

MIDDLE EAST TECHNICAL UNIVERSITY

Electrical and Electronics Engineering Department

EE568 Selected Topics on Electrical Machines

PROJECT 3

PM MOTOR COMPARISON ANALYSIS

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# Introduction

In this report surface-mount permanent magnet (SMPM) machines will be investigated. First section, magnetic loading of given SMPM machine will be analyzed analytically and the results are validated by FEA tool. Second section, we design of the stator side of this machine and we will calculate electrical loading analytically and magnetic stress from tangential part of the magnetic field. In addition, the output power will be calculated for rotor speed of 1500 rpm. Third section, we design a PMSM with rectangular slot-tooth with a 160mm outer diameter. Slot ratio and rotor diameter is estimated for maximum torque and electrical and magnetic loading will be calculated. The results are compared with section 1 and 2 design by using FEA. After design, the magnet NdFeB is replaced by Ferrite magnets and machine with same parameters will be investigated. In addition, the machine will be optimized and compared with previous design.

# Magnetic Loading

In this section, we analyzed the PMSM with constant parameters in table 1.

Table 1 Parameter of the SMPM machine

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1. Magnetic equivalent circuit for one pole-pair includes the flux sources and reluctances which are belongs to magnets, airgap, stator and rotor material and leakage. The equivalent circuit is shown figure 1 and we can simplify the circuit as figure 2.

|  |  |
| --- | --- |
| Figure 1 The equivalent circuit for one pole-pair | Figure 2 The simplified circuit for one pole-pair |

The magnetic circuit can be solved in two ways. One of them is load-line method. The characteristic of the magnet and airgap are drawn in B-H coordinate system. The load line method is shown in figure 3.

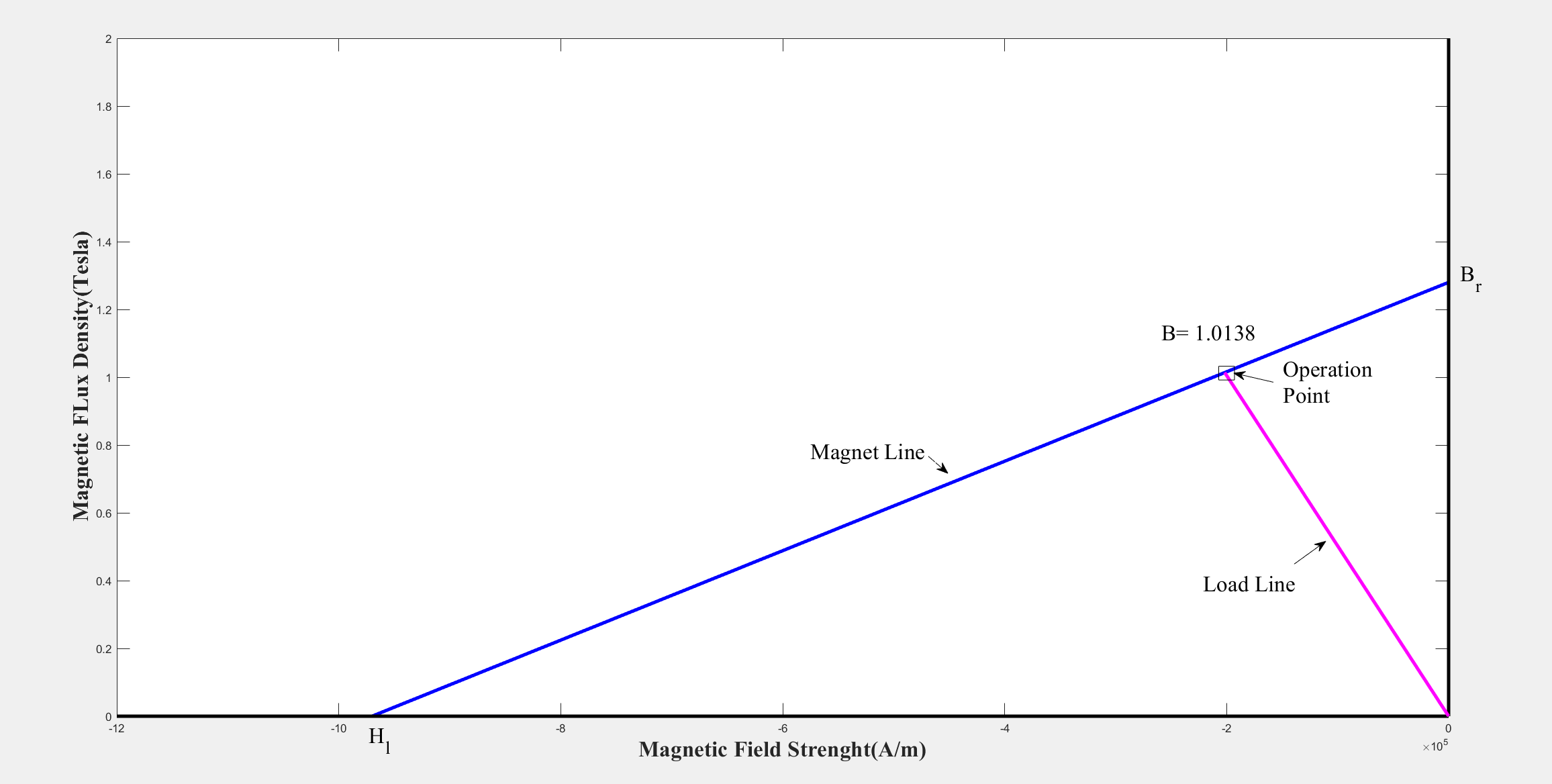


Figure 3 Load-line Method

Also, we can solve the problem with analytically. In figure 2 , we MMF is found with respect to magnet parameters. In addition, the is also written in the kind of .

