DESIGN AND SIMULATION OF A SHUTTLE BASED ELECTROMAGNETIC MICRO-POWER GENERATOR

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Abstract

This work presents a novel electromagnetic micro-power generator. The proposed generator has a construction that allows low magnetic field reluctance and, hence, high field density in the air gap. A generator total volume of 0.28 cm^3 is capable of generating power of 27 µWatt and the power density is found to be 95 µW/cm^3 when a vibrating source of 120 Hz, 2.25 m/sec^2 is utilized. A complete design procedure for the micro-power generation system is presented. The procedure starts from the load power and voltage requirements and goes backward in order to design the structure of the micro-power generator based on the available vibration input source. An example is assumed in order to demonstrate the design steps. Time simulation of the whole system is presented to simulate the system under two different loading conditions; continues power delivering and energy storage with charging a capacitor. Both COMSOL/SIMULINK and SIMULINK simulations are utilized

Keywords: PowerMEMS, Vibration Energy Harvesting, Electromagnetic Energy harvesters

1 - INTRODUCTION

Vibration to electricity conversion can be realized by electrostatic, piezoelectric or electromagnetic transduction. Electrostatic energy converters have an advantage since its fabrication is compatible with the CMOS technology; however, most of them are not self-sustained generators, as they need external power source in order to function. Piezoelectric energy generators have higher power densities, however, thin films have very poor coupling coefficient and their fabrication technique is not compatible with the CMOS technology. Moreover, both electrostatic and piezoelectric energy converters have an aspect of high output voltage and very low output current, which may put a constraint on these types of generators if the powered application draw high current (like multi-phase electromagnetic micromotors). Electromagnetic converters, on the other hand, seem to be a very attractive option as these generators have very simple and well-known operating theory, they are self-sustained micro generators and most of their parts can be fabricated by the modern MEMS micromachining techniques. However, the main drawback of electromagnetic energy generators is the low output voltage which is in the order of mV.

Most of electromagnetic micro-power generators listed in the previous literature suffer from weak air gap magnetic field density, which leads to both reduced generated voltage and low output power density [1]-[10]. The proposed generator has a construction that allows low magnetic field reluctance and, hence, high field density, i.e. 0.85 Tesla, in the air gap. Further, all the magnetic field will be trapped in the air gap to eliminate any effect of such field on any surrounding electronics. However, a small transformer in order to raise the voltage to the required level, according to the load requirements, is used. Conditioning power electronics can not be avoided in all micro power generators. In this design only a simple rectifier bridge is used.

All such system was simulated with FEMLAB/SIMULINK as the mechanical part was simulated by the FEM tool, FEMLAB, and interfaced with circuitry within the SIMULINK environment. In mean time, all the systmem was simulated in the SIMULINK environment only using lumped parameters and an agreement was shown between the two simulation strategies. Section 2 discusses the structural construction of the proposed generator. The basic design procedure is discusses in section 3. In mean while, the system simulations are presented in section 4, and section five concludes this work.

2 - STRUCTURAL CONSTRUCTION OF THE PROOSED ELECTROMAGNETIC MPG

The construction of the proposed electromagnetic micro-power generator (EMPG) is shown in Fig. 1. It consists mainly of a stator and translator. The stator houses the magnetic parts of the generator, which are the permanent magnets and the return path for the magnetic field which is fabricated from any soft magnetic material like iron, nickel … etc. On the other hand, the translator contains both the mechanical suspension and the electrical coil systems , where the electrical energy is converted from the mechanical input.

Mainly the translator consists of a shuttle which is supported by a set of beams, as shown in Fig. 1. In order to extract the electrical energy from the moving mechanical system, an electrical coil is fixed on the surface of the shuttle. When the shuttle, and the attached coil, moves relative to the stationary magnetic field, electrical voltage will be induced in the moving coils and electrical energy can be extracted from the system. The translator, the seismic part of the generator, can be simply modeled as a conventional mass-spring-damper system.

