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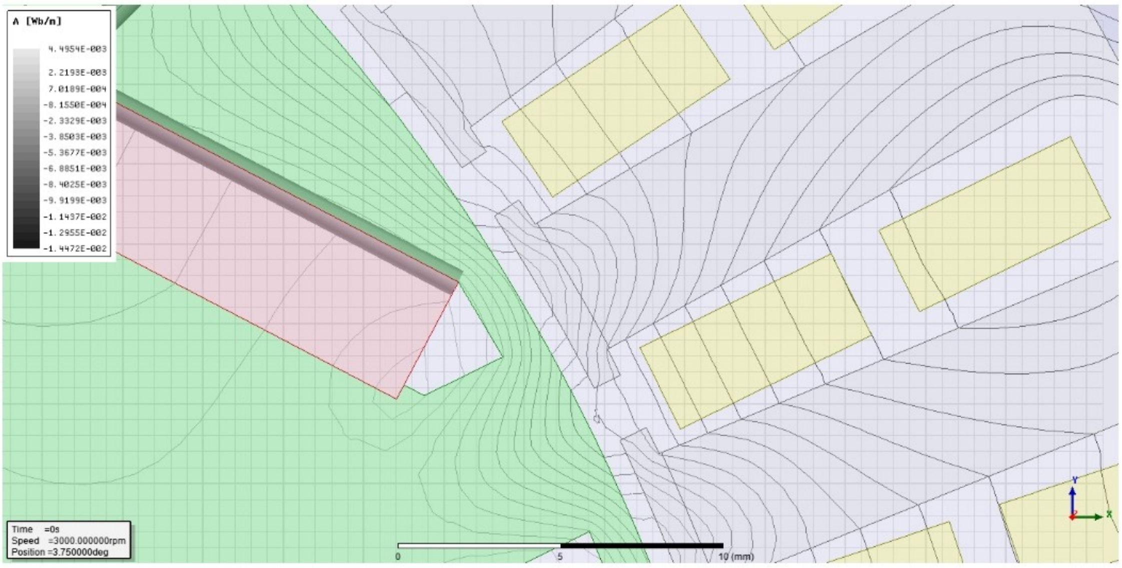

Study of a permanent magnet motor for an electric car during three phase short circuit

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Cover page: Equipotential lines of the magnetic vector potential at high demagnetising current.

Abstract

Permanent magnet synchronous motors are often used in drive trains for electric and hybrid vehicles. They are exposed to high loading, temperature and sometimes to short circuit of the stator. The short circuit currents are analysed with the use of Maxwell and Simulink. The nonlinear inductances are calculated in Maxwell and used in a Simulink model by means of interpolation.

In this report, the calculations show that the currents in d and q-direction oscillates and the amplitudes are high which means that the model need an input of inductances that are analysed up to four times the normal peak current.

The worst case is when the short circuit starts from an operating point that generates maximal negative torque. I.e. when the machine is generating maximum power and operates on maximum torque per ampere. At higher speed the starting torque will be lower due to field weakening. For the investigated machine, the flux density in one of the magnet corners will be as low as -0.3 T in the worst case, but 2 mm's from the corner the conditions are better and the flux density is -0.15 T.

Content

1. Introduction.

The permanent magnet machines are often used in traction applications where the stress on the machine is high. The temperature is high and current levels are also high and some times it is also exposed to a short circuit situation, where the stator is short circuited to avoid over voltages on the DC-link side. The permanent magnets can be demagnetised irreversible if they are exposed to a short circuit leading to a too high demagnetisation current and especially when the rotor magnets are experiencing a high temperature, since the magnet will be more sensitive to low flux density with an elevated temperature. The low flux density is caused by applied flux from the stator winding caused by the current.

In order to prevent the magnets from becoming demagnetised, high temperature magnet materials are used. It's rather normal to use magnets that can withstand 180-200 °C.

This report deals with a short circuit event of an electric machine and both a FEM-program and Simulink are used in the analysis.

This have been studied earlier in synchronous generators [4,5] both using FEM and other methods, but lacking in litterature is the use of nonlinear models on pmsm traction machines.

2. Magnetic material and magnetic domains

A typical NdFeB-material have the behaviour according to Figure 1, which shows the BH-characteristics of a Vacuumschmelze-material called 633, [1]. It is an example of material that can be used in applications with a rather low max temperature.

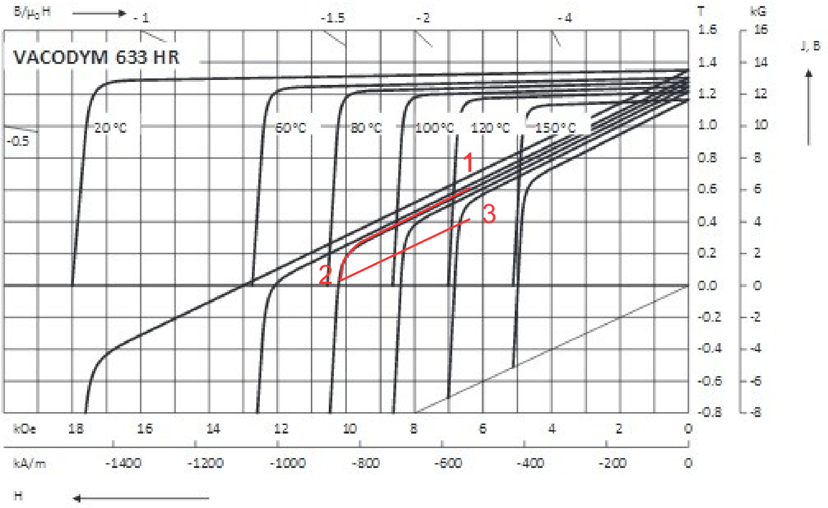


Figure 1. BH-characteristics of Vacodym 633.

The upper curves show the intrinsic flux density, i.e. the flux density of the 'normal' curve minus flux density in vacuum. The normal curves are of more interest and a working point can be established when the geometry and material data of the surroundings are known. A trajectory is depicted with the red line, at 1 the magnet has a flux density that is decided by the geometry and material. When negative d-current is applied to the machine, the flux density is lowered towards 2. And if the current is so large that the flux density in the magnet is decreased towards zero, i.e. we are at a point 2. It will partially be destroyed even at this low temperature of 80 °C . When the current goes back to zero the flux density will not follow the trajectory 2 towards 1, it will follow the line from point 2 to point 3. This results in lower flux density and working conditions of the magnet, which results in higher current in the machine, the machine will become warmer and the next time a short circuit condition occurs it will become even more demagnetised. So there is a possibility that the demagnetisation will have a 'positive' feedback and amplifies itself.

As indicated in Figure 1, the strength of the NdFeB-magnet diminishes as the temperature increases and it is of vital interest to keep the working point on the right side of the knee, where the flux density slope is altered. When the flux density is dropped below the knee it results in an irreversible loss of magnetism.

In traction motors the flux in the air gap is strongly dependent on the stator current which affects the magnets. If the magnets are mounted on the surface of the rotor, the stator current affects the magnets directly but a solution with buried (inset) magnets will protect the magnets. However excess currents affects even these magnets and it is crucial to chose a magnet that can withstand demagnetisation without beeing damaged due to temperature. The temperature can be quite high in these highly utilised machines.

3. The linear model of the motor

The current and voltage of an electric machine can be written as

$$\begin{aligned} u_d &= Rs\, i_d + \frac{d\psi_d}{dt} - \omega\psi_q \\ u_q &= Rs\, i_q + \frac{d\psi_q}{dt} + \omega\psi_d \end{aligned} \qquad (1)$$

If the machine has nonsaturated materials the flux is proportional to the current. The linear equations of the permanent magnet machine are

$$\begin{aligned} u_d &= Rs\, i_d + L_d \frac{di_d}{dt} - \omega L_q i_q \\ u_q &= Rs\, i_q + L_q \frac{di_q}{dt} + \omega\left(L_d i_d + \psi_m\right) \end{aligned} \quad , \qquad (2)$$

, where the analysed machine has

$R_s = stator\ resistance = 0.039\,\Omega$
$L_d = inductance\ d - direction = 0.25\,mH$
$L_q = inductance\ q - direction = 0.6\,mH$
$\psi_m = resulting\ fundamental\ magnet\ flux = 0.075\,Wb$.