We can calculated operation point of magnetic field density in the kind of remanence magnetic field of magnets, magnet length, airgap length and relative permeability of the magnet. We solved the equation and we find that :

1. Magnetic loading is the total flux in the airgap of a machine. We know that magnet to pole pitch ratio is 0.8 and the total pole area is calculated as :

Then we know that flux density at airgap is 1.0138 T. Then magnetic loading is :

1. The airgap flux density is found by using Maxwell 2D model shown in figure 4.

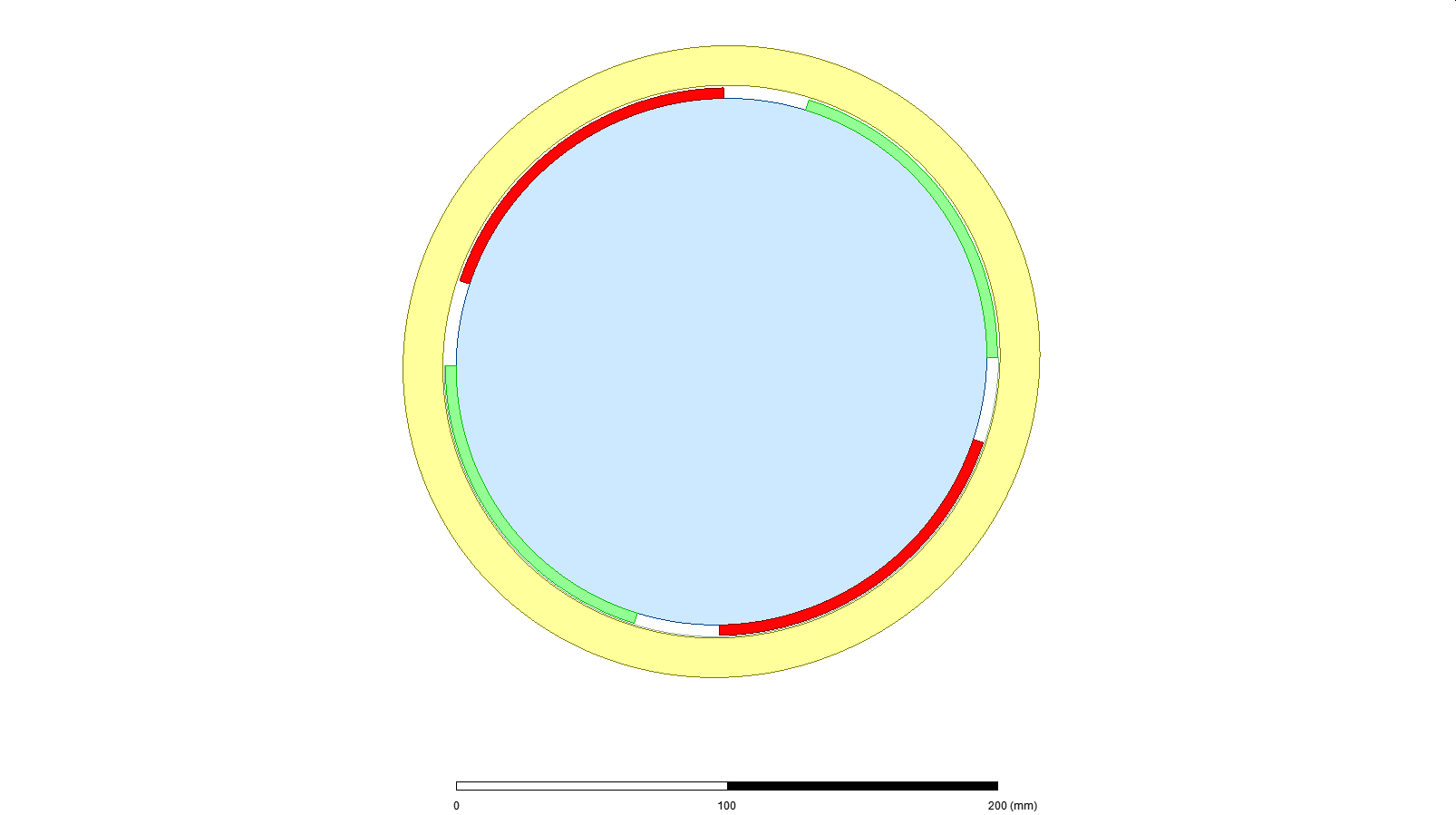


Figure 4 4-pole PMSM machine with solid stator

(Red: North Poles, Green: South Poles, Yellow: Stator, Blue: Rotor )

The airgap flux density is calculated mid-point airgap. The flux density from FEA distribution are shown at figure 5 and also the data points are drawn by matlab at figure 6.

|  |
| --- |
| Figure 5 Airgap Flux Distribution from FEA plot |
| Figure 6 Airgap Flux Distribution from matlab plot | |

The FEA results show that at airgap. The difference between analytical and FEA is . FEA result is smaller than analytical result. The stator and rotor permeability are taken as infinite and leakage flux is ignored at analytical calculation. The differences are stem from these assumptions.

