

Technical Publications

Capacitive Energy Conversion Validation

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Table of Contents

ISSUE RECORD.....	2
SUMMARY.....	3
EXPERIMENTAL VALIDATION.....	3
A second experiment.....	4
ENERGY RECOVERY.....	5

ISSUE RECORD

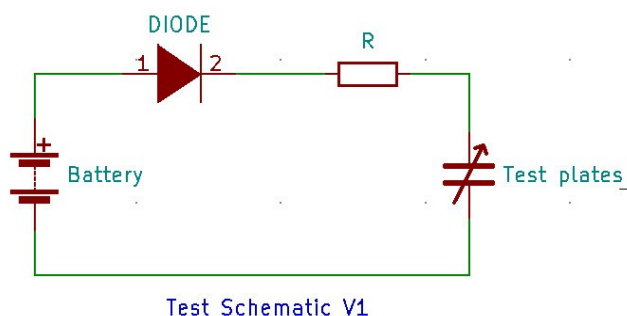
- 4/10/23 Removal of section “reality Check”
- 21/4/22 Clarifications without major changes
- 15/4/22 Initial issue taken from the report dated 15/05/2021

SUMMARY

This report considers the theory explored in the Energy Theory report in this series. It reports on experiments intended to validate the theory and presents a means of harvesting the electrostatic energy efficiently for practical use.

EXPERIMENTAL VALIDATION

To provide a simple experimental validation of the earlier theory, a simple rig was constructed using two small aluminium plates, one of which was protected by a thin film which acted as an insulator. A 5V battery pack provided the initial charge, and was connected via a small-signal diode and a large resistor to minimise back-leakage into the battery. The performance was measured using a digital oscilloscope connected to a laptop computer. The plates were separated manually, and several different techniques were tried to do this.



The figure shows the test schematic diagram.

The component details are:

- The plates comprised 4mm flat aluminium sheet of dimensions 100mm*30mm. These were offcuts from earlier projects, and one of them retained the supplier's protective film on one surface.
- The measured capacitance without pressure was nominally 200pf. This was measured using a 2V 1kHz square-wave generator and a 100kΩ series resistor, and measuring the charge/discharge profile. The 74% (charge) and 37% (discharge) times were 20us, to an accuracy of about 10%. The measured capacitance is a lot lower than theory predicts (see equation 1.2), but it increased strongly with finger pressure, suggesting that the surfaces were not perfectly flat.
- The battery pack comprised four AA rechargeable cells, producing 5.3V at the terminals under no load.
- The diode was a 1N4148 type. This is rated to leak no more than 5nA when reverse biased to 20V, with a reverse breakdown voltage of nominally 75V.
- The series resistor was 1MΩ, giving a charging time constant of nominally 200us.
- The oscilloscope was a Picoscope 3206DMSO with a 200MHz bandwidth used in analogue mode only.

There were two particular problems with this simple rig, the most serious of which was leakage through the oscilloscope probe. The other arose from the difficulty in getting a sufficiently rapid, clean, square lift of the upper plate.

The oscilloscope trace showed a rising voltage when the upper plate was separated, followed by an exponential decay as the charge leaked away. The overall shape was of a mountain in profile, with both sides curving up slowly to begin with but increasing to make a sharp apex.

The charge profile would broadly be expected to conform to equation 2.4 (disregarding leakage effects initially) which, when differentiated, suggests an exponential increase of voltage as the capacitance is reduced. This would be qualified by the upper plate not ascending necessarily at a constant rate, as well as the increasing leakage.

The decay profile is typical of an R-C circuit, showing an exponential profile. This would be qualified by the continuing effect of the reducing capacitance (albeit very small by the time of the peak) followed by the increasing capacitance as the upper plate starts its descent (although this may take place after the charge is nearly all depleted). It was not possible to measure the plate movement, so these factors could not be quantified. The decay time constant was measured at about 3ms, which suggests a leakage resistance of about 15MΩ overall. This is not unexpected within the accuracy of measurement.

From the foregoing theory both sides of the signal profile can be expected to be of an exponential nature, and this is supported by the apparent symmetry of the signal trace, even though their time constants differed.

The problem with this leakage is that it is constantly depleting the charge on the capacitor, even before it has become fully separated. For example, at 15V this resistance would sink 1uA, which is 1nC per ms. This, taken from an initial charge of

only 1nC (nominally 5V into 200pF) seriously impacts on the available charge from which the voltage is constructed, and would necessarily result in a very much reduced peak voltage than might otherwise be achieved.

