The Electrodynamics of Charges in Capacitors-Pulley System & Teaching Physics Discovery Lessons

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Abstract

A novel method in the solving of the College Physics II standard 2-capactor parallel reconnection problem was presented with a focus on the motion of the transferred charges. The reduction in electrostatic field energy of the higher voltage capacitor would be equal to the work required to move the charges to the lower voltage capacitor. A spring with a movable gap capacitor model would connect the teaching of College Physics II field energy concept to College Physics I stored energy concept with some introduction to radiation. The addition of a pulley and mass to a movable gap capacitor in the Atwood machine configuration would serve as a numerical model for the teaching of oscillation, starting with an example of π computation using energy conservation principle in a spring-mass system with a simple period formula. The discovery spirit in electrodynamics development was modeled as extensions of mechanics topics in Physics I and was taught to the students in Physics II. Good Physics Education delivery would be vital for doing Physics Education Research on the collected student performance data to assess student learning in physics problem solving skill and discovery spirit.

1. Introduction

The College Physics standard 2-capacitor parallel reconnection problem is shown in Figure 1. The usual method have been focusing on the final charges on each capacitor with unknown charges as Q1 and Q2 respectively, coupled with the conservation of charge that Q1 and Q2 would be equal to the sum of the initial charges. Solving the simultaneous equations would give Q1 and Q2.

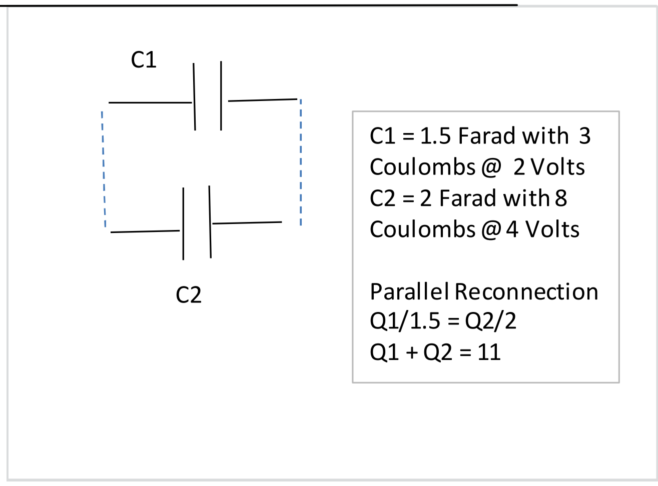

FIG. 1: A schematic view of connecting two capacitors in parallel.

The drawing in Figure 2 shows a solution method where the focus is on the transferred charge, Qt. Setting up the voltage equality would immediately generate the numerical answer for Qt in a single equation.

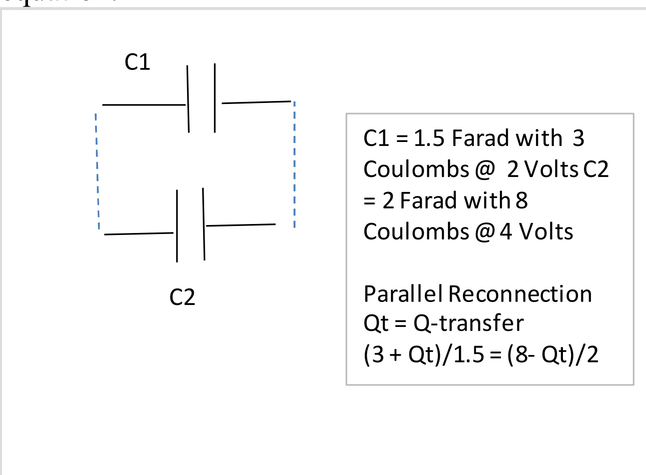

FIG. 2: An illustration of the Q-transfer relationship when two capacitors are connected in parallel.

