**Charge Doubler Vibration Energy Harvester Using Self-Synchronized mechanical switches**

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**Abstract.** In this work, we study an electrostatic vibrational energy harvester e-VEH based on the charge doubler principle introduced by Bennet two centuries ago. We proof the advantages of using self-synchronized mechanical switches instead diodes, to avoid the problems of leakage current and threshold voltage. We made a new device as a proof of concept, which can work with mechanical switches or with diodes. To harvest the kinetic energy, an electrode moves between two fixed ones thanks to external vibration and creates an asymmetric variation of two variable capacitors. Due to his motion, this electrode also drives a sequence of contacts in the mechanical switch’s configuration. A comparison between this design and the one using diodes in the same conditions shows that the output voltage increase with an exponentially form for both design. However, the one using mechanical switches is faster by a factor of 80%. This induce a time reduction of 99% of harvested power at 40nW.

1. Introduction

Nowadays, the use of vibrational energy is becoming a revolutionary source of energy. This latter, is directly extracted form the environment and contributes to the development of compact and self-contained devices like wireless sensors and portable devices.

There is 3 major kinds of transducers, which convert kinetic energy into useful electrical one. First, there is the electromagnetic transducer which is constituted by a wire coil and a magnet [1]. This one generates a high power in a large scale, but it is not adapted to the micro-scale. On the other hand, we find piezoelectric transducers [2]. It can leads to a high power generation at the small scale but the use of this technology induces special steps for fabrication with relatively a high price. Finally, there is the electrostatic transducers. Simple capacitive electrodes compose this kind of transducers [3]. It is easily implementable in small-scale but it generates high voltage and its conditioning electronics can be complex for minimizing the efficiency.

Among the conditioning circuits for electrostatic transducers, there is the charge doubler. It was developed by Bennet two centuries ago and consists of a sequence of contacts for grounding or connecting three conductive plates, which form two variable capacitors [4]. Recently, Queiroz used this technic of charge doubler to harvest vibration energy from the environment by replacing the contacts with diodes [5].

In this work, we have reintroduced the contacts for the purpose of kinetic energy harvesting. Self-synchronized mechanical switches replace the diodes to be ride of the issues induced by diode’s threshold voltage and leakage current. We made a new device as a proof of concept.
based on the same principle that in [6] which can work with mechanical switches or diodes to compare the 2 approaches and prove the advantage of using mechanical switches.

2. The charge doubler for e-VEH with self-synchronized mechanical switches

The functional representation of our charge doubler device for e-VEH is shown in figure 1. It is composed by three electrodes (A, B and C). Thanks to external excitation, the central one B moves between the two others, which are fixed. This induces an asymmetric variation of the two variable capacitors $C_{ab}$ which is formed between the electrodes A and B, and $C_{bc}$ formed between the electrodes B and C. $C_{ab}$ varies between 13pF and 68pF and $C_{bc}$ varies between 25pF and 58pF. The mechanical switches ($S_1$, $S_2$ and $S_3$) play the role of the classically used diodes. $S_1$ and $S_2$ act as stoppers to limit the displacement of the central electrode. The third mechanical switch $S_3$ connects electrode A with electrode C, while $S_1$ and $S_2$ connect electrode B and C to the ground respectively. After a sequence of contacts by these mechanical switches and the asymmetric variation of the capacitance due to the oscillations of the central electrode, the charge increases at each cycle in the electrodes. Figure 2 represents the equivalent electrical circuit of our charge doubler device. We added another capacitor for storage $C_{res}$ of 1nF and a high impedance follower at the output for the characterization, which add an additional 10pF in the circuit.

The sequence for harvesting the kinetic energy is the following. Initially, there is some charge on the electrodes due the ambient noise. The operation starts when the central electrode B is positioned near A while connected to the ground through $S_1$. This induces an increase of charge $-\Delta Q$ on B. In this configuration, all the capacitances are in parallel, while $C_{ab}$ is at its maximum value and $C_{bc}$ is at its minimum values. Then B moves towards C due to the external vibrations. When B reaches C, this one is grounded through $S_2$ and a charge $\Delta Q$ is induced on C. Now, all the capacitances are connected in series, $C_{ab}$ turns to its minimum value and $C_{bc}$ to its maximum values. Finally, the mobile electrode moves back. When B reaches A, B is grounded again through $S_1$ and A is connected to C through $S_3$ and then, the electrode A has a charge increase equal to $+2\Delta Q$. All the capacitances are again in parallel and a charge $-2\Delta Q$ is induced on B. So, the equivalent circuit oscillates between series and parallel configurations of capacitances [3], and at each vibration period the charge double on the electrodes.

3. Experimental validation

To proof the utility of the use of mechanical switches, we have tested our device with mechanical switches and with the diodes in the same conditions. The electrodes are made of steel. A shaker
Figure 3. Operating cycles of the e-VEH charge doubler device with the corresponding equivalent circuit.

creates vibrations and allows the oscillation of the central electrode. The overall dimensions of the active part of the device is about $96cm^3$ against $315mg$ as the weight of the central electrode.

Figure 4. Real charge doubler device mounted on the shaker.

Figure 5. Voltage variation for different initial voltage, 8Hz and 0.5$g_{rms}$.

The first set of experiments consists in varying the initial voltage across $C_{res}$ with the device using the mechanical switches. The vibration conditions was set at 8Hz with 0.5$g_{rms}$ and the experimental setup limits the measurement voltage across $C_{res}$ at 40V. We see in figure 5 that the slope of the voltage increase depends of the initial voltage across $C_{res}$: If the initial voltage decrease, the time to reach 40V increase. For example, with only ambient noise, 40V is reached after 62s against, 33s with 7.5V as initial voltage.

Then we compared the device using diodes and the one using mechanical switches with similare conditions (8Hz at 0.5$g_{rms}$ and 1V as initial voltage). Results are shown in figure 6. Fig 7 shows the corresponding harvested power calculated by deriving the instantaneous energy in $C_{res}$, which is determinated by this equation:

$$E = \frac{1}{2} C_{res} V^2$$
It shows that the device with switches is much faster: 50nW of harvested power is reached in 45s against 87s with the diodes.

Table 1 compares the time to reach 40nW for the two configurations for different initial pre-charges. We can see that the one with mechanical switches is always faster than one with diodes. In addition, we observe that the time gap to reach the 40nW for both design decreases with the growing of the initial voltage. This comes from the voltage drop across diodes which is more predominant with low initial voltage.

Table 1. Time to reach 40nW for different initial voltage using the design with mechanical switches and with diodes, and the time gap between them.

| initial voltage | with mechanical switches | with diodes | time gap |
|-----------------|--------------------------|-------------|----------|
| 1V              | 41.93s                   | 83.73s      | 41.8s    |
| 2.5V            | 41.4s                    | 75.24s      | 33.21s   |
| 5V              | 30.21s                   | 54.53s      | 24.32s   |
| 7.5V            | 23.88s                   | 37.66s      | 13.78s   |

4. Conclusion
Using the self-synchronized mechanical switches instead of diodes in the charge doubler device is more suitable for e-VEH because it suppress the voltage drop and the reverse current across the diodes. For instance, we showed that the design with mechanical switches is faster by a factor of 99% at 40nW. However, the mechanical switches can add reliability issues.

5. References
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