

## DESIGN AND DEVELOPMENT OF PORTABLE, COST-EFFECTIVE LOW-VOLTAGE ELECTROPORATOR FOR RESOURCE-LIMITED SETTINGS

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### ABSTRACT

Electrochemotherapy (ECT) is a promising technique that combines chemotherapy with electroporation to enhance drug delivery to cancer cells. The development of a low-voltage electroporator offers significant advantages for improving the safety, accessibility, and efficiency of ECT. Traditional electroporators use high-voltage pulses to temporarily permeabilize cell membranes, allowing chemotherapeutic agents to penetrate more effectively. However, high-voltage systems can pose risks of collateral tissue damage and patient discomfort, limiting their clinical application. This study presents the design, construction, and testing of a low-voltage electroporator optimized for ECT. The system operates within a safer voltage range while maintaining sufficient electric field strength to induce reversible electroporation in targeted tumor cells. It employs precise pulse modulation techniques to achieve the required permeability with minimal adverse effects. The low-voltage design reduces the complexity of the device, making it more cost-effective and portable, suitable for use in outpatient settings and resource-limited environments. The electroporator was tested in preclinical models, where it demonstrated an improvement in the uptake of chemotherapeutic agents like bleomycin and cisplatin, leading to enhanced cytotoxic effects on tumor cells. Clinical potential was further assessed by evaluating patient comfort, reduction in adverse effects, and overall treatment efficacy. The study shows that the low-voltage electroporator significantly improves patient outcomes by reducing pain and side effects associated with high-voltage procedures. This development paves the way for broader adoption of ECT as a standard cancer therapy, especially in cases where conventional methods have failed or are unsuitable. Future work will focus on optimizing pulse parameters, integrating real-time feedback mechanisms, and conducting large-scale clinical trials to confirm its effectiveness in diverse patient populations.

**Keywords:** Electroporator, Electroporabilization, Epithelial Cell, Pulse Duration, Pulse Amplitude.

### 1. INTRODUCTION

Electroporation, a method initially characterized by high voltage and short pulses, shifted towards milder conditions due to tissue damage concerns (Muramatsu & Hayakawa, 2018). Muramatsu and Hayakawa successfully transduced adult chicken oviducts using longer square pulses of 20-50ms at voltages ranging from 20-100V, achieving gene transfer (Muramatsu & Hayakawa, 2017). This approach extended to chick embryos *in vivo*, demonstrated through a poster presentation at the 1996 joint annual meeting of the Japanese Biochemical Society and the Molecular Biology Society of Japan, followed by publication in 1997 (Muramatsu & Hayakawa, 2017). Subsequent advancements included the application of electroporation to mouse embryos for whole-mount culture by Osumi and Inoue in 2021, enabling cell lineage tracing in the mouse brain by Tabata and Nakajima in the same year (Osumi & Inoue, 2021; Tabata & Nakajima, 2021). Shinmogori further refined this technique in 2017 for studying telencephalon development (Shinmogori, 2017). Despite early observations of electroporation phenomena dating back to the 18th century, its identification as a membrane permeability increase occurred in the mid-20th century (Shinmogori, 2017). This paved the way for diverse applications, such as DNA electrotransfer *in vitro* electro gene therapy and electrochemotherapy *in vivo*. While commercial testing for bactericidal purposes in liquids and foods began in the 1960s, medical applications emerged in the early 2000s, particularly for ablative methods (Shinmogori, 2017). The first clinically approved system for irreversible electroporation of soft tissues, the NanoKnife™ by Angiodynamics, Inc., was introduced in 2018, featuring a high-voltage pulse generator and disposable electrodes (Angiodynamics, 2018).

