Finite Element Model of the Synchronous Machine with FEMM and Matlab – Part 2

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1. Requirements

- FEMM 4.2 (download: www.femm.info)
- Matlab R2020a (or above)
- FEMM model from part 1 of this tutorial, called `tutorial_SM_QUEVAL_yyyymmdd.fem`

2. Introduction

In this document, we detail how to run FEMM from Matlab. This allows us to easily compute the inductance matrix of a synchronous machine (SM) as a function of its rotor angle.

Make a copy of `tutorial_SM_QUEVAL_yyyymmdd.fem`, and rename it `tutorial_SM_fromFEMM.FEM`. It will be used from the FEMM interface.

Make a copy of `tutorial_SM_QUEVAL_yyyymmdd.fem`, and rename it `tutorial_SM_fromMATLAB.FEM`. It will be used from the Matlab.

3. Open, run and close FEMM with Matlab

To load and compute the FEMM model from Matlab, use the following script:

```
% main_SRM_FEMM

clear all, close all, clc

%% load femm model
addpath('C:\femm42\mfiles') % import femm fonctions
openfemm %open femm
opendocument('tutorial_SM_fromMATLAB.fem') %open the femm model
mi_saveas('temp.fem') %save a temporary copy of the femm model

%% run analysis
mi_analyze(0); % run analysis
mi_loadsolution; % open "view results" window
```

To close the FEMM model from Matlab, use the following script:

```
%% close femm model
mo_close; % close "view results" window
mi_close; %close the temporary copy of the femm model
```

4. Current

In this section, we want to modify the currents. As an example, we show how to modify the current of the circuit `f`.

4.1 Current with FEMM interface

Open the model `tutorial_SM_fromFEMM.fem` with FEMM.

In the `Properties` menu, select `Circuits`. In the `Property Definition` dialog, select `f` and click on `Modify Property`. The `Circuit Property` dialog appears. To set the current of the phase `f` to 10 A, enter `10` in the `Circuit Current` (Figure 1). Click `OK` to close both dialogs. Run the analysis with the run icon. Then click on the glasses icon to view the analysis results. Plot the flux density distribution (set the `Lower Bound` to `0` and the `Upper Bound` to `1.2`).

You can repeat the procedure for different currents. You should obtain the results summarized in Figure 2.

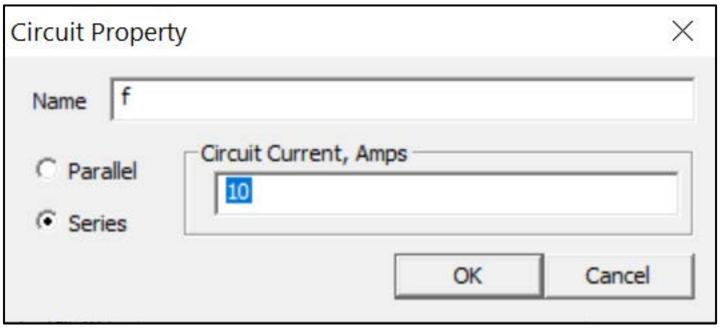


Figure 1 – Circuit property dialog.

4.2 Current with Matlab

To set the current i_f from Matlab, use the following script:

```
%% Set current in circuit f
i_f = 10; %[A] current of circuit 'f'
mi_modifycircprop('f',1,i_f) % modify the current of the circuit
```

Plot manually the flux density distribution (set the `Lower Bound` to `0` and the `Upper Bound` to `1.2`).

You can repeat the procedure for different currents. You should obtain the results summarized in Figure 2.

