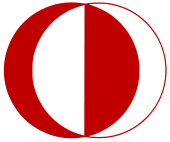
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**MIDDLE EAST TECHNICAL UNIVERSITY**

DEPARTMENT OF ELECTRICAL AND ELECTRONICS ENGINEERING

**EE 564** Project #2

***MOTOR WINDING DESIGN & ANALYSIS***

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# Introduction

In this report, design of inductor and single phase transformer will be studied. Report consists of two main sections, inductor design and transformer design. In the inductor design part, a toroid shaped inductor will be selected. Different core properties will be also investigated. Linear core and non-linear core will be compared. Also, homogenous and non-homogenous core types will be investigated. The inductors with these different properties first calculated analytically and analytical results will be verified using FEM. Lastly, effect of air gap in toroid inductor will be investigated.

In second part of the report, single phase transformer will be designed. Design procedure will be studied in details and a design guide will be provided. In the transformer, effect of different parameters on efficiency and cost will be investigated such as number of turns, core types, laminations etc. Lastly, an optimum solution will be provided with maximum efficiency and lowest cost.

# Winding Design

## Lamination Selection

In the design lamination 3 is used [[1]](https://github.com/odtu/ee564-2018/blob/master/Project2/ks(3).pdf), general properties of which is listed in Table 1.

Table 1: Properties of lamination 3

|  |  |
| --- | --- |
| Property | Value |
| Stator slot number | 36 |
| Rotor slot number | 34 |
| Stator outer diameter | 200 mm |
| Stator inner diameter | 135 |
| Rotor outer diameter | 134.6 |
| Rotor inner diameter | 61 mm |
| Air gap clearance | 0.3 mm |
| Stator slot area | 114 mm2 |

Air gap clearance of 0.3 mm is chosen in the design. This effects reluctance and magnetizing inductance of the induction motor. In rotor side, we have shorted aluminum bars. In the stator, three phase windings are placed with correct order.

## Winding Configuration

In the design, I decided to use **single layer, integral slot** winding diagram. Therefore, number of slots per pole phase can be calculated as follows. **Number of poles** are chosen as 4.

With this configuration, we have following winding connection over one pole pairs.

|  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| A1 | A2 | A3 | -C1 | -C2 | -C3 | B1 | B2 | B3 | -A1 | -A2 | -A3 | C1 | C2 | C3 | -B1 | -B2 | -B3 |

Here, 18 stator slots are shown for one pole pair. Rest of the windings repeat this cycle for each pole pair. Also, 3D winding diagram of the designed motor is shown in Figure 1.

