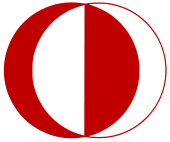
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**MIDDLE EAST TECHNICAL UNIVERSITY**

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:

distribution factor:

winding factor:

where is harmonics number, is coil span, is the number of slots per phase per pole, is the electrical angle between two adjacent slots. In our case, is 2, is 30° and 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 |

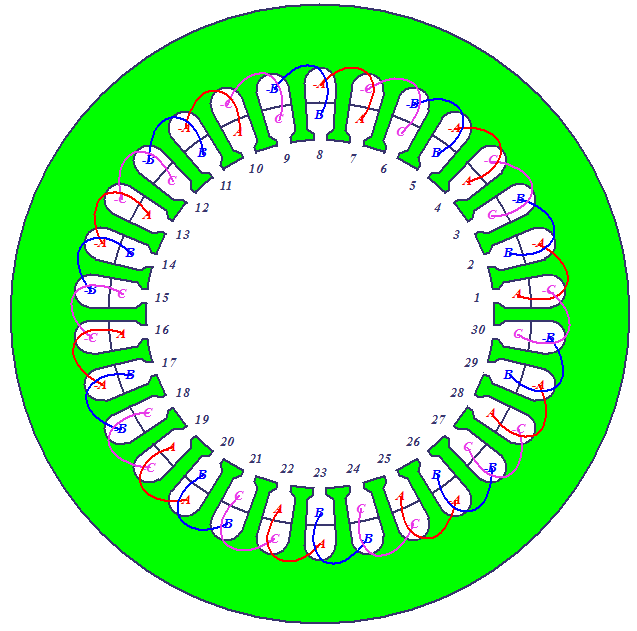


Figure 1: Winding diagram for the stator windings

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 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.

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

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

where is the coil span and 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.

|  |  |  |  |
| --- | --- | --- | --- |
|  | **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 |

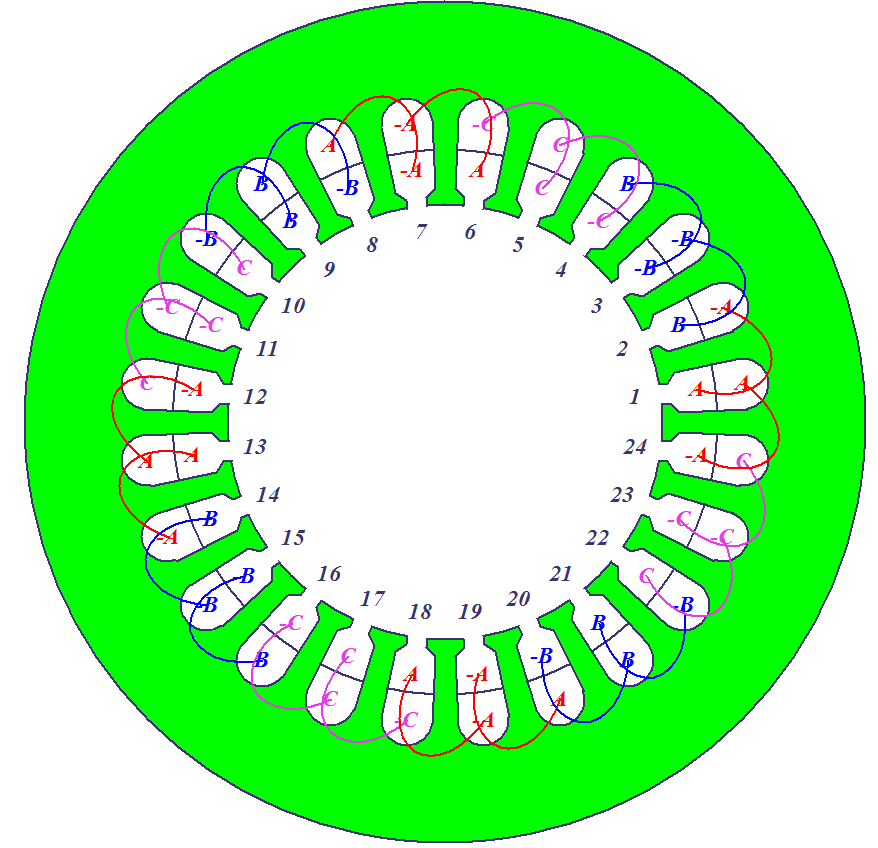


Figure 5: Winding diagram for the stator windings

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | 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

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.



