Embedded multilevel optimization for nonlinear time-stepping mesh-based reluctance network

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***Abstract*— This paper presents an original methodology for machine design. The methodology is based on nonlinear reluctance network modeling and multilevel surrogate based optimization. The reluctance network is solved by computing the meshes magnetic flux and its topology is updated for each rotor position. In order to achieve an optimal design, in terms of satisfying some specifications, a surrogate based optimization inspired from the Space Mapping (SM) technique is considered. Optimization is held on the linear model and is iteratively corrected, through a new embedded strategy, by the nonlinear one. Finally, the proposed application is a constrained minimization of axial flux machine losses on an automotive cycle.**

***Index Terms*— Design methodology, design optimization, Nonlinear systems, Approximation methods, Permanent magnet machines, Automotive applications.**

I. Introduction

Achieving optimal design in engineering applications, in terms of design specifications, is often a compromise between final solution accuracy and fast computation/simulation time.

In electromagnetic modeling magnetic equivalent circuit based on reluctance network method is known to be a good compromise between computation time and precision. Although the computation time using this methodology is reduced, the problem remains when taking into account the magnetic saturation in comparison with the linear model. Hence, in order to optimize the machine, it is more suitable to use the linear model, but the relevant problem remains the final solution accuracy. Surrogate based optimization by means of Space Mapping techniques is proven to be an efficient optimization method when dealing with costly models. Space Mapping technique allows the establishment of a surrogate model substituting a costly one on the bulk of an existing physical cheap model.

This paper presents an original modeling methodology based on reluctance networks (linear/nonlinear) and multilevel optimization by means of an embedded correction strategy.

II. Modeling methodology

The reluctance network can be solved by computing the nodal magnetic potential [1] or by computing the meshes magnetic flux [2]. A comparison between both formulations [3],[4] shows the advantage of using mesh-based model, under nonlinear operating conditions. In nodal formulation the deduced Jacobian can be ill conditioned. Therefore the Newton-Raphson algorithm convergence cannot be assured on the opposite of the mesh-based model.

A. Nonlinear modeling

With the purpose of determining outputs values of a machine, i.e. torque, electromotive forces, magnetic forces, energy. It is important at first sight to determine magnetic flux circulating in the machine. For the chosen model it has to be supplied by three-phase alternative currents. A machine's map in terms of magnetic flux is established for all reluctances. It is function of *nb* rotor position, *nc* current values and *np* phase angle values. From this 4D flux matrix, mean torque and emf coefficients maps are deduced as a function of *nc* current values and *np* phase shift values. Though in saturation mode, the map is established as follows:

Step 1; establish incidence matrix [S], describing reluctance network connections at current rotor position.

Step 2; calculate $f^{stat}= [F_{b1,}\ F_{b2,}\ F_{b3}]$ for the current and phase angle values, magnetomotive forces for all branches: $f_{mm}= [f^{ag}{}_{x},\ f^{ag}{}_{yr},\ f^{rot},\ f^{ag}{}_{yf}, f^{stat}]$, magnetomotive forces for meshes $F_{mm}=[S].f_{mm}$.

Step 3; resolve the system in linear model (1):

$$F_{mm}-[S][R][S]^{T}\Psi^{L}=0 \qquad (1)$$

Step 4; initialize Newton-Raphson such that: $\Psi^{NL}{}_{0} =\Psi^{L}$.

Step 5; solve nonlinear system (2) using (3), $[C_g]$ matrix describing geometrical aspect of reluctances, H magnetic field and Sect a vector describing the sections:

$$f(\Psi)=F_{mm} - [S][C_g]H([S]^{T}\Psi^{NL}.Sect^{-1})=0 \qquad (2)$$

Newton-Raphson: $\Psi^{NL}{}_{iter+1}=\Psi^{NL}{}_{k}-\lambda\ .J(\Psi^{NL}{}_{iter})^{-1}.f(\Psi^{NL}{}_{iter})$ (3)

Step 6; compute branches flux $\varphi^{NL}{}_{nijk} =[S]^{T}\Psi^{NL}{}_{nijk}$ (4)

III. Surrogate model building

A. Space Mapping

The Space Mapping technique, proposed by Bandler in 1994 [5], is considered as an efficient surrogate based optimization, which allows us to exploit costly models without being prohibited by time calculation. In order to do so, optimization is held on a coarser, faster model, and the fine one is used to correct it. The corrected coarse model will be designated as the surrogate model.

B. Embedded multilevel for MEC

To use the reluctance network model efficiently, adjustment of the 4D flux matrix of the linear model (coarse) is done by means of the nonlinear one (fine). The used correction is based on an additive one [6], and the magnetic state is supposed to be constant on a trust region around the surrogate optimal solution. The global outlines of the procedure are:

Step 0; perform optimization on linear model, $x^{iter}=x^{*}_{coarse}$.

Step 1; evaluate nonlinear model at x^{iter}, extract saturated flux map.φ^{*NL}_{nijk}, end if stopping criteria are satisfied.

Step 2; compute flux corrector:

$$\vartheta^{iter}_{nijk}= \varphi^{*NL}_{nijk}- \varphi^{*L}_{nijk}. \qquad (5)$$

Step 3; iter=iter+1, define surrogate model as:

$$\varphi^{SL}_{nijk}(x) = \varphi^{L}_{nijk}(x)+ \vartheta^{iter-1}_{nijk}. \qquad (6)$$

Step 4; set $x^{iter}_{0} = x^{*}_{coarse}$, carry out optimization on surrogate model, back to step 1.

Computation time of the 4D matrix fine model is 25 (min) for the fine model and 20 (s) for the coarse model.

