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Pyroelectric Simulation System - Advancing Programmability and Portability Concepts

Shuza Binzaid[1], Wasim Hafiz Dipon[2]

[1,2]Department of Electrical and Computer Engineering, University of Texas at San Antonio,

One UTSA Circle, San Antonio Texas 78256, e-Mail: Shuza00@yahoo.com

Abstract—A novel technique has been implemented to develop a simulation system comprising of programmability and portability for pyroelectric materials. The technology used an advance form of applications of electronic engineering and uses the technological concept of microcontroller based controllability of the simulation process. This process requires usage of advanced technologies in assuring proper functionality of the simulation system framework. Applications of pyroelectric materials in numerous fields can be further improved and new potent utilizations will be nurtured with the help of this accurate and user-friendly simulation system precisely simulating various real world conditions. The technology discussed here is one such technology which assures reliability of the simulation output. The easy programmability certainly adds an extremely useful feature to the simulation process that was never used before. The concept of portability is also considered and included in the feature. The technology has been devised and implemented with objectives to ensure features like battery rechargeable, programmable, low power usage, portable and over driven load protection.

Keywords— Pyroelectric materials, Simulation System; PSpice Simulation; Microcontroller; Equivalent circuit; Tri-state; Android Oscilloscope; Impedance matching, Hi-Z.

INTRODUCTION

The pyroelectric effect though first described by Theophrastus in 315 BC has been known for many centuries and can be explained as a change in temperature in a material causing a release of electric charge. With more sophisticated research techniques being developed, applications of pyroelectric materials speeded up from 1960. David Brewster first used the term "pyroelectricity" in 1824 [1]. A basic concept of the pyroelectric effect can be simply illustrated as shown in Figure 1.A pyroelectric material displays a release of charges at their surface when its temperature is changed and hence then these charges can be detected as current flowing in the external circuit.

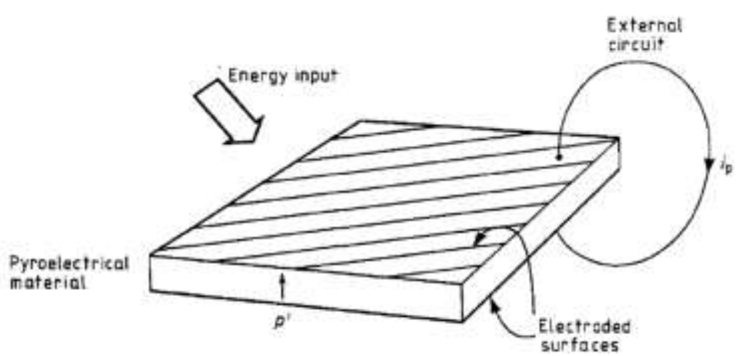


Figure 1: Simple illustration of pyroelectric effect.

More elaborately, the pyroelectric effect is explained as change in electrical dipole moment appearing as macroscopic pyroelectric effect caused by change in mean equilibrium position in lattice by any excitation resulted from change in lattice temperature. Heckmann diagram as shown in Figure 2 illustrates the reversible relations among various properties of a crystal [2, 3]. Pyroelectric effect relates to the electrical and thermal reversible relations in the Heckmann diagram. The pyroelectric effect is a collective contribution of two effects. The primary effect is the constant strain denoted as *S*, prevents expansion or contraction of the crystal and thus a change in temperature causes a change in electrical dipole moment of the crystal. The secondary effect is due to the crystal deformation. Thus, pyroelectricity is a coupled effect that is related between changes in temperature to electrical displacement *D*. Quantitatively the pyroelectric effect is given by the equation $\Delta P_s = p\Delta T$ in terms of vector called the pyroelectric coefficient *p*, given by the rate of change of electrical dipole moment (or spontaneous polarization) P_s with temperature gradient (ΔT).

