Electrodynamic levitation effect in vertical HTSC electrical machines with axial magnetic flux**

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Vertical synchronous electrical machines (alternators and motors) with axial magnetic flux and disk geometry of rotor and stator are characterized by the presence of an electrodynamic force acting perpendicularly to the active zone elements. It depends mainly on the load angle, magnetic flux density in the air gap and armature current. The presence of this force is to be accounted for during alternator development and testing. It may be used for the development of electrical machines with a levitating rotor as well.

Keywords: high-temperature superconductivity (HTSC), levitation force, synchronous electrical machines

1. Introduction

Electrodynamic levitation in electrical machines is based on processes in the active zone and electromagnetic fields in the air gap. The idea of electrodynamic levitation in linear motors for trains was first discussed in refs 1 and 2. Theoretical results were confirmed by experiments on a disk motor.[3] During several years of experimental investigation of HTSC vertical disk generators and motors, we have evinced the presence of this effect in electrical alternators with an axial magnetic flux.

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[1] Powell, J.R. and Danby, G.A. 300-mph magnetically suspended train. *Mech. Engng* **89** (November 1967) 30–35.

[2] Sloman, G.R. et al. A linear synchronous motor for high speed ground transport. *IEEE Trans. Magnetics* **MAG-10** (1974) 435–438.

[3] Atherton, D.L. et al. Superconducting linear synchronous motor tests. *IEEE Trans. Magnetics* **MAG-13** (1977) 1268–1282.

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2. Basis of electrodynamic levitation effect

A cross-section of a disk electrical machine with two HTSC armature windings positioned on both sides of the rotor with circular permanent magnets is presented in Fig. 1 and shows the levitation zone of the rotor. It represents two air gaps between the rotor and two armatures. The 3-phase HTSC armature windings with solenoidal coils are settled on cylindrical magnetic cores manufactured from metallic glass tape. The machine is immersed in liquid nitrogen (LN_2).The rotor of the machine is fixed on a vertical shaft, but presented below are general results about its possible levitation in the air gap.

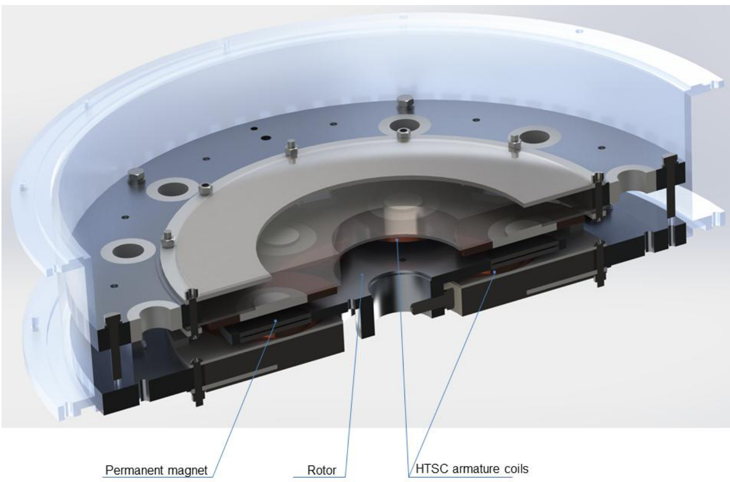


Figure 1. The rotor levitation zone.

Fig. 2 shows the simplified involute of the circular active zone of a disk machine. The upper part is the involute of the rotor with permanent magnets fixed on a non-magnetic cylinder and the bottom one is the involute of the armature with HTSC coils fixed on a ferromagnetic screen.

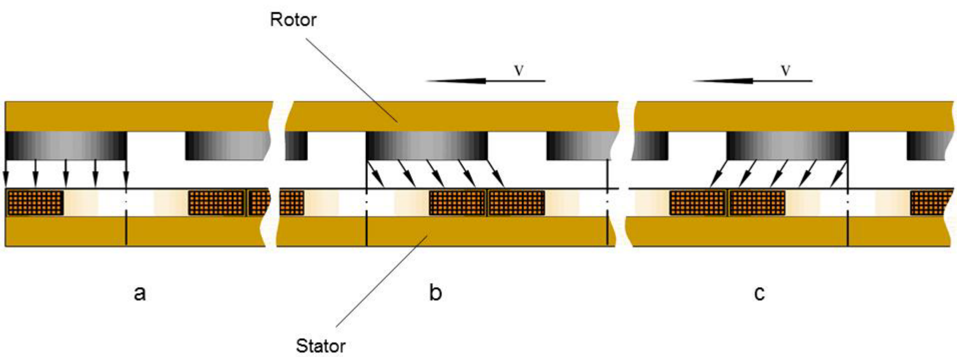


Figure 2. An involute of the active zone of the disk synchronous machine for different modes of operation: a) no-load mode, = 0; b) generator mode, > 0; c) motor mode, < 0.