The amplitude of the currents and voltages has the same value as the amplitude of the phase currents and voltages. In some cases in the report we may mention the RMS-values, just for convenience.

At steady state with the machine terminals short-circuited the currents may be solved analytically resulting in

$$\begin{aligned} &0 = R_s i_d - \omega L_q i_q \\ &0 = R_s i_q + \omega (L_d i_d + \psi_m) \\ &R_s \ll \omega L_d \\ &i_q \approx \frac{R_s i_d}{\omega L_q} \\ &i_d \approx -\frac{\psi_m}{L_d} \end{aligned}$$

, i.e. the quadrature current is low if the resistance is low, which means

there is a low torque formed when this short-circuit occurs and the current in d-direction is opposing to the magnet flux. The magnitude of the direct current is so high that the flux in the magnet is strongly diminished.

However, a problem is that during a transient phase after the short circuit, the quadrature flux exchange energy with the direct flux which results in higher current than the steady state value. It's important to know how high this current might be and especially if the currents exceed normal values, the magnetically conducting material will be saturated.

4. Non linear model of the machine

At high current levels, the core material of the machine will be saturated which means that the linear relation between current and flux will instead become nonlinear with a certain saturation level where increased current will result in a very low flux increase. Transient analysis of the nonlinear model must include the change of the inductances and can be found through expansion of the inductance derivative.

$$\begin{aligned} &u_d = R_s i_d + \frac{d\, L_d(i_d, i_q) i_d}{dt} - \omega L_q(i_d, i_q) i_q \\ &u_d = R_s i_q + \frac{d\, L_q(i_d, i_q) i_q}{dt} + \omega (L_d(i_d, i_q) i_d + \psi_m) \\ &\frac{d\, L_d(i_d, i_q) i_d}{dt} = L_d(i_d, i_q) \frac{di_d}{dt} + \frac{dL_d}{di_d} \frac{di_d}{dt} i_d + \frac{d\, L_d}{di_q} \frac{di_q}{dt} i_d \\ &\frac{d\, L_q(i_d, i_q) i_q}{dt} = L_q(i_d, i_q) \frac{di_q}{dt} + \frac{dL_q}{di_d} \frac{di_d}{dt} i_q + \frac{d\, L_q}{di_q} \frac{di_q}{dt} i_q \end{aligned} \qquad (3)$$

A solution can be found by using a state space model

$$\begin{aligned}&\frac{dx}{dt}=Ax+Bu\\&y=Cx+D\end{aligned}\quad , \qquad (4)$$

where x represent the currents, u is input signals and y is the output from the system, i.e. $y=x$ and assuming that an update of the inductance values during the simulation can represent the machine.

$$\begin{aligned}&x_1=i_d, x_2=i_q\\&u_1=u_d-\omega L_q i_q\\&u_2=u_q+\omega(L_d i_d+\psi_m)\\&A=L^{-1}R\\&B=C=I\\&D=0\end{aligned}\quad , \qquad (5)$$

where I is the unit matrix and the matrix L include the nonlinear inductances which are evaluated every time step, through an interpolation in the data that are found from the FEM-analysis. u will include the rotation components $L\omega$.

The L-matrix is a 2*2 matrix with the components,

$$\begin{aligned}&l_{11}=L_d+\frac{dL_d}{di_d}i_d\\&l_{12}=\frac{dL_d}{di_q}i_d\\&l_{21}=\frac{dL_q}{di_d}i_q\\&l_{22}=L_q+\frac{dL_q}{di_q}i_q\end{aligned}\qquad (6).$$

We may notice that the extra terms in the matrix are multiplied with the current, i.e. the influence of these terms increases with the current.

Another way of handling this is to calculate the flux of the machine,

$$\begin{aligned}&u_d=R_s i_d+\frac{d\psi_d(i_d,i_q)}{dt}-\omega\psi_q(i_d,i_q)\\&u_d=R_s i_q+\frac{d\psi_q(i_d,i_q)}{dt}+\omega\psi_d(i_d,i_q)\\&\frac{d\psi_d(i_d,i_q)}{dt}=\frac{d\psi_d}{di_d}\frac{di_d}{dt}+\frac{d\psi_d}{di_q}\frac{di_q}{dt}\\&\frac{d\psi_q(i_d,i_q)}{dt}=\frac{d\psi_q}{di_d}\frac{di_d}{dt}+\frac{d\psi_q}{di_q}\frac{di_q}{dt}\end{aligned}\qquad (7),$$

which might result in a more simple interpolation but will on the other hand need an interpolation from flux to current.

5. Analysed machine

The machine that is analysed is a modified PRIUS-machine used in several studies at the division of Energy and Environment, [5]. One eight of the machine is shown in Figure 2. It can be seen that there are two magnets per pole and they are arranged in a 'V'-configuration. A bridge at the corners of the magnets supports the structure and as the bridge is saturated, the main flux from the magnet are pressed out in the air gap and into the stator.

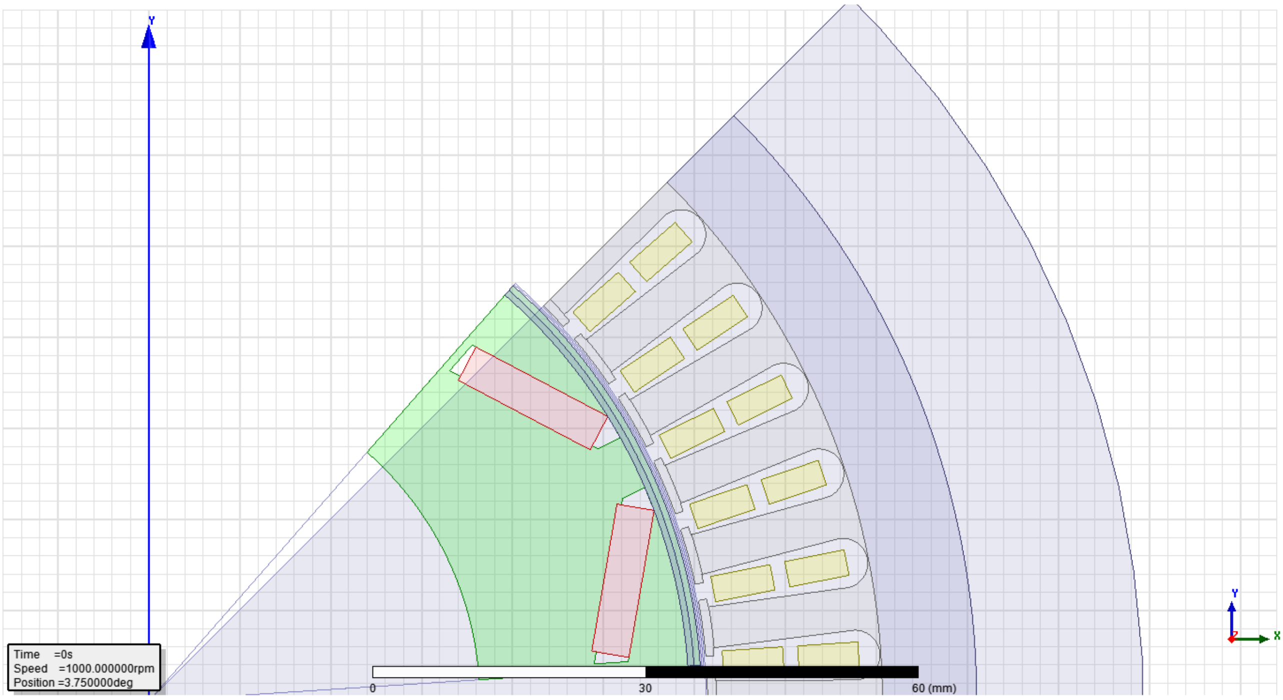


Figure 2. One eight of the analysed machine.

The main data of the machine are displayed in Table 1.

Table 1. Main data of the analysed machine.

