

**EE568 – Selected Topics on Electrical Machines**

Project #2: Motor Winding Design & Analysis

by

Hakan Saraç - 2408086

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# Introduction

In this homework, the winding diagrams for electrical machines will be investigated. The effect of pitch factor and distribution factor to the voltages induced is analyzed and studied. In the end, the aim was to prove the analytical results on the using a FEA tool, which was not successful for my case.

# Question 1: Integral-Slot Winding Design

## Winding Diagram (Full Pitched)

The stator consists of 72 slots, 6 poles and 3 phases. This configuration results in a q value of 4, which states number of slots per pole per phase.

(1)

This slot and pole value results in an electrical angle of 30° degrees between each slot, whose derivation is given in (2).

(2)

Table : Coil Distribution for full pitched coil design for full pitched winding

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Slot Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Electrical Angle** | 0° | 15° | 30° | 45° | 60° | 75° | 90° | 105° | 120° | 135° | 150° | 165° |
| **Coil distribution** | A | A | A | A | -C | -C | -C | -C | B | B | B | B |
| **Slot Number** | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| **Electrical Angle** | 180° | 195° | 210° | 225° | 240° | 255° | 270° | 285° | 300° | 315° | 330° | 345° |
| **Coil distribution** | -A | -A | -A | -A | C | C | C | C | -B | -B | -B | -B |

## Distribution factor, Pitch factor, Winding factor calculation for full pitched winding

The results of distribution factor, pitch factor and winding factor are provided in (3), (4) & (5) respectively for the fundamental frequency.

(3)

(4)

(5)

The results of distribution factor, pitch factor and winding factor are provided in (6), (7) & (8) respectively for the 3rd, (9), (10), (11) for the 5th harmonic.

(6)

(7)

(8)

(9)

(10)

(11)

Table : Winding Factor of the 72 Slot 6 Pole Full Pitched Machine

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 1st | 3rd | 5th | |
| kp | 1 | -1 | 1 | |
| kd | 0.9577 | 0.6533 | 0.2053 | |
| kw | 0.9577 | -0.6533 | 0.2053 |

## Winding Diagram (11/12 Pitched)

The distribution factor is not affected due the reduced pitch, only the pitch factor is affected. The values of distribution and pitch factors are provided below.

(12)

(13)

(1)

Table 3 : Winding Factor of the 72 Slot 6 Pole 11/12 Pitched Machine

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | 1st | 3rd | 5th | |
| kp | 0.99 | -0.924 | 0.793 | |
| kd | 0.9577 | 0.6533 | 0.2053 | |
| kw | 0.94951 | -0.60357 | 0.163 |

Table : Coil Distribution for full pitched coil design for full pitched winding

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Slot Number** | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| **Electrical Angle** | 0° | 15° | 30° | 45° | 60° | 75° | 90° | 105° | 120° | 135° | 150° | 165° |
| **Coil distribution** | A | A | A | A | -C | -C | -C | -C | B | B | B | B |
| -B | A | A | A | A | -C | -C | -C | -C | B | B | B |
| **Slot Number** | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| **Electrical Angle** | 180° | 195° | 210° | 225° | 240° | 255° | 270° | 285° | 300° | 315° | 330° | 345° |
| **Coil distribution** | -A | -A | -A | -A | C | C | C | C | -B | -B | -B | -B |
| B | -A | -A | -A | -A | C | C | C | C | -B | -B | -B |

## Comments

For the full pitched configuration, the winding factors are provided 0.9577, -0.6533, 0.2053 for first, third and fifth harmonic respectively. Looking at these winding factor values, the third harmonic component not only considerably high, but also reverse in direction due to the negative sign. This can induce third harmonic voltages in the phases. Even though the third harmonic component will not appear in the line-to-line voltage, it will still cause an additional core loss & eddy and torque ripple in the machine.

With 11/12 pitching, the overall loss in the winding factor for the fundamental changes less than 1%. Even though the winding factor for the other harmonics are reduced, they are still considerably high.

# Question 2: Fractional-Slot Winding Design

## Calculations for Machine 1:24 slots 20 poles

In this part, I have chosen a machine which has 24 slots, 20 poles and 3 phases. From [Emetor Winding Design [2]](https://www.emetor.com/windings/) tool, it can be seen that this configuration results in a winding factor of 0.966.