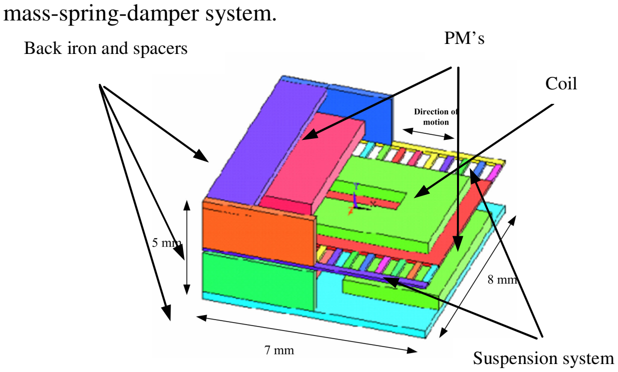

Figure 1 – Basic construction of the proposed MPG.

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Spring constant, effective moving mass and damping coefficient are very important design parameters in the design of any vibration based MPG.

Folded beam spring is chosen, as it is a highly linear spring flexure. It was concluded in [11] that, for equal truss and beam widths, the spring constants in the motion's direction and normal to it are expressed as Kx and Kz respectively:

$$K_x = n\frac{Et_b w_b^3}{L_b^3}\frac{L_t^2 + 14\beta L_t L_b + 36\beta^2 L_b^2}{4L_t^2 + 41\beta L_t L_b + 36\beta^2 L_b^2} \quad (1)$$

$$K_z = n\frac{Ew_b t_b^3}{L_b^3} \quad (2)$$

Where n is the total number of folded beam flexures, $\beta = (wt/wb)^3$, w_t and w_b are the truss and beam widths respectively, L_t and L_b are the truss and beam lengths, respectively. Note that K_z should be much higher than K_x in order to minimize any undesired out of plan motion.

The moving mass consists of the sum of all moving masses in the system. The effective mass of the folded beam flexure is given in [11] as:

$$m_{eff} = m_s + \frac{1}{4}m_t + \frac{12}{35}m_b \quad (3)$$

Where m_s, m_t and m_b are the shuttle mass, the truss mass and the total beams mass respectively.

Once both the spring constant and the effective mass are known, the natural frequency can be calculated as follows:

$$\omega_n = \sqrt{\frac{K_x}{m_{eff}}} = \sqrt{\frac{K_x}{m_s + \frac{1}{4}m_t + \frac{12}{35}m_b}} \quad (4)$$

The damping coefficient is mainly composed of two parts, the electrical damping and the mechanical damping coefficients. While the electrical damping coefficient depends on the electrical load and is well known, the air-damping coefficient needs to be evaluated. It is not an easy task to predict the air damping, but according to [11] it can be assumed that the shuttle (the moving plate between the two permanent magnets) suffers from air damping due to Couette flow on both sides and the direct air resistance on the front edge.

For the sake of simplicity, only the air damping due to Couette flow will be considered. This assumption is accepted when the area exposed to the Couette flow damping is much larger than the area exposed to the direct air resistance. The air damping coefficient can be expressed as: [11]

$$b = 2\frac{\mu A}{d} \quad (5)$$

Where μ is the air viscosity, d is is the displacement between the shuttle and the permanent magnet and A in the exposed area to Couette flow damping.

3 - BASIC DESIGN PROCEDURE

A complete micro-power generation system is shown in Fig. 2. A number of MPG's, determined by the total load power and voltage requirements can be connected in series. The reason behind the series connection is that the output voltage of the electromagnetic MPG's is usually small, in the order of few 10's of mV, so it would be required to connect them in series in order to increase the total voltage. However, sometimes it is further required to increase the generated voltage to reach a useful level. So, a small step up transformer is added with appropriate turns-ratio to increase the voltage to the required level.

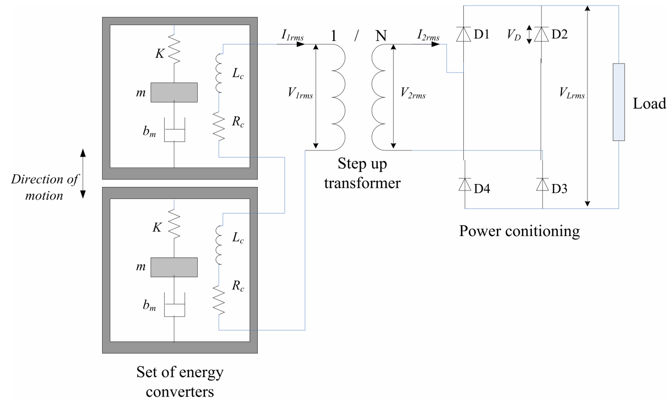

Figure 2 – An overview of the proposed micro-power generation system.