Air gap diameter	123
Outer yoke diameter	182
Core length	150
Number of slots	48
Number of poles	8
Slot area	81.44 mm2
Magnet cross section	40 * 4.55 mm2
Number of conductors/slot	12
No of parallell branches	4

Nominal current (1 p.u.)	251 Arms
Resistance	0.039 Ω
Magnet, B_r	1.18 T
Magnet, H_c	750469 A/m

The remanent flux density corresponds to the material NMX_37F @ 70 ºC, from Hitachi Metals. It is a material that can be fully demagnetised at temperatures up to 140 ºC.

The current density of the machine at peak current is 30 A/mm^2, which is slightly higher compared to what is used in the Prius application.

The inductances of the machine are calculated using Maxwell and the inductances L_d and L_q are shown in Figure 3.

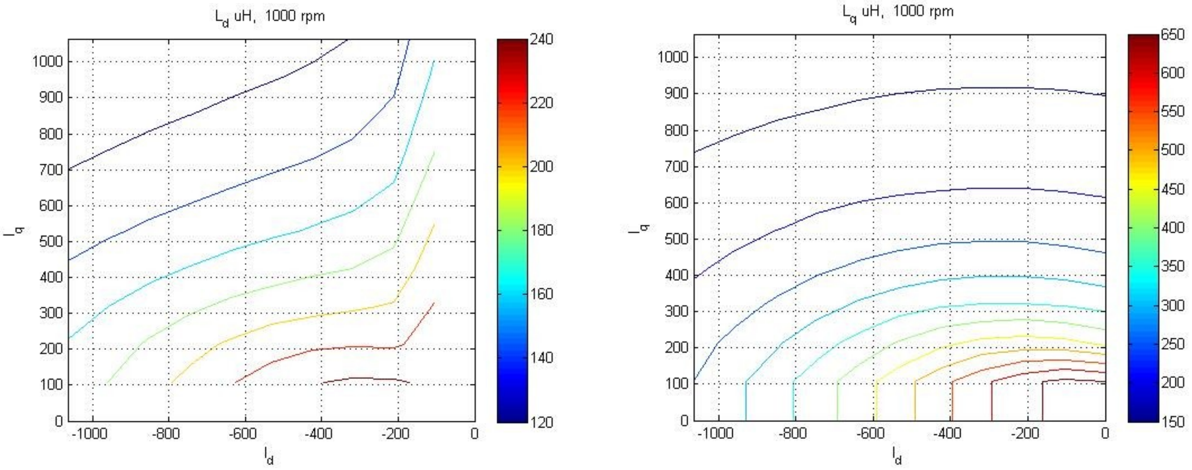


Figure 3. Inductance values, L_d and L_q vs currents i_d and i_q.

The derivation of the inductance is described by the matrix displayed in Figure 4. It is also displayed how the flux from the magnet changes with the currents.

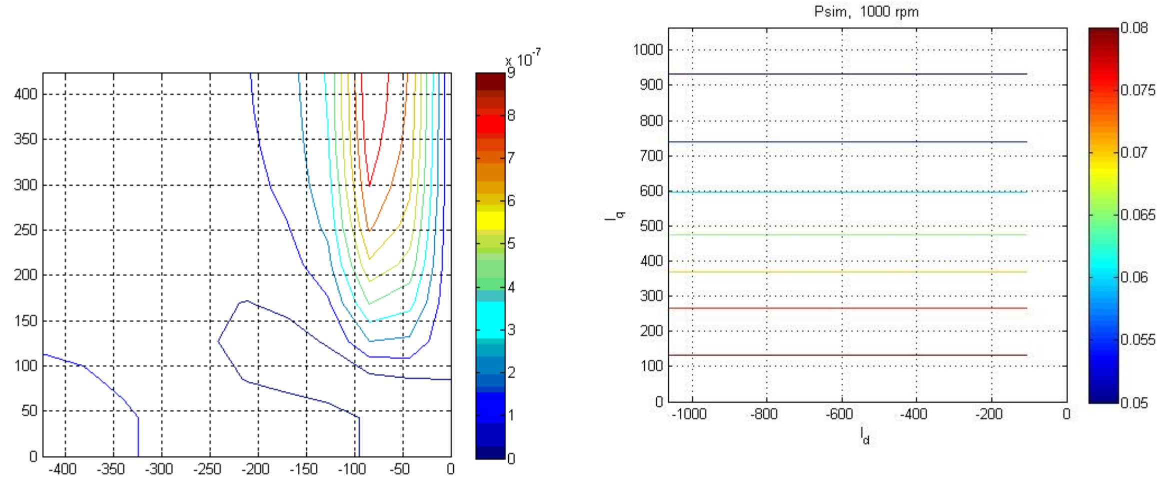


Figure 4. Iso-curves of dL_d/di_d and the flux from the magnet.

6. Simulink model

In order to simulate the short circuit, a model is created and by using an ordinary time-domain simulation program as Matlab Simulink a solution can be found. In the case where we have nonlinear material in the machine the model shall take care of the crossacting terms in (6).

From the Maxwell program the inductances are determined and they are represented by a matrix of values that depends on the actual current i_d and i_d. In the simulink model the actual value of the inductance and partial derivatives of the inductances, that are outputs originating from Maxwell, are interpolated using the interpolation with prelookup-blocks. See Figure 5.

The PM-motor is represented using an s-function with inductance and inductance derivative as inputs. In the s-function the inversion of the L-matrix is done for each calculation step.

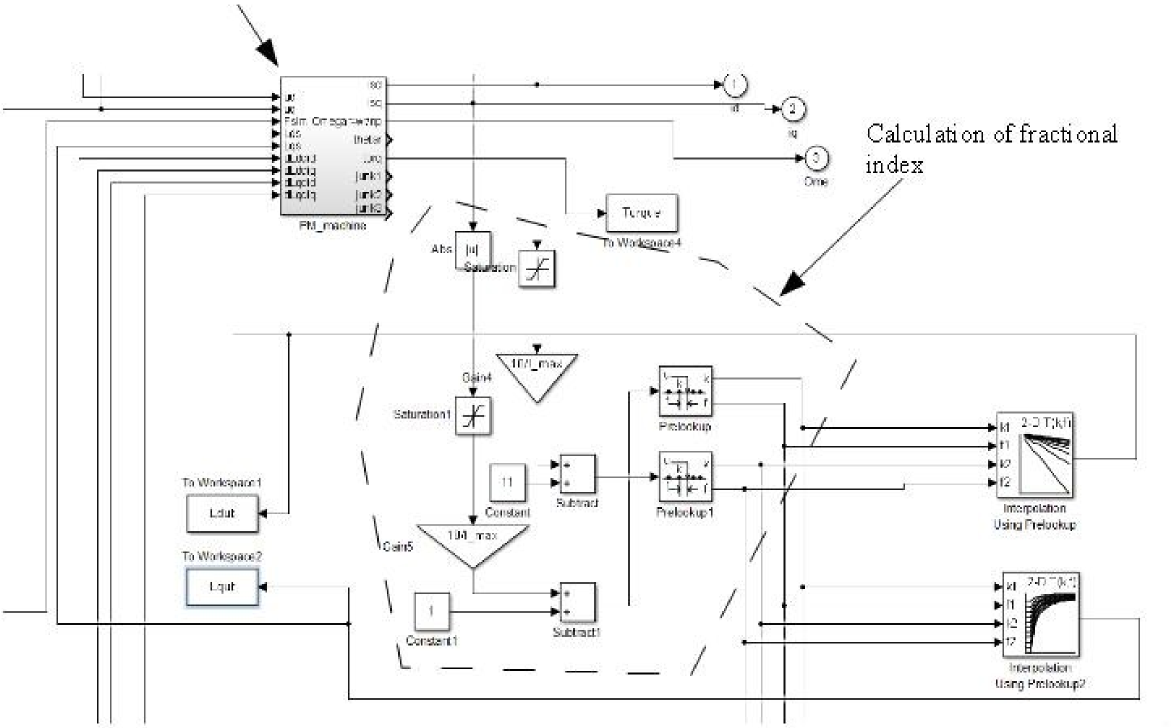


Figure 5. Simulink model

7. Result

7.1 Verification of the simulink model

In order to verify that the simulink model is correct it is verified in two steps. At first a linear simulation is done with Maxwell where the current starts at,

$$i_d(t=0)=-50\,A$$
$$i_q(t=0)=320\,A$$

and the winding voltages are set to 0 V. For verification, the permeability of the iron core is set to 200 and the inductances are calculated to L_d=0.551 mH, L_q=0.668 mH. The flux from the magnets are ψ_m=0.022 Wb, which are used in the Simulink model. I.e. we use a linear model of the machine both in the Simulink and Maxwell model.

