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Minimization of losses of PMSM for HEV

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Abstract

This paper will put the focus on the losses of power in electrical machines for HEV. Well designed permanent magnet synchronous machines (PMSM) have a grade of efficiency of over 90% at their nominal rating. PMSM for HEV are operated most of the time at low or no load conditions. At those operating points the machine will cause energy losses which have to be provided by the stored energy or by the combustion engine.

There are in principle two different ways to reduce the waste of energy in PMSM. First step is to exercise measures in the design of PMSM reducing losses directly. Possible arrangements are well known but not easy to practice because of constructional constraints such as the size of those machines. Another way is to reduce losses by a special control strategy.

This paper will zoom in on measures in the machine design which will help to reduce losses actively by applying a new strategy in controlling this kind of machines. As PMSM for HEV have to work at a wide range of speed it is usually necessary to apply a purely reactive current to weaken the flux at higher speeds. This causes losses in the copper of those PMSM. The amount of current needed for flux weakening depends on the inductivity in the direct axis. Increasing this inductivity provides good flux weakening capabilities.

A new control strategy to diminish losses has been developed and will be presented. This strategy works for all kind of PMSM but will obtain best results together with PMSM designed for this kind of control.

To achieve the above mentioned objectives a PMSM with special electrical behavior has been developed, build and analyzed at a wide range of operating points. This PMSM fulfills all requirements concerning passive means of loss reduction as well as the capability to reduce losses actively by a special control mechanism.

Keywords: HEV, efficiency, permanent magnet motor, control system, modelling

1 Introduction

To reduce losses in a HEV, concerning the electrical part of the drive train, it's necessary to examine the losses of all parts at all possible operating points. In this paper the electrical machine and the appropriate control will be put on the focus.

It's a challenging task to insert the electrical part of the drive train into the conventional component. Therefore the machine, the inverter and the battery have to be as small as possible. This demand on the other side will lead to increased losses in the electrical machine.

PMSM are, compared to induction machines, of course the best solution in the attempt to reduce weight and volume at the same rated power. One of the tasks on the way to reduce losses in the propulsion chain is diminishing losses in the machine by design. Knowledge of the loss mechanism is crucial to achieve this goal.

But not only passive ways, as described above, are possible in the design of the machine. A layout to reduce losses actively by a special control can be executed during the design process.

Knowing the losses at different operating points, the waste of energy can be reduced by the right choice of the amount of current in the magnetic axles of the machine. To hit this object losses don't have to be known precisely by their amount but the location of the minimum has to be known for all operating points.

For any combination of given speed and demanded torque a pair of current data can be provided in a characteristic map in the control. This leads to a different strategy to direct the machine in the field weakening region.

At least this kind of control can be enhanced by a characteristic map which provides knowledge about the right combination of currents not only for the machine, but the whole electrical part of the drive train.

2 Machine design

Well designed PMSM reach values of efficiency over 90% at their best point. PMSM for HEV should be designed for a minimum of over all losses, because they are driven most of the time far out of the points of good efficiency.

2.1 Losses in PMSM

There are four kind of losses in PMSM.

First of all copper losses corresponding the following equations:

$$P_{V,Cu} = R(\vartheta, A_{Cu}, l_{Cu}) \cdot I^2 \quad (1)$$

where I applies for $I^2 = I_d^2 + I_q^2$ (2)

and Id and Iq are the rms values of the corresponding time depending fundamental current values in the d- respective q-axis.

Well known are the equations for the iron losses:

$$P_{V,Fe} = m \cdot \left(c_h \cdot f \cdot B^n + c_e \cdot f^2 \cdot B^2\right) \quad (3)$$

$$n = n(B) \quad (4)$$

where B is the peak value of the flux density caused by the magnets, f the frequency of the fundamental of the magnetic field and c_h and c_e are material- dependant parameters of the iron core and m is the mass of the iron core.

$$c_e = c_e(B, f, d_{Fe}) \quad (5)$$

$$c_h = c_h(B, f, d_{Fe}) \quad (6)$$

where d_{Fe} is the thickness of the iron layers.

