

# Finite Element Method based investigation of IPMSM losses

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**Abstract:** With the use of COMSOL Multiphysics Software, the design of a IPMSM (interior permanent magnet synchronous machine) is investigated. In this research the electric and magnetic losses, that accrue during the energy transformation in electric machines, were simulated with FEM and used to predict and optimize the thermal behavior of the machine. Those are primarily known as winding-, hysteresis- and eddy current losses. The temperature behavior, as consequence of winding losses are analyzed by a transient 3D-FEM model. Postprocessing the magnetic field solutions has proven as efficient method to determine hysteresis- and eddy current losses. The necessary magnetic field solution is generated by a transient 2D-FEM Modell.

**Keywords:** Electrical machines, IPMSM, winding losses, hysteresis losses, eddy current losses,

## Introduction:

### A) Motivation:

This paper investigates the design of an IPMSM as drive motor for an electric race car in the competition called Formula Student Electric (FSE). A key parameter for electrical motors is the power density which is very important for the performance of such race vehicles to keep the overall mass small at high power. Furthermore, to run the motor at high power and to prevent it from overheating due to electrical and magnetic losses the motors and its power electronics are watercooled in series [1].

In the design phase of the cooling system the knowledge of the component losses are very important. The overall goal of the project is a flexible motor design that can be easily adapted to new design constraints. In order to keep the development time short, it is useful to get a reliable prediction of the motor losses with the use of simulation without having the physical motor for measurements [2].

For this work a predefined motor design will be used. The electromagnetic design is basically the same as described by [3]. Based on this concept, the losses and the heating behavior are evaluated using FEM-Models for different operating points with COMSOL Multiphysics.

### B) Motor Design Concept

The used type of motor is a synchronous motor with buried permanent magnets in the interior rotor. As mentioned before, the motor concept is very similar to the motor concept of [3]. Since the investigation outlined in this work, the motor was adapted to the new four-wheel drive concept of the race vehicle. Because of this, the motor must be reduced in size, weight and power to meet the new requirements. Due to the fact, that the overall motor development process isn't finished yet, some parameters are named as "requested". The most important data for this new motor are shown in Table 1:

Table 1: Motor Parameters

Motor Data	
Motor Type	IPMSM
Connection Type	Star Connection
Stator Slots	12
Pole Pairs	5
Number of Winding	19
Max. Phase Current	70 A
System Voltage DC	600V
Max. Torque	21 Nm
No-Load Base Speed	Ca. 16.000 Nm
Outer Diameter	89,9 mm
Estimated Weight	5 kg
Requested Power Peak	21 kW
Requested Power Nominal	12,5 kW

## Theory

Like in every power transformation process a certain amount of losses occur, perceivable as a heat dissipation. The relation between input ( $P_{in}$ ) and output ( $P_{out}$ ) power is defined as the efficiency value  $\eta_{el}$  [4]:

$$\eta_{el} = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + \sum losses} \quad (1)$$

Specifically, in electrical machines the amount of losses ( $\sum losses$ ) consists of mechanical and electrical properties. This research will focus on the precise calculation of the electrical losses using the FEM simulation. Those can also be separated into [2]:

- Winding or Copper Losses
- Iron Losses:
  - Hysteresis
  - Eddy Current

#### A) Winding Losses:

Winding or copper losses accrue due to the electrical resistance of the windings. The resistance depends on material and geometric properties of the winding. Coil cross section shape  $A_{coil}$ , length  $L_{coil}$  and their interconnection concept rule the resistance value. The electrical conductivity  $\sigma_{cop}$  is a parameter given by material [5]:

$$R = \frac{L_{coil}}{\sigma_{cop} * A_{coil}} \quad (2)$$

Considering that the conductivity depends on temperature  $\vartheta$ , this value is usually linearized by the material depending coefficient  $\alpha$ . As reference a certain temperature (*index ref*) is used [2]:

$$R(\vartheta) = R_{ref} * [1 + \alpha(\vartheta - \vartheta_{ref})] \quad (3)$$

For a motor with a number of  $m$  phases the winding losses  $P_{win}$  for a current  $I$  is given by [6]:

$$P_{win} = m * R * I^2 \quad (4)$$

In case of AC-currents the RMS current value has to be used in equation 4.

