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Subsea Permanent Magnet Motor with Damper winding

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Subsea pumps are often used in oil and gas production, but these pumps are often influenced by load variations that can cause problems for permanent magnet (PM) motors. In worst case can this cause the PM machine to jump out of synchronous speed. By placing damper winding in the rotor of the machine can prevent this from happening.

The student shall develop a numeric model of a permanent magnet motor with damper winding, where one can implement different rotor and damper winding configurations. The numerical model should be able to rotate depending on load variation and the stator field. The numerical model needs to be verified by analyzing well known cases. The results from these simulations should be the basis for new rotor design proposals for the intended subsea application of the machine.

Supervisor:
Robert Nilssen

Sammendrag:

Permanent magnet maskiner kan ha problemer med å håndtere ustabil last, som i verste fall kan føre til at motoren går ut av synkront turtall. Dette problemet kan bli unngått vis man utruster rotoren med dempeviklinger. Under lastvariasjon vill det bli indusert ett moment ved hjelp av dempeviklingen som vill dempe effekten av lastvariasjonen.

I denne masteroppgaven har det blitt laget en numerisk modell for en permanent magnet maskin med dempevikling, hvor motoren opererer med tanke på last momentet og stator feltet. Stator konstruksjonen som har blitt brukt i simuleringen var veldig kompleks noe som medførte at man måtte benytte en forenklet strøm kilden til statoren som er påtrykket som en strømtetthet, i vær fase. Denne forenklingen gjorde at motoren fikk en unaturlig demping i simuleringene, dette skyldes at ved å bruke strømtettheten gjorde at stator spenningen ikke ble tatt med i betraktningen under simuleringene.

Fra simuleringene kan man se at med en dempevikling med høy konduktivitet, vill dempe fortere enn en vikling med lav konduktivitet. Dette er på grunn av at en dempevikling med lav resistans vil produsere ett høyt moment når motoren er nært synkront turtall. Størrelsen på viklingen utgjorde også en forskjell, men dette var veldig lite. Under simuleringene viste det seg at en dempevikling med størrelsen 5-10% av størrelsen på stator viklingen dempet last variasjonene raskest.

Summary:

Permanent Magnet (PM) machines can have difficulties dealing with unstable loads, which in worst case can make the machine to step-out of synchronous speed. This problem can be avoided by equipping the rotor with damper windings. During load variation the damper winding will induce a torque to dampen the impact of the load variation.

To investigate the effects from using damper windings a numerical model of a PM machine was developed and studied in this thesis. The model is intended to operate with regards to load torque and the stator field. The stator configuration which was used in this thesis is very complex, which resulted in a lot of trial and error. Due to the complexity of the stator meant it had to be applied with a current density, which means that the voltage over the phases was not taken into account during the simulations. This simplification appears to have created an unnatural damping factor in the simulations.

Simulations show that a high-conductive damper winding performs faster during load variations then a low conductive damper winding. The reason for this is that a low resistance will induce a high torque at low slip. The size of the windings also affects the performance but these are small and difficult to notice. Simulations show that the size of the damper winding should be between 5-10% of the size of the stator winding.

Subsea Permanent Magnet Motor with Damper Windings

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***Abstract*—Permanent Magnet (PM) machines can have difficulties dealing with unstable loads, which in worst case can make the machine to step-out of synchronous speed. This problem can be avoided by equipping the rotor with damper windings. During load variation the damper winding will induce a torque to dampen the impact of the load variation.**

To investigate the effects from using damper windings a numerical model of a PM machine was developed and studied in this thesis. The model is intended to operate with regards to load torque and the stator field. The stator configuration which was used in this thesis is very complex, which resulted in a lot of trial and error. Due to the complexity of the stator meant it had to be applied with a current density, which means that the voltage over the phases was not taken into account during the simulations. This simplification appears to have created an unnatural damping factor in the simulations.

Simulations show that a high-conductive damper winding performs faster during load variations then a low conductive damper winding. The reason for this is that a low resistance will induce a high torque at low slip. The size of the windings also affects the performance but these are small and difficult to notice. Simulations show that the size of the damper winding should be between 5-10% of the size of the stator winding.

***Index Terms*—Permanent magnet machines, damper windings, COMSOL Multiphysics.**

I. INTRODUCTION

This thesis has been made in collaboration with SmartMotor AS, who is in the process of developing a solution for subsea pumps. The purpose of this thesis is to investigate and develop a numerical model for a permanent magnet (PM) machine with damper windings.

A. Background

Subsea pumps are often used in industrial plants such as oil and gas installations on the seabed, to build up pressure to allow for transportation over long distances. In Subsea pumps there are occasionally problems with unstable loads, which is often due to air bubbles in the system. The air bubbles in the system can make load torque fluctuations. In worst case the load torque can go from 100% to 20% within seconds, stay at 20% for two seconds, and then back up to 100%. This load fluctuation can make the PM-machine to step out of the synchronous speed. Because PM-machines are not intended to work outside synchronous speeds, it may fail to synchronize after the load variation [1].

A way to get the machine to self-synchronize is to attach amortisseur windings, commonly known as damper windings to the rotor. The damper winding acts in a similar manner as a cage winding in an induction machine [2] [3].

When the motor is running in non-synchronous speed there will be induced a voltage in the damper winding, which will set up a current that start to flow. This current will produce a torque which will try to push the rotor back into synchronism with the stator field. When the rotor is in synchronism with the stator field, there will not be induced any voltage in the damper winding, which in principle mean that the winding does not affect the machine in steady state operation.

B. Scope of Work

The scope of this thesis is to make a numerical model in COMSOL Multiphysics of an electrical machine that has the ability to rotate as regards to the stator field and load torque. The machine shall also be tested in two cases with different load situations. Another aspect is to find a method for calculate motor parameters that can be used in simulation such as Matlab/Simulink simulations. The thesis also covers aspects of how to construct damper windings for PM-machines.

C. Nomenclature

B_s:	Magnetic field from stator
B_w:	Induced magnetic field
c_1:	Correction coefficient [4]
f:	System frequency
e_{ind}:	Induced voltage
l:	lengt
m:	Number of phases
p:	Number of pole pairs
Q_r:	Number of rotor slots
Q_s:	Number of stator slots
R_s:	Stator resistance
R_r:	Rotor resistance
s:	Slip
T_{ind}:	Induced torque
U:	Voltage
v:	Speed
X_s:	Stator leakage reactance
X_r:	Rotor leakage reactance
δ:	Phase shift

II. THEORY

A. Damper Windings

Damper windings can be used in two ways, either by stabilizing the terminal voltage or by improving the asynchronous performance of the machine [4]. In generators the main function of the damper winding is to dampen counter rotating fields and to reduce losses [3]. For a synchronous motor the damper winding needs to be able to reduce speed variations caused by load variations and can also improve the starting properties [3]. During load variation the rotor speed will change and the machine might jump out of synchronous speed. The damper winding will then try to counteract this change by inducing a voltage in the damper winding. This voltage makes a current flow in the winding which produces a magnetic field. The result of the stator and the induced field will make what is called an asynchronous torque or induced torque [5].

Under asynchronous speed, the induced voltage (e_{ind}) in the damper winding is determined by the velocity (v) of the machine and the magnetic field (B_S) from the stator winding. e_{ind} can be calculated by using equation (1) [5], l is the length of the damper bar.

$$e_{ind} = (v \times B_s)l \tag{1}$$

This induced voltage makes a current flow in the bars, which puts up a magnetic field (B_W) [5]. The result of the magnetic field from the stator and the damper winding, induces a torque, that can be calculated by the equation below [5]:

$$T_{ind} = kB_W \times B_S \tag{2}$$

The induced torque can also be calculated by using equation 3 [6]. In this equation it is a bit easier to see how the machine reacts during slip. We can see that if the slip(s) is zero, as there will not be induced any torque. One can also see that the R_r (resistance of the damper winding) varies with slip. This means that the torque will change with respect to the slip.

$$T_{ind} = \frac{mpU^2R_rs}{2\pi f[(R_s + c_1\frac{R_r}{s})^2 + (X_s + c_1X_r)^2]} \tag{3}$$

The size and position of the damper winding can vary and will affect the performance of the motor [7] [8]. A low resistance damper winding will produce a high torque at low slip, while a high resistance damper winding will produce a high torque at a high slip [4]. Placing the bars close to the rotor surface reduces the leakage reactance of the rotor. This will make the pullout torque high, but it will also make the starting torque small and the starting current high [7].

