CE721 Electronics Design Coursework First Assignment Report

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Abstract: This report will cover the design, simulation, and analysis of the Photopopper circuit, which is a low-power energy harvesting system that accumulates energy before bursting out. The system is designed to mimic a small solar-powered device that is not powerful enough to run a DC motor continuously but instead accumulates energy in a large capacitor while being monitored by a voltage threshold detection circuit using a 555 timer IC.

Keywords: photopopper, energy harvesting, capacitor charging, threshold detection, 555 timer, low-power electronics, DC motor, Multisim simulation.

GitHub: https://github.com/simaygoktug/embedded_programming_stm32

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1 Introduction

The aim and objective of this assignment are to design, simulate, and analyze a Photopopper circuit using NI Multisim. A photopopper is a self-sustaining, low-power electronic system that functions under critical energy constraints. Unlike a conventional system driven by a motor, a photopopper system does not have the capability to continuously deliver sufficient power to the actuator.

This design philosophy is similar to real-world energy harvesting systems, including solar-powered micro-robots, wireless sensor nodes, and autonomous embedded devices that operate in a low-energy environment. This assignment offers valuable insight into the real-world constraints related to the availability of power, energy storage, threshold detection, and energy discharge.

The objectives of this assignment are:

- to design a working photopopper circuit,
- to simulate and test its behaviour in Multisim,
- to analyse voltage and timing characteristics using an oscilloscope,
- to justify design choices using theoretical calculations and to discuss practical implementation methods.

1.1 555 Monostable

In this design, the 555 integrated circuit is used in a monostable configuration. This means a single pulse is generated at the output when the voltage on the capacitor is above a set threshold. Unlike in astable multivibrators, in which a continuous oscillating waveform is produced, in a monostable multivibrator, the motor is switched once per cycle. This is exactly what is required in photopopper because the stored energy is released in a single burst before the cycle resets and begins again.

2 Principle of Operation of the Photopopper (Explanation of Operation)

The main operating principle of a photopopper is based on energy accumulation and release.

A small solar panel (or its electrical equivalent) is used to generate a low current, limited supply. This is not enough to run a DC motor directly. The energy is gradually built up on a large capacitor. As the capacitor voltage builds up, it is continually monitored by a threshold detection circuit. Once it has built up to a certain threshold value, a switching circuit is used to run a motor for a short time. During this time, the capacitor is rapidly discharged, and then the cycle resets again. The operating principle follows the conventional photopopper configuration as described in **[2]**.

This process can be broken down into four distinct phases:

1. Charging phase - capacitor voltage rises slowly
2. Threshold detection - control circuit senses sufficient stored energy
3. Pop event - motor is briefly activated
4. Discharge and reset - capacitor voltage drops and the cycle repeats

2.1 Justification for Choice of Circuit

The photopopper circuit was chosen for its simplicity and effectiveness in showing the accumulation and controlled release of energy under low-power operation. A capacitor-based approach was chosen for energy storage as it permits the gradual accumulation of energy from a limited power source and the controlled release of the stored energy once the required voltage level is attained. The 555 timer was chosen for its dependable and well-defined threshold detection capability without the need for additional complex circuitry. A diode network was also included to prevent premature triggering. A transistor was added for the safe handling of the increased discharge current for the motor.

3 System-Level Design Overview and Evidence of Operation

According to the monostable configuration of the 555 timer is conventional in single-shot energy release applications **[2][4]** so circuit consists of five main subsystems:

1. Power source modelling
2. Energy storage
3. Threshold detection network
4. Control and timing (555 timer)
5. Motor drive and discharge stage

