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# MEMS electrostatic vibration energy harvester without switches and inductive elements

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**Abstract**. The paper is devoted to a novel study of monophase MEMS electrostatic Vibration Energy Harvester (e-VEH) with conditioning circuit based on Bennet's doubler. Unlike the majority of conditioning circuits that charge a power supply, the circuit based on Bennet's doubler is characterized by the absence of switches requiring additional control electronics, and is free from hardly compatible with batch fabrication process inductive elements. Our experiment with a 0.042 $cm^3$ batch fabricated MEMS e-VEH shows that a pre-charged capacitor as a power supply causes a voltage increase, followed by a saturation which was not reported before. This saturation is due to the nonlinear dynamics of the system and the electromechanical damping that is typical for MEMS. It has been found that because of that coupled behavior there exists an optimal power supply voltage at which output power is maximum. At 187 Hz / 4 g external vibrations the system is shown to charge a 12 V supply with a output power of 1.8 μW.

## 1. Introduction

The rapid progress in wireless technologies is stimulating the development of new types of autonomous power supplies for microelectronic devices, instead of traditional batteries requiring periodic replacement or recharging. Power supplies converting energy of ambient energy sources such as vibrations, solar, thermal, wind, wave and RF energies into electrical energy (energy harvesters) are becoming promising substitutes of batteries. However, it is not possible to get rid of using traditional batteries up to now, partly, because of inconstant availability of ambient energy sources (for example, at sunset). Therefore, the best option for autonomous power supplies is the coupling of a rechargeable battery and an energy harvester.

Among the available ambient energy sources mentioned, the mechanical vibration energy source is of specific interest due to its wide availability. There are several types of vibration energy harvesters such as electromagnetic, piezoelectric, electrostatic, etc. Electrostatic vibration energy harvesters (e-VEHs) appear to be the most suitable for miniaturization. They are not as bulky as electromagnetic harvesters, and they do not suffer from fatigue or depolarization like piezoelectric devices.

One of the main challenges of e-VEH implementation is the design of conditioning and interface electronics. Conditioning circuits that use the energy of vibration for increasing the charge of the power supply are of particular interest. The majority of such conditioning circuits contain inductive elements, which are hardly compatible with batch fabrication process, and switches, which require additional power-consuming control electronics for the correct sequencing of the different phases of energy conversion [1–4]. Recently proposed in [5], a conditioning circuit based on Bennet's doubler operates without any external controllable switches or inductors. To date, its operation has only been proven with macroscale variable differential capacitors (a couple of capacitors varying synchronously with opposite phases), whose variation was induced by an external motor. However, practical e-VEHs are implemented in MEMS technologies. The use of a realistic MEMS device (a microresonator + a capacitive transducer) induces three consequences: (i) limited transducer capacitance variation magnitude, (ii) strong electromechanical coupling impacting the dynamics of the system, (iii) use of monophase (single) variable capacitor, rather than a differential one made of 2 capacitors. These consequences could adversely affect the operation of the circuit.

The paper presents the results of theoretical and experimental study of a monophase (single-capacitor) MEMS e-VEH with a conditioning circuit based on Bennet's doubler. This novel experimental study of the circuit with real MEMS device shows results that differ significantly from those obtained in the previous experimental study with a macroscale device.

## 2. Theory

The e-VEH conditioning circuit based on Bennet's doubler with a single variable capacitor is shown in figure 1. It consists of a power supply ($V_0$), three diodes ($D_1 - D_3$), a fixed capacitor ($C_{store}$) and a variable capacitor ($C_{var}$) representing the transducer, associated with a mechanical resonator. The load ($R_{load}$) may be connected in parallel to the power supply. We will analyze the operation of the circuit without losses, assuming that diodes are ideal (no reverse current and threshold voltage).

