ sum}{scalar\ sum} = \frac{3.7574}{4} = \quad 0.3277$$

$$k_p = \sin\left(\frac{3\lambda}{2}\right) = \sin(256.5) = -0.9723$$

$$k_w = 0.318 \text{ for } 3^{\text{rd}}\ harmonics$$

$$k_d = \frac{vectorel\ sum}{scalar\ sum} = \frac{0}{4} = 0$$

$$k_p = \sin\left(\frac{5\lambda}{2}\right) = \sin(427.5) = 0.923$$

$$k_w = 0 \text{ for } 5^{th}\ harmonics$$

2D FEA Modelling

24 slot 20 pole 3 phase machine is drawn by Maxwell 2D. Field is fed by DC current to create the magnetic poles. Stator side is 3 phase fractional pitch coil. The field is 20 pole and 200A.Turn and conductor number of phases is 80. The rotor diameter is 47 cm and airgap is 5mm.

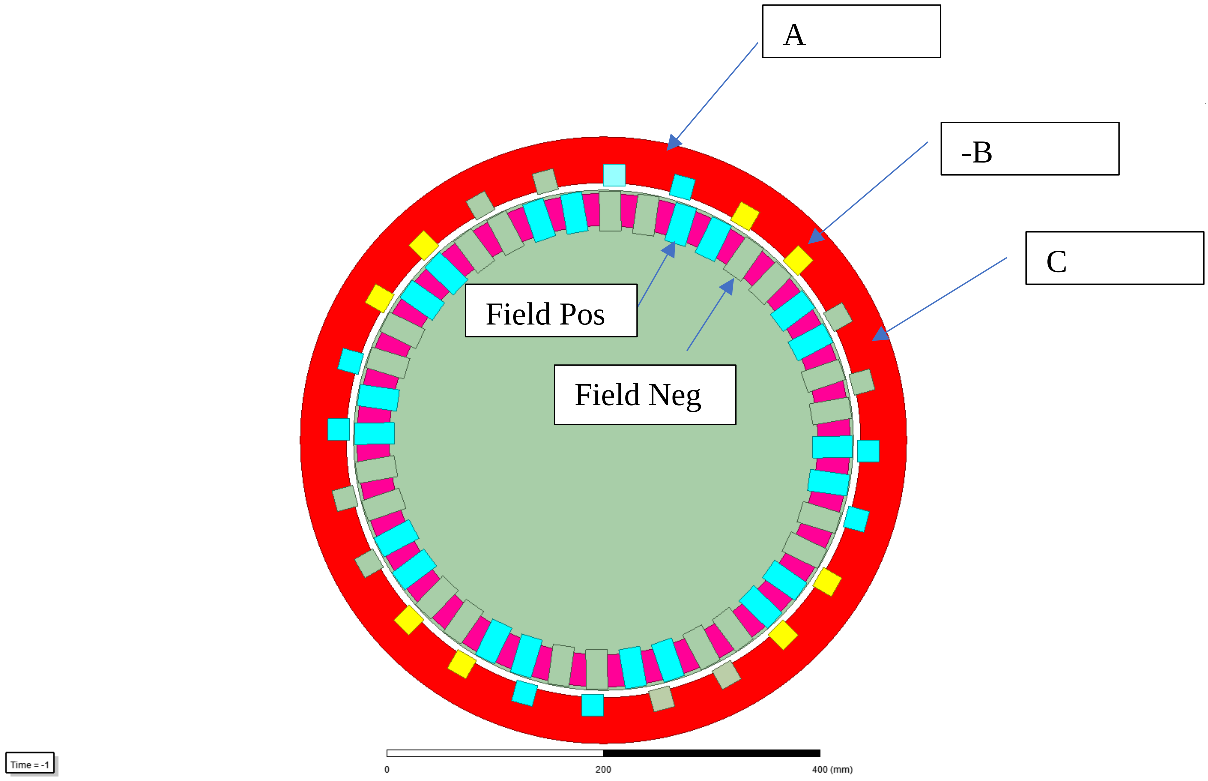

Figure 6   2D Drawing of Motor

- The airgap flux density is drawn by using a search coil and the rotor is rotated by rated speed. The flux density repeated for each 36 degree mechanical.