It's obvious no simple correlation in equation (3).

In addition the influence of the flux produced by the currents in the magnetic axes has to be considered. A suggestion how this can be implied for any operating points can be found in [1].

Losses in the magnets could occur, due to their ability to lead eddy currents about for times "better" than usual iron cores. Losses in the magnet as a tribute to eddy currents are definitely not desirable. Not only in view of the aim to reduce over all losses, but as well to minimize the magnets temperature, which is limited by reason of danger to demagnetize the permanent magnets.

Friction will occur in the bearing, the air gap and at the front end of the rotor. Those losses can be reduced by constructional means which will not be under investigation here.

2.2 Passive measures

So called passive measures are constructional measures to reduce losses which can not be influenced actively by the machine control.

Its obvious that the amount of current should be kept at small values to reduce the copper losses.

Another way to reduce those losses is to reduce the resistance R, depending on ϑ the actual temperature of the copper, A_{Cu}, the cross-section area of the conductor and l_{Cu}, the length of the conductor of one phase. This way on the other hand will increase volume, weight and cost of the PMSM and therefore is not preferable.

To keep the amount of current small reaching the desired power, the magnetic flux density has to increase, which will, at the same volume, lead to higher losses in the iron.

To keep copper losses small it's crucial to reduce the iron losses at high flux density values. This can be done by a good choice of the iron. Another way is calculating the peak flux density by means of FEM which will keep hotspots of flux density minimized.

Keeping the iron losses at a minimum without reducing the flux linkage and without increasing the volume, will enable the machine to be driven with low currents for the same rated power.

To avoid losses in the magnets, the magnets have to be buried in the rotor. This will keep most of the alternating flux, provoked by the alternating reluctance due to the slots in the stator and by harmonics in the current induced magnetic flux, away from the magnets. Of course this will increase the rotor iron losses but those losses will be of a smaller amount compared to the losses in the magnets and can be delimited by a reasonable choice of the coil windings.

2.3 Active measures

As already mentioned PMSM in HEV are driven at low loads or even no load most of the time in realistic load cases. In these cases the PMSM will "produce" iron losses, which only can be reduced by a purely reactive stator current increasing copper losses. The minimum of over all losses has to be found. This can be done by a special kind of control which will be described in chapter 3.

The design process allows to vary the machine parameters such as the inductivities in the magnetic axes to a certain amount.

Inductivities in PMSM for HEV are limited by several factors. For high power density design, the flux density in the air gap has to reach high values, which leads, together with a high number of magnetic poles needed for high torque, to a small number of coil windings. This will reduce the phase resistance, but as well the rate of inductance to be possibly reached. Especially will the d-inductivity be, caused by the reluctance of the magnets in the magnetic path, small-sized. It's the d-axis inductivity which should have high values to get better abilities to diminish flux linkage and in succession the flux density in the iron, which is needed to reduce iron losses without increasing copper losses too much. A design of a PMSM, which fulfils the demand for high d-axis inductance is presented in [1].

There are many other ways to increase d-inductivity L_d, without increasing the q-inductivity L_q at the same time. In [2] are shown some more ways to do so. Unfortunately some of the possibilities shown in [2] will increase L_d, but will not decrease the iron losses to the same amount as the design shown in [1]. The iron losses will at higher speed exceed the copper losses, which makes the reduction of iron losses essential for the best result.

A reasonable measure to reduce losses in the PMSM, the appropriate converter and the battery is to minimize the power factor. This can be done in the design process by downsizing the q-axis inductance. The following figures will depict this fact together with the effect obtained by the enlargement of the d-inductance.

