MIDDLE EAST TECHNICAL UNIVERSITY
Electrical & Electronics Engineering

EE568-Selected Topics on Electrical Machines

Project 2

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1. Introduction

In this project, motor winding diagrams and their effects on characteristics of an electrical machines are analyzed. Starting with integral-slot winding design, the effect of the pitch angle and distribution factor to the machine is examined. Then, the fractional-slot winding design is performed and the effects of this design to induced voltages are investigated. 2 designs are compared with each other. Finally, a fractional-slot winding design is verified using the finite element analysis tool which is ANSYS Maxwell FEA tool.

2. Integral-Slot Winding Design

Properties of the electrical machine are as follows:

- 20 pole
- 120 slot
- 3 phase

a) Winding diagram

For this machine, a full-pitched winding is designed. The number of slots per pole per phase is calculated as 2 (120 slots/20 poles/3 phase). The machine is designed assuming double layer winding configuration. The winding diagram considering these properties is shown in Table 1.

Table 1.Integral-slot winding diagram

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

b) Distribution factor, pitch factor and winding factor calculation for fundamental component

To calculate distribution factor, pitch factor and winding factor, equations (1), (2) and (3) are used.

$$Distribution\ Factor: \quad k_d = \frac{\sin(h * \frac{q*\alpha}{2})}{q*\sin(h*\frac{\alpha}{2})} \tag{1}$$

$$Pitch\ Factor: \quad k_p = \sin(h * \frac{\lambda}{2}) \tag{2}$$

$$Winding\ Factor: \quad k_w = k_p * k_d \tag{3}$$

α: Electrical angle between two adjacent coils.

h: Harmonics number.

q: Number of coils (Number of slots per phase per pole)

λ: Coil-pitch in electrical degrees

As the machine is designed being full-pitched, pitch factor is 1. Also, q is found as 2 which is explained in part a. Electrical angle (α) is equal to 30˚ (360˚/12). Coil pitch (λ) is equal to 180˚. Using equations above, results are found using a calculator for fundamental component as follows;

$$k_d = 0.9659$$

$$k_p = 1$$

$$k_w = 0.9659$$

c) Parameters for 3rd and 5th harmonics

To calculate the same parameters for 3rd and 5th harmonics, we need to insert harmonics value to the equations (1), (2) and (3).

For 3rd harmonics;

$$k_d = 0.707$$

$$k_p = -1$$

$$k_w = -0.707$$

For 5th harmonics;

$$k_d = 0.259$$

$$k_p = 1$$

$$k_w = 0.259$$

As we include the harmonics, we can see that winding factors can be negative. Thus, this may affect our machine negatively as it would introduce negative voltages to the machine, and it is not a desired effect. Hence, winding can be designed short-pitched or over-pitched to eliminate 3rd harmonics which would increase the efficiency of the machine.

3. Fractional-Slot Winding Design

A 3-phase permanent magnet synchronous machine with a fractional-slot winding is analyzed. Emetor Winding Desing is used to choose pole and slot number. According to program, pole number is determined to be 20 and slot number is determined as 24 because choosing these variables accordingly would give the highest winding factor which is 0.966.

a) Phase angles of the induced voltage

q is calculated as 0.4 (24 slots/20 poles/3 phase). Electrical angle (α) is equal to 150˚ (360˚/(24/10)).

Slot number	1	2	3	4	5	6	7	8	9	10	11	12
Phase angle of 1st component	0	150	300	90	240	30	180	330	120	270	60	210
Phase angle of 3rd component	0	90	180	270	0	90	180	270	0	90	180	270
Phase angle of 5th component	0	30	60	90	120	150	180	210	240	270	300	330
Coil Distribution	A1	-A1	B1	-B1	C1	-C1	-A2	A2	-B2	B2	-C2	C2

Slot number	13	14	15	16	17	18	19	20	21	22	23	24
Phase angle of 1st component	0	150	300	90	240	30	180	330	120	270	60	210
Phase angle of 3rd component	0	90	180	270	0	90	180	270	0	90	180	270
Phase angle of 5th component	0	30	60	90	120	150	180	210	240	270	300	330
Coil Distribution	A3	-A3	B3	-B3	C3	-C3	-A4	A4	-B4	B4	-C4	C4

b) Pitch Factor, Distribution factor and winding factor for all components

Using equation (1), (2) and (3), distribution factor of all components are calculated as follows;

$$k_{d-1} = 1$$

$$k_{p-1} = 0.9659$$

$$k_{w-1} = 0.9659$$

$$k_{d-3} = 1$$

$$k_{p-3} = -0.707$$

$$k_{w-3} = -0.707$$

$$k_{d-5} = 1$$

$$k_{p-5} = 0.259$$

$$k_{w-5} = 0.259$$

In this machine, the winding factor of fundamental component is much higher than winding factor of the harmonics. Hence, the machine can work more efficient. Also, it should be noted that negative winding factors of harmonics may cause reverse speed in the machine which is not a desired characteristic.

c) Another motor with same pole with different slot number

I have chosen 20 pole, 30 slot, 3 phase machine in this case. q is calculated for this machine as 0.5 (30 slots/20 poles/3 phase). Electrical angle (α) is equal to 120˚ (360˚/ (30/10)).

Slot number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Phase angle of 1st component	0	120	240	0	120	240	0	120	240	0	120	240	0	120	240
Phase angle of 3rd component	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phase angle of 5th component	0	240	120	0	240	120	0	240	120	0	240	120	0	240	120
Coil Distribution	A1	-A1	B1	-B1	C1	-C1	-A2	A2	-B2	B2	-C2	C2	A3	-A3	B3

Slot number	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
Phase angle of 1st component	0	120	240	0	120	240	0	120	240	0	120	240	0	120	240
Phase angle of 3rd component	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Phase angle of 5th component	0	240	120	0	240	120	0	240	120	0	240	120	0	240	120
Coil Distribution	-B3	C3	-C3	-A4	A4	-B4	B4	-C4	C4	A5	-A5	C5	-C5	B5	-B5

Using equation (1), (2) and (3);

$$k_{d-1} = 1$$

$$k_{p-1} = 0.866$$

$$k_{w-1} = 0.866$$

$$k_{d-3} = 1$$

$$k_{p-3} = 0$$

$$k_{w-3} = 0$$

$$k_{d-5} = 1$$

$$k_{p-5} = -0.866$$

$$k_{w-5} = -0.866$$

With this design, 3rd harmonics are eliminated. Hence, system is said to be more efficient. However, the magnitude and direction of the voltages at 5th harmonics are quite large. Therefore, machine is not designed well.

Comparing two designs, first machine would be preferred as its winding factor is higher at the fundamental although it includes negative 3rd harmonics.

4. FEA Modelling (2D)

5. Conclusion

In this project, the analysis of different machines with different winding methods are performed. Firstly, integral-slot winding designed machines are investigated. Then, fractional-slot winding designed machines with different pole and slot numbers are examined and compared.. Later, FEA model would be planned to analyzed. However, it is left as unfinished work.