The rotor electrodynamic levitation effect in a disk electrical machine appears with the load angle δ. It equals zero in the no-load mode. δ represents the divergence between magnetic axes of inductor and armature; it depends on the armature synchronous reactance value (Fig. 3). Its maximum is $\delta = 90°$, but synchronous machines never operate with the limiting load angle.[4,5]

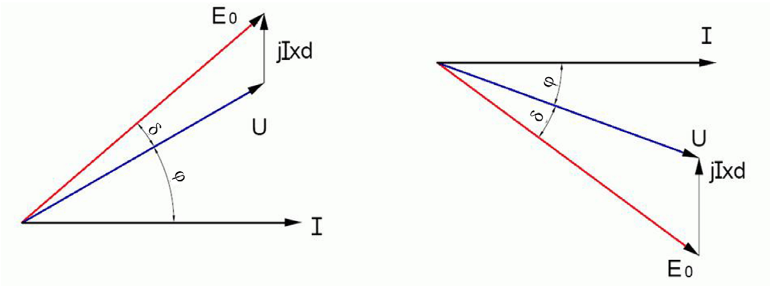


Figure 3. Simplified vector diagrams for the generator and motor modes of operation of a synchronous machine.

The density of electromagnetic forces influenced by electromagnetic fields of the alternator is determined as

$$f = \boldsymbol{jB}, \tag{1}$$

where $\boldsymbol{j}$ is the current density vector and $\boldsymbol{B}$ the magnetic flux density vector.

The value of the electromagnetic force F_{em} depends on the value and the rate of deformation of the electromagnetic field in the air gap. The latter is dependent on the load angle. The components of electromagnetic force, acting perpendicular to the air gap $F_{\text{em}x}$ and along it $F_{\text{em}y}$, equal:

$$E_{\text{em}x} = iw\int_0^l B_{\delta y}\,\text{d}l, \qquad E_{\text{em}y} = iw\int_0^l B_{\delta x}\,\text{d}l, \tag{2}$$

where i is the armature winding current, w the number of turns in the armature winding, $B_{\delta x}$ and $B_{\delta y}$ the components of the total magnetic flux density in the air gap, and l the armature winding coil length.

The components of the magnetic flux density are determined as:

$$B_{\delta x} = B_\delta \sin\delta, \qquad B_{\delta y} = B_\delta \cos\delta, \tag{3}$$

where B_δ is the geometrical sum of the rotor and stator magnetic fields acting in the air gap under load.

The electromagnetic force $F_{\text{em}y}$ acts along the air gap. It is perpendicular to the inductor and armature surfaces and may cause either mutual attraction or repulsion of the rotor and stator elements and unbalance the machine operation. It also permits an electrical machine with a levitating rotor to be developed. In the case of two armature windings it is possible to suspend the rotor in the air gap either by attractive or repulsive forces. The force direction depends on the mode of operation of the electrical machine: alternator or motor mode.

[4] Nasar, S.A. (ed.). *Handbook on Electric Machines*. New York: McGraw-Hill (1987).

[5] Kostenko, M.P. and Piotrovsky, L.M. *Electrical Machines,* vol. 2. Moscow: Mir (1974) (in Russian).

3. Results of magnetic field and levitation force modeling

To calculate the levitation force acting on the rotor, a full-scale model of the synchronous electrical machine (the ELCUT software) was developed, the parameters of the model blocks were set to account for the real properties of the materials used, such as high-coercive permanent magnets, HTSC, metallic glass, LN_2, etc.

The finite element mesh was optimized to reduce the error of the calculations (Fig. 4). Calculation of magnetic flux distribution was undertaken for the model described above with one rotor and two HTSC armature windings on both sides of it. Some results are presented below (Figs 5–8). They were carried out for the lower layer HTSC winding.

