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OPTIMUM DESIGN OF A PERMANENT-MAGNET-BASED SELF-CHARGING DEVICE FOR A SMARTPHONE

OPTIMALNO OBLIKOVANJE SAMO-POLNILNIH NAPRAV NA OSNOVI TRAJNIH MAGNETOV ZA PAMETNE TELEFONE

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A smartphone battery can be charged without an external power source by applying a portable charger that transforms mechanical energy into electricity by means of magnetic induction. Its essential part is a permanent magnet made of a rather expensive and, from the point of view of availability as well ecology, problematic material. The magnet is usually assembled from cylindrical parts. In order to reduce the raw-material consumption and to simplify the production, we propose a single-piece design in the form of a cylinder with notches. By means of the finite-element modelling, we optimize the dimensional parameters and prove that our proposal is more efficient than standard solutions.

Keywords: permanent magnet, electric generator, smartphones, self-recharge, finite-element modelling

Baterija za pametni telefon se lahko polni tudi brez zunanjega napajanja z uporabo prenosnega polnilca, ki pretvarja mehansko energijo v električno. Njen najbolj pomemben element je trajni magnet, ki je izdelan iz dokaj dragega, težko dostopnega in okoljsko problematičnega materiala. Ta magnet je običajno sestavljen iz cilindričnih delov. Avtorja članka predlagata z namenom zmanjšanja porabe osnovnih surovin in poenostavitve proizvodnje uporabo enovitega cilindričnega izdelka z zarezami. S pomočjo modeliranja na osnovi metode končnih elementov sta avtorja optimizirala dimezijske parametre in dokazala, da je njuna rešitev bolj učinkovita kot so standardne izvedbe.

Ključne besede: trajni magnet, električni generator, pametni telefoni, samo-polnitev, modeliranje na osnovi metode končnih elementov

1 INTRODUCTION

Energy consumption is one of the main problems faced by society. It is of strategic importance to put efforts into energy saving during all activities. At the same time, it is also necessary to reduce the consumption of raw-material resources for ecological and economic reasons. On the other hand, technological progress is unstoppable; therefore, the goal must be to stimulate innovations, acceptable in the present situation. An example is a smartphone, a small device which is nowadays indispensable in many aspects. Although it is not a significant energy consumer, its operation depends on the battery capacity – one of the crucial topics of contemporary applied science.[1,2] It would be desirable to avoid inconvenient situations occurring due to an empty battery by not burdening the environment or drastically increasing the price of the device.[3] A possible solution is to use a portable battery self-charger,[4,5] which is basically an electric generator producing electricity from the kinetic energy associated with walking or shaking by the phone's carrier.[6] Various studies have been conducted to characterize different moving activities as a potential energy source.[7,8]

The idea is to exploit human motion, which excites a vibration of the coil in a magnetic field, inducing a voltage.[9]

A scheme of such a charger is presented in **Figure 1**. So far, the size of the only commercially realized example exceeds the size of a smartphone.[10] It must be carried separately in a bag, which is inconvenient and reflected in only limited commercial success.[11]

The problem is how to produce a sufficiently strong, non-uniform magnetic field using a reasonably small, light and easily manufactured magnet. The fulfilment of the first two criteria obviously contributes to a light weight and small size as well as to a low price of the final product, needless to say, crucial for the applicability. Similarly, a simplified manufacture without assembling the magnet from different pre-magnetized parts, as it is the case with the existing self-chargers, would certainly have a positive impact too. We propose a design, suitable for additive manufacturing by means of 3d printing, making a single-piece magnet that can be magnetized in a uniaxial direction. It should be small enough to be embedded in the housing of the smartphone. The objective is to determine the shape of a tube-like magnet that yields the optimum performance, defined by the estimated induced voltage per volume of the magnetic material. To achieve this goal, we optimize the magnet-geom-