2. Work-Energy Theorem

The energy used to transfer the charges can be calculated as the product of Qt and voltage difference. However the numerical value for the voltage difference is not obvious since the voltage on either capacitor is changing until both capacitors reach the final voltage, 3.142857 Volts. The standard formulation of ½QV can still be used with the ½ factor being explained in Figure 3. The area bounded by the triangle would be ½ * base * height = ½ * (4-2) * 1.71 = 1.71 Joules, with Qt= 1.71 Coulomb.

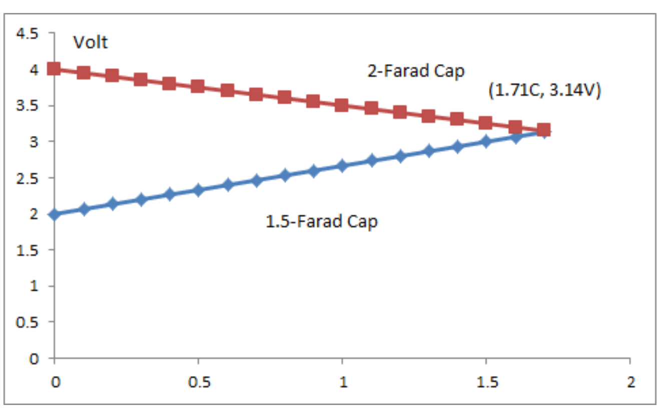

FIG. 3: Voltage (y-axis) versus Coulomb (x-axis)

The energy of the system can be computed using the expression $½*Q^2/C$ or $½*\varepsilon_0*E^2*$Volume when focusing on the electric field energy in the gap space of a capacitor with ε_0 as the permittivity. The energy before reconnection would be 19 Joules ($3^2/2/1.5 + 8^2/2/2$ numerically). After reconnection, the energy would then become 17.29 Joules ($(3+1.71)^2/2/1.5 + (8-1.71)^2/2/2$ numerically) such that the loss energy 1.71 Joules is equal to the work which is illustrated in Figure 3, thus verify the Work-Energy Theorem. The work in Joules is also related to the voltage drop of C2 and the voltage increase in C1, as illustrated in Figure 3. In fact the voltage change concept can also be used to compute the transferred charge, as shown in Figure 4. In other words, the voltage difference of 2 Volts needs to be divided into the ratio of 1/C1 to 1/C2, that is, 0.67 to 0.5. Given a magnitude of 2, the division would be 1.15 to 0.85 such that C2 would have (4 – 1.15) = 3.15 Volt and C1 would have (2 + 0.15) = 3.15 Volt, with small round-off errors as shown in Figure 4.

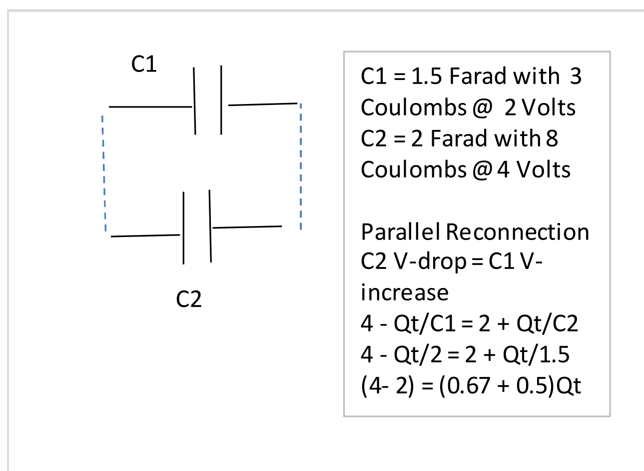

FIG. 4: An illustration of the voltage change relationship when two capacitors are connected in parallel

