Multi–Objective Optimization of an Interior PM Motor for a High–Performance Drive

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“Multi–Objective Optimization of an Interior PM Motor for a High–Performance Drive”

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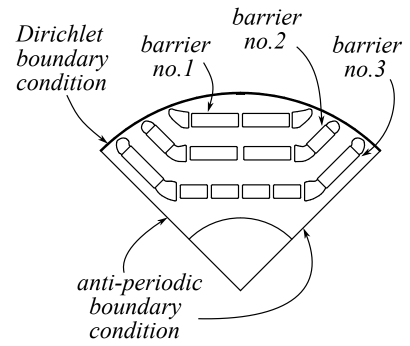
Outline

Aim of the work

Optimization of a IPM Machine with genetic algorithm



- 48 slots, 4 poles machine;
- Anisotropic rotor;
- Three flux–barriers per pole.

Aim of the work

Variable	symbol	measure unity
Number of slots	48	–
Number of poles	4	–
External diameter D_e	460	(mm)
Air–gap diameter D_i	298	(mm)
Active length L_{stk}	500	(mm)

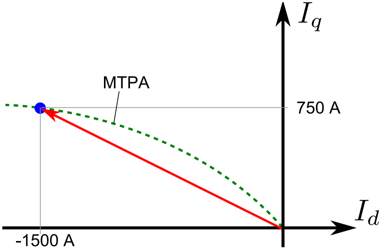
Objectives of the optimization

- Maximization of the **torque** (external dimensions and current density are fixed);
- Maximization of the high frequency magnetic **saliency**.

Optimization's steps

- **Finite elements analysis** to compute torque and saliency (four simulations are needed)
- **Genetic algorithm**, coupled with FE model, to optimize the rotor geometry

Torque computation



- The working point is chosen to be along the Maximum Torque Per Ampere (MTPA) trajectory
- The nominal current is imposed and d– and q–axis flux linkages, $\lambda_{d,n}$ and $\lambda_{q,n}$ are determined.

First Objective

- The torque is estimated by the following relationship

$$T_{em} = 3/2p(\lambda_{d,n} I_q - \lambda_{q,n} I_d)$$

Introduction

Finite elements computations

Optimization

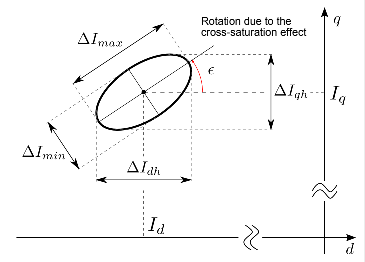
Results

Conclusions

Differential Saliency computation

$$\mathbf{L} = \begin{bmatrix} L_d & L_{dq} \\ L_{qd} & L_q \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \mathbf{L}^{-1} \begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix}$$



Second objective

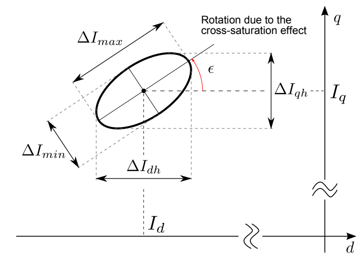
- The ratio between the maximum and the minimum HF current variation determines the **HF saliency** ξ_{HF}:

$$\xi_{HF} \triangleq \frac{\Delta I_{max}}{\Delta I_{min}}$$

Differential Saliency computation

$$\mathbf{L} = \begin{bmatrix} L_d & L_{dq} \\ L_{qd} & L_q \end{bmatrix}$$

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = \mathbf{L}^{-1} \begin{bmatrix} \lambda_d \\ \lambda_q \end{bmatrix}$$

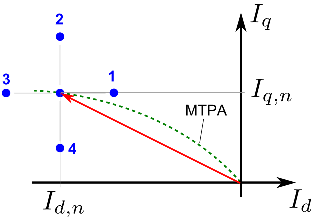


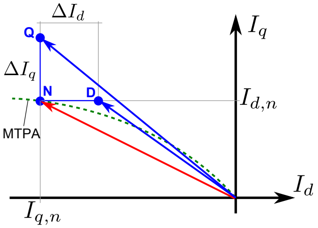
Second objective

- The saliency ξ_{HF} can be also expressed as

$$\xi_{HF} = \frac{(L_d + L_q) + \sqrt{(L_d - L_q)^2 + 4L_{dq}^2}}{(L_d + L_q) - \sqrt{(L_d - L_q)^2 + 4L_{dq}^2}}$$

Differential Saliency computation





Two further simulations are necessary to determine the differential saliency

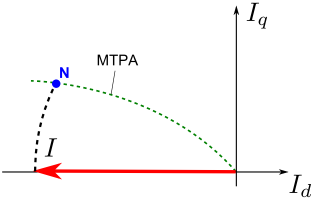
- First simulation:

$$L_d = \frac{\partial \lambda_d}{\partial i_d} \simeq \frac{\lambda_{d,\Delta I_d} - \lambda_{d,n}}{\Delta I_d} \qquad L_{qd} = \frac{\partial \lambda_q}{\partial i_d} \simeq \frac{\lambda_{q,\Delta I_d} - \lambda_{q,n}}{\Delta I_d}$$

