

# Evolution of Electric Motor Design Approaches: The Domel Case

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## ABSTRACT

The paper presents the evolution of geometry design approaches in the optimisation of an electric motor, more specifically its rotor and stator. It starts with the initial manual approach, which was replaced with the automatic approach that introduced evolutionary algorithms to allow the intelligent search in collaboration with evaluation tools. Next, the new platform for remote optimisation was recently introduced that allows remote optimisation with various algorithmic approaches, including multi-objective optimisation. At the end we propose further solutions that will improve high performance of the design process.

## Keywords

electric motor, design, evolution, high-performance

## 1. INTRODUCTION

Many widely-used home appliances (e.g., mixers, vacuum cleaners, drills, etc.) use electric motors. These small motors are required to have high power and provide high starting and running torques, despite their small sizes. While having sufficient output power they should be energy efficient and inexpensive to manufacture [12].

There is a number of past works addressing the geometry optimisation design of rotor and stator parts [6], [10], [12], electric motor casing [7] and impeller [4]. These works, performed on various products of Domel company [1], introduced various artificial intelligence methods to implement automatic search of an optimal design. The reported optimisation approaches were mostly single objective. Still, there were some initial steps identified towards multi-objective handling of the design process.

This paper focuses on the approaches for automatic optimisation of the electric motor geometry. The main parts of the electric motor, i.e., stator and rotor, are presented in Figure 1.

While improving the applicability of the multi-objective optimisation, supported by parallelisation and surrogate modelling through the support of the Horizon 2020 Twinning project SYNERGY - Synergy for smart multi-objective optimisation [3], we implemented a platform for an efficient optimisation with different methods and approaches. The platform is briefly presented in this paper. In line with

Slovenian smart specialisation strategy [2], it is planned to transfer this solution into Slovenian industry.

The rest of the paper is organized as follows: Section 2 briefly describes the geometry elements of an electric motor and the optimisation goal; Section 3 presents the conventional manual approach to the motor design; in Section 4 the use of evolutionary algorithms in electric motor design is outlined; Section 5 introduces the new developed platform for remote optimisation; and Section 6 draws conclusions and proposes possible future work.



Figure 1: Rotor and stator of an electric motor [10].

## 2. PROBLEM DESCRIPTION

The rotor and the stator of an electric motor are constructed by stacking the iron laminations. The shape of these (rotor and stator) laminations is described by several geometry parameters that define the rotor and stator in two dimensions (2D).

The whole set of geometry parameters consists of invariable and variable ones. Invariable parameters are fixed, as they cannot be altered, either for technical reasons (e.g., the air gap) or because of the physical constraints on the motor (e.g., the radius of the rotor's shaft). Variable parameters, on the other side, do not have predefined optimal values. Among these parameters, some are dependent (upon others variables), while some variable parameters are mutually independent and without any constraints. The mutually independent set of variable parameters of the rotor and stator geometry (see details in Figure 2) can be subject to optimisation:

- rotor yoke thickness (ryt),
- rotor external radius (rer),
- rotor pole width (rpw).
- stator width (sw),
- stator yoke horizontal thickness (syh),
- stator yoke vertical thickness (syv),
- stator middle part length (sml),
- stator internal edge radius (sie),
- stator teeth radius (str),
- stator slot radius (ssr).

One of the optimisation tasks is to find the values of geometry parameters that would generate the rotor and stator geometry with minimum power losses.

## 2.1 Mathematical formulation of the problem

The efficiency of an electric motor is defined as the ratio of the output power to the input power. It depends on various power losses (see details in [9]), which include:

- Copper losses: the joule losses in the windings of the stator and the rotor.
- Iron losses: including the hysteresis losses and the eddy-current losses, which are primarily in the armature core and in the saturated parts of the stator core.
- Other losses: brush losses, ventilation losses and friction losses.

The overall copper losses (in all stator and rotor slots) are as follows:

$$P_{Cu} = \sum_i (J^2 A \rho l_{turn})_i \quad (1)$$

where  $i$  stands for each slot,  $J$  is the current density,  $A$  is the slot area,  $\rho$  is the copper's specific resistance and  $l_{turn}$  is the length of the winding turn.