3. Capacitor-Pulley Problems

The case of a capacitor plate connected to a spring in a variable gap distance design has been worked out in open literature [1]. The electrostatic attraction force between the capacitor plates would be Q*Q/ (2*A* ε_0) and the spring compression via Hooke's Law would be Q*Q/ (2kAε_0), with k represent the spring constant, and A represented the plate area. The electrostatic field energy is coupled with the stored mechanical spring energy. A small displacement with energy ½*k* Amplitude*Amplitude would enable oscillation with damping governed by the dipole field radiation loss. Working on a simple postulation that an accelerated charge will radiate, the radiation should be proportional to acceleration-squared because the Cartesian representation of acceleration in the negative axis should not give different result from acceleration in the positive axis without symmetry breaking. Knowing that acceleration is proportional to frequency-squared in an oscillation, then the radiation of this capacitor-spring system should be proportional to frequency^4, thus capturing an essential feature in the Rayleigh scattering model. When a variable gap capacitor is connected to another mass via a pulley as shown in Figure 5, the standard Atwood Machine configuration would become an oscillatory system when the capacitor charges are changing with time.

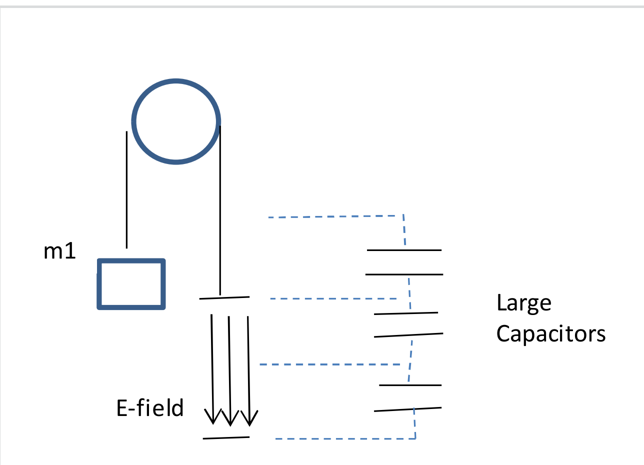

FIG. 5: A schematic view of the capacitor-pulley system.

The Figure 5 scenario can be illustrated with a numerical simulation using Microsoft Excel. The numerical simulation technique can be learned with relative ease for the case of the simple harmonic motion as illustrated in Figure 6.

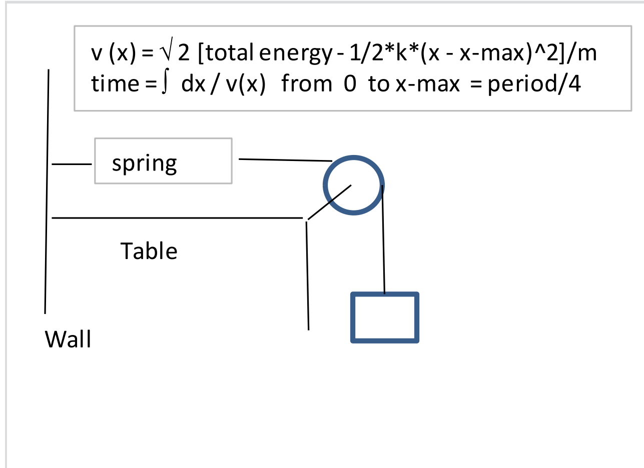

FIG. 6: A schematic view of the simple harmonic motion system used in the simulation with spring constant = 500 N/m, block mass = 40 kg, and pulley has negligible mass.

The simple harmonic motion of a spring-mass system simulation, with period T = 2 π √ (mass/ spring constant), was based on dividing the amplitude into small distance increments. An application of the energy conservation principle for a small distance would give the velocity or speed, as illustrated in Figure 6. The time for that small distance interval was then obtained by dividing the distance by the calculated speed from energy conservation principle. The total time would be obtained by summing all the small distance increment durations numerically such that π can be computed. The number of iterations would be the number of distance intervals used in the simulation. In fact, an approximation of π can be computed using this energy conservation principle simulation, which is similar to the polynomial expansion of π in calculus, as illustrated in Figure 7. We know that Arc-tan (1) = π/4. In Calculus the Arc-tan(1) value can be computed with $\int dx/ (1 + x^2)$ with x from 0 to 1, and that is also equal to the infinite series of Σ 1 - 1/3 + 1/5 - 1/7 + 1/9 ………. via the Leibniz formula for π computation. Whether the Leibniz formula or energy conservation principle is more computational efficient would be a good Excel exercise for software engineering majors.