A case study will be described to demonstrate the complete design flow of the proposed MPG system. For the electrical side, it is assumed that an electrical load requires continues power of 100 μW at an average voltage of 2.4 V, according to [13] this power is high enough to supply four temperature sensors, model number LM19. For the mechanical side, the mechanical vibration source with first fundamental frequency of 120 Hz and acceleration of 2.25 m/sec^2 is assumed; this vibration is produced from a small microwave oven [14]. The design procedure starts by taking the load requirements as reference and going backward from the load side to the generator side to determine the power and voltage that the generator should deliver to meet the load requirements. The following steps will illustrate the design procedure.

1- Determine both the load requirements and the available vibration source:

P_{av} = 100 μW, V_{dc} = 2.4 V, $\omega = 2\pi(120)$ rad/sec and A = 2.25 m/sec^2.

2- Determine the voltage (maximum and rms) input to the rectifier bridge to establish the required load DC voltage, the voltage drop on the bridge rectifier diodes cannot be neglected here, as it is comparable with the load voltage. It was assumed that the bridge is constructed of four Germanium diodes with forward voltage drop of 0.32 V for each one. The average load voltage can be calculated as follows:

$$V_{dc} = \frac{1}{\pi}\int_{\alpha}^{\pi-\gamma}(V_{2\max}\sin\omega t - 2V_D)d(\omega t) \quad (6)$$

where γ is the angle at which the diode starts conducting, V_{2max} is the transformer secondary maximum voltage and V_D is the forward diode voltage. Solving Eq. (6) yields:

$$V_{dc} = \frac{2V_{2\max}\cos(\gamma) + V_D(4\gamma - 2\pi)}{\pi} \quad (7)$$

Also it is known that:

$$V_{2\max}\sin\gamma = 2V_D \quad (8)$$

solving Eqs. (7) and (8), both γ and V_{2max} can be calculated, for this case of study:

V_{2max} = 4.73 V and γ = 0.1356 rad or 7.77°.

3- The RMS load voltage can be calculated as follows:

$$V_{Lrms} = \sqrt{\frac{1}{\pi}\int_{\alpha}^{\pi-\gamma}(V_{2\max}\sin\omega t - 2V_D)^2 d(\omega t)} \qquad (9)$$

solving Eq. (9), V_{Lrms} can be expressed as follows:

$$V_{Lrms} = \sqrt{\frac{(V_{2\max})^2\left(\cos\gamma\sin\gamma + \frac{\pi}{2} - \gamma\right) + (V_D)^2(4\pi - 8\gamma) - 8V_{2\max}V_D\cos\gamma}{\pi}} \qquad (10)$$

substituting the values of V_{2max} and α from step 2 in Eq. (10) leads:

V_{Lrms} = *2.7803 V* and the load rms current, which it is the same as the transformer secondary rms current, will be I_{Lrms} = 36 µA.

4- A transformer ration of 20:1 with 90% transformer efficiency is assumed, for this case P_1 = 134 µW and V_{1rms} = 167.23 mV and I_{1rms} = 801.27 µA. Also V_{1max} = 236.5 mV.

5- Using 5 identical generators connected in series, the power and voltage calculated in step 4 will be divided by 5 and the current will be the same.Maximum power and displacement can be written as follows [11]:

$$P_g = \frac{m^2 Y_o^{\ 2} b_e \omega_n^{\ 4}}{2(b_e + b_m)^2} \qquad (11)$$

$$Z_{o\max} = \frac{m\omega_n Y_o}{b_e + b_m} \qquad (12)$$

For this case solving equations (11) and (12) leads to the calculation of both be and m,

$b_e = \frac{(Bl)^2}{R_g} = \frac{(Bl)^2}{41.75} = 4.191 \times 10^{-3}$ Nsec/m, Bl =0.4183 Tm and m = 208.3 × 10^{-3} g.