(12)

(13)

Table : Winding Distribution of the 24 Slots 20 Pole Fractional Slot Machine

|  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Slot Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
| Fundamental Angle (Normalized) | 0° | 150° | 300° | 90° | 240° | 30° | 180° | 330° | 120° | 270° | 60° | 210° |
| Third Harmonic Angle (Normalized) | 0° | 90° | 180° | 270° | 0° | 90° | 180° | 270° | 0° | 90° | 180° | 270° |
| Fifth Harmonic Angle (Normalized) | 0° | 30° | 60° | 90° | 120° | 150° | 180° | 210° | 240° | 270° | 300° | 330° |
| Coil distribution | A1 | C1 | -C1 | -B1 | B1 | A3 | -A3 | -C3 | C3 | B3 | -B3 | -A2 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |
| Slot Number | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| Electrical Angle (Normalized) | 0° | 150° | 300° | 90° | 240° | 30° | 180° | 330° | 120° | 270° | 60° | 210° |
| Third Harmonic Angle (Normalized) | 0° | 90° | 180° | 270° | 0° | 90° | 120° | 270° | 0° | 90° | 180° | 270° |
| Fifth Harmonic Angle (Normalized) | 0° | 30° | 60° | 90° | 120° | 150° | 180° | 210° | 240° | 270° | 300° | 330° |
| Coil distribution | A2 | C2 | -C2 | -B2 | B2 | A4 | -A4 | -C4 | C4 | B4 | -B4 | -A1 |

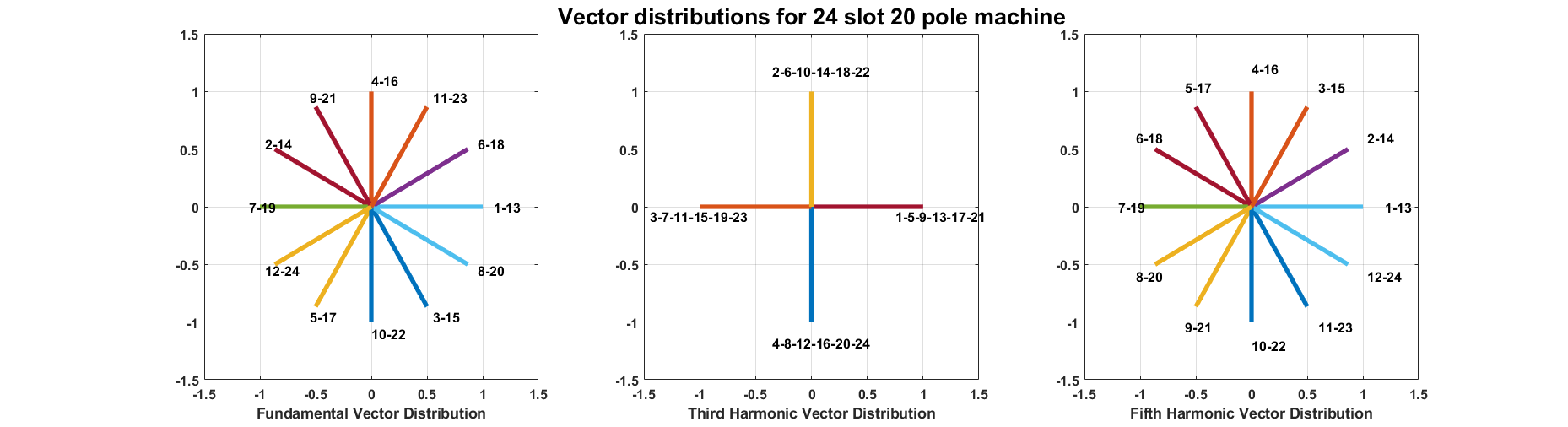


Figure : Voltage Vectors of the 24 Slots 20 Pole Fractional Slot Machine

(14)

\* (15)

(16)

(17)

\* (18)

(19)

(20)

\* (21)

(22)

*\*Distribution factor calculations are taken from the formulas 4,5,6,7 of [1].*

Table : Winding factor of the 24 Slot 20 Pole Machine

|  |  |  |  |
| --- | --- | --- | --- |
|  | 1st | 3rd | 5th |
| kp | 0.966 | -0.707 | 0.2588 |
| kd | 1 | 1 | 1 |
| kw | 0.966 | -0.707 | 0.2588 |

## Calculations for Machine 2:30 slots 20 poles

The pole number kept constant and number of slots is changed to 30 from 24. The resultant winding factors and winding diagrams are provided.

