– 60% Total Harmonic Distortion
– 40% Cogging
+ 9% Torque
+ 2% Power Factor

CUSTOMER STORY // ELECTRICAL ENGINEERING

OPTIMIZATION OF A SERIES PRODUCTION ELECTRIC MACHINE IN SHORTEST TIME

SIEMENS Large Drives (Nuremberg) develops high-efficiency electric machines. In cooperation with CADFEM and Dynardo, a transferable workflow was devised for automatized motor geometry optimization.

Electric machine design means finding the perfect geometry for multiple load cases

Electric machines handle the highest energy densities and power flows within extremely small space while converting between electric and mechanical power with efficiencies up to 90-98%. Contemporary design challenges arise from ensuring high power and efficiency ratings across a broad range of loads while at the same time keeping an eye on other machine properties, e.g. with respect to noise, vibration, and harshness (NVH). Efficient simulation-based design approaches are of particular value when going from single-load-point motors (e.g. cranes, lifts) to variable load, multi-purpose applications (machining, mobility, robotics). This case study targeted the geometry optimization of the rotor of an internal permanent magnet (IPM) machine based on a 2D FEM model in ANSYS Maxwell. The conflicting goals are to keep the rotor mechanically stable while minimizing electrical steel sheet bridges between the magnetic poles, restricting magnet material usage, and shaping the rotor design. Here, torque ripples should be minimized while maximizing the torque output. An additional goal deals with avoiding higher-order harmonics in the driving electric circuit by minimizing the so-called total harmonic

distortion (THD) of the back-EMF (electromotive force). This means facing a multi-criteria optimization problem formulated for a multi-load-case simulation. This task was efficiently solved with purely meta-model-based global and local optimization.

The MOP and what-if questions

A thorough sensitivity study scanning a broad design space is the basis for almost any investigation with optiSLang. The sensitivity study yields a Metamodel of Optimal Prognosis (MOP) for each response. The MOP captures nonlinear dependencies, not only from single inputs but also from combined influences. An MOP of high quality allows to systematically explore many different solutions to design conflict problems in short time without the need for additional simulations.

In this case study, a large design space of the internal permanent magnet (IPM) electric machine depicted in Fig. 1 (see next page) was explored purely based on response meta-models. Fig. 2 (see next page) shows the MOP for the response exhibiting the most complex behavior, the cogging torque amplitude. The plot shows nicely that varying

Fig. 1: The IPM synchronous motor: exemplary photography with exemplary geometry and marked side pockets
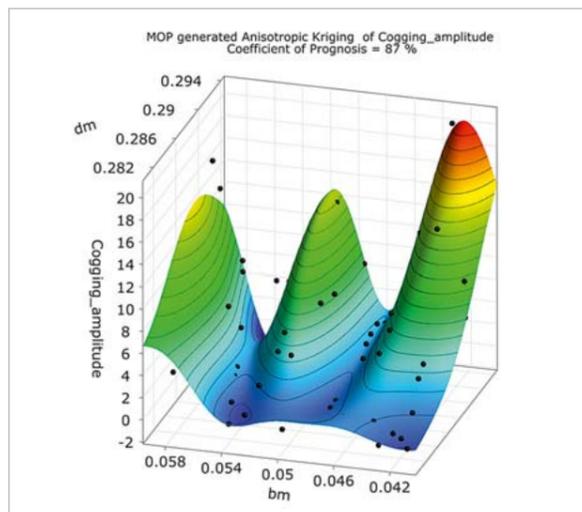
Fig. 2: MOP for the cogging torque amplitude over the two most important input variables determining the magnet size and shape. Complex responses with local minima and maxima as seen here make an optimization problem challenging, in particular when goals and constraints arising from several responses have to be negotiated.

the magnet size yields a sequence of amplitude maxima and minima. Four of the eleven varied parameters contribute substantially to the variation of the cogging torque amplitude. The plot shows only the subspace of the two most important input dimensions. By the associated Coefficient of Prognosis (CoP) of 87% an objective measure is given that the meta-model has indeed captured most of the system behavior. Only 13% of this response's variance remain unexplained by the meta-model. The other investigated responses comprise i.a. torque, torque ripple amplitude, power factor at critical load, and the THD of the back-EMF. Their MOPs exhibit even

higher CoP values based on scanning the design space with 170 successfully evaluated design variations distributed as Advanced Latin Hypercube Sampling (ALHS).