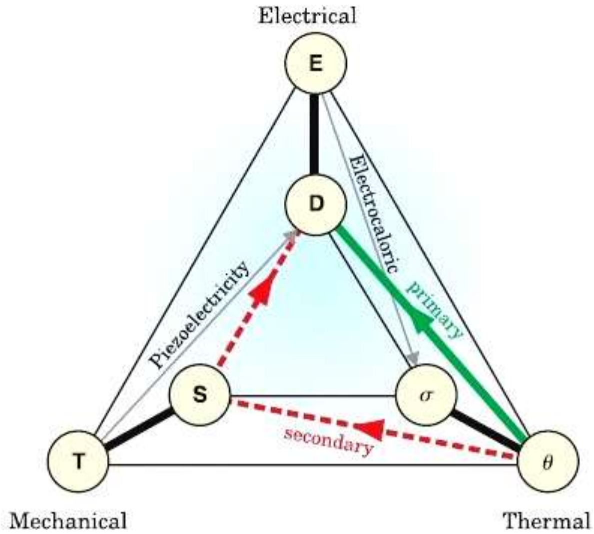


Figure 2: Heckmann energy diagram.

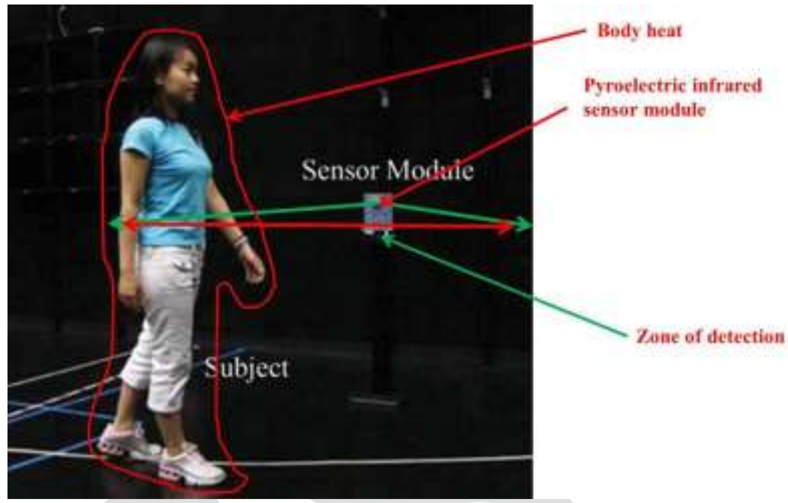


Figure 3: Application of pyroelectricity in detection.

Pyroelectric materials have wide range of applications as detectors and sensors. The major advantage of pyroelectric detectors over semiconductor detectors is that it works on wide range of wavelengths provided some means for absorbing the radiation, have higher sensitivity over wide range of temperature, requires low power, fast in response and requires low cost to manufacture[4]. Pyroelectric elements can be used to attenuate noise caused by ambient temperature changes and from vibrations. These advantages have led their vast use in firefighting, law enforcement, border patrol, land mine detection, building surveillance, process control, vision testing, facial recognition and traffic control. An example of pyroectricity in sensor technology is shown in Figure 3 [5].With growing energy demands all over the world, harvesting energy from alternate energy sources is currently considered a topic of huge interest. In this regard pyroelectric materials can play an important role as an alternate energy source and hence can be put in use for numerous applications in various fields as energy harvesters. Pyroelectric harvesters work by converting a time-dependent temperature variation into electric current. A pyroelectric cells based energy harvesting technique is shown in Figure 4 [6].Pyroelectric materials can be used as the power source of many lifesaving and pain relief medical applications from implanted cardiovascular devices and pacemakers to muscle stimulation for pain management using implanted pulse generators by using of the temperature variations within human body to generate required power for such implanted medical devices. An application of pyroelectric material as energy harvester in various implanted medical devices as shown in Figure 5 [7].

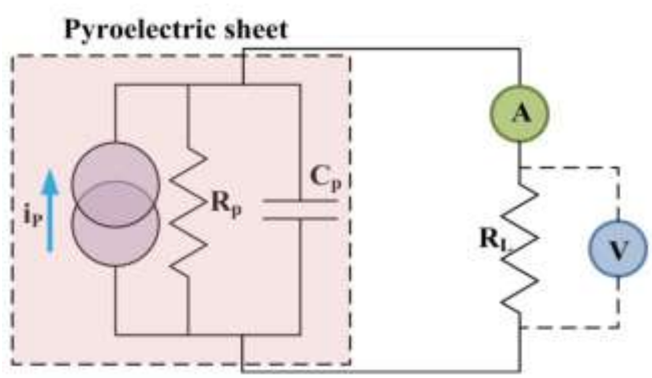


Figure 4: Energy Harvesting from Pyroelectric cell.