(23)

(24)

Table : Winding Distribution of the 30 Slots 20 Pole Fractional Slot Machine

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Slot Number | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 |
| Fundamental Angle (Normalized) | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° |
| Third Harmonic Angle (Normalized) | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° |
| Fifth Harmonic Angle (Normalized) | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° |
| Coil distribution | A1 | -A1 | C1 | -C1 | B1 | -B1 | A2 | -A2 | C2 | -C2 | B2 | -B2 | A3 | -A3 | C3 |
|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| Slot Number | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | 25 | 26 | 27 | 28 | 29 | 30 |
| Fundamental Angle (Normalized) | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° | 0° | 120° | 240° |
| Third Harmonic Angle (Normalized) | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° | 0° |
| Fifth Harmonic Angle (Normalized) | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° | 0° | 240° | 120° |
| Coil distribution | -C3 | B3 | -B3 | A4 | -A4 | C4 | -C4 | B4 | -B4 | A5 | -A5 | C5 | -C5 | B5 | -B5 |

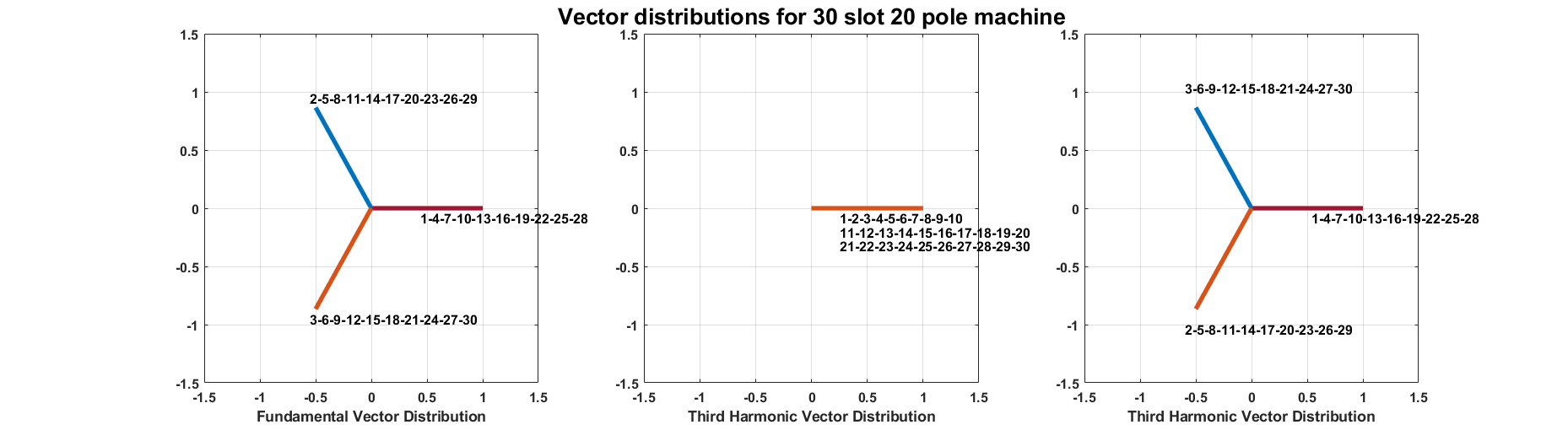


Figure : Voltage Vectors of the 30 Slots 20 Pole Fractional Slot Machine

(25)

\* (26)

(27)

(28)

\* (29)

(30)

(31)

\* (32)

(33)

*\*Distribution factor calculations are taken from the formulas 4,5,6,7 of [1].*

Table : Winding factor of the 30 Slot 20 Pole Machine

|  |  |  |  |
| --- | --- | --- | --- |
|  | 1st | 3rd | 5th |
| kp | 0.866 | 0 | -0.866 |
| kd | 1 | 1 | 1 |
| kw | 0.866 | 0 | -0.866 |

