Project 1: Analysis of an induction machine using a FEM based software
EJ2222 - Design of Electrical Machines

1 General instructions

In this assignment we will analyze an induction machine using Matlab and the freely available finite element software FEMM. All files needed, including documentation of the software FEMM, will be distributed by the course teachers.

1.1 Report

A written report is to be handed in to Oskar Wallmark's post box. You may work together in groups of two when collaborating with the simulations but you must write and hand in the report individually. You will *not* get the corrected report in return so please keep an additional copy for your personal reference. Make sure to write down your e-mail address where the results of the examination of your report will be sent.

Remark 1: If you have problems solving the assignments, the computer lab is staffed by course teachers as outlined in the schedule. It is recommended that you primarily pose your questions related to the course tasks in that forum. Also, do not hesitate to pose questions to other fellow students. If you do not receive proper assistance after this, do not hesitate to contact Oskar Wallmark.

Remark 2: Include relevant pieces of your own Matlab code in the written report so that it is evident for the reader that you *have solved the assignments yourself and understand your solutions in* <u>*all*</u> *details*.

Remark 3: If you are unable to print your report in color, please make sure that individual curves can be distinguished anyway. For example by displaying curves using dashed and dashed-dotted lines.

2 Assignment

A small induction machine will be analyzed in this task. You will have to determine relevant geometrical and material parameters by carrying out relevant caliper measurements and looking up correct material data tables. The rotational movement of the rotor is modeled indirectly in the sense that the rotor implemented in the FEM program is at standstill and the stator is fed with currents with a frequency corresponding to the slip frequency.

The FEMM simulation model is started by running the Matlab script `RunMe.m` which, in turn, calls for other script files. All files are properly commented so going through all script files in detail provides you with a good introduction to both the FEMM software and the induction machine model.

Remark 4: To remove the impact of the slotting effect, all simulations should be carried out for different rotor positions and the average result should be used as output. However, to reduce the work effort somewhat, we neglect this averaging procedure and consider only a single rotor position.

Remark 5: With the exception of assignment i) (where you compare your result with actual measured parameters), you may neglect axial end effects completely.

Tip 1: Relevant material information about the used electrical steel can be downloaded from Surahammars Bruk's web page (www.sura.se).

Tip 2: ABB's motor catalog can be downloaded from ABB's web page (www.abb.com). Search for *Lågspänningsmotorer* and then *Processmotorer*.

Tip 3: Each turn in a slot consists of three, parallel connected strands. All coils in each phase are connected in series.

Tip 4: In the FEMM model, the number of turns in each stator slot `Turns` is assumed to be connected in series and each turn has a wire diameter of `WireDiam`. To take into account that each turn comprises of three, parallel connected strands, you need to compensate the measured wire diameter `WireDiam` so that the correct average current density is obtained in each stator slot.

Tip 5: You will find that solving the FEM problem with a nonlinear BH-curve will take considerably longer time compared to a linear material (as outlined in [1]). Hence, when setting up the proper model dimensions, you can save a lot of time by using a linear material which you replace when you extract the final data for your report.

Tip 6: When comparing your predicted parameters with corresponding measured values, do not forget to include the fact that the rotor is skewed.

2.1   Initial analysis

a) At *rated* slip frequency and *rated* phase current, plot the radial and tangential components of the flux density (the real, the imaginary part as well as the absolute value) in the middle of the air gap and along the whole rotor circumference. Note: You may need to increase the mesh density in the air gap and other machine parts in order to obtain accurate results.

b) At *zero* slip frequency and *rated* phase current, plot the radial flux density along the air gap and compare (i.e., plot in the same graph) with the analytical model derived in Chapter 1 in [1]. Tip: In this task, you are allowed to remove the impact of the rotor slots. This is most easily done by increasing the relative permeability of the rotor slots to a very high value.

c) At *rated* slip frequency and *rated* phase current, plot the tangential flux density *as a function of time* in the middle of the rotor back.

2.2   Torque computation

d) Compute the torque for different slip frequencies at rated phase current by evaluating the proper integral based on Maxwell's stress tensor in the middle of the air gap. Note: As outlined in the lectures, it is very important that the mesh density is high in the air gap region to obtain accurate results. How well does the computed torque agree with the rated torque?

2.3   Machine model parameter extraction

In this section, we will learn how the FEMM model in consideration can be used to extract model parameters suitable for transient simulations (which will be carried out in Project 3 in this course).

e) Following the technique outlined in Chapter 5 in [1], identify the parameters R_s, R_R, L_M and L_σ for the induction machine in consideration. In order to reduce the impact of magnetic saturation, which may cause the parameters to vary substantially at different slip frequencies, this evaluation should be carried out at *half the rated current*. Tip: To

avoid errors in R_s due to mismatches in the already computed values of R_R, L_M and L_σ, it is recommended that R_s is determined simply from the resistive losses at $\omega_{\text{slip}}=0$ rad/s.