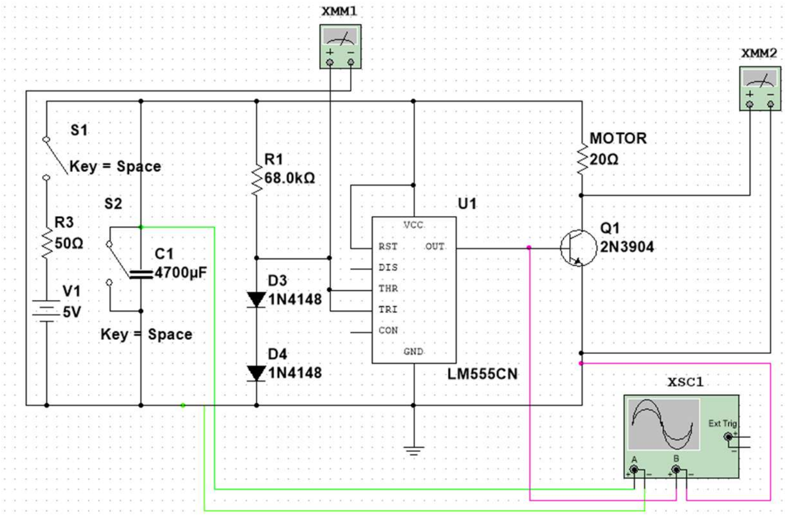

Figure 3.1 MULTISIM Circuit Schematic

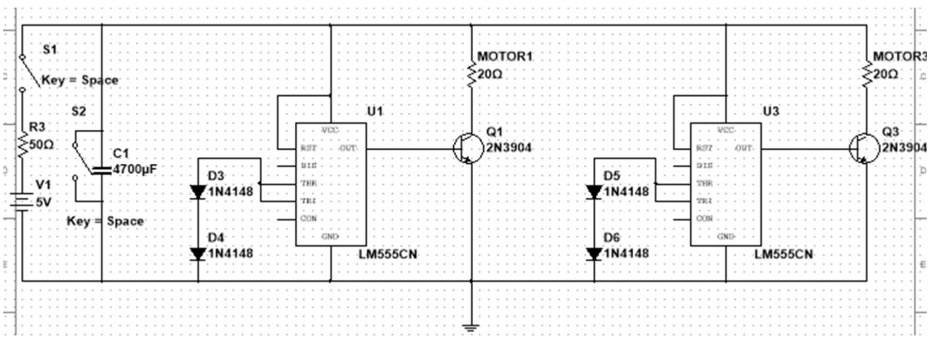

Figure 3.2 MULTISIM Circuit Schematic of Doubled Photopopper **[2]**

3.1 PCB Layout

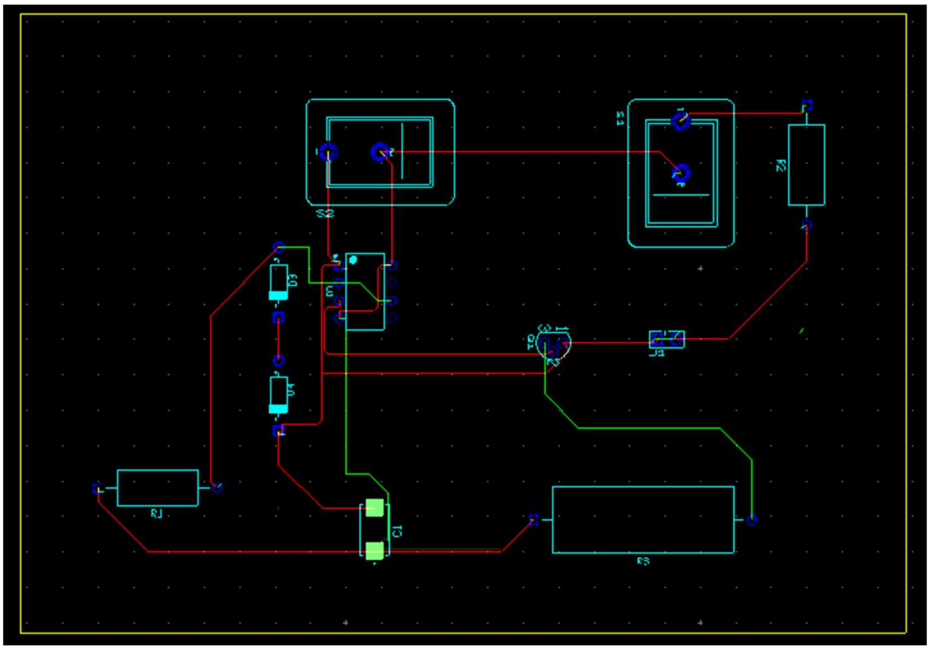

Figure 3.1.1 The final PCB layout is ready for production as it satisfies the criteria for production readiness, as validated by a visual evaluation and a design rule check. The trace width of 40 mils is selected to increase manufacturing flexibility, improve solderability, and provide margins for current ratings, especially for the supply and motor drive routes. The component placement is adequate, ensuring a good distance between the components, such as the 555 timer IC, diodes, and transistor, thereby making it easier for assembly and avoiding solder bridges. The route is well-organized with a minimum number of unnecessary bends, and the board outline is well-defined for export to a manufacturer. The power routes have wider traces, and the signal routes are simple and uncluttered. Improvements such