## Comments

Properties of Machine 1 has resulted in a winding distribution as shown in Table 5. The winding factor coefficient of the third and fifth harmonic is noticeably high, meaning that the machine 1 will have high harmonics in its airgap MMF waveform. From Figure 1, the voltage vectors for third component are distributed on 0°,90°,180°,270° degrees. Due to the machine winding configuration, the third harmonic component vectors will have an angle of either 45° or 225° degrees, stating that the third harmonic component will have a nonzero comparable coefficient. This is proven by the winding factor coefficients provided in Table 6. The fifth harmonic component for machine 1 has a similar voltage vector distribution when compared to the fundamental component. However, since the angles of the voltages are different, the fifth harmonic component will exist, but its magnitude will be relatively low.

Properties of Machine 2 has led to a winding distribution show in Table 7. All the voltage vectors are provided in Figure 2. For the fundamental component, the resultant voltage vectors will have an angle of 330°, 210° or 90°. All the third harmonic component voltage vectors have 0° angles, meaning that independent of the winding configuration, there will be no third harmonic component on the airgap MMF. This can also be seen in Table 8; the winding factor coefficient of the third harmonic is zero. The voltage vector distribution of fifth harmonic is the reverse of the fundamental. This causes a negative fifth harmonic in the airgap MMF, it will rotate in the reverse direction. Including the large winding factor for fifth component, negative fifth component will probably result in undesirable, such as torque ripple, losses etc.

# Question 3: 2D FEA Modelling

Following machine model is constructed for 24 slot 20 pole machine The winding distribution is provided in Table 5. The sizes of machine is taken from [3]. In [3], an IPM machine parameters were provided, I tried to convert those parameters to a SMPMSM. The resultant machine, provided in Figure 3, is quite open for optimization.

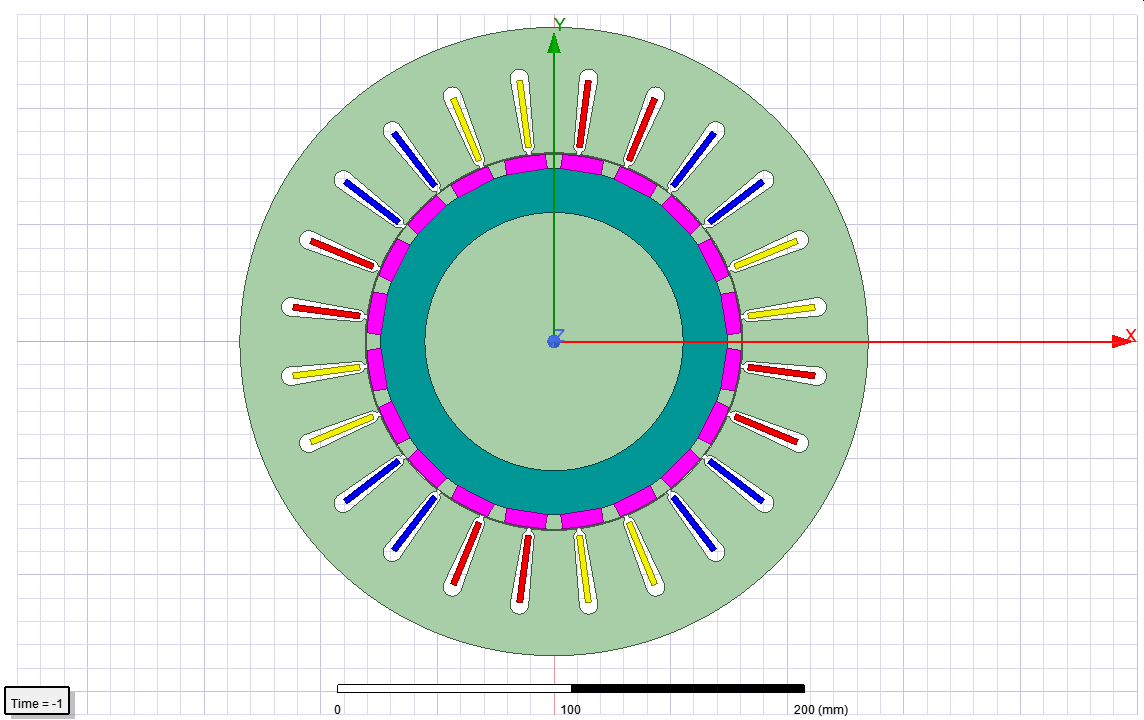


Figure : FEA Model of the Machine

With no excitation and 500rpm rotation, induced phase voltages are provided in Figure 4, phase to phase voltages are provided in Figure 5.