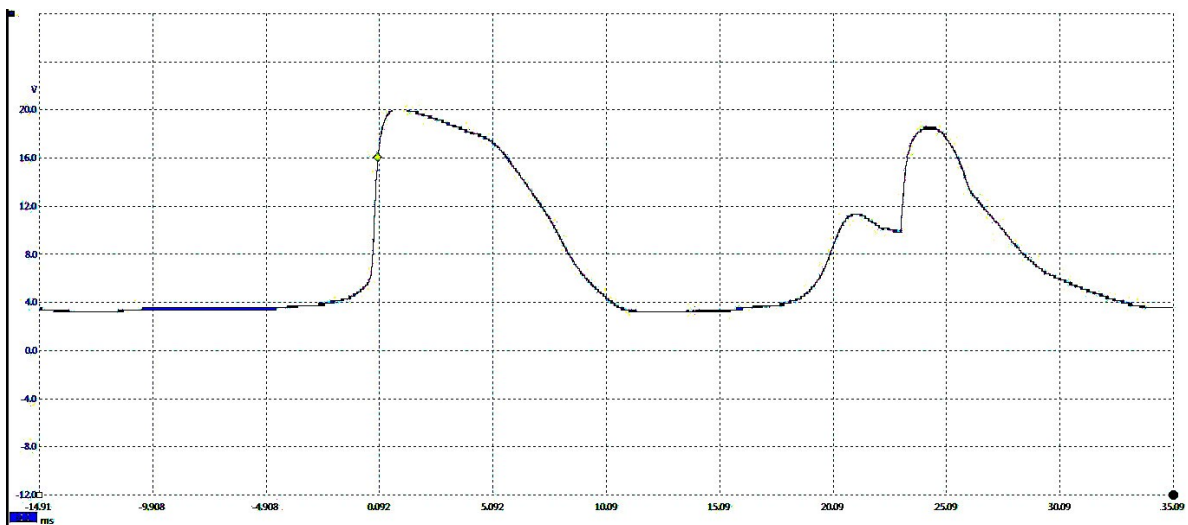
However, the charge rate could be accelerated by slightly lifting and dropping the upper plate. This resulted in “bounce” that caused much sharper peaks, and (when a perfectly flat bounce could be achieved) resulted in a maximum achieved output in excess of 80V. This was rarely achieved, most efforts being in the region of 20V.

Overall the experiment proved that the theory is generally viable, even though within the limitations of the rig it could not be shown to be accurate.

A second experiment

Following this very crude exercise, an attempt was made to tidy it up, albeit with still very limited resources.

- The protective film was removed from the plate, both plates were rubbed down with abrasive and polished. Using a straight-edge there were visible gaps, so the surfaces were still not perfectly matched.
- A trial was conducted using cling-film (nominal thickness 0.035 mm) but it was too fragile and short-circuited at the edges. But more reliable results were obtained by using car acrylic paint to a thickness of about 0.15 mm (a perfectly even thickness was difficult to obtain)
- Whether the paint was thinner than the original protective film or whether paint has a higher relative permittivity has not been investigated but the result was 800pF, measured as before, which is a distinct improvement albeit a lot less than the hoped-for 25nF
- A 3.3 MΩ resistor was placed in series with the scope probe to increase the resistance and delay the decay time, although this would have slightly reduced the measured output.



Other details were as before.

The oscilloscope trace shows the multiple-bounce effect of dropping the upper plate:

- Measured outputs of 20V were fairly often obtainable, although this depended on getting a perfectly square drop.
- The bounce gave a much sharper mechanical rise rate than could be obtained manually, so the electrostatic effect could accumulate further before the R-C decay effect took over.

In order to suppress the decay through the oscilloscope probe a 10V zener diode was placed between it and the probe. The zener diode was rated at 10mA, and it can be expected there would have been a small leakage at below the rated breakdown voltage. However, the leakage was separately measured at 0.3nA at 5V which would have been insignificant in this case, assuming that it increased pro-rata until close to the rated breakdown voltage.

Results approaching 20V were then obtained much more consistently, which supports the view that leakage through the test connection has a substantial effect on the measured output.