Where Bl is called as the coupling coefficient and R_g is the generator's loading resistance

In order to calculate the magnetic field density in the air gap, a 2D FEA was preformed on a structure having 4 permanent magnets of dimension 3 mm width × 7 mm long × 1 mm height with an air gap of 1 mm. The material of the permanent magnet used in the simulation was Neodymium-Iron-Born grade N44H with residual flux of 1.27 Tesla and coercive force of 1200 KA/m [12]. The magnetic field was calculated to be 0.85 T. that leads to the determination of the length, *l*, required to produce a coupling coefficient *Bl* of 0.4183 Tm. The effective length was calculated to be 49 cm.

The total moving mass has to be 208.3 × 10^{-3} g and the natural frequency should match the input frequency for optimum performance, 120 Hz. The spring stiffness can be calculated from Eq. (4) to be 118.42 N/m. The total number of folded beam flexures can be calculated from Eq. (1) provided that the flexure dimensions are known.Using the Silicon-On-Insulator (SOI) technology, the moving shuttle can be fabricated of 50 µm height silicon with 2 µm silicon dioxide (SiO_2). Silicon's Young's modulus is 131 GPa with 800 µm beam length, 9.68 µm beam width, the resultant number of required folded beam flexures will be 12 flexures, by using Eq. (7). The FEA showed that it was required to reduce the spring beam's width to 9 µm to eliminate the nonlinearity in the spring; otherwise, the structure will resonate at 125 Hz instead of 120 Hz, and less power and voltage will be generated

4 - SYSTEM SIMULATION

The system shown in Fig. 2 was simulated using COMSOL/SIMULINK package provided by COMSOL version 3.2a. The simulation package provides a real-time interface between the SIMULINK model and the FE model. In the simulated model; everything was modeled in the SIMULINK except the dynamic response of the moving shuttle as it is determined by the COMSOL finite element simulation. The net force acting on the shuttle is the difference between the input mechanical force and the electrical damping force ($B \times L_{coil} \times I$), as the estimated load current is producing force counters the input mechanical force. Unfortunately, only 2D and one sixth of the whole moving shuttle was simulated in the COMSOL finite element analysis due to the restriction put on the maximum number of degrees of freedom allowed to be interfaced from the finite element dynamic solver to the SIMULINK dynamic model.

The system shown in Fig. 2 simulates a continues power delivering of 100 µWatt at an average voltage of 2.4 volt and maximum allowed displacement of 150 µm, the COMSOL/ SIMULINK simulation results are shown in Fig. 3.

Wireless sensor nodes can be powered from the proposed system if the energy generated is stored in a capacitor in order to accumulate the produced energy to make it enough for that application. However, it was noticed that as the capacitor charges up, the shuttle's displacement increases rapidly to be more than the restricted displacement of 150 µm.

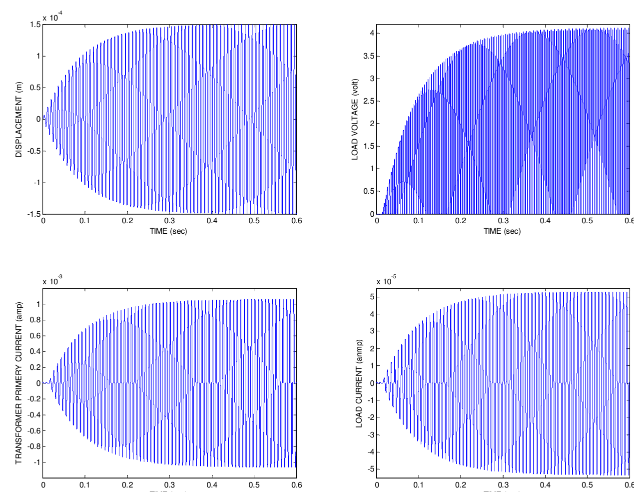

Figure 3 – COMSOL/ SIMULINK simulation results for continues power delivering.