# 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](https://www.emetor.com/windings/). 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=

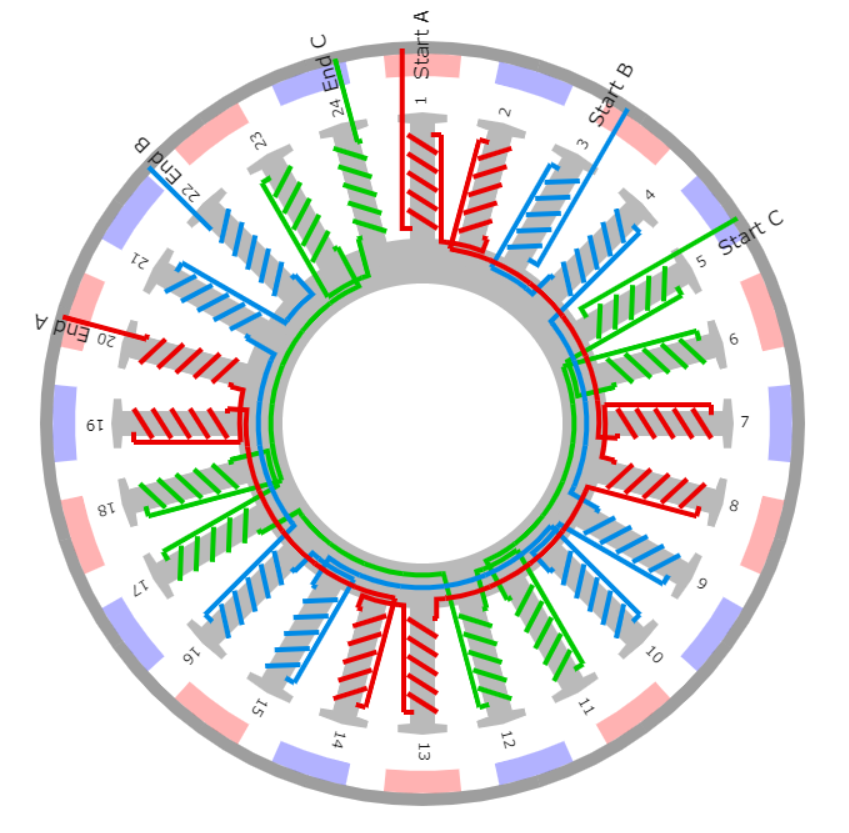


Figure 7 Fractional Slot Machine (24 Slot 20 Pole)

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

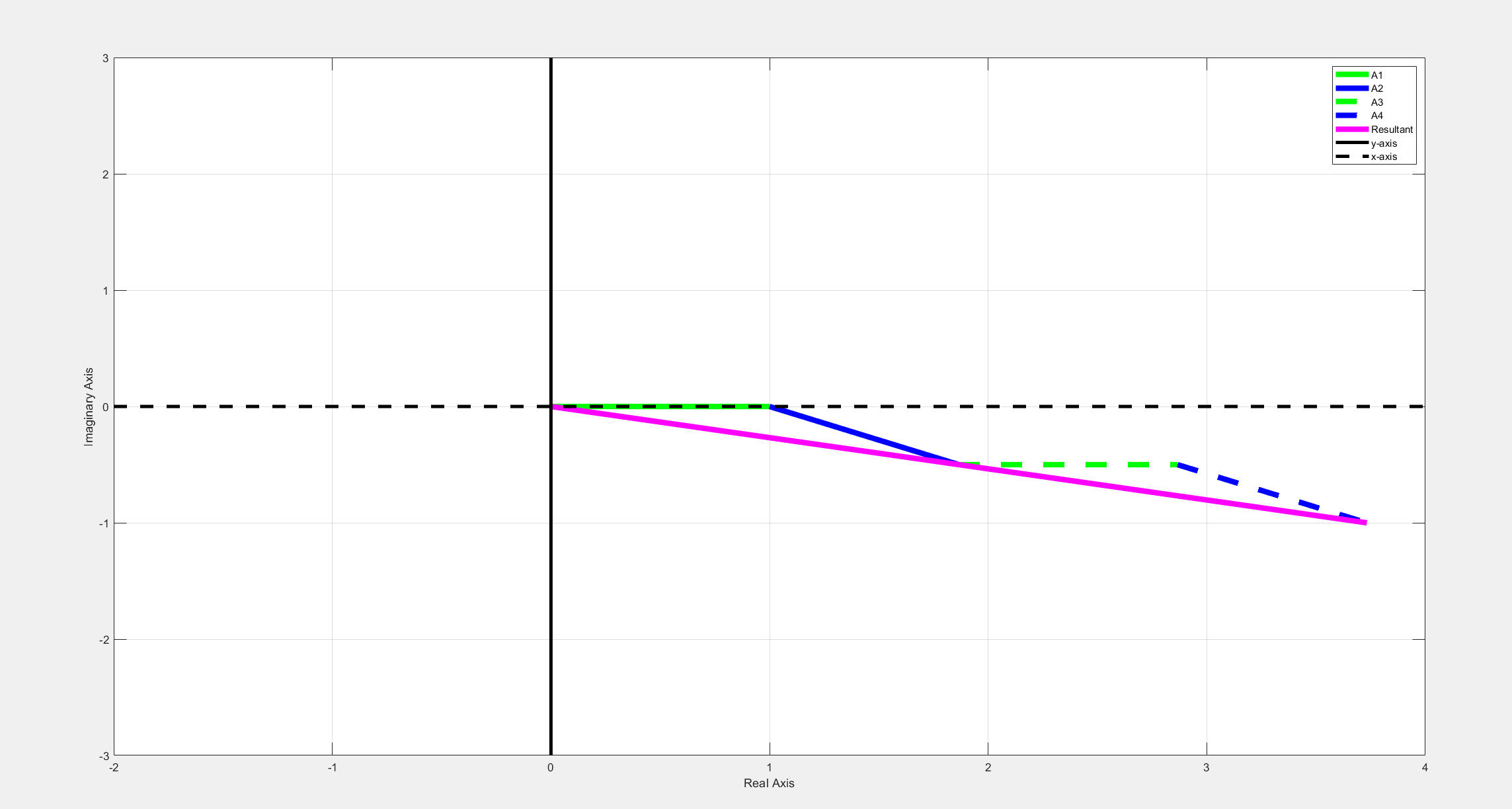


Figure 8 Phasor Diagram of phase A Voltages

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.