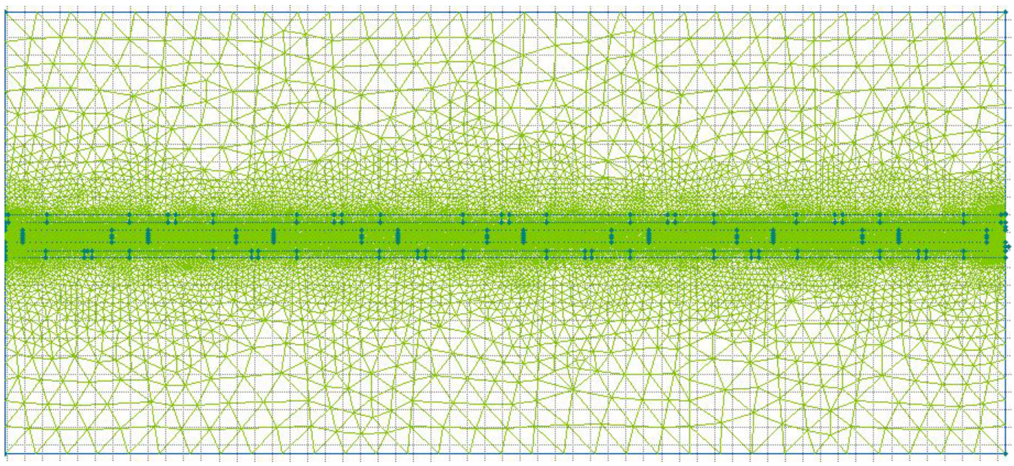


Figure 4. Finite element mesh for calculation of magnetic field distribution and of levitating force.

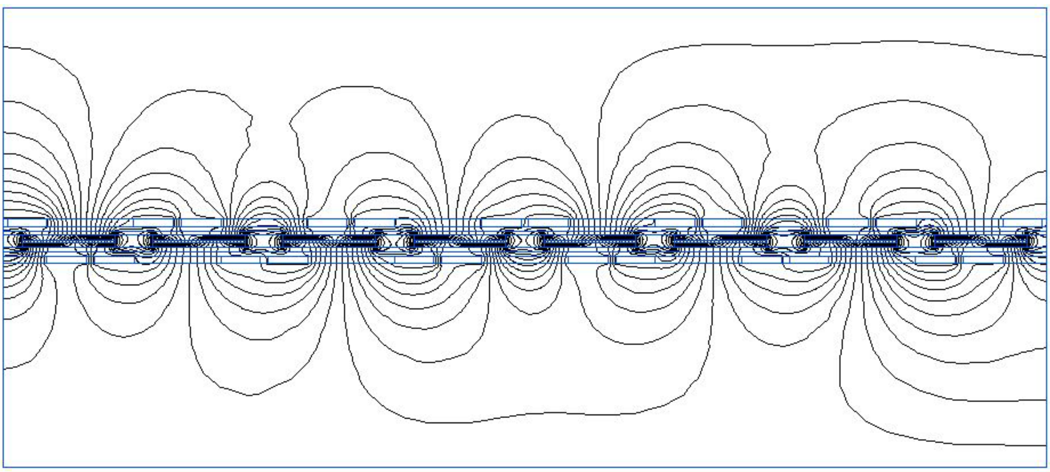


Figure 5. An example of intermediate calculations of magnetic flux of the model without magnetic screens.

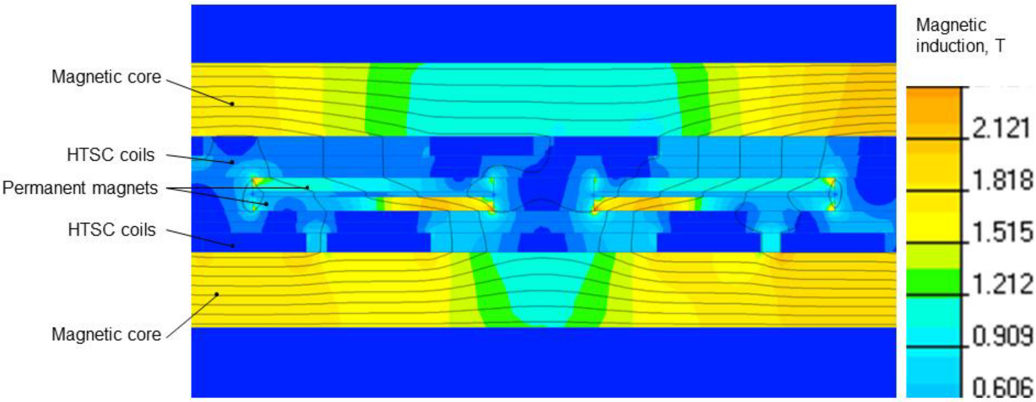


Figure 6.An example of magnetic field modeling for a part of the involute in the levitation zone.