Finding an optimized design point means going to a place in the design space where the most important responses adopt desired values while other responses stay within acceptable limits (constrained optimization). Having a high-quality MOP at hand for every single response means that many interesting what-if questions can be answered. The combined set of response surfaces can answer the question as to where in the design space torque and efficiency will be maximized without compromising design constraints, such as the smoothness of the torque delivered.

"Optimization on the MOP" means that the meta-models allow the application of thorough global search strategies (e.g. evolutionary algorithms) without the need for additional FEM simulations. It also creates the freedom to experiment with different combinations of optimization goals and constraints. This is the second level of what-if questions answered: Where does the optimizer move when maximizing torque while constraining vibration amplitudes and THD? Where will the best design be found when minimizing THD while constraining the other responses? Where will Pareto-efficient designs be found in a multi-objective optimization setup?

The optimized motor
In this case study of a high-pole IPM synchronous motor, a purely meta-model-based optimization yielded substantial improvements with respect to every single response:

- THD decreased by 60%
- Cogging amplitude decreased by 40% (see Fig.5)
- Torque at maximum phase current increased from 2540 to 2770 Nm (corresponding to a 9% increase while the magnet cross section grew by 8%)
- Power factor increased from 84 to 86%

All this could be achieved by simply varying only the rotor cross section geometry and the driving voltage phase angle. This means that tuning the stator as well will allow leveraging even further optimization potential.

Challenges – workflow – optimized design

Electric machine optimization challenges
Leaving the number of embedded magnets of this IPM machine constant, the rotor cross section geometry is determined by the magnet size and width, the shape of the side pockets, and the radial positioning of the magnets. Why is it not the case that more magnet material generally translates into more torque, and why is the best machine not the one with the largest magnets? Firstly, this is because

the other two materials also have a purpose. The electrical steel has the task of guiding magnetic field lines and the copper carries electric current. It translates into an economizing problem of allocating the given allowable motor volume and mass to the three materials: magnets, iron, and copper. Secondly, it is also a matter of topology: given amounts of the materials need to be distributed wisely in order to give rise to strong fields from magnets and copper windings, and to allow for these fields the strongest possible interaction. Two simple exemplary cases of misallocation can be easily understood: if the copper cross section is not sufficient, there will be excessive ohmic losses which is a drag on the efficiency and, at the same time, a cooling issue; or, as mentioned above, if the magnets are too small, their weak field means low torque.

Focusing solely on the rotor geometry, as done here, the design challenges are somewhat more subtle and involve three different aspects of the physics of permanent magnet machines: field line shortcuts, mechanical stability against centrifugal forces, and torque ripples. When magnets are embedded within the rotor's iron, this opens a flux path solely inside the rotor's steel going narrowly around the magnets sides. One speaks of flux leakage. This is why side pockets (marked white in Fig. 1) are introduced. They reduce the iron cross section of shortcut paths and force more field lines to go through the air gap and around the stator's coils. This is especially true if the machine is designed in such a way that these paths are magnetically saturated. One can see that for a given magnet size the iron topology determines whether a lower or higher fraction of the potentially available field will be used for generating output torque.

The second issue deals with the mechanical stability of the rotor. Commonly, rotors are made of sheet metal piles (reduction of eddy currents) whereby the space for positioning magnets is created by punching holes into the sheets. Thus the mechanical stability of the rotor's steel is heavily dependent on the rotor's diameter and the bridge's thickness. The design conflict becomes clear, thicker bridges mean better stability but more flux leakage.

The third issue is the one of the homogeneity of the torque over rotor position, both under load (torque ripple) and at no-load operation (cogging). It arises from the interaction of the fields of the rotor and stator and depends on the shape of the electrical steel bodies close to the airgap between rotor and stator. Similar to the torsion forces, also the local radial forces between rotor and stator are time-varying functions of the rotation angle depending on the working point. All these forces give rise to NVH side-effects.

Wrapping this up, windings and magnets create the magnetic fields and the iron guides the field lines. Motor manufacturers have to pay attention to finding an ideal cross section geometry for the rotor's steel because it crucially

influences the main design conflicts in terms of flux leakage, mechanical stability, and smoothness of operation. Variation studies with optiSLang cannot completely replace sound engineering knowledge, but they help to sort out the high-dimensional input and output parameter spaces. They help to get to better designs quicker.

