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Multi-Objective Optimization of the Rotor Design to Improve the Acoustic Behavior of High Power Density Interior Permanent Magnet Synchronous Machines

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Abstract

The shape of the flux barriers in IPMSM has a significant influence on the acoustic behavior as well as on equivalent stress and torque. The magnetic field is the main source of noise excitation of electric machines. In this paper a method is proposed which constantly fits an approximation model with simulation results to improve its accuracy of predicting torque as well as NVH. Due to significantly large simulation time a non-dominated sorting genetic algorithm searches for new Pareto optimal designs based on approximation model predictions. By optimizing the shape of flux barriers in IPMSM this method minimizes NVH and maximizes torque as a trade-off between electromagnetism and structural strength in a weakly coupled simulation. In this case the maximum equivalent stress is used as a constraint.

1 Introduction

The changes in the automotive industry towards electromobility reveals multiple challenges. One of them is that customers are used to quality standards of combustion cars including noise, vibration and harshness (NVH). The sound of battery electric vehicles (BEV) is different to the sound of combustion cars. On the one hand the engine's sound power level is lower and on the other hand the noise spectrum is tonal. Furthermore, ambient noise is more present than in combustion cars. Due to the tonal spectrum and low ambient noise power level BEV should be silent and comfortable to improve the customer acceptance.

Permanent magnet synchronous machines are characterized by high power density. Thus, they are widely used in traction drives. Interior permanent magnet synchronous machines (IPMSM) offer an additional reluctance torque. IPMSM use flux barriers close to the air gap to control flux.

There are several publications where it is shown that minor design modifications of the flux barriers close to the air gap result in significant changes in torque and NVH. This is the main reason why finite element analysis (FEA) is used for optimization purposes for electric machines.

Furthermore, these modifications impact the bridges of electric steel since for high speed the maximum equivalent stress exceeds its threshold value. It is not only the equivalent stress but also the fatigue strength which has to be taken into account. Due to fatigue strength the maximum equivalent stress is lowered in comparison to tensile tests.

So the optimization of electric machines is a multidisciplinary optimization problem. In this paper the focus is on the trade-off between electromagnetic and mechanical characteristics. The acoustic behavior of electric machines has to be carefully investigated in an early stage of the design phase.

2 Noise and Vibration of Electric Machines

Jordan proposed the source of noise of electric machines as an interaction of electromagnetic force density waves with the mechanical and acoustic characteristics of electric machines. Furthermore, he derives formulas for ordinal numbers of the rotating field waves using the rotating field theory. [1]

Hence the air gap magnetic field is the main cause of excitation. This excitation can lead to sound radiation as well as structure-borne sound. The air gap radial force density can be derived from Maxwell's formulas using Maxwell's stress tensor so that the radial and tangential force density can be described as in equations 1 to 2 in terms of the magnetic flux density in the air gap field. [2]

$$f_{tan} = \frac{B_{rad} \cdot B_{tan}}{\mu_0} \tag{1}$$

$$f_{rad} = \frac{B_{rad}^2 - {B_{tan}}^2}{2\mu_0} \tag{2}$$

It was shown that radial force density is around ten times larger than tangential force density. Therefore the tangential force density as a source of noise is neglected in this paper. The force acting on a tooth is calculated by integrating the air gap radial flux density along a line underneath the tooth. The superposition of all resulting forces on teeth result in excitation which can be measured on the machine's surface. Using Fourier transformation the amplitude of all relevant orders can be calculated. Furthermore, the electromagnetic torque is calculated as follows in equation 3.

$$T_e = l_z r^2 \int_0^{2\pi} f_{tan} d\varphi \tag{3}$$

It is assumed that there is a trade-off between structural strength, torque and NVH. So the structural strength needs to be evaluated. As high rotational speed helps to build high power density electric machines structural strength is a relevant criteria to be evaluated. Therefore the maximum equivalent stress of the electrical steel for high rotational speed is calculated.

