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3/2 Fractional Bennet's multiplier for capacitive energy harvesters based on Dickson charge-pump

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Abstract—This article presents the results of the theoretical and experimental study of the fractional Bennet's electricity doubler based on the Dickson charge-pump topology. This electrical network is used for the conditioning of capacitive transducers in kinetic energy harvesters. This study investigates the operation of the circuit in a purely electrical mode (no electromechanical coupling), addressing the transient processes and the influence of the parameters' values on the circuit behaviour. Several original results are obtained: (i) the existence of three different transient processes, (ii) a strong qualitative influence of the diode's threshold compared with the ideal behavior, and a stability criterion on one of the transient processes. These results provide useful insight into the operation of the circuit and are of practical interest for its application in electrostatic kinetic energy harvesters. The analysis is validated by Spice simulations and by measurements performed on a silicon MEMS (MicroElectroMechanical Systems) device.

Index Terms—Bennet's doubler, Dickson charge-pump, kinetic energy harvesting, capacitive transducers, MEMS, Spice simulation

I. INTRODUCTION

Electrostatic kinetic energy harvesters use electromechanical transducers, in the which mechanical motion results in a variation of the transducer's electric capacitance. In order to generate electricity out of capacitance variation, electrostatic transducers need a special dynamic biasing achieved by conditioning circuits. In the majority of cases, such circuits are inspired by capacitive charge-pumps used in conventional DC-DC or AC-DC converters. Yet, their operation is very different when the energy comes from the mechanical domain (the capacitance variation) instead of from a DC or AC voltage source. A conditioning circuit based on a charge-pump can be seen as a two-port network whose input is connected to the variable capacitor, and whose output is connected to a large fixed reservoir capacitance accumulating the converted energy.

One can subdivide charge-pump based conditioning circuits into two categories: stable and unstable circuits [1]. While in stable circuits, all of the circuit's voltages saturate (equivalently, the energy stored in the circuit saturates), unstable charge-pumps show unlimited exponential increase of some

voltages (equivalently, of the circuit's total energy). The use of unstable charge-pumps for conditioning of capacitive transducers was investigated by de Queiroz [2], who proposed to use the Bennet's electricity doubler. This is one of the oldest invented circuits dated by 1787 [3]). It is composed of three capacitors and three diodes (Fig. 1a). It operates as a series-parallel charge-pump, whose reconfiguration is ordered by the sign of the transducer's capacitance variation, see Fig. 1c. The Bennet's electricity doubler has been extensively studied in several works covering the analysis of the influence of the parameters, and its practical implementation. This circuit has two main properties useful for capacitive energy harvesters:

- It yields a rectangular charge-voltage energy conversion cycle on the capacitive transducer, with the max-to-min voltage ratio close to 2,
- The voltages of the charge-voltage cycle increase exponentially with time.

The first property applies a strict requirement on the transducer's capacitance variation, whose max-to-min ratio must be greater than 2 [4]. The second property is very interesting since the circuit allows one to generate a high bias voltage out of an initially low-voltage, provided by, e.g., a battery, or even by the ambient noise.

One can notice that the Bennet's doubler uses a sub-network which has the topology of a one-stage modified Dickson charge-pump (Fig. 1b). Modified Dickson charge-pump are typically used for voltage multiplication in RF energy harvesters [5]. Wei *et al.* have proposed to increase the number of stages of the Dickson charge-pump in the Bennet's doubler and have obtained a class of circuit represented in Fig. 2 [6]. This circuit has the same properties as the Bennet's doubler, except that the ratio between the charge-voltage cycle extreme voltages is $(n + 1)/n$, where n is the number of stages of the Dickson charge-pump. As a consequence, this circuit relaxes the constraints on the max-to-min ratio of the transducers's capacitance variation, reducing it to $(n + 1)/n$ — which is very favorable for MEMS transducers whose typical

