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Separation of Volume and Surface Forces and Torques in a DC excited Flux Switching Machine

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Abstract—In this paper the separation of volume and surface forces and torques of a highly saturated DC excited Flux Switching Machine (DCFSM) is presented. The volumetric and surface forces are derived from the stress tensor caused by the magnetic field. High saturation of the iron will contribute in the increase of the internal forces, as a consequence, the resultant torque is also separated in volume and surface torque. The simulation results show that the torque created by the volume forces is contributing to significant part of the total torque. Therefore, the research of the volume forces consequences is becoming a relevant topic for further research.


I. INTRODUCTION

Permanent magnet free motors are of the particular interest for automotive applications due to their robustness and simple production [1]. However, the topologies of this machines, such as switched reluctance machines or flux switching machines suffer from a high saturated soft magnetic material, consequently limiting the analytical or semianalytical tools to model their physical behavior [2]–[4]. Moreover, the DCFSM topologies with 6/5 configuration experience high vibrations. High saturation in the iron is generating considerable high iron losses. In addition, high saturation of the soft magnetic material, increases the volume force density distribution inside the iron, therefore, becoming a considerable component of the resultant force and torque. The volume force density is created by the gradient of the distribution of relative permeability of the iron [5]–[8]. This phenomena is generally neglected in electrical machine analysis, and the surface forces are considered the only contributors to the resultant force or torque [9], [10]. Consequently, the computation of the force distribution on the iron surface is performed using the Maxwell Stress Tensor (MST) taken on the immediate proximity of the iron surface. As it will be shown in this paper, this assumption holds for the materials with linear B(H) curves, or for the low saturation level of the soft magnetic material, in other cases this assumption does not hold.

In this paper the quantification of the volume and surface forces is performed and their contribution to the resultant torque is computed, in this way, the ratio between two components is observed. The definitions of the surface and volume forces based on the stress tensor due to magnetic field are presented. The results of each torque component are shown and the discussions and conclusions are drawn at the end.
Virtual Work principle, which is based on the observation of the energy change $\partial W$ with the displacement $\partial l$

\[
\vec{F}_r = \frac{\partial W}{\partial l} \vec{r}
\]

where $\vec{r}$ is the unit vector of the direction.

Integration of the Maxwell stress tensor $\vec{T}_n$ on an arbitrary surface enclosing the object of interest (rotor for instance)

\[
\vec{F} = \int_{S} \vec{T}_n \, d\vec{S}.
\]

The relationship in (2) is widely used in post processing of the magnetic field computed in electrical machines models, especially generated by the analytical or semi-analitical models [12], [13]. The surface $\vec{S}$ is placed in the airgap, so that it encapsulates the rotor. Very often in the literature, this method is called Maxwell Stress Tensor. However, the same tensor is used for the formulation of volume and surface forces.

The sum of the volume $\vec{f}$ and surface $\vec{f}_s$ force densities.

\[
\vec{F} = \int_{V} \vec{f} \, dV + \int_{S} \vec{f}_s \, dS_t.
\]

Both $\vec{f}$ and $\vec{f}_s$ are derived from the tensor $\vec{T}_n$ which is defined on a point on the surface encapsulating an arbitrary volume

\[
\vec{T}_n = \frac{1}{\mu} \left( \vec{B} B_n - \frac{1}{2} B^2 \vec{n} \right)
\]

where $B$ is the modulus of magnetic flux density $\vec{B}$, $\vec{n}$ is the normal to the surface, $B_n$ is the normal component of the magnetic flux density and $\mu$ is the permeability of the material.

For the decomposition of the volume and surface forces (3) is used in this paper. The forces on the surface $\vec{S}_i$, which are interfacing the rotor are calculated as

\[
\vec{f}_s = \frac{1}{2} \left( B_n^2 \left( \frac{1}{\mu_r \mu_0} - \frac{1}{\mu_0} \right) + H_r^2 (\mu_r \mu_0 - \mu_0) \right) \vec{n}_i,
\]

where $H_r$ is the tangential component of the magnetic field strength with respect to the surface and $\mu_r$ is the relative permeability of the soft magnetic material which is dependent on the position when a nonlinear material is used. From (5) it is obvious, that the forces will only be aligned with the surface normal, this is a result of the discontinuity of the permeability at the surface $\vec{S}_i$. The volume force density is given as

\[
\vec{f} = \vec{J} \times \vec{B} - \nabla \mu \frac{1}{2} H^2.
\]

The first term on the right hand side of (6) is known as the Lorentz force where $\vec{J}$ is the vector of the current density distribution. Since in the iron parts the current density is zero when the eddy currents are neglected, only the gradient of the permeability distribution and the magnitude of the magnetic field strength will generate volume forces.
The overall sum of the torque is presented. The formulation of the magnetic component for DCFSM, further research on the other consequences of these forces such as noise and vibration or losses should be carried out.

IV. CONCLUSION

An analysis of surface and volume force contribution to the overall torque is presented. The formulation of the magnetic surface and volume force based on the stress tensor is used to compute the corresponding torques. The simulation results show that when the current is increased 5× from its nominal value, the volume torque component consists 25% from the total torque. Having obtained a considerable volume torque component for DCFSM, further research on the other consequences of these forces such as noise and vibration or losses should be carried out.