Batteryless Electrostatic Energy Harvester and Control System

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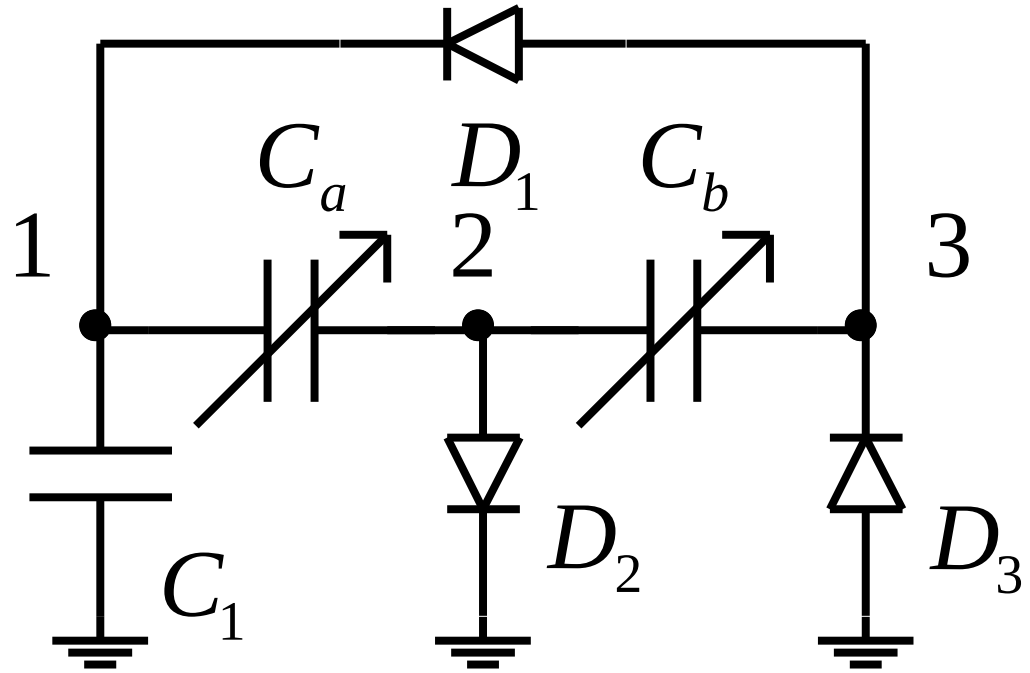
This work shows how an electrostatic energy harvester based on a "doubler of electricity" can be used as energy source for low-power applications, without the need of a battery, and describes a suitable control system for it. The fact that the generator can be made to start from very small initial charge, which can be provided by electrical noise or external interference, is used to eliminate the need of a battery.