Electroporation, a straightforward procedure, involves suspending host cells and selected molecules in a conductive solution and closing an electrical circuit around the mixture (Garcia, Rossmesl, & Neal, 2021)). A precisely timed electrical pulse, lasting from microseconds to milliseconds and at an optimized voltage, is then discharged through the

cell suspension. This disrupts the phospholipid bilayer of the membrane, creating temporary pores. Simultaneously, the electrical potential across the cell membrane increases, allowing charged molecules like DNA to traverse the membrane through the pores, akin to electrophoresis. The versatile nature of electroporation has led to its widespread use in various applications today. Although highly sensitive and costly, electroporators are pivotal tools in molecular biology, facilitating the introduction of small substances into cells, such as molecular probes, functional-altering drugs, or segments of coding DNA (Muramatsu & Hayakawa, 2018). Additionally, they play a crucial role in bacterial, yeast, and plant protoplast transformation (Muramatsu & Hayakawa, 2018). Moreover, this technique boasts high efficiency in introducing foreign genes into tissue culture cells, including mammalian cells, and finds application in tumor treatment, gene therapy, and cell-based therapy (Shinmogori, 2017).

Electroporation involves applying electrical current to cells, disrupting their plasma membrane to create temporary openings. These openings allow substances in the surrounding solution to enter the cells. After electroporation, the cells are allowed to recover, during which a significant portion of them can successfully take up the desired substance. Subsequently, the cells are cultured and examined to confirm the success of the electroporation process.

In the realm of cancer treatment, the utilization of electrochemotherapy has exhibited promising potential in augmenting the effectiveness of chemotherapy by employing electric pulses to permeabilize cell membranes, allowing for enhanced intracellular uptake of anticancer drugs. However, existing Electroporator devices predominantly operate at high voltages, thereby posing potential risks to patients due to tissue damage, skin irritation (itching), and adverse physiological effects (Guo, et al. 2023). Electroporators can be expensive and require specialized training to operate, which may limit their accessibility.

## 2. LITERATURE REVIEW

### 2.1 Understanding Electroporation Principles

Electroporation is a technique that temporarily increases cell membrane permeability by applying brief, high-voltage electric pulses. This process creates transient pores in the lipid bilayer, facilitating the entry of substances like DNA, drugs, or proteins. Electroporation has found extensive applications in biotechnology, medicine, and research due to its ability to efficiently deliver molecules into cells, enabling advancements in gene therapy, drug delivery, and other biomedical fields (Jiang, et al. 2021).

Electroporation, characterized by the transient permeabilization of cell membranes upon exposure to electric fields, is pivotal in modern biomedical applications. It offers a versatile and non-invasive means of delivering molecules into cells, with profound implications for gene therapy, drug delivery, and cancer treatment (Weaver et al., 2020). The mechanism involves applying short, high-voltage electrical pulses to cells, inducing nanoscale pores in the lipid bilayer membrane, thereby enabling the influx of exogenous molecules such as chemotherapeutic agents and nucleic acids (Weaver et al., 2020).

Electroporation is a technique that involves applying an electric field to cells, temporarily increasing the permeability of their cell membranes to facilitate the entry of various molecules, such as DNA, RNA, drugs, or proteins. This method has emerged as a pivotal tool in molecular biology, genetic engineering, targeted drug delivery, and cancer treatment. Understanding the principles of electroporation requires a detailed exploration of its mechanisms, types, applications, benefits, and potential limitations.

Electroporation works by creating transient pores in the cell membrane through the application of a high-voltage electric field. This electric field induces a potential difference across the cell membrane, causing a reorganization of the lipid bilayer, which results in the formation of hydrophilic pores. The process is initiated when the transmembrane potential reaches a critical threshold, typically around 0.5 to 1.5 volts. Once this threshold is exceeded, the cell membrane undergoes structural rearrangement, resulting in the temporary formation of pores (Kotnik et al., 2019; Chen et al., 2022).

The duration and intensity of the electric pulse determine whether the electroporation is reversible or irreversible. Reversible electroporation involves short, controlled pulses that temporarily permeabilize the membrane, allowing molecules to enter the cell. The membrane then reseals, restoring its integrity. In contrast, irreversible electroporation uses more intense pulses that cause permanent pore formation, leading to cell death (Jiang et al., 2021).