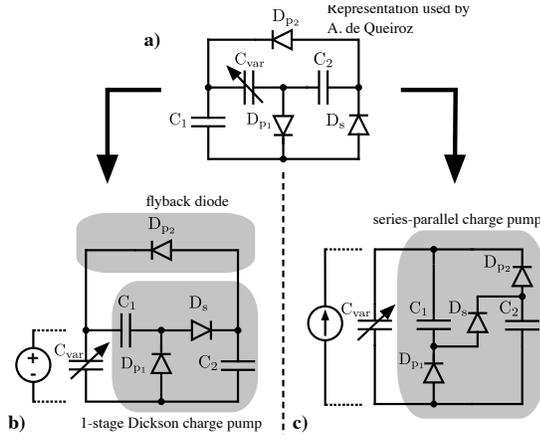


Fig. 1. Bennet's doubler as proposed by de Queiroz for the conditioning of capacitive transducers in kinetic energy harvesters [2].

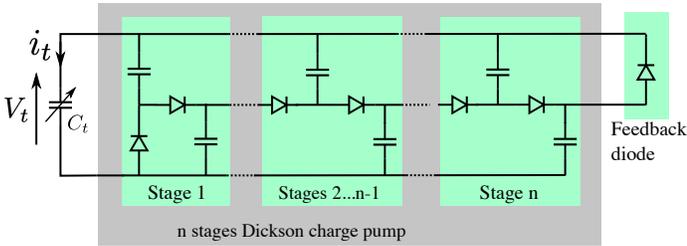


Fig. 2. Generic schematic of the fractional Bennet's multiplier

max-to-min ratio of capacitance variation is rather low. We call this circuit the " $(n+1)/n$ fractional Bennet's multiplier".

Practical aspects related to the use of this topology in capacitive kinetic energy harvesters have been investigated in [7], [8], addressing the interaction between the mechanical device and the Bennet's multiplier. However, to the best of our knowledge, there are no reported in-depth analysis of the circuit's operation in the electrical mode (without electromechanical interaction). Such analysis should include the study of the transient processes, of the influence of the diode thresholds, and of the circuit's parameters. It should result in particular in a formal derivation of the condition for exponential (or unstable) operation. This paper presents a summary of such an analysis, performed for the circuit with $n = 2$, i.e., for a $3/2$ fractional Bennet's multiplier. Two original properties of the circuit were discovered that have never been mentioned in previous works: (i) there exists a transient process prior to the steady-state behavior, and this transient process may be exponential or saturating depending on the circuit parameters, (ii) there is a significant influence of the diode thresholds on the circuit behavior in the transient phase, even when the operation voltages are much higher than the diode thresholds.

The experimental validation of the analysis was achieved using a MEMS transducer implemented in Silicon-On-Glass technology [9], whose picture is presented in Fig. 3. This device is reported in the PhD dissertation of B. Vysotskyi [10] and it is similar to a device used in the study [8].

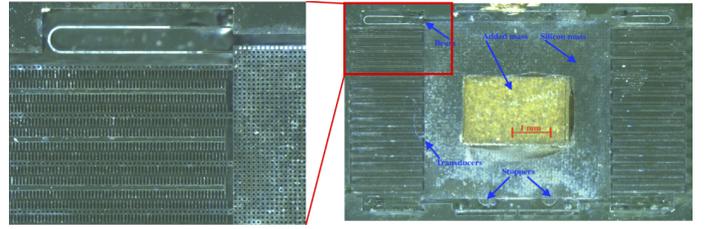


Fig. 3. Photo of the MEMS device used for the experiments.

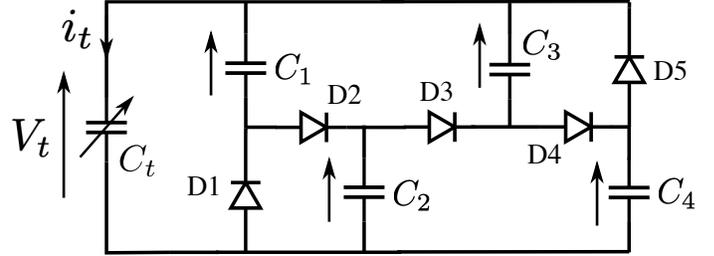


Fig. 4. Schematic of the studied $3/2$ Bennet's multiplier.