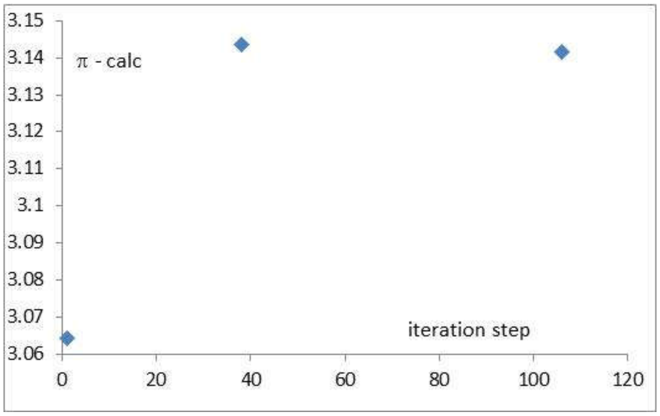

FIG. 7: A graphical illustration of the π calculation versus the number of iterations in the simple harmonic motion simulation.

Note that the capacitor-pulley simulation used a non-linear voltage variation along the gap of the capacitor (Figure 8). The voltage sources are constant and the simulation assumed that the charge transfer needed negligible time. The electrostatic force supplied by the 4,000 Volt constant voltage source plus the weight of the 2.7 kg electrode on the pulley right side would exceed the weight of the 4 kg block on the pulley left side initially. When the 2.7 kg electrode passes the 10 Volt source, charge transfer would diminish the electrostatic force such that the pulley left side effective weight would be heavier and stop the 2.7 kg electrode from falling. Similarly when the 2.7 kg electrode passes the upper 5,000 Volt constant voltage source, the charge transfer would increase the electrostatic force such that the pulley right side effective weight would be heavier and stop the 2.7 kg electrode from raising. This alternating effective weight scheme would result in an oscillatory phenomenon until the 2.7 kg electrode touches the bottom electrode eventually.

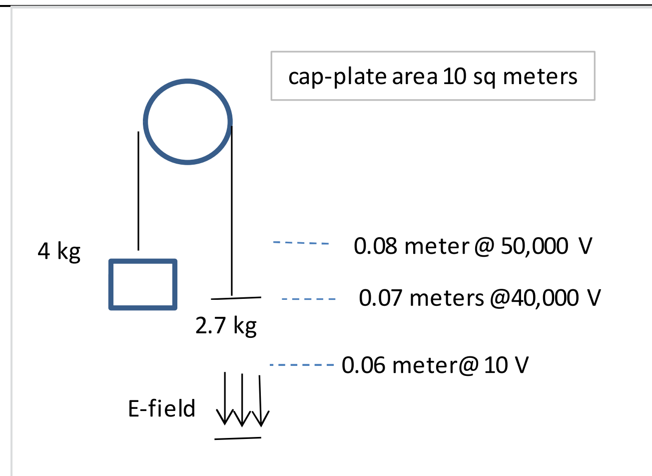

FIG. 8: A schematic view of the parameters used in the simulation.

The result showed an oscillation with increasing amplitude since the mechanical work by the (4 – 2.7) kg mass difference would exceed the electrical energy gain. The displayed cycle between the time intervals from 2 sec to 5 sec in Figure 9 carries a mechanical work of 2.578 Joules and an electrical energy gain of 2.433 Joules. The final situation where the upper capacitor plate will eventually reach the lower plate with zero gap distance will stop the oscillation when the charges become neutralized. Then the 4 kg block will fall and the 2.7 kg electrode with no charge will rise. The expected Casimir effect for the sub-micron gap parallel plate geometry with no charge could be mentioned briefly. Anyway the changing dipole filed would still generate a radiation field, though extremely weak and was not included in the simulation.