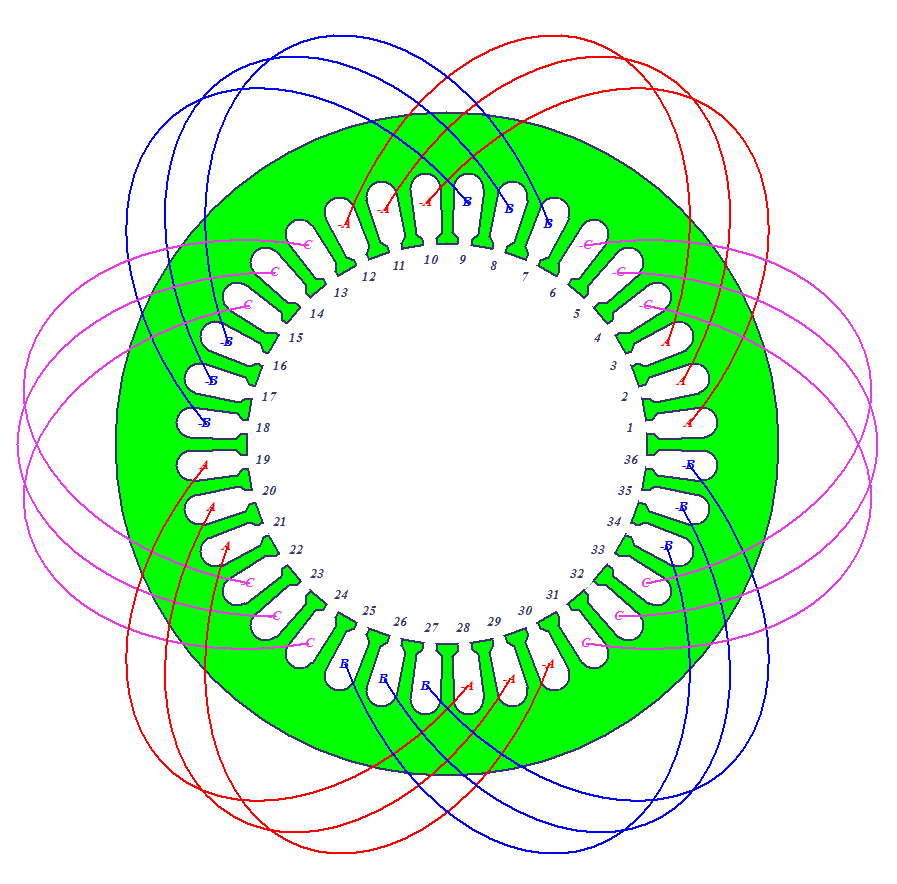


Figure 1: Winding diagram for single layer integral slot winding

## Winding Factors

Here, we have distributed winding diagram with full pithed coils. Pitch factor is unity due to full pitched coils. Distribution factor is calculated as follows.

Where h represents harmonics and coil span is 180 degrees due to full pitched coils.

Where h is harmonics, q is number of slots per pole per phase, which is 3 as calculated before, and α is the slot angle in electrical degrees. It is calculated as follows.

Using pitch factor and distribution factor, winding factor is calculated as follows. Also, winding factor for some harmonics are listed in following table.

Table 2: Winding factor for some harmonics

|  |  |  |  |
| --- | --- | --- | --- |
|  | kp | kd | kw |
| Fundamental | 1 | 0.9598 | 0.9598 |
| 3rd | -1 | 0.6667 | -0.6667 |
| 5th | 1 | 0.2176 | 0.2176 |
| 7th | -1 | -0.1774 | 1.774 |

Note that even harmonics does not exist because they have zero pitch factor.

## Number of Turns & Conductors Calculation

In order to calculate number of turns per phase, we can use induced voltage relation. To do this, we first determine some machine parameters. First of all, let’s assume machine is **wye connected** and supplied from **380 Vll-rms** voltage source. In that case, we have 220 Vrms phase voltage.

Where erms is the induced phase voltage, which is 220 V, Nph is the number of turns per phase, f is the supply frequency, kw is the fundamental winding factor, which is 0.9588, and is the peak flux per pole. Flux per pole is calculated as average flux density in the air gap and pole area. Average flux density is also known as **magnetic loading** of the machine, which is usually taken as 0.35-0.6 T. In the design, let’s assume **supply frequency is 50 Hz.**

where diagap is air gap diameter and length is the axial length of the motor. **Let’s define axial length of the motor is equal to inner stator diameter of the motor, which is 135 mm.**

Using this, number of turns per phase can be calculated easily.

Number of conductors in a stator slot is calculated as follows.

## Fill Factor & Wire Size

Here, let’s define **fill factor of the machine is 0.7**. This determines ratio of total wire cross section area to total slot area in a slot. Using this, we can calculate cross section area of a wire.

In this part, we should also consider current density in the account. At the end of the design, current density should be checked whether we are safe or not.

Current density up to 5 A/mm2 is safe.

## Voltage & Current Ratings, Output Power

In the design, we have 380 Vrms line voltage and wye connection. This means 220 Vrms phase voltage. For current calculation, we should first determine electrical loading of the machine. Electrical loading is rms ampere turns per unit length of the air gap and its unit is A/m. It is calculated as follows.

In this equation, only unknown is phase current and we should also set electrical loading. In the induction machines, it is safe to have 20-65 kA/m of electrical loading. In our design, let’s set **electrical loading as 24 kA/m.** Then, phase current can be calculated easily.

To be safe, let’s check current density of windings.

Which is safe to go.

Using these findings, we can calculate power ratings of the machine. To do this, we should first make power factor and efficiency assumptions. Let’s assume power factor of machine is **0.82 and efficiency is 0.9.** At rated operation, these assumptions hold and real values are very close. Using them, let’s calculate input and output power.

## MMF Waveforms

In this part, MMF waveforms for given winding configuration will be provided. In the design, we have 34 conductors for each slot. Three different instants for a balanced three phase current will be provided.





Figure 2: Sample MMF waveform





Figure 3: Sample MMF waveform





Figure 4: Sample MMF waveform

# Motor Parameter Estimation

In the design, **axial length of the motor** is chosen the same as stator inner diameter, which is **135 mm.** Additionally, **air gap clearance** is chosen as **0.35 mm**.

## Magnetic and Electric Loading

In previous parts, we determined these values in order to find current and number of turns parameters. In order to remind them, **magnetic loading is chosen as 0.35 T**, which is air gap average flux density. 0.35-0.6 T is safe to choose values for magnetic loading. In order to find stator teeth and yoke flux density, we can get help from RMxprt tool of Maxwell. In the Maxwell, dimensions of the design are provided and design is analyzed. Following results are obtained for magnetic data.