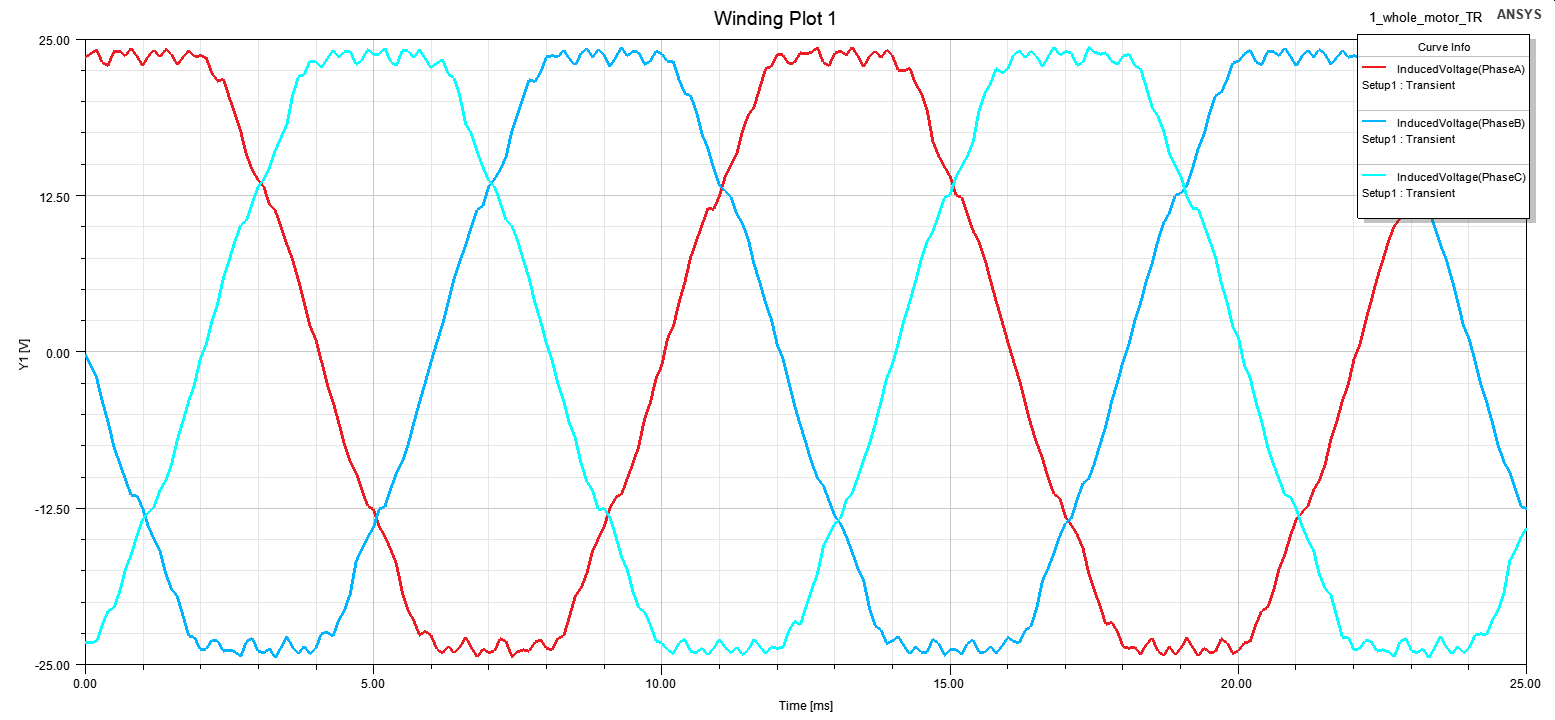


Figure : Induced Phase Voltages

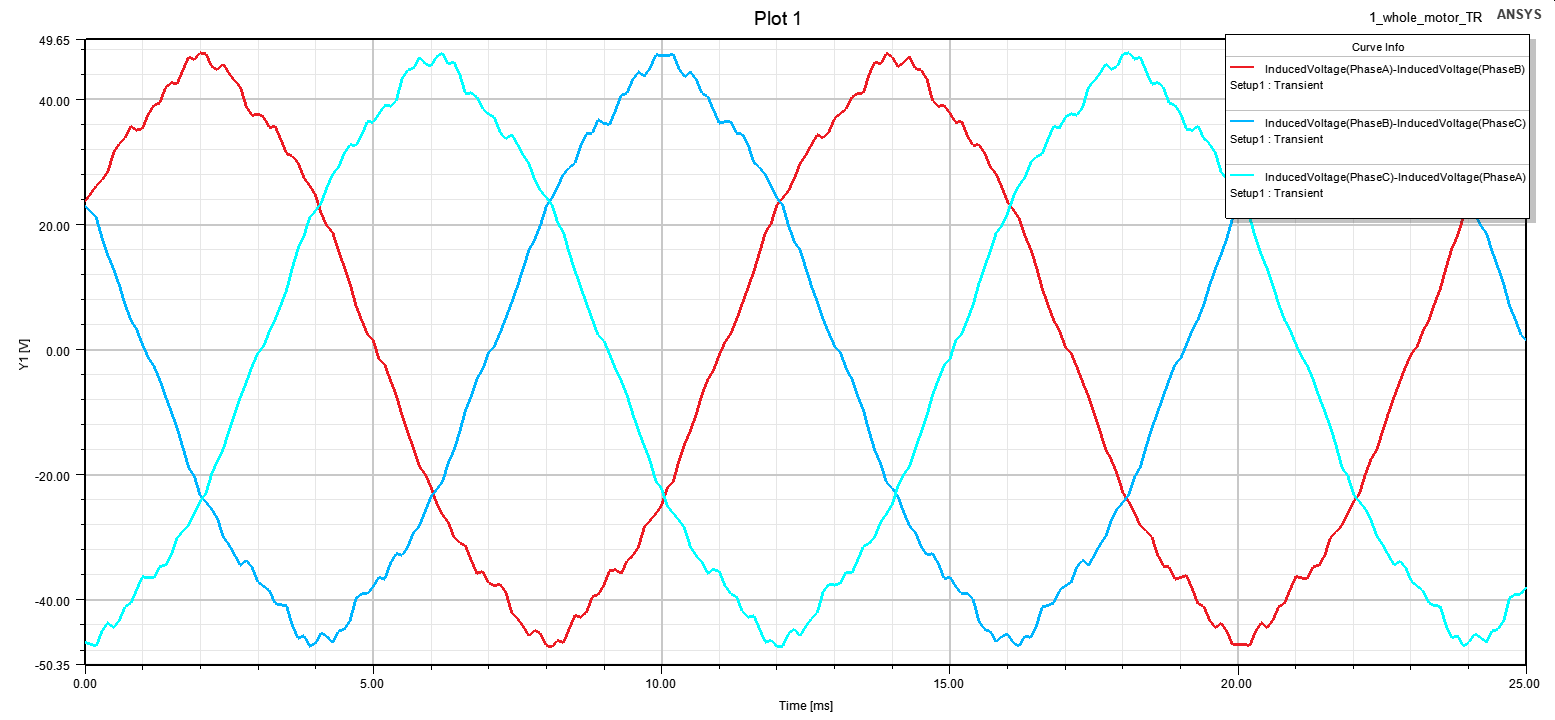


Figure : Induced Phase to Phase Voltages

Table : Harmonic components of back emf voltages

|  |  |  |  |
| --- | --- | --- | --- |
|  | 1st component | 3rd component | 5th component |
| Phase | 0.866 | 1.628 | 0.462 |
| Phase to Phase | 44.07 | 1.22 | 1.25 |

Flux density distribution at time 1.85ms is provided in Figure 6.

