Lab 2: Modeling a brushed DC machine

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Introduction

In this report, a brushed DC machine was analysed with an FE model. Different operating conditions with linear and nonlinear magnetic materials are modelled. On those models we analyse the variations of the radial component of the flux, the pole flux and the torque of the DC machine.

1 Analytical calculations

The rated speed is given as 1000 rpm this is equal to 104.72 rad/s. This speed is assumed constant and independent of the load because the motor is connected in shunt. The rated torque is given by:

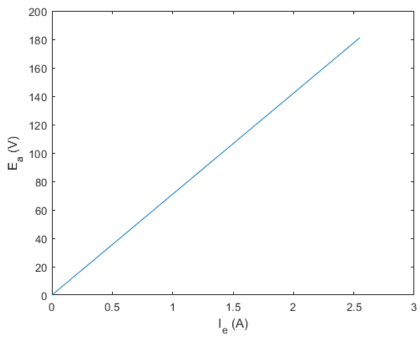
$$T = \frac{V_{an} \cdot I_{an}}{\Omega} = \frac{110 \cdot 90}{104.72} = 94.5\,\mathrm{N\,m}$$

2 Noload operation

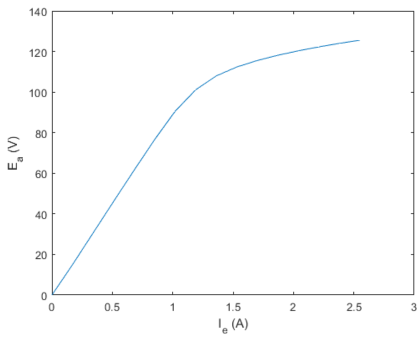
In this section we analyse the DC machine in noload operation with nominal field current I_{en} and armature current $I_a = 0$. First we estimate the torque and e.m.f. constant k_e by setting a load current I_a and a small I_e (to avoid saturation) using $T_e = k_e \phi I_a$.

The flux lines for the nonlinear case are shown in figure 2a. The linear case looks very similar but has larger values in certain areas where the flux density is high since no saturation is present.

Noload characteristic The e.m.f. is calculated using $E_a = k_e \Phi \Omega$ by varying the field current. Here is k_e the previously determined constant, Φ the pole flux and Ω the rotation speed. The resulting characteristic for a linear and non-linear material is shown in figure 1.



(a) Linear

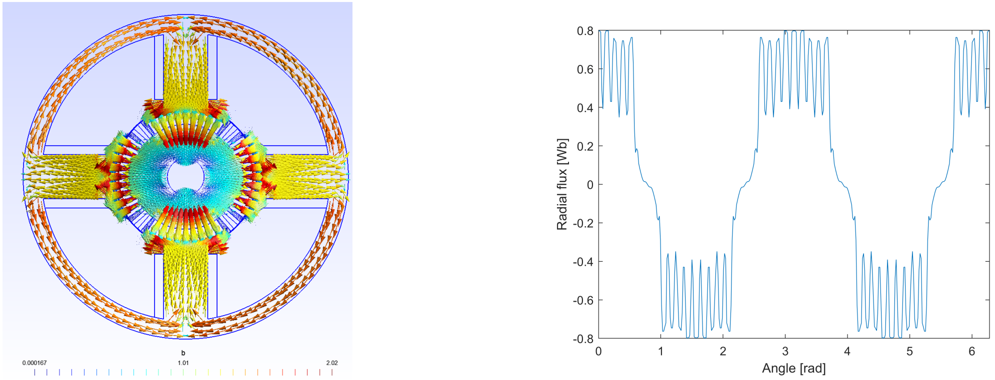


(b) Non-Linear

Figure 1: The noload characteristic

Radial induction in air gap The variation of the radial induction around the machine for the nonlinear case is shown in figure 2b. The magnitudes around the rotor teeth under a pole shoe are more equal in the linear case, but otherwise there is not much difference. The highest radial flux is clearly around the rotor tooth in the middle of a pole shoe. The radial flux is also zero in the middle between two poles.

Pole flux The nonlinear case has 0.014 166 Wb and the linear case has 0.014 692 Wb for the pole flux. These values are close because the material is not very saturated.