The resulting currents from the two simulations are shown in Figure 6 and there are good conformity between the models.

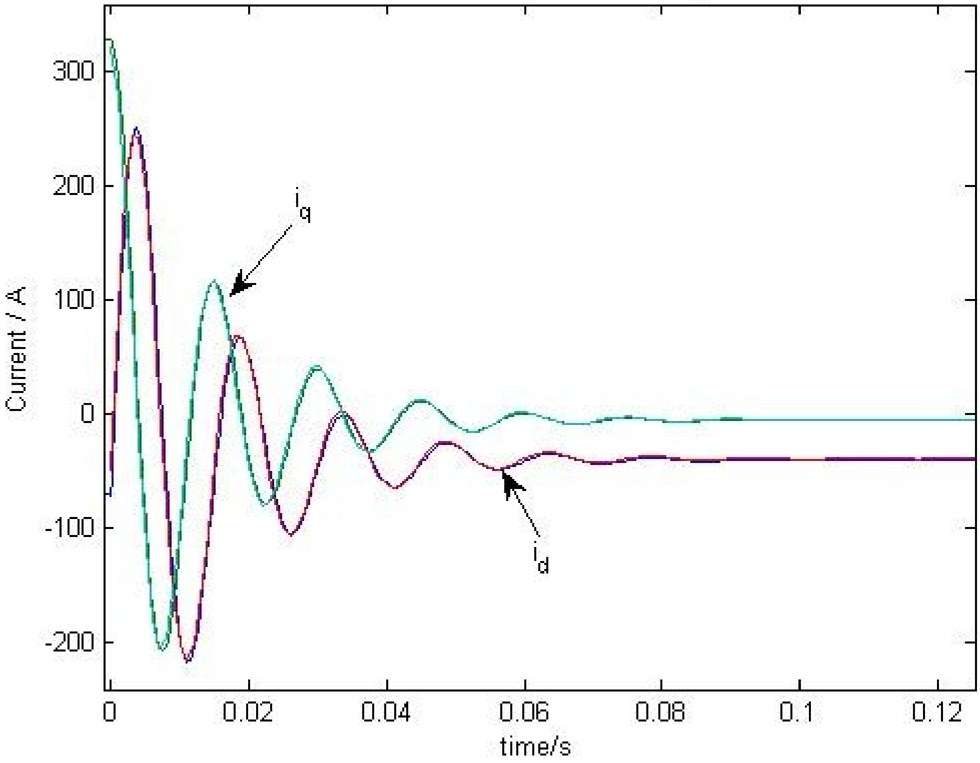
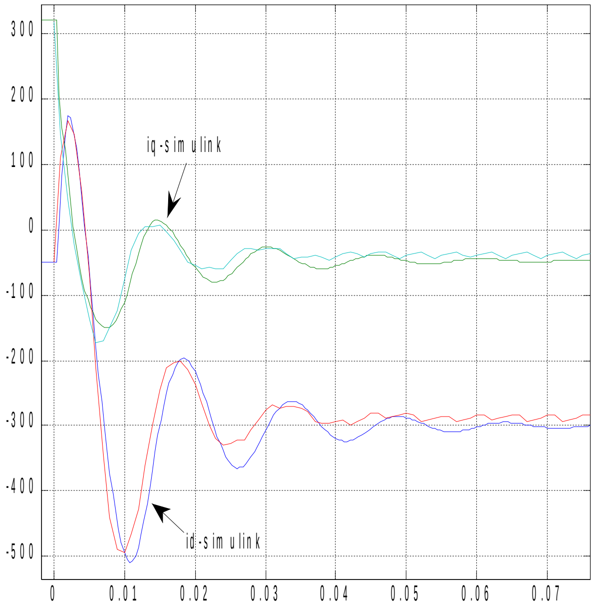


Figure 6. Resulting currents from linear Maxwell simulation and from the Simulink model.

7.2 Nonlinear model

In order to verify the nonlinear model, a simulation is done with the same starting value as the linear simulation but in this case the material is nonlinear and this is also taken into account in the Simulink model, see Figure 7 where we can see that the models produces the same current.



Figur 7. Nonlinear material Maxwell and Simulink modell.

When the short-circuit occurs the flux decays to a point determined by the flux from the magnets themselves.

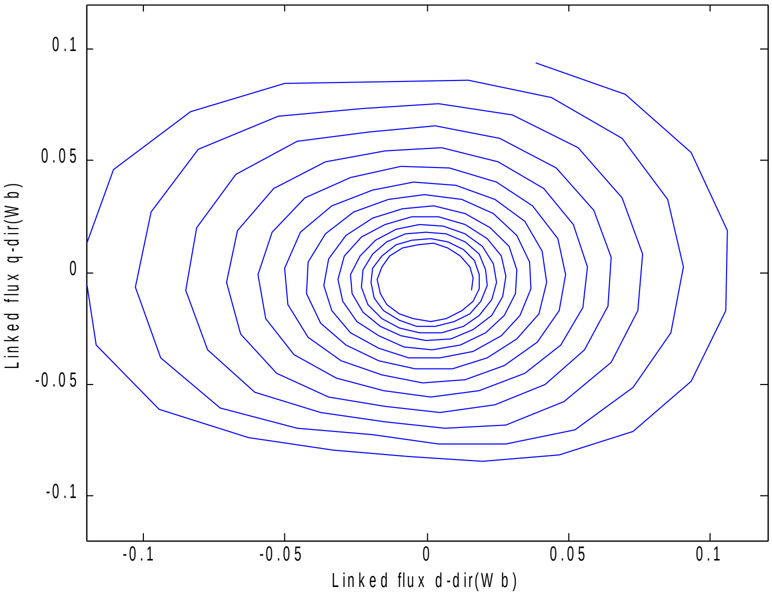


Figure 8. Flux in d- and q-direction.

8. Demagnetising current and resulting flux density in the magnet

A negative d-current is applied to the machine and the flux density in the magnet is analysed by means of the Maxwell program. The flux density is evaluated along four lines at the positions indicated in Figure 9. A negative current of 1, 2 and 3 p.u., where 1 p.u. corresponds to maximum current from the converter, i.e. 3 p.u. is quite a high currrent level. The current is applied in the negative d-direction. The resulting flux density is shown in Figures 10-11.

