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Modeling of Flux Switching Permanent Magnet Machines with Fourier Analysis.

B. L. Gyssen, E. Ilhan, K. Meessen, J. Paulides, E. Lomonova
Electrical Engineering, Eindhoven University of Technology, Eindhoven, Netherlands

There is an increasing demand for electromechanical machines with a high toque density together with a high and variable speed capability in, for example, the automotive industry. The flux switching permanent magnet (FSPM) machine is a good candidate since it combines the advantages of a switched reluctance machine (high speed and robust rotor structure) and a brushless permanent magnet machine (high torque density). This combination is achieved by placing the permanent magnets in the stator part, see Fig. 1(a), together with the three phase windings, hereby pre-biasing the magnetic field in the soft-magnetic material. This leads to an increased variation in the magnetic energy, resulting in a higher torque density. Furthermore, since the permanent magnets are situated in the stator part, very high speeds can be reached and the rotor is robust and suitable to work in harsh environments. Due to the nonlinear behavior and double salient structure, modeling and analysis becomes difficult and it is in the literature particularly done with finite element analysis (FEA) or with the magnetic equivalent circuit (MEC) model [1]. The FEA has the disadvantage of a large computational time whereas the MEC model suffers from coarse discretization of the result field solution, leading to inaccurate prediction of the output torque. This indicates the necessity of investigating alternative modeling tools in order to analyze the behavior of this machine. Therefore, this paper deals with an alternative modeling technique using Fourier analysis [2, 3]. Although this modeling technique considers the iron as infinitely permeable, it still allows for investigation of topologies, parameter sweep and characteristic behavior.

The periodic nature of the machine allows the use of Fourier analysis. If a FSPM machine with Np number of stator poles, Nr number of rotor teeth and Nph number of phases is considered, (Np should be an integer multiple of the number of phases Nph) the main periodicity in degrees can be calculated as 360/gcd(Np, Nr), where gcd(a,b) is the greatest common divider of a and b. The boundary value problem only has to consider a single period which is divided into regions, according to their tangential boundary conditions (periodic or Neumann) and material properties. One period of the FSPM machine consists of Np/gcd(Np, Nr) elementary stator cells and Nr/gcd(Np, Nr) rotor teeth or slots. Every stator cell and rotor tooth/slot can be divided into regions as shown in Fig. 1(b). Only the airgap (region II) and surrounding air (region V) have periodical boundary conditions in the tangential direction, the rotor slots (regions I), permanent magnets (regions III) and coils (regions IV) have Neumann boundary conditions in the tangential direction. The magnetostatic Maxwell equations are written as a Poisson equation in terms of the magnetic vector potential. Since the solution for the magnetic flux density is described as a sum of Fourier series, the periodic and Neumann boundary conditions are inherently satisfied. The resulting unknown coefficients are solved by considering the normal boundary conditions.

The solution of the flux density distribution in the centre of the airgap for the 10/12 FSPM machine of Fig. 1(a) is shown in Fig. 2(a) together with the linear FEA. Exact agreement is obtained which is as expected since both models have similar assumptions. The limitation in accuracy for the Fourier analysis is the limitation of the number of harmonics that can be included. The torque calculation can be performed analytically by means of the Maxwell Stress tensor method applied in the centre of the airgap. This leads to the ability of calculating the electromagnetic torque, including the torque ripple and cogging torque. The verification with linear FEA is shown in Fig. 2(b) where good agreement is obtained. This model allows for fast parameter sweep and investigation of several topologies.

Figure 1. (a) Schematic drawing of a FSPM machine, (b) boundary value problem and division in regions.

Figure 2. (a) Flux density distribution in the centre of the airgap, (b) electromagnetic torque calculation.

Reference: