Available online at www.sciencedirect.com
ScienceDirect
Mathematics and Computers in Simulation 130 (2016) 3–21
MATHEMATICS AND COMPUTERS IN SIMULATION
www.elsevier.com/locate/matcom

Original articles

Comparison of hybrid analytical modelling and reluctance network modelling for pre-design purposes

Sofiane Ouagued, Yacine Amara*, Georges Barakat

GREAH, Université du Havre, 75, rue Bellot, 76058 Le Havre cedex, France

Received 19 October 2014; received in revised form 19 February 2016; accepted 1 May 2016
Available online 14 May 2016

Abstract

The aim of this paper is to compare two modelling approaches, used for the pre-design of electrical machines. A new hybrid analytical modelling (HAM) approach, based on a direct coupling of analytical solution of Maxwell's equations with reluctance networks (RN), is compared to mesh-based generated reluctance networks modelling, in terms of computation time and results quality. In order to assess the quality of results obtained from both models, both approaches are compared to finite element simulations. A permanent magnet linear structure is chosen as a case study. It is shown that the new hybrid analytical model allows to combine advantages of analytical and reluctance networks modelling. As compared to RN, the new approach helps reduce calculation time and gives good results.

Keywords: Analytical modelling; Magnetic equivalent circuits; Direct coupling; Air-gap modelling; Magnetic saturation

1. Introduction

Generally, accurate modelling of electrical machines requires the use of finite-element (FE) method. However, FE analysis is highly time consuming, especially at first design stages, from the point of view of engineers working in R&D departments in the electrical machine industry.

Different modelling approaches are used for analysis and design purposes in engineering problems. They can be classified within three main families:

- Analytical models [4,6,9,14,27,30];
- Numerical models [5,7,10,11,18,25,28];
- Semi-analytical, semi-numerical or hybrid models [1–3,8,12,13,15–17,19,20,22,23,21,24,26,29].

Analytical and semi-analytical models are often used at first design stages, and numerical models are often used for refinement and verification at the end of the design process. Analytical or semi-analytical models are often preferred at the beginning, in order to the reduce pre-design stages duration. Indeed, analytical, or semi-analytical, models are often obtained through simplifying assumptions, which help to whether simplify the mathematical equations

* Corresponding author.
E-mail address: yaunivlehavre@gmail.com (Y. Amara).

http://dx.doi.org/10.1016/j.matcom.2016.05.001

formulation, and consequently to obtain simpler solutions, or directly to obtain manageable solutions. The terms "simpler solutions" or "manageable solutions" are here used to denote fast execution solutions that do not require long computation time. In some engineering problems where time saving is not the main constraint, as those where safety is the main requirement, methods to consider additional constraints are developed [7,25]. Interesting overviews of mathematical models used for analysis and design purposes can be found in [5,9,11,16,18,26–28,30].

For electric machines pre-design, two types of models are often used: reluctance network models (RN) and analytical models (AM) [27] based on the formal solution of Maxwell's equations in constant permeability regions. However, classical RN method is not as generic as the finite element method. In fact, even in the case of a given magnetic device geometry, the associated Reluctance Network have to be modified if the geometric parameters vary in a large scale. To remedy to this problem, some authors have proposed automatic mesh based generated RN methods (MBGRN) [1,15,16,20,26] to compete with the finite element method. However, the automatic and adequate mesh of the airgap region leads to a strong number of reluctances which increases the computation time degrading by the fact the mesh based RN competitiveness compared to finite element method. For this concern, in contrast to FE method, it should be noticed that till now commercial software packages based on this method still not available. At this stage, it is important to note that analytical models based on the formal solution of Maxwell's equations help overcome the aforementioned problems, but they neglect the magnetic saturation.

In order to combine advantages of both methods such as genericity, reduced computation time and magnetic saturation consideration, a new modelling approach, based on the direct (strong) coupling of analytical solution of Maxwell's equations and reluctance networks, is used in this study [8,15,22,23]. While the approach used by the authors in [8,15] is based on the magnetic vector potential analytical solution, the approach adopted in this paper is based on the analytical solution of the magnetic scalar potential in low permeability regions (permanent magnet and air-gap regions). The RN method is used to model the stator. For the stator and rotor magnetic circuits, mesh-based generated RN approach is used in this study [1,15,16,20,26].

A case study is used to introduce the new modelling approach and to assess its effectiveness. The new hybrid analytical modelling (HAM) approach is compared to mesh-based generated reluctance networks modelling (MBGRN), in terms of computation time and results quality. In order to assess the quality of results obtained from both models, both approaches are compared to FE simulations.

2. PM linear structure

Fig. 1 shows the periodic linear structure which has been modelled using the three methods: FE, RN model, and HAM. The aim of the study being the comparison of three modelling methods, the studied linear machine is assumed to be periodic allowing the authors to not consider the side effects as it is usually done for linear machine structures. Table 1 gives the linear machine main characteristics. This figure also shows how the HAM model is structured. The mobile armature is considered having an infinite relative permeability to simplify the modelling study.

The studied structure has been first modelled using finite element method. Results obtained from this method will be considered as the reference to which the quality of results obtained from the two other methods will be assessed. Both open circuit and at load performances are compared.

Fig. 2 shows the different boundary conditions applied in order to perform the FE analysis. Roughly, the same conditions are applied for the two other approaches. Instead of cyclic boundary conditions, odd-periodic boundary conditions are used due to per pole symmetry of the geometry. The goal of this paper being to compare RN modelling and HAM essentially in terms of computation time, the magnetic saturation has not been considered. Thus, stator core is assumed to have a constant relative permeability of 7500.

The number of nodes for the finite element model is equal to 28502. It should be noticed that the studied domain has been relatively finely meshed and that sufficient precise results could have been obtained with less number of nodes. A second order FE method is used to solve the 2D magnetostatic field formulation in terms of vector potential. Local and global quantities can then be derived from FE simulations for the comparison study.

3. Reluctance network model

Reluctance network method based on a regular mesh of the studied domain (MBGRN) has been used for the modelling of the linear structure. Although this approach is relatively old [1,15,16,20,24] and gives relatively good