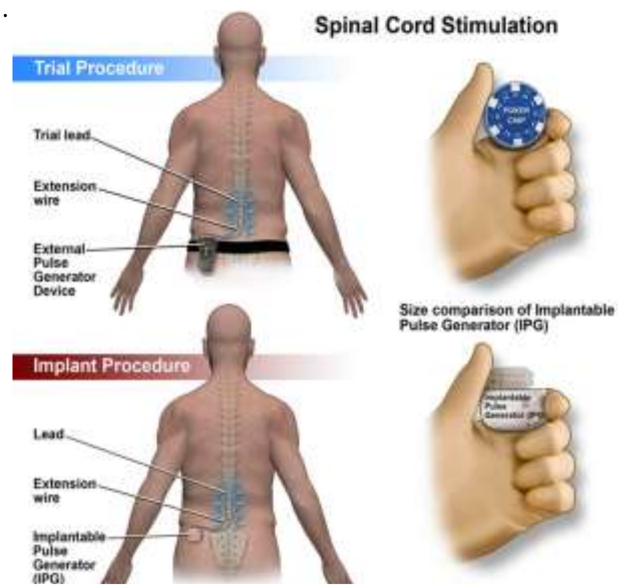


Figure 5: Pyroelectric energy harvester for implanted medical devices.

Dire and even catastrophic consequences may arise from using pyroelectric devices without prior tests and trials which can be avoided today by this simulation system to determine the various characteristics and behavior of pyro electric materials while using as the life-long power source for these implants. Taking into account the tremendous applicability of pyroelectric materials in numerous fields it is imperative to validate proper and precise testing methods to determine the behavior of pyroelectric materials under any particular application to make it work best to serve the intended purpose. These goals can be reached if precise and real world simulation is possible for pyroelectric materials considering a particular condition and application. In this regard a fully programmable pocket sized portable simulation system for pyroelectric material is designed and implemented with wide range of variations in the loading to depict precisely various applications and conditions.

DESCRIPTION OF THE SIMULATION SYSTEM

The objectives considered while implementing the idea of a simulation system for pyroelectric material are profound for the fact that they are all contributors in making a fully programmable simulation system and constitute all the parameters require to simulate the energy output of a pyroelectric material under any given condition and for any given application. The system simulates using some manually given parameters for the program simulating the signal output which, in fact, resembles that of the expected signature of the signal of a pyroelectric material under a particular condition. Using the same signature, additional output amplification is controlled by the microprocessor in order to give the same output power by the simulation of the same pyroelectric material. This provides data of great value while considering pyroelectric material as an energy harvester. Taking into account all these necessitates, a pocket sized ((1.75”X2.5”X1”) portable fully programmable simulation system is devised that can be powered by a set of rechargeable batteries. The simulator system has been implemented incorporating some essential features that ensure wide range of applications to be simulated, user-friendliness of operation, simulating behavior of pyroelectric materials under various load conditions, low power consumption by the system, fully programmable and pocket sized portable. Also, it is possible from the simulation system to calculate the stored energy in the pyroelectric material and the deliverable energy to the load, thus, helping system designers to precisely approximate the energy requirement and energy deliverable from pyroelectric materials.

Design and Simulation of the Circuitry:

The design and implementation of the simulation system burgeoned from simulating the equivalent circuit of the pyroelectric material. Mathematical derivations and computations carried out beforehand to ensure theoretically that the functionality of the final system will yield. Taking these further, the draft hardware were designed considering necessary electrical components of required values in designing the circuitry in order to yield the required outcomes from the circuit. This designed circuit was then simulated using PSpice simulation software under various conditions by varying the parameters and electrical components’ values, monitoring and recording every time the corresponding results of the simulation and are compared to ensure the functionality of the circuit is zeroing in to the final and desired outcome confirming the functionality of the circuit as required for the simulation system. The PSpice simulation result is provided in Figure 6 below. The simulation was conducted with the objective to best resemble the voltage and current outputs of the designed circuit to the actual voltage and current behavior of pyroelectric material under a particular condition. Precise changes are made in the hardware until the required voltage and current waveforms are obtained at the output of the circuit resembles precisely the voltage and current waveforms of a pyroelectric material. The variation of the output waveforms according to the loading of the circuit is also ensured through simulations so that the expected range of operation is achieved. Various parameters of the input signal to the circuit (which is from the microcontroller) are also varied in the PSpice simulation to monitor changes in the outcomes of the circuit. This provided extremely useful information and the basic understanding of the programming codes for the microcontroller that will be used to drive the equivalent circuit.