The optimization workflow
For achieving this optimization, a single sensitivity study was followed by three MOP-based optimization runs and verification simulations:

- Design of experiment (DoE): an LHS yielding a substantial fraction of geometrically infeasible designs and 170 successful simulations
- MOP results: the complex nonlinear response behavior was captured with CoP values of 87% and greater
- MOP settings: complex responses deserve meta-models made for elevated complexity like anisotropic Kriging models
- Thorough global optimization on MOPs with an evolutionary algorithm (elevated population size, 3500 MOP calls per run) in single-objective setup, i.e. one goal and several constraints, three different runs switching goals and constraints
- Gradient-based local optimization
- Two additional FEM simulations for verifying optimized designs

This case study was based on single-objective global optimizations with optiSLang's evolutionary algorithm (EA). Besides the beneficial global search properties of the EA, the key contributions to the optimization success were the definition of the goal and constraint functions and the high-quality MOPs. The EA was able to find feasible designs although constraints were formulated harsher than the responses of the reference design would have suggested which meant that none of the 170 DoE simulations fulfilled all constraints. Fig. 3 (see next page) illustrates how the EA first hits only infeasible (i.e. geometrically infeasible or constraint-violating) designs. Then feasible designs are discovered sporadically. Lastly, more and more feasible design "mutations" show up and the EA optimizes their parameter combinations or "genes" based on the principle of "survival of the fittest". That the "green insula" can be found within a "red ocean" of prohibited designs is a substantial proof of the global search capability of EAs. Other algorithms have a hard time being faced with this task under the circumstance that the system responses are highly nonlinear and not monotonic.

The benefits for SIEMENS
This electric motor optimization workflow is beneficial for the Large Drives team, if it is more than a single lucky hit, if it is a systematically repeatable recipe for success. optiSLang sets the right infrastructure to make it repeatable with ease:
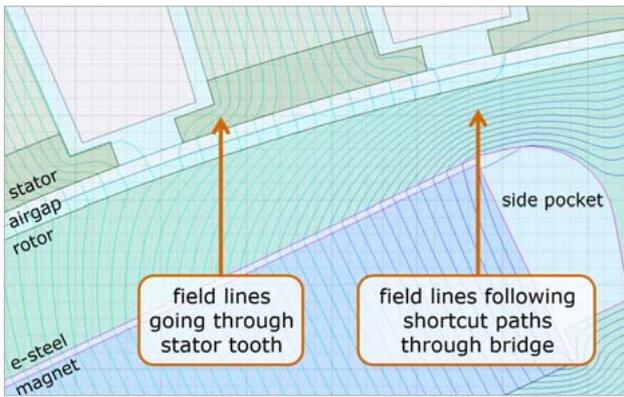
Fig. 3: Flux leakage – some field lines are not going through the stator as shortcut paths through the electrical steel bridge are available. The bridge is undesired from a magnetic point of view but necessary for mechanical stability.

Fig. 5: Cogging torque – comparison of initial versus optimized design

- Templatization for the text-based or Workbench-based integration of Maxwell models
- Templatization for the whole optimization workflow
- optiSLang 6 allows export and import of criteria definitions
- The model parametrization does not need to be perfect, high-quality MOPs are achievable in spite of a high fraction of failed designs
- Safety infrastructure for dealing with crashes, interrupts, or database reevaluations
- MOPs answer what-if questions, (a) when the user inspects the postprocessing, and (b) when optimization algorithms explore the design space
- Instead of relying on blind runs of blackbox-optimizers, optiSLang users build on knowledge-based targeted optimization. Constantly expanding the engineering knowledge base via variation studies, data mining and causality analyses leads to long-term success

Conclusion

Electric machine design has always been a challenging task at the multi-physics intersection of electromagnetism, mechanics, and thermal optimization. An economizing problem of allocating space to copper windings, iron and magnets is intertwined with a field shaping problem where many geometry details count. When going from single-working-point motors to demanding dynamic applications, the motor design has to be balanced across a broad range of speeds and loads. The presented IPM motor optimization case study shows that a meta-model-based approach of design understanding and well-targeted optimization is able to reach highly optimized design points at greatly reduced computational cost. MOP-based evolutionary optimization was able to substantially upgrade a successful series production machine.

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Fig. 4: EA history: geometrically feasible and constraint-fulfilling designs (green dots) first appear only sporadically. The EA principle of survival of the fittest leads to a higher and higher ratio of feasible designs and pushes the feasible subpopulation towards the optimum.