II. IDEAL OPERATION OF THE CIRCUIT

The schematic of the studied $3/2$ fractional Bennet's multiplier is presented in Fig. 4. This schematic defines the conventional positive directions of the transducer's current i_t and of the fixed capacitor voltages V_i , $i = 1 \dots 4$. One of the fixed capacitors must be selected to be the reservoir capacitance, and needs to be much greater than the others. This is because, as the energy is converted from the mechanical domain, the voltages of all capacitors increase. If all capacitors are of close values, the converted energy is distributed over all capacitors, and it is difficult to use it, since each capacitor then needs to be separately discharged. When one of the capacitors is much greater than the others, it accumulates a substantial share of the converted energy, which then can easily be extracted from it with standard DC-DC interfaces. In this circuit, the capacitor C_2 is used as the reservoir. All other fixed capacitors are chosen equal and much greater than the transducer's maximum capacitance C_{max} :

$$C_2 \gg C_1 = C_3 = C_4 = C \gg C_{max} \quad (1)$$

At $t = 0$, the capacitor C_2 is pre-charged to a voltage V_0 . One can see that the capacitors C_4 and C_t are pre-charged with the same voltage through the diodes, up to the diode thresholds.

A Spice simulation helps one to get an insight into the circuit operation. The circuit has been simulated with the following parameters: $C_2 = 30$ nF, $C = 1$ nF, diodes are ideal with zero threshold. The simulation results are shown in Fig. 5.

It appears that two exponential processes take place. The first one, that we call "the main transient", corresponds to a pre-charge of the fixed capacitors: it lasts until

$$V_1 < V_4, \quad V_3 < V_2. \quad (2)$$

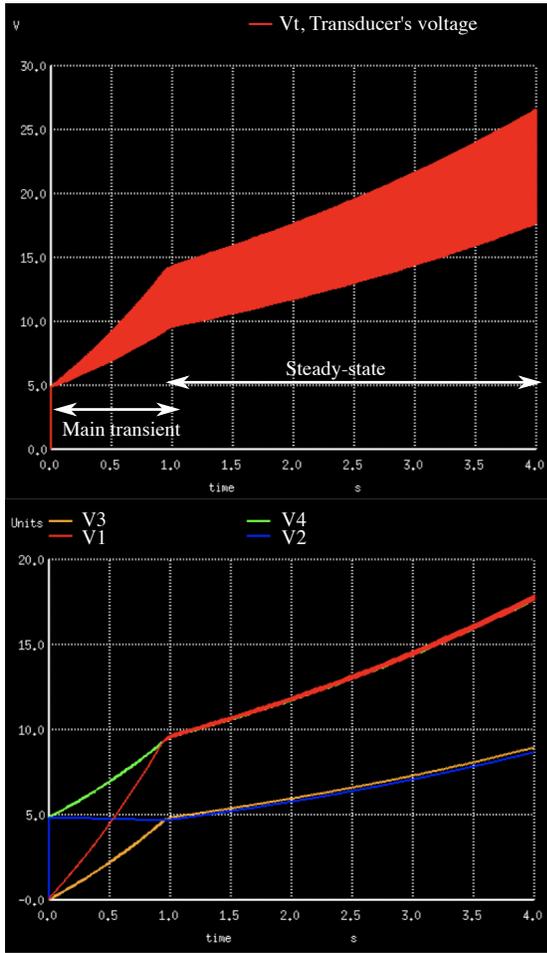


Fig. 5. Spice simulation of the $3/2$ fractional Bennet multiplier with ideal zero threshold diodes.

Immediately after that main transient phase, the process that we call "steady-state" starts. In this mode, all voltages evolve exponentially with the same base, and one can notice that $V_1 \approx V_4 \approx 2V_2 \approx 2V_3$, so that the transducer voltage varies between two extremes: $2V_2$ and $3V_2$, yielding a ratio of $3/2$.

The operation of the circuit can be understood if one considers the variable capacitor as a current source, whose direction depends on the sign of the capacitance variation: when the capacitance increases, the transducer "appeals" charges and its current is (conventionally) positive, otherwise the transducer "pushes away" charges and its current is negative. This operation yields a dynamic reconfiguration of the capacitive network, by activating different diodes according to the current direction. Fig. 6 presents the current paths for the positive and negative phases of the transducer's current. This figure highlights the difference between the main transient mode operation and the steady-state operation: in the main transient mode, the path $D1C_1$ for the positive current phase is not activated.