as corner routing at a 45-degree angle and ground copper pours can be added for increased electromagnetic integrity, but they are not critical for this low-frequency, low-current circuit. The Design Rule Check (DRC) shows no short circuits or rule violations, validating the PCB's readiness for manufacturing. **[1]**

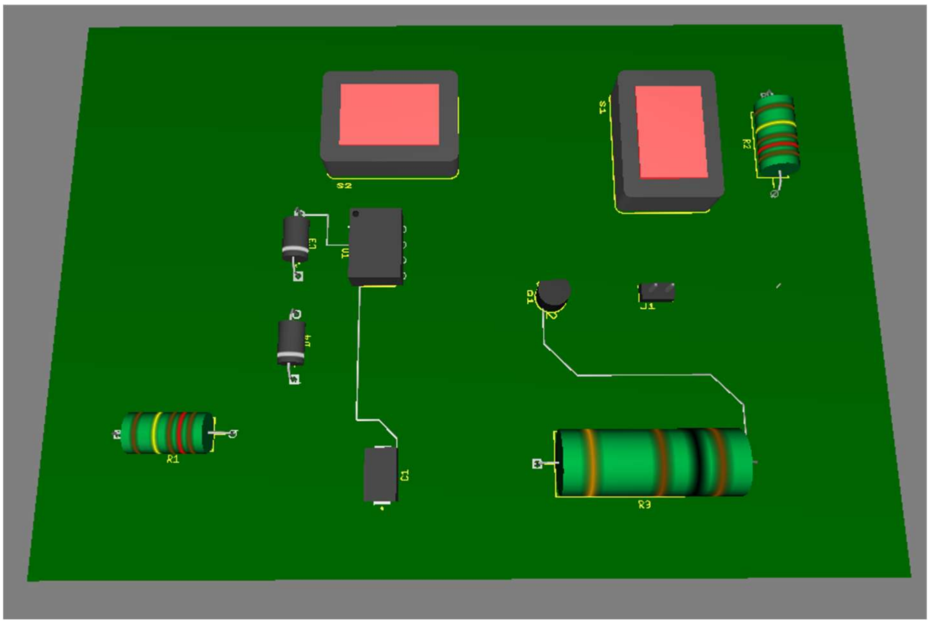

Figure 3.1.2 Ultiboard PCB 3D View (5000 mil x 3500 mil) For Vcc and GND I implemented HEADER1X2 connector.

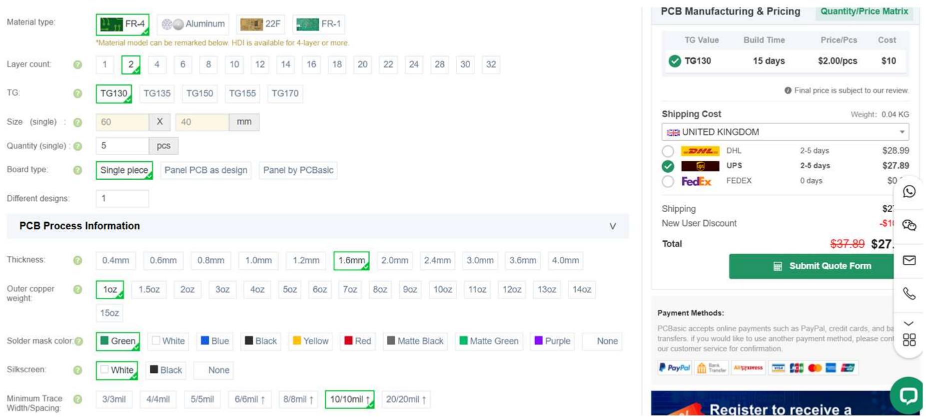

Figure 3.1.3 PCB manufacturing configuration and cost estimation was performed through the PCBasic online quotation tool, where FR-4 substrate, 2-layer stack, board thickness of 1.6 mm, and copper weight of 1 oz were used. The final PCB design was evaluated using an online quotation tool for manufacturing. The parameters used are common in PCB manufacturing and consist of an FR-4 substrate, 2 copper layers, board thickness of 1.6 mm, and 1 oz copper. Conservative constraints are applied to traces and spacing to guarantee manufacturability. **[6]**