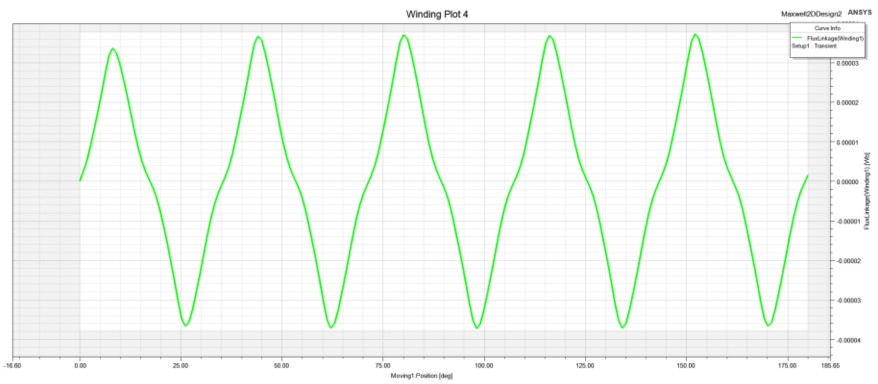

Figure 7 Distribution of Airgap Flux Density Maxwell Raw Plot

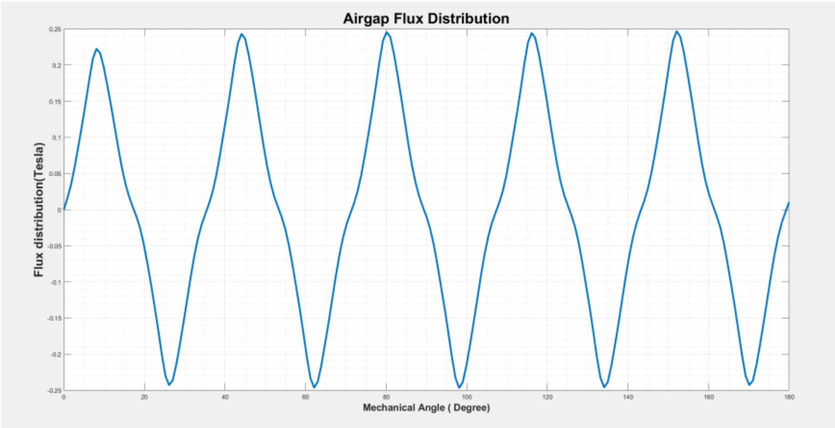

Figure 8 Distribution of Airgap Flux Density

- The phase voltages are disturbed sinusoidal waveform. It includes 3rd and 5th harmonics. The line voltage is more sinusoidal.

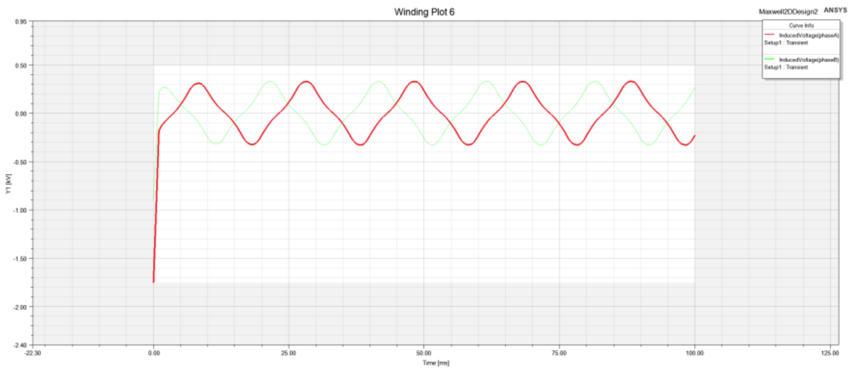

Figure 9 Phase A and Phase B Voltages Maxwell

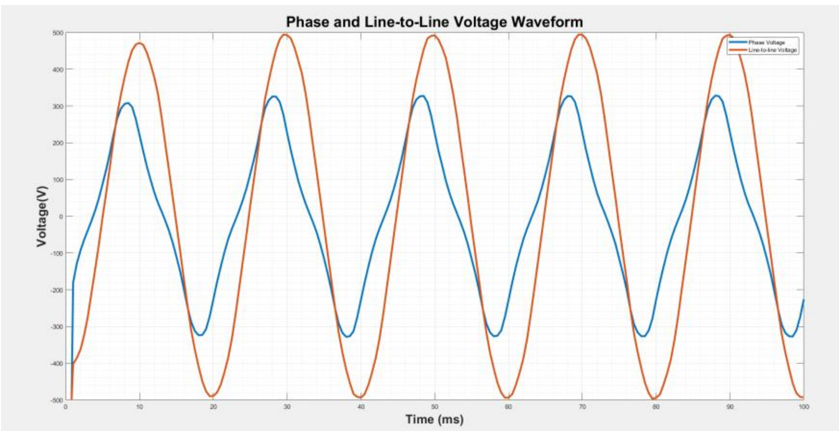

Figure 10 Phase and Line Voltages Matlab Plot

Conclusion

In this report, different motor winding designs are compared. Firstly, integral slot winding was investigated and we observed that winding factor is attenuated with increasing harmonics. Thus, fundamental induced voltage of coil is dominant. Secondly, different fractional slot winding designs were investigated. It was observed that the fractional slot windings decrease end windings for the same vectors of voltage phasors. Also, it was observed that fractional slot windings can be used to eliminate some harmonics. Finally, finite element analysis for motor design is made and the analytical calculation for a design is validated by finite element analysis.