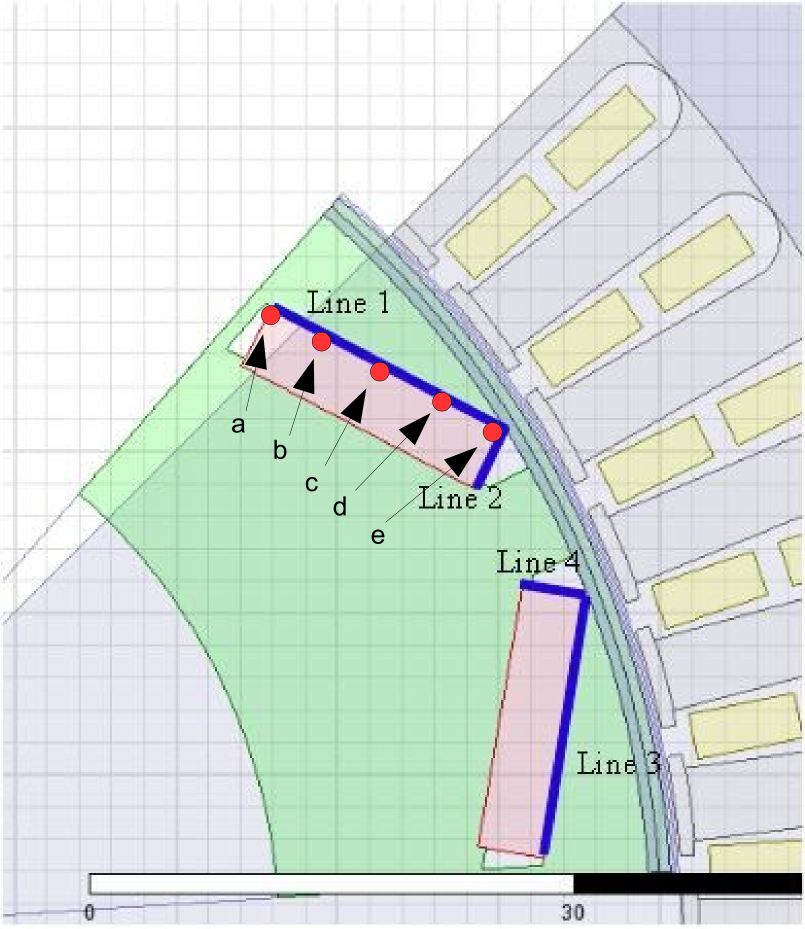


Figure 9. Lines and points along which the flux density is evaluated

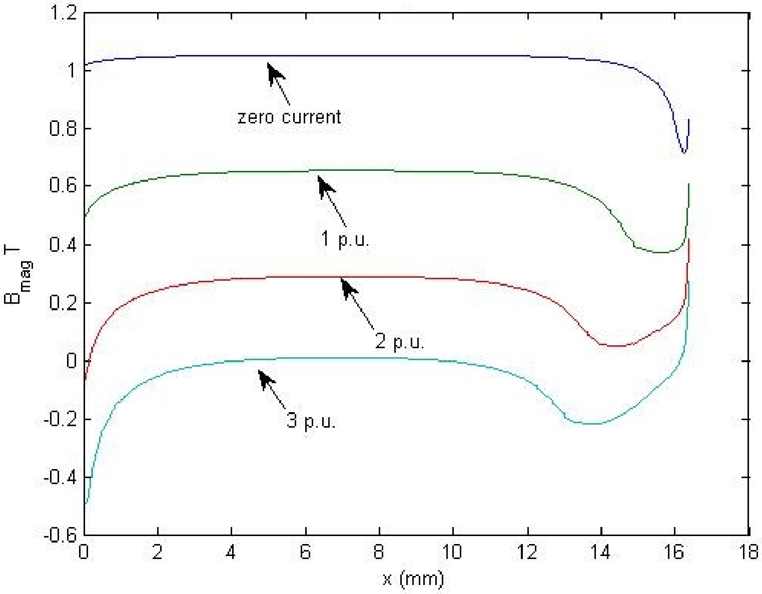


Figure 10 Flux density along line 1.

At normal operation the flux density is above 0.4 T which shouldn't be any problem but at higher current levels the flux density goes even below zero flux density.

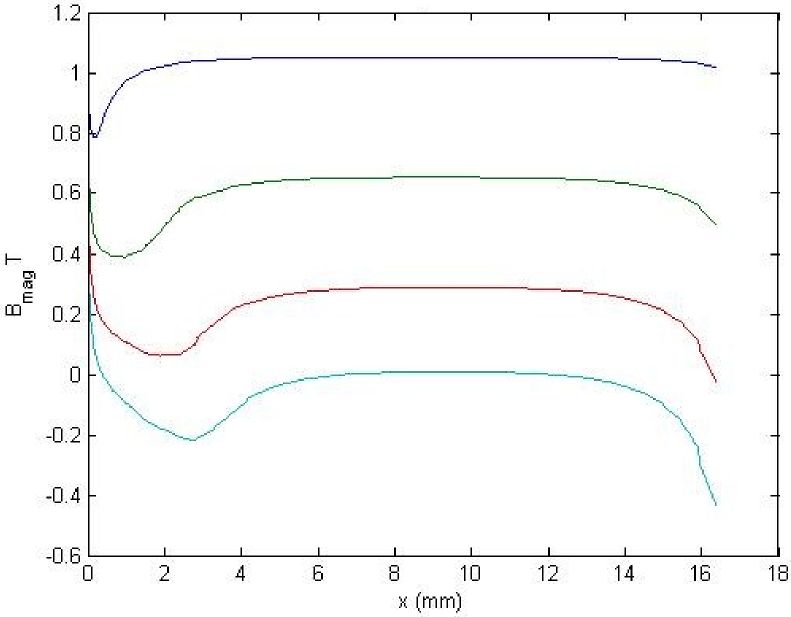


Figure 11. Flux density along line 3.

Along lines 2 and 4 the counteracting flux density from the winding is directed in a direction that is 90 degrees from the magnetisation. Along these lines, there is little risk of demagnetization of the magnet.

As can be seen, the flux density on the surface, i.e. along line 1 and line 3 starts to be negative when the current exceeds 2 p.u. of negative d-current in some parts of the magnets. The flux density towards the edges of the magnet drops below zero. A current in the range of 3 p.u is highly troublesome because the flux density is negative on the most of the magnet surface and pairing this with high temperature will certainly start to demagnetise the magnet, unless it is of a very high quality and can withstand high temperature.

The equipotential lines of the magnetic field are shown in Figure 12, when negative d-current is 1 and 2.pu.

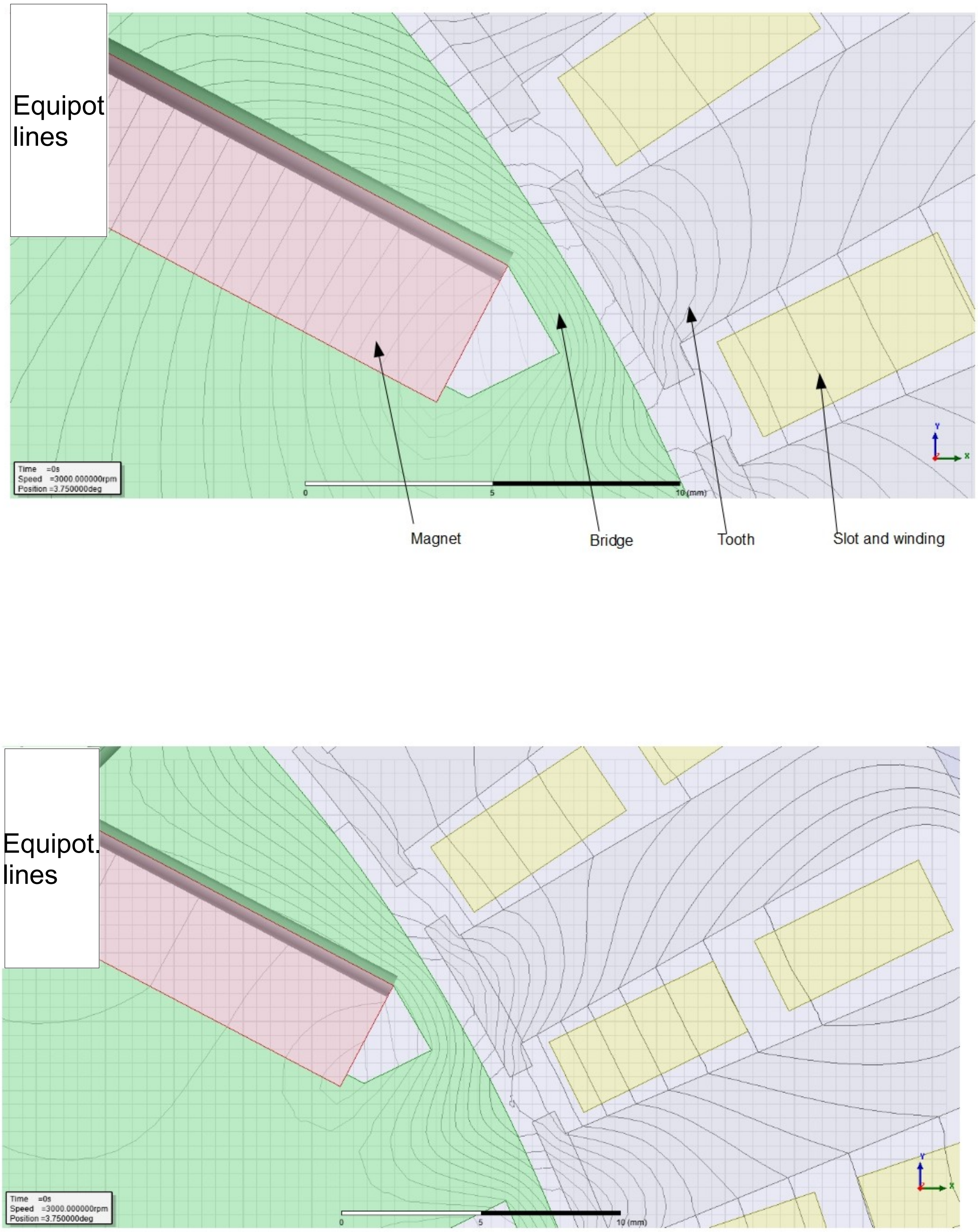


Figure 12.a Equipotential lines at i_d=-1 p.u. b. Equipotential lines at i_d=-2 p.u.