- Second simulation:

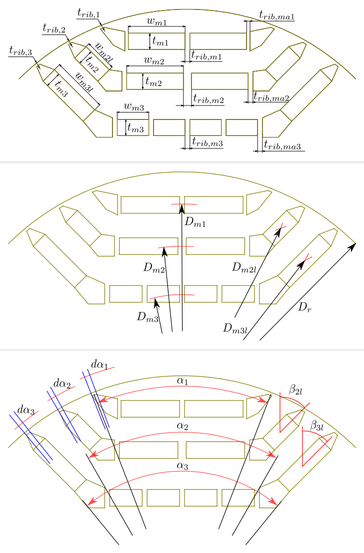
$$L_{dq} = \frac{\partial \lambda_d}{\partial i_q} \simeq \frac{\lambda_{d,\Delta I_q} - \lambda_{q,n}}{\Delta I_q} \qquad L_q = \frac{\partial \lambda_q}{\partial i_q} \simeq \frac{\lambda_{q,\Delta I_q} - \lambda_{q,n}}{\Delta I_q}$$

PM Demagnetization



- A minimum value of the PM flux density is fixed as a limit, so as to avoid the irreversible **demagnetization** of the permanent magnets.
- A further simulation is used to check the PM demagnetization

Design Variables



- Several rotor geometric variables are modified in a established range
- PM thickness changes but is equal for all magnets
- External dimensions are fixed

Optimization constraints

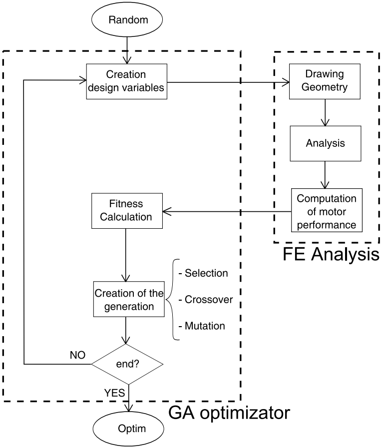
Geometrical constraints

Variable	symbol	measure unity
Number of slots	48	–
Number of poles	4	–
External diameter D_e	460	(mm)
Air–gap diameter D_i	298	(mm)
Air–gap g	1	(mm)
Active length L_{stk}	500	(mm)
End winding length L_{ew}	300	(mm)

Operating limit constraints

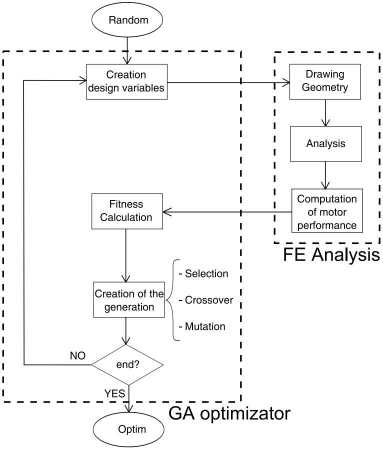
- Maximum losses of the motor (linked to the capability to dissipate the heat) are fixed;
- Minimum PMs flux density, $B_{min} = 0.4T$.

Optimization Scheme



- The **Genetic Algorithms** (GA) are used in the optimization process.
- They include the well-known **natural selection**, **crossover** and **mutation** procedures.
- These GA are linked with the FE model (analysis) of the motor

Optimization Scheme



Fitness function

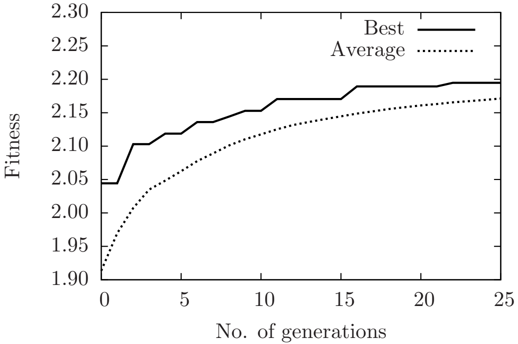
- The **fitness function** is calculated as follows:

$$obj = \frac{\xi_{HF}}{\xi_{REF}} + \frac{T_{em}}{T_{REF}}$$

(weighted sum method)

- The coefficients T_{REF} and ξ_{REF} are chosen in order to give the same weight to torque and saliency.

Optimization Results

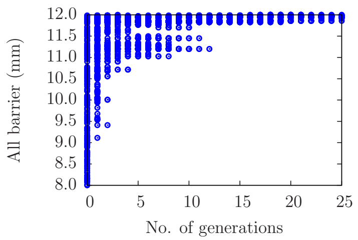


- Best and average fitness tend asymptotically to the same value.