3.2 Bill of Materials

Item No.	Component Description	Specification / Value	Quantity	Unit Cost (£)	Total Cost (£
1	Solar Panel	BP2433, 2.5 V, –40–50 mA	1	3.00	3.00
2	Energy Storage Capacitor	470 uF, electolytic, ≥6.3 V	1	0.80	8.80
3	Threshold Resistor	68 kO	1	0.05	0.05
4	Motor Load Resistor	20 O	1	0.05	0.05
5	Signal Diode	1N4148	2	0.10	0.20
6	Timer IC	LM55CN	1	0.60	0.60
7	NPN Transistor	2N3904	1	0.10	0.10
8	Base Resistor	1 kO	1	0.05	0.05
9	Push Button (fest/ Reset)	SPST	1	2.20	2.20
10	PCB/Protoyping Board	Single-sided PCB	1	2.00	2.00

Figure 3.2.1 BoM Table by Amazon UK **[5]**

Item	Component	Manufacturer Part No / Description	Farnell Order Co	Qty Needed	MOQ	Order Qty	Min / Mult
1	Monocrystalline Solar Panel (5V regula	DFROBOT FIT0601	4308227	1	1	1	1 / 1
2	Energy Storage Capacitor (Electrolytic	Panasonic EEU-FR1E472 (4700µF, 25V)	2492146	1	1	1	1 / 1
3	Threshold Resistor	Yageo CFR-25JR-52-68K (68kΩ, 0.25W)	4063932	1	1	1	1 / 1
4	Motor Load Resistor	Multicomp Pro MF25 20R (20Ω, 0.25W)	9341510	1	10	10	10 / 10
5	Signal Diode	Diotec 1N4148 (DO-35)	4555436	2	5	5	5 / 5
6	Timer IC	Texas Instruments LM555CN/NOPB (DIP-8)	3121177	1	1	1	1 / 1
7	NPN Transistor	Multicomp Pro 2N3904 (TO-92)	1574370	1	5	5	5 / 5
8	Base Resistor	Yageo MFR-25FTF52-1K (1kΩ, 0.25W)	4169110	1	1	1	1 / 1
9	Push Button (Test/Reset)	Multicomp Pro TS0A26 (Tactile, SPST, momentary)	1550255	1	1	1	1 / 1
10	PCB / Prototyping Board (Single-sided	CIF AGP10 (100×160mm, FR4)	1267761	1	1	1	1 / 1