It is quite clear that the magnets are protected from the negative flux, most of it circulates in the stator and through the bridges of the rotor. In the case of 2 p.u. negative d-current the fluxlines through the magnet are few and most of the flux is pressed into the bridges.

9 Worst case analysis

When a short circuit of the machine occurs it may operate in different conditions. The torque vs speed diagram is illustrated in Figure 13. Depending on if the speed is low or high, different amplitudes of the currents can be expected. The actual position of the current vector can also have a profound effect on the transient that is developed after the short circuit.

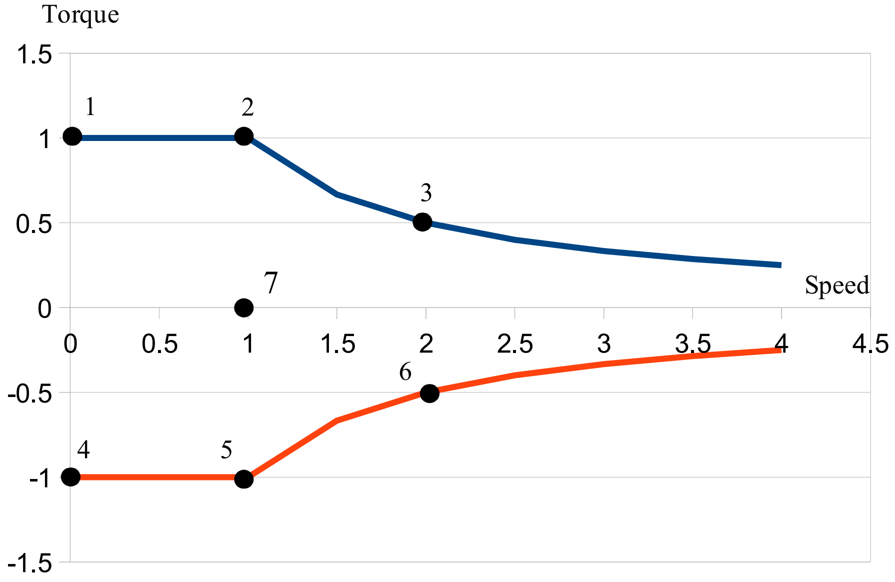


Figure 13. Torque vs speed of a traction motor, with numbered operating points.

Table 2. Different operating points

Point	Characteristics	Current (Arms)
1	Low speed, high torque	i_q=176, i_d=-176
2	Medium speed, high torque	i_q=176, i_d=-176
3	Heigh speed medium torque	i_q=100, i_d=-230
4		i_q=-176, i_d=-176
5		i_q=-176, i_d=-176
6		i_q=-100, i_d=-230
7	Medium speed no torque	i_q=0, i_d=0

As a start the, linear model is used in order to find the worst case of demagnetisation. The operating point of the machine and converter is assumed to be the starting current when the short circuit occurs. At first different magnitudes of the q-current are used and the current in d-direction is zero. See Figure 14 where it is shown that the q-current starts an oscillation together with the current in d-direction when the short circuit occurs. When the current in q-direction starts at 2 p.u. , the current in d-direction oscillates with almost the same magnitude as the starting current in d-direction. The currents are damped towards the final value decided by the flux and inductance. The speed of *n*=1000 rpm is used which means that the inductance is relatively high compared to the resistance of the machine.

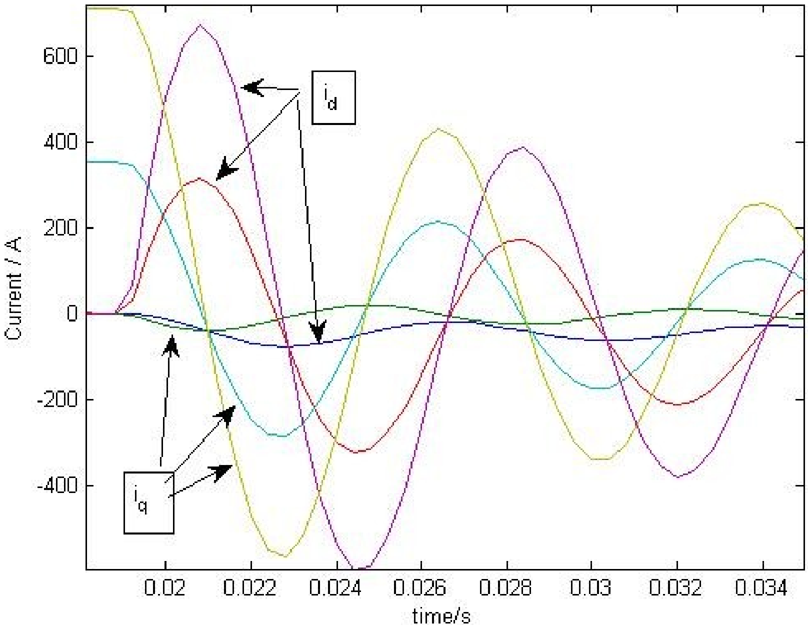


Figure 14. Resulting short circuit currents when starting with different quadrature current. *n*=1000 rpm

A high initial current in q-direction influences the oscillation in d-direction. In Figure 15 it is shown that the negative peak in d-direction is mostly dependant on the initial value of the current in q-direction.

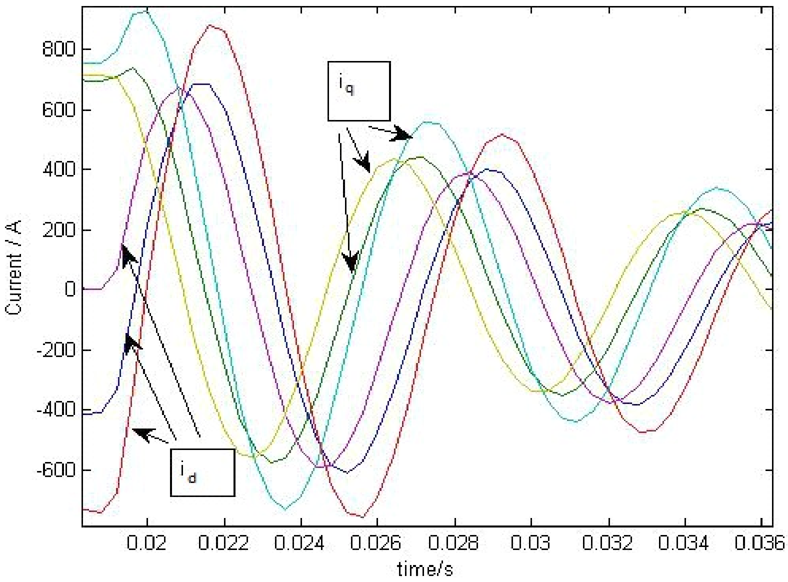


Figure 15. Resulting short circuit currents starting with 2 p.u. In q-direction and different starting amplitude in d-direction. *n*=1000 rpm

Difficult is judging from linear theory when starting with high current in d-direction. Worst is when there is high current in both d- and q- direction, the resulting peaks will be high.

