FEM-Based Shape-Optimization of Electrical Motors

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***Abstract*—By introducing spectral or polynomial functions to perturb the shape of the rotor in an electrical machine that was previously optimized by conventional means, it was shown that performance parameters can be further improved, in some cases significantly.**

This was accomplished by developing and applying an optimization method designed for use with a commercial finite element simulation software (Maxwell). This report describes the method and its development. Also issues the user must consider when applying the method, e.g. related to accuracy or choice of objectives, are discussed. Further, some results from the optimizations are presented - even though not all details can be published for confidentiality reasons.

The results shows a success in improving the objectives (e.g. torque ripple and/or power factor) while keeping other parameters of the motor unchanged (e.g. inductances). The method can take different load points into consideration, and works for different kinds of motors. The improvement can be significant, for one motor design, torque ripple and power factor were simultaneously improved: reduced by 13 %-units and increased by 2.5 %-units, respectively.

This is a public version of an internal ABB report, and hence some sources of information and results are confidential.

***Index Terms*—Electrical motor, FEM, design, optimization, rotor**

I. INTRODUCTION

A. Thesis Specification

Traditionally, most designs are made up by straight lines and arcs around the origin partly because this is what could be analyzed with available methods, and partly because these geometries are easier to construct. However, in some cases manufacturing is not restricted to simple geometrical shapes. This thesis is to investigate how machine performance can be improved when more arbitrary geometric shapes using multiple variables are allowed for the machine design.

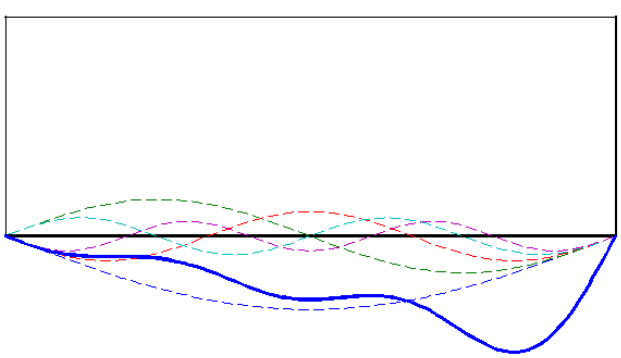


Fig. 1. Perturbing a line by adding spectral functions

There will be both practical and theoretical answers. The goal here is to find first experiences and rules of thumb. Another goal is to create a generalized program structure for applying this method on different kinds of motors.

B. Purpose

The target audience for this report is varied, motor design engineers already in possession of a by conventional means previously optimized motor model is an important group.

In this case, finite element analysis with parameterized geometries is required to calculate objective functions. The objective functions are calculated using a secondary software, in this case MATLAB, while the simulations are run by a stand-alone FEM software, in this case Maxwell 2D. The choice of software is free and will only affect the syntax used, methodology is the same.

C. Scope

The thesis creates a model for how free form optimization can be performed, which factors are important and what early mistakes are possible to avoid. The paper will not go in to detail about the inner workings of electric motors and will not make any assumptions on what result such an optimization would give, but provide a method to find a well-grounded sound result based on user input. To accomplish this several measures are being taken to perform validity checks, like adding boundaries and limitations. An open mind is however crucial when doing this optimization, it's important to remember that the goal is to find geometries not before considered.

Other than creating a model following the set objectives, it's also desirable to build a method that can be used on different kinds of motors and with different objective functions.

D. Past Work

Optimized motor geometries will be used, all based on previous conventional optimizations. Considerations will be given to what assumption will have to be made to simplify the calculations, and how they affect the result. Some understanding of the motor's physical behavior is required, to make sure the adjustments are made where they can affect the targeted objective. Most of the information used in this thesis comes from ABB internal reports and by using the know-how available in-house, but also from [1] and [2].

II. OBJECTIVE FUNCTIONS

A. Torque

Since torque is the product of a motor and is the parameter that governs how well it will act as a machine, its characteristic is undoubtedly an important factor to consider when tuning the rotor design. Torque curve shape and size is affected by many factors in the motor, making it difficult to foresee and control.

B. Inductance

Different motors have different sensitivity to the inductance factor, and this objective function is not always needed to be considered. In the case of some machines however, it is an important objective to investigate. Below follows how this calculation is done. A Discrete Fourier Transform (DFT) is performed on the current and the flux vectors. This result will then be multiplied with a correction constant. The constant is needed because there is a phase shift from the load angle of the stator current. When looking at the inductance, you want to divide it into different component to show inductance in different parts of the rotor[1]. Here they are called d and q axis. This can be done by shifting the coordinate system of the DFT-result, so that the real part corresponds to d-axis and imaginary part to q-axis.