Figure 3.2.2 BoM Table by Farnell UK **[7]**

3.3 Real-Time Breadboard Demonstration

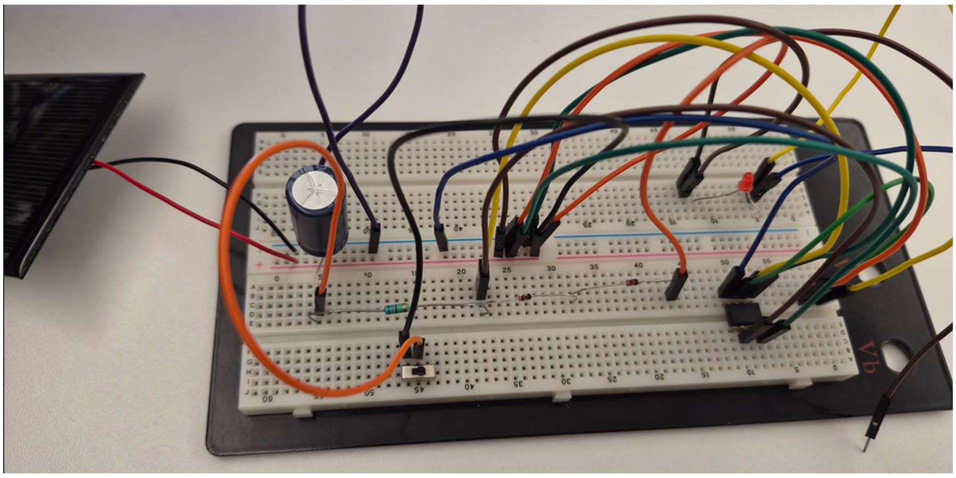

Figure 3.3.1 LED OFF state under low illumination

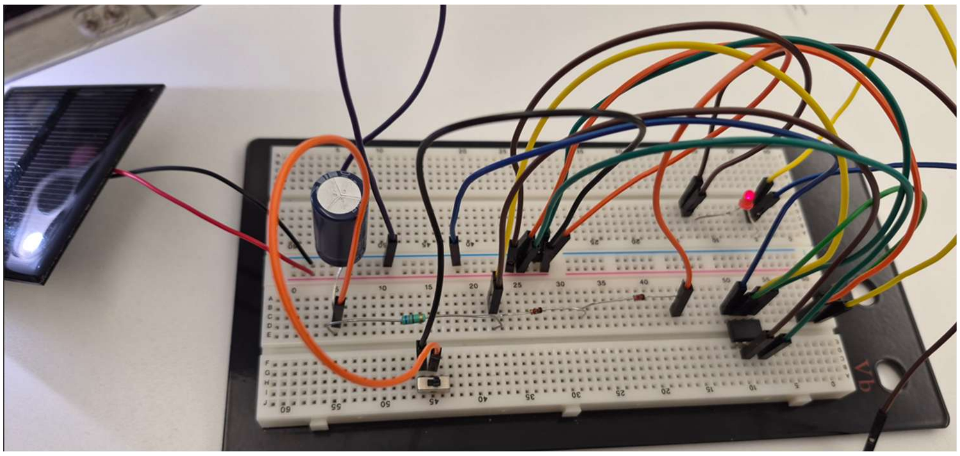

Figure 3.3.2 LED ON state indicates discharge (“pop”) under increased illumination by flashlight

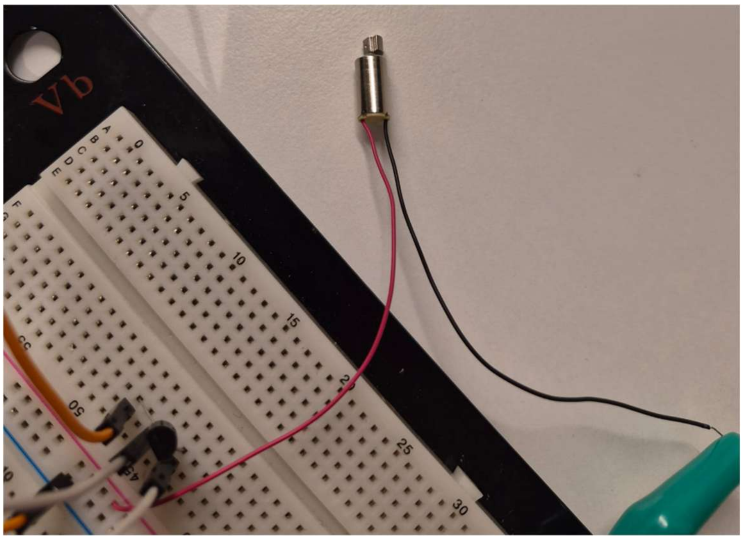

Figure 3.3.3 In order to clearly observe the discharge ("bzzzt") event in the course of the practical test, the LED load was replaced with a small DC motor. It was observed that the LED, with its relatively high effective impedance, allowed the capacitor to continuously charge but provided insufficient discharge current to clearly observe the energy release event. The small DC motor, with its relatively lower impedance, provided the necessary discharge to clearly hear and see the pop effect in the course of the operation. **[1]**

4. Power Source Modelling

4.1 Solar Panel Representation

The original reference design used a BP2433 solar panel. As Multisim does not offer a photovoltaic model in its student version, the solar panel was modelled using an equivalent electrical model. The model consists of:

- a DC voltage source $V_1 = 2.5$ V,
- a series resistance $R_3 = 50$.
- This configuration realistically emulates the limited current capability of a small solar panel.

The maximum available current is approximated by:

$$I_{\max} = \frac{V_1}{R_3} = \frac{2.5}{50} = 50 \text{ mA}$$

This is much less than what is usually needed to continuously power even a very small DC motor, which again emphasizes the need for energy buffering.