The influence of speed is exemplified with a series of simulations with the speed 200, 1000 and 4000 rpm. 8000 rpm is also analysed but the difference to the result in the case of 4000 rpm is only the frequency at which the currents oscillates. Figure 16 shows the transient currents after a short circuit but with different speed. In this study the d and q-currents have the same amplitude but different signs.

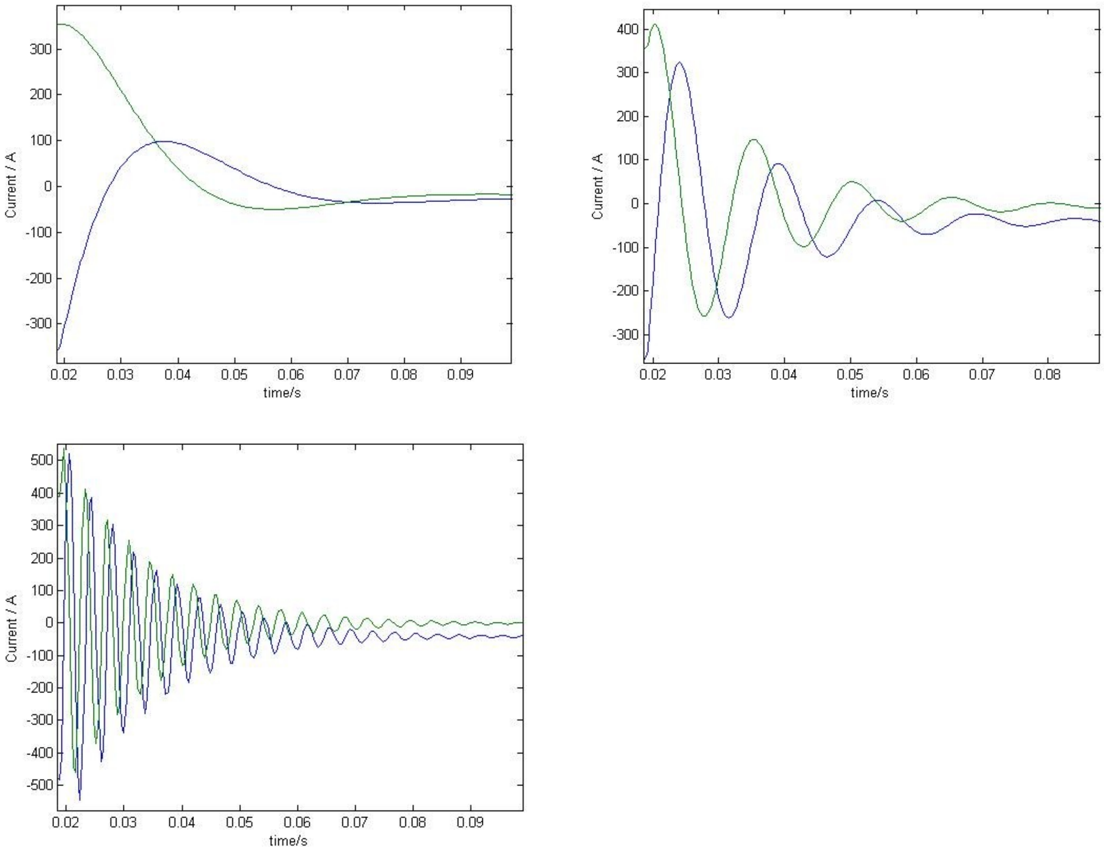


Figure 16. Short circuit currents at 200, 1000 and 4000 rpm

The amplitudes of the currents follow the same falling slope with the difference of oscillation frequency. The currents oscillate with the fundamental electrical frequency of the machine.

There is a difference in torque production during a short circuit, when the speed is low, 200 rpm in the case in Figure 17, the torque just decays to a low value. At higher speed the torque oscillates with the same magnitude as the starting torque. The steady-state value is higher at low speed compared to the steady-state value at high speed.

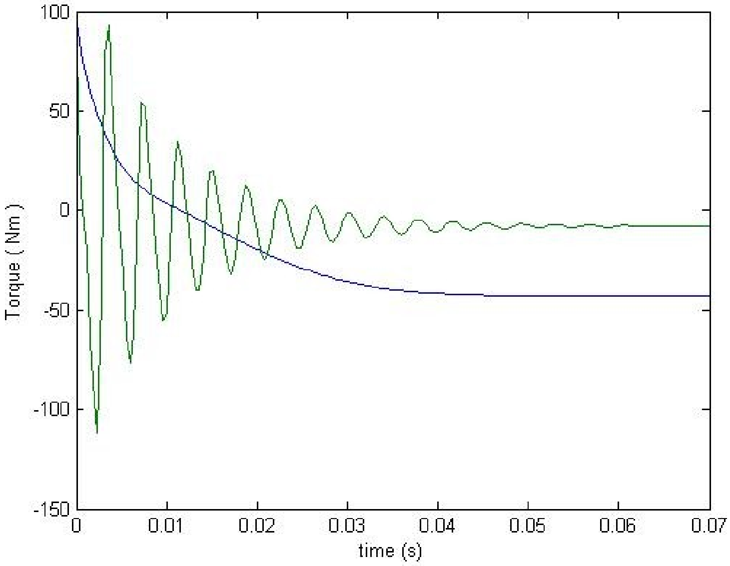


Figure 17. Machine torque during a short circuit at 200 and 4000 rpm.

Now we use the nonlinear model to find the minimum current level in d-direction. The results are shown in Table 3.

Table 3. Resulting minimum d-current from non-linear model at different operating points and speed

Speed (rpm)	i_d=0 i_q=0	i_d=-126 i_q=0	i_d=-126 i_q=-126	i_d=-176 i_q=-126	i_d=-176 i_q=-176	i_d=0 i_q=-251
500	-581	-431	-656	-630	-762	-1015
1000	-671	-533	-766	-733	-896	
2000	-724	-562	-832	-789	-965	
3000	-735	-566	-848	-805	-995	
4000	-753	-577	-884	-815	-1010	
5000	-759	-580	-905	-810	-1000	

From the Table 3 we can see that a high current i q-direction is producing a high current in the d-direction just as the linear model concludes. The amplitude of negative d-current also increase with the speed, but above 3-4000 rpm it is constant.

10. Study of the flux density on the magnet surface

During the simulation of a short circuit the flux density is evaluated in different parts of the magnet. The surface facing the pole direction is evaluated. In Figure 18 the minimum flux density on the surface of the magnet is shown during a short circuit. The speed is 3000 rpm and the initial currents are i_d=-1065 and i_q=533 A.

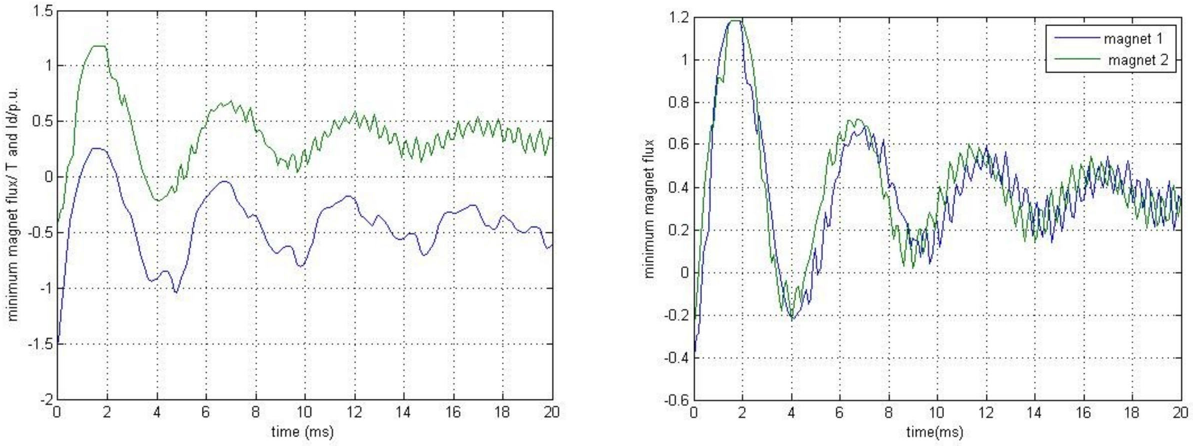


Figure 18. Flux density on magnet 1 and current in d-direction, (scaled with 753 A). Minimum magnet flux density on the magnets surfaces.