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

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

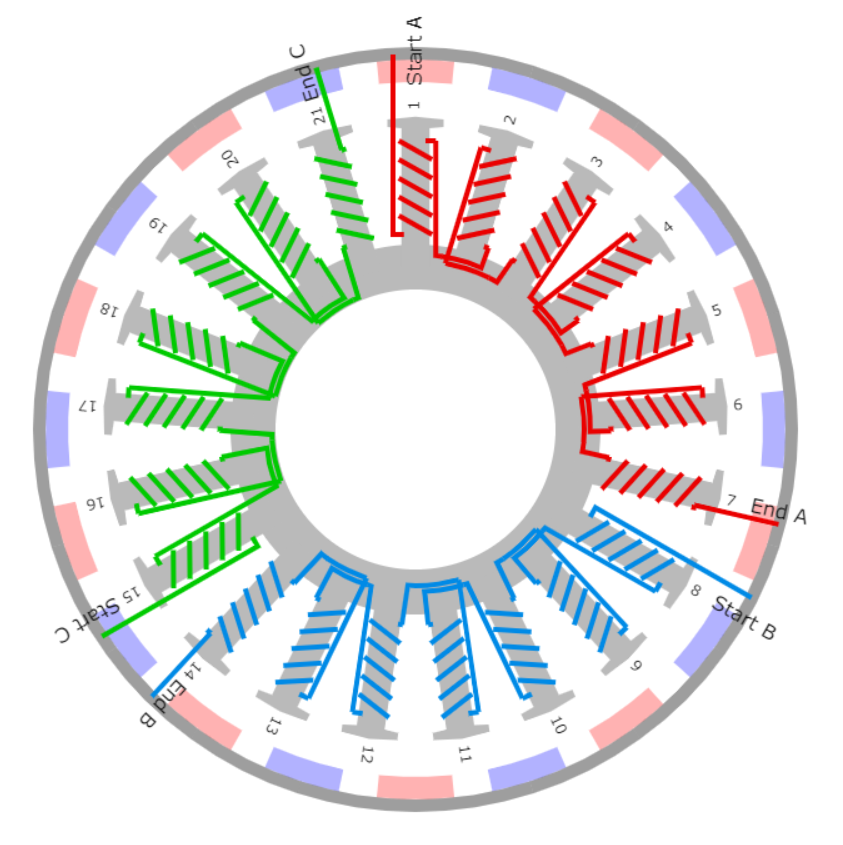


Figure 9 Fractional Slot Machine (21 Slot 20 Pole)

* 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 |

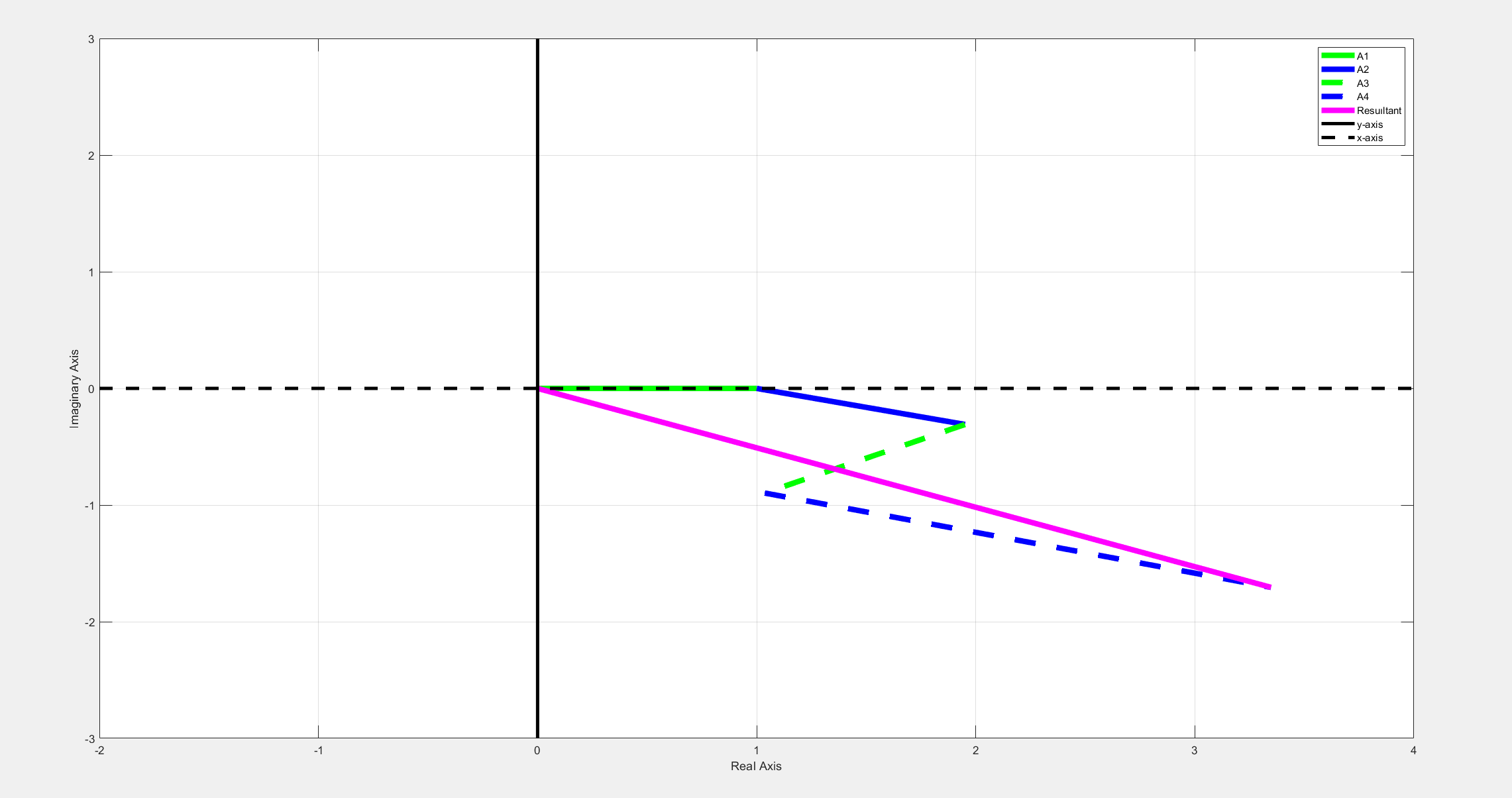


Figure 10 Phasor Diagram of phase A Voltages

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.