In material science the equivalent tensile stress or von Mises stress is a scalar value that corresponds to a real three dimensional stress displayed by the Cauchy stress tensor in equation 4. This theory is commonly known as the Mises yield criterion or Maximum Distortion Energy Theory of Failure. In equation 5 only three of the six components of the shear stress are used since for symmetrical stress tensors there are only six independent values. [3]

$$\sigma = \begin{pmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{pmatrix} \tag{4}$$

$$\sigma_v = \sqrt{\sigma_x^2 + \sigma_y^2 + \sigma_z^2 - \sigma_x\sigma_y - \sigma_x\sigma_z - \sigma_y\sigma_z + 3(\tau_{xy}^2 + \tau_{xz}^2 + \tau_{yz}^2)} \tag{5}$$

3 Optimization

The initial design used for the optimization is shown in figure 1 a). The electric machine used is an IPMSM with single layer V-magnet arrangement. This electric machine has got two interior permanent magnets and six slots per pole. The initial design including the position and size of the permanent magnets and the flux barrier design close to the air gap is already optimized regarding torque and iron losses with several boundary conditions like the maximum permanent magnet weight for instance.

So in this paper the stator and rotor design except the flux barriers close to the air gap are fixed. The flux barriers design close to the air gap is optimized to display the trade-off between torque, NVH and structural strength. The stator design does not impact the maximum equivalent stress. To really focus on the trade-off for the flux barriers design close to the air gap one has to guarantee that the maximum equivalent stress in all other part of the electrical steel is less than the stress in the bridges close to the air gap. So previous simulations, which are not shown in this paper, indicate that the initial flux barrier design close to the rotor shaft is not critical concerning maximum equivalent stress. This is why the maximum equivalent stress is expected to be located at the flux barriers close to the air gap.

In this paper the flux barrier design is parameterized so that coordinates of characteristic points are design parameters of the optimization problem. The parametric model used in this paper is displayed in figure 1 b). The parameterization is a crucial part of the optimization process. The number of design parameters has to be minimized because the design space increases exponentially with the number of design parameters.

The parametric model consists of the characteristic points P1, P2, H1 and P4. The points P1, P2 and P4 are defined in polar coordinates with the distance in angle to line L1 and the distance in radius to the coordinate origin. The edge at point P1 is rounded off with the radius R1. Furthermore, point H1 is defined by the distance to P2 on the one hand and by a tangency condition on the other hand. This circle also has got a tangency condition at P2.

This parametric model guarantees a physical approach since the radius for P1 and P2 is proportional to the bridges' thickness. This is where the maximum equivalent stress is assumed. Besides, the parametric model is capable of rounding off edges to reduce the noise excitation. This is where a trade-off between structural strength, NVH and torque exists. Rounding off edges may decrease torque but may increase structural strength and NVH.

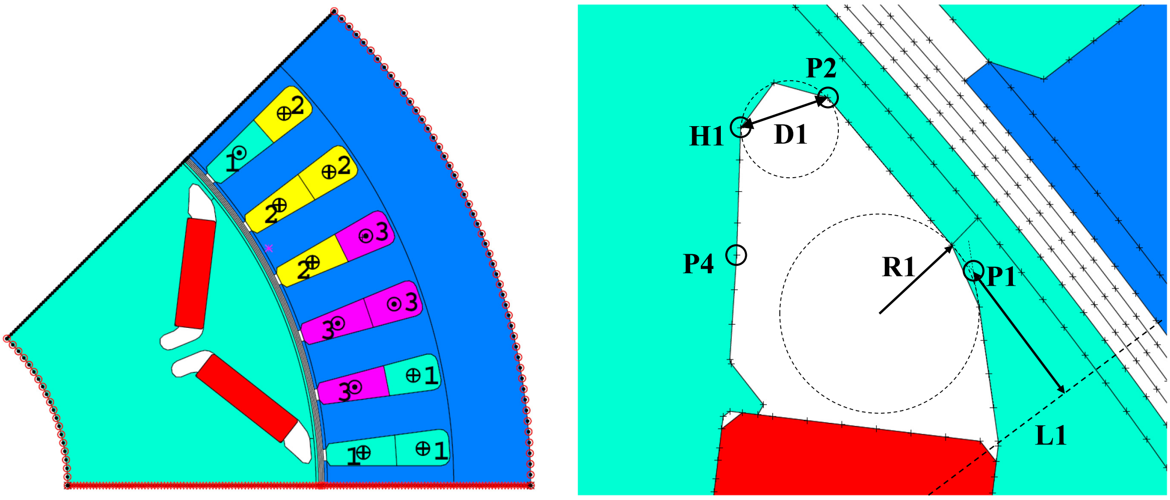

Figure 1: a) Electric machine b) Parametric Model

Since the FEA calculation time is very crucial to the optimization the simulation's step size and the mesh of the electromagnetic model is adjusted to fit both the calculation time as well as the quality criterion. The simulation's step size for instance is adjusted to the maximum ordinal number expected for the superposed radial force excitation according to the Whittaker-Kotelnikov-Shannon sampling theorem. [4] [5]