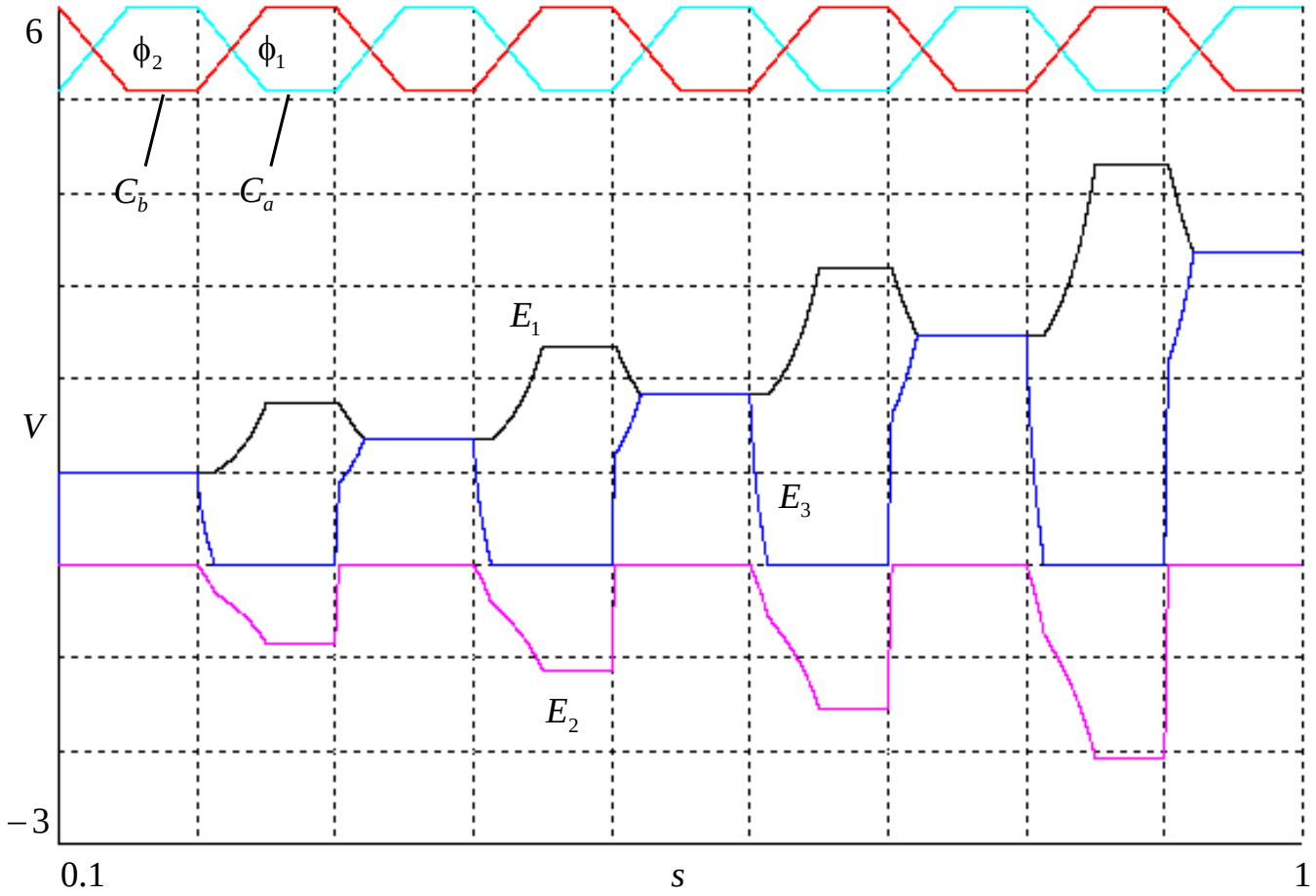
Doubler of Electricity

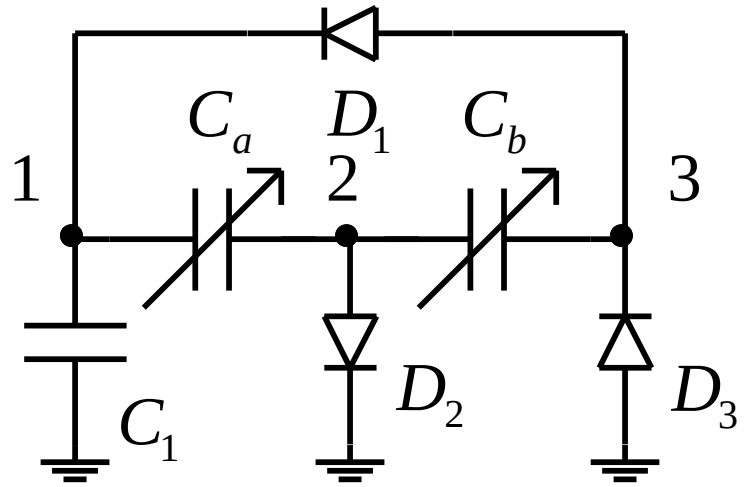
- Simple variable-capacitor electrostatic generator derived from the classical Bennet's doubler (1787).



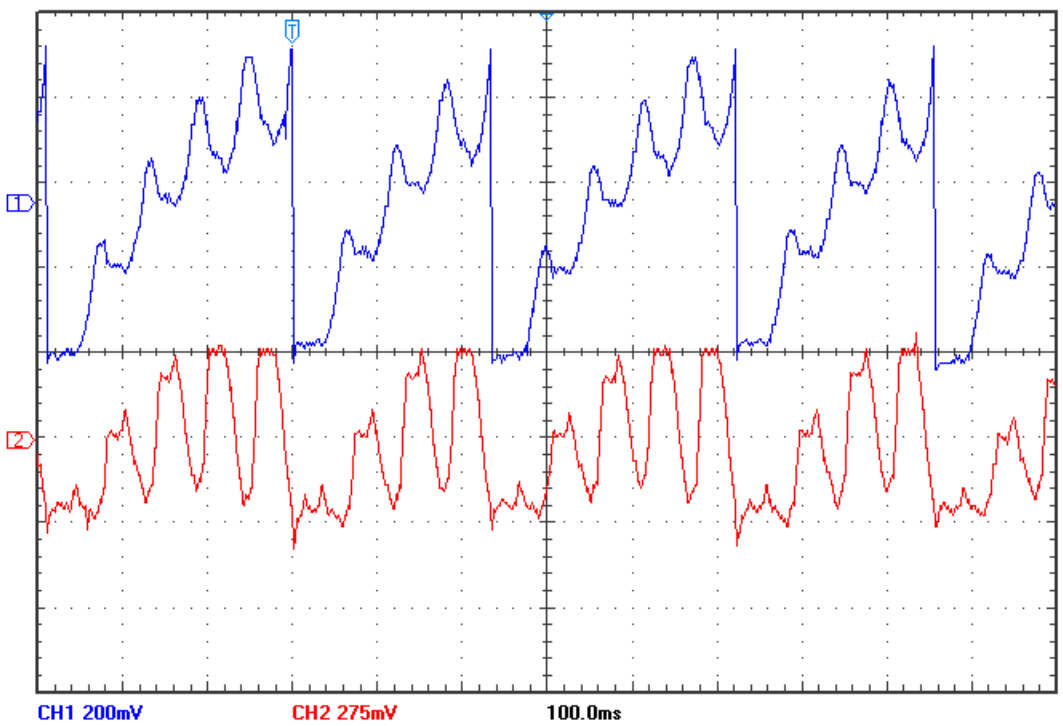
- The voltage at node 1 increases (~2x) at each cycle of complementary capacitance variation.
- No explicit initial charge is required. Starts from "noise" easily.