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

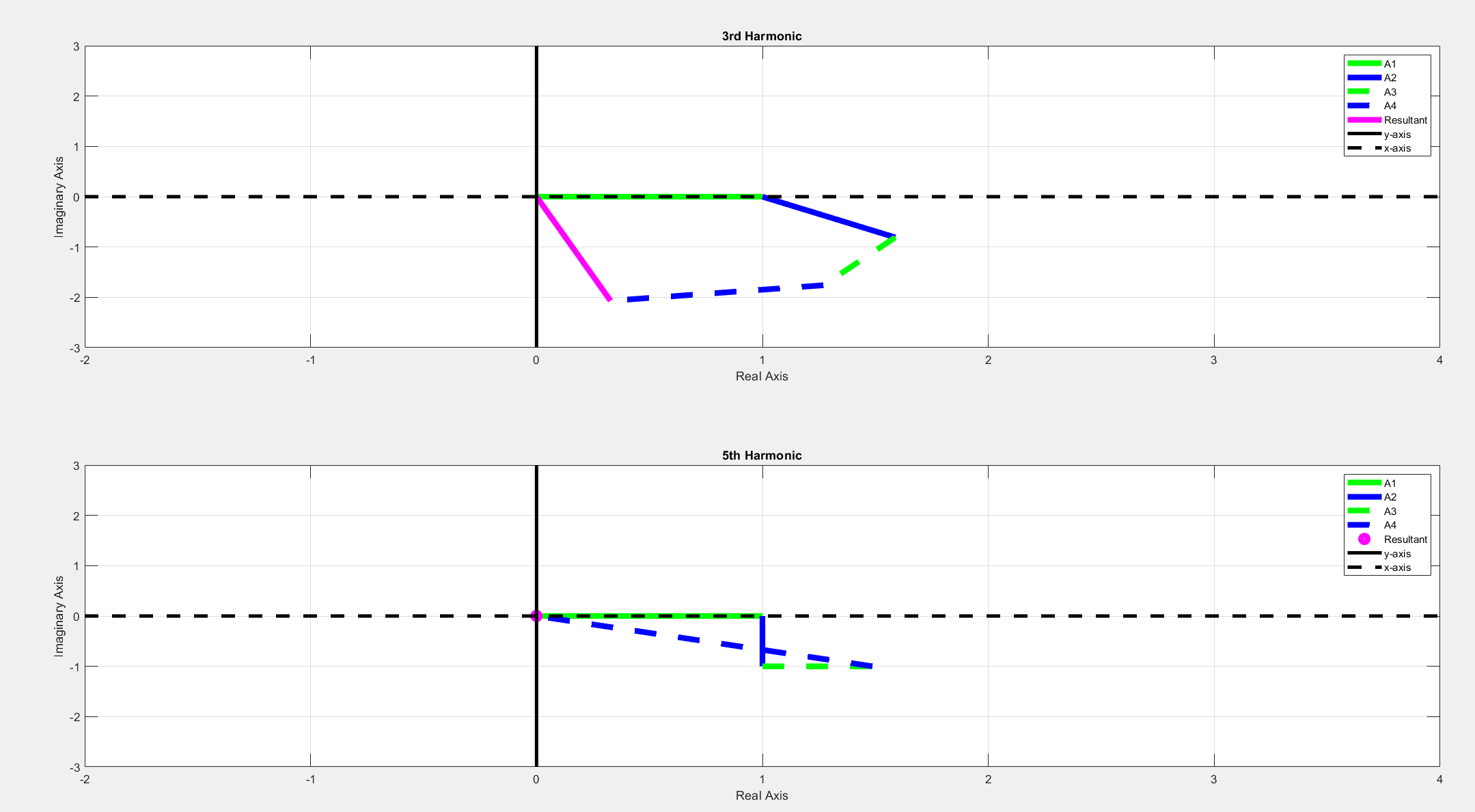
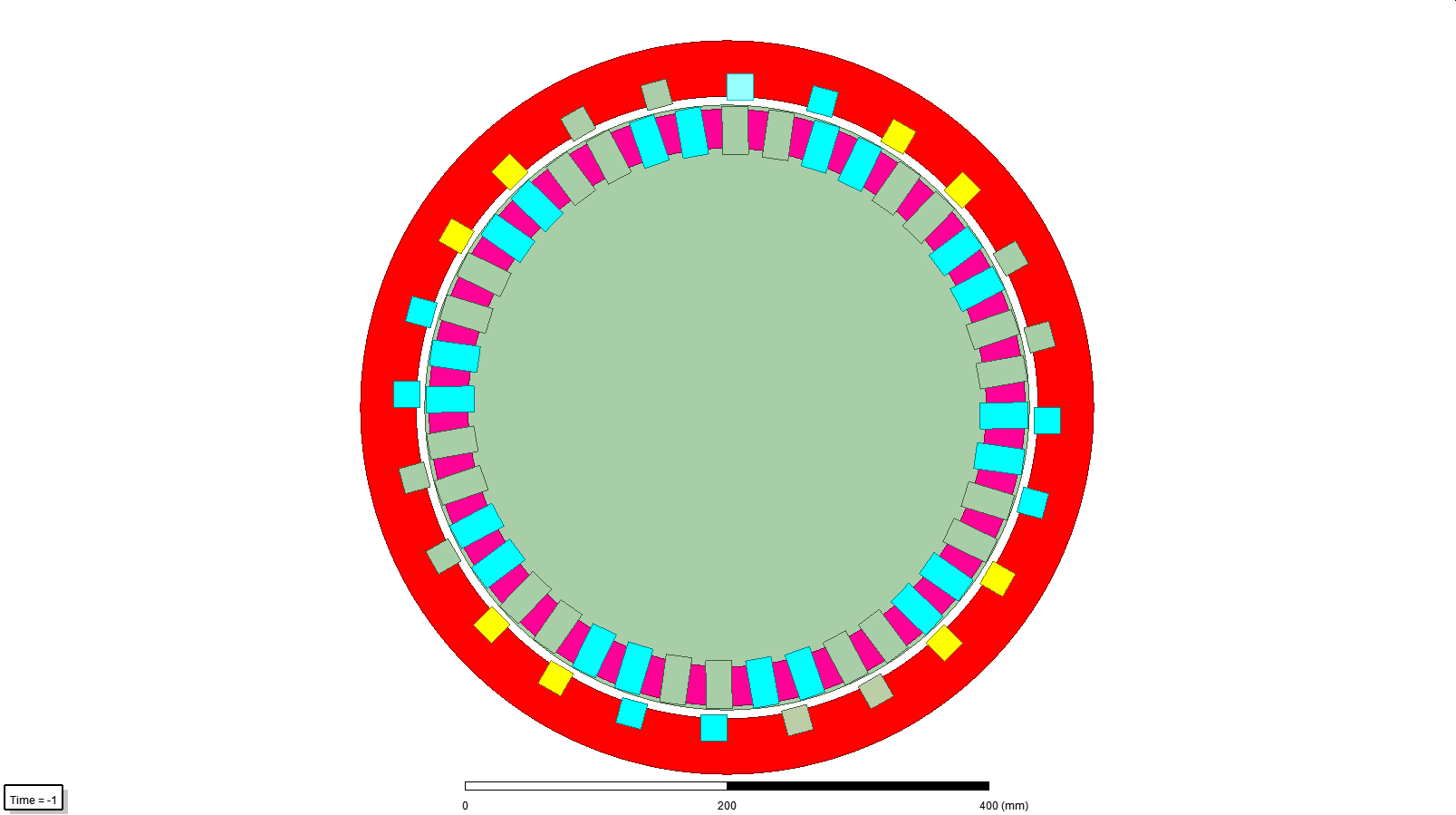