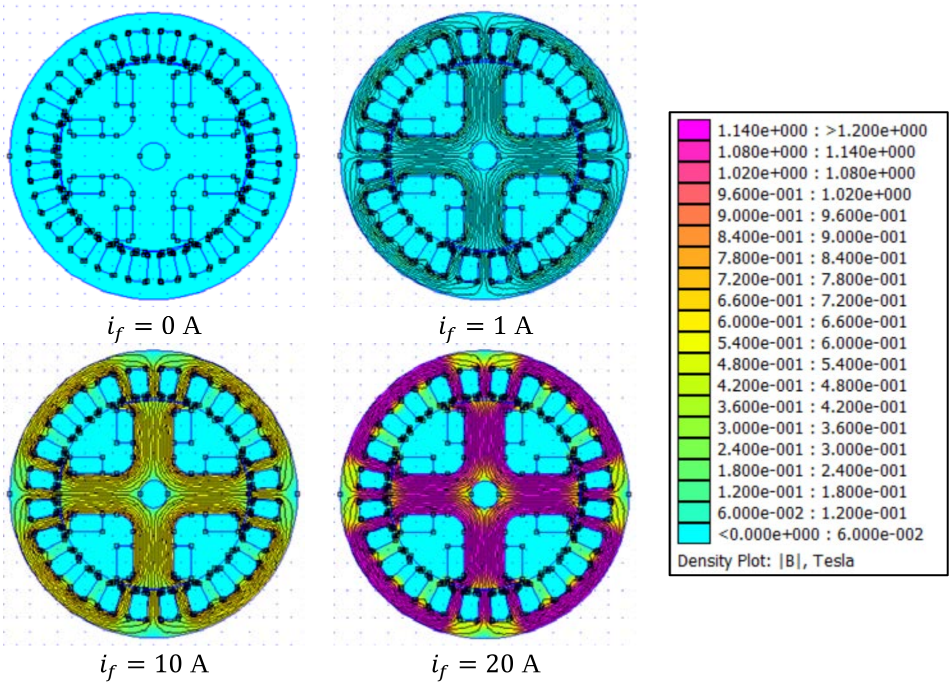


Figure 2 – Flux density distribution as a function of the field current (θ_m = 0 A).

5. Rotation

In this section, we want to modify the rotor angle θ_m. The initial rotor angle is assumed to be zero ($\theta_m = 0$ deg).

5.1 Rotation with FEMM interface

Open the model `tutorial_SM_fromFEMM.fem` with FEMM. Set the currents to $(i_a, i_b, i_c, i_f) =$ (0,0,0,1) A.

Switch to Groupe mode by pressing `Operate on group of objects` icon. Right click on the rotor. The rotor group (group 1) will turn red, denoting that it is selected (Figure 3). Click on the `Move/Rotate selected objects` icon. The `Move` dialog opens. Set `Rotation Angular shift` to `15` degrees (Figure 4). Click `OK`. The rotor rotates 15 degrees in the counterclockwise direction; as a result the rotor angle is now $\theta_m = 15$ deg (Figure 3). Run the analysis with . Then click on the glasses icon to view the analysis results.

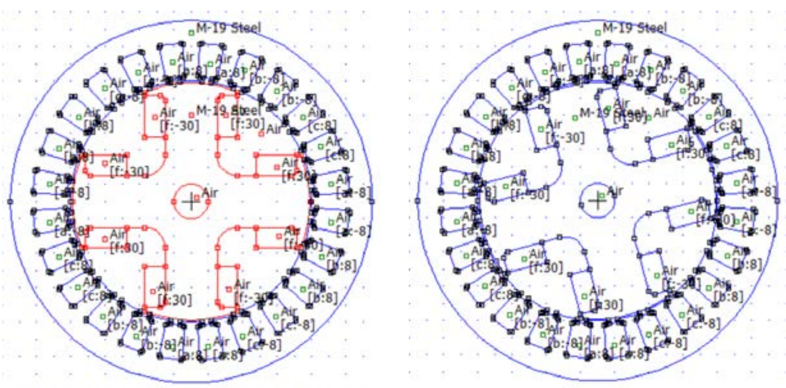

Before rotation After rotation

Figure 3 – Selection of the rotor before rotation, and results after the rotation ($\theta_m = 15$ deg).

You can repeat the procedure for different rotor angles (remember that the rotation is relative to the previous rotor angle). You should obtain the results summarized in Figure 5.