C. Voltage

Voltage is calculated as the derivative of flux linkage in the stator windings. The voltage has two main components, the fundamental frequency, that is the same as the current, and higher harmonics. The fundamental frequency is used to calculate the power factor while harmonics are used as a way to optimize the losses.

For reducing the harmonics of the voltage, a DFT operation is carried out on the simulation results. The amplitude of the harmonics of frequencies other than the fundamental are summed together and used as a objective function.

D. Power Factor

The power factor of a machine is defined as the phase difference between current and voltage. Governs the amount of reactive power used by the motor.

E. Losses

Core losses are mainly produced in teeth of the stator and rotor or a area close to the air-gap, when high amounts of energy is transported from the stator winding to the rotor, and vice-versa. This factor is affected by the overall efficiency, but other objectives can have a contribution to this value. This is an important objective to monitor.

For solid rotors, ohmic losses are introduced by voltages harmonics in the tip of the rotor.

III. METHOD DESCRIPTION

A lot of work has already been put into calculating the optimum shape and size of many rotors in use today, and extensive parameter studies have been conducted in internal ABB reports. These reports are used as a basis for models used in this thesis. These reports and hence also the background studies for this thesis can not be covered here, because of classifications and restrictions given by ABB.

Understanding the results of previous work is crucial to be able to set up intelligent objectives for optimization. If one is able to make these choices correctly there is a lot that can be gained in terms of accuracy and computation time. There is however another side to it, that is important to remember, and that is that this is an computer aided optimization and the more freedom is given to the simulations, the more interesting the result should be.

The result of the optimizations will have to be able to cover several objective functions, given by the user. Any calculation that needs to be done should have to be handled, either within the simulation software or by a external controlling software. This is to ensure no limitation are put on how complex the objective could be.

The simulation should also be able to take into consideration and weight-in different work points for the motor. This since different conditions will likely have different optimum geometries. Finding a geometry that suits the most conditions is desirable.

A. Using Analytical Model and Adding Free Form

By adding this "free form" to the design, many more design variables are available compared to conventional methods.

Free form might lead to geometries that are difficult to put into practical use. Limitations need to be constructed to avoid impossible geometries being generated, only giving inaccuracy and taking up simulation time. This issue is resolved by adding penalties for geometries that are stepping out of a valid geometric variable range, defined by the user. When invalid geometries are being pushed onto the simulation software, a error usually occurs. This error will have to be handled for the optimization to be able to continue, adding a penalty when this happens.

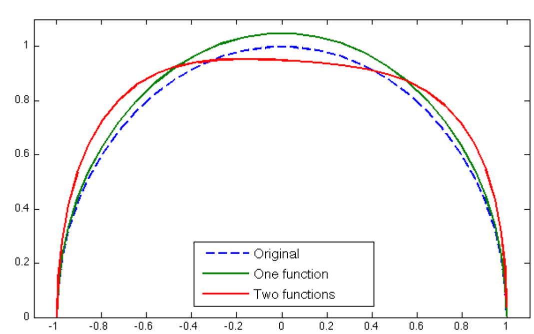


Fig. 2. The effect of perturbations

B. Optimization

First and foremost an understanding of the system that is being optimized is required; whether it has one or several local minimums, how 'deep' are these possible solutions and is the solution linear or not. The motors used are

[1] Further shifting needs to be done depending on stator/rotor relationships

already optimized to best effort. This fact makes the use of a deterministic algorithm the best choice, since a search for a global minimum has already been performed.

The possibility to define which point to examine in the first optimization sweep is important to get a fast and accurate solver. While the starting position will always be chosen by the user, the search area is often chosen by the algorithm.

This optimization problem is a function with constraints, but because the function is non-linear, multi-variable and non-analytical it's difficult to use any built in MATLAB function. Because of this an error correction and boundary function has to be written for this program. Then an unconstrained algorithm can be called, which also leads to a higher freedom from the user side. The downside is that the code gets more complicated, and that more customization needs to be done at the change of each geometry model. Here it is assumed that the model is not changed often, and that the increased required time is beneficial as the understanding increases in the process.

The Nelder-Mead algorithm [3] is used for this method. It is a deterministic algorithm which creates a solution simplex[2], and by the use of this steps toward a (local) minimum. The simplex can contain several local minimums and move towards the most optimum one, all depending on the size of the first simplex.

C. Simulation

A high accuracy in the simulation result is important to be able to achieve a consistency in the results. Inconsistent results will lead to failure in the optimization, because it will generate false values for different search points. So even if the simulation are done faster with a lower resolution, a higher resolution (and longer simulation time) will likely lead to faster convergence.