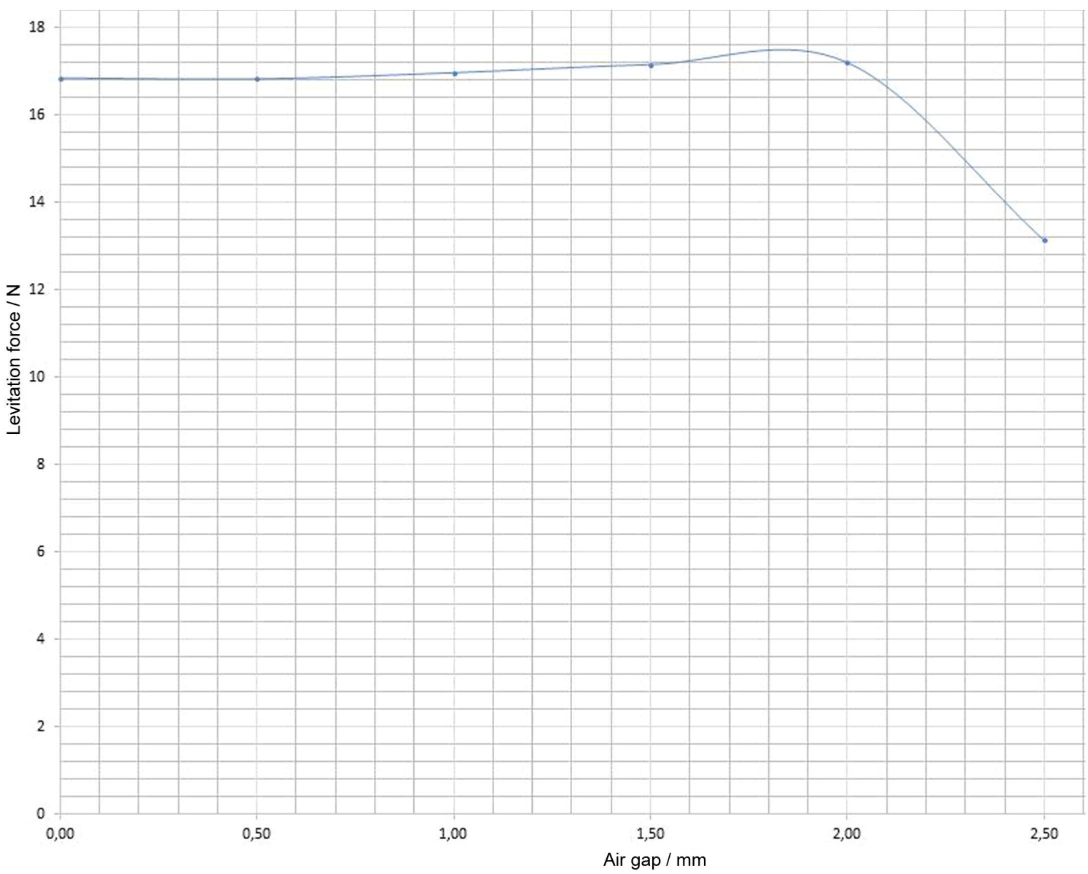
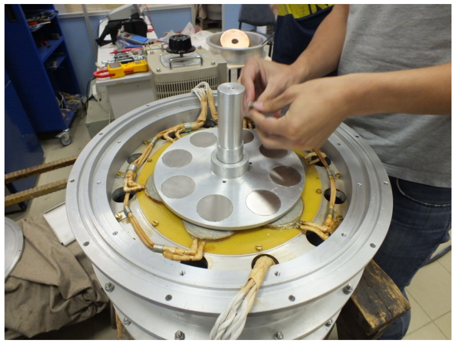


Figure 7. Variation of the levitation force along the air gap

The calculation results show that the rotor of the synchronous electrical machine can levitate under load. The weight of the aluminum rotor with Nd-Fe-B magnets is less than the levitation force and equals 11.0 N. In the case of repulsion, the levitation force produced by the upper HTSC armature winding with permanent magnets facing it is similar in value minus the rotor weight and weight of LN_2 below and above the rotor, and acts in the opposite direction. The calculations shown in Figs 4–7 were carried out for the model machine having the design presented in Fig.1. The average magnetic flux in each air-gap equals 0.5 T, armature winding coil has 550 ampere-turns, and the synchronous reactance of the armature winding is 0.6 per unit. Assembled lower-level HTSC winding coils are presented in Fig. 8a; Fig. 8b shows the aluminum rotor with permanent magnets.

(a)



(b)

Figure 8. Model assembly: HTSC armature winding coils (a), aluminum rotor with permanent magnets (b).

In the case of an attractive force the upper level winding must produce a larger force, accounting for the rotor weight. The calculation results are attached to a definite synchronous model electrical machine and show the principles of the levitation effect.

It is possible to have one HTSC armature winding on one side of the rotor. In this case the rotor levitation process will be more dependent on the load angle variation. At zero load angle (no-load mode of operation) the levitation force equals zero, therefore special low-friction bearings are to be foreseen in the machine design.

4. Conclusions

1. A disk-type electrical machine with axial magnetic flux of permanent magnets and a HTSC armature winding permits a device with a levitating rotor to be developed. It may levitate under load; in the no-load mode of operation special low-friction bearings are to be used.

2. The electrodynamic levitation effect in electrical machines with a HTSC armature winding, the high magnetomotive force of the armature and large load angle may cause problems during assembly and balancing.