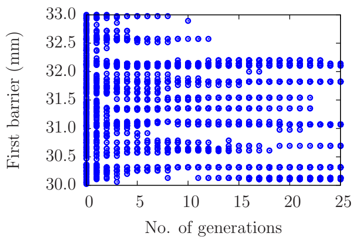
Optimization Results

Population Distribution

PM thickness



PM width

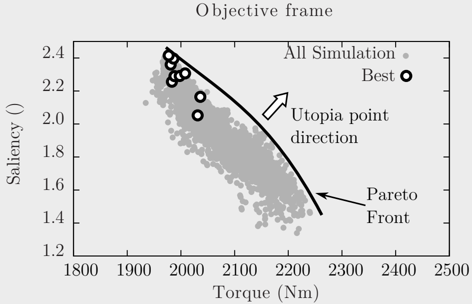


With the increase of the generation number:

- some variables tend to assume values in a limited range $\Rightarrow$ an **optimal value** exists
- other variables cover a wide range of values in each generation $\Rightarrow$ **low impact** on optimization

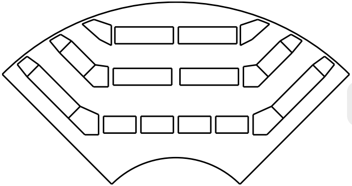
Optimization Results

The plane $\xi_{HF} - T_{em}$ and Pareto Front

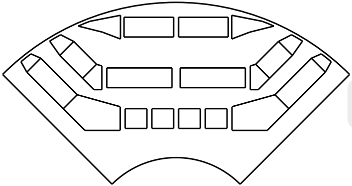


- The initial machine (before optimization) already represents a good design for the application under analysis.
- The optimization process moves the optimal solutions toward slightly lower torque (-2%) and higher HF saliency ($+14\%$) (**fitness increased of 10%**)

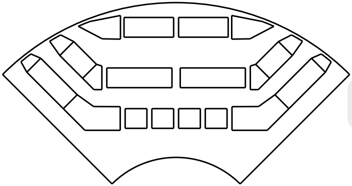
Optimization Results



Initial machine

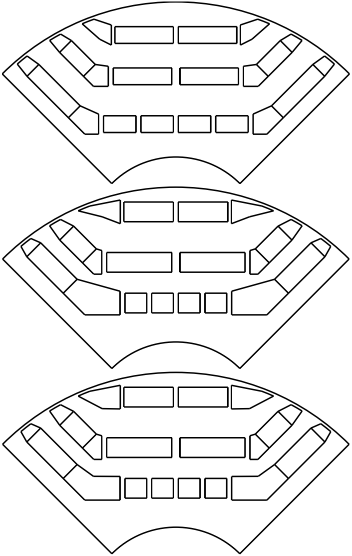


Optimized machine



Regularized machine

Optimization Results



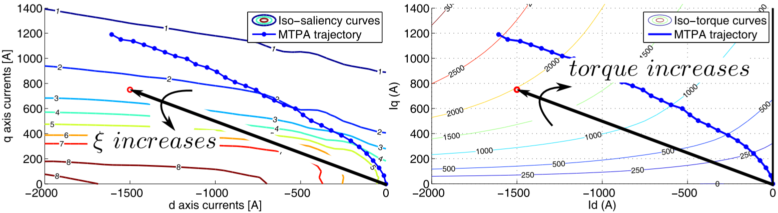
Considerations on design variables

- The first and third barriers move toward the air gap.
- The magnet thickness tends to increase.
- The angle span of first barrier increases while the angle span of the third barrier tends to decrease.
- The magnet width has low influence in the fitness function computation. Only the third barrier width requests low value.

Optimization Results

MTPA of the optimized machine

- The MTPA trajectory changes during optimization
- It moves toward the q–axis



Conclusions

- A multi–objective optimization, with a GA coupled with FEA, is carried out on an IPM motor in order to maximize the nominal torque as well as the sensorless rotor position detection capability
- The optimization process is carried out considering both geometrical limits and PM demagnetization
- The two objectives are in opposition, so that the optimal machine is able to exhibit higher HF saliency with the disadvantage of a lower average torque respect to the initial design.
- Moving on the Pareto front, higher torque can be achieved, accepting a decrease of the saliency.

Related Papers by the Authors

- N. Bianchi and T. Jahns (editors), "Design, Analysis, and Control of Interior PM Synchronous Machines", ser. IEEE IAS Tutorial Course notes, IAS'04 Annual Meeting. Seattle: CLEUP, Padova (Italy), October 3 2004, (info@cleup.it).
- Bolognani, S.; Calligaro,S; Petrella, R.; Tursini, M. "Sensorless control of ipm motors in the low-speed range and at standstill by hf injection and dft processing," *IEEE Transactions on Industry Applications*, vol. 47, no. 1, pp. 96–104, Jan.-Feb. 2011.

Thank you for your attention