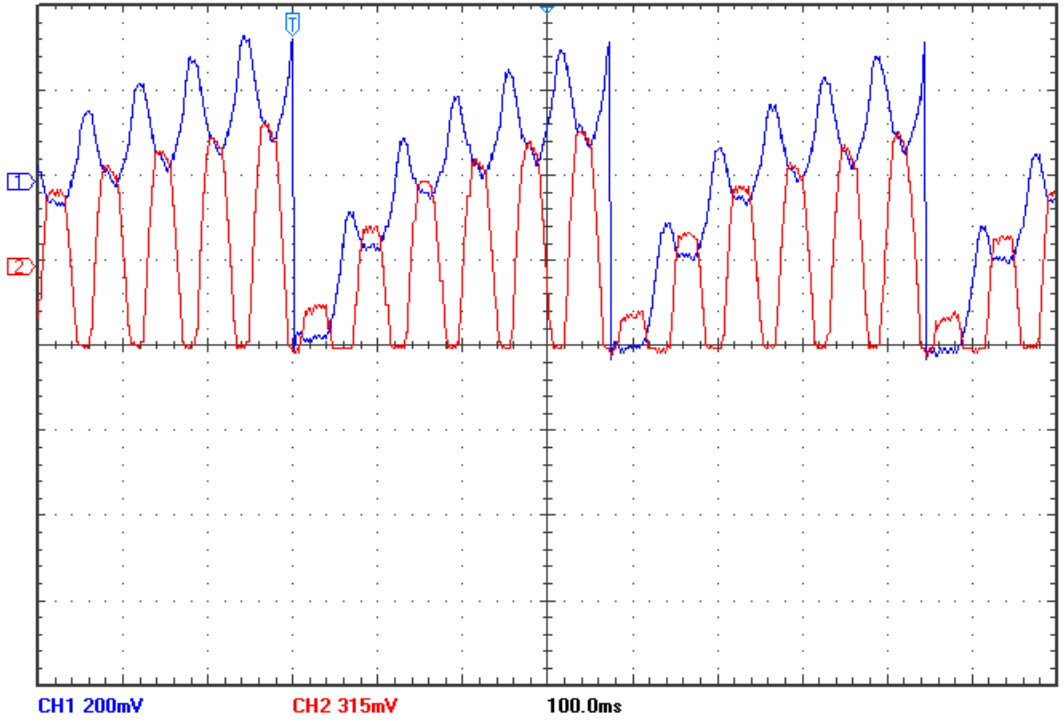
Doubler waveforms





Experimental waveforms

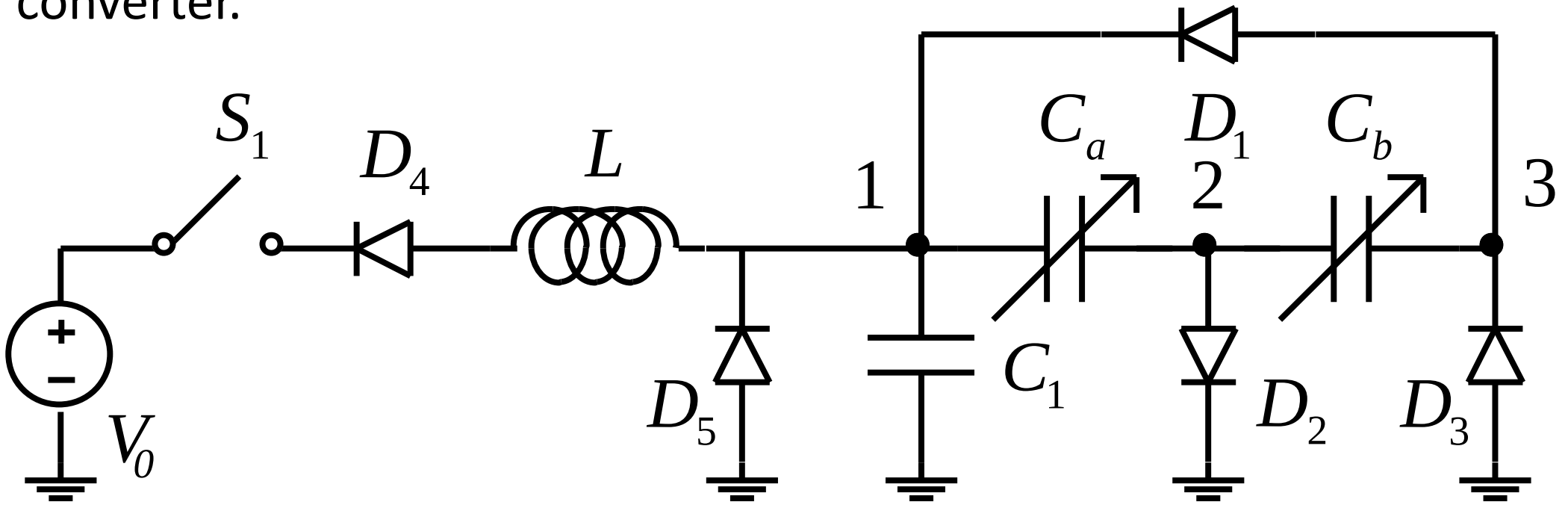




Waveforms at high voltage, seen through capacitive dividers. Left: nodes 1 and 2. Right: nodes 1 and 3.

Doubler and DC/DC converter

- The doubler is allowed to operate until a certain voltage is