A routine for improvement of coil turns distribution for permanent-magnet microgenerators used in vibration energy harvesters

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A design routine improving distribution of separate turns within the coils for better exploitation of the magnetic flux in permanent-magnet microgenerator used in vibration energy harvester is proposed. The distribution of the magnetic field is determined using the 3-d integral formula. Initially, the coil is considered as a cluster of loops formed by separate turns. The routine decides whether the loops are valid or void based on the simulated performance of the generator supplying load via electronic converter. The procedure considerably increases output power generated by the system which is confirmed experimentally.

Index Terms—Design optimization, energy harvesting, electromagnetic modeling

I. INTRODUCTION

The coreless magnetic circuits containing permanent magnets are often considered for generators in vibration energy harvesters due to simple design routine [1]. Their unity power density is however, small due to practically lack of concentration of the magnetic field. In order to increase the induced voltage the number of turns within the coil must be high. This leads to rise of the internal impedance which restricts the possibility to boost the voltage via electronic converter. In this work we present a routine which improves coupling of separate turns with the magnetic flux and allows reduction of the internal impedance of the coil. Using the 3-d integral formula the flux linkage is determined individually for each turn avoiding the need to determine the magnetic field distribution for the whole system. Based on the results of computations the physical system is built and tested.

II. CONSIDERED SYSTEM

Fig. 1 displays details of the system which belong to a class of nonlinear vibration energy harvesters. The linear kinematic effect is caused by the cantilever-beam spring, whilst the nonlinear one by magnetic interaction between vibrating and nonvibrating magnets (see Fig. 1a). As shown in Fig. 1b the space available allows for relatively flexible location of the coils (regions enclosed by dashed line). In [2] we examined if the flux linkage can be increased by optimization of placement of the coils modeling the coils as block of materials. Although the obtained numerical results were optimistic the physical validation was negative. The latter confirms the need to evaluate the magnetic flux linkage for each turn individually.

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III. COMPUTATIONS

A. Coil parameters

The axial component of the magnetic flux density at any distance from the magnet magnetized uniformly along z-axis direction can be determined using formula [3, 4]

$$B_z = \mu_0 \frac{3(z-z_0)Q_m}{4\pi |r-r'|^3} ds - \mu_0 \frac{3(z-z')Q_m}{4\pi |r-r'|^3} ds$$  (1)

Where \( \mu_0 \) is permeability of vacuum, \( Q_m = M \cdot n \) the magnetic dipole density, \( M \) and \( n \) the magnetization and surface-normal vector, whilst \( r, r' \), and \( S, S' \) are explained in Fig 2. Formula (1) is evaluated only at the nodes of triangulation of the surface bounded by the contour of single turn (see Fig. 2).
The magnetic flux linkage of single turn

$$\lambda_t = \int_{S_t} B_s \, ds$$  \hspace{1cm} (2)$$

is evaluated using triangulation of surface $S_t$ in Fig. 2. The total flux linkage $\lambda_{coil}$ is a sum of contributions from all turns considering superposition of the magnetic fields due to the two vibrating magnets. The resistance $R_{coil}$ and inductance $L_{coil}$ for circular coil composed of separate turns are determined using analytic formulas.

B. Routine for improvement of turn distribution

The routine begins with filling the shaded areas in Fig. 1b with a cluster of uniformly distributed circles whose diameter corresponds with the diameter of the wire and considering a small gap between the wires. After that $\lambda_{tk}$ for $k = 1$ to $K$ with $K$ being the number of turns of the cluster and $\lambda_{coil} = \sum_{k=1}^{K} \lambda_{tk}$ are determined for the two relative positions of vibrating magnets. The two computations of the magnetic field around $y = 0$ are required for determination of $\partial \lambda_{tk} / \partial y$ which is in proportion to maximum value of turn-induced emf. Based on these quantities it is possible to identify turns with the worst contribution to emf and to consider their rejection as they considerably increase impedance of the coil.

C. Results

The electric performance of the system is predicted using a circuit simulation at single frequency considering the converter in Fig.1c. Initial $K$ is equal to 2178, although a noticeable rise of power is obtained when the ratio of rejected turns is as high as 53 percent.

Fig. 3 displays configurations of the coils with different percentages of rejected turns. As one can observe the turns with the best magnetic coupling are located close to each other which enables practical realization of the design. Fig. 4 presents variations of output power generated by the system for parallel connection of coils $A$ and $B$, which are obtained from the steady-state circuit simulation considering the power converter. The system with 400 best turns was selected for physical validation showing the adequacy and proportionality of the turn selection routine. Though, this design is not the optimal one. Optimization of the considered system for maximum generated power will be presented in the full paper.

Fig. 2. Evaluation of magnetic field distribution produced by single rectangular magnet (one of the vibrating magnets in Fig. 1) magnetized along $z$-axis over single circular turn using triangulation of coil turn surface $S_t$.

The electric performance of the system is predicted using circuit simulation at single frequency considering the converter in Fig.1c. Initial $K$ is equal to 2178, although a noticeable rise of power is obtained when the ratio of rejected turns is as high as 53 percent.

Fig. 3. Distributions of turns over coils cross-sections after successive rejections of turns with worst magnetic coupling: a) $K=2178$ turns - initial design, b) 1000 best turns, c) 800 best turns, d) 600 best turns, e) 400 best turns, f) 200 best turns.

Fig. 4 Variation of output power vs. load resistance determined by means of circuit simulation for different numbers of rejected turns with worst magnetic coupling.

REFERENCES