Figure 11 Phasor Diagram of phase A Voltages for 3rd and 5th harmonics

# 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.

A



Field Neg

Field Pos

spPos

C

-B

Figure 12 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.

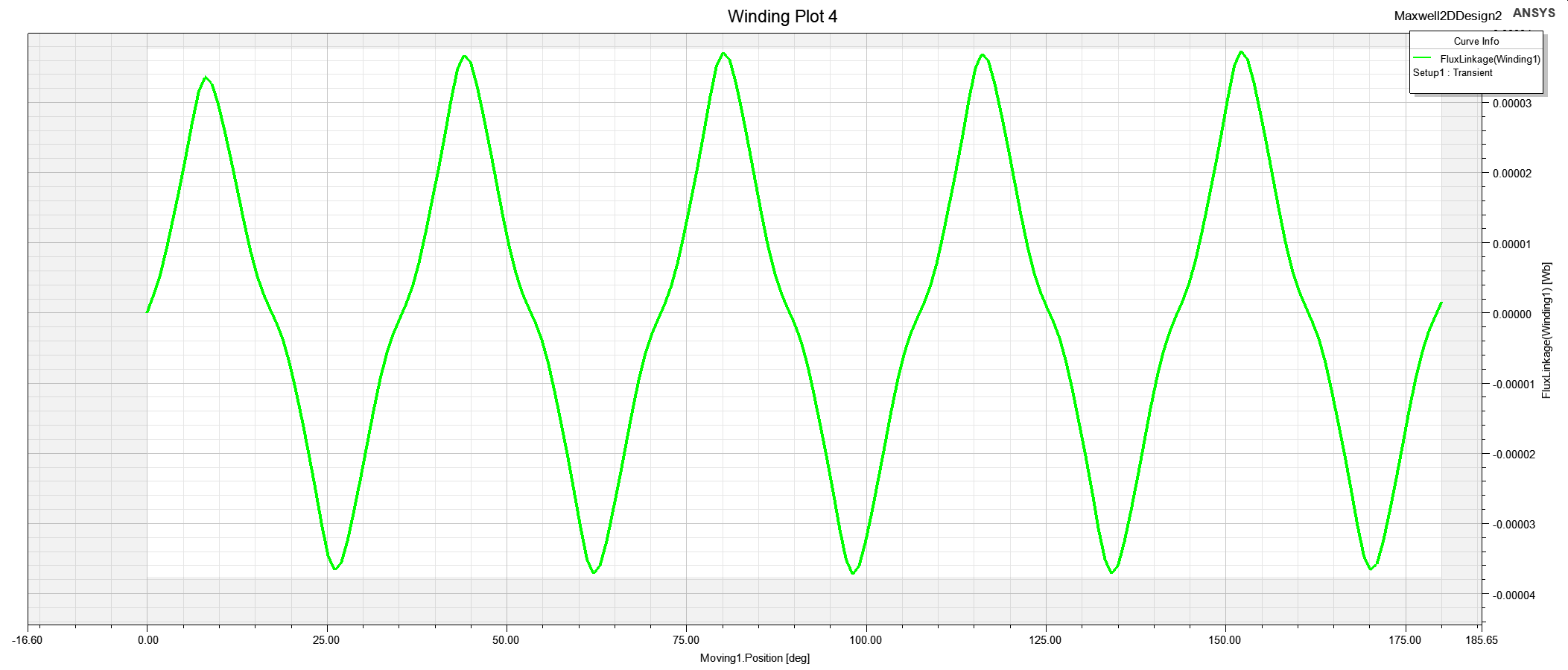


Figure 13 Distribution of Airgap Flux Density Maxwell Raw Plot

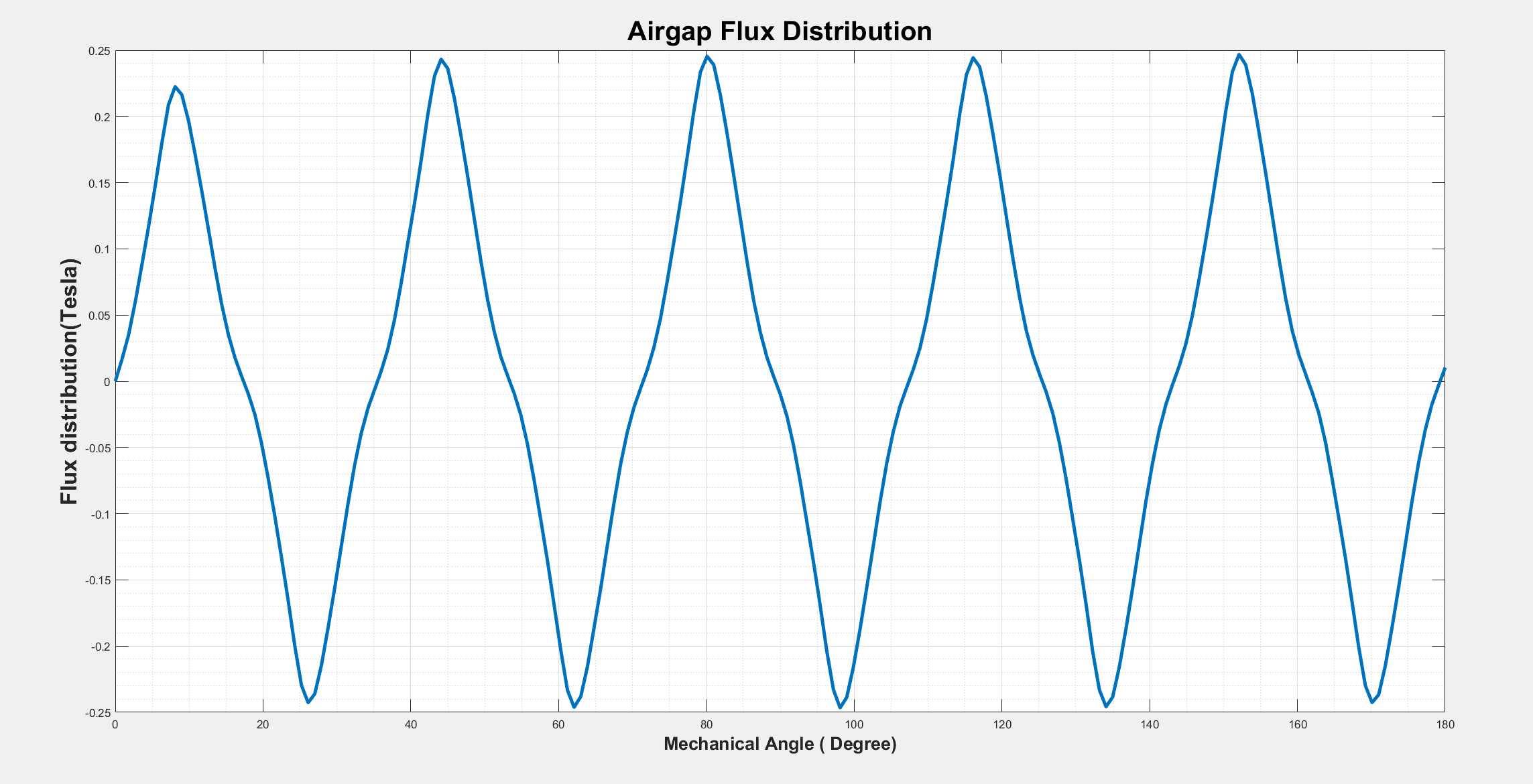


Figure 14 Distribution of Airgap Flux Density

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