reached and then is discharged to the battery through a buck DC/DC converter.



Charge transferred per cycle

- Charge delivered to the battery by the DC/DC converter:

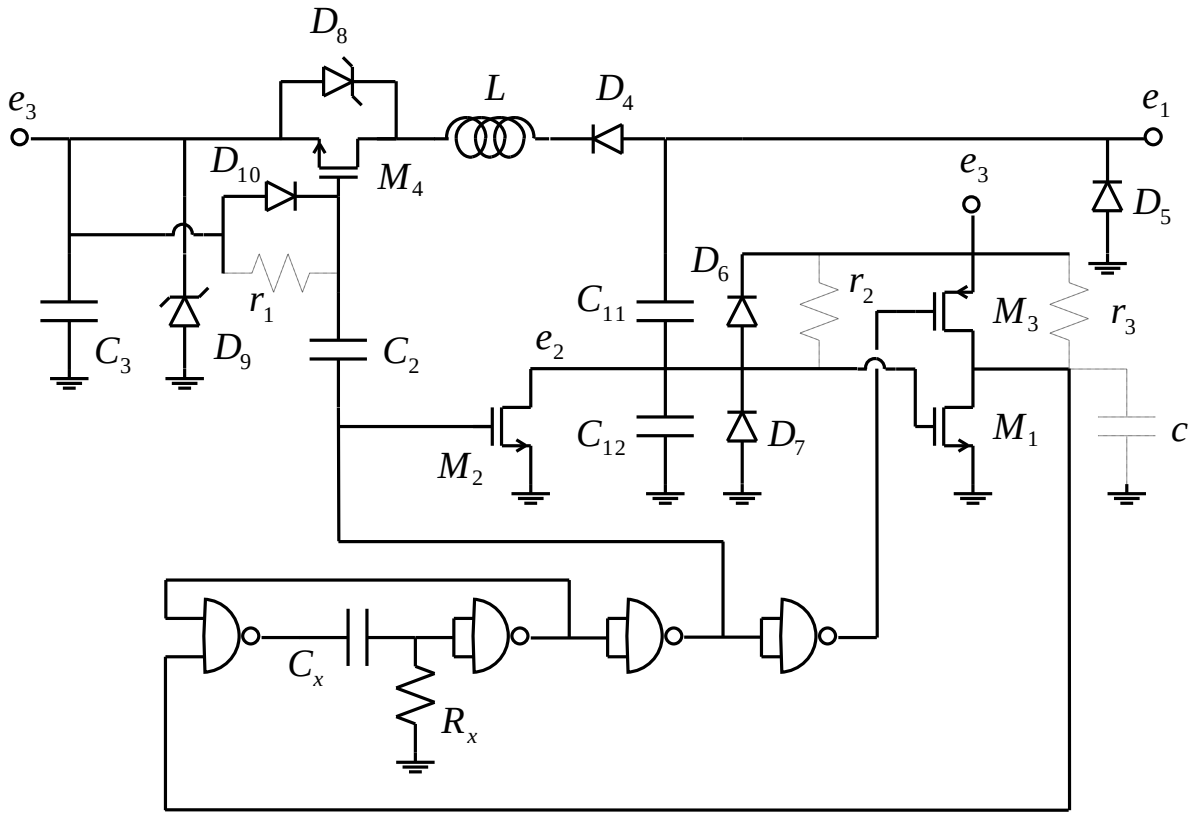
$$Q = \frac{(C_1 + C_{ab})(V_{C1} + V_{D5})^2}{2(V_0 + V_{D4} + V_{D5})} \approx \frac{(C_1 + C_{ab})V_{C1}^{\ 2}}{2V_0}$$