B. Operation During Load Variation

Load variation such as a sudden drop in load torque in a synchronous motor will cause the machine to speed up, and can make the machine exceed synchronous speed [1]. The behavior of the machine during the asynchronous operation is dependent on the induced torque of the damper winding [1]. The machine will continue to increase the speed to it finds a stabile working point, and slowly slows down until it slips back into synchronous speed [1]. When the rotor is in synchronism with the stator field it will oscillate, but these oscillations should be damped by the damper winding [1]. If there is no damping in the system, the fluctuation will continue. The reason for these oscillations is due to excess energy in the system between the rotor and magnetic field [1].

C. Induction Starting

Synchronous machines can be started direct on line, or also called induction starting. This type of start–up uses the damper winding to start from stand still. The machine will then act as an induction machine during the start–up [1]. Starting time for induction machines that uses a cage winding, can range from fractions of a second to several seconds before it reaches nominal speed depending on the load [1].

D. Stator current

During direct on-line start of a machine, the stator current becomes a bit higher than the nominal current. For an induction machine the start current can be between 5 to 7 times the nominal current [1]. If an induction machine is running near too synchronous speed the stator current should be phase shifted almost 90^0 compared to the voltage because of the magnetizing inductance is much larger than the stator impedance [5]. At this speed the rotor current should be zero because of the slip is very small, and the rotor resistance is dependent on the slip (as seen in equation 3).

E. Harmonic Components in the Air Gap

Due to the damper windings the rotor becomes more exposed to harmonics in the air gap [9]. Harmonics in the air gap can lead to reduced performance [10], vibrations and noises [9]. The harmonic components that impacts the winding the most are the 5th and 7th harmonic [7]. This is because they have the same shape as the fundamental component except that they are rotating at 1/5th and 1/7th of the synchronous speed, and this can then lead to dips in the torque-speed characteristic of the machine [7]. The stator winding can be constructed to reduce the harmonic components in the air gap. This can be done by the use of distributed- and fractional-slot winding [10].

F. Rotor Construction

The rotor can be constructed in many ways, but the main aspects are the placement of the magnets and the design/size of the damper winding.

1) Magnet Placement: There are in general three ways of mounting magnets on a rotor for a PM-machine; surface mounted magnets, inserted magnets, and interior permanent magnet [3] [11]. Surface mounted magnets are magnets that are placed on the surface of the rotor. Inserted magnets are magnets that are placed in slots on the surface of the rotor. With interior mounted magnets the magnets are placed in the rotor core. An illustration of these three can be seen in figure 1.

Embedding magnets in the rotor protects the magnets against mechanical- and magnetic stresses, but about a quarter of the flux produced by the magnets gets wasted due to flux leakage in the rotor core [3]. Magnets are best utilized if they

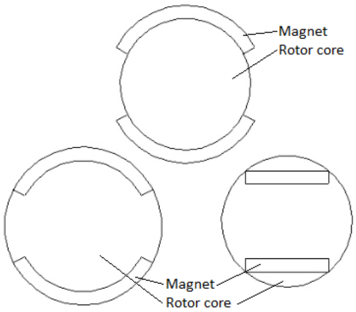

Fig. 1. Two pole machines with surface mounted, inserted-, and interior permanent magnet rotors [11]

are mounted on to the rotor surface (surface mounted) [3], but this will make the magnets more exposed to mechanical stresses, magnetic stresses, and losses due to eddy currents. In worst case can magnetic stresses lead to demagnetization of the magnets [3]. The mechanical stresses can be avoided by using a protective shield around the magnets. If the shield is conductive it can prevent eddy-current losses [12].

2) Damper Winding Construction: Damper windings for permanent magnet machines can generally be constructed in two ways. Either by using bars which are placed in the rotor core as a cage winding in an induction motor, or by covering the rotor with a shield (canned rotor) of conductive and non-magnetic material [3] [13].

3) Cage Winding: The most commonly used damper winding construction is use of bars that are placed in the rotor core. The bars are short circuited on each end of the rotor with end rings. The reason being that current flowing in the bar needs to have a return path through another bar to produce the magnetic field [5].

For a cage winding design (of the damper winding), the number of rotor slots/bars plays an important part of the performance of the motor. This is because of the number of stator slots and harmonic components in the air gap can cause losses and cogging torque [7] [8]. For an induction machine the number of rotor slots should be as small as possible to reduce the asynchronous harmonic torques ($Q_r < 1.25Q_s$) [3]. Where Q_r is the number of rotor slots, and Q_s is the number of stator slots. Some additional conditions that should be followed are shown in the equations below [3] [7] [8]:

$$Q_r \neq Q_s \tag{4}$$

$$Q_r \neq Q_s \pm 2p \tag{5}$$

$$Q_r \neq 2Q_s \pm 2p \tag{6}$$

$$Q_r \neq Q_s \pm p \tag{7}$$

$$Q_r \neq \frac{Q_s}{2} \pm p \tag{8}$$

To reduce cogging torques the bars are usually skewed along the rotor [3].

4) Canned Rotor: Using a shield around the rotor is one way of making damper windings for PM-machines [3] [13]. The shield needs to be made of a conductive and non-magnetic material such as aluminum, copper, or stainless steel [3], so it will induce a voltage in the shield. As described above the shield can protect surface mounted magnets against eddy current losses and help to reduce mechanical stress in high speed operation [14].

G. Sizing of the Damper Winding

The main parameter that determine the effect of the damper winding is the resistance [15]. The resistance of the damper winding is determined by the size of the winding and the conductivity.

There is no exact way of calculating the size of the damper winding. One commonly used method is to select the size of the damper winding from the size of the stator winding [3]. In a synchronous generator the cross-sectional area of the damper winding is selected to be between 20-30% of the copper used in the cross-sectional area of the stator winding. For a motor it is about 10% [3] [13]. This does not show how it will react during operation, or whether the damping is sufficient. Another way to find the dimensions of the damper winding is to look at the induction torque compered to load torque [1]. The induced torque should be able to overcome the load torque under start-up; this implies that the machine needs to be able to start direct on line from standstill. In principle, this should mean that one can determine the size by how it responds to load variations as well.

III. SIMULATION MODEL

The simulation model is made in the simulation program, Comsol Multiphysics which uses Finite Element Method. The machine that has been tested is a two pole machine with rated power of 5 MW. In table I one can see general specifications for the model.

TABLE I
GENERAL MOTOR PARAMETERS

Rated Power:	5 MW
Nominal Torque:	7957Nm
Rated Speed:	6000 rpm
Frequency:	$100H_z$
Rated voltage:	6.6 kV
Number of Poles:	2
Axial length:	2 m
Pressure inside the machine:	$\leq$ 1000 bar
Pressure outside the machine:	100-300 bar

A. Stator Model

Two models were made; the first model was made as an example to prove the principle, the second stator model (test model/simulation Model) was designed by SmartMotor, but has been simplified to improve the speed of simulation and reduce the source of errors. It is a two pole, three phase stator with distributed windings. The three phases are applied with a sinusoidal current density. Current density is used because one assumes that the current in all the wires in one phase is the same. According to Kirchhoff's current law, which states that the total current flowing into one node is the same as the current flowing out of the node. The current density phases are shifted with an angle δ to help the machine start in synchronous speed, without unwanted fluctuations in the speed. Figure 2 shows one quarter the stator model.

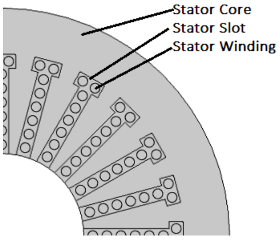

Fig. 2. One quarter of the 2D stator model

In the model the stator winding and the stator core are assumed to have conductivity equal to zero because the main aspect of this thesis is to see how the rotor will react during simulation, as regards to load variations. Specifications for the stator can be seen in table II.

TABLE II
STATOR PARAMETERS

Number of stator slots:	24
Number of stator slots per phase per pole:	8
Outer diameter of stator laminations:	< 1 m
Conductor diameter:	$1.828mm^2$
Applied Current Density:	$3.72A/mm^2$

B. Rotor Model

Figure 3 shows the rotor model. The rotor has surface mounted magnets that are assumed of having the same magnetic properties as air, but with a remanent flux density of 1.2T. The space between the magnet poles is air. The canned damper windings design is used in the simulation. Material of the damper windings that has been tested are copper and steel. The size of the damper winding is selected with consideration to the size of the stator winding as discussed in section II-G. The sizes that have been tested are 5%, 10%, and 20% of the size of the stator winding. In some tests, the air between the magnet poles has been replaced by bars made of copper and steel to act as a damper winding. Moment of inertia for the rotor is calculated to be approximately $3.113kg \times m^2$. The parameters for the rotor can be seen in table III.