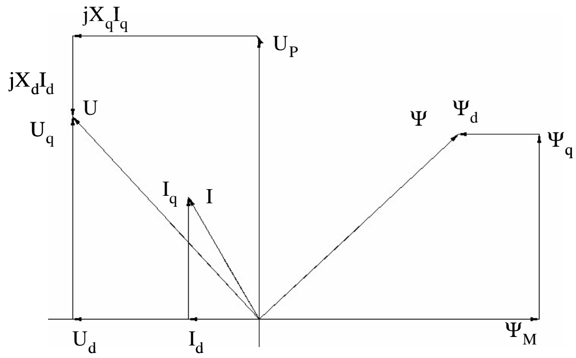

Figure 1: PMSM with $L_q > L_d$

In this example with a motoring current in field weakening mode, a PMSM with a ratio of L_d/L_q smaller than one is shown. The power factor is close to one.

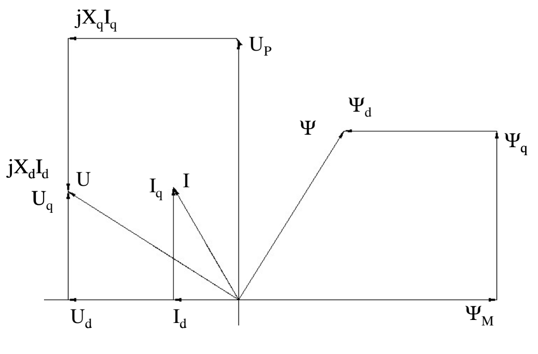

Figure 2: PMSM with increased L_d

Increasing L_d will reduce the flux linkage and therefore iron losses. Unfortunately the power factor will be smaller at the same operating point.

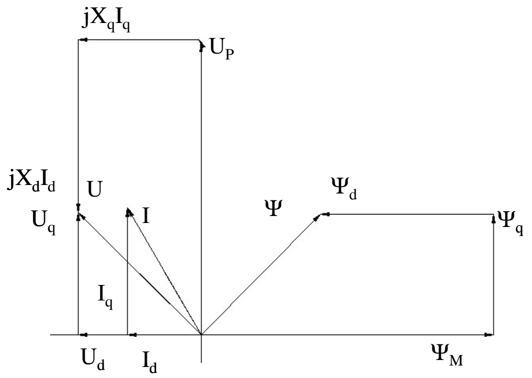

Figure 3: PMSM with decreased L_q

The downsized inductance in q-axis will together with the increased d-inductance help to decrease the flux linkage, the iron losses and the power factor at the same time.

A PMSM with that kind of characteristic has been build. This PMSM has the following data:

Table2: PMSM

Rated power (kW)	52 kW
Rated voltage (V)	350
Rated current (A)	113
Rated PF	0.8
Rated speed (rpm)	3300
Rated torque (Nm)	150
Max speed (rpm)	6600
L_d (mH)	1.035
L_q (mH)	0.675
R (mΩ)	18.4

3 Control

The next step on the way to a highly efficient electric power train is to find the current and the angle γ between I and U_P producing the same torque at the same speed inducing the smallest amount off over all losses. This has been done by calculating iron losses, copper and additional losses in the stator as well as in the rotor for a large number of operating points. These calculations have been carried out by means of FEM and will be compared to metered data.

The idea of the control is pretty simple. For each desired value of torque at a certain speed there is a combination of currents in the magnetic axes which gives the minimal amount of losses.

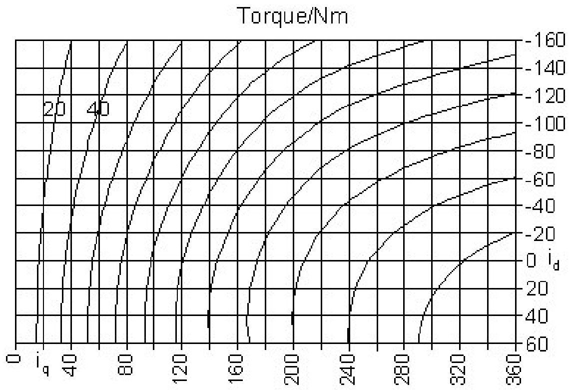

Figure 4: Lines of constant torque

Figure 4 shows the amount of torque for all possible combinations of currents in the magnetic axes. The dependence on speed can be neglected.