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

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

|  |  |  |  |
| --- | --- | --- | --- |
|  | **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 |

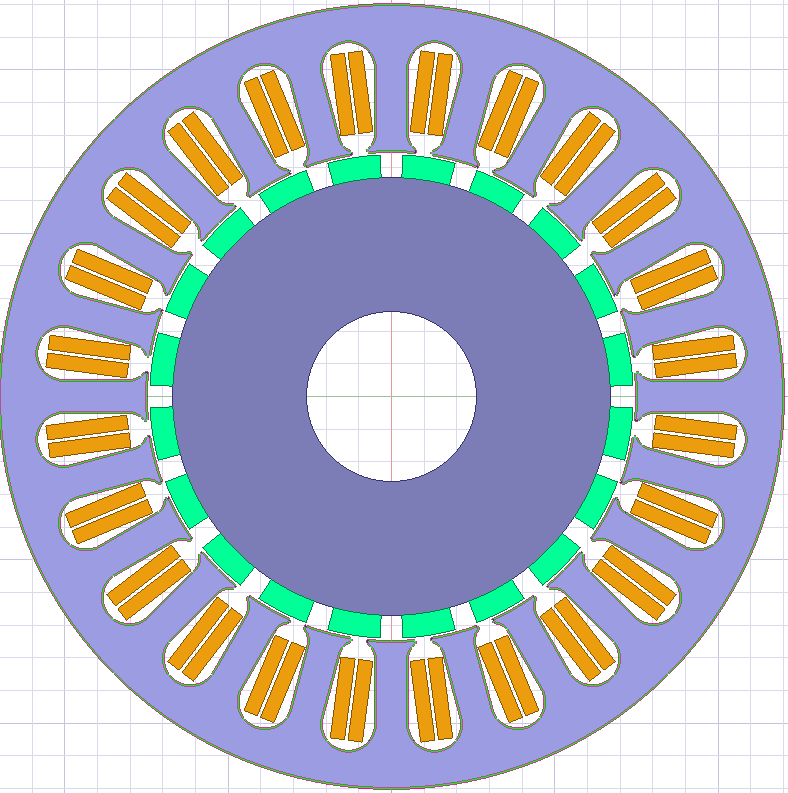


Figure 10: 20-pole 24-slot reference design

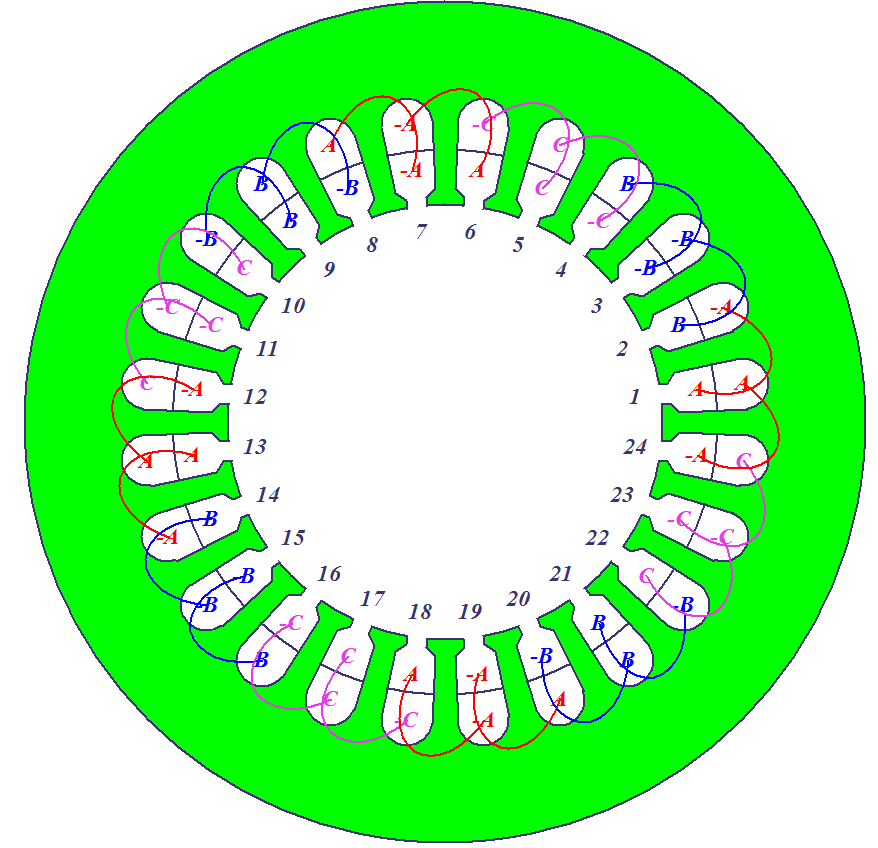


Figure 11: Winding diagram for 20-pole 24-slot machine