The target values of this optimization are torque and NVH. The boundary condition is that the maximum equivalent stress in the rotor sheet is below a certain equivalent stress threshold for maximum speed.

In this paper a method is proposed which constantly fits an approximation model [6] with simulation results to improve its accuracy in predicting physical quantities. Due to significantly large simulation time in comparison to the optimization's computational time a non-dominated sorting genetic algorithm [7] searches for new Pareto optimal solutions based on approximation model predictions. The designs which should lead to these Pareto optimal solutions are simulated next. This process repeats as long as the termination criteria is not yet satisfied.

Simulation process is divided into parallel branches with strength calculation and electromagnetic simulation. For both simulations FEM is used since NVH is very sensitive to minor flux barrier design changes.

With the assumption that the electromagnetic forces interfere with each other on the stator surface, the superposition of the radial forces is calculated. In figure 2 a) the sum of the interfering radial forces along the circumference against the rotor position is displayed in time domain. The superposed radial force acts on all stator teeth. This time domain signal looks very familiar with the torque ripple. Nevertheless the radial forces are significantly higher than the tangential forces. Therefore the source of noise can be found in the radial forces. Furthermore, the order analysis in figure 2 b) highlights the relevant orders of the calculated electric machine. Using order analysis the amplitude of the relevant orders of an electric machine in respect to noise can be noticed. For example one can the see the 48th order which corresponds to the number of stator teeth for example. Therefore the root mean square of amplitudes over all ordinal numbers is calculated in a post processing routine using the air gap flux density distribution. The root mean square can be seen as a NVH measure which is to be minimized in the optimization process.

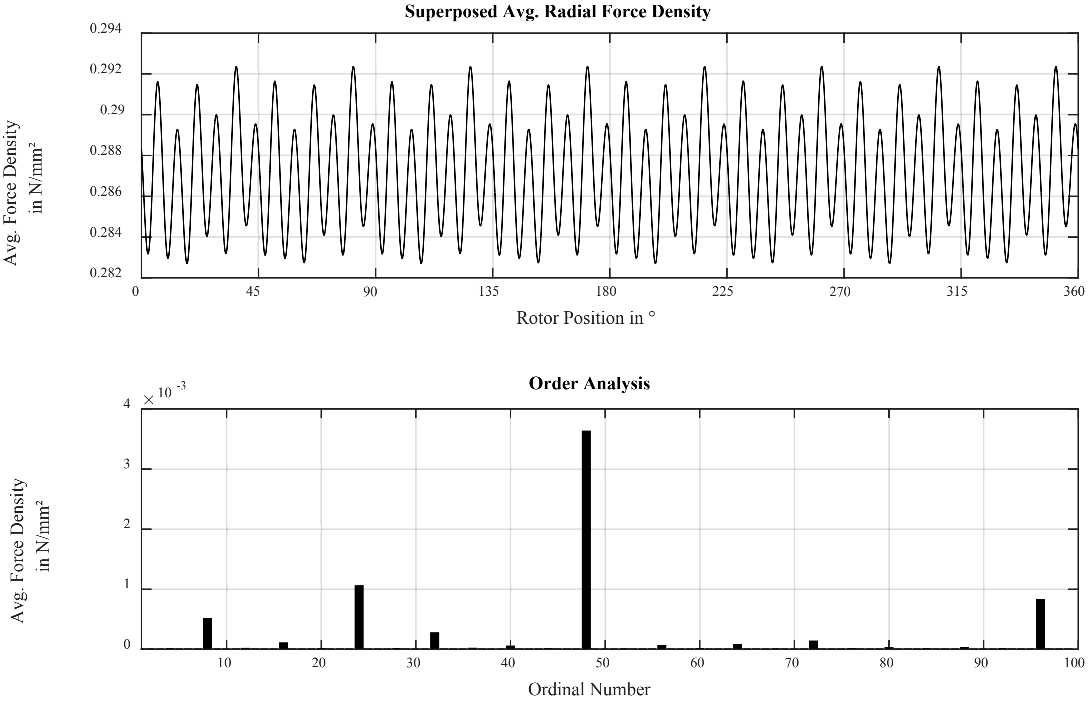

Figure 2: Superposition of the radial forces acting on the stator surface a) time domain signal b) order analysis