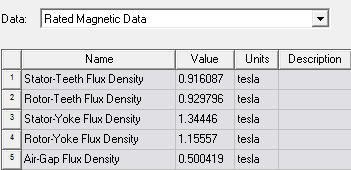


Figure 5: Magnetic parameters of the design

As can be seen, air gap flux density is 0.5 T. In our analytical model, we take magnetic loading as 0.35 T, which is average flux density in the air gap. Above values are peak values and our analytical calculation has peak value of 0.35\*pi/2 = 0.55 T, which is quite close the simulation results above. As can be seen, stator yoke has peak flux density of 1.34 T. Our material saturates at 1.6-1.7 T and this much magnetic loading is safe for our design.

In order to find current rating, we set electrical loading in previous part. In order to remind, electrical loading is rms ampere turns per unit length of the air gap. It is calculated as follows.

In the induction machines, it is safe to have 20-65 kA/m of electrical loading. In our design, we have **electrical loading of 24 kA/m,** which is acceptable.

## Torque & Speed Calculation

We can find speed using synchronous speed and assume some slip. In the design, we have synchronous speed of following value;

Induction machines work close to synchronous speed at rated operation. Therefore, it is reasonable to assume small slip, such as **s=0.03**. Therefore, actual speed can be calculated as follows.

Assuming power factor and efficiency values 0.82 and 0.9 respectively, we calculated output power as 4 kW in previous part. Using these values, rated torque can be calculated easily.

## Equivalent Circuit Parameters

* Stator phase resistance

In order to determine this, let’s focus on one turns total length. We have axial length of 0.135 m for each conductor in a slot. Considering slot diameter of the design, end windings are calculated as 0.12 m for each turn. Therefore, one turn length of the design is calculated as follows.

Where, Nph is the number of turns per phase and lphase is the total length of the copper conductors in a phase. Therefore, phase resistance can be calculated as follows.

Note that here resistivity is calculated for 75 °C, which is operating temperature.

* Phase inductance
* Leakage inductance
* Magnetizing inductance

## Approximate Core and Copper Losses

Copper losses are calculated as follows.

Core losses are calculated on stator. At rated operation, since rotor induced voltage & current frequencies are very small, core losses on rotor are can be ignored. We can calculate core losses on stator core as follows.

Where Bm is the peak flux density in the stator, which is 1.35 T, kh, kc and ke are coefficients for hysteresis loss, eddy-current loss and excess core loss respectively. These are defined for each material. In our core material they are 173.3 0.086 2.068, respectively. In the equation, f is the frequency of induced voltage and currents in the armature, which is 50 Hz. In the above equation, core loss is defined per volume.

# Conclusion

In this report, we first designed a toroid inductor. Different properties of the core are investigated. In the results, we observed that homogenous and non-homogenous core types have not much difference in inductance and homogeneity assumption can be made in analytical calculations. However, when we compare the linear and non-linear cores, we see significant difference. In linear core, we had constant permeability and core never saturated. But this case was not practical and has no reality. In non-linear case, which is practical, we have changing permeability with changing excitation. Core starts to saturate when inductor is excited with enough current. This leads to higher reluctance and less inductance. These observations are made in analytical calculations and also they are verified in FEM in Maxwell software. We had very small difference between calculations in analytical and in FEM. This difference is mainly caused from leakage flux, which is ignored in analytical case and meshing in FEM. In further study, we investigated the effect of 2 mm air gap in the core. As we introduce air gap, reluctance is increased and inductance is decreased significantly. In FEM, we also observe fringing flux effect. Effective air gap cross section area is higher when we take fringing flux into account and therefore we have less reluctance in this case.

In second part of the report, we focused on transformer design. Given specifications are analyzed and a laminated core from Cogent is selected. Laminated cores have less core losses but they are expensive compared to cores without lamination. A brief design procedure is introduced in this section and effect of different parameters are interpreted. In optimum design, core losses are equal to copper losses and ın our design, this point are found. All parameters are moved to Excel and a smart designer are created in this software. Variation of efficiency with respect to secondary number of turns are plotted. It is observed that when number of turns in secondary side is 1100, maximum efficiency is achieved. Also, it is verified that in this point, core losses are equal to copper losses. In the optimization process, efficiency is taken as key performance index rather than initial cost. Initial cost is also important but when we think that the transformer will be used to 20-30 years, efficiency will be more important in terms of cost.

In overall, this study was teaching and we learnt how to design an inductor and transformer considering practical issues.

# References

[1] https://github.com/odtu/ee564-2018/blob/master/Project2/ks(3).pdf