The flux density drops to zero during the first period and stabilises after that.

The flux density on different spots during the short cicuit is shown in Figure 19.

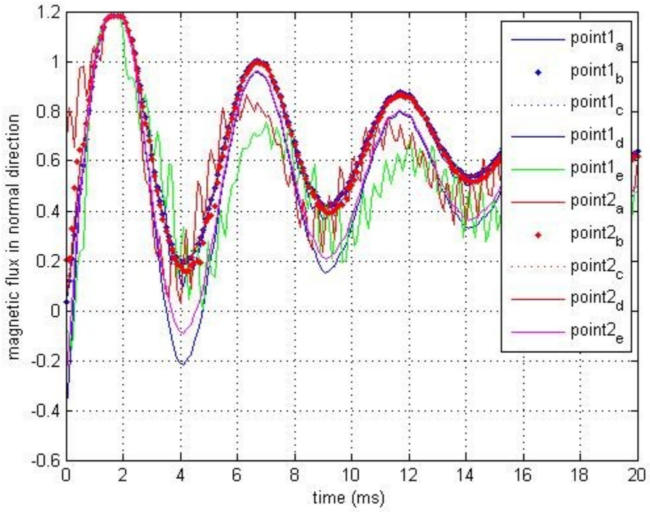


Figure 19. Flux density at different locations along the magnet surface. Evaluation points according to Figure 9.

At higher speed the flux density is somewhat lower but almost the same as at 3000 rpm.

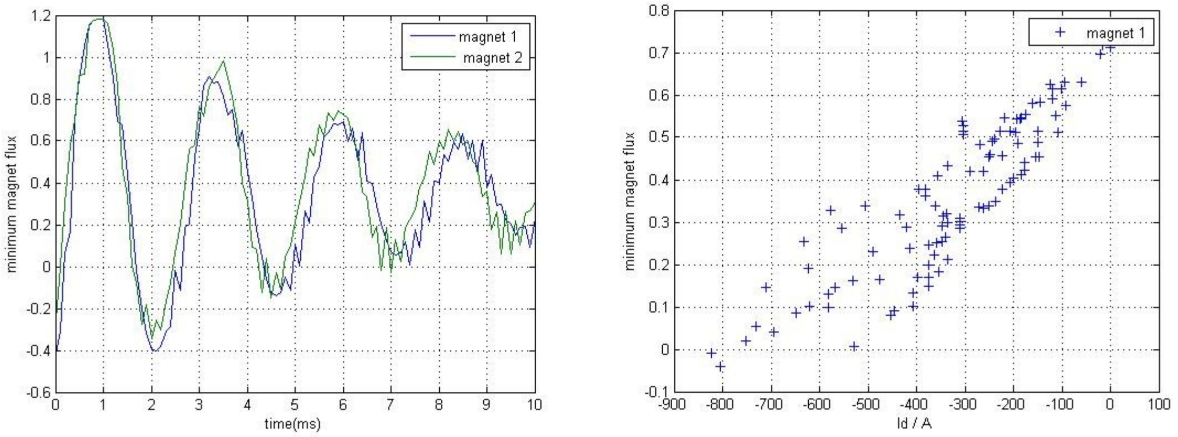


Figure 20. Minimum flux density at 6000 rpm along the magnet surface as function of time and of Id.

The minimum flux density at different starting currents are summarised in Table 4 and the conclusion is that the magnet is stressed in as most when the current vector starts between the negative d-axis and negative q-axis.

Table 4. Minimum flux density on the magnet surface at different starting current.

Starting current (Arms)	Magnet 1 (T)	Magnet 2 (T)
$i_q=251$, $i_d=0$	0.17	0.26
$i_q=0$, $i_d=0$	0.01	-0.01
$i_q=-251$, $i_d=0$	-0.32	-0.3
$i_q=-176$, $i_d=-176$	-0.24	-0.27
$i_q=0$, $i_d=-251$	0.17	0.26
$i_q=176$, $i_d=-176$	-0.15	-0.19

The resulting flux density doesn't differ so much but generally it's worse when the machine works in generator operation.

A test at low speed doesn't result in so high current as when the inductances dominate. At 300 rpm and starting with Iq=-251, Id=0 result in a minimum flux density of 0.5T which isn't worrying at all. The demagnetising problem seems to be a high speed problem.

In this latest study the lowest flux density is concentrated to the corner of the magnet, we can of course argue that there is always a radius on the corner which means that this low flux density isn't realistic. In Figure 10 and 11 it's obvious that the flux density increases fast if we evaluate the flux density, for instance of 1 mm from the corner. The flux density increases with some tenth of a tesla.

A new calculation is done and instead of studying the minimum flux density in the corner, the minimum flux density found in a region that is 1 and 2 mm from the corners is studied. In fact we have to move away 2 mm from the corner before the flux density is significantly changed. In Table 5 the minimum flux density is found when 2 mm's of the corner is omitted from the search, which is relevant if for instance the corner is round or if we can sacrifice the outer part of the corner.

Table 5. Minimum flux density on magnet surface at different starting current, when excluding 2 mm from the corner.

Starting current (Arms)	Magnet 1 (T)	Magnet 2 (T)
i_q=0, i_d=0	0.14	0.16
i_q=-251, i_d=0	-0.12	-0.15
i_q=-176, i_d=-176	-0.07	-0.09
i_q=0, i_d=-251	0.42	0.45
i_q=176, i_d=-176	0	0

The worst case is when starting from max current in negative q-direction, i.e. generator operation. If the speed is increased to 6000 rpm the negative flux density is Bmin=-0.23T and it increase slightly when speed is increased to 9000 rpm but the minimum flux density stabilises for higher speed. However when increasing the speed it is not possible to position all current in q-direction, the machine has to be supplied with a negative d-current in order to suppress the induced voltage.

11. Conclusion

In this report a modified Prius-motor has been examinated during short circuit. The analysis has been done using a dynamic simulation model in Simulink. The model includes nonlinear inductances and cross-coupling terms that include the influence of saturation in one direction due to the other axis. The short circuit of the machine has also been analysed with Maxwell, a FEM-program developed by Ansys.

During a short circuit, a transient starts that produces current in both d- and q-axis. The currents decay with a time constant of 40-50 ms, which is almost independent on the speed. The speed however has a direct influence on the frequency which with the currents oscillates. The steady state current in the d- axis is,

$i_d=\frac{-\psi_m}{L_d}$, if the resistance can be neglected. The peak value during the transient can be a lot higher and the worst case is when starting with all of the available current in negative q-direction. This means that the worst point is the point where field weakening starts in generator operation. At higher speeds, an amount of current has to be positioned in negative d-current which lowers the current in q-direction and hence the stress on the magnet.

The current in q-direction is close to zero, when the machine speed is high enough. This results in low steady state torque but during the transient the peaks can be high. The torque oscillates at high speed but at low speed the torque just decays towards a lower value. The mechanical impact of the transient has to be evaluated. For instance a short circuit at a slippery road that makes a bend can have a crucial impact on the vehicle behaviour.

The flux density on the magnet surface is strongly linked with the current in d-direction, so the current during the transient phase of a short circuit has to be investigated. The temperature of the magnet and the actual currents that can occur is of interest when designing the machine. An elevated temperature and a negative d-current could demagnetise at least parts of the magnet. In the studied construction the tips of the 'V' is the most affected parts.

Simulations on the actual constructions shows that the magnet can be impacted with a flux density that is as low as -0.27 T, when the starting current is between the negative d-axis and negative q-axis. i.e. when operating as a generator. If we restrict the survey to the magnets except the outer 2 mm's of the corners the flux density minimum is limited to -0.15 T.

Using a time-domain simulation of the currents can be done with a model in Simulink, with the inductance value also determined for high currents. In the report the ananlysis was made for currents up to three times the normal values but there were operating points where the simulation didn't produce relevant data.

12. References

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