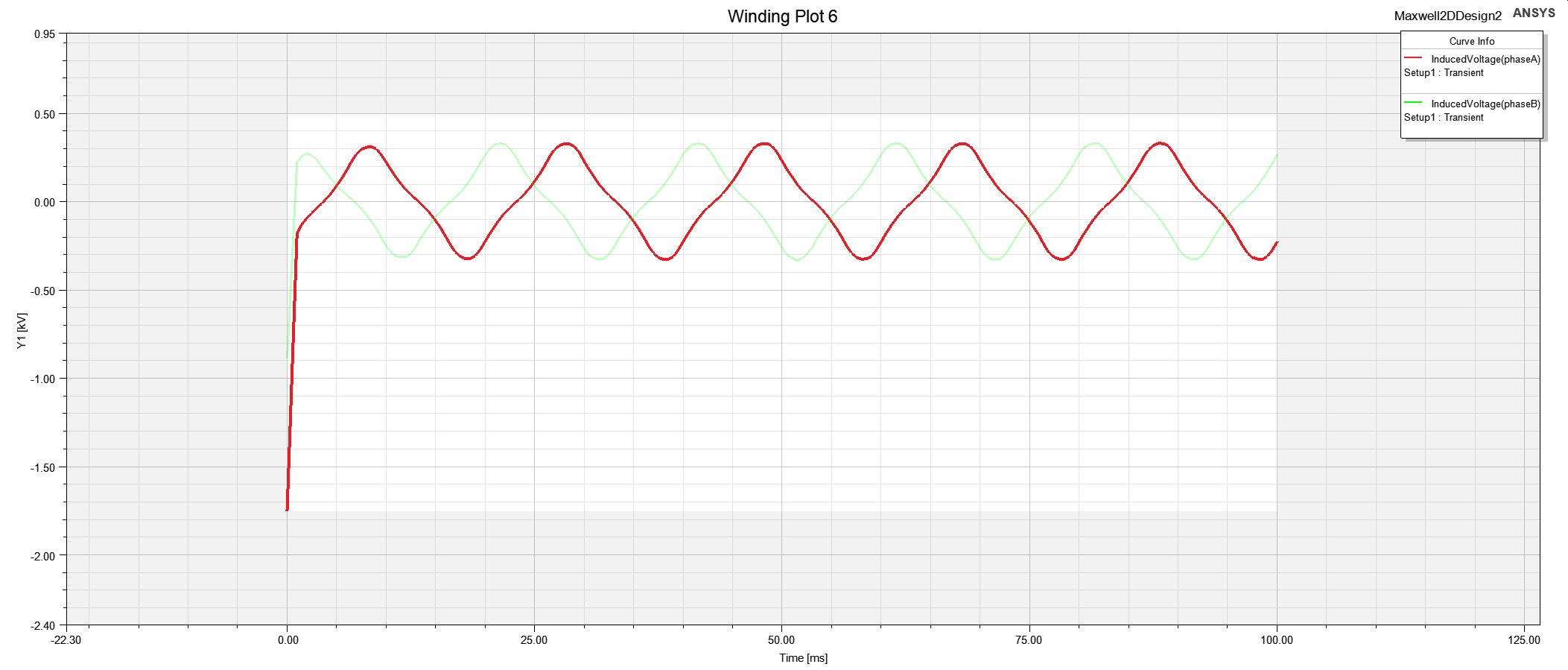


Figure 15 Phase A and Phase B Voltages Maxwell

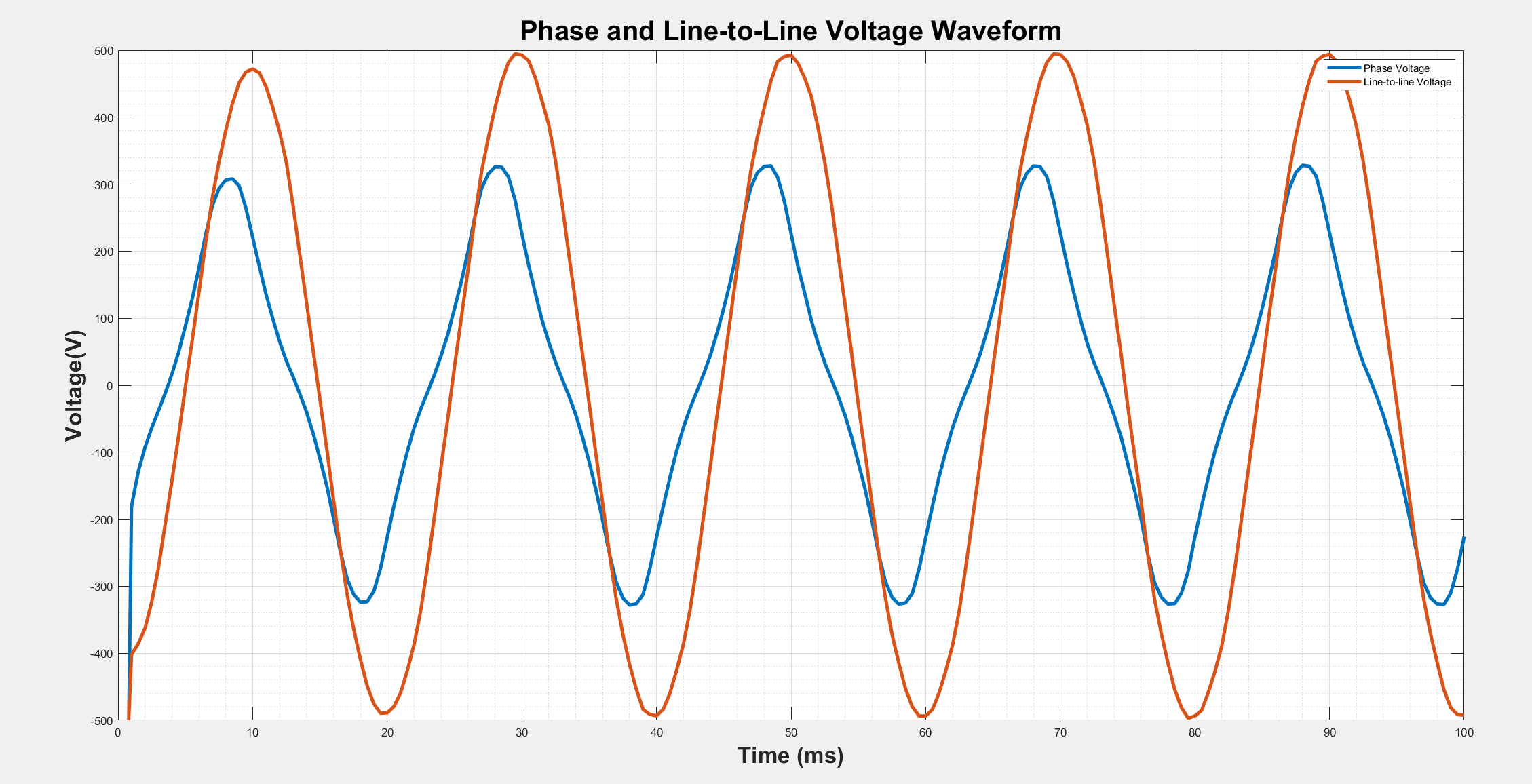


Figure 16 Phase and Line Voltages Matlab Plot

# 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.