This can be explained as the capacitor charges up, the drawn current from the generator decreases and the induced electrical damping reduces as well, which may increase the stress produced in the spring beams and may lead to the spring fracture. Therefore, stoppers should be added the system to limit the displacement to be 160 µm and prevents the system to plunge into the nonlinear operating region. Unfortunately, COMSOL, the finite element package, does not have mechanical contact analysis, so before building a SIMULINK model to simulate the energy storage system, a SIMULINK model was built to simulate the same system described in Fig.2 and the simulation results compared to that obtained from COMSOL/SIMULINK simulation are shown in Fig. 4. The agreement between both simulations comes from the fact that approximately all the mass of the system is concentrated in the moving. In addition, the spring works in its linear region. Having validated the SIMULINK model, such model is used to charge a capacitor of 3 mF and the simulation results are shown in Fig. 5. It is concluded from the simulation results that an amount of energy of 26 mJ can be extracted from such system in a 12 minutes operating period.

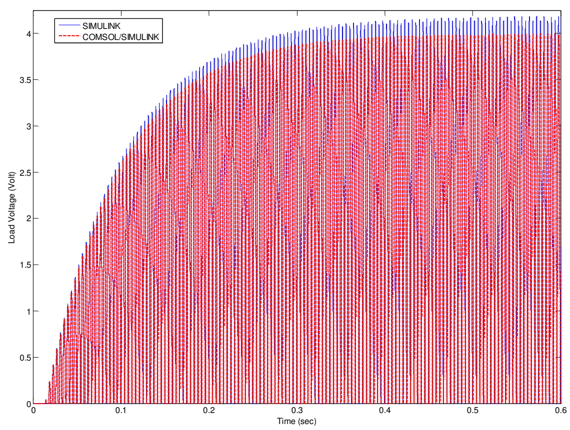

Figure 4 – Comparison between COMSOL/SIMULINK and SIMULINK dynamic simulation results.

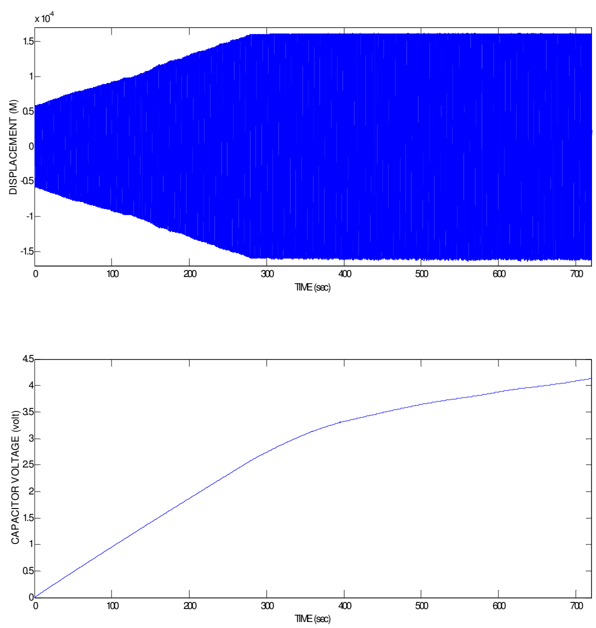

Figure 5 – Time based simulations of structural dynamic response and capacitor voltage.

5 - CONCLUSION

This paper presents a novel electromagnetic MPG system. The proposed system results in a total volume of one micro generator of 0.28 cm^3 and it generates 26.8 μW which leads to a power density of 95.7 $\mu W/cm^3$ at 120 Hz, 2.25 m/sec^2 vibration environment (or 91.2 $\mu W/cm^3$ if copper losses are taken into account). The total generator size (consisting of five identical unites) will be 1.4 cm^3. If the surrounding vibration environment changes to 200 Hz at 12 m/sec^2, the generated power density from such volume increases to 0.847 mW/cm^3. The whole system design procedure was discussed and both finite element analyses interfaced with SIMULINK and SIMULINK-only simulations were performed and compared together. Both the continuous power delivering and energy storage principles were verified by the dynamic simulation.

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