Electrostatic vibration energy harvester with increased charging current

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Abstract. The analysis of the operation of the electrostatic vibration energy harvester to charge self-contained power supply is carried out. An analytical expression to estimate the average charging current taking into account diode’s reverse current is obtained. The ways to increase the charging current were found. The harvester with increased charging current containing no switches and inductive elements is suggested.

1. Introduction
Recent achievements in microelectronics and microelectromechanical systems technology led to the appearance of mobile, compact and absolutely self-contained devices with very low energy consumption. Nowadays, batteries requiring periodic replacement, or recharging that is not always possible are used as self-contained power source for such devices.

The most suitable alternatives to traditional batteries are electrostatic vibration energy harvesters that allow harvesting the energy from the environment directly at the place of operation. However, in many cases, the application of traditional batteries cannot be completely excluded. Therefore, the most optimal solution of the problem of a self-contained power source is the using of electrostatic vibration energy harvesters to charge compact rechargeable battery.

The main limitations for the most such harvesters are an inductive element and the necessity to use switches. Moreover for operation of these switches the control circuits consuming energy are needed [1, 2].

One of the harvesters without these limitations is the harvester based on Bennet’s doubler [3, 4], however the charging current in the harvester is limited by battery voltage. In [3, 4], a modification of such harvester with the increased charging current is proposed, but it includes an inductive element and requires a switch. Furthermore, in this harvester the charging of the battery is implemented through periodical connecting the capacitor charged to high voltage to the battery.

The paper proposes the electrostatic vibration energy harvester with increased charging current without inducting elements and switches. Its theoretical and experimental investigation is described.

2. Basic harvester based on Bennet’s doubler
The electrical circuit of the basic harvester based on Bennet’s doubler is shown in figure 1. This harvester contains a battery \(V_0\), three diodes \(D_1, D_2\) and \(D_3\) and two variable capacitors \(C_1\) and \(C_2\) operating in antiphase. The load is connected in parallel to a battery.
An analysis of the harvester operation is carried out in [3, 4]. However, during the analysis the diode model without reverse current was used. At the same time, our study shows that the charging current at this circuit is comparable in many cases with the magnitude of the diode’s reverse current.

In this paper, the harvester operation was analyzed using the Shockley diode equation as a diode’s model.

![Figure 1. Basic harvester based on Bennet’s doubler.](image)

### 2.1. Numerical model and analysis

The differential equation system to describe the operation of the harvester taking into account diode’s reverse current is:

\[
\frac{dq_1(t)}{dt} = I_s \left[ \exp\left(\frac{\varphi_2}{m\varphi_T}\right) - 1 \right] + I_s \left[ \exp\left(\frac{\varphi_3 - \varphi_1}{m\varphi_T}\right) - 1 \right] - I_s \left[ \exp\left(\frac{-\varphi_3}{m\varphi_T}\right) - 1 \right]
\]

\[
\frac{dq_2(t)}{dt} = I_s \left[ \exp\left(\frac{-\varphi_2}{m\varphi_T}\right) - 1 \right] - I_s \left[ \exp\left(\frac{-\varphi_1 + \varphi_3}{m\varphi_T}\right) - 1 \right]
\]

where \( q_1(t) \) and \( q_2(t) \) are charges on \( C_1 \) and \( C_2 \) capacitors plates respectively, \( I_s \) is reverse bias saturation current, \( \varphi_i \) is potential of node \( i \), \( m \) is the ideality factor, \( \varphi_T \) is the thermal voltage.

Simulation results using equation (1) are presented in figure 2. During the calculations the interelectrode gap varied in a sinusoidal manner, and the harvester’s parameters were as follows: \( q_i(0) = q_2(0) = 0 \), \( V_0 = 3 \) V, \( I_s = 3 \) nA, \( m = 1 \), \( \varphi_T = 25 \) mV, maximum capacitance is \( C_{\text{max}} = 100 \) pF, minimum capacitance is \( C_{\text{min}} = 20 \) pF and frequency of mechanical vibrations is \( f = 40 \) Hz (\( T = 1/f = 0.025 \) s). Figure 2 shows that when connected battery to the circuit, the diode \( D_2 \) opens and capacitor \( C_1 \) is charged to a voltage of battery. Further operation of the harvester can be divided into two phases. The first phase corresponds to the decrease in capacitance \( C_1 \), meanwhile \( C_1 \) is discharged through the chain \( C_1 \Rightarrow V_0 \Rightarrow D_2 \Rightarrow C_2 \) charging the battery and the capacitor \( C_2 \). The second phase corresponds to the increase in capacity \( C_1 \), meanwhile \( C_1 \) is charged and \( C_2 \) is discharged through the chain \( C_2 \Rightarrow D_1 \Rightarrow C_1 \).

The analysis shows that the efficiency of the harvester decreases because of the diode’s reverse current. Note that the diode \( D_2 \) theoretically required for the initial charging capacitor \( C_1 \). Thus, the disabling the circuit diode \( D_2 \) after the initial charging of the capacitor \( C_1 \) could enhance the effectiveness of the harvester. But in practice due to uncontrolled self-discharge capacitors the need for their recharge remains and the diode \( D_2 \) must not be interrupted.