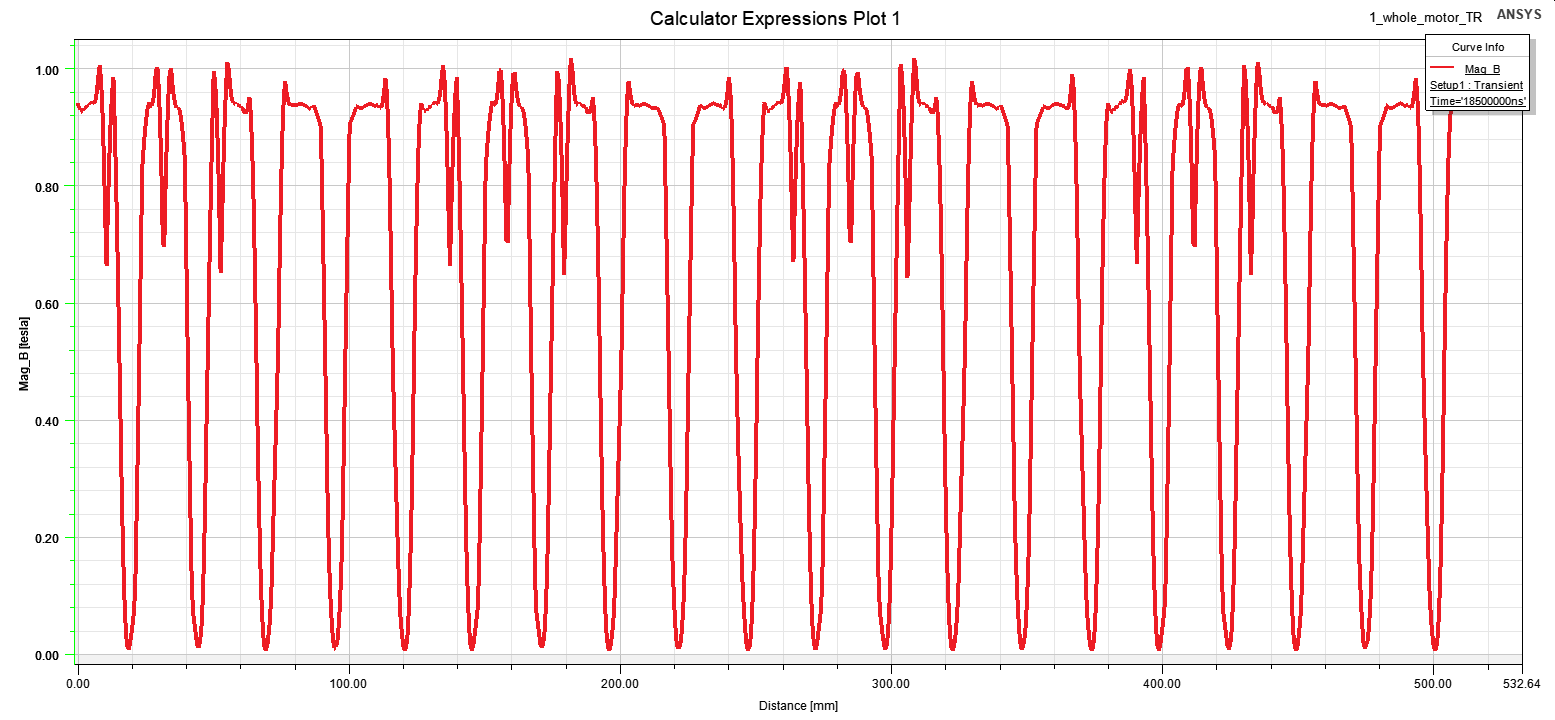


Figure : Flux Density Magnitude Distribution at t=18.5ms

# References

[1] - Li, G. J., Ren, B., & Zhu, Z. Q. (2017). Design guidelines for fractional slot multi-phase modular permanent magnet machines. *IET Electric Power Applications*, *11*(6), 1023–1031. https://doi.org/10.1049/iet-epa.2016.0616

[2] - <https://www.emetor.com/windings/>

[3] - Study of a Permanent Magnet Motor with MAXWELL 2D: Example of the 2004 Prius IPM Motor - ANSYS