A quantitative analysis of the circuit can be done by writing down the network equations in each modes and expressing the voltages at the beginning of each cycle through the voltages at

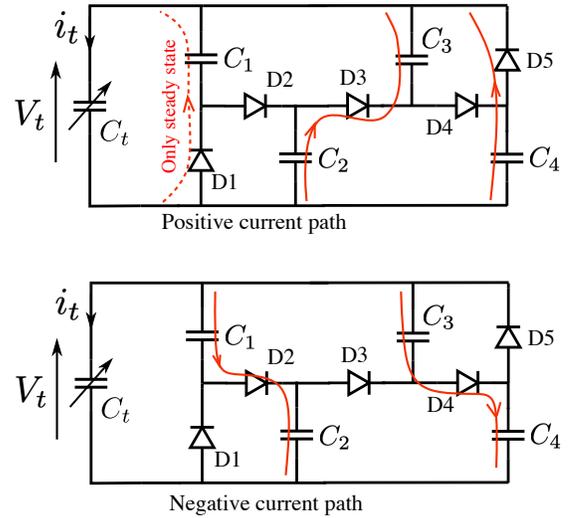


Fig. 6. Positive and negative current paths during transient (solid line) and steady-state (solid + dashed lines) modes.

the beginning of the previous cycle (not detailed in this paper). This yields a recurrence equation given by:

$$\vec{V}_{i+1} = A\vec{V}_i \quad (3)$$

where \vec{V} is the vector of all network voltages and A is the transition matrix. The properties of the circuit are exhaustively described by the eigenvalues of the matrix A , which provide information about the stability and the existence of exponential modes. Use of symbolic algebra software like Mathematica or Maxima is recommended for this analysis.

The most interesting question is the condition of the exponential (unstable) behaviour of the circuit. Our analytical study (not detailed here) allowed us to make the following practical conclusions:

- For the main transient process to switch to the steady state (so to satisfy the condition (2), it is necessary and sufficient to have $2C_{max} > 3C_{min}$.
- For the main transient process to be exponential with a base superior to 1, it is necessary and sufficient to have $C_{max} > 2C_{min}$. The fact that the main transient process may or may not be unstable is one of the original conclusions of this study.
- For the steady-state process to be exponential, it is necessary and sufficient to have $2C_{max} > 3C_{min}$, which is the same condition than the necessary condition for the main transient process to end. This condition has already been found in previous works [6]; our work provides its formal analytical demonstration. The same study [6] mentions that the energy converted per cycle in the unstable steady-state mode is

$$\Delta W = V_2^2(2C_{max} - 3C_{min}). \quad (4)$$

This formula is fully consistent with the condition required for the circuit to reach this steady-state unstable mode.

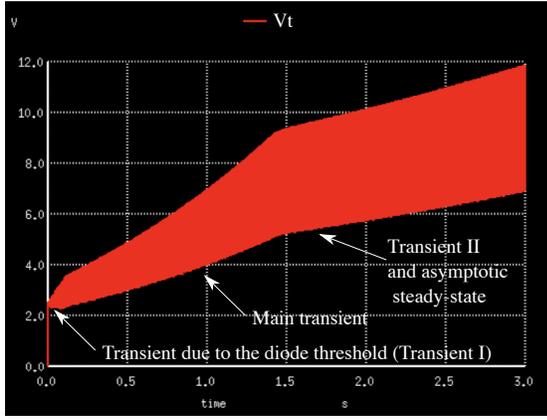


Fig. 7. Transducer's voltage in presence of non-ideal diodes ($V_d = 0.6$ V threshold).

III. OPERATION OF THE CIRCUIT WITH NON-ZERO DIODE THRESHOLD

Non-zero diode thresholds have two qualitative impacts on the circuit behaviour.

