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Technical Publications

Capacitive Energy Conversion

Overview

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Table of Contents

ISSUE RECORD

7/11/23	Initial report

THE QUESTIONS

While reviewing the standard Physics syllabus for undergraduates, the topics of electrostatic energies and electrical capacitive energies are found to be presented separately. But as energy and work are essentially the same thing, it is of interest to see how these two forms of energy can work together.

It is straightforward to analyse what happens when surfaces carrying a fixed electrical charge are separated or brought together, with the forces required and the energy input or output that occurs. Similarly, it is straightforward to analyse the changes in stored energy that results when a charged capacitor is changed in value e.g. by changing the separation of the plates. All this is presented in standard course material.

It is therefore a routine calculation to discover that by changing a capacitor by separating the plates some mechanical work is done according to Newton's laws of motion, and this exactly corresponds to the change in stored electrical energy. The equations showing this are presented in detail in the Theory section of this document series.

But the question then arises: if electrical energy is created by separating the plates of a charged capacitor, what can be done with that energy? Is it possible to somehow harvest this energy and put it to practical use? And, as a single "shot" of energy is of little value unless it is part of a continual, repetitive process, this begs the question – how can this energy transfer, from mechanical to electrical, be made into a cyclic process? And this requires such a process to be constructed so that it always returns through the same initial state.

CHALLENGING CONVENTION

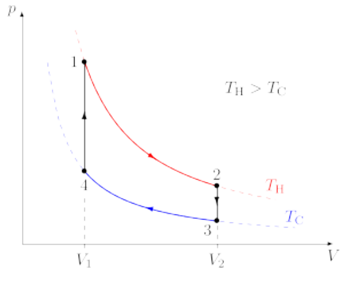
In the generation of electrical power from mechanical energy, the most common equipment takes the form of dynamos or alternators. Many of these are self-exciting, in the sense that with permanent magnets they require no external electrical stimulus to provide their output, but some dynamo designs require an excitation current before they can produce any power. So, while many generators produce power autonomously, it is not necessarily a pre-requisite for something new. However, realistically, if a device requires external excitation it should first restore the energy it received from the excitation source before delivering power elsewhere.

Another feature of conventional generator systems is that they produce electrical energy in a directly usable form, at a particular voltage in DC or a particular voltage and frequency in AC. But this usually requires some sort of regulator system or speed control which consumes some of the source or generated power and reduces efficiency. But is it possible to take whatever energy is available at whatever voltage and frequency it can conveniently be supplied without the energy cost or other limitations of a regulator?

Challenging the necessity of these conventional features opens up new possibilities.

A NEW VIEWPOINT

When studying thermodynamics, and Stirling engines in particular, the student is introduced to a diagram that very neatly describes the operation of an engine that converts between mechanical energy and heat. It plots gas pressure against volume, so as the phases of the Stirling engine cycle are drawn on it they describe a loop. But the product of pressure and volume represents energy or work, so the area contained within the loop represents the transfer of energy from one form to the other.



Such a P-V diagram (as shown[1]) is extremely helpful in understanding so-called “heat engines”. The direction of energy transfer is entirely reversible, and is simply represented by the direction of travel around the loop; the diagram shows mechanical energy being generated from heat.

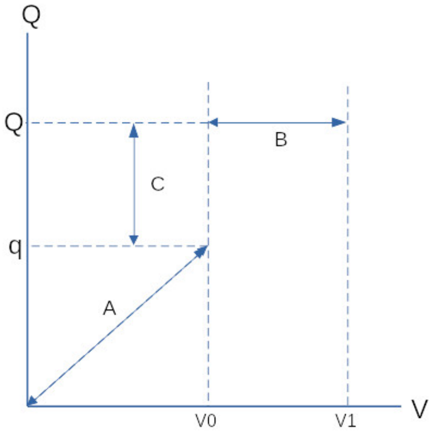
It is important to note that, wherever the cycle is deemed to start (the initial conditions), the loop must always return to the same point if the energy process is to be repeatable and sustainable.

Using this principle it becomes apparent that a similar diagram could be constructed for electrical energy in a capacitor by using electrical charge and voltage. The product of charge and voltage represents electrical energy (electron-Volts are a conventional unit of energy in atomic physics), so perhaps a Q-V diagram promises to help illustrate the electrical energy problem and potential solutions with similar clarity to the thermodynamic P-V diagram.