An important factor to consider is whether the numerical value received from the simulation software needs to have complete accuracy, or if the relative accuracy between iterations is sufficient to get a correct optimization result. This is a though question to answer since it is completely dependent on which objective function is used. Intensive studies will have to be done to investigate to resolutions effect on the relative result. This means running one simulation on very high resolution and manually evaluate the need, depending on objective functions. Since the gains are often quite small and this is done on a case to case basis, a higher resolution to start with is the best way to go. Alternatively running many different functions on low resolution, and re-running interesting ones on higher later.

[2] An n-simplex is an n-dimensional polytope with n + 1 vertices, of which the simplex is the convex hull. A single point may be considered a 0-simplex, and a line segment may be viewed as a 1-simplex.

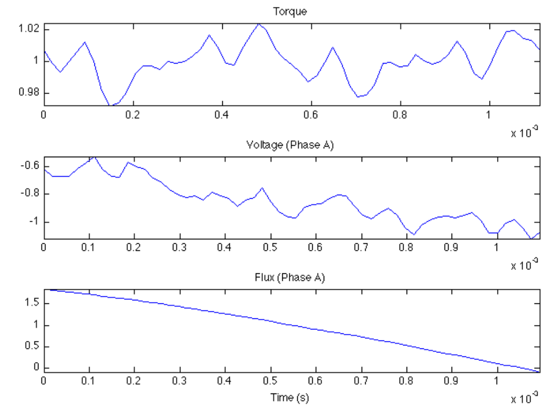


Fig. 3. Waveform comparison

Time resolution is about deciding on what degree one can be willing to sacrifice speed for accuracy, this depends on the optimization target function and the expected simulation time against available time. Different parameters of the motor characteristics have different wave forms. Torque contains high frequency information important for post-processing, while flux mainly has a fundamental component of interest when analyzed separately. A comparison between torque, voltage and flux is shown i figure 3. This leads to the fact that depending on what parameter is of interest, a different time resolution is required.

Mesh resolution determines how much details are available when performing the simulations. A high resolution is mostly important in areas where flux shape is changing quickly, for example the rotor tip. In areas with a constant flow, less details are required. If a to course mesh is used, many important factors can be missed. Such factors as losses would not be possible to compute accurately without a fine enough mesh.

IV. Results

To show the success rate of this method, some important results obtained during the development will be shown. In the end a mixed objective optimization with good results will be shown, for two different load angles.

A. Torque Ripple

Few optimization, using high enough tie resolution, for torque ripple were performed. However, the results are clear that this is a factor that can be highly improved by this method. Together with inductance it is the most successful objective, which is also shown in the later mixed objectives section. In Fig. 4 ripple is reduced from 18 % to 5 %, a large difference. The cost is a reduction of mean torque by 8 %, which is mostly due to elimination of torque peaks in the waveform and not necessarily a bad thing.

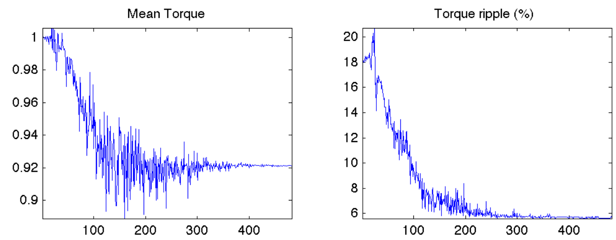
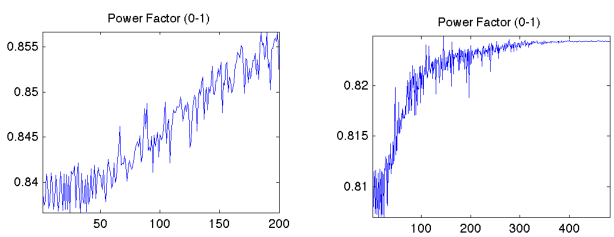


Fig. 4. Looking at ripple optimization

B. Power Factor / Inductance

Power factor is closely related to inductance in the motor type used for these evaluations, hence this section merges these together. Even though the torque curves and overall characteristics are different in the simulations for 5, the link between power factor and d-inductance is clear.



(a) Power Factor objective (b) Inductance objective

Fig. 5. Optimizing power factor and d-inductance shows similar results for power factor objective

C. Voltage Harmonics

For testing the ability to affect the voltage harmonics by changing the geometric shape, a second motor type was introduced. Here harmonics where added in the source, simulating a noise common when using power electronics. The result is shown in Fig. 6, and the effect on torque in Fig. 7.