If the winding geometry is known the calculation of winding losses can be done analytical easily. Using FEM establish an effective method to obtain the transient temperature behavior because of those losses. In fact, this statement is valid for all losses, but becomes important to winding losses as they are dominating. As shown later the linearization of the resistance becomes significant for elevated temperatures too. To express this interdependency with FEM comprehensible.

The copper losses are calculated in a 3D FEM-Model of one motor pole.

#### B) Core Losses:

Core or also called iron losses occur in rotor and stator lamination steel sheets due to time varying excitations. This energy dissipation can be separated into hysteresis and eddy currents effects which are related to the material properties. Core losses depend on the flux density, core geometry and excitation frequency [5].

Losses in conducting ferromagnetic materials are all based on Joule heating effect, caused by changes in magnetization. For the prediction of iron losses different methods are available, summarized in [7]. For this approach a method based on Bertotti is used [8]. Therefore, a postprocessing of the magnetic field solution must be done in a 2D FEM-Model.

#### C) Hysteresis Losses:

In ferromagnetic material hysteresis effects occur. Because the material consists of small regions with aligned magnetic properties. Those domains will align according to an applied external magnetic field. After removing this external field, the material stays magnetized. If an alternating field is applied to this material some extra work needs to be done for every reversal of the external field [5].

Due to the research from [8] the hysteresis can be expressed with:

$$w_{hyst} = \frac{1}{\pi * T} \int_0^T [k_{hyst} * B(t) * (\frac{dB}{dt})] dt \quad (5)$$

Where T is the period time for one electrical period. B(t) is the magnetic flux density in the iron sheets where hysteresis occurs. The coefficient  $k_{hyst}$  is determined by:

$$k_{hyst} = \frac{\pi}{\rho} * \frac{H_c}{B_{max}} \quad (6)$$

The value  $H_c$ , extracted by material datasheet, is identified as the positive field value at zero induction.  $B_{max}$  express the peak value of induction in the hysteresis cycle. The density of the sheet lamination is defined by  $\rho$ . The specific hysteresis loss is determined by:

$$w_{hyst} = \frac{1}{\rho * T} \int_0^T [H_c * (\frac{dB}{dt})] dt \quad (7)$$

#### D) Eddy-Current Losses:

Due to the time varying, magnetic field, electric currents are induced into the ferromagnetic material. Like copper those materials possess an electrical

resistivity. Consequently, there also is a power loss effect [5]. The used equations to analyze this effect are also given by [8]:

$$w_{hyst} = \frac{1}{2\pi T} \int_0^T \left[ k_{eddy} * \left( \frac{dB}{dt} \right)^2 \right] dt \quad (8)$$

The coefficient  $k_{eddy}$  is introduced:

$$k_{eddy} = \frac{\pi^2 * \sigma * d^2}{2 * \lambda * \rho} * \frac{\sinh \lambda - \sin \lambda}{\cosh \lambda - \cos \lambda} \quad (9)$$

$$\lambda = \frac{d}{\delta} \quad (10)$$

$$\delta = \frac{1}{\sqrt{\pi * f_{el} * \mu * \sigma}} \quad (11)$$

Material parameter like conductivity  $\sigma$ , and permeability  $\mu$  can be extracted by the datasheet. The system frequency  $f_{el}$  and lamination sheet thickness  $d$  are model specifications set by the user.

## Modell Configuration & Solution:

### A) Winding Losses:

The winding consists of 3 phases connected with a star point. According, to the number of stator slots each phase takes place in 4 slots. Within one phase the coils are arranged by two coil groups parallel within two coils series. This concept defined by [3] is shown in Figure 1 for phase U respectively:

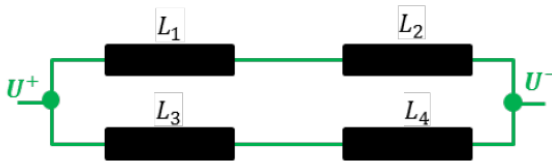


Figure 1: Winding Topology for Phase U [3]

Each coil has a winding number of 19 windings. Due to the symmetry, every coil carries the same current value, the same resistance and so the same losses also if production tolerances are neglected. Due to this significant advantage, the model can be reduced to one coil to save computing time.