In other words, if a process can be devised that is shown as a loop on a Q-V diagram then the diagram will show how much energy is being transferred per cycle, and in which direction it is going. And if the loop is closed, then the cycle may be repeatable and sustainable, which are requirements of a usable conversion process.

ENERGY TRANSITIONS

The simplest diagram to draw on Cartesian axes is a straight line. Line A in the diagram shows how charge and voltage change while the capacitance is fixed, The slope of the line is simply the unchanging capacitance. Although the energy increases with charge and voltage, which requires an external mechanical input, the same energy is returned to the mechanical system along the same line when the voltage and charge are returned to their initial values. So no nett energy is transferred in the cycle.

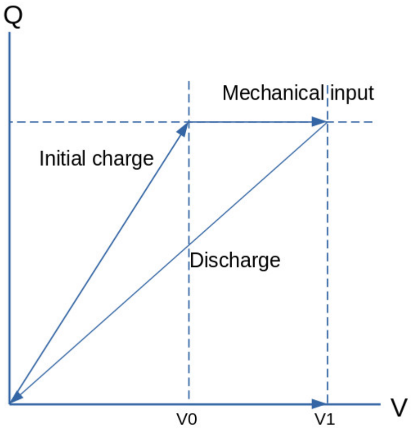


Energy transitions

Line B in the diagram shows how the voltage changes if the capacitance changes (decreased capacitance leads to increased voltage), but without changing the charge (i.e. the capacitor is electrically isolated). Although the energy increases with voltage, which requires an external mechanical input, the result is the same as before in that the energy is returned and no nett energy is transferred if the process returns along the same line.

Line C in the diagram shows what happens if the voltage is fixed, which causes the charge to vary with the capacitance as current flows in or out. Again, the cycle is constrained to a straight line and no nett energy is transferred in the cycle after returning.

The next simplest diagram is a triangle, with one point at the zero origin. It shows what happens if a charge is placed on a capacitor, the capacitor is then reduced in value without changing the charge, and the capacitor is then discharged. The diagram is constructed simply by connecting previously discussed lines end to end.



Charge vs Voltage (Energy) Cycle

It shows a clockwise, closed loop. This contains an area, and therefore describes a transfer of energy – the diagram shows energy transferred from mechanical to electrical. The gain in electrical energy is the difference between the energy of the initial charge input and the energy of the discharge from the higher voltage. This can be easily determined from the areas of the triangles. As the initial conditions are restored on completion the loop is repeatable and continually sustainable so long as the initial charge can be restored and the mechanical input is available.

This begins to suggest a solution to the energy harvesting problem, but to discharge the capacitor to zero volts is simply wasting the generated energy as heat in the wiring. While the current may be routed through a transformer in which the secondary winding is connected to an electrical energy store of some sort, this project is intended to avoid the use

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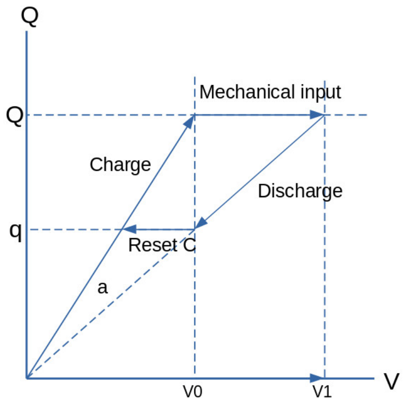
[1] Cristian Quinzacara - Own work, CC BY-SA 4.0, https://commons.wikimedia.org/w/index.php?curid=103898084

of heavy and bulky magnetic components with windings that have resistance and waste thermal energy. It would also slow the discharge rate and therefore the possible frequency of repetition.

If the diagram is modified to show only a partial discharge the energy loop is shown as a quadrilateral. This requires an initial phase where an initial charge is placed on the capacitor, and then an indefinitely repeatable four-phase loop provides a continual energy conversion process:

1. From the initial charged state (Q,V0) the capacitance is mechanically reduced, resulting in an increase in voltage.
2. At a designated voltage (V1) the capacitance is discharged into an electrical energy store.
3. When the original charged voltage (V0) is reached the discharge is interrupted and the capacitance is increased to the initial value, resulting in a further reduction in voltage at constant charge.
4. The reduced charge (q) is "topped up" to the initial charged state.