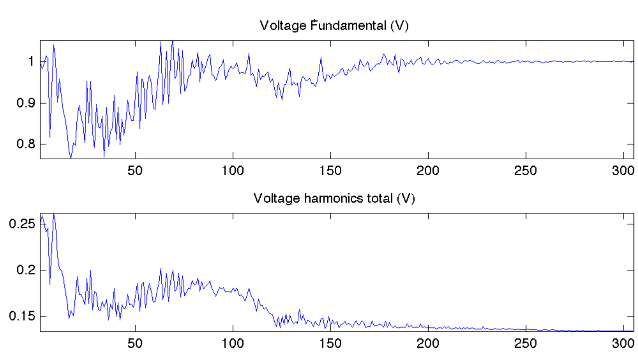


Fig. 6. Voltage harmonics optimization

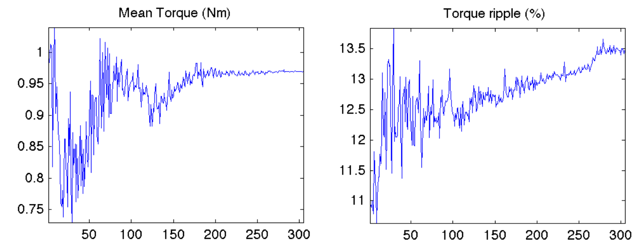


Fig. 7. Voltage harmonics optimization has a minor effect on torque values

D. Mixed Objectives

After performing optimization for each of the set-up objective functions, and evaluating how each response to the method, a mixed objective was created. Many variations in weighting was tested, but in the end a final mixed objective optimization was performed. It used 20 steps per 1/6 period and was performed in two load angles, on with high torque and one with low.

Notable in the results are that all set-up objectives has improved by some extent, in some cases very much. A summary of important results are shown in table I. Most notable are; high change in torque ripple, improved power factor, stable mean torque and fundamental voltage.

A second important results is also the difference in result for different load angles. It seems as using a low torque work point leaves more room for improvement. This could be explained by the lower amount of energy flowing inside the rotor, but further analysis need to be done.

	High torque	Low torque
Torque ripple *	- 14.0 %	-12.7 %
Mean torque	- 0.15 %	0.1 %
Power factor *	0.39 %	2.58 %
d-inductance	- 0.28 %	- 1.0 %
q-inductance	- 2.7 %	- 11.4 %
Fundamental voltage	- 0.5 %	- 3.4 %
Voltage harmonics	- 1.0 %	- 6.4 %

TABLE I
Mixed objectives, results. (* Relative percentage points)

V. Conclusions

Many method-related issues have been mentioned during this report and those problems and solutions are in the area of program structure and general methodology. It is hard to describe a method in a complete manor, but the points mentioned in the report gives the user a good basis to stand on and to proceed from.

A. Objective Correlation

This factor depends on what kind of motor is used for the optimization, but can affect the result if it is not considered when setting up the objective functions. Correlation can be seen in the results of motor A, especially saliency ratio/power factor and torque/voltage/d-inductance.

B. Objective Weighting

Different objectives will react differently to optimization. Some will show a high percentage of change (torque ripple), while others will only change by a few percent (power factor). This is hard to know before performing the simulations, but is important to handle to make sure optimization is performed on the objective that is most important. By having a to low weight put on an important objective, this can be completely shrouded by a less important factor with a high rate of change.

C. Resolution

Resolution is always important to ensure the results gathered are correct and represent what is investigated. Having a to low resolution will result in high frequency information loss, this will have a great affect on the optimizer and will lead to a invalid solution. A balance need to be found, but a minimum value must always be keep.

Finding a good mesh resolution is a hard task, since different geometries will have different areas in need of high resolution. Often a basic understanding of the motor functionality is enough to increase mesh density in relevant areas. Increasing the mesh often has a lower impact on simulation time than time resolution, but a lower density will often lead to shorter simulation times.

Mesh resolution will give a base simulation time, which is then multiplied by the number of time steps.

D. Load Angle

Work points will have a high impact on the results of an optimization and are crucial for whether the results are relevant for practical use or not. In the optimizations performed here there is a clear difference between high load and medium load. No in-depth studies have been done to find out exactly why. One reason is however that the higher the load is on the rotor, the more iron is required to conduct, leading to less freedom in geometrical shape.

VI. FUTURE WORK

A few things need to be tested before this method should be considered consistent enough to provide results on which one would base actual motor design.

A. Investigate Mechanical and Thermal Properties

This method only involves simulations in electromagnetic properties. To make sure the geometry generated is usable in practice, mechanical and thermal calculations are necessary.

B. Work Points

Further testing of different work points is necessary, only two where tested on motor A in this case.

C. Evaluate Results On Actual Machine

The optimizations performed for this work where done in such a way as to test the software and for error checking primarily, and not for the purpose of actually optimizing the motor. Because of this, there is no real consistency in the results and it's hard to make any well-grounded conclusions out of them. When applying to a real product, clearer goals will have to be defined.

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