ENERGY RECOVERY

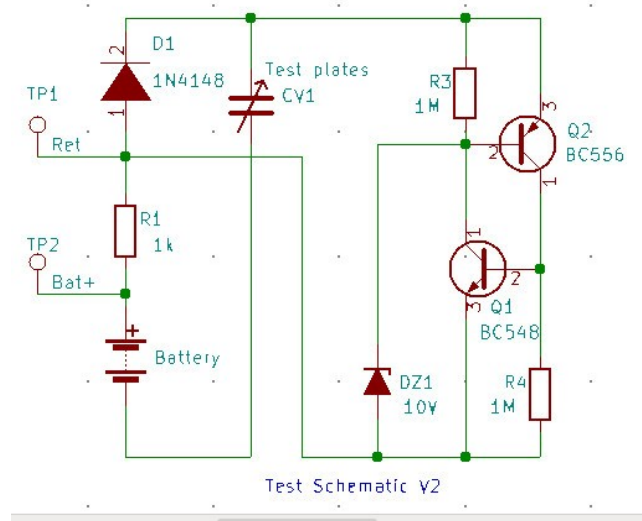
A particular problem, as shown above, involves collecting the energy from the capacitor. There must be an absolute minimum of “leakage” until the required voltage is reached, because this represents a loss of charge which would reduce or prevent any further energy conversion. Also the collection process must be as quick as possible to retrieve all the energy before the capacitor starts increasing in value again for the next cycle.

To act as a switch the initial idea was to use a thyristor. These provide a high resistance between the main terminals until a current is injected into a third terminal (the “gate”). They then present a very low resistance, regardless of what happens at the gate, until the terminal voltage is discharged almost completely, whereupon they revert to high resistance until the next gate injection. These are commonly used in dimmer circuits on A/C mains supplies. But in researching available devices several problems emerged.

Firstly they take far too long to turn on. There are very few thyristors that turn on in less than a microsecond and need less than a milliAmp at the gate, which amounts to at least a nanoCoulomb. This might not sound much but for this experiment it accounts for most if not all of the available charge before the switch begins to operate. And even the low power devices leak up to 2 microAmps when they are supposed to be “off”, which is too high for this experiment.

The principle used in the next experiment was to employ a zener diode as a threshold sensor, controlling a fast-acting switch to collect the energy. Tests on a low-voltage zener diode showed a leakage of only a few nA (nano-Amps), which would be good for this test if the discharge time could be kept very short. The problem then is that when the capacitor starts to discharge, the zener no longer gets the required breakdown voltage and turns off again. The effect of this is to maintain an intermediate voltage that leaks away the charge very slowly. So some sort of latching switch is required – one that, once triggered, remains latched until the terminal voltage is almost exhausted, effectively bypassing the zener.

Therefore a latching switch was constructed from a pair of bipolar transistors (types BC556 and BC548), as shown in Test Schematic V2.



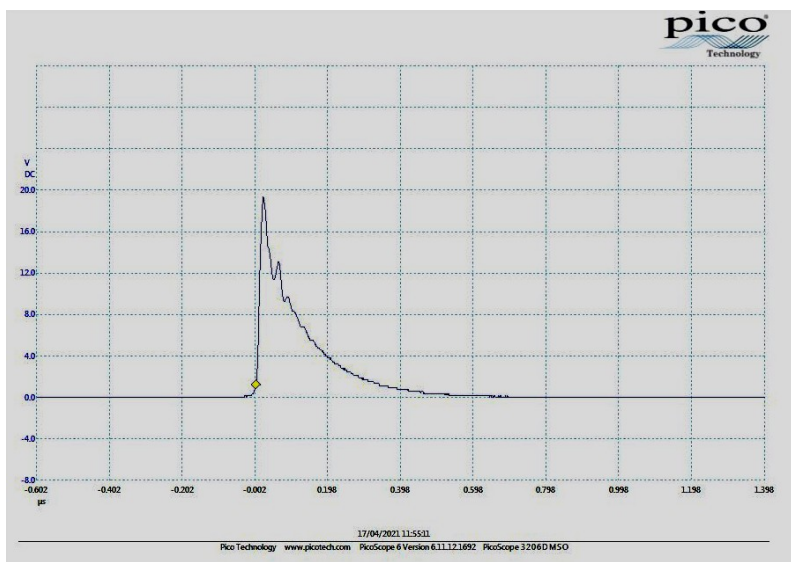
- The charging arrangement is as before, with R1 and D1 from a nominal 2.5V rechargeable battery.
- The zener is shown as DZ1, which starts to turn on Q2 when the threshold voltage (nominally 10V) is reached.
- Q2 immediately starts to turn on Q1, which amplifies the effect, and draws more current from the base of Q2.
- The two transistors very rapidly turn each other “on”, and bypass the zener. So they remain “on” until the capacitor is discharged to about 0.5V above battery voltage.
- The transistors then turn “off” and await current through DZ1 to turn back on and repeat the cycle.
- The resistors R3 and R4 (an arbitrary high value of 1.0MΩ was used) sink the small leakage from DZ1, Q1 and Q2 to prevent early switch-on. After Q1 and Q2 have “latched” these resistors have no further effect until the next cycle.
- The resistor R1 returns the discharge current back into the battery. A separate return resistor/path was not used.
- The voltage monitored across R1 indicated the current flows.