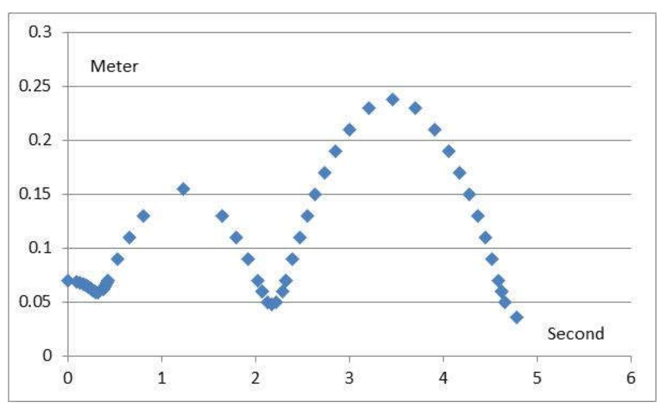

FIG. 9: Upper plate position versus time

4. Discussion

Good Physics Education delivery would be vital for doing productive Physics Education Research with the collected student performance data to assess the use of discovery strategy in teaching physics. The understanding of the reciprocal relationship in capacitor gap distance and the compensation of a faster growing function in voltage such as quadratic feature would generate multiple numerical examples for students to engage in designing different situations. The numerical simulation example in using the capacitor-pulley system is just one example among many others. For example two capacitors connected in series could be configured as an uplift device as shown in Figure 10. This engineering physics model would help students to think about the energy storage issue for wind and solar power alternatives without the electric power grid. The force and electric field application details are also available in the open literature.

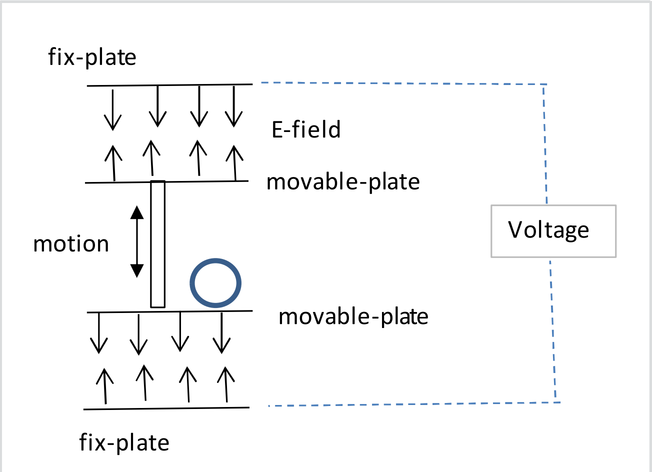

FIG. 10: A schematic view of an uplift device.

The engineering physics example illustrates the importance of hinting/pointing to higher physics class materials, and help students to decide if they are ready as electrical engineering majors when transferring to a 4-year college from our community college pre-engineering program. When in doubt, a student with a discovery spirit usually would appreciate an instructor's guidance and search the web for ideas. For example, the Townsend Brown work on capacitor is available on popular media [2], and Wikipedia also has an explanation on the Biefield-Brown Effect [3]. Technical sites like NASA has a publication on propulsion using asymmetrical capacitor design [4], and that US Army Research Laboratory also has a related article in archive [5]. Recent research for space propulsion system via the Biefield-Brown Effect is also available in pen literature [6]. An instructor knowledgeable with these information resources would be able to sustain the discovery spirt of a student with various problem solving skills linking Physics II explicitly to Physics I; and be vital to providing a good physics education.

5. Conclusions

We have demonstrated the charge movement concept in teaching capacitor related problems, and capacitor-pulley system oscillation with numerical simulation was found to be successful to encourage student discovery spirit.

Acknowledgements

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