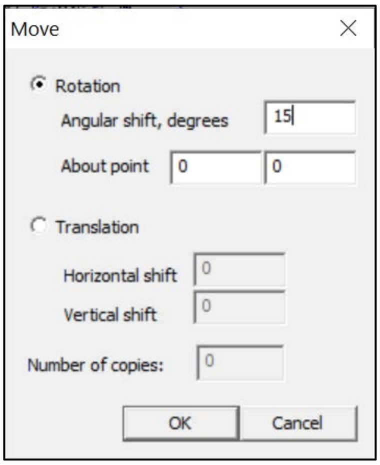


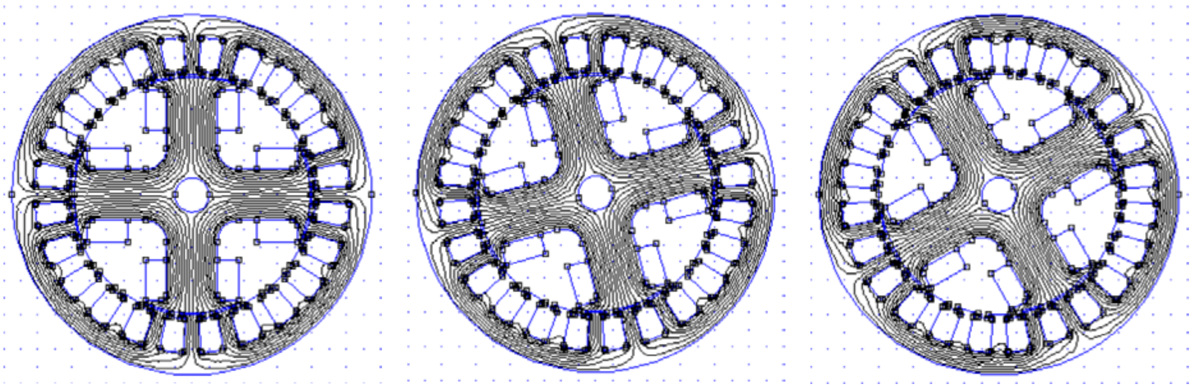
Figure 4 – Move dialog.

5.2 Rotation with Matlab

To set the rotor angle from Matlab, use the following script:

```
%% Set rotor angle
Dtheta_m = 45; %[deg] rotation step
mi_seteditmode('group'); %switch to group mode
mi_selectgroup(1); %select the rotor group
mi_moverotate(0,0,Dtheta_m); %rotate the group
```

Change the rotor angle and run the analysis from Matlab. You should obtain the results summarized in Figure 5.



$\theta_m = 0$ deg $\quad$ $\theta_m = 15$ deg $\quad$ $\theta_m = 30$ deg

Figure 5 – Flux lines as a function of the rotor angle for $(i_a, i_b, i_c, i_f) = (0,0,0,1)$ A.

6. Flux linkage & Inductance

In this section, we want to compute the flux linkages.

6.1 Flux linkage with FEMM interface

Open the model `tutorial_SM_fromFEMM.fem` with FEMM. Set the rotor angle to 0 deg. Set the currents to $(i_a, i_b, i_c, i_f) = (0,0,0,1)$ A.

Run the analysis with . Then click on the glasses icon to view the analysis results. Press the button to display the resulting attributes of each `Circuit Property` that has been defined. For each circuit, the calculated flux linkages are shown in Figure 6.

Since there is only one current, and since this current is equal to 1 A, the flux linkages can be unambiguously interpreted as the coil self and mutual inductances. Indeed, in the linear case, by definition,

$$L_f = \frac{\lambda_f}{i_f}, \quad M_{af} = \frac{\lambda_a}{i_f}, \quad M_{bf} = \frac{\lambda_b}{i_f}, \quad M_{cf} = \frac{\lambda_c}{i_f}$$