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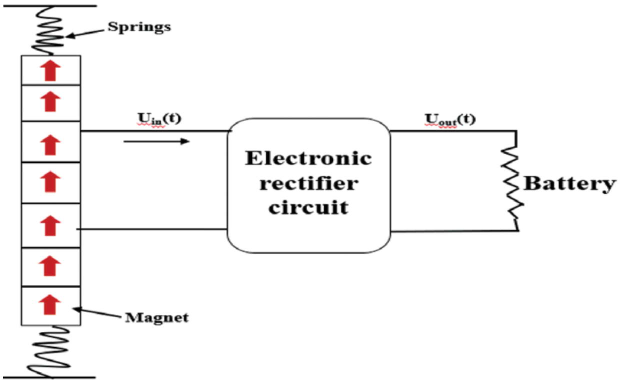

Figure 1: Schematic of the charger

etry parameters by modelling in the frame of the finite-element formalism.

2 DESCRIPTION OF THE CHARGER

As presented in **Figure 1**, the charger under consideration comprises a rectifier circuit, a magnet, and an oscillating coil coupled to a pair of strings.[2,12] Whereas the springs must be tuned to match the walking and oscillating-coil frequencies, and the rectifier circuit should supply an appropriate voltage to charge the battery, the focus of the present research is to find the ideal shape of the magnet as the source of the magnetic field.

According to the Faraday's law the induced voltage is expressed as the time derivative of the magnetic flux[13] φ_m:

$$U_i = -\frac{d\varphi_m}{dt} \tag{1}$$

$$\varphi_m(t) = NBA \tag{2}$$

where N is the number of turns in the coil, A represents the coil's cross-section, and B denotes the magnetic-flux density. The target average induced voltage is about 10 V.

Under consideration is a cylindrical shape with notches, which makes it possible to stick to a planar problem due to the rotational symmetry. The length and the maximum diameter are set to 10 mm and 4 mm, respectively, which implies a reasonable size of the device, and, as a rule of thumb, matches to N = 400 turns in the coil.

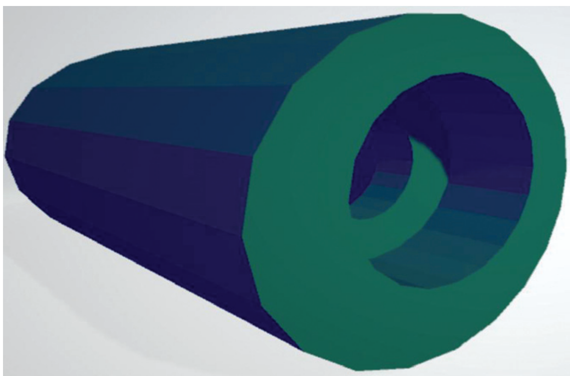

Figure 2: Schematic diagram of the proposed permanent-magnet shape for the self-generation system

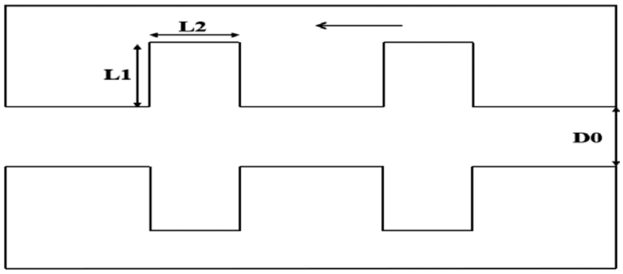

Figure 3: Magnet dimensions and black arrows present the magnetization direction

We adopt the magnetic properties of a state-of-the-art sintered magnet (NdFeB-50) with sufficiently high remanent magnetization. An example of the proposed magnet shape is presented in **Figure 2**, with the dimensions defined in **Figure 3** and **Table 1**.

Table 1: Magnet dimensions

Parameter	Notation
Inner diameter	(D0)
Height of the notch	(L1)
Width of the notch	(L2)

The notches in the magnet design are the key innovation, contributing to a lower weight, reduced consumption of the raw material, and the required field inhomogeneity necessary for a non-zero time derivative in Equation (1).