TABLE III
ROTOR PARAMETERS

Moment of inertia:	$3.113kg \times m^2$
Copper conductivity:	$5.99 \times 10^7 S/m$
Steel conductivity:	$4.032 \times 10^6 S/m$
Rotor diameter:	0.2- 0.4 m
Magnets remanent flux density:	1.2 Tesla

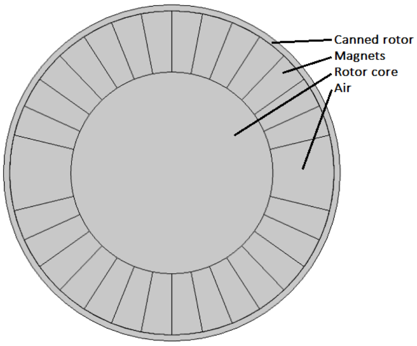

Fig. 3. 2D rotor model

C. Mechanical Model

The mechanical model is made with the use of the equation of motion (equation 9), which determines the speed of the machine with the help of the induced torque and the inertia for the rotor. The external/load torque is used as a constant torque.

IV. METHOD

A. Test Cases

Two test cases were tested in this thesis.

Case I: Machine is running in synchronous speed with no–load torque, and an applied current density of $0.05pu$. Three rotor setups were tested during this case:
a) Magnets in the rotor.
b) Damper winding.
c) Magnets and damper winding.

Case II: Machine is running in synchronous speed with nominal load torque, and an applied current density of $1pu$.
a) Magnets in the rotor.
b) Damper winding.
c) Magnets and damper winding.
d) Magnets and damper winding with a load torque drop from $1pu$ to $0.9pu$.
e) Magnets and damper winding with a load torque drop from $1pu$ to $0.5pu$

B. Implementation in COMSOL

A more detailed description of setup, notes and sources of errors for the COMSOL model is found in Appendix A.

The stator is applied with a three phase current, which is set up as a current density in each phase. To ensure a steady state of operation from the starting point without unwanted fluctuations in the speed, the rotor is set to rotate under synchronous speed and the stator current is phase shifted. The phase shift is done with the angle δ. δ is found by rotating the rotor with magnets with no stator current. Then integrate over each phase to find the induced voltage. When the voltages are found the stator winding layout, rotor position, and the induced voltages are compared to find the optimal start for the stator current.

To enable the machine to rotate as regards to the stator field and the load torque the equation of motion is used (equation 9) [1] [16]. The induced torque is T_{ind}, if there is an external torque that affects the machine it is represented with T_{ext}. J is the total inertia of the machine and ω_{mech} is the angular velocity of the machine.

$$T_{ind} - T_{ext} = J\frac{d\omega_{mech}}{dt} \tag{9}$$

The induced torque is calculated with a force node in COMSOL that uses Maxwell's stress tensor. Load variations are done by adding a step function, which makes the load torque drop from nominal torque at a specific time.

C. Determining Motor Parameters

The motor parameters can be found in various ways, in this thesis the stator parameters are found with two calculations. Determining the rotor parameters and the magnetizing inductance, no-load and locked rotor tests are performed, and with the help of the equivalent motor circuit (figure 4)) [5] the parameters can be calculated. These types of test are also described in the IEEE Standard 112 [17].

1) Stator Parameters: The stator inductance (L_s) can be calculated by the use of the total magnetic energy (W_{magn}) stored in the machine and the RMS phase current (I) as can be seen in equation 10, and should be found under no-load conditions [18] [19]. The resistance of the stator winding is calculated by the use of the conductivity of the cable, as seen in equation 11 [20].

$$L_s = 2\frac{W_{magn}}{I^2} \tag{10}$$

$$R_s = \rho\frac{l}{A} \tag{11}$$

2) No-Load test: No-Load test is done by making the rotor rotate in synchronous speed and then measure current and voltage across the stator winding. By looking at the figure 4 one can see that if the machine is in synchronous speed the slip is equal to zero ($s = 0$). As seen in figure 4 the rotor resistance is dependent on the slip, at low slip the resistance becomes large. Which in turn means that i_R is small and can be neglected [5]. The stator current is then equal to the magnetizing current. By simple circuit calculation the magnetizing inductance (L_M) can be found.

3) Locked-Rotor test: The Locked-rotor test functions in the same manner as the no-load test, except that the rotor is locked and unable to move. Because the rotor speed is zero the slip is equal to one ($s = 1$). The total impedance of the rotor circuit is much smaller than the magnetizing inductance, which means that the current will flow through rotor circuit instead of the magnetizing inductance [5].

V. RESULTS

A. Determining the Phase Shift Angle δ

To enable the machine to start from synchronous with reduced speed fluctuations the stator field and the rotor field should be aligned at the starting point. The induced voltage in stator from a rotating rotor is shown in Figure 5. By comparing the results in figure 5 and how the stator winding is laid out, the voltage Vr must have a high positive value at the start. The starting point is then selected to be at t = 0.009 which means that the phase shift angle $\delta = 5.65rad$.

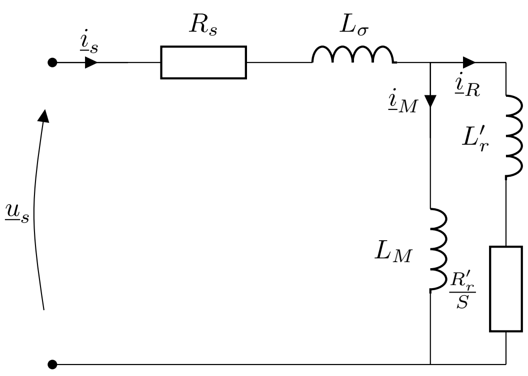

Fig. 4. Per phase equivalent circuit

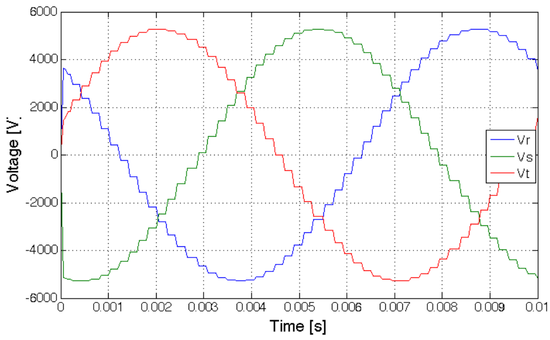

Fig. 5. The induced phase voltages in the stator winding

B. Case I

In this case the model was tested with 3 rotor configurations, A) magnets, B) damper winding, and C) damper winding and magnets. The damper winding was a canned rotor configuration with the size of 10%, of the stator winding and made of copper. The machine was operating in no load conditions, with a stator current at 0.05pu. At the starting point the machine was set to run at synchronous speed. The speed of the different rotor configurations can be seen in figure 6.

From this figure one can see that the two machines using magnets do start to accelerate, but then slowly starts to slow down towards synchronous speed (628.318 rad/s). While the canned rotor will keep rotating at synchronous speed. The reason for this is due to the nature of the magnets as they are depending on following the stator field which is only slightly ahead of the rotor. δ is probably not adjusted completely correct. The torque during the simulations can be seen in figure 7.

C. Case II

In this case the machine was tested from synchronous speed with magnets and different sizes of the damper winding to

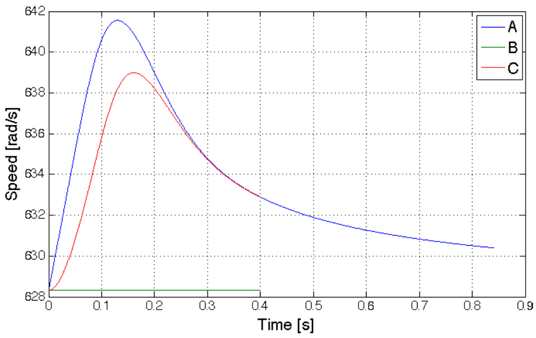

Fig. 6. Speed during no-load conditions.

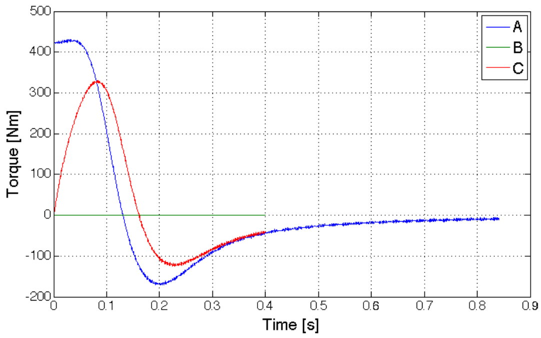

Fig. 7. Torque during no-load conditions.