4.2 Available Power Estimation

The approximate maximum deliverable power can be estimated as:

$$P_{\max} \approx \frac{V^2}{4R}$$

$$P_{\max} = \frac{(2.5)^2}{4 \times 50} = 31.25 \text{ mW}$$

5. Energy Storage Subsystem

5.1 Capacitor Selection

Energy storage is achieved using a large electrolytic capacitor:

$$C_1 = 4700\ \mu\text{F}$$

A large capacitance is required to accumulate sufficient energy over time while operating under a low charging current.

5.2 Stored Energy Calculation

The energy stored in a capacitor is given by:

$$E = \frac{1}{2}CV^2$$

Assuming a capacitor voltage of approximately $V_C = 1.5$ V before triggering:

$$E = \frac{1}{2} \times 4700 \times 10^{-6} \times (1.5)^2 \approx 5.29\ \text{mJ}$$

This energy is released almost instantaneously during the motor activation phase.

5.3 Charging Behaviour and Time Constant

The capacitor charging follows the standard RC exponential model **[3]**:

$$V_C(t) = V_1\left(1 - e^{-t/(R_{\text{eq}}C)}\right)$$

$$\text{Req} \approx \text{R3} = 50\ \Omega$$

$$\tau = \text{Req} \cdot \text{C}$$

$$\tau = 50 \times 4.7 \times 10\text{^-3} = 0.235\ \text{s}$$

where R_{eq}includes the series resistance of the source and any additional resistive paths. This equation explains the slow, exponential voltage rise observed during simulation. Generally, in RC circuits:

1τ → %63 charged, 5τ → ~%99 charged

6. Threshold Detection Network

6.1 Purpose of the Diode Network

The threshold detection network ensures that the control circuit only triggers when sufficient energy has been stored. This is implemented using:

- a resistor $R_1 = 68\ \text{k}\Omega$,
- two series-connected signal diodes (1N4148).

Each diode introduces a forward voltage drop of approximately 0.7 V, resulting in a combined offset of:

$$V_{\text{offset}} \approx 1.4\ \text{V}$$

This offset raises the effective trigger voltage, preventing premature activation of the motor.

7. Control Circuit: 555 Timer

7.1 Role of the 555 Timer

In this case, the LM555 timer is used as a voltage threshold detector rather than as an oscillator. The trigger pin and the threshold pin of the timer are connected to the capacitor voltage node.

7.2 Internal Threshold Levels

The internal comparator thresholds of the 555 are defined as:

$$V_{\text{TRIG}} = \frac{1}{3} V_{CC}$$
$$V_{\text{THR}} = \frac{2}{3} V_{CC}$$

When the capacitor voltage exceeds the effective threshold, the output produces a short pulse, initiating the pop event. The internal comparators of the 555 timer IC have threshold levels of 1/3 Vcc and 2/3 Vcc **[4]**.

8. Motor Drive and Discharge Stage

8.1 Motor Representation

Following the instructor's recommendation, the DC motor was modelled as a resistor:

$$R_{\text{motor}} = 20\ \Omega$$

This value approximates the effective resistance of a very small DC motor under load and simplifies analysis.

8.2 Switching Transistor

A 2N3904 NPN transistor is used as a low-side switch. As the 555 goes high, base current flows into the transistor. This makes the transistor saturated, allowing a large discharge current to pass through the motor resistance.

8.3 Discharge Current Estimation

Assuming a capacitor voltage of 1.5 V:

$$I_{\text{discharge}} = \frac{V}{R_{\text{motor}}} = \frac{1.5}{20} = 75\ \text{mA}$$

This current is sufficient to briefly drive the motor and rapidly discharge the capacitor.