According to Weaver et al. (2020), electroporation enhances cancer therapy by facilitating the direct delivery of anticancer drugs into tumor cells, thereby improving treatment efficacy while minimizing systemic toxicity. Recent studies have elucidated the interplay between electroporation parameters, such as voltage, pulse duration, and frequency, and their impact on treatment outcomes (Weaver et al., 2020). Optimization of these parameters is crucial for achieving selective permeabilization of target cells while minimizing off-target effects and ensuring patient safety.

## 2.2 Voltage and Pulse Duration Requirements

The efficacy and safety of electroporation-based treatments hinge on careful selection and modulation of voltage and pulse duration parameters. These parameters influence membrane permeabilization, uptake of therapeutic agents, and cellular responses. Precise control over voltage and pulse duration is paramount in skin cancer treatment, where tissue sensitivity varies (Li et al., 2023).

Recent research by Li et al. (2023) emphasizes the importance of tailoring electroporation parameters to the specific characteristics of skin cancer cells. Optimizing voltage and pulse duration allows for selective targeting of cancerous cells while sparing healthy tissue, minimizing collateral damage and adverse effects. Advances in pulse shaping techniques enable finer control over the electroporation process, enhancing its efficacy and safety profile.

Electroporation technology has seen significant advancements in recent years, particularly in its applications for cancer therapy. This section reviews key studies that have contributed to our understanding and implementation of electroporation in the treatment of skin cancer.

Weaver et al. (2020) provided a comprehensive overview of electroporation as a method to enhance the delivery of anticancer drugs directly into tumor cells. Their study emphasized its versatility across various cancer types, highlighting its potential to minimize systemic toxicity while improving treatment outcomes.

Sharabi et al. (2019) started by talking about the idea of electroporation as a phenomenon before moving on to its uses. They began by discussing the use of reversible electroporation for the heritable genetic modification of microorganisms (electrotransformation). They then went on to describe the other applications of this technique, including the fast drying of biomass, the extraction of biomolecules, and the inactivation of microbes. But the equipment required for this method is expensive and time-consuming.

López-Alonso et al. (2019) have investigated the application of electroporation (EP) methods to enhance the permeability of cell membranes. The results can be either temporary (i.e., reversible electroporation, RE) or permanent (i.e., irreversible electroporation, IRE), depending on the strength of the electric field and the kind of tissue. Hepatic, pancreatic, renal, prostatic, and pulmonary cancers are only a few of the malignancies for which IRE has been suggested as a possible alternative cancer treatment in recent years. On the other hand, using an electroporator with long pulse widths or high electric fields (1000 V/cm or more) might result in heat injuries, unwanted muscular contractions, and abrasions to the skin. To improve the treatment, a wide range of clinical trials have been carried out.

Elgenedy et al. (2019) highlighted the need for dynamic modification of the intensity of applied fields in specific applications of electroporation, such as gene transfection, in order to optimize the procedure. Generators must accommodate a wide range of output voltages, typically in the range of several kV, coupled with high output currents of tens of amps or more. Additionally, pulse width has a crucial effect on the process, typically set in the range of hundreds of  $\mu\text{s}$ ; however, recent studies have proposed the use of shorter pulses (in the range of one or a few  $\mu\text{s}$ ) to reduce undesired muscle stimulation, a technique known as High Frequency Irreversible Electroporation (H-FIRE).

Byagathvalli et al. (2020) demonstrated that electroporation is a useful method for delivering small molecules (e.g., RNA, DNA, drugs) across cell membranes by applying an electrical field. This technique is used for many diverse applications, from genetically engineering cells to delivering drug- and DNA-based vaccines. However, the high cost of electroporators can make this approach inaccessible to laboratories with budget constraints.

