OPTIMIZATION OF MAGNETIC FLUX IN ELECTROMAGNETIC VIBRATING GENERATORS

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Abstract: *Recent development in manufacturing of rare-earth permanent magnets provides a large variety of their shapes and magnetic properties. Ring shaped permanent magnets, mainly FeNdB magnets with high magnetic flux density (1.5 T), are frequently used for the construction of electromagnetic vibrating power generators for example in battery electric vehicles. The key parameter for optimal construction is the efficiency of power conversion which characterizes how effectively vibrating power generator converts kinetic energy into electric energy and stores it in batteries. The presented contribution brings an overview of concepts which increase this efficiency: 1) magnetic structure of axial magnets with like-poles facing each other incorporating soft magnet spacers; 2) cylindrical Halbach array magnetic structure; 3) outer magnetic shield structure for the concentration of magnetic flux. In the experimental section is also introduced constructed prototype of electromagnetic vibrating power generator and measurements of induced voltages.*

Keywords: RARE-EARTH PERMANENT MAGNET, ELECTROMAGNETIC VIBRATING GENERATOR, MAGNETIC FLUX, MAGNETIC STRUCTURE, MAGNETIC SHIELD.

1. Introduction

Recent development in construction of battery electric vehicles brings a possibility to extend their driving range by a recovery of the excess kinetic energy. Besides recovery of the kinetic energy during the regenerative breaking of battery electric vehicles, also concepts dealing with the conversion of vibrating kinetic energy of wheels back into electric energy have been published [1-3]. Ring shaped permanent magnets, mainly FeNdB magnets with high magnetic flux density (up to 1.5 T), are frequently used for the construction of electromagnetic vibrating power generators for electric vehicle [1, 2]. The design of electromagnetic linear vibrating generator can be explained in model of magnetic circuits [4, 5] consisting from 1) axial magnets with like-poles facing each other, 2) soft ferromagnetic spacers, 3) air gaps, where undesirable leakage of magnetic flux occurs, 4) magnetic shield, which eliminates magnetic flux leakages into the open space. Various cylindrical Halbach array magnetic structures have been studied to minimize magnetic flux leakages [2]. Suggested double-concentric Halbach array seems to be effective in concentration of magnetic flux. However the construction of such magnetic structures is very difficult and expensive.

Although air gaps are disadvantageous for the vibrating generator, on the other hand they are essential for multiple copper coil windings placed on the moveable non-magnetic holder. Dimensions of holder with copper induction coils must be optimally designed to eliminate the magnetic flux leakage into the coil windings (see Fig. 1).

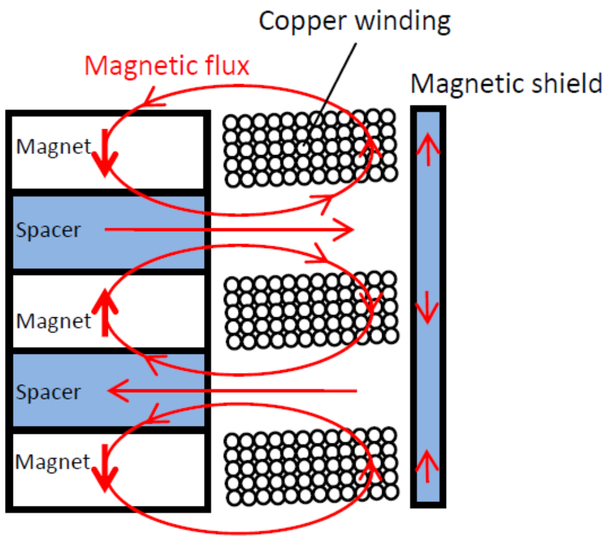

Fig. 1 *Scheme of magnetic circuits displaying non-optimal magnetic flux circulation through air gaps.*

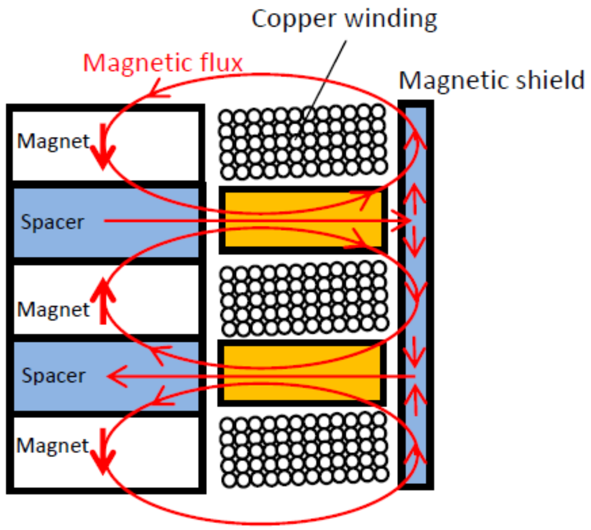

Fig. 2 *Scheme of magnetic circuits with optimized magnetic flux circulation by inserted moveable soft magnetic portions (yellow).*

