Permanent magnet geometry optimization for surface PM motor with maximum power density by using a particular Vernier technique

Konstantinos I. Laskaris, Member, *IEEE*, and Antonios G. Kladas, Senior Member, *IEEE*
Faculty of Electrical and Computer Engineering, National Technical University of Athens
9 Iroon Polytechneiou Street, 15780 Athens, Greece
E-mails: laskaris@central.ntua.gr, kladasel@central.ntua.gr

Abstract — This paper develops a methodology for permanent magnet (PM) shape optimization in surface PM motor with targets high power density and reduced losses. The mean air-gap as well as the stator design adopted is based on sensitivity analysis while the permanent magnet material selected is high remanence Neodymium Iron Boron alloy. The PMs and rotor geometries are defined by using a particular optimization algorithm based on moving boundary technique in conjunction with sequential Vernier increase of optimization variables. The optimized motor configuration characteristics have been validated by measurements on a prototype.

I. INTRODUCTION

This paper describes an optimization methodology in order to derive optimal permanent magnet (PM) shape for surface PM motors involving high power density as well as reduced losses. Geometry optimization in PM motors constitutes an important research field [1], [2]. In particular various optimization approaches for PM machines have been developed recently searching for an appropriate compromise between torque and efficiency, i.e. [1], [3]. Due to the important computational means required in such problems, parallel techniques can offer important services in analysing practical problems [3].

The proposed methodology originality lies on the consideration of iron losses that magnet harmonics introduce, leading to a permanent magnet shape that gives enhanced power density for a defined motor size combining reduced iron losses.

As shown in previous investigations [4] trapezoidal magnets deliver high torque but also high iron losses that keep a relatively low power to loss ratio. On the other hand, sinusoidal magnets, deliver lower torque due to the lower magnetic loading, but higher rotating speed due to the lower iron losses [5]. Under the specific optimization strategy the optimal topology resides between these two extreme cases.

Due to space constraints in the specific electric vehicle application the stator is limited to very specific dimensions. In this way, stator outer and inner diameter, air gap, as well as motor poles are practically predefined. A preliminary analysis has been performed prior to the optimization procedure in order to derive the main active part dimensions. The major constraints that are taken into account are tabulated in Table I.

II. OPTIMIZATION METHODOLOGY

The proposed methodology involves a composite cost function with terms relating the magnet geometry to the motor torque and core losses, including inequality constraints concerning efficiency. The analysis problem is solved by using a two dimensional finite element model.

The rotor magnetic circuit is cylindrical while the magnet outer surface is defined by an array $\overline{h}$ which denotes the optimisation variable width values $h(i)$, where $i = 1, 2,..,N$, for a total number of N equidistant nodes within a pole pitch, shown in Fig. 1 for the case for N=9.

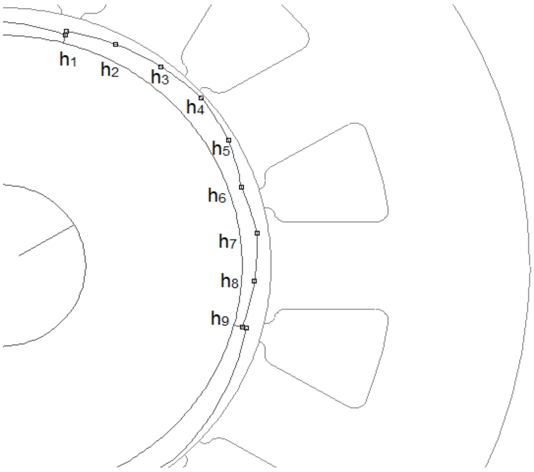

Fig. 1. Variable Magnet Width snapshot, defined by the optimization variable array h(i), for a total number of nodes N= 9.

The composite optimization function that has been adopted is described in eq. (1) and has to be maximized. In this equation T_m denotes the mechanical torque, ω_m the angular frequency while P_{cu}, P_{core} and P_{mloss} represent copper, core and friction losses, respectively. The values of T_m and P_{core} are calculated by the FE modeling.

$$F(\overline{h}) = \frac{T_m(\overline{h}) \cdot \omega_m}{P_{cu} + P_{mloss} + P_{core}(\overline{h})} \tag{1}$$

In order to evaluate iron losses a single snapshot method, that allows core losses to be evaluated with adequate compromise in accuracy, is introduced that is satisfactory for this class of problems.

The problem is initialized by setting the number of nodes N defining magnet geometry, that is the dimension of the array h as well as the minimum step dh that each $h(i)$ value can vary. The initialization array $\overline{h_0}$ contains the initial magnet shape that optimization will take place from.