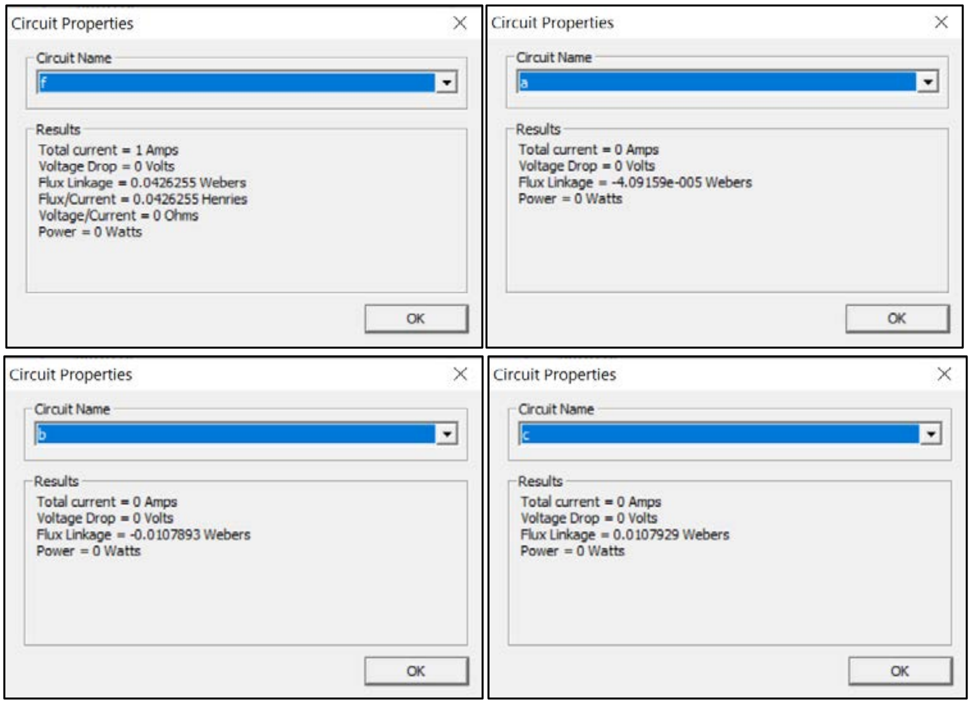


Figure 6 – ”Circuit Properties” dialog (θ_m = 0 deg, i_a = 0 A, i_b = 0 A, i_c = 0 A, i_f = 1 A).

You can change the combination of currents and repeat above procedure to obtain the other inductances. You can change the rotor angle to obtain the inductances as a function of the rotor angle. You should obtain the results summarized in Table 1.

6.2 Flux linkage with Matlab

To get the flux linkages from Matlab, use the following script:

```
% get flux linkage
cir_a = mo_getcircuitproperties('a'); % get properties of circuit 'a'
cir_b = mo_getcircuitproperties('b'); % get properties of circuit 'b'
cir_c = mo_getcircuitproperties('c'); % get properties of circuit 'c'
cir_f = mo_getcircuitproperties('f'); % get properties of circuit 'f'
lambda_a = cir_a(3) % get flux linkage of circuit 'a'
lambda_b = cir_b(3) % get flux linkage of circuit 'b'
lambda_c = cir_c(3) % get flux linkage of circuit 'c'
lambda_f = cir_f(3) % get flux linkage of circuit 'f'
```

Make sure that you obtain the results summarized in Table 1.

Table 1 - Flux linkage as a function of rotor angle and current.

θ_m [deg]	i_a [A]	i_b [A]	i_c [A]	i_d [A]	λ_a [Wb]	λ_b [Wb]	λ_c [Wb]	λ_f [Wb]
0	0	0	0	1	0	-0.011	0.011	0.043
15	0	0	0	1	0.007	-0.011	0.007	0.043
30	0	0	0	1	0.011	-0.011	0	0.043
0	1	0	0	0	0.002	0	0	0
15	1	0	0	0	0.002	-0.002	0	0.007
30	1	0	0	0	0.003	-0.003	0	0.011

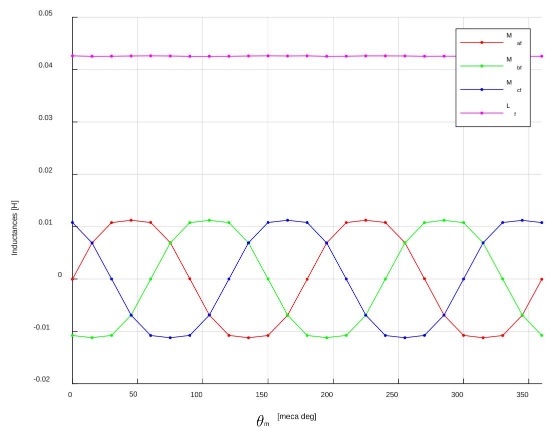
7. Inductance matrix

We are now able to calculate the inductances for a given rotor angle θ_m. We want to obtain the inductances for $\theta_m \in [0, 360]$ meca deg with a step of 15 deg.