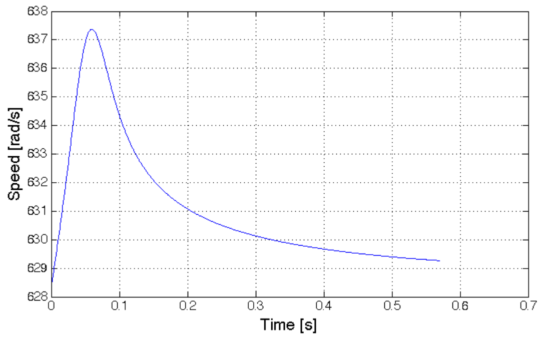

Fig. 8. Speed of rotor with magnets during nominal operating conditions.

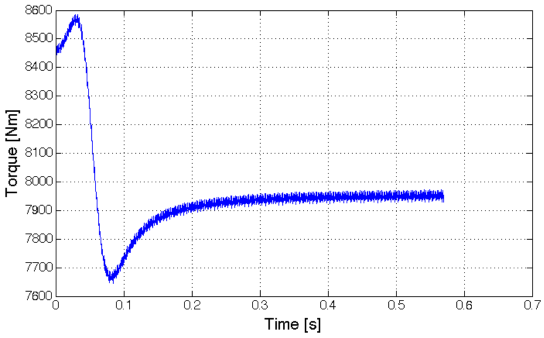

Fig. 9. Torque of rotor with magnets during nominal operating conditions.

see how they reacted during full load and load variations. The copper damper winding had problems during the initial phase of the simulations. Because of this problem δ was adjusted and the load torque was ramped up in the first 100ms of the simulations, to ensure a smooth start. This improvement was only done on the simulations that used copper damper windings and magnets.

Because of the difficulties with the simulations with the copper damper winding the machine was tested first only tested with damper windings made of steel. Later when these problems were solved the machine was tested with copper.

1) A: In this test the rotor was only tested with magnets, to see how it reacted during nominal operatonal conditions. The external torque was set to 0.95 pu during this simulation. Speed of the machine can be seen in figure 8 and the torque can be seen in figure 9. Similar to the result from Case I, the rotor starts to speed up, but after a short time gradually starts to slow down. The torque of the machine starts high but changes quickly to produce nominal torque. The reason for this sudden torque change is due to the rotor rotates faster then synchronous speed.

2) B: In this test the machine was tested with only damper winding and no magnets. The damper winding was simulated as copper and steel, with the size of 5% and 10% of the size of the stator winding. The speed of the different damper windings can be seen in figure 10, the torque can be seen in figure 11. Due to errors most of the simulations were not fully completed. However, as shown in the figures the damper winding was not able to maintain nominal torque, and gradually started to slow down. The negative speed is caused by the constant load torque, which is not dependent on the speed. From figure 11 one can also see that the higher conductivity in the copper makes the machine more unstable and makes it difficult to maintain constant torque during the simulations.

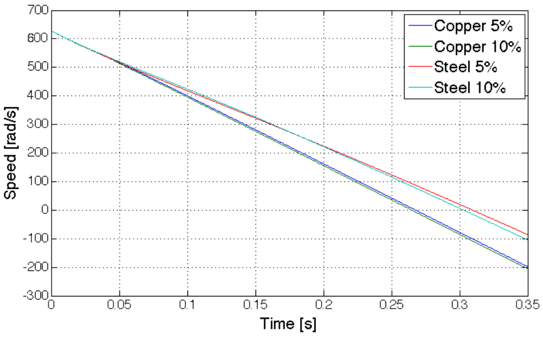

Fig. 10. Speed of rotor with damper windings during nominal operating conditions.

3) C: Simulations were done with magnets and damper winding present in the rotor, with a load torque of 0.95 pu. The damper winding that was tested with a canned rotor of copper and steel. The size was 5%, 10%, and 20% of the size of the stator winding. But simulations were also done by putting bars of copper and steel between the magnet poles, to see how they performed as a damper winding. Speed of the rotor with copper winding can be seen in figure 12, for the steel winding is seen in figure 13. Torque can be seen in figures 14 and 15.

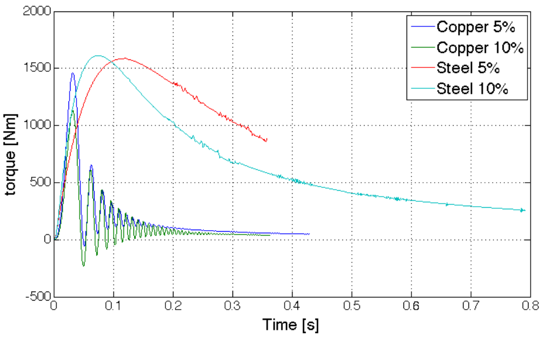

Fig. 11. Torque of rotor with damper windings during nominal operating conditions.

From the simulations one can find that the copper damper winding with the bars and the 20% canned rotor design is not able to keep synchronous speed, and starts to decelerate. The reason for the oscillations in the torque is due to the field from the magnets.

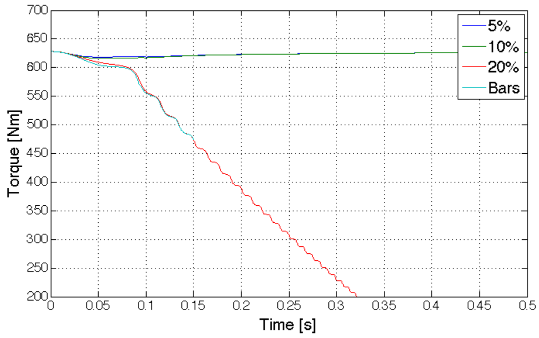

Fig. 12. Speed of rotor with magnets and damper windings of copper during nominal operating conditions.

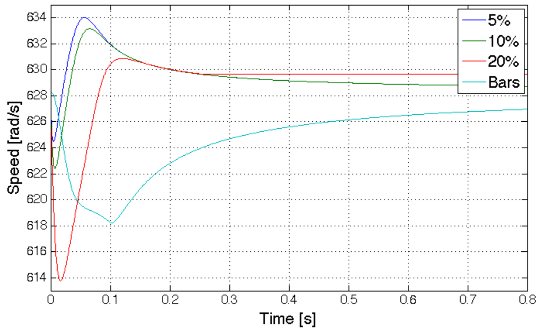

Fig. 13. Speed of rotor with magnets and damper windings of steel during nominal operating conditions.

The steel damper windings did all lock on the synchronous speed of the stator field and operated steady at the given torque. Simulations of the bars were started in the same manner as the copper windings, and this is why the results are slightly different.

4) D: In this simulations the rotor configurations from Case II C were tested with a load torque drop from 1pu to 0.9pu.

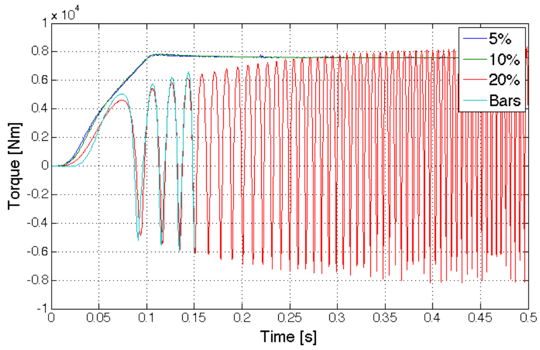

Fig. 14. Torque of rotor with magnets and damper windings of copper during nominal operating conditions.

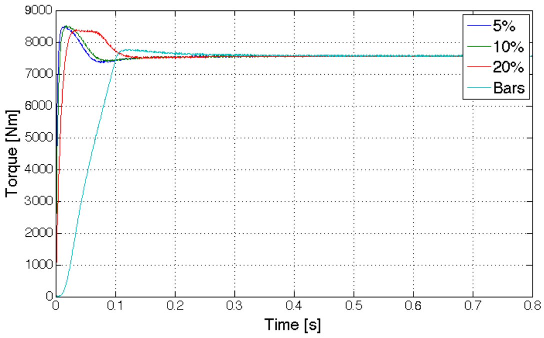

Fig. 15. Torque of rotor with magnets and damper windings of steel during nominal operating conditions.

For the copper winding the drop was at t = 0.5s and for the steel was at t =0.3s. The 20% steel damper winding was not able to operate at nominal torque and was started with 0.95pu load torque. The steel bar was tested with the same start as the copper winding. Due to the poor performance of the copper damper winding of 20% and the bars, were these not tested.

The speed during the load variation can be seen in figures 16 and 17. The tests were done when the machine was in synchronised with the stator field but not exactly on synchronous speed, around ±0.2%. From the figures one can see the damper winding responding fast and that the load variation did not affect the speed much. This can also be seen in the torque (figures 18 and 19) where it drops to 0.9 pu in only 5 ms. By comparing the torque from the copper and steel we can see that the copper is slightly faster than the steel damper winding. The sizes of the damper winding does influence the performers but the differences are very minor.