The optimization process then evaluates iron losses under no load, and subsequently applies fixed current

TABLE I

MOTOR CHARACTERISTICS AND SPECIFICATIONS

Motor type	4 pole - 3phase PM synchronous
Power Feed	3-phase Inverter
Stator outer radius	125 mm
Stator inner radius	63 mm
Active motor length	150 mm
Phase current under optimization	Fixed at 150A (6 A/mm^2)
Speed under optimization	6000 rpm
Efficiency constraint	Over 93% at nominal speed
Rated Mechanical Power	Under optimization
Torque	Under optimization
Power compaction factor	Under optimization
Total weight	~ 65 kg

values as shown in the flowchart of Fig. 2. Finally the composite function value is compared to the previous iteration one. If $|F_t(\bar{h}) - F_{t-1}(\bar{h})| < conv\_tol$, where *conv_tol* is the convergence tolerance, and the array $\bar{h}$ is defined according to the optimization algorithm adopted.

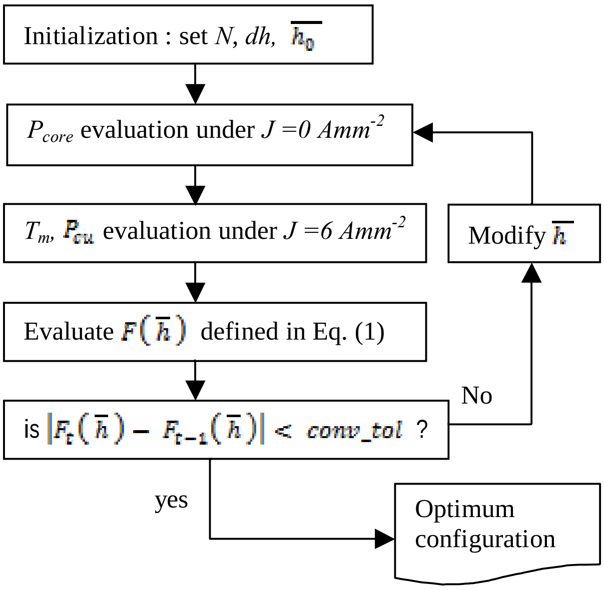

Fig. 2. Optimization flowchart

When the convergence is attained for the number of N optimization variables then an evolutionary approach is followed by increasing N and then decreasing the step *dh* (Vernier approach). The optimal PM shape is obtained when the cost function converges to a prescribed tolerance.

III. RESULTS AND DISCUSSION

The method has been applied in a surface permanent magnet motor case for electric vehicle with the specifications reported in Table I. Although sinusoidal back EMF waveforms are reported to provide optimal losses [5] the proposed methodology illustrated that the optimized magnet shape is quite different in the problem considered (Fig. 3).

The computed and measured motor efficiencies with rotor speed for the optimized magnet geometry are compared in Fig. 4. This figure shows that the proposed methodology provides acceptable accuracy even in high frequency ranges, illustrating its suitability for this class of problems.

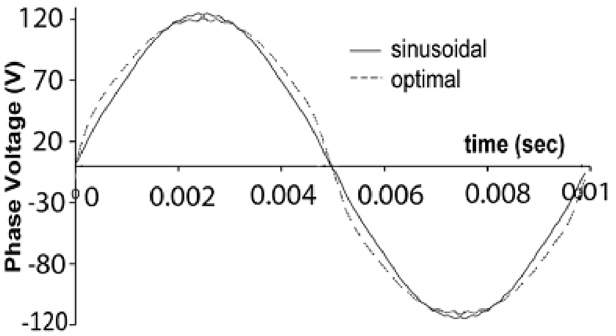

Fig. 3. Simulated Back EMF waveforms for two different PM configurations at the frequency f=100Hz

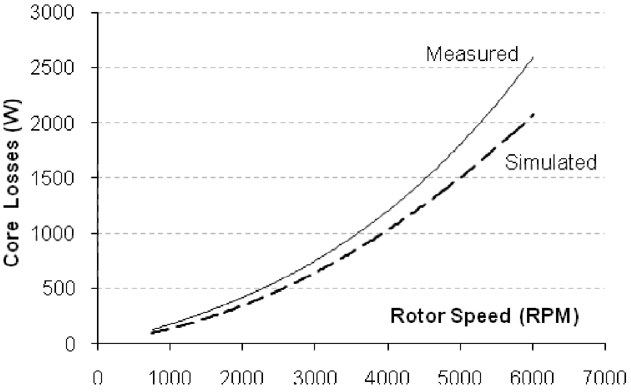

Fig. 4. Comparison of simulated and measured iron losses with rotor speed for the optimized magnet shape

IV. REFERENCES

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