The finally used geometry shown in Figure 2 was created with CAD software. Like mentioned before the model was reduced to one tooth of the stator. The geometry only neglects the connection between the single coils.

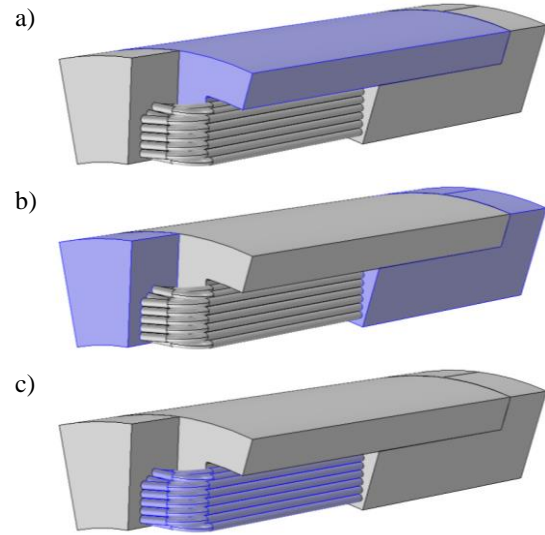


Figure 2: Geometry Winding Model a) Selection Iron b) Selection Cast c) Selection Copper

In Figure 2 also shown with blue market domains is the material selection for the model. To get to a fast solution and a stable model, for this research only materials from the COMSOL library are used. Domain a) is defined as *Soft iron (with losses)*, domain c) as *Copper*. As the Winding should be casted a third domain b) must be defined. For the casting material, the material properties were set manually.

To model the heating process caused by the loss effects of the coil a multiphysics model is necessary. In COMSOL this can be done by combining the *Electric Currents* node with the *Heat Transfer in Solids* node.

The *Electric Currents* physics is attached to the coil geometry (Figure 2c) only. In this physics current can be supplied to the model with a *Terminal* node to one end of the coil endings. Consequently, a *Ground* node must be attached to the other ending. Applying the *Electric Currents* node automatically adds the *Current Conservation* node to the model where the linearization of the electrical conductivity can be defined.

The defined currents serve as the source of heating for the *Heat Transfer in Solids* node, which is automatically defined by the *Electric Currents* physics. So, the boundary conditions that must be chosen are those connecting the model geometry to the environment. With the *Diffuse Surface* and the *Heat Flux* nodes these conditions can be realized as shown in Figure 3. In that case the surface emissivity and a heat transfer coefficient are necessary parameters.

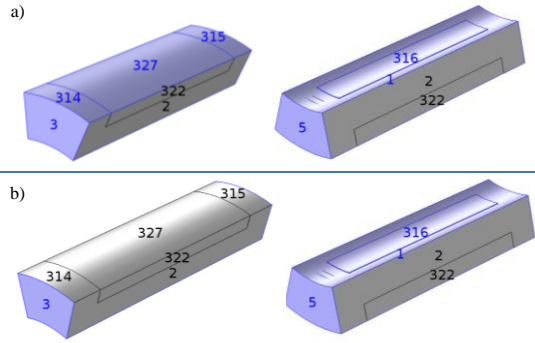


Figure 3: Boundary Selection for a) Diffuse Surface and b) Heat Flux

The domains 314, 327 and 315 miss the *Heat Flux* node. That's because those domains should be cooled by the vehicles cooling system. For the first simulations, these boundaries were supplied with a constant *Temperature* node to consider this effect.

The side wise domains of the stator tooth are those where the symmetry must be defined. For this reason, the *Periodic Condition* is added to the model.

Because of the filigree geometric shape of the windings the mesh has to be very fine at different domains to prohibit intersections of the mesh. Especially at the end of the windings this problem is significant. This fine mesh results in a longer computing time. To handle this, it's recommended to mesh the coil geometry section wise to improve the efficiency of the model as much as possible. In Figure 4 the mesh of the different domains is visualized.

To analyze the temperature distribution a transient solver is implemented. The simulation time is set to a value where the steady state of the temperature behavior is reached.