(a) Flux lines (b) Variation of the radial induction component

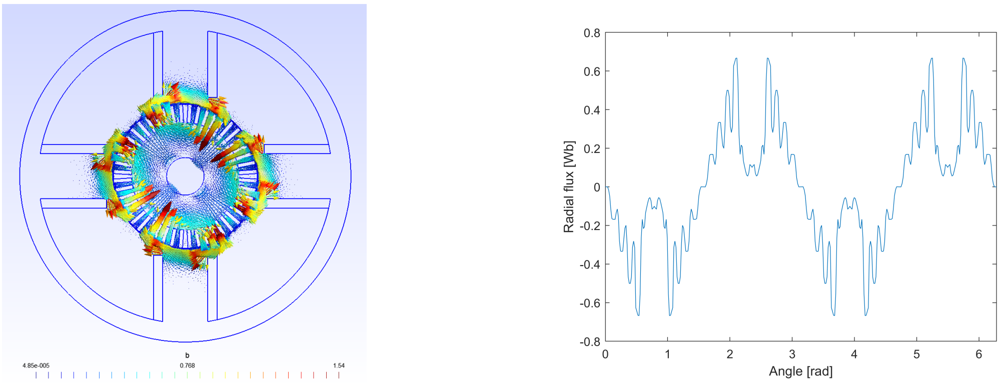
Figure 2: No load operation for the nonlinear case

Torque calculation The torque is calculated in three different regions: the rotor, stator and in the moving band. In this case the values differ a lot (up to 500%) but this has very little meaning since it is close to zero. This is normal because there is no load.

3 Zero field operation

Now the DC machine is modelled with a nominal armature current and no field current. The flux lines for the nonlinear case are shown in figure 3a. The linear case looks very similar for the same reasons as the previous part.

Radial induction in air gap Figure 3b shows the variation around the machine for the nonlinear case. The difference with the linear case is minimal because there is not much saturation. Per pole shoe the current in the armature windings runs in the same axial direction, therefore the radial induction is minimal in the middle of the pole shoe. At the edges, where the current changes direction, the radial induction is maximal.



(a) Flux lines (b) Variation of the radial induction component

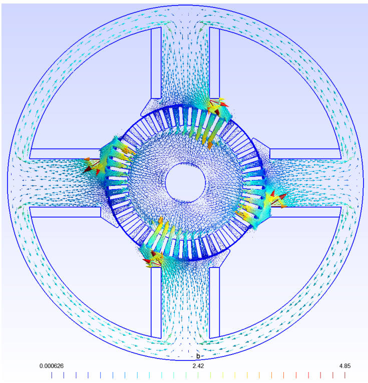
Figure 3: Zero field operation for the nonlinear case

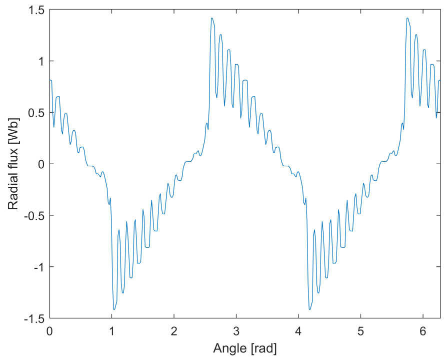
Pole flux The nonlinear case has $-4.2188 \cdot 10^{-7}$ Wb and the linear case has $-3.3683 \cdot 10^{-7}$ Wb pole flux. There is a small difference, but this is neglectable when compared to the nominal excitation field.

Torque Once again the values between the three measurements differ a lot, but since they are close to zero it is not very meaningful.

