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A new autostabilization mechanism in the Bennet doubler circuit-based electrostatic vibrational energy harvester

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ABSTRACT

In this work, the theoretical and experimental study of the electric circuit is carried out for the electrostatic microgenerators based on the Bennet doubler with a power source in a variable capacitor branch. It is established that the circuit is able to operate at different capacitance modulation depth values. For the circuit with one variable capacitor, when the maximal-to-minimal capacitance ratio is less than 2, one can observe a saturation of the storage capacitor voltage (voltage autostabilization process). The equation for the saturation voltage evaluation is derived. As it is revealed for a maximal-to-minimal capacitance ratio more than 1.5, the saturation voltage is higher than power source voltage V_0. When the maximal-to-minimal capacitance ratio is greater than 2, one can observe a continuous growth of the capacitor voltages as for the basic Bennet doubler conditioning circuit. A similar change of the regimes in the same circuit, but with two variable capacitors, takes place when a maximal-to-minimal capacitance ratio is about 1.618. The employment of the considered Bennet doubler conditioning circuit enables solving two main problems: operation only for a capacitance modulation depth above 2 (1.618) and the uncontrolled capacitors voltages growth. The circuit under study can be also used for electret microgenerators and for microgenerators based on using electrodes with materials having different work functions.

1. Introduction

The necessity for batteries replacement or its recharging is one of the most important problems of modern wireless electronics. It is believed that a perspective way to solve the problem is to make autonomous power sources which can directly harvest the energy from the environment where devices are located. Electric energy can be taken from different environmental energy sources: solar energy, chemical reaction energy, electromagnetic, electrostatic and gravity fields, temperature gradients, liquid and gas flows, mechanical vibrations energy and the energy generated during human activities [1–7].

Electrostatic (capacitive) vibration energy harvesters (e-VEHs) are the most perspective among others due to the ubiquity and availability of mechanical vibration sources in the environment, as well as their manufacturing is based on the MEMS technology, which is fully compatible with the modern integrated circuits technology [8]. The e-VEHs are based on electrically charged capacitors, the capacitance of which is varied by a mechanical motion. The mechanical motion energy is converted into the electric energy of the variable capacitor. The electrostatic energy harvesters need either electret materials [9,10], work function difference of the electrode materials [11–13] or an external power supply [14–18], such as a battery, for charging variable capacitor electrodes.

Since mechanical vibrations are periodical, the e-VEHs produce the ac voltage that cannot be directly used for feeding power electronic devices (e.g. sensors). Moreover, by using only the variable capacitor, it will be impossible to store a sufficient amount of energy for powering the devices. Therefore, one of the main problems associated with the e-VEHs development is the realization of the power management (conditioning) circuit representing an interface between consuming devices and energy converting (harvesting) devices. There are a lot of requirements for the conditioning circuits, and the possibility of ac-dc conversion is among them, providing the necessary output power and voltage level required by the consuming devices. The output voltage should be adjustable depending on the external mechanical vibration parameters and the consumer power demands. Also, the conditioning circuit itself should not consume much energy; so, it is essential to reduce energy loses caused by the circuit elements and loses due to using an electronic conjunction circuit that is necessary for the synchronization between switches operation and mechanical

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vibration phases or for voltage levels controlling. For most cases, the power consumed during the switching process is comparable to the power produced by e-VEHs.

For the last time, the e-VEH conditioning circuits based on the Bennet doubler [19] are of great interest because of their high efficiency and ability to work without switches. The basic version of the circuit was suggested by de Queiroz [20,21]. However, this circuit operates only when the capacitance modulation depth is higher than 2 (in case of a single capacitor transducer) where there is a monotonous growth of the circuit elements voltages causing an electric breakdown. Thus, this basic circuit is not able to operate under low-amplitude mechanical vibrations (when a capacitance modulation depth is lower than 2) and cannot be directly used for device powering due to the monotonous voltage growth. For decreasing the minimally required capacitance modulation depth, Lefeuvre et al. [22] proposed the circuit with a voltage multiplier. Such approach, however, led to a significant increase of the circuit elements number and, so, to the leakages increase, especially through diodes. To increase the harvested energy, we proposed to introduce a storage capacitor and Zener diode to the basic harvester circuit allowing a significant increase of the average charging current and the circuit elements voltage stabilization [23]. However, this method does not enable adjusting the voltages, as well as the utilization of a Zener diode as a voltage stabilizer resulted in energy losses.

An interface circuit with an adjustable bias voltage for the optimization of harvested power for charging an external battery was devised earlier [24]. This approach, however, requires an additional energy-consuming switching control circuit as well. The autostabilization effect due to the electromechanical coupling was observed in [25,26], where the electrostatic force acts like a negative spring leading to the so-called electrostatic "spring-softening" effect. The resonance frequency of the harvester becomes lower with its increasing biasing by the conditioning circuit, and, respectively, for higher voltages, the external vibration frequency is away from the bandwidth of the mechanical system. Thus, the vibration amplitude is decreased causing the voltage saturation phenomenon. Karami et al. [27] presented the first experiment combining the Bennet doubler conditioning circuit to an electrostatic transducer with a weakly charged electret layer. Their experimental results showed that an electret, even of low voltage, can be used as the necessary pre-charge for the e-VEHs. However, the authors did not emphasize that, for their case, the voltage source is located not like in the basic Bennet doubler circuit, but in a variable capacitor branch producing a new Bennet circuit modification [27]. Unfortunately, the lack of a theoretical model that can fully describe the circuit operation does not enable revealing all its features and possibilities. Therefore, the present work is aimed at a detailed theoretical analysis and experimental study of the suggested circuit operation allowing the full evaluation of its characteristics and advantages.