2.4 Validation of extracted machine model parameters

From the simplified per-phase equivalent circuit shown in Figure 5.5 in [1], it can be derived (and is well known from basic courses covering electrical machinery) that the torque T_e can be expressed as

$$T_e = \frac{3p}{2} L_M |i_{a,\text{rms}}|^2 \left(\frac{\tau \omega_{\text{slip}}}{1 + (\tau \omega_{\text{slip}})^2} \right) \tag{1}$$

where p is the number of poles, $i_{a,\text{rms}}$ is the *rms* phase current phasor, and $\tau = L_M/R_R$.

f) Confirm the validity of the derived machine parameters by comparing the resulting torque for different slip frequencies at *half the rated current* using (1) with the results obtained using the Maxwell's stress tensor approach.

g) Compare the obtained value for L_M with the analytical formulas derived in [1].

h) Compare the obtained value for R_s and R_R with the analytical formulas derived in [1].

2.5 Comparison with measured parameters

The following machine parameters have been obtained experimentally: $R_R = 4.7\ \Omega$ (referred to the stator side), $L_M = 790$ mH and $L_\sigma = 54$ mH.

i) Taking axial and end effects into account by the analytical formulas outlined in the course literature, compare R_s, R_R and L_M as obtained from FEMM, from analytical formulations and from experiments.

2.6 Non-compulsory optional assignments (compulsory for PhD students following the course)

*) Estimate the stator- and rotor-slot leakage inductances using the analytical derivations outlined in [1].

Acknowledgements

References

[1] O. Wallmark, *AC Machine Analysis – Fundamental Theory.* Stockholm, Sweden: KTH Royal Institute of Technology, 2016.

Project 2: Electromagnetic sizing of an induction machine
EJ2222 - Design of Electrical Machines

1 General instructions

In this assignment we will carry out a preliminary electromagnetic design of a small induction machine and compare with the dimensions of a corresponding machine manufactured by ABB.

1.1 Report

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2 Assignment

Assume the same number of poles, number of stator slots, number of rotor slots, axial length, and rated torque as the machine considered in Project 1. Implement the algorithm for electromagnetic sizing outlined in Chapter 4 in [1] (which, in turn, is obtained from [2]) and compare the resulting dimensions with the actual machine. Do you think the engineer(s) designing the actual machine has/have done a good job?

Acknowledgements

ABB LV Motors are acknowledged for kindly donating the induction machine used for comparison in this project.

References

[1] O. Wallmark, *AC Machine Analysis – Fundamental Theory.* Stockholm, Sweden: KTH Royal Institute of Technology, 2016.

[2] A. Boglietti, A. Cavagnino, M. Lazzari, and S. Vaschetto, "Preliminary induction motor electromagnetic sizing based on a geometrical approach," *IET Electric Power Applications*, vol. 6, no. 9, pp. 583–592, Apr. 2012.

Project 3: Transient modeling of a PMSM
EJ2222 - Design of Electrical Machines

1 General instructions

In this assignment we will extract data from a FEM model in order to implement a transient PMSM model in Matlab/Simulink[1].

1.1 Report

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2 Assignment

Adapt the delivered FEMM model of a PMSM so that it has the same stator geometry and uses the same materials as in Project 1 and Project 2. Introduce a four-pole rotor with inset-mounted permanent magnets and size the permanent magnets so that the stator and rotor laminations are suitably magnetically loaded (i.e, without too excessive magnetic saturation).

a) As outlined in Chapter 5 in [1], extract suitable data from the FEMM model and implement a corresponding Matlab/Simulink model so that magnetic saturation "along" the d- and q-axis is considered. You may or may not choose to incorporate the effect of magnetic cross saturation but you need to take into consideration flux-linkage harmonics. The latter is sufficiently modeled if the open-circuit no-load voltage is reproduced properly.

b) Simulate a balanced short circuit of the three-phase converter by setting $v_d = v_q = 0$ V. Set the rotor speed to increase (linearly and slowly from zero and plot the resulting torque and current waveforms. Explain why the stator currents and torque arise and the shape of the torque. Compare the obtained results with a simpler machine model using constant machine parameters (obtained using the analytical formulas derived in [1]) and neglecting the impact of harmonics.

c) In [1], it is found that the developed torque T_e can be expressed as

$$T_e = \frac{3p}{2} \left(\psi_d i_q - \psi_q i_d \right). \tag{1}$$

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[1]Matlab and Simulink are registered trademarks of The MathWorks, Inc., Natick, MA.

However, if you follow the derivation of (1) in [1] carefully, you will see that it relies upon analytical models where magnetic saturation has not been considered. Use the implemented FEMM model and investigate the validity of (1) also in the presence of magnetic saturation.

Tip 1: Relevant material information about permanent magnets can be found at, e.g,. www.vacuumschmelze.com.