- Charge delivered to a constant voltage source V_{break} in place of C_1:

$$Q = V_{break} \frac{\frac{C_{a2}}{C_{a1}} - \frac{C_{b2}}{C_{b1}} - 1}{\frac{1}{C_{a1}} + \frac{1}{C_{b1}}}$$

Control system

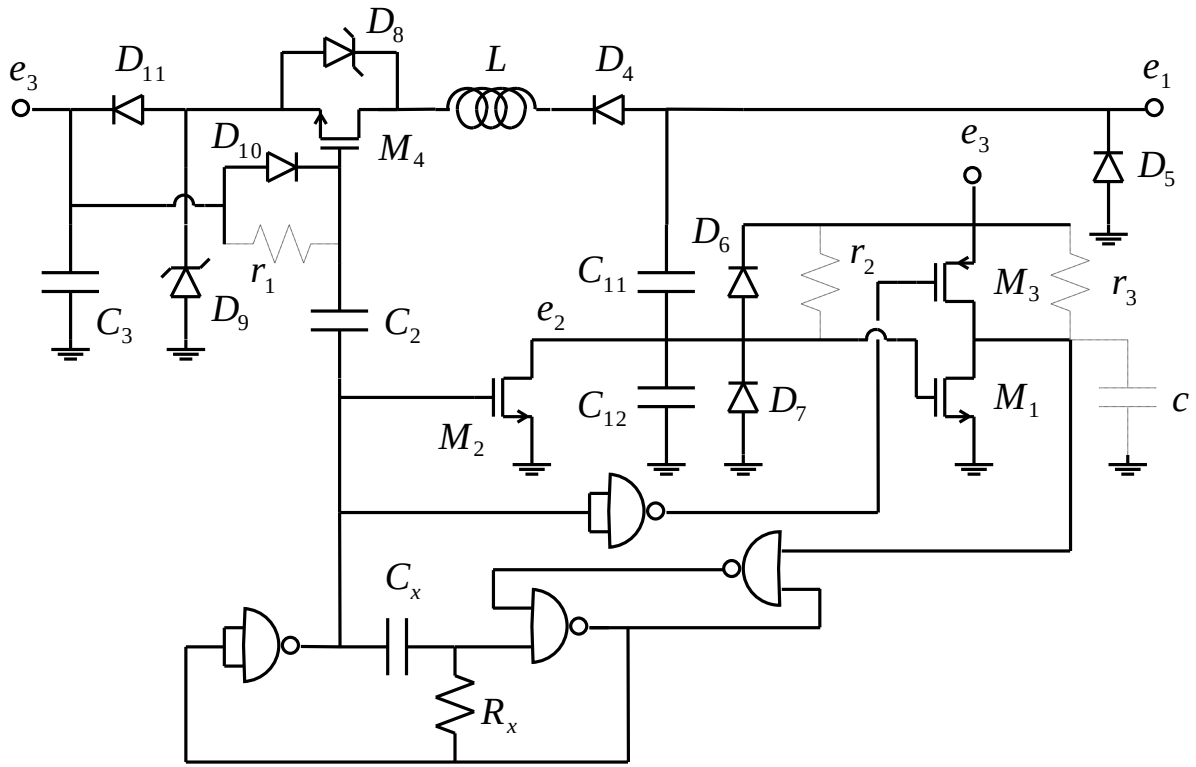
- Previously used control system for the DC/DC converter.



- Doubler output e_1 sensed by a capacitive divider.
- The divider is reset at each operation of the converter.
- When the converter is not operating, the output voltage of the doubler rises to the breakdown voltage of D_8, and the load e_3 can be directly powered (inefficiently).