From the analysis of equation (1) we have obtained an expression that allows to estimate the average charging current taking into account diode’s reverse current

\[
I_0 = V_0 C_{\text{max}} f \frac{\eta - 1/\eta - 1}{\eta + 1} - I_s \frac{1.5\eta + 1}{\eta + 1}
\]
where $\eta = C_{\text{max}}/C_{\text{min}}$. 

![Figure 2](image-url) **Figure 2.** Dependences of the capacitances, capacitors voltages, diode currents and the charging current on the normalized time.

The second term in equation (2) is the discharge current of the battery caused by the diode’s reverse current. According to equation (2) at $I_0 > 2V_oC_{\text{max}}f(\eta^2 - \eta - 1)/(3\eta^2 + 2\eta)$ charging battery becomes impossible. For example, at harvester parameters used previously, the use of diodes with reverse current value of 6 nA will lead to a negative average charging current, i.e. instead of battery charging there will be battery discharge.

In [5] the obtained expressions allow to estimate the critical values of the main characteristics of the harvester components, such as the minimum ratio $\eta$, the minimum frequency of mechanical vibration and minimum battery voltage.

### 2.2. Ways to increase the average charging current

According to equation (1) the average charging current can be increased through higher values of the following characteristics: battery voltage, mechanical vibrations frequency, maximum values of the capacitors and ratio $C_{\text{max}}/C_{\text{min}}$. However, in reality, the battery voltage and the frequency of mechanical vibrations are determined by the operation conditions of the harvester. The maximum value of the capacitors are dependent on technological capabilities and mass-dimensional characteristics of the harvester. The analysis of equation (1) also shows that an increase in $C_{\text{max}}/C_{\text{min}}$ more than 10 does not lead to a significant increase in the charging current.

Thus, while developing converters with higher charging current it is necessary to consider the restrictions mentioned above.

### 3. Electrostatic vibration energy harvester with increased charging current

The proposed harvester circuit with increased charging current is shown in figure 3. In this harvester the increase in charging current is done by enhancing the potential of node 1 by means of setting the storage capacitor $C_S$ accumulating the charge and Zener diode $D_0$. As a result, the potential of the node 1 is increased, that is equivalent to the use of a battery with high voltage in harvester (figure 1).
3.1. Simulation

Figure 4 and figure 5 shows the dependence of the voltage at the storage capacitor $C_S$ and the battery charging current on the normalized time. This dependence is obtained by solving a system of differential equations describing the operation of the circuit shown in figure 2. The calculations assumed zener voltage of 90 V, capacitance, $C_0 = 0.1$ nF, and other parameters the same as when calculating the dependences given in figure 2.

Figure 4 shows that in the proposed scheme, the storage capacitor voltage in steady state is equal to the zener voltage, with an average charging current (figure 5) $\approx 227$ nA, whereas without this storage capacitor, the average charging current is $\approx 3.4$ nA (figure 2).

Theoretically, by increasing the zener voltage it is possible to increase the charging current of battery indefinitely. However, in reality, this current will be limited by obstinate parameters in particular. Moreover experimental studies are required to determine the attainable parameters.

3.2. Experiment

In experimental studies, as two variable capacitors with a variable capacitance in antiphase, there was used the structure of three electrodes area of 49 cm$^2$, two of which are rigidly interconnected with the electrode gap of 8 mm, and the third electrode is mounted there between. Electrode gap varied harmonically with frequency of 40 Hz. A series connection of five diodes 1N4004 was used as diodes and a series connection of two diodes 1N4004 was used as the Zener diode. Capacitance of the storage capacitor was $C_0 = 3.3$ nF, the battery voltage $V_0 = 30$ V.

Figures 6 and 7 show the dependence of voltage at the storage capacitor $C_S$ and the charging current on the charging time obtained experimentally. Time difference is caused by the fact that when measuring the voltage, 1 GOhm is in parallel connected to $C_S$. Upon that the steady state time is increasing.
It is seen that the average voltage in the steady state is equal to 1150 V and the average charging current in the steady state is 1.8 uA. At the same time, the experiment without storage capacitor showed charging current about 1.6 nA.

Thus, in the proposed harvester, through increasing the zener voltage, and, accordingly, the voltage at the storage capacitor, charging current can be significantly increased without higher voltage of battery and without inductive elements and switches.

4. Conclusion
In this paper the simulation of the basic harvester for charging a rechargeable self-contained power supply is carried out. An analytical expression that allows to estimate the average charging current taking into account diode’s reverse current was obtained. It is shown that at high diode’s reverse current average charging current can be negative, i.e. instead of battery charging there will be battery discharge.

The ways to increase the average charging current were found. It is shown that the average charging current can be increased through higher values of the following characteristics: battery voltage, mechanical vibrations frequency, maximum values of the capacitors and ratio $C_{\text{max}}/C_{\text{min}}$. Determined that an increase in $C_{\text{max}}/C_{\text{min}}$ more than 10 does not lead to a significant increase in the charging current.

An electrostatic vibration energy harvester, theoretically has unlimited charging current, and without inductive elements and switches was proposed. The simulation and experimental study of this harvester were carried out. A significant increase in the charging current in comparison with the basic harvester was proved. An experimental study in which the average charging current was 1.8 uA at a voltage on a storage capacitor kV.

References
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