4 Results

In figure 2 the relative change in radial force excitation and the relative change in torque in comparison to the initial design's solution are shown in percentage. The relative change in radial force excitation is to be minimized while the relative change in torque is to be maximized in this optimization problem. Solutions exceeding the maximum equivalent stress are marked in circles as invalid. Three designs are emphasized because they are characterized by more torque, by the minimum radial force excitation or by an optimized trade-off between torque and radial force excitation. In general the relative change in torque and radial force excitation is in a range of -10 to 5 and -55 to 250 percentage, respectively (see table 1).

Table 1: Relative changes of the Pareto optimal compared to the initial solution

	Torque (%)	Excitation (%)
Design 28	**5,7**	33,1
Design 195	-0,6	**-55,0**
Design 250	**4,2**	**-48,0**

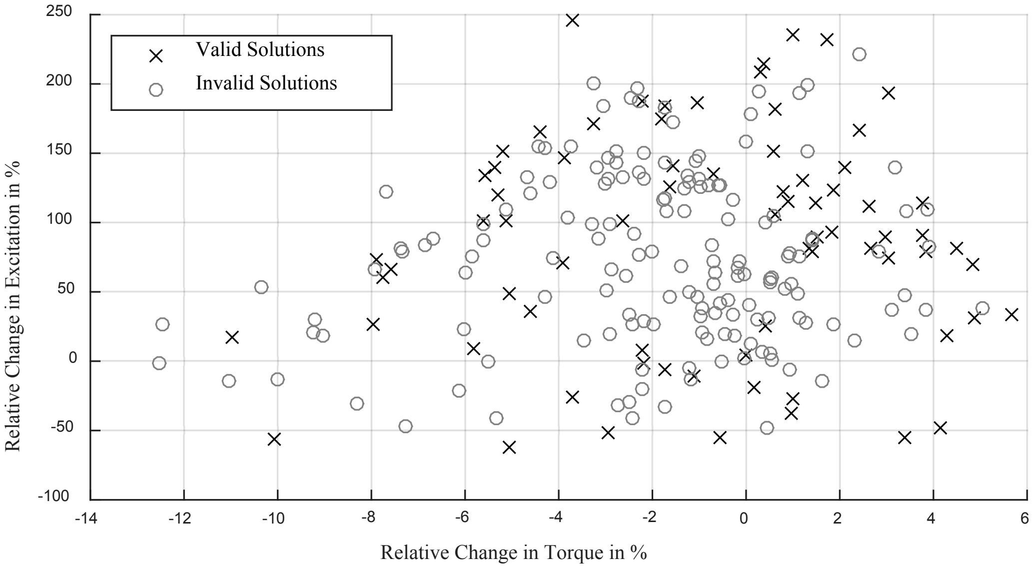

Figure 2: Relative change in torque and radial force excitation as a Pareto chart of the optimization

Invalid solutions refer to designs with thin bridges close to the air gap. The thinner these bridges are the more torque and the less excitation the design has. This effect illustrates the trade-off between structural strength and electromagnetism.

The different shapes of the flux barriers are displayed in figures 3 to 6. In comparison to the initial shape of the flux barriers in figure 3 the design with improved torque in figure 4 is steeper and very close to the air gap. Another optimized design in shown in figure 5. This design offers approximately the same torque as the initial design but is significantly better in radial force excitation. One can see that on the one hand the flux barriers are smaller and on the other hand the radius used to round off the edge is rather large. Furthermore, the bridge is thicker than the one of the initial design.

The design 250 in figure 6 is not only a trade-off in target values since torque is higher and NVH is lower but also the designs themselves appeal to mix up. The flux barriers reach out to the air gap as well as in tangential direction.