Improved control system

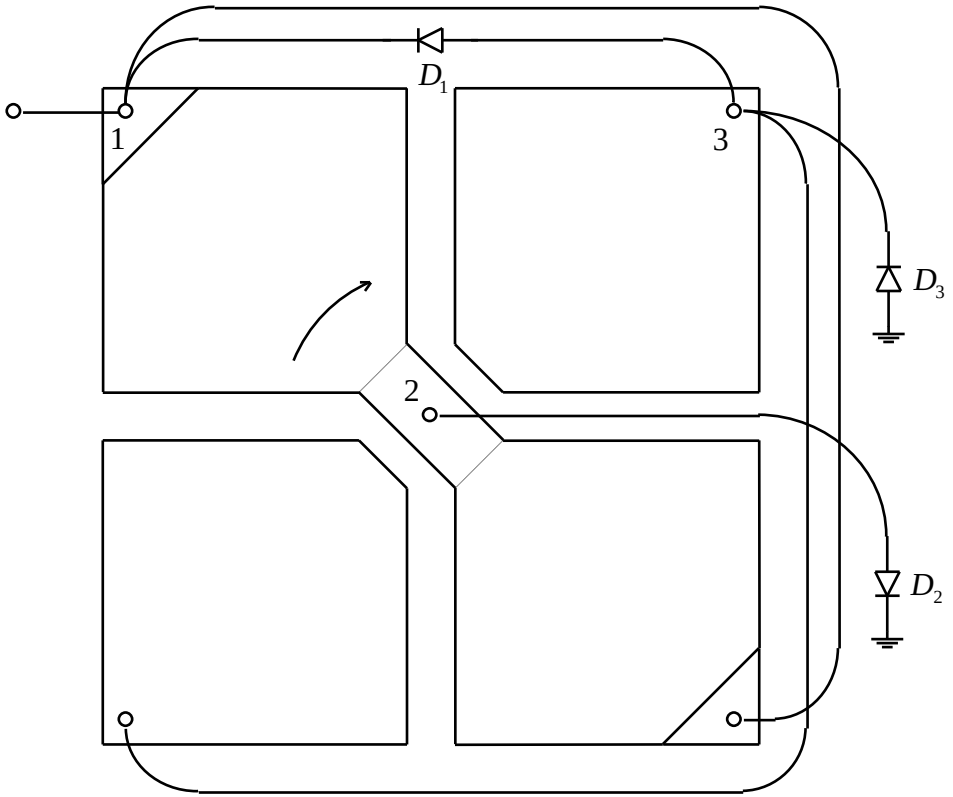
- Modified driver that operates safely powering itself.



- Better regulation with added D_{11}.
- Reliable operation with an astable oscillator stopping itself instead of a monostable circuit.
- Starting resistor r_2 still a problem.

Experimental doubler structure

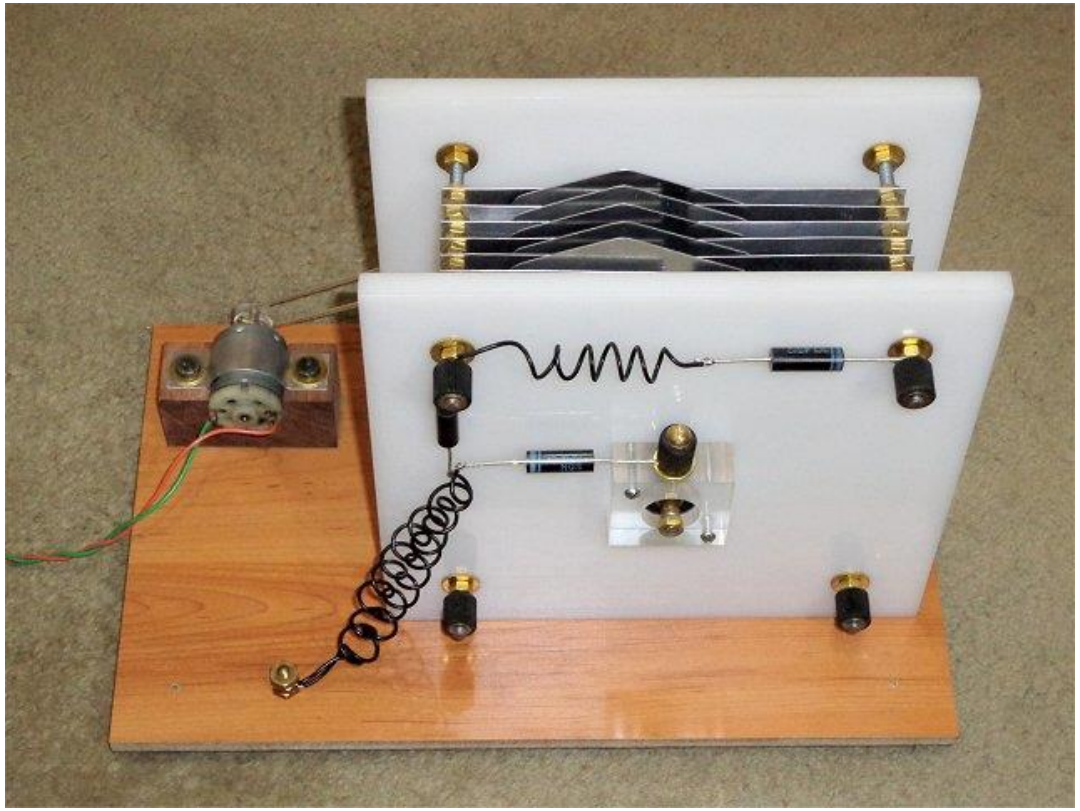
- Rotating doubler with two capacitor variation cycles per turn.



- Double “butterfly” capacitor with several plates.
- Parameters emulating a vibrating MEMS device.
- Operation at high voltage (~4 kV) possible.

Experimental doubler

- "Macroscopic" rotating doubler used in the experiments.



- Six groups of four fixed plates (~7x7 cm).
- Five rotor plates.
- Capacitance variation: 30 to 330 pF.
- Rotation speed: 12.5 turns/second, 25 cycles of capacitance variation per second.
- High-voltage diodes for low leakage, low capacitance, and robust operation up to the maximum voltage (~4 kV).