3.1 Calculation of losses at various operating points

In [3], [4] and [5] an alternative method to calculate iron losses by FEM together with additional losses in the stator iron, based on the loss data of the manufacturer of the iron core is described. It can be summarized by the following steps:

- 2-dimensional, static calculation of flux density in all elements by FEM in the stator iron turning the rotor stepwise for a number of steps over 180 degree of the electrical angle.
- Analysing the Harmonics due to the rotation for all elements.
- Calculating a factor out of the Fourier analysis which will take the effect of the harmonics on the iron loss in account.
- Identification of the direction of the highest amplitude of the flux density of every element and transformation of the flux density into a elliptic coordinate system where the main axis has the same direction as the maximum magnitude of flux density.
- Building a function to take the rotating magnetisation of the elements into account.
- Calculating the specific losses of the elements for both axles of the elliptic coordinate system using the specific loss data of the manufacturer for the desired frequency.
- Multiplication of the sum of the specific losses of the elements with the function and the factor detected for adaptation of the calculation before.
- Summarising the losses of the elements weighted by their surface area and

multiplication of the summarised losses with the length of the stack.

The iron losses calculated in this way will give results which are close to those calculated by the method described in [1]. The biggest difference lies in the additional rotor iron losses, which are not to be neglected at higher speeds.

For the aim of a control minimising over all losses only a qualitative characteristic of those losses is needed to find a minimum.

In Figure 5 lines of constant losses for 6000 rpm are depicted. It's easy now to find the points where losses are minimized for a requested amount of torque. These combinations of currents will be recorded in a characteristic map which will be implemented in the control.

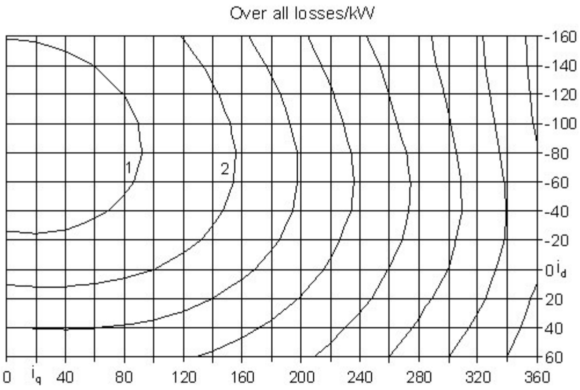

Figure 5: Lines of constant losses

3.2 Structure of the control

As drives for HEV don't have to be very dynamic, it's possible to build the control as a cascaded control structure with a current control in the inner fast circle and overlaying a slower torque control in which the current values are found for the minimum of over all losses.

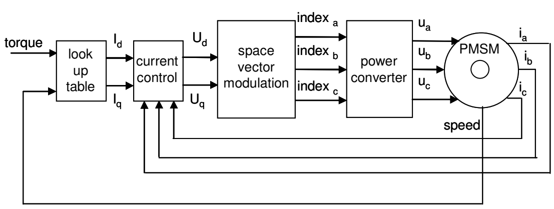

Figure 6: Structure of the control

The current control can be designed in a conventional way.

The look up table gives the appropriate values of the currents to the actual speed and the desired torque.

3.3 Torque limitation

In the characteristic map there are memorized operating points which can, under certain circumstances, not be reached. Limiting factor is the DC-link voltage V_DC which of course varies. As the requested torque T_w especially at higher speeds can not be provided by the machine if the DC-link voltage is not sufficient to supply the needed machine terminal voltage, the only way to keep control is to delimit torque. Within the range of torque limitation, the control always provides the PMSM with the amount of d-axis current and q-axis current needed to minimise losses.