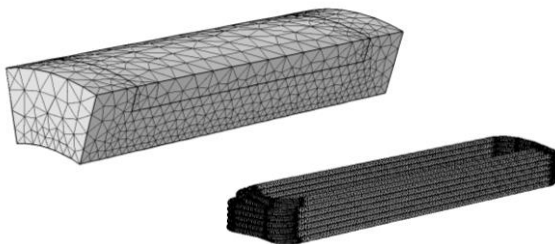


Figure 4: Mesh

The steady state solutions are shown in Figure 5, Figure 6 and Figure 7. In all Figures, a current of 30 A is supplied to the coil. The cooling temperature at the outer surface of the iron is set to 30 °C. Figure 5 shows the hottest spot in the end windings what meets the established opinion. The overview in Figure 6 assures that the periodic condition works well and shows the symmetric temperature distribution in all areas. The temperature gradient for a cross section through the

stator tooth is plotted in Figure 7. It's also visualized that each coil section has a different temperature depending on its position.

So, with that model it is possible to predict the steady state temperature for different currents and cooling temperatures. The influences of those parameter variations are illustrated in Figure 8. The transient behavior is plotted for the position of the coil winding with the highest and lowest temperature value.

With COMSOL it is also possible to extract the values for resistance and copper losses. The linearized electrical conductivity is already considered. An Overview about those values is given in Table 2.

Table 2: Overview about Temperature Depending Resistance and Power Loss

I_coil [A]	Resistance [ $\Omega$ ]	Power Loss [W]
15	0.0801	18,01
30	0.0923	83,06
45	0.1357	312,60