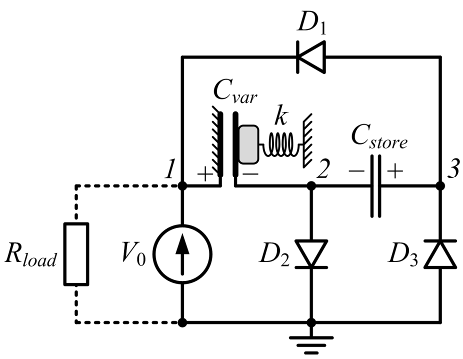


**Figure 1.** e-VEH conditioning circuit based on Bennet's doubler with a single variable capacitor.

The element called "power supply" may have different practical implementations: it can be a chemical accumulator or a large reservoir capacitor. As we will show, its voltage determines the energy conversion rate of the network. Hence, if the operation conditions of the circuit vary in time and if optimal circuit operation is maintained, this voltage may be variable (adjustable). However, the analysis of the circuit assumes a slow variation of power supply voltage in steady state: at the time scale of a mechanical vibration period, this voltage is constant.

### *2.1. Start-up stage*

Suppose that $C_{var}$ and $C_{store}$ are initially discharged, $C_{var}$ is maximum and the power supply is disconnected from the circuit. When the power supply is connected, the diode $D_2$ becomes ON ($D_1$ and $D_3$ are OFF) and $C_{var}$ charges to $V_0$, whereas $C_{store}$ is still discharged. So as $C_{var}$ decreases because of the vibrations, its voltage increases, $D_3$ becomes ON ($D_1$ and $D_2$ are OFF) and a portion of the $C_{var}$ charges flows into $C_{store}$. When $C_{var}$ increases again, its voltage decreases, $D_1$ becomes ON ($D_2$ and $D_3$ are OFF) and a portion of the $C_{store}$ charges flows back into $C_{var}$, after that $D_2$ becomes ON ($D_1$ and $D_3$ are OFF) and $C_{var}$ is charged from the power supply till voltage $V_0$. Then, the capacitance decreases again and the cycle repeats. After several cycles, the system goes into steady state in which there is no more power supply discharge ($D_2$ is always OFF).

### 2.2. Steady state

In steady state, the total charge on the capacitors $C_{var}$ and $C_{store}$ is constant. During the variation of $C_{var}$, this total charge is continuously redistributed between $C_{store}$ and $C_{var}$. The charging of the power supply occurs when charges flow from $C_{var}$ into $C_{store}$.

Figure 2 presents the relationship between the variable capacitor charge $Q$ and its voltage $V$ in a steady-state operation. Point $A$ corresponds to the state at which $C_{var}$ is maximum; $C$ corresponds to the state at which $C_{var}$ is minimal; $B$ and $D$ correspond to the states at which diodes $D_3$ and $D_1$ respectively become ON. Voltages at which the diodes $D_3$ and $D_1$ opens (see figure 2): $V_1 = V_0\left(1+\left(C_{\max}-2C_{\min}\right)/\left(C_{store}+C_{\min}\right)\right)$, $V_2 = V_0\left(2+\left(C_{\max}-2C_{\min}\right)/\left(C_{store}+C_{\min}\right)\right)$, where $C_{\max}$ and $C_{\min}$ are respectively the maximum and minimum capacitances of $C_{var}$ on the cycle.

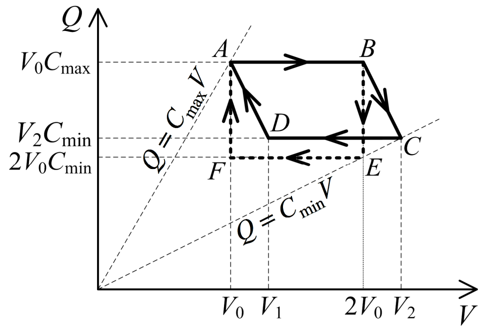


**Figure 2.** QV-diagram of the harvesting cycle in a steady state.

The cycle area $ABCD$ is equal to the energy converted by the transducer into electricity (harvested energy) during one operation cycle, which is defined by one $C_{var}$ variation period. This energy can be estimated by the expression:

$$E_{cycle} = V_0^2 C_{store} \frac{1-2/\eta}{C_{store}/C_{\max}+1/\eta}, \tag{1}$$

where $\eta = C_{\max}/C_{\min}$. If there are no losses in the diodes, this energy is totally injected into the power supply. Note that (1) is only positive if the requirement $\eta > 2$ is fulfilled. Otherwise, the voltage variation on the variable capacitor is not large enough to modify the states of the diodes, and the circuit does not operate in the energy conversion mode. The requirement of $\eta > 2$ is strong, and is often difficult to fulfill with MEMS transducers. However, it can be shown that by modulating the total charge on the capacitors $C_{var}$ and $C_{store}$, energy conversion is possible for lower $\eta$, however, with different circuit topology.