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.



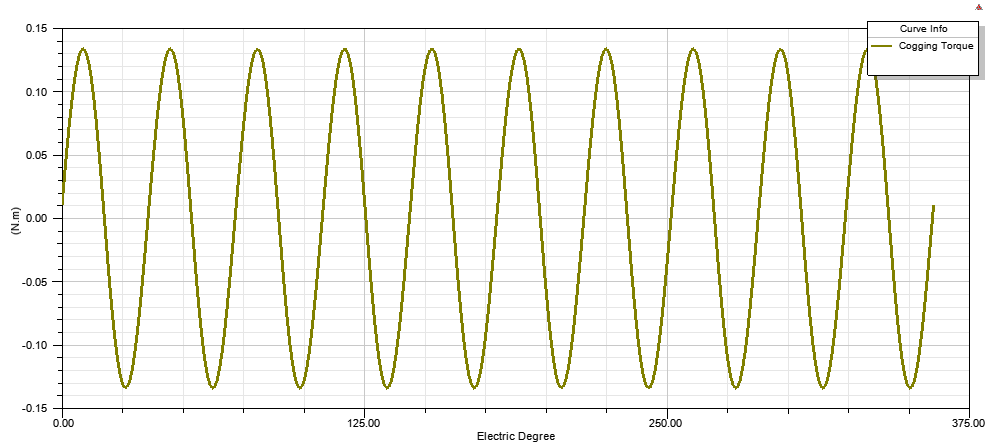


Figure 12: Cogging torque

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.

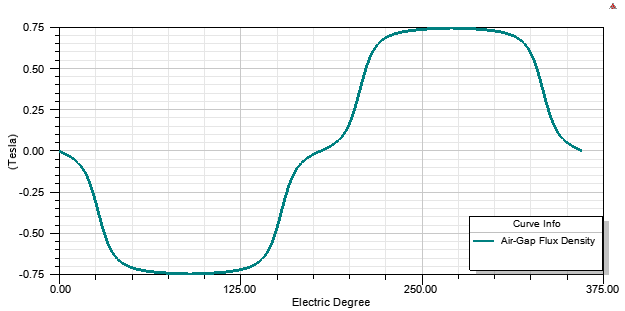


Figure 13: Air gap flux density

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.

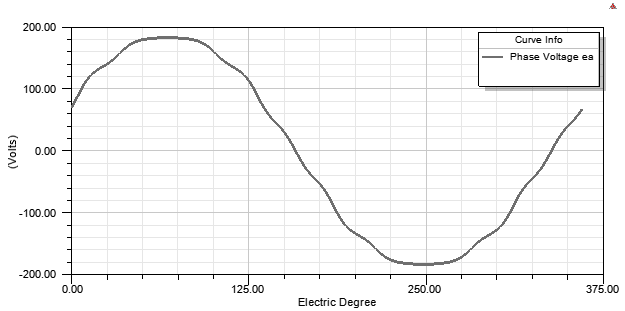


Figure 14: Induced phase voltage at rated speed