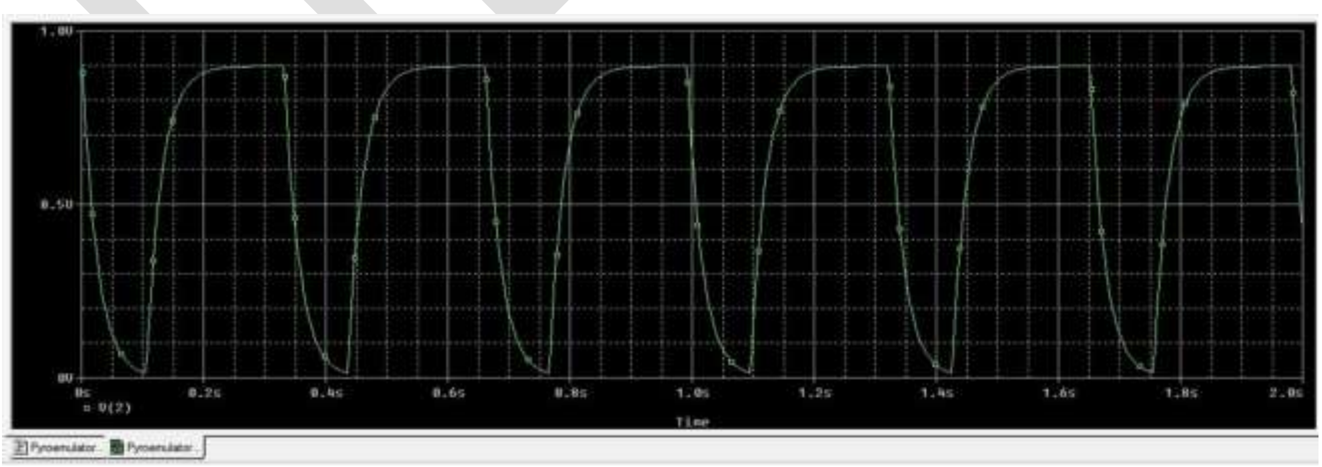


Figure 6: PSpice simulation result of the designed pyroelectric equivalent circuit at minimum (no) load.

Microcontroller and Software Framework:

ATmega328 based microcontroller board is used to perform the controlling of the circuit and thus making the entire system fully programmable with a user friendly interface [8]. The programming codes are written to depict any particular condition the pyroelectric material will be subjected to. Various forms of ATmega328 boards are shown in Figure 7. The user friendly interface is obtained by programming the microcontroller in a way that only few parameter changes are required in order to achieve the desired simulation output. The coding of the program for the microcontroller is performed with an objective that various components of the circuitry can be switched on and off depending on the loading conditions the user desires. The logics of the codes are such that the microcontroller drives the circuitry according to the desired condition and hence attains the intended waveforms at the output of the circuit. The frequency variation of the simulated output signal depicts the outcome of a pyroelectric material when subjected to such frequency of temperature changes.

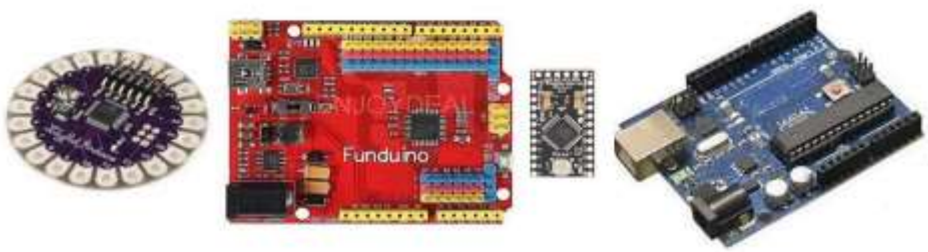
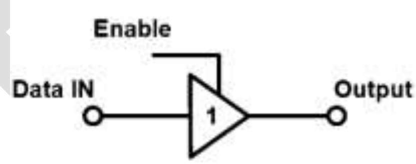


Figure 7: ATmega328 based microcontroller boards.