Analysis shows that the larger $C_{store}$ is, compared to $C_{\max}$, the more energy is harvested and the more rectangular $ABCD$ is. When $C_{store} >> C_{\max}$, the variable capacitor voltage ranges from $V_0$ to $2V_0$ and the energy is equal to the rectangular $ABEF$ area (figure 2):

$$E_{cycle\_rect} = V_0^2 C_{\max}\left(1-2/\eta\right). \tag{2}$$

From (1) and (2), it follows that the harvested energy can be increased by increasing the power supply voltage or increasing the potential of the node 1 through circuit modification [6], since the supply voltage is determined by the load. However, increasing this voltage leads to strong electromechanical coupling, which brings restrictions on the operation of e-VEHs. For example, if the variable capacitor has parallel electrodes with out-of-plane gap-closing construction (figure 1) the power supply voltage cannot be more then $\sqrt{8kd_0^3\left(27\varepsilon S\right)^{-1}}$ (where $k$ – linear spring stiffness, $d_0$ – gap between the electrodes in quiescent state, $\varepsilon$ – electric permittivity, $S$ – electrodes area), otherwise electrodes collapse (pull-in effect occurs) and the system stops operating [7]. By inserting this maximum allowed voltage in (1) one can estimate maximum harvested power taking into account design parameters. However, real devices have more complex constructions with more complicated electromechanical interactions and the optimal voltage at which the harvested energy is maximum can only be determined experimentally or by mathematical analysis.

## 3. Experiment

Figure 3 shows the schematic diagram of the used experimental equipment. The experiment was carried out using a 0.042 cm$^3$ batch fabricated MEMS e-VEH with in-plane cap-closing interdigitated comb geometry (figure 4). The e-VEH main characteristics and its fabrication technique are very similar to the one described in [8]. The measured unbiased capacitance variation ratio of the used e-VEH induced by harmonic vibrations at 187 Hz with acceleration amplitude 4 g, was $\eta = 3.25$ ($C_{\max} = 175$ pF).