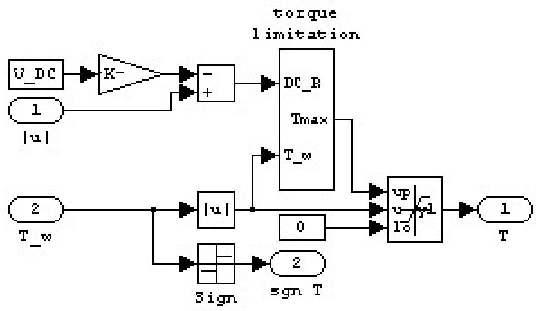

Figure 7: Outer circle of torque limiter

In the outer circle of the limiter the variable DC_R is build as the difference of the requested terminal voltage and the DC-link voltage. A limiter which limits torque to a fixed value for the lower limit and the value build by the inner circle of the limiter completes the outer circle.

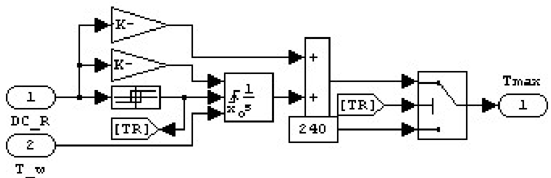

Figure 8: Inner circle of torque limiter

In the inner circle the variable DC_R triggers the integrator of an PI-controller and a switch which chooses between a fixed torque limit and the torque limit build by the PI-controller. The integrator takes the momentarily requested torque as the starting point.

3.4 Results and analogy to i_{min} strategy

The following example will show that losses using the P_{Vmin} strategy can be minimised to less than 50% of the value applying the i_{min} strategy at certain operating points. Friction as well as copper losses due to the converter are not included here. The reason here for is the better ability to show the effect of the strategies.

Table2: Distinctions of different control strategies for T = 0 Nm and n = 6000 rpm

Control strategy	i_{min}	P_{Vmin}
i_d (A)	-44	-97
i_q (A)	0	0
$P_{V,Cu}$ (W)	53	260
$P_{V,Fe,S}$ (W)	444	113
$P_{V,Fe,R}$ (W)	50	47
P_V (W)	647	420

Table3: Distinctions of different control strategies for T = 10 Nm and n = 3600 rpm

Control strategy	i_{min}	P_{Vmin}
i_d (A)	0	-68
i_q (A)	8	12
$P_{V,Cu}$ (W)	17	128
$P_{V,Fe,S}$ (W)	510	100
$P_{V,Fe,R}$ (W)	22	20
P_V (W)	549	248

It can be shown that the P_{Vmin} control works exactly like the i_{min} control for most of the operating points at low speed and high torque. But in low load cases the P_{Vmin} strategy delivers better results. This shall be depicted in the following diagram.

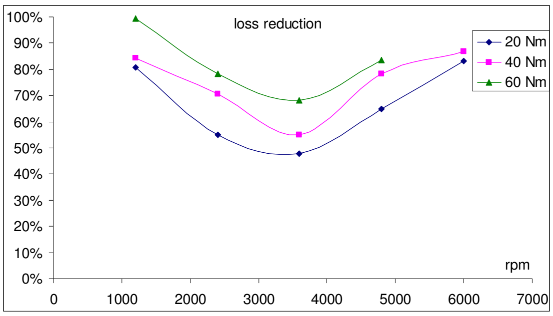

Figure 9: relation of losses of two different control strategies

The diagram shows the ratio of copper, iron and rotor iron losses of the P_{Vmin} control to the same losses of the i_{min} control.

At low speeds and with increasing torque the ratio approaches 100% as expected.

There is a minimum of the ratio at about 3300 rpm which is the rated speed of the PMSM. Beyond this speed the i_{min} strategy needs to produce reactive power as well to drive the machine at a DC-link voltage of 500 V. This leads to results which are alike no matter which strategy.

4 Verification of losses

Finally measured results have to be contrasted with calculated results. The focus will hereby been set on the idle losses. Those losses can be identified as the iron losses in the stator and rotor together with the friction losses. To get contrastable results speed should not exceed about 4000 rpm because at higher speeds the friction losses will increase due to air friction. Friction in the bearings can be modelled as a constant value without making a big mistake.
The following graph and table show that friction in the bearings are about 1 Nm. The iron losses can be seen in figure 10 as a constantly increasing torque value. This gives together with the increasing speed the expected quadratic line of losses as measured and calculated.
Discounting the friction delivers the iron losses which are pretty close to the calculated iron losses.