The switching on and off of circuit components as per the commands directed from the microcontroller in order to simulate a particular condition required the components that are intended to be switched "on" at a different state where as the components that are intended to be switched "off" at a different state such that they do not affect the operation of the circuit. Hence, the Tri-state logic on input/output (IO) pins of the microcontroller is put into effect. The two modes of IO pins are attained by setting the IO pins to "Low" when the pins are in effect and setting at Hi-Z mode when the pins are required to be at High Impedance mode and hence not in operation. The tri-state acts as a buffer that allows controlling when current will pass and when not through the IO pins which is essential for the operation of shared electronic bus. The truth table along with gate design for tri-state operation of the microcontroller is given in Figure 8 [9, 10].



Truth Table		
Enable	A	Q
1	0	0
1	1	1
0	0	Hi-Z
0	1	Hi-Z

Figure 8: Gate design and truth table for Hi-Z operation of the IO pins of the microcontroller.

Programmable Pyroelectric Equivalent Circuit:

The pyroelectric equivalent circuit as shown below in Figure 9 consists of a current source, capacitor and resistor. The circuit is a current source in parallel with internal capacitance C_P and internal resistance R_P and the voltage V_P is the voltage at the output of the pyroelectric equivalent circuit. The current I_P from the pyroelectric element is proportional to the rate of change of temperature and is given by the formula shown below [11]:

$$i_P = \frac{dQ}{dt} = pA\frac{dT}{dt}$$

Here '*P*' is the pyroelectric coefficient; '*A*' is the surface area and '*T*' is the rate of temperature difference with respect to time.

The net charge "*Q*" developed due to the temperature change ΔT can be found by integrating the equation of 'i_P' with respect to time "*t*":

$$Q = \int (pAdT/dt)\, dt = pA\Delta TC = \frac{A\epsilon_{33}^{\sigma}}{h}V = \frac{p}{\epsilon_{33}^{\sigma}} h\Delta T$$

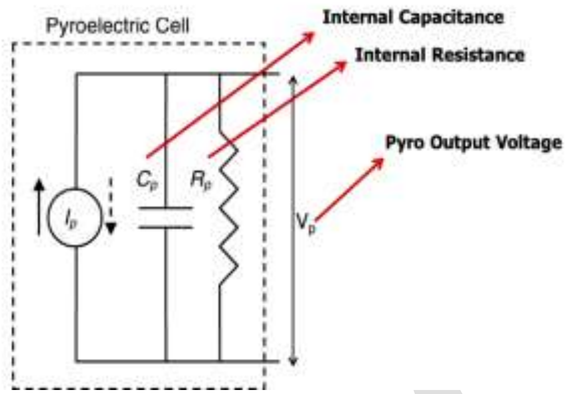


Figure 9: Pyroelectric equivalent circuit.

The pyroelectric material is typically of dielectric in nature and the equivalent capacitance (C) given by formula shown above and the open circuit voltage and the electric field developed can be derived from the $Q = CV$ equation, where ε_{33} is the permittivity in the polarization direction at a constant stress. This circuit is most commonly called RC circuit. The charges produced by temperature changes charges the capacitor which discharges through the resistor connected. These charging and discharging of the capacitor is related exponentially to the time constant (τ) which is given by the product of the value of capacitor and the resistor by the below mentioned equations [12].The time constant (τ) is inversely related to the cutoff frequency f_c which is an alternative parameter for the RC circuit. Relation between the time constant and cutoff frequency are also shown below:

Charging: $V(t) = V_o (1- e^{-t/\tau})$ **Discharging:** $V(t) = V_o (e^{-t/\tau})$ **Time Constant:** $\tau = RC = \frac{1}{2\pi fc}$

The charging and discharging of the capacitor are varied by the programmable circuit driven by the microcontroller as shown in the equivalent pyroelectric circuit with loadings in Figure 10. R_E and C_E are external or load resistor and capacitor respectively. The command from the microcontroller drives the circuit according to the loading condition user wants to conduct simulation by connecting components of the circuit or by putting into a buffered condition by attaining Hi-Z state of the IO pin. This confirms that the component does not to even slightest extent affect operation of the circuit. This grounding and Hi-Z state of capacitors and resistors varies the time constant of the RC circuit and hence the waveforms at the output of the circuit. The waveforms at the output of the circuit are generated by repeated charging and discharging of the capacitors through resistors by the input signal from the microcontroller at a definite frequency and therefore resemble different loading conditions the pyroelectric material is simulated for. IO pins assigned for each capacitor and resistor are changed by the microcontroller between Hi-Z state and ground state as required to obtain simulation of a particular real world condition.