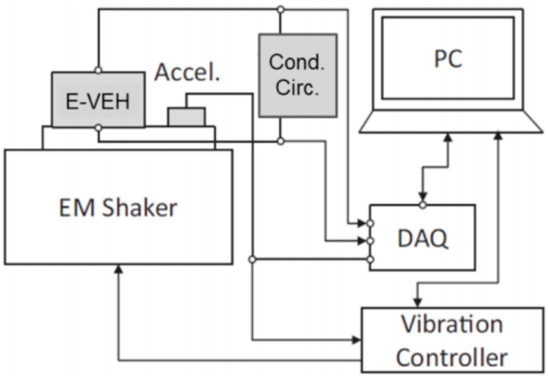


**Figure 3.** Schematic diagram of the used experimental equipment.

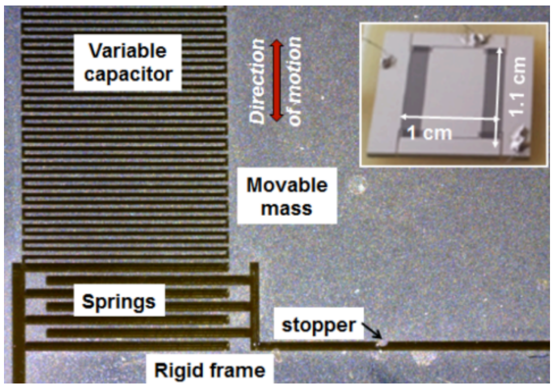


**Figure 4.** Photograph of the using MEMS e-VEH with interdigitated comb geometry.

To find the optimal power supply voltage, an initially pre-charged high-capacitance reservoir capacitor $C_{res} = 1$ µF was used. During the operation of the e-VEH, the voltage on $C_{res}$ increased. Figure 5 shows the evolution of the voltage on $C_{res}$ at 187 Hz / 4 g external vibrations and with $C_{store} = 2.8$ nF. At time $t = 0$, $C_{res}$ is charged to 5 V. An increase of the voltage on $C_{res}$ corresponds to an increase of the accumulated energy. It can be seen that voltage and accumulated energy (figure 6) initially increases, with an increasing rate (according to (1), the energy accumulation rate is proportional to $V_0^2$). Then, after several cycles of the harvester operation, the increasing rate of the voltage decreases, eventually leading to saturation at which voltage and energy on $C_{res}$ stop increasing.

This saturation phenomenon was not observed in the experiment presented in [5], where a macroscale capacitor was used. The saturation is due to the electromechanical coupling and not to the reverse current of the diodes which becomes significant only above 30 V: (i) the resonance frequency of the harvester decreases because of its biasing by the conditioning circuit and the input frequency is not anymore in the mechanical system bandwidth for large $V_0$; (ii) the electromechanical damping increases with $V_0$, reducing the amplitude of vibrations, hence the parameter $\eta$. These phenomena enforce the fundamental law: only a limited amount of energy can be converted from a mechanical resonator at given external vibrations [9].

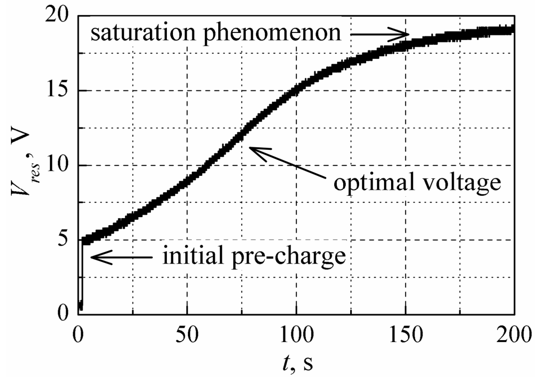


**Figure 5.** Measurement of $C_{res}$ voltage during harvester operation, excited by 187 Hz / 4 g external vibrations.

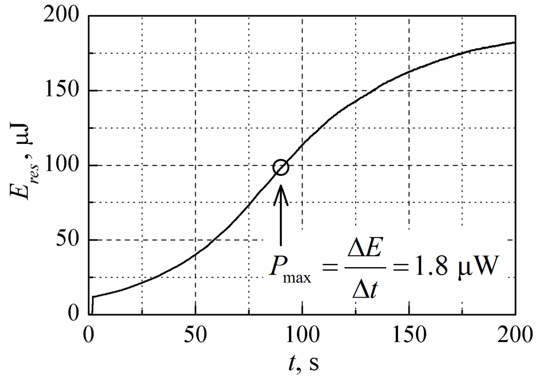


**Figure 6.** Evolution of the energy accumulated on $C_{res}$.

From figure 6, the available output power can be estimated as the time derivative of the energy stored on $C_{res}$. The maximum measured output power $P_{\max} = 1.8$ μW, obtained at $V_0 \approx 12$ V. Expression (1) predicts approximately the same result. Thus, it is seen that there is an optimum power supply voltage at which the e-VEH output power is maximum.

## 4. Conclusion

In this paper a novel experimental study of monophase (single-capacitor) MEMS e-VEH with conditioning circuit based on Bennet's doubler has been presented. This circuit allows charging a power supply without inductive elements and additional power-consuming control electronics.

The experiment was carried out using a 0.042 $cm^3$ batch fabricated MEMS e-VEH with in-plane cap-closing interdigitated comb geometry. The existence of an optimum power supply voltage at which e-VEH output power is maximum has been shown by the observation of the self-increasing voltage and energy on a reservoir capacitor used in place of the power supply. The presence of this optimum voltage is due to the electromechanical coupling in MEMS and had not been previously observed in studies with macroscale devices.

At 187 Hz external vibrations with 4 g acceleration amplitude and at optimal voltage of 12 V, the measured output power was 1.8 μW.

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