3 METHODOLOGY

The complete flow chart of the magnet-modelling procedure is presented in **Figure 4**. The finite-element calculations of the magnetic flux density were carried out with FEMM software.[14,17]

The first-type (Dirichlet) boundary conditions and a triangular mesh were applied. Its density was determined

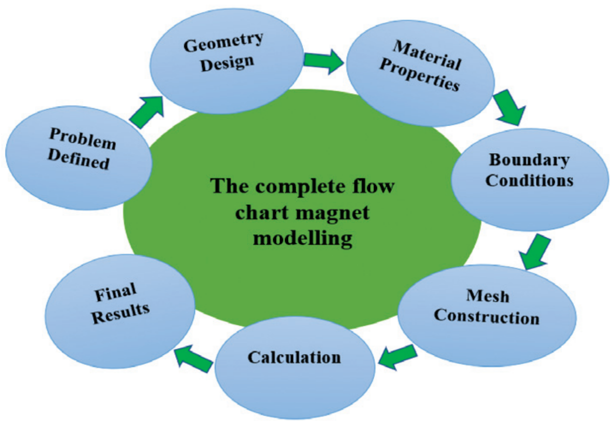

Figure 4: Complete flow chart of the magnet-modelling procedure

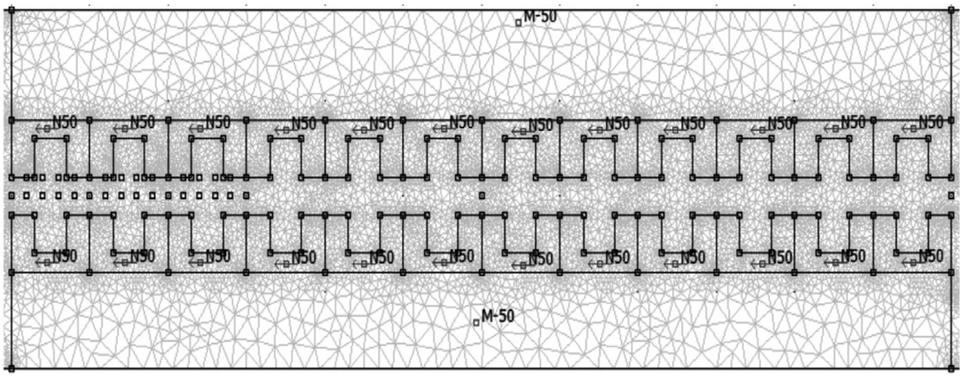

Figure 5: Meshing for the considered magnet

on the basis of the convergence tests.[15,16] **Figure 5** presents the meshing for the magnet geometry under consideration. The mesh is denser close to the magnet, where the field gradients are more pronounced. The time dependence of the calculated flux is modelled by examining various displacements between the coil and the magnet assuming a harmonic motion.

For simplicity, the angular frequency was set to $\omega = 1\ s^{-1}$. The time derivative in Equation (1) is carried out in terms of the finite-difference method, and the average value B of the magnetic-flux density for a given cross-section is applied in Equation (2).

4 RESULTS AND DISCUSSION

The following geometry parameters yielding the optimum performance were optimized: L1 (height of the notch), L2 (width of the notch), and the inner diameter of the tube (D0) of the magnet. The optimization criterium was the induced voltage divided by the magnet volume.

We adopted the simplest optimization procedure by fixing one and optimizing the other two parameters at the first stage. It makes sense to compare the calculated output average voltage normalized to the volume of a particular magnet with notches. First, we fixed the diameter D0 and plotted the normalized voltage for four different notch heights L1 as functions of the notch width L2 in **Figure 6**. Although a bigger notch certainly contributes to a smaller volume and simultaneously to a less homogenous magnetic field, there is obviously an optimum combination of L1 and L2 corresponding to 4 and 6, respectively in **Figure 6**.

In the second stage, we applied this combination L1 and L2 and examine the influence of the diameter D0. To check the stability of our solution, we fixed the width L2 to 6 and present the results of several values of L1. Again, L1 equals four yields the highest normalized voltage for diameter D0 value equals 8 giving the optimum set of the three parameters.