Controller with external power

- The controller was first tested with a RC load, R=5 MΩ, C=100 nF.
- Expected output voltage: 12.6 V.

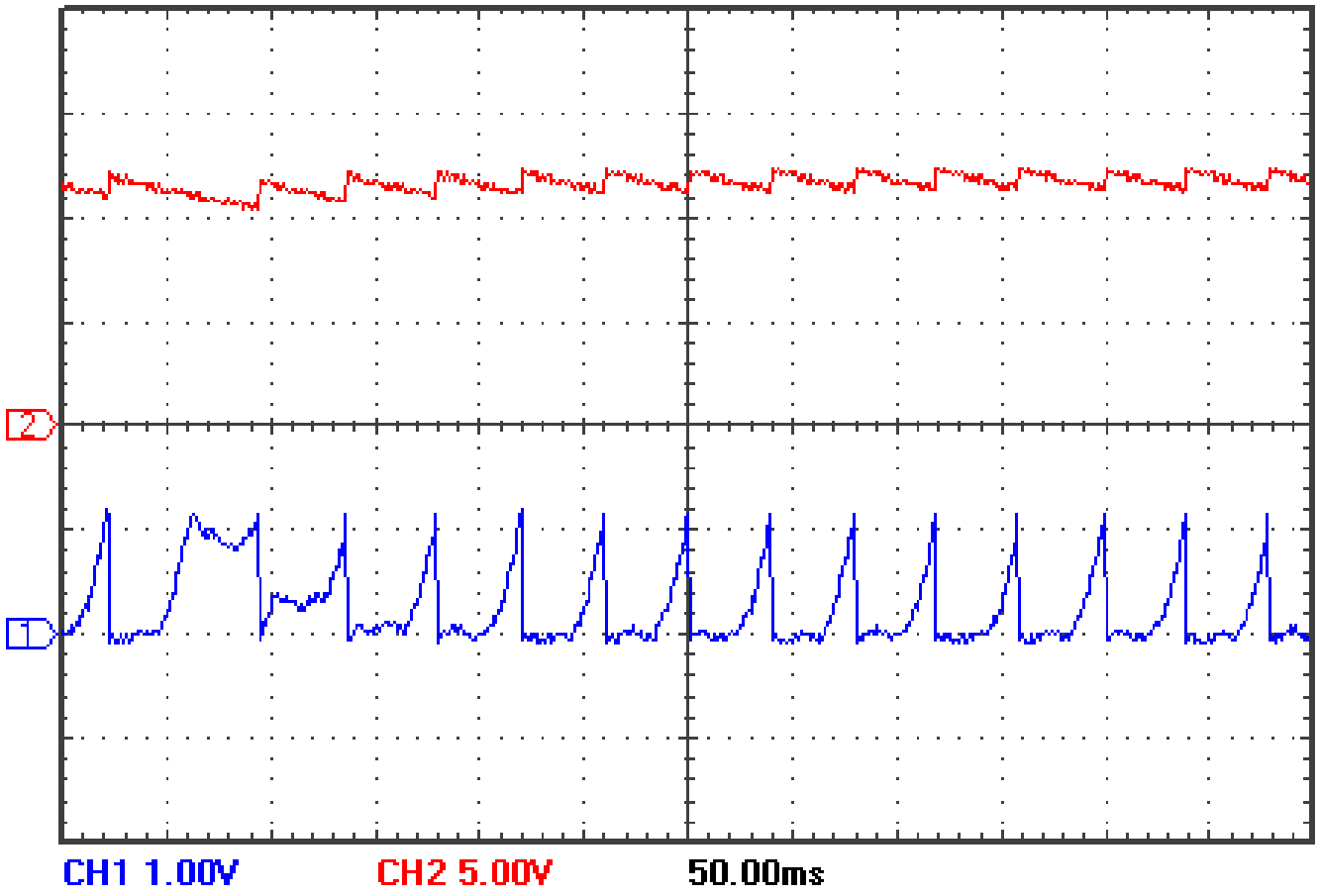
$$V_0 = \frac{\sqrt{2(V_{C1}+V_{D5})^2(C_1+C_{ab})Rf+(V_{D4}+V_{D5})^2}-V_{D4}-V_{D5}}{2}$$

- Equivalent load resistance and output current with Zener regulator:
- R=1.14 MΩ, I_0=5 μA.

$$R = \frac{2V_0(V_0+V_{D4}+V_{D5})}{(V_1+V_{D4})^2(C_1+C_{ab})f}$$

$$I_0 = \frac{V_0}{R} = \frac{(V_{C1}+V_{D5})^2(C_1+C_{ab})f}{2(V_0+V_{D4}+V_{D5})}$$