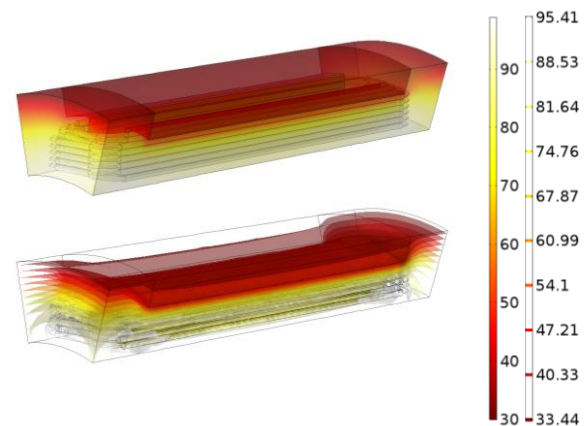


Figure 5: Steady State Plot of the Temperature

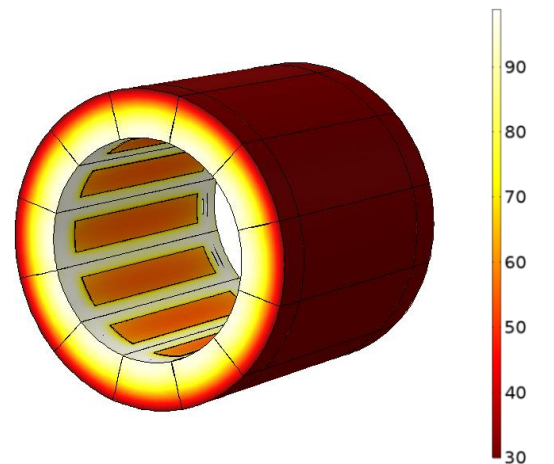


Figure 6: Steady State Plot of the Temperature without Symmetry

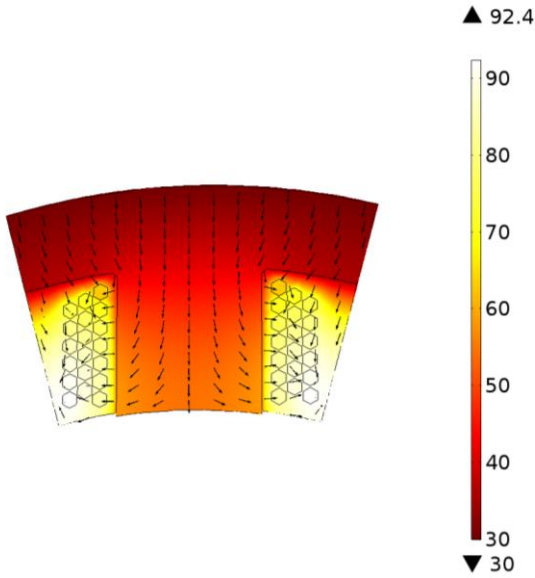


Figure 7: Steady State Plot of the Temperatur over Cross Section

## B) Core Losses

As mentioned before, to model the core losses it's necessary to obtain the magnetic field solution and use it for postprocessing. Therefore the transient behavior model setup as described in [3] can be used. To solve the problem some parameters like the sheet thickness  $d$ , the coercivity field  $H_c$  and permeability  $\mu$  has to be added. The 2D-model from [3] assumes that the iron core consists of one massive block over the active iron length. To get a convergent solution of the magnetic field the electrical conductivity of the iron has to be set to zero. For the core losses, the conductivity is added as a separate parameter. So, it is possible to solve the eddy current equations without losing the convergent solution for magnetic field. An overview about added parameters is shown in Table 3. The equations 5-11 can be added to the model with the *variable* tool.

The Multiphysics was not used in this case in order to keep a reasonable simulation time.

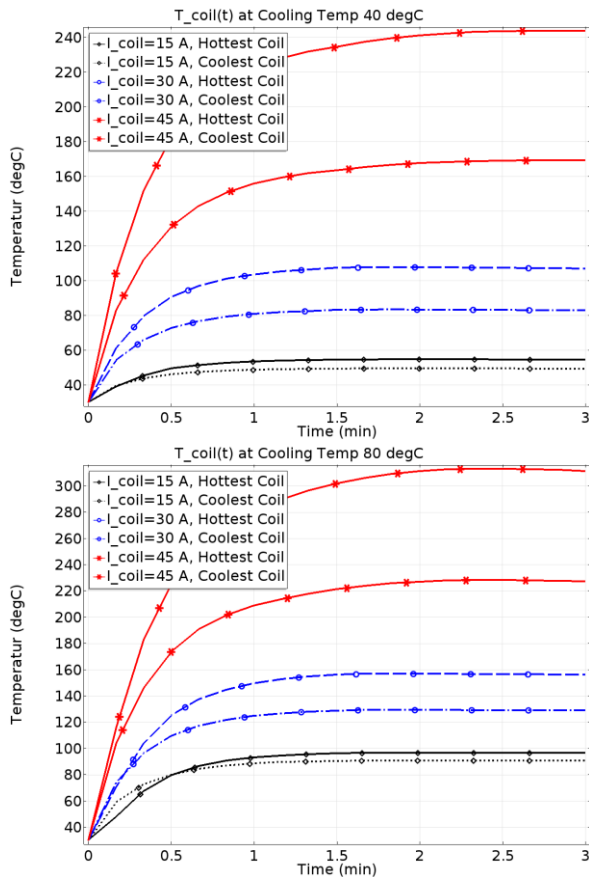


Figure 8: Transient Temperature Behavior at Different Coil Currents and Cooling Temperatures

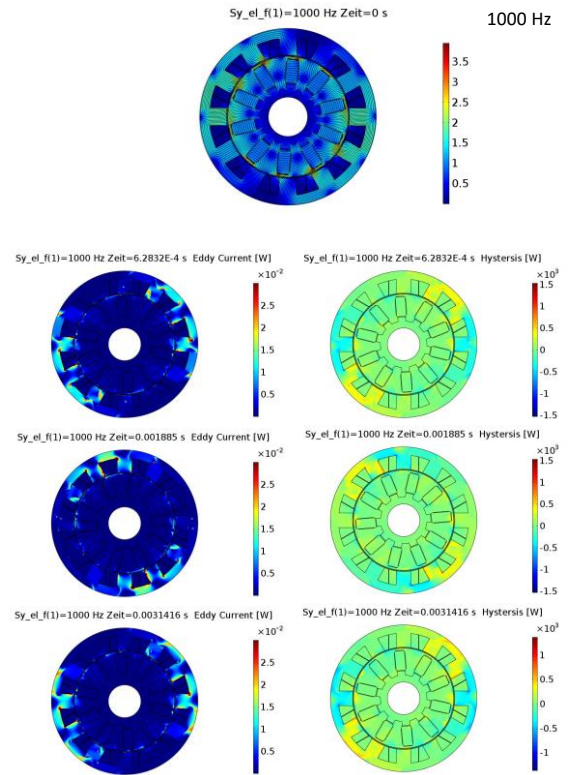


Figure 9: Field distribution Hysteresis (right column) and Eddy Current Losses (left column) at 1000 Hz and different Times

Figure 9 and Figure 10 show the distributions of the eddy current losses (left column) and the hysteresis losses (right column) for two different frequencies. Both losses increase with frequencies values what meets the expectations. The peak value of the

hysteresis losses legends seems to be very high. As illustrated in Figure 11 this peak value belongs to very small domains.