2. Theoretical part

Figures 1, 2 show right part of parallel magnetic circuits axially magnetized by permanent magnets (white portions with red arrows). Blue portions of the circuits (spacers) are made from soft ferromagnetic material. Spacers redirect the magnetic flux Φ in the radial direction and represent shunts of magnetic circuits. Each spacer generates the leakage of the magnetic flux into the open space (red arrows in Fig. 1, 2). Thus the magnetic circuits have to be closed by soft magnetic shield. During the vibration motion (upward and downward) of copper winding with velocity v, the axial component of the magnetic flux density B_z alternates in the winding cross-section area S. From Faraday's induction law the EMF voltage U_i induced in the winding of N turns is:

$$U_i = -\frac{\partial \Phi}{\partial t} = 2NB_z S v . \qquad (1)$$

Further important construction parameter is the maximum current $I_{\max}$ generated by the vibrating coils with short circuit:

$$I_{\max} = \frac{U_i}{R} = \frac{B_z S v \pi d^2}{2\rho_{Cu} L_w}, \qquad (2)$$

where ρ_{Cu} is the electrical resistivity of copper, L_w is the copper winding length of vibrating coils and d is copper wire diameter.

3. Experimental part

For the analysis of magnetic flux we have adopted the four-phase linear generator (Fig. 3) containing ring-shaped permanent FeNdB magnets, which are arranged with like-poles of adjacent magnets facing each other to redirect the magnetic flux in the radial direction. The concentric outer cylinders made of soft magnetic high permeable (spacers) are used to overcome the repulsive forces between magnets and concentrate magnetic flux. The improved coil assembly consists of holder with copper coils separated with moveable soft magnetic rings, as it is schematically displayed in Figure 2. The use of high magnetically permeable material optimally conducts the magnetic flux far from spacers and increases radial flux density circulation. Figure 4 shows EMF voltage U_i induced in the four windings of experimental prototype of electromagnetic vibrating generator during the vibration motion (upward and downward). The peak voltage of each winding corresponds to Equation 1. After connection of the selected winding to a rectifier set-up with short circuit the measured maximum current has been slightly lower than theoretically predicted in Equation 2. The explanation is the eddy current loss which occurs inside moveable soft magnetic rings at low frequencies (< 10 Hz).

Fig. 3 Experimental prototype of electromagnetic vibrating generator. From the left hand side is the „backbone" consisting from FeNdB permanent magnets and soft ferromagnetic spacers. The improved coil assembly consisting of holder with copper coils during the vibration motion (upward and downward).

4. Results and discussion

The experiments have been performed with and without magnetic shield to estimate magnetic flux leakages into the open space. The experimental prototype of electromagnetic vibrating generator without magnetic shield, as displayed in Fig. 3, was only able to produce approximately half of theoretically predicted EMF voltage U_i in Equation 1. Using the magnetic shield increases magnetic flux density in cross-section of copper winding by more than 50%.

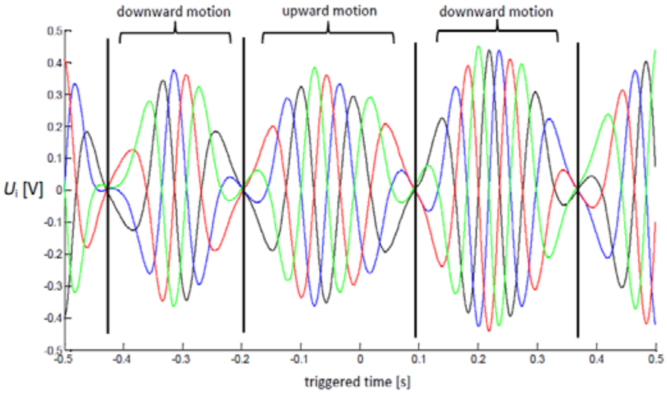

Fig. 4 EMF voltage U_i induced in the windings of experimental prototype of electromagnetic vibrating generator (from Fig. 3) during the vibration motion (upward and downward) with magnetic shield .

5. Conclusion

In the presented paper the construction of electromagnetic linear vibrating generator is optimized and tested by means of: 1) the magnetic shield, which eliminates magnetic flux leakages into the open space, increases magnetic flux density in cross-section of copper winding; 2) the improved coil assembly consisting of holder with copper coils separated with moveable soft magnetic rings; 3) the use of high magnetically permeable materials optimally conducting the magnetic flux far from spacers and increasing the radial flux density circulation; 4) induction coils optimally designed to eliminate the magnetic flux leakage into the coil windings.

Nevertheless the further research is necessary to increase the maximum current when the winding is connected to the rectifier set-up with short circuit.

Acknowledgement

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