The first impact is a non-equality of the voltages V_2 , V_t and V_4 during the initial pre-charge of C_2 . Indeed, as C_2 is pre-charged (for instance, with a fixed voltage source connected to this capacitor for a short time), we have $V_4 = V_2 - 2V_d$ and $V_t = V_4$. This provokes a (short) transient process prior to the main transient process presented above. We call it the "transient process I". This transient process I is indeed observed in the experiments, as it will be presented below in sec. IV. Fig. 7 presents the voltage across the transducer, obtained by simulation with *ideal* diodes complemented with a fixed threshold voltage (an ideal diode in series with a V_d DC voltage source).

The second impact is the existence of *one more* transient process after the end of the main transient, that we call "Transient process II". One can notice on Fig. 7 that after the main transient process, the ratio between the maximum and minimum voltage across the transducer is not equal to 3/2: for instance at $t = 3$ s, $V_{t \max}/V_{t \min} = 11.9/6.9 = 1.7$, which is much greater than 1.5. This discrepancy cannot be explained by a sole superposition of the diode threshold to the voltages; moreover, one can see that this ratio evolves with time: in reality, this is another transient process, which consists in an asymptotic evolution of the ratio $V_{t \max}/V_{t \min}$ to the value 3/2. Fig. 8 plots the quantity $V_{t \max}/V_{t \min}$ as a function of time for the same circuit with and without diode threshold.

The analysis provides a formal explanation of this behaviour: the presence of diodes is equivalent to the presence of independent voltage sources, and the recurrence equation (3) becomes non-homogeneous:

$$\vec{V}_{i+1} = A\vec{V}_i + \vec{B} \quad (5)$$

where \vec{B} is a constant vector whose components have the physical dimension of a voltage. As a consequence, the system

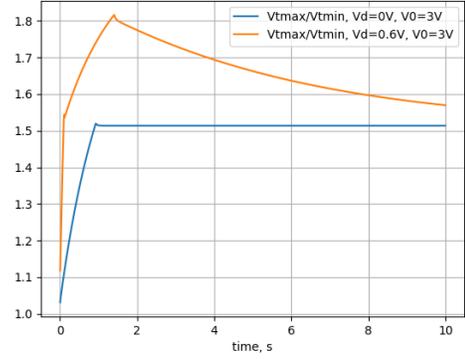


Fig. 8. $V_{t \max}/V_{t \min}$ ratio versus time for the cases of zero and 0.6 diode thresholds.

needs some time before entering into a pure exponential mode, i.e., $\vec{V}_{i+1} \approx A\vec{V}_i$), so that the contribution of \vec{B} is negligible.

IV. EXPERIMENTAL RESULTS

The experiment was carried out with the MEMS device presented in the introduction. The Fig. 9 highlights its measured capacitance-displacement characteristics. Given that the maximum mobile mass displacement is $\pm 85 \mu\text{m}$, the maximum max-to-min ratio of the transducer capacitance C_t is $37 \text{ pF}/8.8 \text{ pF} = 4.2$.

One of the difficulties associated with MEMS devices for the experimental characterisation of Bennet's multipliers is due to the electromechanical coupling. Indeed, as the network's voltages increase, the mechanical force generated by the transducer becomes significant and modifies the frequency-response of the MEMS mechanical resonator, so that the vibration amplitude may change with time. This results in a time-varying C_{\max}/C_{\min} ratio. However, the electrical study of the circuit is based on the hypothesis that C_{\max}/C_{\min} is fixed – otherwise the behaviour becomes too complex and not suitable for a fundamental study of the network properties.

In order to circumvent this difficulty, we submitted the device to a high-amplitude input vibration: this guarantees that the displacement of the resonator remains constant, equal to the maximum allowed by the stoppers position. We have submitted the device to an input vibration of frequency $f_{ext} = 86.15 \text{ Hz}$ using a controlled shaker.

