Tubular permanent magnet motor with Integrated Coaxial Transformer

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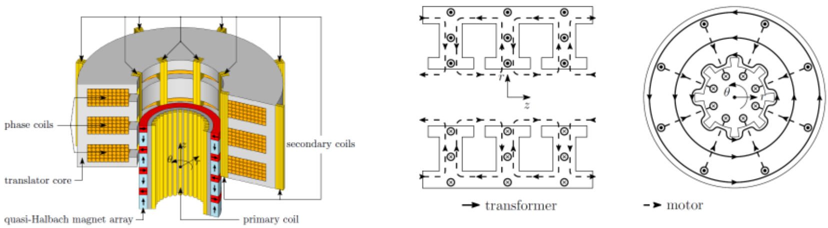
Abstract

A moving coil, permanent magnet, tubular, linear motor with an electromagnetically integrated coaxial transformer is presented in this paper. The soft-magnetic core of the motor consists of isotropic, soft-magnetic composite material which acts simultaneously as the flux guide for both the motor and transformer. The transformer is designed for a wireless apparent power transfer of 800 VA with a frequency of 5 kHz. 500 W of power is reserved to operate the motor at a peak force of 250 N at a maximum rated speed of 2 m/s. The surplus of wirelessly transferred power can be employed to energize additional electronic equipment on the moving platform. The working principle of the integrated design is addressed in this paper. The electromagnetic integration gives rise to mutual electromagnetic cross-coupling effects between the transformer and motor operation. It is discussed how these cross-coupling effects are attempted to be minimized in the electromagnetic design by applying an orthogonal, spatial orientation of the flux in the core due to transformer coils with respect to the flux originating from the phase coils and permanent magnets of the motor. Remaining cross-coupling effects on account of the nonlinearity of the core material are discussed and quantified by means of magnetostatic Finite Element Analysis simulations.

1 Introduction

Moving power cables for the power supply of moving coil, permanent magnet (PM), linear motors significantly limit the freedom of movement of the mover with respect to the stator. Moreover, friction, dynamical mechanical distortion, increased moving mass, and hysteresis effects occur on account of the cables being dragged along. On top of that, moving cables are susceptible to wear which leads to downtime for maintenance intervals. The moving cables can be replaced with separate contactless energy transfer systems that consist of a sliding transformer in conjunction with power inverts [1, 2]. The electromagnetic phenomena that govern the working principle of machines and transformers are closely related. The aim of this research is, therefore, focused on the feasibility of the electromagnetic integration of the transformer and machine in a single device. A tubular actuator with an integrated coaxial transformer has been proposed in [3] together with the electromagnetic modeling strategy for design. The proposed topology is able to transfer 800 W of power continuously at 5 kHz and generate 250 N of thrust force. A segment with periodicity in both the axial and circumferential directions of the proposed integrated topology is shown in Fig. 1a.



(a) (b)

Fig. 1: Periodical segment of the integrated topology of the tubular motor with integrated transformer (a), orthogonal orientation of the magnetic field components of the transformer (solid arrows) and motor (dashed arrows) (b).

2 Electromagnetic cross-coupling effects

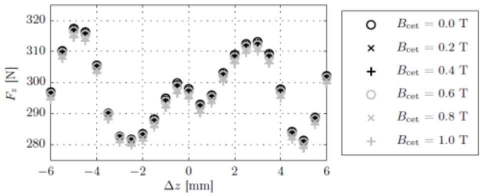
The superposition of two magnetic fields of different amplitude, orientation, and operating frequencies results in cross-coupling effects between the two functionalities on account of the soft-magnetic material being nonlinear.

2.1 Working principle and electromagnetic decoupling

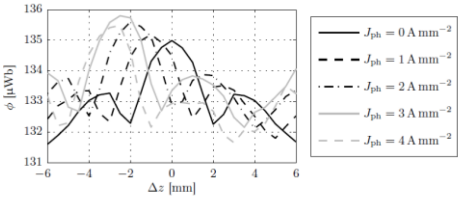
The magnetic field of the transformer originating from the primary coil in the hollow shaft of the stator is predominantly oriented in the direction parallel to the circumferential direction, whereas the magnetic field of the motor is predominantly confined to the plane parallel to the *z*-axis. The flux of the transformer is picked up by the secondary coils on the mover. It has to be noted that the permanent magnet array on the tube of the stator is of the quasi-Halbach type. A quasi-Halbach array is required to focus the field in the airgap, since a soft-magnetic tube would short-circuit the flux of the transformer. A short-circuited transformer flux would significantly reduce the magnetic coupling of the transformer. The orientation of the magnetic fields is schematically depicted Fig. 1b. This particular magnetic field orientation ensures that no electromotive force (emf) is induced in the transformer coils due to time-variations in the magnetic field of the motor and, conversely, that no emf is induced in the phase coils originating from time-variations in the magnetic field of the transformer. Furthermore, the orthogonal orientation of both fields allows the soft-magnetic material of the core to be more effectively utilized in terms of the magnitudes of the flux density components [3]. Additionally, the magnetic coupling of the transformer is ideally independent of the relative displacement of the mover with respect to the stator, since displacement does not result in a change in the magnetic circuit seen by the transformer flux. However, due to the variation in the magnetic loading of the motor with position the permeability distribution through the nonlinear soft-magnetic core does change with position. This change in permeability causes the secondary flux linkage of the transformer to be dependent on the displacement as well as on the electric loading of the motor. On the other hand, the sinusoidally varying transformer flux also affects the permeability distribution which reverberates in a pulsating disturbance torque at two times the frequency of the transformer field.

2.2 FEA Simulations

The cross-coupling effect of the magnitude of the transformer flux density on the thrust force profile and the effect of changes in the electric loading of the motor and displacement of the mover in the flux linkage of the transformer have been simulated with 3D, magnetostatic, FEA simulations. The results are shown in Fig. 2. From Fig. 2a it can be seen that the change in force is only 0.9% at B_{cet} = 1.0 T as compared to B_{cet} = 0.0 T. The change in the flux linkage is maximally 3.2% over the full range of both the displacement and rated electric loading.



(a)



(b)

Fig. 2: Change in the trust force profile as function of displacement and amplitude of the transformer flux density value, B_{cet}, (a), change in transformer flux linkage as a function of displacement and electric loading, J_{ph}, (b).

3 Conclusions

A tubular permanent magnet motor with an integrated coaxial transformer has been presented. The core simultaneously functions as the flux guide of the transformer and motor. Electromagnetic decoupling has been obtained by an orthogonal magnetic field distribution of the transformer flux with respect to the motor flux. The cross-coupling effects associated with the nonlinear behavior of the core have been identified and quantified through magnetostatic, 3D, FEA simulations. A disturbance force ripple of 0.9% of the force without transformer has been observed. Variations in the electric loading and displacement result in a 3.2% variation in the flux linkage of the transformer.

References:

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