The switching circuit only discharges the capacitor to slightly above the battery level – it does not discharge it completely – so the energy cycle conforms similarly to equations 4.1 et seq of the Theory section. When the capacitance increases again it drops the voltage further and draws current from the battery. In theory this means that, once the battery has provided an initial charge the circuit will continue requiring a small “top up” charge for each repeated cycle.

So whatever net charge is returned through R1 will be essentially “profit” harvested from the mechanical input. Therefore the overall effect of the design is to convert mechanical energy into a charging current that can either charge a battery or maintain its charge when supplying a load circuit.

In an active device the capacitor discharge would be returned directly to the battery instead of through resistor R1, but the arrangement used in the test circuit enables the capacitor voltage and return current to be monitored conveniently.

The measured result is shown in the oscilloscope trace.



- A peak voltage of about 9V was achieved easily using the same capacitor details as before. Note that this does not include the battery voltage.
- This is lower than the nominal 10V rating of the zener for several reasons: Transistor Q2 requires about 0.6 Vbe to remain switched on; Q2 saturates at about 0.2 Vce; zener diodes have a manufacturing tolerance in the region 5% to 10%; and zener diodes do not switch on sharply – they begin to leak before their rated voltage. The latter can be approximately calculated from the rated resistance and current of the component, so a device specified to have 20Ω at 5mA, the conductive “slope” would start at about 0.1V below the rated threshold. These factors reasonably account for the observed results.
- The rise time, from the trigger point to the peak, was 18ns, which is a vast improvement on the very “rounded” profile obtained without a zener. This is the combined times of the zener diode response and the switching times of the latching transistors.
- The decay time constant reduced to about 300ns, compared to about 3ms in earlier experiments, which is also a vast improvement. This would decrease further by returning energy directly to the battery instead of through R1, but would be limited by the characteristics of the battery in use.
- The trace is triggered when the zener starts the switching process. Not shown is the preceding time from the moment the capacitor starts to change, as this had no effect on the measured voltage. Therefore, in planning a possible maximum repetition rate, the overall operational cycle time should include not only the decay time but the possible several milliseconds for the voltage to reach the zener threshold. This would depend on the mechanics of the system.
- It is not clear what might be causing the wobbly decay profile, but with such sharp transitions it may have arisen from parasitic feedback effects from the “birds’ nest” construction.

This test circuit demonstrates how the problem of retrieving the electrostatic energy without significant losses can be overcome. It was repeated with a 20V zener with similar results except of course with a higher voltage achieved. No doubt higher voltages could be achieved with corresponding zeners, but it was felt the theory had been validated to a sufficient degree with available resources.

With an initial charge of nominally 5V on a 800pF capacitor, which amounts to 4nC, and discharged at a voltage of 19.6V, the energy converted in this test cycle amounts to just under 80nJ. For this crude design to be of any use it would have to be implemented with a much more footprint-efficient capacitor construction (e.g. 25nF), a higher battery voltage, a more efficient mechanical process and frequent repetition.

Having considered all that, it also remains that this type of circuit does not require any other switching or co-ordination with the mechanical device, which should make the mechanical problem easier to deal with.

It is important to note that not all battery types stand up to pulse charging, but reports indicate that LiIon batteries, which are currently most favoured for powered models and electric vehicles, are considered suitable. While lead-acid batteries can benefit from pulse charging at high voltage as it can reverse the common problem of ageing (sulphation), there are variations in chemistry which would need to be investigated further.