In figure 19 the bars produce a slightly higher torque than canned rotor configuration. This is due to the velocity is slightly less, because it is using the same start at the copper damper winding.

5) E: This simulation has the same starting point as in Case II D, the only thing that was changed was that the load torque was dropted from 1pu to 0.5pu. The speed of the machine during the load drop can be seen in figures 20 and 21. The torque is seen in figures 22 and 23.

The characteristics of the machine are similar to those seen in Case II D. The copper damper winding responded faster to

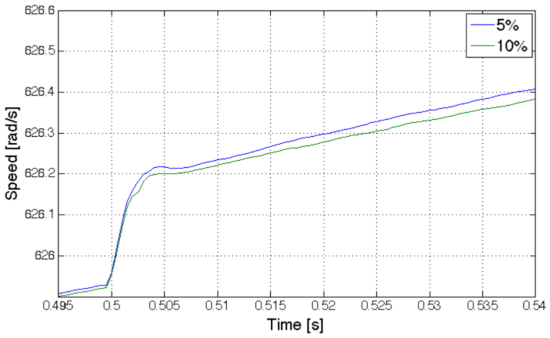

Fig. 16. Speed of rotor with magnets and copper damper winding during load torque drop from 1pu to 0.9pu.

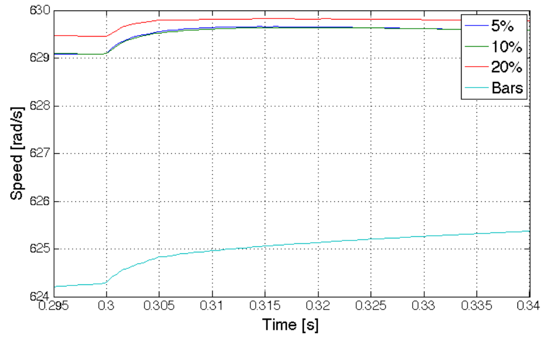

Fig. 17. Speed of rotor with magnets and steel damper winding during load torque drop from 1pu to 0.9pu.

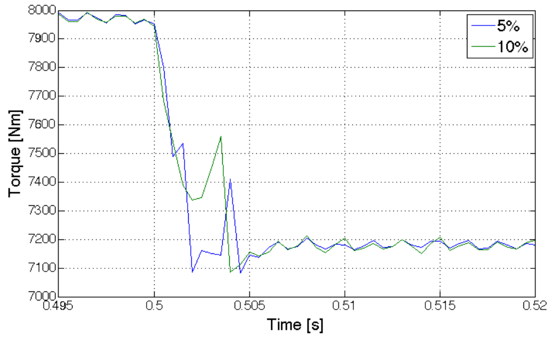

Fig. 18. Torque of rotor with magnets and copper damper winding during load torque drop from 1pu to 0.9pu.

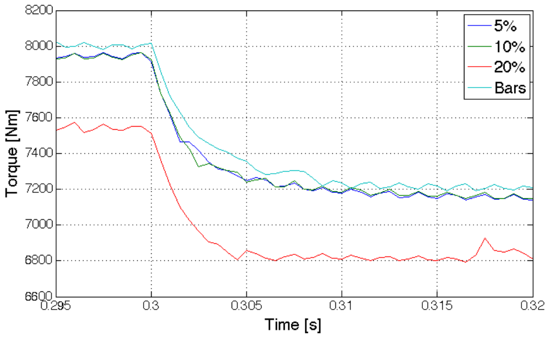

Fig. 19. Torque of rotor with magnets and steel damper winding during load torque drop from 1pu to 0.9pu.

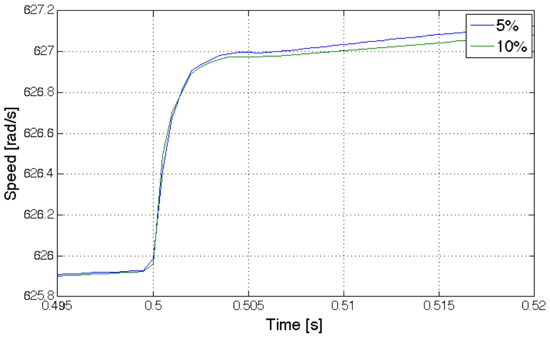

Fig. 20. Speed of rotor with magnets and copper damper winding during load torque drop from 1pu to 0.5pu.

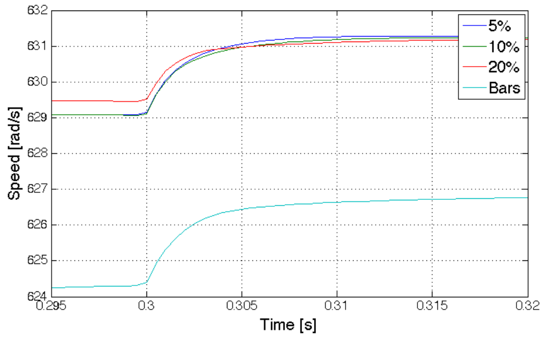

Fig. 21. Speed of rotor with magnets and steel damper winding during load torque drop from 1pu to 0.5pu.

the load variation then the steel windings. The size difference did not have any major significant impact, except that the 20% steel winding was not able to operate at nominal torque.

D. Load Drop Tests with PM-Rotor

The PM-rotor was tested with load variation to see how the machine responded without damper windings present. The load drop was set to start at t=0.2s and the load torque was dropt from 1pu to 0.9pu, and 1pu to 0.5pu. The results from these tests can be seen in the figures 24 and 25. The machine reacted in the same manner as the tests that were performed with the damper winding, except slower. A strange behavior in this simulation, which is also present in Case I A and Case II A, is that the machine gets dampened without any damping function present in the machine. One would assume that the torque were to oscillate, not reach a stable level immediately after the load drops. In appendix B the full time simulation of the PM-motor load drop test from 1pu to 0.5pu can be seen.

E. Induct Current in the Damper Winding During Operation

As discussed in section II-A the damper winding should only affect the machine during load variations and asynchronous operation, however, it can also be affected by harmonics of the air gap (section II-E). In figure 26 one can see the induced current in the damper winding at steady state of operation, after the load drop in case II E had passed. Even

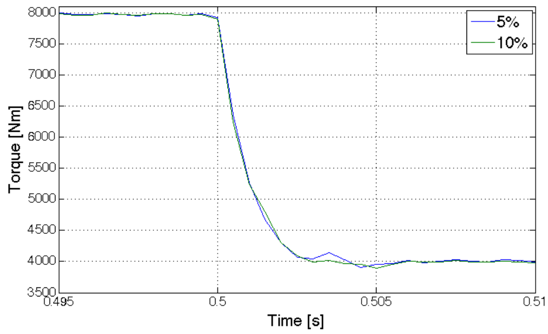

Fig. 22. Torque of rotor with magnets and copper damper winding during load torque drop from 1pu to 0.5pu.

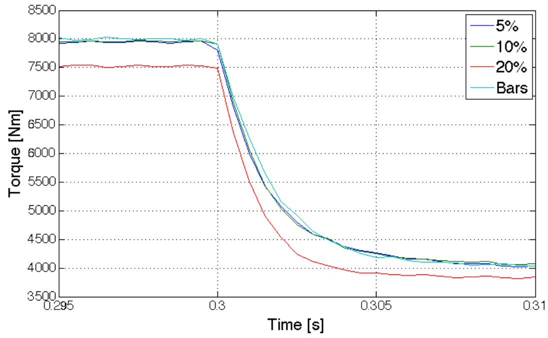

Fig. 23. Torque of rotor with magnets and steel damper winding during load torque drop from 1pu to 0.5pu.

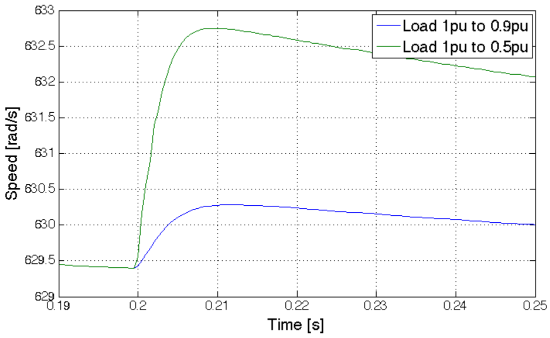

Fig. 24. Speed during load drop tests with PM-rotor.