8.4 Evidence of Measurements

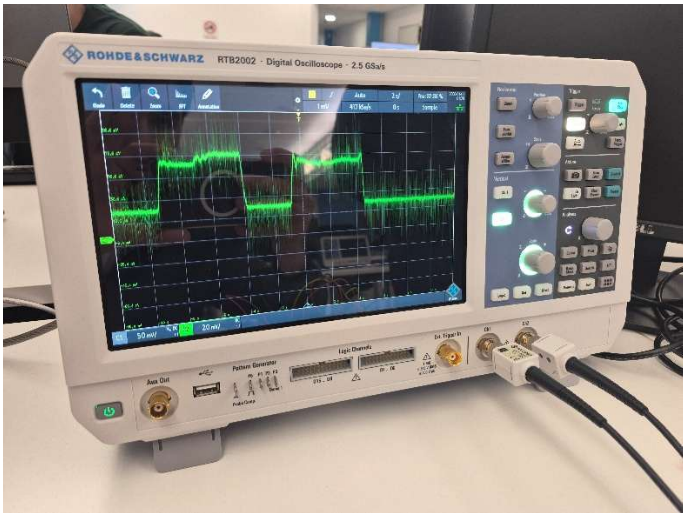

Figure 8.4.1 This is further evidenced by real oscilloscope readings that measure the charging curve of a capacitor, followed by a sharp decline in voltage as a result of the "pop" event of discharge.

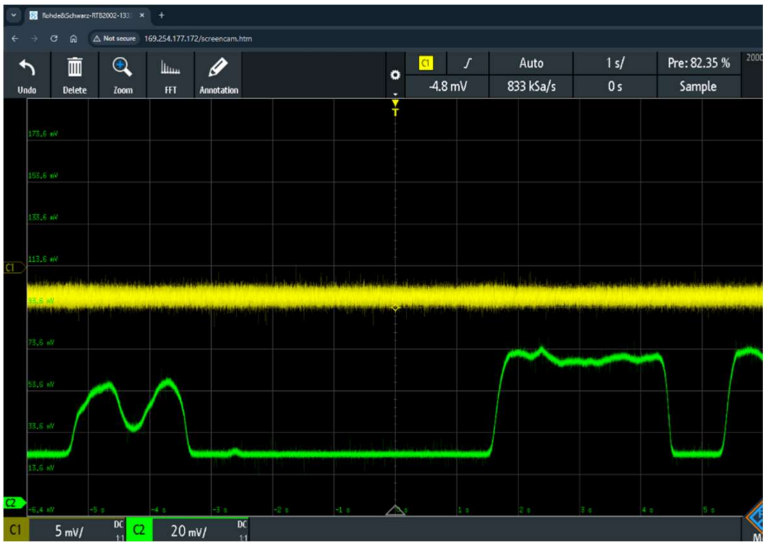

Figure 8.4.2 The pop event is recorded both visually and electrically: the LED lights up at the exact moment when the discharge transition is viewed on the oscilloscope. The scope output shows the charging plateau followed by the switching transition at the pop moment, confirming that the discharge is triggered by the threshold in the real circuit.

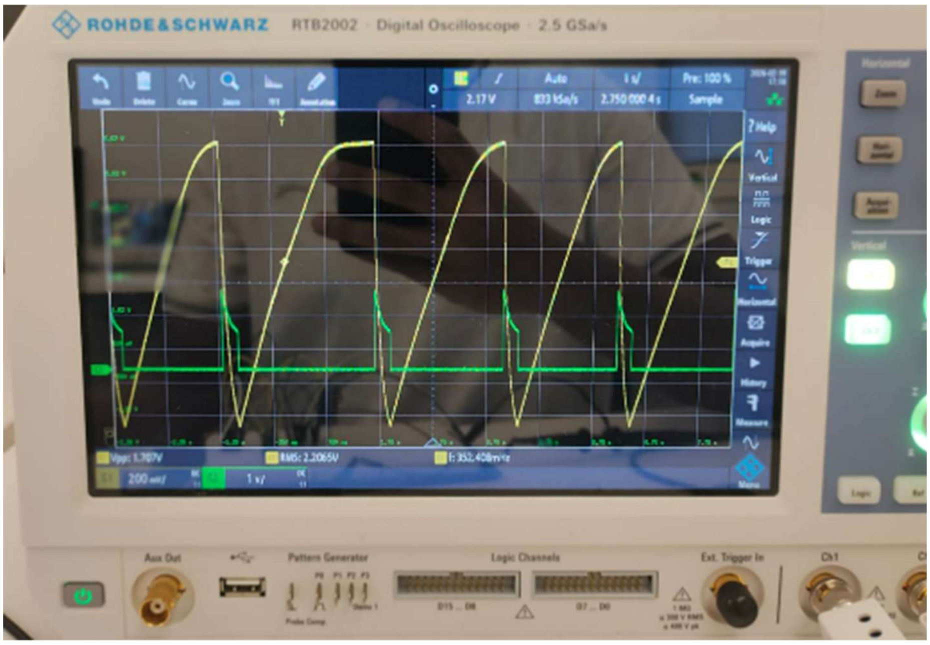

Figure 8.4.3 After decreasing the resistance, we obtained the following successful oscilloscope measurements from the board my friend and I were working on: CH1 (yellow) capacitor charging, CH2 (green) motor "pop" effect.