Energy Stored and Energy Deliverable from the Pyroelectric Equivalent Circuit:

The energy produced from the pyroelectric material is certainly comparable to the energy stored in a capacitor and it is very similar to the energy from a battery used for charging a capacitor. As stated earlier the voltage across the capacitor is proportional to the charge stored in the capacitor and hence the stored energy. The energy stored in a pyroelectric material at the end of the temperature change is equal to energy stored in the equivalent capacitor and can be deduced from the open circuit voltage by using the formula for the energy stored in capacitors [13, 14]. These relations can be expressed by equations given below:

$$E_{capacitor} = \frac{1}{2}\sum_{n=1}^{k} Q_k \sum_{n=1}^{k} V_k = \frac{1}{2}\sum_{n=1}^{k} C_k \sum_{n=1}^{k} V_k^2 E_{pyro} = \frac{1}{2}\frac{p^2}{\epsilon_{33}^{\sigma}} Ah\,(\Delta T)^2$$

Where, Q (charge in Coulombs), V (in volts) and C (capacitance in Farads) are charge, voltage and capacitance and E_{pyro} is the stored energy in pyroelectric material with ΔT temperature difference across the pyroelectric material. Therefore in order to infer the energy stored in the pyroelectric material from simulation, the energy stored in the capacitor needs to be calculated. Since varying the capacitor and resistor varies the total energy stored and energy deliverable it is essential to find the variations between the time constant (τ) which also depends on RC as stated earlier and the E_{pyro}. The Table 1 shows the total energy available and the stored energy for external load with respect to time constant.

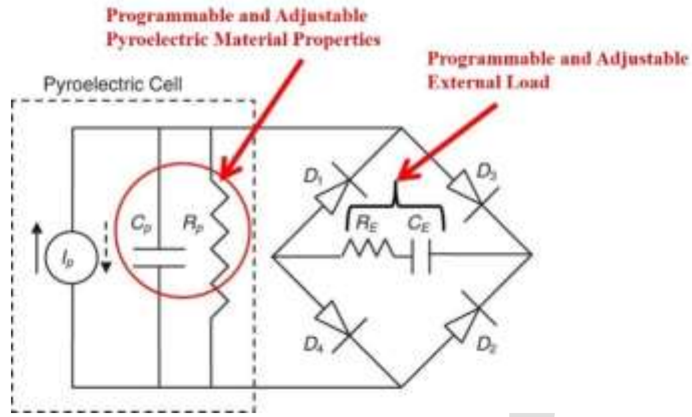


Figure 10: Pyroelectric equivalent circuit along with adjustable loading circuit.

Table 1: Simulated total output energy from the Pyroelectric material at certain program setup from few hundred selection choices.

RC Time Constant, τ (milliseconds)	Simulated total energy available from Pyroelectric material (micro-Joules)	Stored energy available for external load (micro- Joules)
103	3.35	3.2
22	7.2	7.1
16	0.163	0.161

Simulation System Setup:

The simulation system setup can come in different forms of packages that are shown in the Figure 11 and Figure 12. The pocket sized simulation system comes with the simulation system module and a pocket sized oscilloscope. The system needs to be preprogrammed in this setup and the user will just connect the probes of the oscilloscope to the module in order to get the waveforms. The desktop system consists of the simulation system module and a desktop oscilloscope and is considered to be not portable. Another setup which is portable consists of an android display made compatible by android coding along with the simulation system module.