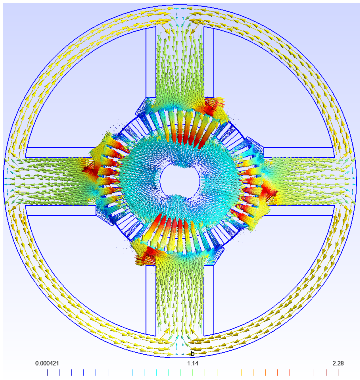
4 Load operation

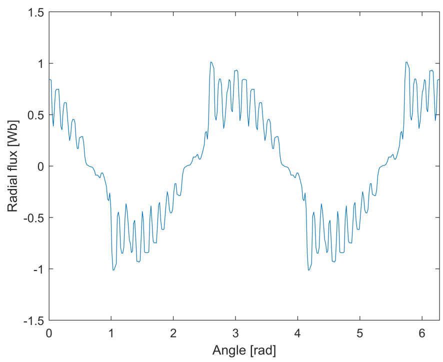
Here an armature current is applied to the motor, to model a load. The flux lines and variation of the radial induction in the air gap are shown in figure 4 on the left and right side respectively, for both the linear and nonlinear case.





(a) Linear model





(b) Nonlinear model

Figure 4: Nominal load operation

Radial induction in air gap In the table below it is clear that with increasing I_a for a nominal I_e, the radial induction decreases because the field generated by I_a counteracts the excitation field. When increasing I_e for a nominal I_a, the radial induction increases because the excitation field is getting stronger but it does not increase linearly due to saturation.

$I_e = I_{en}$		$I_a = I_{an}$	
I_a [A]	B_{radial} [Wb]	I_e [A]	B_{radial} [Wb]
45	0.013965	0.85	0.0081482
90	0.013412	1.70	0.0134122
135	0.012528	2.55	0.0150689

Maximal and minimal pole flux The load operation is essentially the previous two configurations combined. This is clearly visible when looking at the radial induction in figure 4. The maximal pole flux occurs where the excitation field is in the same direction as the flux created by the armature current. This decreases along the pole shoe until a minimum is reached at the middle between two poles.

Pole flux calculation Using the radial induction in the air gap calculated by the model, we can calculate the pole flux as:

$$\phi = R_\delta L_{az} \int_{\frac{3\pi}{4}}^{\frac{5\pi}{4}} B d\theta = 0.0133\,\mathrm{Wb}$$

Here is $R_\delta = R_{ro} + a_g = 116\,\mathrm{mm}$. The value from the FE model is $0.013\,412\,2\,\mathrm{Wb}$, which is in the right order of magnitude.

Torque In table 1 the torques are given for the three parts of the air gap. The relative difference in percentages are:

- Rotor - Stator: 0.7%
- Rotor - Moving band: 0.3%
- Stator - Moving Band: 0.1%

These values should be within 5% of each other to prove the model is precise enough. This has been done making sure the mesh inside the air gap is fine enough. This torque is also the average torque a DC machine will deliver under nominal load. The rated value of the torque was calculated to be $94.5\,\mathrm{N\,m}$, which is about 5% from to the ones we get from the FE analysis.

Location	**Torque** [Nm]
Rotor	100.161
Stator	100.882
Moving Band	99.8304

Table 1: Torques in load condition

Torque and e.m.f. constant Now the k_e is calculated for the nominal field current and three different armature currents: $0.5I_{an}$, I_{an} and $1.5I_a$. The results are given in table 2. We see the values for k_e rise as the load current rises and the k_e's are also larger than the one calculated for the noload characteristic. This is because there is saturation at work here. The nominal I_e causes already some saturation but the extra flux from the load current makes the steel go even further in saturation.

I_a [A]	T_e [N m]	ϕ [Wb]	k_e
45	51.514	0.013965	81.975
90	100.161	0.013412	82.977
135	141.935	0.012528	83.922

Table 2: k_e calculation for different loads

5 Symmetry

For the modeling of this machine, symmetry could be used to reduce the model complexity. Only one fourth of this motor needs to be modelled to get a full result of the MVP. From the flux density plots it can be seen that if one pole is modeled with on both sides half of the gap between the poles, every phenomena would be modeled. The boundary conditions for the outer edge of the stator stay the same, but at the symmetry axis between the poles an anti-periodic boundary condition must be applied. Each subsequent pole has an inversed polarity, so at the other side of the symmetry axis the effects have to be inversed as well.

Conclusion

In this report a brushed DC machine was modelled and multiple working conditions were analysed. Both linear and nonlinear materials were modelled, and the differences were checked. This was mostly visible in the noload characteristic and the flux densities in the air gap. The effects of the saturation were also visible in the torque under load.