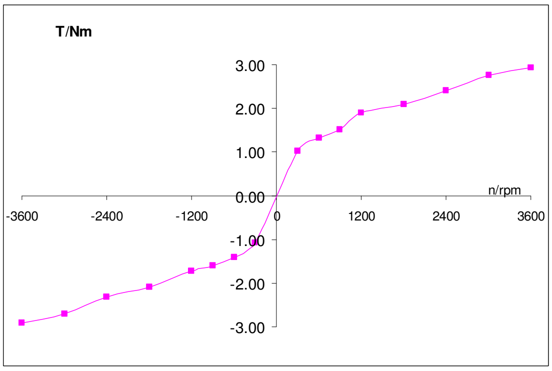

Figure 10: measured torque at no load

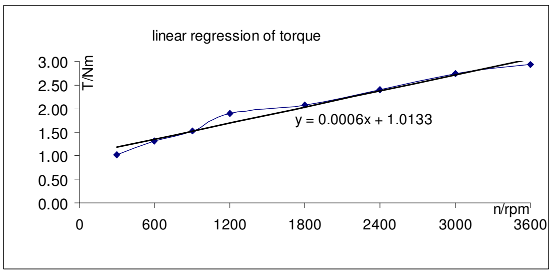

Figure 11: linear regression

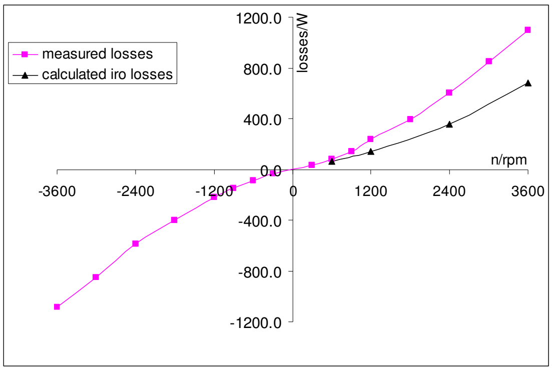

Figure 12: calculated and measured losses

Table4: measured and calculated losses

n/rpm	measured (W)	calculated (W)	measured less friction
600	83	60	21
1200	238	141	113
2400	607	360	355
3600	1095	683	718

In the calculated losses rotor as well as stator iron losses are included.

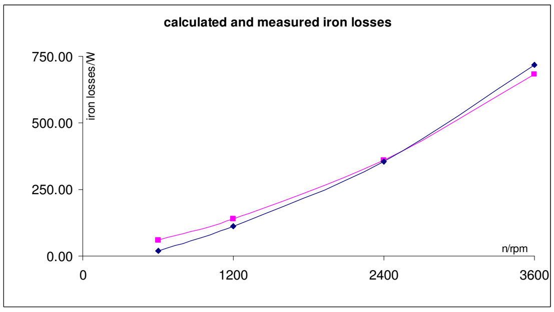

Figure 13: calculated and measured losses

5 Conclusion

Preconditions for PMSM for HEV are such as power, torque speed range. Further conditions are energy storage, for example batteries and the power converter. There are constraints for PMSM like the space where they have to be build in, the heat flux of the adjacent parts of the power train and cooling of the PMSM. All this together leads to the need to reduce losses in PMSM in two different ways.

The passive measures help to keep losses at low levels but are not simply to arrange due to the above mentioned constraints and for reasons of economy.

Active measures in the design process will help to drive the PMSM with a control strategy which will help to keep losses at low levels at many operating points.

A special control strategy has been developed to utilise the PMSM's ability to minimise losses.

In future works this strategy should not only regard the losses in PMSM, but as well the losses occurring in the power converter and the appropriate energy store. This can be done in advance by calculating the losses in the converter and the energy store. To do so one needs of course models of those parts which do not only show the principal behaviour of those parts, but as well the emerging losses. The calculated losses have to be compared to metered losses in a real drive train.

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