Revised Energy Cycle

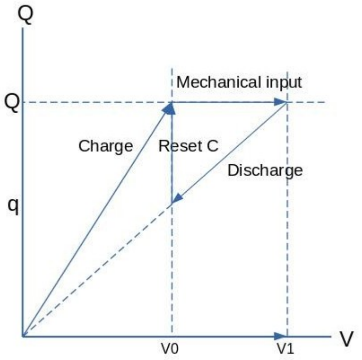
For this model the energy transfer per cycle can again be easily calculated from the areas of triangles. If the entire energy is to be harvested it is necessary that the energy store has a very low internal resistance, such as a capacitor or rechargeable battery (or both in parallel).

The recharge and discharge paths are shorter here than before, and the nett energy transfer is clearly less per cycle. But if the capacitance ratio (and therefore the voltage ratio) is large then the "lost" energy yield would be small in proportion. This can be seen by imagining V0 in the diagram being moved to the left so it becomes a comparatively small fraction of V1. But as less charge, and therefore electrical current, is being passed back and forth to the electrical energy store there would be lower resistive losses and shorter times, leading to potentially better efficiency and faster operation.

Here it is necessary to be clear about the distinction between yield and efficiency. Efficiency is concerned with the waste of the mechanical energy that has been harvested, perhaps in the form of heat generated electrically or mechanically. Yield is concerned with the amount of energy that is harvested. It is of course desirable to maximise both these parameters.

However, with this cycle a problem arises because the discharge voltage is then lower than the required top-up voltage (V0 in the diagram). So either an electrical store other than the original supply is required, which will cause the original supply source to be progressively depleted, or, if the input source is to be charged by the device, then some sort of boost circuit will be needed. Either of these presents problems of complexity and potential wastage of power.

But if the electrical energy store has a reasonably stable voltage, such as a rechargeable battery, then it can remain connected while the capacitance is restored, so phases 3 and 4 in the above cycle can be combined into a single fixed-voltage reset transition. This simplifies the overall profile into a triangle. The size of the energy loop is now smaller, but should be more than compensated by the simpler control requirement and potentially faster operation. Thus, while some yield is lost, the efficiency would be improved.



Revised Energy Cycle 2

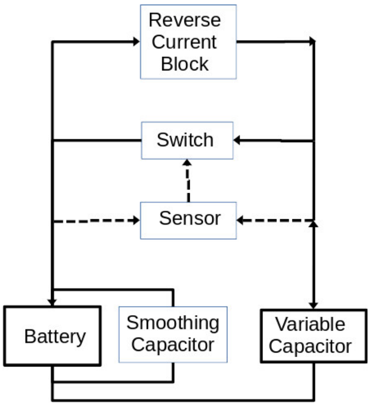
Again, if V0 in the diagram is imagined to be moved to the left, then the yield would not be significantly less than the previous models.

To achieve something close to this "ideal" energy profile the following is required:

- Connection to a rechargeable battery, to supply the initial charge and top-up charges, and to receive the electrical discharges.
- A smoothing capacitor may be placed across the battery terminals to present a low transient impedance to the switch, which increases the capture efficiency and reduces the transient "shock" to the battery.
- Some means of determining the point of discharge. If the capacitance is mechanically cycled then the discharge must take place when the capacitance is at a minimum, and before it significantly increases again. This should preferably avoid any mechanical synchronising devices to avoid complexity and cost.

- Some means of preventing the increased capacitor voltage from leaking charge back into the battery before the correct time of discharge. Any leakage will diminish the charge and seriously compromise the yield.
- The discharge switching circuit must also have the highest possible isolation resistance, for the same reason.
- The sensor must consume the least possible current until it triggers, for the same reason.
- The switching circuit must have the lowest possible resistance during discharge, so the energy is captured quickly at peak voltage.
- For high efficiency and yield the discharge voltage (V1 in the diagrams) needs to be a substantial multiple of the initial voltage (V0), which implies a large proportionate change in the variable capacitor.

A block diagram for a proposed control system is shown, in which the sensor detects the correct discharge timing from the “super” voltage, or it’s rate of change.



Control System