To prove that our concept makes sense, we present a comparison between the calculated voltages resulting from applying the optimized magnet geometry and different conventional solid (without notches) magnets magnetized uniaxially (Normal), axially (Axis) as a sequence of segments magnetized periodically in the left or right direction, and along the Halbach pattern (Halbach): **Figure 8**. Although the solid magnets, particularly the one magnetized along the Halbach pattern, might yield a higher absolute voltage, the benefit of the notches due to a reduced amount of the used material is obvious and even a non-optimum solution (L1 equals 5) gives a higher normalized voltage.

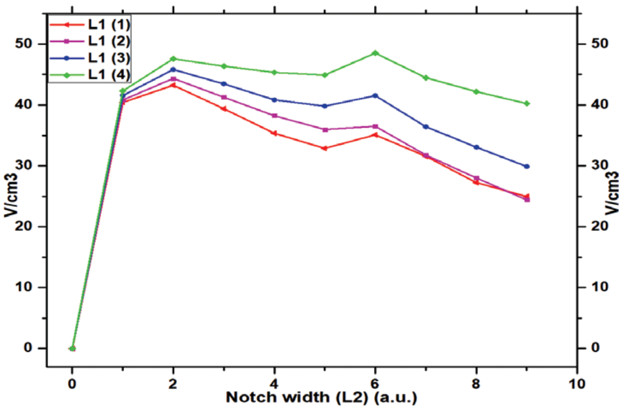

Figure 6: Voltage vs. volume as a function of the notch width L2 for different values of the notch height L1 and a fixed value of D0

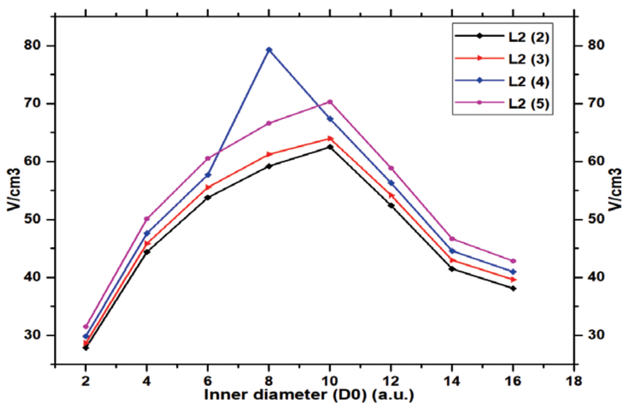

Figure 7: The calculated normalized voltage for L2 fixed to 6 for different values of L1 as functions of the inner diameter D0

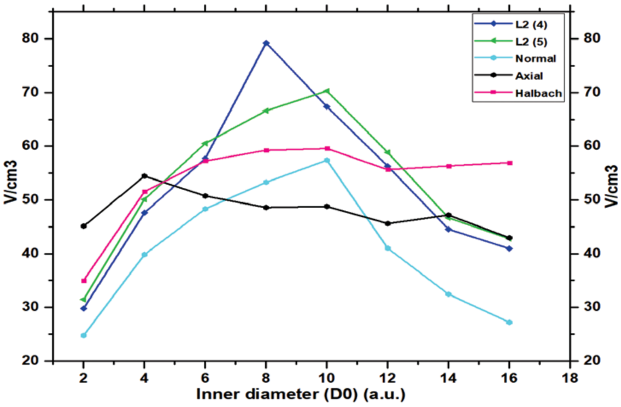

Figure 8: Comparison between our proposal and conventionally magnetized solid magnets of magnets of tube-like shape

5 CONCLUSION

The subject of our investigation was a self-charging device for portable electronics, for example, smartphones, adopting magnetic induction generated by a permanent magnet surrounding an oscillating coil. The focus was on the magnet geometry, to save raw material and to simplify the production. Therefore, we introduced notches in a uniformly magnetized tube-like magnet, which at the same time contribute to the required non-homogeneity of the produced magnetic. A comparison with the performance of conventional cylindrical magnets of equal outer dimensions proved that our proposal, which can be produced by means of 3d printing, indeed yielded the highest output voltage normalized to the volume of the consumed material. The overall result might contribute to the general efforts for sustainable development.