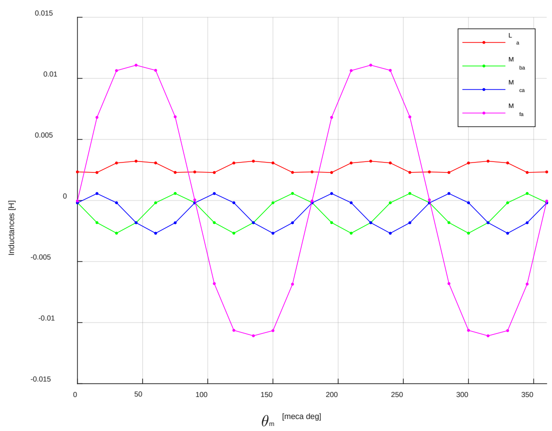
Create a Matlab script that calculates the inductances as a function of the rotor angle, store them in a .mat file and plot them. You should obtain the results summarized in Figure 7.

Note: Build your code step by step and avoid calculating all the points each time! You can for example start by reproducing the results of Table I.

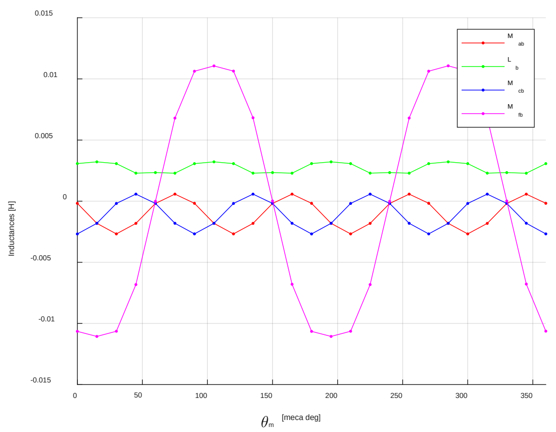
Check that, when neglecting third and higher harmonics, the inductances are of the form given during the lecture. If not, what do you propose ?



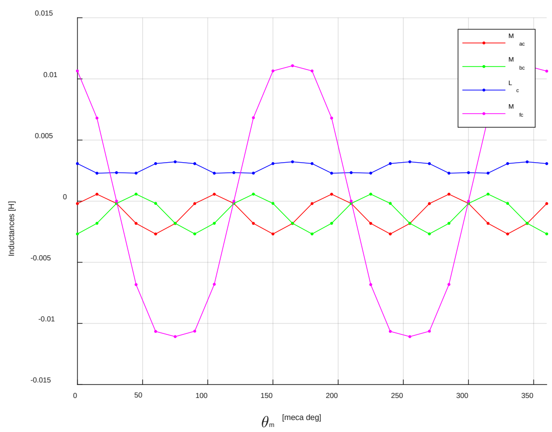
$(i_a, i_b, i_c, i_f) = (0,0,0,1)$ A



$(i_a, i_b, i_c, i_f) = (1,0,0,0)$ A



$(i_a, i_b, i_c, i_f) = (0,1,0,0)$ A



$(i_a, i_b, i_c, i_f) = (0,0,1,0)$ A

Figure 7 – Inductances as a function of the rotor angle.

8. Conclusions

You have now completed the finite element modeling of the SM with FEMM and Matlab (part 2). In this tutorial, you learned how to:

- Open, run and close FEMM from Matlab
- Set currents from FEMM interface and from Matlab
- Set rotor angle from FEMM interface and from Matlab
- Compute flux linkage and inductances from FEMM interface and from Matlab
- Get the inductance matrix of a synchronous machine.