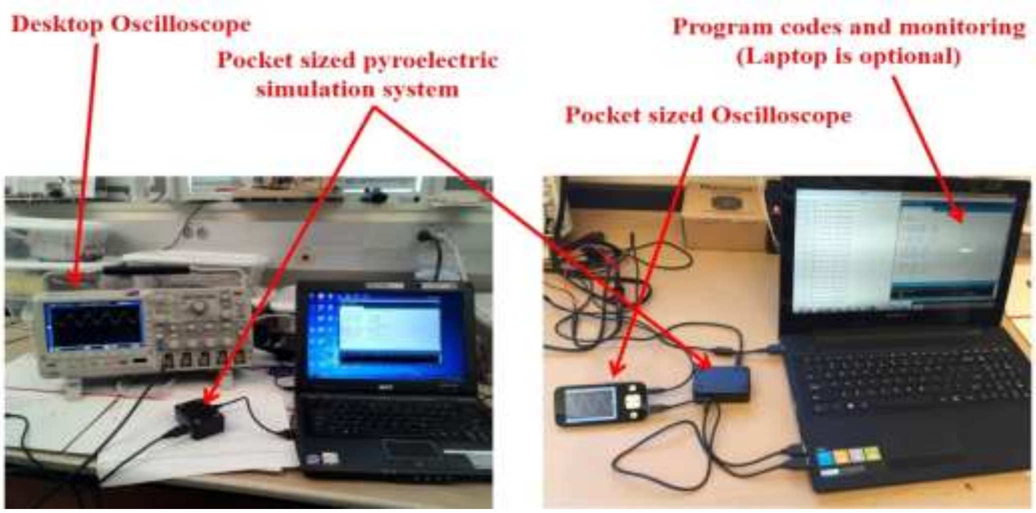


Figure 11: Desktop simulation system setup. Figure 12: Pocket sized simulation system setup.

System Process and Flow Chart:

The flow chart of the system in given and shows the various steps the simulation system goes through depending on different logics and condition. The program logic is based on the inputs from Hi-Z state and ground switching that decides which IO pins and in turn which capacitor and resistor will undergo state change and eventually allows conduction through them. This allows energy to be stored in the capacitor. This multifunctional operation makes the system very simple and highly user friendly to operate and is illustrated in Figure 13.

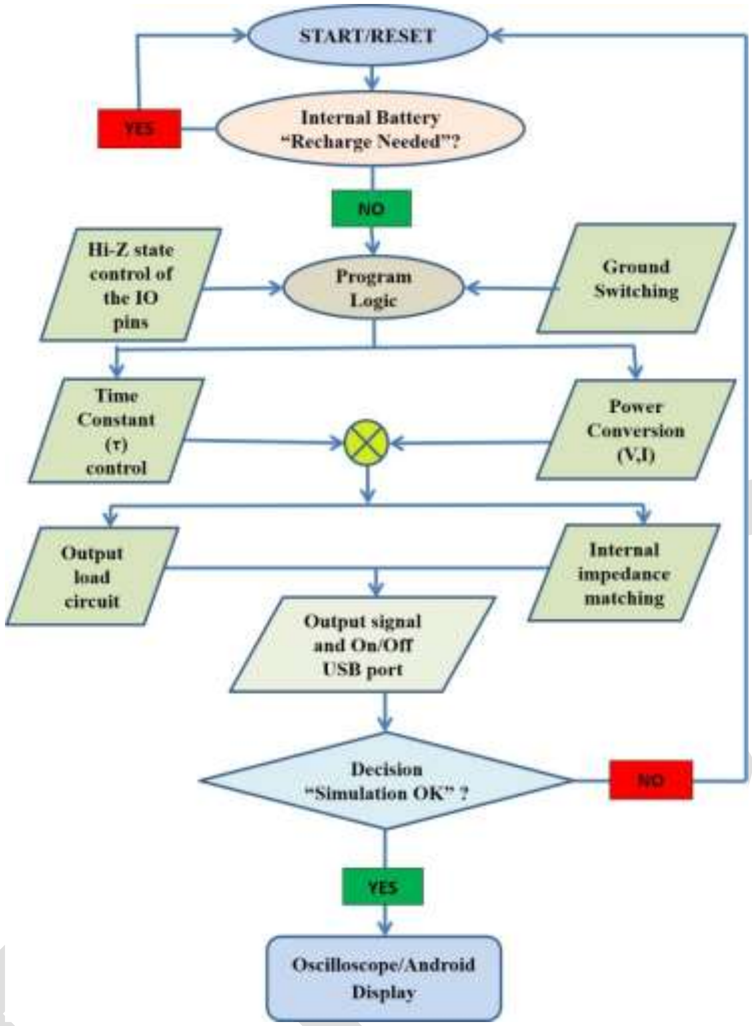


Figure 13: Flow chart of the pyroelectric simulation system.