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6 REFERENCES

[1] C. R. Saha, T. O'Donnell, N. Wang, P. McCloskey, Electromagnetic generator for harvesting energy from human motion, Sensors Actuators, A Phys., 147 (**2008**) 1, 248–253, doi:10.1016/j.sna.2008.03.008

[2] Park C hyun, Choi D hoon, Design Optimization of a Vent Valve for Minimizing Fuel Leak, Optimization:3-5

[3] J. Jun, Y. Shin, S. J. Cho, Y. W. Cho, S. H. Lee, J. H. Kim, Optimal linear generator with Halbach array for harvesting of vibration energy during human walking. Adv Mech Eng., 8 (**2016**) 5, 1–8, doi:10.1177/1687814016649880

[4] L. I. Anatychuk, V. Y. Mykhailovsky, L. T. Strutynska, Self-contained thermoelectric generator for cell phones, J Electron Mater., 40 (**2011**) 5, 1119–1123, doi:10.1007/s11664-011-1554-8

[5] W. J. Kim, B. C. Murphy, Design and construction of a novel tubular linear motor with controller for robotics applications, Am Soc Mech Eng Dyn Syst Control Div DSC, 72 (**2003**) 1, 475–484, doi:10.1115/IMECE2003-41131

[6] R. Baghebani, M. Ashoorirad, A power generating system for mobile electronic devices using human walking motion, 2009 Int Conf Comput Electr Eng ICCEE 2009, 2009, 2, 385–388, doi:10.1109/ICCEE.2009.58

[7] K. Halbach, Design of permanent multipole magnets with oriented rare earth cobalt material, Nucl Instruments Methods, 169 (**1980**) 1, 1–10, doi:10.1016/0029-554X(80)90094-4

[8] S. M. Jang, S. S. Jeong, D. W. Ryu, S. K. Choi, Design and analysis of high speed slotless PM machine with Halbach array, IEEE Trans Magn., 37 (**2001**) 4 I, 2827–2830, doi:10.1109/20.951319

[9] S. Park, B. Kim, S. Kim, K. Lee, J. Kim, 1461, Electric generator embedded in cellular phone for self-recharge, J Vibroengineering, 16 (**2014**) 8, 3797–3806

[10] J. S. Choi, J. Yoo, Design of a Halbach magnet array based on optimization techniques, IEEE Trans Magn., 44 (**2008**) 10, 2361–2366, doi:10.1109/TMAG.2008.2001482

[11] P. Constantinou, P. H. Mellor, P. Wilcox, A model of a magnetically sprung vibration generator for power harvesting applications, Proc IEEE Int Electr Mach Drives Conf IEMDC 2007, 1, 725–730, doi:10.1109/IEMDC.2007.382757

[12] S. Jeong, M. Murayama, K. Yamamoto, Efficient optimization design method using kriging model, J Aircr., 42 (**2005**) 2, 413–420, doi:10.2514/1.6386

[13] S. M. Jang, J. Y. Choi, S. H. Lee, H. W. Cho, W. B. Jang, Analysis and experimental verification of moving-magnet linear actuator with cylindrical Halbach array, IEEE Trans Magn., 40 (**2004**) 4 II, 2068–2070, doi:10.1109/TMAG.2004.832157

[14] Z. Wang, B. Wang, M. Wang, H. Zhang, W. Huang, Model and experimental study of permanent magnet vibration-to-electrical power generator, IEEE Trans Appl Supercond., 20 (**2010**) 3, 1110–1113, doi:10.1109/TASC.2010.2040072

[15] A. Vishwakarma, M. Komelj, A permanent magnet-based design for a smart-phone self-charger, Mater Today Proc., 65 (**2022**) xxxx, 3642–3645, doi:10.1016/j.matpr.2022.06.190

[16] A. Vishwakarma, M. Komelj, Design of a Smart Phone Self-Charging Device Based on Permanent Magnets, Adv Transdiscipl Eng., 27 (**2022**), 507–513, doi:10.3233/ATDE220787

[17] https://www.femm.info/wiki/HomePage