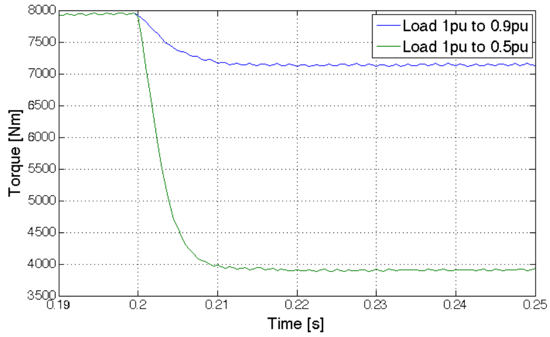

Fig. 25. Torque during load drop tests with PM-rotor.

when the rotor is very close to synchronous speed it seems to get an induced current, however these are more in spots. This can be because of slot harmonics. As can be seen in figure 27, the magnetic field in the air gap is influenced by slot harmonics. This is why it gets the ripples in the field meaning that the machine gest affected by harmonic components in the air gap under steady state.

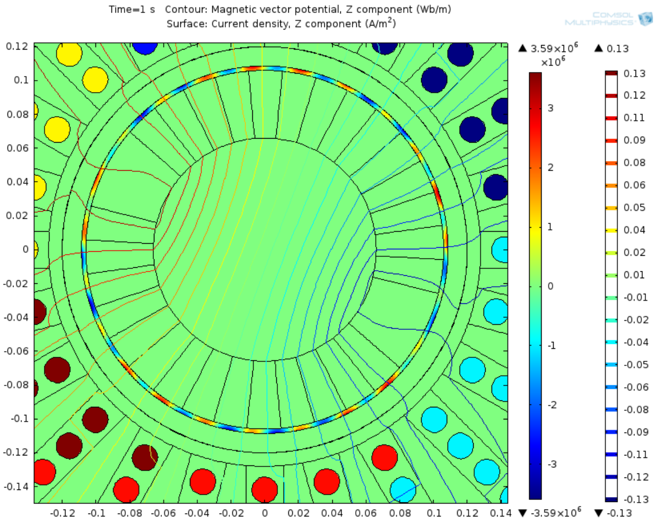

Fig. 26. Induced current in the rotor under nominal operation.

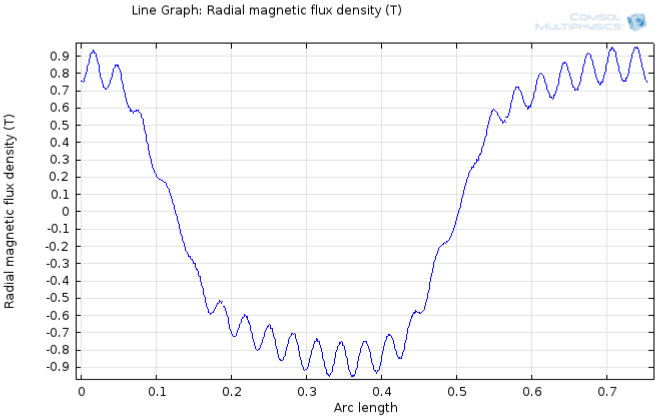

Fig. 27. Magnetic flux density in the air gap.

When the damper winding tries to dampen the unstable load the induced current changes. Figure 28 shows the induced current during right after the load drop from 1pu to 0.5pu. From the figure we can see that the induced current has become divided into a positive and a negative part, resulting in an induced torque which dampens the speed increase due to the load drop.

F. Line-Start Characteristics of the Machine

A line-start test was performed in order to see if the machine was able to perform such a start. The machine was set to start from stand still with no load torque. This was first tested on the simplified model that was a pure induction machine. The results from this test can be seen in appendix C. When it was

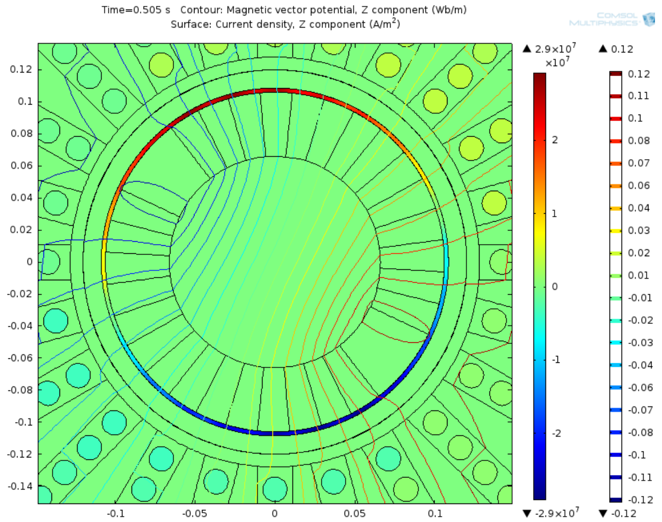

Fig. 28. Induced current in the rotor under torque drop.

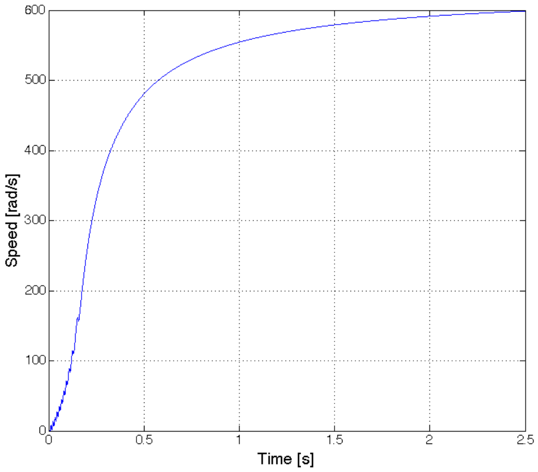

Fig. 29. Line-Start performance on simulation model

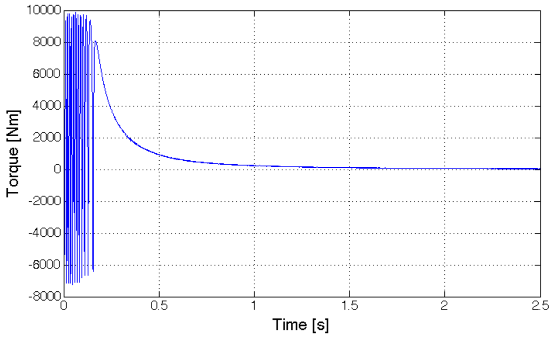

Fig. 30. Line-start torque during starting

working it was tested on the simulation model. The result from this test of the simulation model can be seen in figures 29 and 30. At the beginning of the simulation the machine is experienced pole slipping that can be see seen from the speed of the machine, the pole slipping seem to stop at around t = 0.2s. This is also seen in the torque, until it starts to keep up with the speed of the stator field. It still rotates quite slowly compared to the stator field. So it is bit strange that the machine jumps into synchronism that early.

The machine should still be affected by pole slipping but the induced field from the damper winding appears to have become the determining factor in torque and the effects of the magnets are not as visible. Another important factor is that it never reaches synchronous speed at $628.32 rad/s$, it rather stabilizes at about $600 rad/s$.

VI. DISCUSSION

A significant problem during this thesis was to make a simulation model that operated as intended. One of the most significant problems was when trying to applying a voltage source to the stator winding. The reason being that when applying a voltage source the program needed to calculate the losses in the stator winding and eddy currents, which resulted in errors. By changing the source to current density the program avoided these calculations. There are examples where a voltage source has been used as in the paper *Numerical Calculation of the Dynamic Behavior of Asynchronous Motors with COMSOL Multiphysics* [16], but the stator winding had a much simpler construction. The simplified model (which results of the induction starting can be found in appendix C), was applied with a current source. But it was applied in the same manner as one would do with a voltage source and the result from the line start test seem more dynamic than in the simulation model.

Motor parameters were not calculated because when applying a current density the stator voltage could not be recorded.

A. *Case I*

Under no-load circumstances from case I, one can see that the damper winding does impact the machine. But one important factor is that the rotor with magnets seems to have a damping function without any damping factor applied. As discussed in section II-B, a machine with no damping should oscillate around the synchronous speed, but this could not be seen in the simulations. The reason might be that the simulations are not long enough, or possible because of the high inertia of the rotor, but this can also indicate that there is an error in the simulation model. As discussed above, the current density source may be the reason for the error. The machine was also tested with a low inertia but the result was the same. The peak under these simulations is due to the fact that the stator and rotor field is not completely aligned. For the rotor with only damper windings this will not affect the performance because the magnetic field over the rotor is not determined by any magnets.

B. *Case II*

In the simulations we can see how the different rotor configurations reacted during operation with constant load and with load variation, but also how the conductivity of the damper winding influenced the performance of the machine. At steady state of operation the rotor with only magnets had no problem operating with nominal torque. The model was also tested with nominal load with only damper winding present in the rotor. This resulted in loss of speed as the damper winding was not able to provide enough torque to operate at nominal operation. When the machine was tested with damper windings and magnets, the machine seemed to have problems starting with nominal torque. Meaning that the rotors that used copper damper windings needed to have the load torque gradually introduced to ensure a smooth start. Even with only magnets the machine started without problems, this is due to the torque. Applying only magnets in the rotor, the machine starts with a high torque, but by adding damper winding the torque needed to be build up before it could deliver nominal torque. This can be seen in figure 15 where the torque starts from 0 Nm and then accelerates fast towards nominal load. The copper damper winding was most likely not fast enough to build up torque before it lost too much velocity, and was unable to synchronize.