Due of the non-linear magnetic characteristic, the calculation of the iron losses is less exact; they are separated into

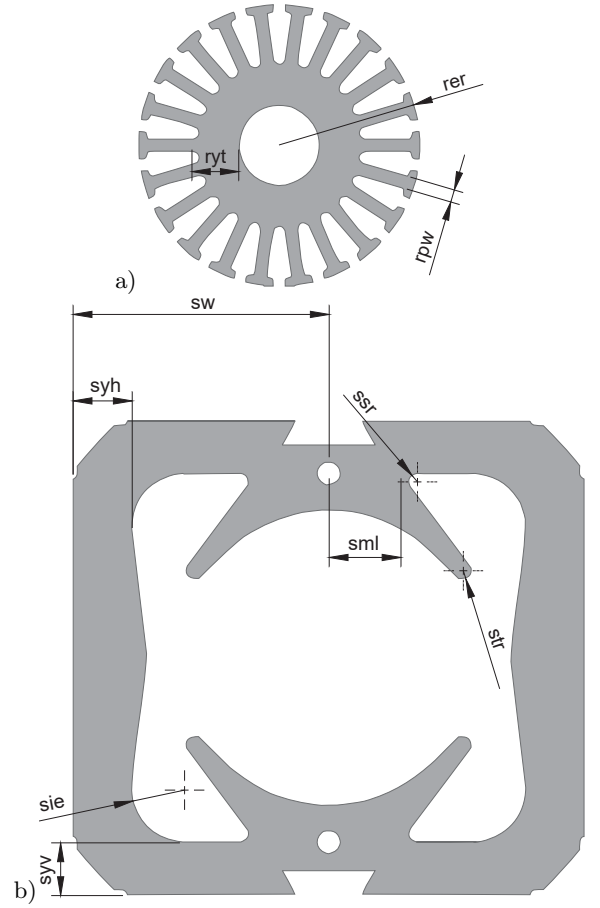


Figure 2: Geometry parameters of a) rotor and b) stator [12].

two components: the eddy-current losses and the hysteresis losses:

$$P_{Fe} = k_e B^2 f_{rot}^2 m_{rot} + k_e B^2 f_{stat}^2 m_{stat} + k_h B^2 f_{stat} m_{stat} \quad (2)$$

where  $k_e$  is an eddy-current material constant of 50 Hz,  $k_h$  is a hysteresis material constant of 50 Hz,  $B$  is the maximum magnetic flux density,  $f$  is the frequency, and  $m$  is the mass.

Three additional types of losses also occur, i.e., brush losses  $P_{Brush}$ , ventilation losses  $P_{Vent}$ , and friction losses  $P_{Frict}$ .

The output power  $P_2$  of the motor is a product of the electromagnetic torque  $T$ , and the angular velocity  $\omega$ ,

$$P_2 = T\omega \quad (3)$$

where  $\omega$  is set by the motor's speed, and  $T$  is a vector product of the distance from the origin  $r$ , and the electromagnetic force  $F$ .

The overall efficiency of an electric motor is defined as:

$$\eta = \frac{P_2}{P_2 + P_{Cu} + P_{Fe} + P_{Brush} + P_{Vent} + P_{Frict}} \quad (4)$$

## 2.2 Fitness evaluation

Each solution candidate of the population was decoded into a set of the rotor and stator parameters. The fitness was estimated by performing a finite-element numerical simulation to calculate the iron and the copper power losses (using the above mentioned equations). The sum of power losses corresponds to the solution's fitness.

For multi-objective version we can also introduce additional objective like material costs, making it a typical price/performance optimisation. The cost is calculated by taking into account the amount of materials (i.e., iron and copper), that are used to produce the electric motor, and their corresponding prices.

## 3. MANUAL OPTIMISATION

A manual design procedure of an electric motor consists of the geometry estimation of the rotor and the stator of an electric motor by an experienced engineer. The suitability of the proposed geometry is usually analyzed by means of numerical simulation (e.g., FEM with an automatic finite-element-mesh generation) of the electromagnetic field of each proposed solution separately.

The manual procedure can be repeated until the satisfied evaluation results is obtained. Similarly, the conventional approach in most new designs starts with manual design, as there exist no prior design.