2. Theoretical analysis

The electric circuit of the electrostatic microgenerator based on the Bennet doubler with a power source in a variable capacitor branch is shown in Fig. 1. It consists of three diodes $D_1 - D_3$, storage capacitor C_1, constant capacitor C_2, variable capacitor C_{var} and power source V_0. The load resistor in this circuit can be connected in parallel to power source V_0 or in parallel to storage capacitor C_1. The mechanical-to-electrical energy conversion occurs due to the periodical capacitance change under the external mechanical force.

The generator operation can be divided into two stages: charge and discharge of variable capacitor C_{var}. During the first stage, the capacitance of C_{var} is increased under the external mechanical force and, then, C_{var} is charged through $V_0 \to D_2 \to C_1 \to C_{var}$ and $V_0 \to C_2 \to D_1 \to C_{var}$. During the second stage, the capacitance of C_{var} is decreased under the external mechanical force and C_{var} is discharged through $C_1 \to D_3 \to C_2 \to V_0 \to C_{var}$. After that the conversion cycle is repeated.

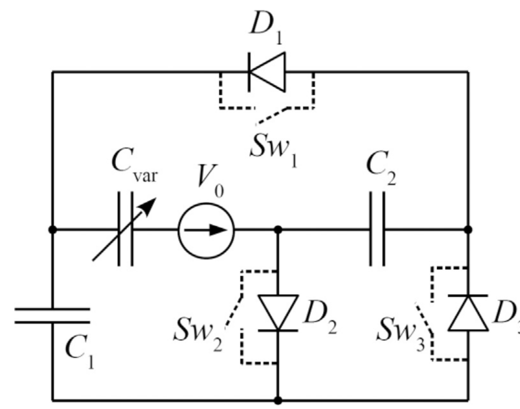

Fig. 1. The electric circuit of the Bennet doubler-based electrostatic microgenerator with a power source in a variable capacitor branch.

2.1. Circuit with ideal switches

First, let us analyze the generator operation in the quasi-static mode considering the switches to be ideal (marked by the dashed line in Fig. 1) and that the capacitance of C_{var} can be varied from C_{max} to C_{min}. At the stage of the capacitor C_{var} charging when its capacitance is C_{max}, switches Sw_1 and Sw_2 are turned on and C_{var} is charged through $V_0 \to Sw_2 \to C_1 \to C_{max}$ and $V_0 \to C_2 \to Sw_1 \to C_{max}$. At that, the electric circuit of the generator becomes like that shown in Fig. 2(a). One can see that capacitors C_1 and C_2 are connected in parallel to each other for the capacitor charging stage. Here, the variable capacitor C_{var} voltage has a minimal value of V_{min}. According to Fig. 2(a), minimal voltage V_{min} is given by

$$V_{min} = V_{1,char} + V_0 = V_{2,char} + V_0, \quad (1)$$

where $V_{1,char}$ and $V_{2,char}$ are capacitor C_1 and C_2 voltages at the stage of C_{var} charging.

At the stage of the capacitor C_{var} discharging, when its capacitance is C_{min}, switches Sw_1 and Sw_2 are turned off, whereas Sw_3 is turned on and C_{var} is discharged through $C_1 \to D_3 \to C_2 \to V_0 \to C_{min}$, the electric circuit of the generator at this operation stage is show in Fig. 2(b). For the capacitor C_{var} discharging stage, when $C_{var} = C_{min}$ capacitors C_1 and C_2 are connected in series and the variable capacitor C_{var} voltage reaches its maximal value V_{max}, and, according to Fig. 2(b), this value is given by

$$V_{max} = V_{1,disch} + V_{2,disch} + V_0, \quad (2)$$

where $V_{1,disch}$ and $V_{2,disch}$ are capacitor C_1 and C_2 voltages at the stage of C_{var} discharging.

Let us consider that, at the first moment, all capacitors are discharged. When $C_{var} = C_{max}$, power source V_0 is connected to the circuit and the variable capacitor gets the charge

$$q_0 = \frac{V_0}{C_{max}^{-1} + (C_1 + C_2)^{-1}}, \quad (3)$$

and capacitors C_1 and C_2 get the charges

$$q_{C_1} = \frac{-q_0}{1 + C_2/C_1}, \quad q_{C_2} = \frac{-q_0}{1 + C_1/C_2}. \quad (4)$$

The negative sign in Eq. (4) indicates that, at the beginning of the conversion process, the charge polarities on C_1 and C_2 electrodes are opposite to the polarities shown in Fig. 2(a). Further, for the nth