9. Simulation and Measurement Setup

9.1 Oscilloscope Configuration

A two-channel oscilloscope was used:

- **Channel A:** capacitor voltage
- **Channel B:** 555 output voltage

9.2 Observed Waveforms

Channel A shows:

- slow exponential voltage rise,
- followed by a sharp voltage drop during the pop event.

Channel B shows:

- a short output pulse coinciding with the voltage drop on Channel A. So, these waveforms confirm correct photopopper operation.

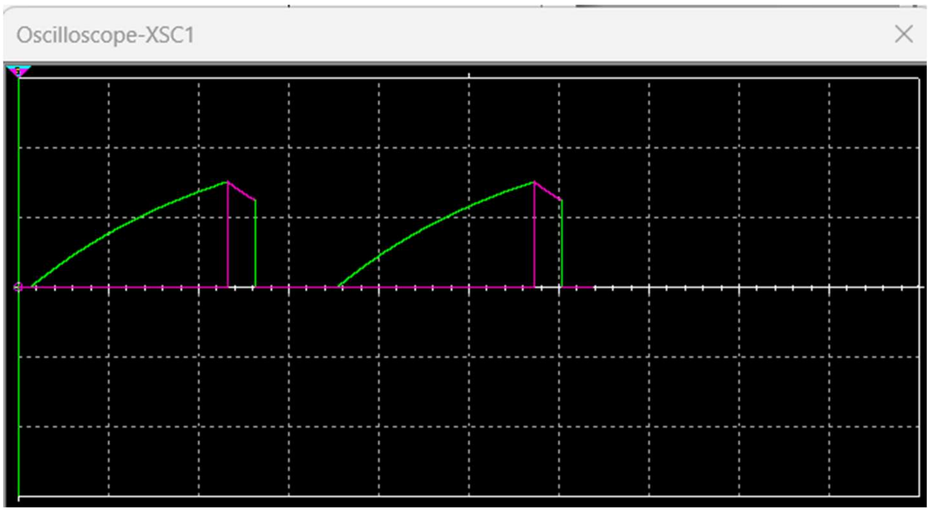

Figure 9.1 MULTISIM Simulation Result

10. Conclusion and Critical Circuit Evaluation

This project demonstrated, in practice, how a low power photopopper works, using energy storage and then releasing it in bursts. The computer simulation and breadboard implementation agreed with the theory, showing that the capacitor is charging correctly and that there is a di charge when the threshold is reached.

An issue that needed to be worked around was getting sufficient discharge current to obtain a clean pop. By using an LED instead of the motor and performing a quick test, it was discovered that the capacitor could charge the LED node but could not discharge efficiently because an LED is not a low-resistance load, such as a DC motor. This meant that the energy could not be discharged in a clean manner and that the system became unstable. The solution to this problem is to model the load as a 20 Ω resistor and then add a switch using a 2N3904 transistor.

Another challenge was in balancing the threshold detection network. The diode offset voltage and resistor values had to be properly tuned to avoid premature triggering yet allow for a reliable reset following the discharge. The sensitivity of the system to small variations in the components was evident in the large effect small changes in the components had on the timing and pop characteristics.

From a critical viewpoint, the photopopper has been able to fulfil its purpose of presenting the idea of energy harvesting under strict power conditions. However, the efficiency of the system has been reduced by the voltage drops in the diodes and the saturation of the transistor. Furthermore, the fact that Multisim does not have a photovoltaic cell model has made it necessary to use an equivalent DC model, which does not accurately represent the solar cell.

In conclusion, the project has been able to effectively present the fundamental concepts of energy buffering, threshold detection, and controlled discharging in the design of low-power electronics.

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