In Fig.10, we present the resulting time-evolution of the voltage across the transducer, and the displacement of the mobile mass. The latter was measured in real-time using a laser interferometer. One can see that until $t = 8$ s the amplitude is constant. Then, a bifurcation similar to what is observed in nonlinear Duffing oscillators occurs [11]: because of the increasing biasing, the frequency-amplitude characteristic of the MEMS resonator shifts towards lower frequencies. Thus, at some level of the transducer voltage, the external vibration frequency is out of the resonator band and the vibration amplitude drops abruptly. However, until $t = 8$ s, the vibration

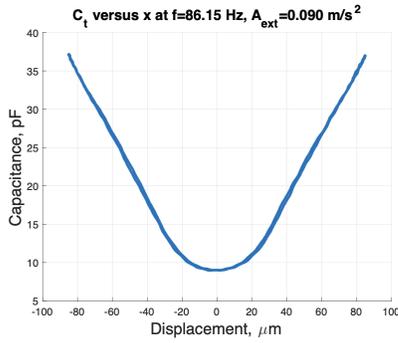


Fig. 9. Measured transducer's capacitance versus mobile mass displacement in the used MEMS device.

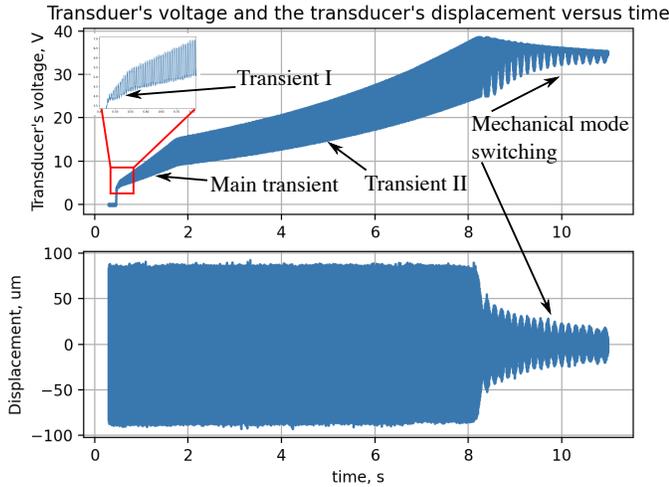


Fig. 10. Experimental results: voltage on the transducer and the mobile mass displacement versus time

amplitude and hence C_{max}/C_{min} are constant and the circuit operates as presented in the above model.

On Fig. 10, one can observe the transient process I (see the zoom in the insert) and the main transient. In order to make obvious the presence of the transient process II, we plot the max-to-min ratio of the transducer voltage across each mechanical period (Fig. 11). The observed behaviour is exactly the same as shown in Fig. 8. The max-to-min ratio of the transducer voltage does not reach 1.5, since the MEMS device mechanics does not allow the voltage to go above 40 V, and the run time is not enough for the transient II to end. However, one can see that the steady-state is approached, as the max-to-min ratio of the voltage across the transducer asymptotically approaches 1.5.

V. CONCLUSION

This paper presented a qualitative analysis of a new family of unstable charge-pumps inspired by the Bennet's electricity doubler and by the Dickson charge-pump: $(n+1)/n$ fractional Bennet's multipliers. This circuit is of great interest for the energy harvesting community, since it relaxes the requirement of the max-to-min transducer capacitance variation ratio.

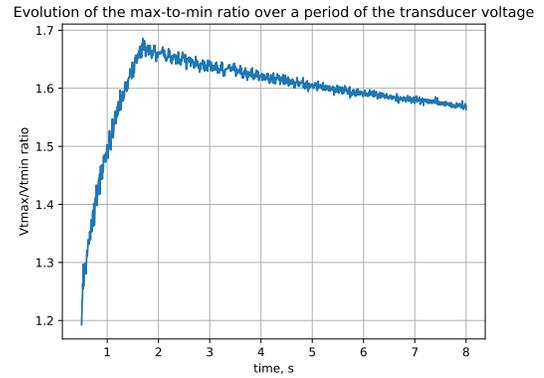


Fig. 11. Max-to-min ratio over a period of the voltage on the transducer obtained by the experiment.

This paper summarizes results of a first in-depth study of the $3/2$ fractional Bennet's multiplier, whose goal is to rigorously analyse the operation of the network by describing and quantifying all existent transient modes, as well as the influence of the parameters. Some original properties of the circuits were discovered, namely, the possibly exponential character of the main transient mode, and the strong influence of the diode thresholds on the transient modes of the circuit. The simulation model is in very good agreement with the experiment performed with a MEMS device. The format of a conference paper does not allow to go into the details of the performed analysis, for this reason only essential qualitative results were presented.

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