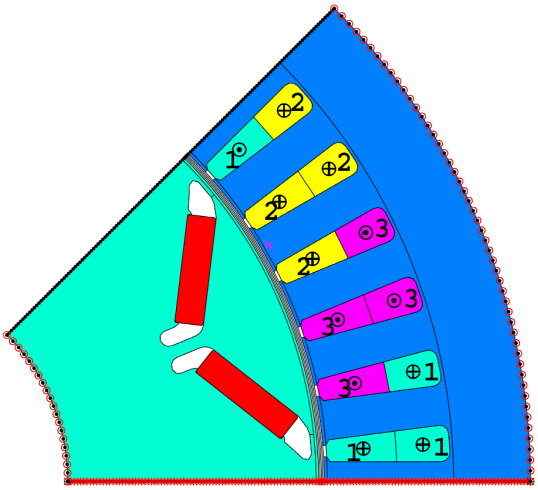

Figure 3: Initial Design

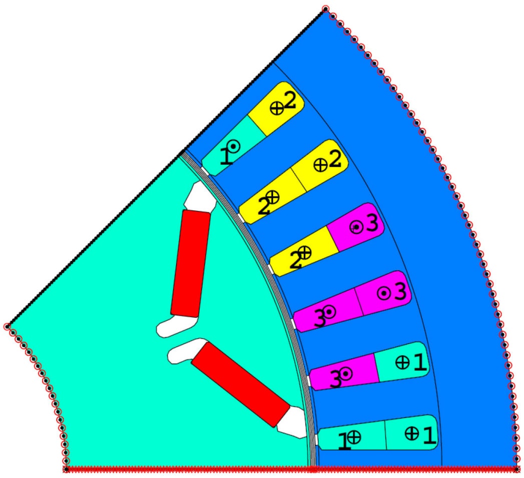

Figure 4: Design 28

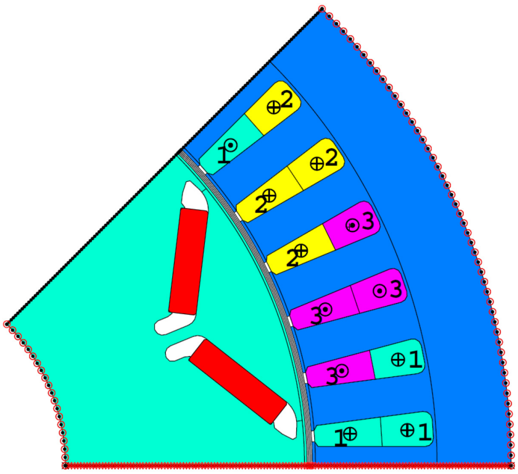

Figure 5: Design 195

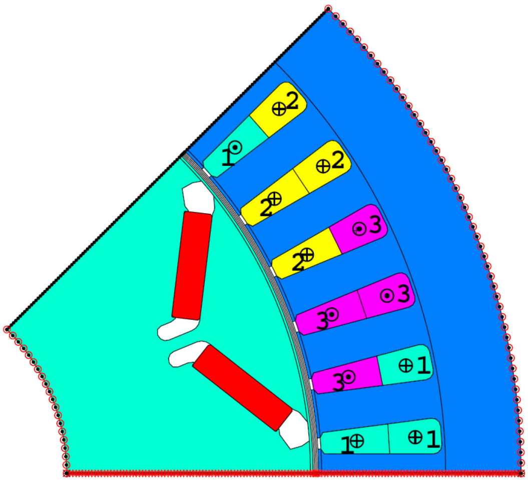

Figure 6: Design 250

5 Conclusion

The proposed method enables a time efficient optimization of the flux barrier shape to maximize torque and to minimize the radial force excitation which is the main source of noise of electric machines. Furthermore, the method ensures that the design is valid in respect to the maximum equivalent stress for maximum speed. This method is characterized by fast convergence.

It is shown that the shape of the flux barriers in IPMSM will lead to a trade-off between structural strength and electromagnetism. Besides the shape of the flux barriers the thickness of the bridges above the flux barriers is a critical optimization aspect. This method ensures that the bridges fit both the electromagnetic as well as the structural strength criteria.

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