The output load connection and the internal impedance matching are completed which leads to the output of the circuit to be displayed on the oscilloscope. The provision for recharging the batteries through the same universal serial bus (USB) as uploading program codes adds to the flexibility of the entire system. There is another provision in the system that it allows the system to switch "ON" only when the oscilloscope probe is connected to it. The sensing used to switch the system "ON" when the oscilloscope probe is connected and is the process to recharge the battery is unique in the sense that this switching process is implemented with an objective to save unnecessary power usage from the system. The design of the software framework also allowing the user to monitor all necessary data from the simulation on the computer screen exactly showing the simulation result values required to get to a detailed understanding of the behavior of the pyroelectric material under simulation.

RESULTS AND DISCUSSION

The simulation system functioned properly meeting the intended and desired objectives for a fully programmable pyroelectric portable simulation system. The system performance has been verified to various changes in the deciding parameters and every time the system has performed satisfactorily. Different load changes are precisely simulated by the simulating system and matching the waveforms resulted from the PSpice simulation of that particular condition. The waveforms resemble precisely the waveforms from pyroelectric material and have proved extremely handy in simulation of various applications of pyroelectric material. The program for controlling the circuit has achieved the expectations of a user friendly platform that is very essential for easy operation of the simulation system. The deciding parameters of the system can be easily changed using the program and thus save valuable time to make necessary changes adapting to various condition intended to be simulated. This system can play a defining role in designing futuristic applications of pyroelectric materials as they can provide deciding values necessary to engender a flawless and working application. Engineers and researchers will be the most benefited and will be greatly encouraged to explore wider area of pyroelectric material applications. The simulation system provides the energy generated from the pyroelectric material that will help decide the applications defined by energy requirements. The output signal waveforms obtained at different loading of the pyroelectric material are shown in the Figure 14 and Figure 15. The variations expected in the waveforms when simulating a particular condition also resembles that of a pyroelectric material under that particular condition.

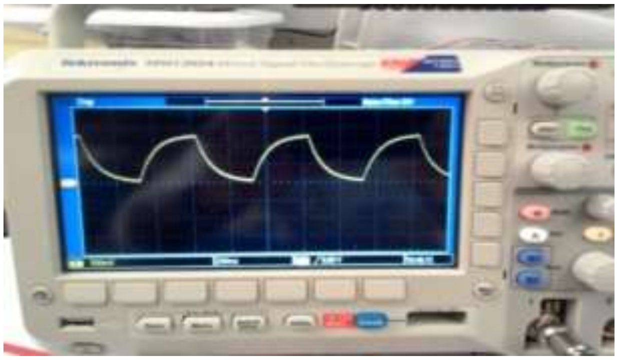


Figure 14: Output signal waveform at lower loading.

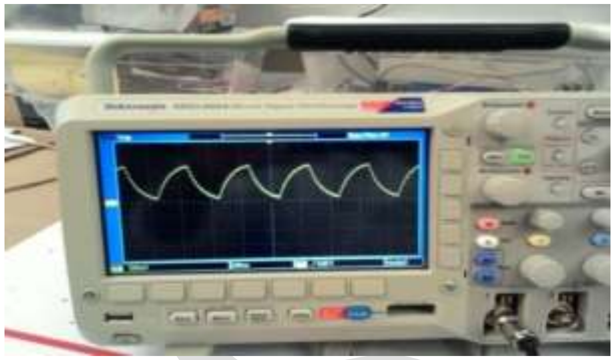


Figure 15: Output signal waveform at higher loading.

ACKNOWLEDGMENT

Authors like to thank UTSA_OCI for encouragements and assistance towards advancement of this technology. Furthermore, few online picture illustrations are made available here to clarify existing systems and technologies. This technology is currently under process of filing for a patent at USPTO through UTSA_OCI.

CONCLUSION

The use and benefits of the pyroelectric simulation system cannot be limited to sophisticated applications by researchers and engineers working on the application of pyroelectric materials. This simulation system can also come to the learning of pyroelectric material behavior. This simulation system can be easily carried for display and teaching to school pupils regarding the pyroelectricity and their behavior under different condition that will encourage future generations to take up challenging experiments in the application of pyroelectric material. For more realistic and successful application of the alternate energy source that world is craving for, the simulation system can help bring about breakthroughs in the research of pyroelectric material and their applications. This simulation system is thus equally useful in industries as well as research institutions and should be an inseparable part of researches involving pyroelectric materials and their applications.

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