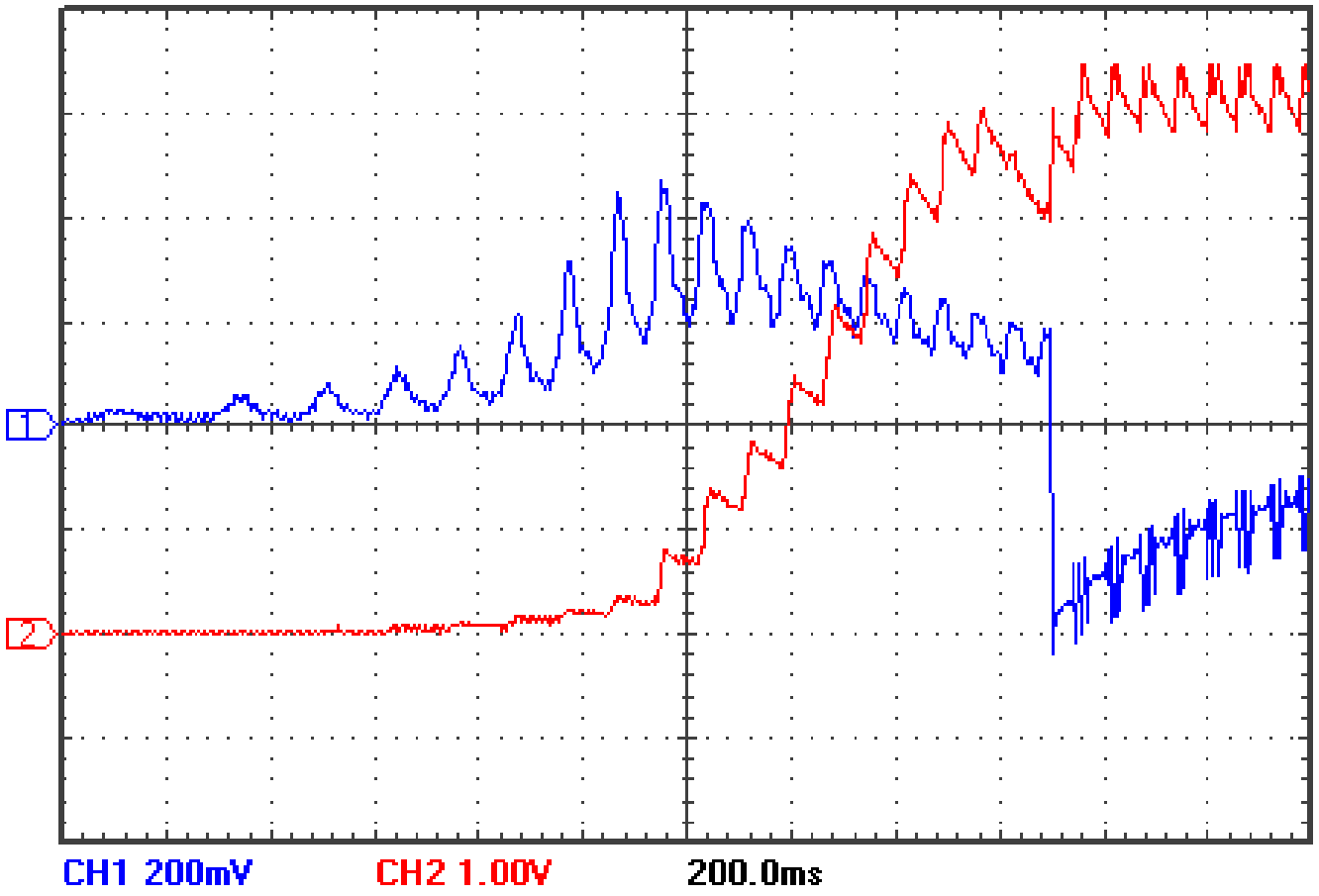
Operation with RC load, external power



Red: Output voltage of the DC/DC converter, ~12.6 V
Blue: Capacitive divider.

- The doubler recovers in one or two cycles.
- Peak output voltage of the doubler: 140 V
- The driver consumes 0.9 µA from 5 V.

Operation with the controller powering itself



Blue: Doubler output seen through a capacitive divider (high-pass filtering observable).
Red: Output of the DC/DC converter.

- 0-1.2s: Doubler multiplication to 600 V.
- 1.2s-1.9s: Output charging to 5V through D_8.
- 1.9s-2.4s: Normal operation, with increased output due to the remaining 600 V bias.

Conclusions

- It was experimentally demonstrated that it is possible to use an electrostatic energy harvester that powers its own control system and an additional load without the need of a battery for startup.
- The experimental device used too high voltage for a MEMS device (600 V for startup, with operation at 400 V also verified to be possible), but the idea can be scaled down to lower voltages by the use of larger variable capacitances or a controller with smaller power consumption. The technique may then be made to work with a MEMS doubler.

References

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