Performance during load variation was tested in Case II D and Case II E (sections V-C4 and V-C5). An interesting result from this test is how fast the machine reacted during the load variation. In both cases the produced torque was stabile in just 5ms. It is uncertain if this is a reasonable result but as noted in section II-C, some induction motors has the ability to start on from stand still and reach nominal speed in fractions of a second, so it might be possible that the machine can reacts that fast during a load drop. The size of the damper winding did affect the performance but this was very insignificant, but the conductivity showed that the machine reacted slightly different. From the figures 22 and 23, the copper damper windings responded faster than the steel winding as describe in section II-A. A low resistance bare will produce a high torque at low slip. The load drop tests were also performed on the PM-rotor without damper windings. By comparing the result with the damper winding tests, one can see that the results are not very different. The damper windings damped the variation faster, but nothing more than 5ms. Because the pure PM-rotor did not have any damping factor, the speed of the machine should have fluctuated after the load drop, as described in the section II-B.

The bars compared with the canned rotor configuration did not seem to change the characteristics of the machine very much. It has an area almost equal to that of the 10% canned rotor. In the load drop in Case II E it performed equivalent to the steel 10% canned rotor damper winding.

C. Line-Start Performance

The line-start performance was tested with a 10% damper winding made of steel. From this test one can see that the machine was able to accelerate from stand still towards synchronous speed. It accelerates fast at the beginning but gradually starts to decrease once it reaches 400 rad/s. After 2.5 seconds it had still not reached synchronous speed but had stabilized at 600 rad/s. Line start in PM-machines have been presented in other studies; *line-start permanent- magnet machines using a canned rotor* [21] and *Synchronization of line-start permanent- magnet AC motors* [22]. One major difference between these two papers and the line-start simulation done in this thesis is that during the acceleration the machines speed seem to oscillate due to the magnets and pole slipping. This can also be seen at the beginning of the line-start simulation in this thesis. However the oscillations seem to stop during the simulation making it look as if it has synchronized with the stator field but the rotor is still rotating at 200 rad/s and the stator field is rotating at 628.3 rad/s. This error might be caused by the time step under the simulation being too large and the fluctuations does not appear. This is also a sign that the machine is too much damped and the current density source can be the reason.

VII. CONCLUSION

In this thesis a numerical model of a permanent magnet motor has been developed. The simulation model was developed to be able to operate with regards to load torque and the stator field. During the simulations the machine was tested at no-load, nominal load, and load variations. It was also tested with induction starting and seems to be able to run this operation, but this simulation does not coincide with similar work. The simulations also indicate that the machine is too much damped, as seen in the load variations tests with both damper windings and magnets, and the tests with only magnets present in the rotor. These simulations are very similar, and the rotor with only magnets seems to be able to dampen the load variation without any difficulty. This indicates that the machine has a damping factor that should not be there which means that the machine is not operating correctly. After analyzing the machine it seems that the error is due to the current density source, which does not take into account the voltage over the stator winding. The error can also be located in other parts of the model, but it appears that the stator source is the most likely source of the error. Because the program did not managed to use a stator source that was able to operate with regards to the stator current and stator voltage, and it has worked on simpler stator models the stator model should be redesigned and simplified in order to run this kind of simulations in COMSOL.

During the load variation the high conductivity of the copper damper winding did perform faster than the steel damper winding that has a lower conductivity. But with the use of copper the machine had problems during the start-up. Meaning that the external torque needed to be gradually introduced during the first 100 ms.

Size of the damper winding did affect the performance of the machine but this was very insignificant. The damper windings that performed fastest during the load variation were the canned rotor made of copper with the size of 5% and 10% of the size of the stator winding.

VIII. FURTHUR WORK

Further work should focus on creating a simpler stator model that has the ability to use a voltage source, and to test different rotor design for a permanent motor with damper windings

IX. ACKNOWLEDGEMENT

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APPENDIX A
NOTES FOR SETTING UP COMSOL MULTIPHYSICS FOR A 2D PERMANET MAGNET MOTOR WITH DAMPER WINDINGS

This setup uses: Rotating Machinery, Magnetic (rmm), and study types Stationary and Time Dependent

A. Geometry:

The stator and rotor needs to be separated in two separate objects (one Union for the stator and one Union for the rotor). The stator and the rotor should be separated in the air gap, this can be done by making a circle in the air gap between the stator and the rotor. After the geometry is finished, click on the Form Union (fin) node in the geometry. Change the Action from *Form a Union* to *Form an assembly*. This will make a node that is named Identity Pair (can be found in definitions). If the Identity Pair has not appeared, or there are more than one, or it has not appeared in the air gap, then the geometry objects are wrong. It is a good routine to check the Selection list before changing to *Form an assembly*. With the selection list one can see if the objects are separated in the air gap. There should only be two objects in the list before *Form an assembly* is selected. Identity Pair forms the boundaries for the two objects that are made in the geometry.

Sharp edges: Sharp edges can cause problems for the simulations, which can be avoided by smoothing over the surfaces by the use of filet node in the geometry.

B. Physics: Rotating Machinery, Magnetic:

To ensure that the conductivity between the stator and rotor the Conductivity node needs to be applied. In the Conductivity node select *Pair selection* and then click *Identity Pair*.

Voltage/Current source: Voltage or current can be applied by the use of Single-Turn Coil or Multi-Turn Coil Domain. Remember to select Coil Group in the nodes to ensure that the applied voltage is over the entire phase. Voltage phases such as T and –T needs to be split into two Coil Domains. The advantage of using a coil domain is that the voltage and the current are logged, but this will increase the simulation time.

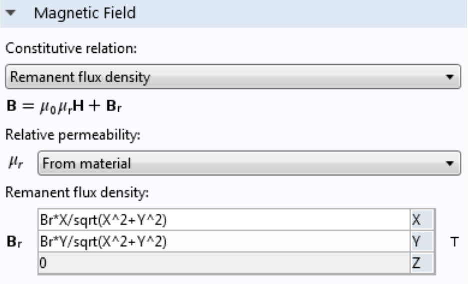
A current can be applied by the use of External Current Density. The advantage of using external current density is that the simulations will compute faster than with the use of coil domain as well as reduce sources of errors. Disadvantage is that the voltage over the phase will not be taken into account during the simulation.

Rotation: To make the machine rotate one can use Prescribed Rotational Velocity node or the Prescribed Rotation node. If the machine is rotating with a constant speed the Prescribed Rotational Velocity needs be used. The domains that needs to be selected in the model is the entire rotor with the air gap part of the rotor geometry. To make the machine able to rotate as regards to the stator field and the load torque see Global ODEs and DAEs.

Force Calculation: Calculation of the torque of the machine can be done by using of the Force Calculation node. The domains that needs to be selected are just the metallic parts of the rotor. NOT the air gap part of the rotor geometry!

Length of the machine: The length of the machine can be determined by the use of node Change Thickness (out-of -Plane). Remember to select the different domains. Default length in Comsol is 1 meter.

Magnets: The magnets can be made by use of the $Ampére's\ Law$ node. After the magnets are selected, go to Magnetic Field, and change Constitutive Relation from *Relative Permeability* to *Remanent Flux Density*. If the global coordinate system is used the remanent flux density of the magnets needs to be dependent on the X and Y component. For inputs see figure 31. One can also use a cylindrical coordinate system; the only input is to select *r* equal to the remanent flux density of the magnets.



Constitutive relation:

Remanent flux density

$\mathbf{B} = \mu_0\mu_r\mathbf{H} + \mathbf{B}_r$

Relative permeability:

μ_r From material

Remanent flux density:

$\mathbf{B}_r$

Br*X/sqrt(X^2+Y^2) X

Br*Y/sqrt(X^2+Y^2) Y

0 Z

T

Fig. 31. Input for remanent flux density for magnets, positive section.

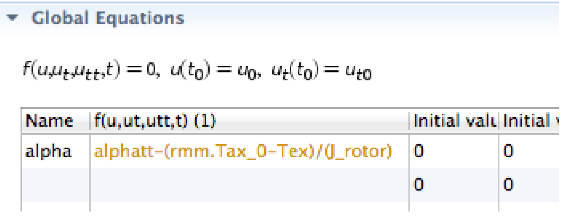
Damper Windings: To ensure that the current in the damper winding is equal to zero Single-Turn Coil node can be used, but this can lead to errors. One can also use the $Ampére's\ Law$ node which will reduce errors in the simulation.