2.1 Non-compulsory optional assignment

*) If you have suitable knowledge in control of electric drives, implement a closed-loop current controller (preferably, implemented in the dq-axis reference frame) and compare the resulting torque and current waveforms to corresponding results from a constant-parameter machine model.

References

[1] O. Wallmark, *AC Machine Analysis – Fundamental Theory.* Stockholm, Sweden: KTH Royal Institute of Technology, 2016.

Project 4: Thermal and magnetic analysis of a PMSM
EJ2222 - Design of Electrical Machines

1   General instructions

In this assignment we will analyze how the magnetic *and* thermal characteristics of a PMSM changes when different geometrical parameters are changed. To speed up the simulations, in the model hand out, the magnetic and thermal simulations are running in parallel on separate processor cores (using Matlab's[1] parallel processing toolbox).

1.1   Report

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2   Assignment

a) Change key geometrical parameters (e.g. the air-gap length, slot dimensions, stator yoke thickness,...) and thermal parameters (e.g. stator-enclosure material and thickness and equivalent thermal conductivity in the stator slots) and study how the temperature distribution and electromagnetic torque changes. Aim at drawing general conclusions concerning sensitivity of key geometrical and material parameters.

Remark 3: You may see that the heat transfer coefficient `hCyl` is somewhat larger than what obtained using the formula provided in [1]. This is done in order to (somehow) take into consideration the axial heat transfer not included in the two-dimensional model considered here.

Tip 1: If you have a modern computer, you may have more than two processor cores. To reduce the simulation time, adapt the code so that all cores are working in parallel with different tasks.

References

[1] O. Wallmark, *AC Machine Analysis – Fundamental Theory.* Stockholm, Sweden: KTH Royal Institute of Technology, 2016.

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[1]Matlab is a registered trademark of The MathWorks, Inc., Natick, MA.

Project 5: Implementation of a finite-element based solver in Matlab
EJ2222 - Design of Electrical Machines

1 General instructions

Having a good understanding of the underlying computational machinery when working with a finite-element based software is very beneficial for several reasons. In this assignment, we will implement a simple finite-element based solver in Matlab and compare the result with corresponding output from the software FEMM (or any other FEM-based software that you prefer).

1.1 Report

A written report is to be handed in to Oskar Wallmark's post box. You may work together in groups of two when collaborating with the simulations but you must write and hand in the report individually. You will *not* get the corrected report in return so please keep an additional copy for your personal reference. Make sure to include your e-mail address where the results of the examination of your report will be sent. *Additionally*, you should send your finished Matlab code (as a single zip-file) by e-mail to owa@kth.se. Please name the executable file `RunMe.m`.

2 Assignment

Consider the simple electromagnet shown in Figure 1. The coil is fed with a dc current and the current density in the copper is, hence, constant. The iron can be assumed to be ideal with a high, constant permeability. You can select the dimensions of the magnet and current density in the copper freely. Implement and solve the relevant equations as outlined in [1].
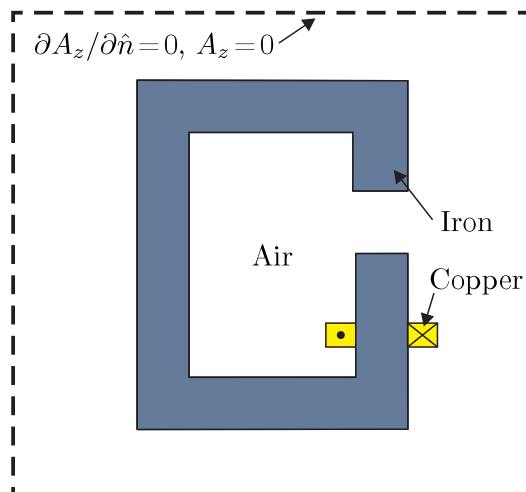

Figure 1: Geometry of a simple electromagnet.

a) Plot the resulting flux lines and compare with the corresponding solution implemented in FEMM (or any other FEM-based software that you prefer). Set the material and geometrical parameters so that a *fringing effect* of the flux lines when passing the air gap is visible.

b) Plot the resulting flux density and compare with the corresponding solution in FEMM. Estimate the flux density in the iron and air gap analytically and compare with your obtained solution.

By making improvements and additions to your implemented Matlab code, you can learn a lot more. Below are just a sample of ideas (not compulsory) that can be implemented by the interested student.

- Implement an iterative approach for solving the problem in consideration with a non linear iron.

- Implement the code using Matlab's sparse matrix formulations and compare the resulting solution times.

- Modify the geometry and compute forces using Maxwell's stress tensor approach.

- Modify the code so that any freely available mesh generator is used for mesh generation.

References

[1] O. Wallmark, *AC Machine Analysis – Fundamental Theory.* Stockholm, Sweden: KTH Royal Institute of Technology, 2016.