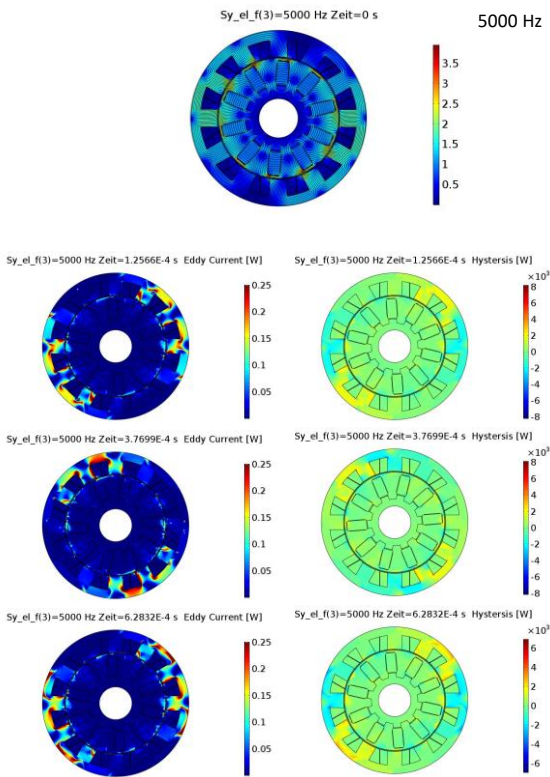


Figure 10: Field distribution Hysteresis (right column) and Eddy Current Losses (left column) at 5000 Hz and different Times

Table 3: Parameters Added for Loss Calculation

Parameter	Value
d	0.35 mm
$H_c$	140 A/m
$\mu$	12
$\sigma$	5

The distribution shown in Figure 12 seems to be very coarse compared to the magnetic flux density distribution. That behavior is caused by the squared derivative of equation 8.

### Conclusion

The simulation of the losses strongly depends on material properties. The models meet the qualitative expectations. However, the accuracy of the simulation has to be validated with a first prototype in the next step.

As next steps of the project the models of the core losses had to be expanded so that it is impossible to see the temperature behavior as consequence of them too. According to the long-lasting calculations this wasn't possible for this research. Another next step has to be the validation of those simulations by a physical test and the identification of the real material parameters.

For the beginning the results of the simulation help to increase the understanding of loss effects contribution to the thermal behavior in electrical machines. Also, it is now possible to get an idea about the dimension of those losses. The modeling process is defined. As the concept of the motor doesn't change significantly these models can be used for any new development revision.

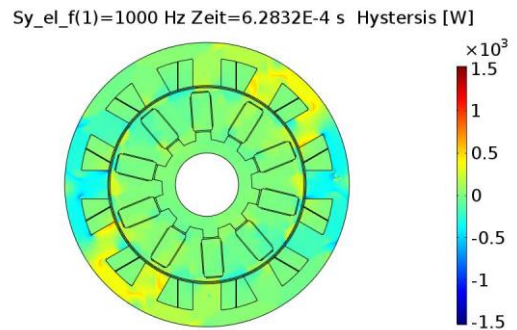


Figure 11: Detailed view on Hysteresis Loss Distribution

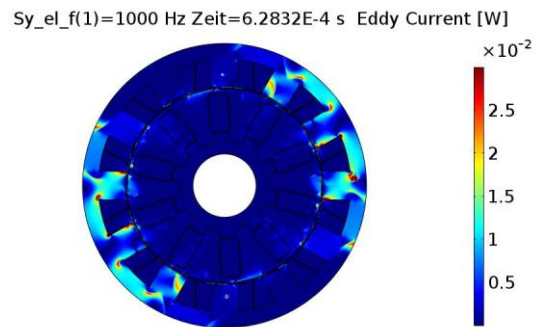


Figure 12: Detailed view on Eddy Current Distribution

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