The advantage of the manual approach is that the engineers can significantly influence the progress of the design process with their experiences and react intelligently to any noticeable electromagnetic response with proper geometry redesign.

The drawback of this approach is that an experienced engineer and a large amount of time (that is mostly spent on computation) are needed.

## 4. AUTOMATIC OPTIMISATION

The above-described manual design approach can be upgraded with one of the stochastic optimisation techniques which, in connection with reliable numerical simulators, allow for highly automated design process where the need for an experienced engineer to navigate the process is significantly reduced.

So far, several evolutionary approaches have already been proven to be efficient in the process of the electric motor geometry optimisation; e.g., electromagnetism-like algorithm [5], multi-level ant-stigmergy algorithm [6], adaptive evolutionary search algorithm [8], genetic algorithm [9], particle swarm optimization, and differential evolution [12].

The automatic approach with the use of an evolutionary algorithm can be summarized into the following steps:

1. The initial set of solutions is defined according to an initial electric motor.
2. It provides a set of problem solutions (i.e., different configurations of the mutually independent geometrical parameters of the rotor and the stator).

3. For evaluation of each solution (i.e., their fitness) each geometrical configuration is analyzed using some FEM program (e.g., ANSYS). This step requires a decoding of the encoded parameters into a set of geometrical parameters that define the rotor and the stator.
4. After the fitness calculation, the reproduction of the individual solutions is performed and the application of various recombination operators to a new population are done.
5. The evolutionary algorithm repeats the above procedure until some predefined number of iterations have been accomplished or some other stopping criteria is met.

Some evident advantages of this approach are:

- There is no need for an experienced engineer to be present during the whole process. He is required only at the beginning to decide on the initial design.
- There is no need to know the mechanical and physical details of the problem. The problem can be solved, by the use of optimisation algorithm, irrespective of any knowledge about the problem.

Some possible drawbacks of this approach can appear:

- The improper use of recombination operators leads to slow search progress.
- An initial solution set that is not divergent enough, can lead to a longer convergence time.

## 5. REMOTE OPTIMISATION PLATFORM

The multi-objective optimisation is a natural approach to solve difficult real-world problems. As the presented electric motor geometry design can have several contradictory constraints, it is useful to introduce the multi-objective algorithms (e.g., NSGA-II, IBEA) into this process [11].

Within the project SYNERGY, we developed and implemented a platform for an efficient optimisation with different methods and approaches. Its main role is to allow comparison and testing of an effective optimisation methods for the optimisation of electric motor geometry. The platform allows comparison of single objective as well as multi-objective algorithms.

The platform is based on web-based services to allow remote work of different experts, while keeping some important, secret features and characteristics hidden. The remote tool also allows for parallel processing, which allows for fast calculations, without any intervention from the expert.

Remote access enables experts to use the evaluation of the proposed solution regardless of his location. The platform allows remote access towards any simulation tools (e.g., FEM analysis). Furthermore, all evaluations are being stored in database and in case the same solution is being put to evaluation, the result is immediately returned without the need

to wait for it to be actually evaluated again, which furthers speed up the evaluation process.

Since actual parameter values are not relevant for optimisation process and to ensure that no secrets about the problem are being shared, the platform hides the important properties of the solutions. Meaning all parameter values and evaluation results are being normalised within the interval  $[0.0, 1.0]$ . This way, the problem can be tackled by any optimisation expert without acquiring any relevant knowledge (e.g., actual dimensions, problem specifications) about the problem.

Parallelisation within the platform is considered on the level of solution evaluation. Any other parallelisation on the level of optimisation algorithm is left to the optimisation expert.

## 6. CONCLUSION

This paper presented the evolution of approaches to the optimisation of the geometry design of the electric motor. From the initial manual approach, through the automatic approach that uses some evolutionary algorithm combined with evaluation tools, towards the platform that allows remote optimisation with various algorithms. The latter allows simple comparison and study of different methodologies and algorithms.

In the future version of the optimisation platform we plan to introduce some surrogate models as well as some multi-level approaches, which would allow for additional speed up of the evaluation process, since most of the real-world problems have time-complex evaluations.

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