IV. Application

A. Optimization problem

For the proposed application, our aim is to find optimal physical characteristics of an axial flux 6 slots 8 poles machine with a view to minimize the machine's total losses on an Artemis automotive cycles and respect five constraints about the machine's torques, electromotive forces and current density [7]. The problem is in (7)

$$\begin{cases} find\ X = [x_1, x_2, x_3, x_4, x_5, x_6] \\ \text{Minimize } E_{total} = E_{copper} + E_{iron} + E_{inverter} + E_{magnet} \\ \text{Under} \\ Emf_{bs} \le 200\,(\text{V}) \qquad Emf_{hs} \le 260\,(\text{V}) \\ \Gamma_{bs} = 100\,(\text{N.m}) \qquad \Gamma_{hs} = 33.3\,(\text{N.m}) \quad J \le 9\,(\text{A.mm}^{-2}) \end{cases} \qquad (7)$$

B. Results and comparison

SQP algorithm is used in order to perform this mono objectif optimization. In this type of algorithms the final solution depends on the chosen starting point. Multistart points are chosen to perform optimization on the coarse model. Fig. 1-3 present the convergence histories for the space mapping optimization for two starting points. Fig. 4-5 present the comparison between reluctance network flux and finite element method under linear and nonlinear conditions.

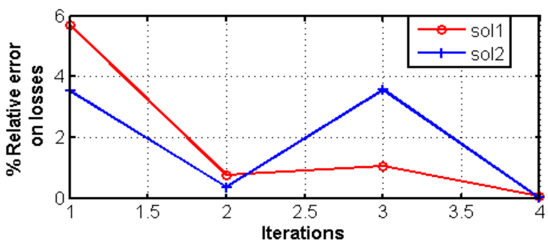

Fig.1. Total losses convergence history

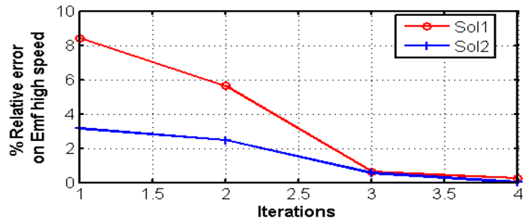

Fig.2. Emf high speed convergence history

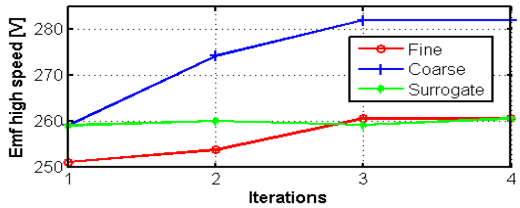

Fig.3. Detailed high speed emf convergence history

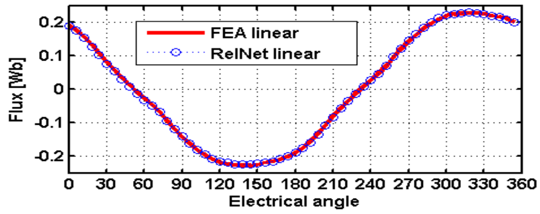

Fig.4.Comparison of flux linkage at 200 (A) linear

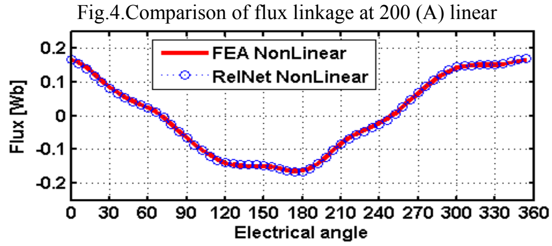

Fig.5.Comparison of flux linkage at 200 (A) nonlinear

V. Conclusion

In the final paper, detailed explanations of the proposed method optimization and results will be further investigated as well as the results of a 6 slots 8 poles machine.

References

[1] T. Raminosoa, I. Rasoanarivo, F. Meibody-Tabar, F.-M. Sargos, "Time-Stepping Simulation of Synchronous Reluctance Motors Using a Nonlinear Reluctance Network Method," *IEEE Transactions on Magnetics,* vol.44, no.12, pp.4618-4625, 2008.

[2] A. Delale, L. Albert, L. Gerbaud, F. Wurtz, "Automatic generation of sizing models for the optimization of electromagnetic devices using reluctance networks," *IEEE Transactions on Magnetics*, vol.40, no.2, pp. 830- 833, March 2004.

[3] H.W.Derbas, J.M.Williams, A.C. Koenig, S.D.Pekarek, "A Comparison of Nodal- and Mesh-Based Magnetic Equivalent Circuit Models," *IEEE Transactions on Energy Conversion*, vol.24, no.2, pp.388-396, 2009.

[4] M.L. Bash, J.M. Williams, S.D. Pekarek, "Incorporating Motion in Mesh-Based Magnetic Equivalent Circuits," *IEEE Transactions on Energy Conversion,* vol.25, no.2, pp. 329-338, 2010.

[5] J.W. Bandler, Q.S. Cheng, S.A. Dakroury, A.S. Mohamed, M.H. Bakr, K. Madsen, J. Sondergaard, "Space mapping: the state of the art," *IEEE Transactions on Microwave Theory and Techniques*, vol.52, 2004, no.1, pp. 337- 361.

[6] S.Koziel, J.W.Bandler, K. Madsen. "Space mapping with adaptive response correction for microwave design optimization," *IEEE Transactions on Microwave Theory and Technique,* vol.57, 2009, no.2, pp.478-486.

[7] M.Hage Hassan, G.Remy, G. Krebs, C.Marchand. "Radial output space mapping for electromechanical systems design," *OIPE* 2012, pp.22-23.