C. Global ODEs and DAEs

To enable the machine able to rotate with respect to the stator field and the load torque, the program needs to solve the equation of motion as seen below (equation 12).

$$f(u, ut, utt, t) = \alpha tt - \frac{T - T_{ex}}{J_{rotor}} \tag{12}$$

αtt is the second time derivative of the angle α. T is the electromagnetic torque, T_{ex} is the external torque. J_{rotor} is the moment of inertia. In COMSOL the input in the ODE can look as shown in figure 32. The initial speed can be selected in the ODE solver.



$f(u,u_t,u_{tt},t) = 0,\ u(t_0) = u_0,\ u_t(t_0) = u_{t0}$

Name	f(u,ut,utt,t) (1)	Initial valu	Initial
alpha	alphatt-(rmm.Tax_0-Tex)/(J_rotor)	0	0
		0	0

Fig. 32. ODE Setup

To make the machine rotate the input for the rotation is dependent on what kind of node that is used. If the Prescribed Rotation node is used the input is α. If one uses Prescribed Rotational Velocity the input is $\alpha t/(2\pi)$.

D. Mesh

In FEM simulations one of the most important part is the mesh, where it is important that it is not too coarse as this can cause errors.

Stator Coil: The maximum length of one mesh segment should be smaller than the penetration depth in the material.

Air gap: Since the airgap is divided into two parts (stator and rotor), it is important that the mesh segments lines up to ensure that the field in the air gap overlaps.

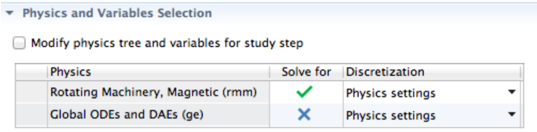
Damper windings: The maximum length of one mesh segment needs to be small to get an accurate torque result. A good assumption is to use at least three rows if a canned rotor is used, or select a maximum mesh segment length than is smaller then the penetration depth.

Sharp edges: Sharp edges can cause problems for the simulations. Use corner refinement to get a finer mesh around the edge, or use the fillet node in the geometry.

E. Study

The use of Stationary and Time dependent solvers together will reduce the number of errors in the simulation. Using the stationary solver first will make a very accurate solution of the magnetic field in the rotor, which reduces the number of errors during the simulation. The Time dependent solver makes the model time dependent.

Step 1: Stationary: The stationary solver should be study step 1. The Global ODE cannot be solved in the stationary solver because the equation is dependent on the time. The physical and variable selection for the stationary study should be as shown in figure 33.



Physics and Variables Selection

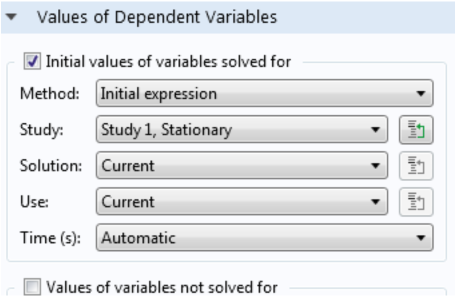
☐ Modify physics tree and variables for study step

Physics	Solve for	Discretization
Rotating Machinery, Magnetic (rmm)	✓	Physics settings
Global ODEs and DAEs (ge)	✗	Physics settings

Fig. 33. Physical and variable selection for the stationary study setup.

Step 2: Time dependent: The time step should be selected with regard too the frequency, at least 20-40 steps per period. Tolerance factor should be locked to 0.01 to remove errors before next step is taken. To ensure the initial values from the time dependent solver gets use in the Stationary solver, open *Values of Dependent Variables* select *Initial values of variables solved for*, and change Method from *Solution* to *Initial expression*, se figure 34.

Number of integrations: By increasing the number of integrations the simulation has the ability to do more integrations per time step. But this also leads to longer simulation time and will increase the size of the file because it needs to store the extra integration results. This parameter can be changed by opening: study > solver configurations > solver 1 > Time-Dependent solver 1 > Fully coupled 1. The parameter is under: Method and terminations. Try changing the number of integrations from 7 to 25.



Values of Dependent Variables

☑ Initial values of variables solved for

Method: Initial expression

Study: Study 1, Stationary

Solution: Current

Use: Current

Time (s): Automatic

☐ Values of variables not solved for

Fig. 34. Setup for time dependent solver.

F. Errors

2D Plots: If the Magnetic vector potential lines between the stator and the rotor in the 2D plot (Magnetic Flux Density plot) are not aligned, there are a problem with the solution setup. To solve this problem click: Results > Data Sets > Solution, and then change the Frame from *Material (X Y Z)* to *Spatial (x y z)*.

Maximum number of Newton integration reached: This error can come from a number of reasons. Most likely the mesh is too coarse, try sectioning the mesh. One can also try to increase the number of integrations and/or select the tolerance factor between 0.001-0.0001 (see the study chapter).

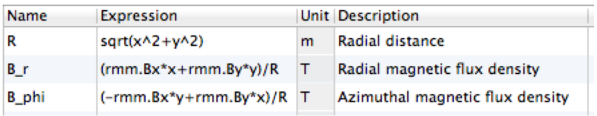
Reached singularity: The problem is that the mesh is too fine in some places, and you get gatherings of very fine mesh.

Note: Many errors can be avoided by updating the Jacobian matrix on every iteration. But this will increase the simulation time dramatically. This is done by going to study > solver configurations > solver 1 > Time-Dependent solver 1 > Fully coupled 1. The parameter is under: Method and terminations. Change Jacobian update from *Once per time step* to *On every interation*.

G. Results

Speed and torque calculation: Speed and torque calculations are found by opening; Results > Derived Values > right click: Derived Values and select Global Evaluation. The parameters are found under Expression.

Magnetic flux density in the air gap: To the plot of the flux density in the air gap, one needs to make a variable. The inputs for the variable can be found in figure 35. After the simulation has been performed make a 1D plot, and select Line graph. Use the Identity par line as the selection. The y-axis Data input must be Radial magnetic flux density (B_r). It should found under definitions if the variable inputs are configured correctly.



Name	Expression	Unit	Description
R	sqrt(x^2+y^2)	m	Radial distance
B_r	(rmm.Bx*x+rmm.By*y)/R	T	Radial magnetic flux density
B_phi	(-rmm.Bx*y+rmm.By*x)/R	T	Azimuthal magnetic flux density

Fig. 35. Variable inputs for the magnetic flux density in the air gap.

APPENDIX B
LOAD DROP TESTS WITH PM-ROTOR

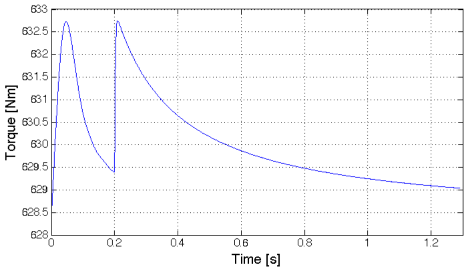


Fig. 36. Speed during load drop from 1pu to 0.5pu with PM-rotor.

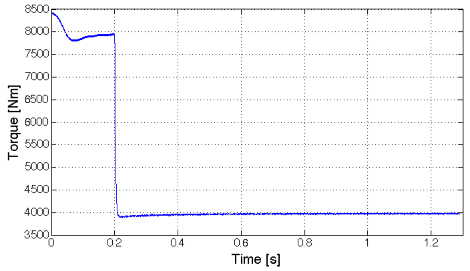


Fig. 37. Torque during load drop from 1pu to 0.5pu with PM-rotor.

APPENDIX C
SIMPLIFIED INDUCTION MOTOR LINE START

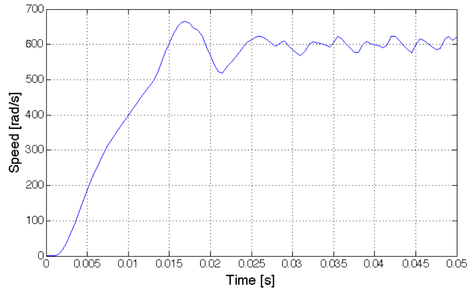


Fig. 38. Speed during line start test of induction motor.

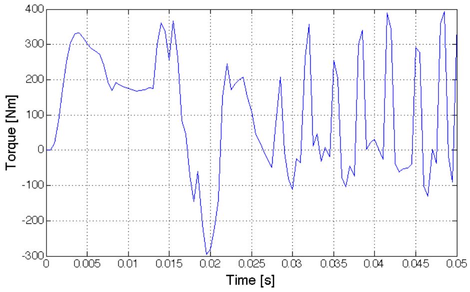


Fig. 39. Torque during line start test of induction motor.