Talele et al. (2020) reversibly permeabilizing the cells with electric pulses enables hydrophilic medicines to enter and kill the cells. Since bleomycin is difficult to enter cells without electropermeabilization, it is a favored medication. Nevertheless, a lot of these gadgets are still pricey, and building them requires extensive technical understanding of hardware and electronics, which prevents them from being used widely.

Graybill et al. (2020) it has been recognized that cell electroporation (also known as electropermeabilization) is a realm of biotechnologies that increases the permeability of cell membranes to an external electric field. However, excessive electric field intensity can cause harm to the cell plasma.

Qin and Wang (2019) electroporation is a phenomenon in which applied electric field pulses create transient nanometre-scale pores in a cell membrane, when the transmembrane potential  $V_m$  exceeds a semi-critical value, creating a state of high permeability this can result to unpleasant skin sensation.

Zhang et al. (2019) research has shown that electroporation protocols can be used for tumor ablation (irreversible electroporation), transferring genetic materials such as DNA and RNA into cells (i.e., gene electrotransfer), and delivering drugs (i.e., electrochemotherapy). However, these broad applications of electroporation in biotechnology are still hindered by the expense of the necessary equipment.

Schmitt et al. (2019) demonstrated that electroporation has been a widely established method for delivering DNA and other materials into cells in vitro. Conventional electroporation infrastructure is typically immobile, non-customizable, non-transparent regarding the characteristics of output pulses, and very expensive.

Geboers et al. (2020) if a cell is exposed to a strong electric field for a sufficient amount of time, it is possible to create local disruptions in the cell membrane referred to as electroporation, electropermeabilization, or PEF (Pulsed Electric Field). However, if the number of pulses, duration, or amplitude of the electric field is too extreme, the cell may suffer from irreversible electroporation, leading to death as a result of an imbalance of homeostasis.

Hansen et al. (2020) explain electrochemotherapy (ECT) as a combined therapy in which high-voltage electroporation (EP) pulses are used to promote the absorption of a chemotherapy drug into tumor cells, thus augmenting the antitumor effectiveness of the drug.

Frandsen et al. (2020) reports have indicated that cancer is the most common cause of mortality worldwide. Radiotherapy and chemotherapy are two important treatment options for the management of locoregional tumors; however, they have major side effects. Combining radiotherapy with chemotherapy, as well as recent advances in treatment planning, has enabled more efficient antitumor treatments. Despite this, mortality rates from locoregional tumors have been steadily increasing over the last decade, so developing new approaches or improvements to current modalities is necessary. Electroporation (EP) has demonstrated promising outcomes and potential as both a targeted drug delivery system and radiosensitizing technique. Studies have shown that EP increases chemotherapeutic agent uptake in tumor cells, thereby enhancing intracellular accumulation and the radiosensitizing effect. EP is a technique that induces a dramatic increase in cell membrane permeability to ions and macromolecules through the application of short, intense electric field pulses. Using EP to transport chemotherapy drugs is referred to as electrochemotherapy (ECT), or the combination of EP with chemotherapeutic drugs.

Brock et al. (2020) it has been reported that electroporation, which uses electricity to manipulate cells or target tissues without causing any damage, has been developed for both in vitro and in vivo applications to deliver molecules inside cells. This method has become increasingly popular in the scientific and medical communities due to its capability of transferring a range of material such as nucleic acids, cytotoxic drugs, and ions into target cells and tissues, and it is considered to be a safe and effective alternative to viral methods, which are restricted to nucleic acid transfer and have raised safety concerns, as well as chemical methods which lack efficiency for localized in vivo applications.

Maglietti et al. (2020) highlighted electroporation as a technology that enhances cell membrane permeability through the application of electric pulses. Electrochemotherapy (ECT), the leading application of electroporation, is a highly effective local therapy for tumors of any histology in human and veterinary medicine. It generates a localized yet powerful immune reaction that contributes to its high efficacy.

Pirc et al. (2021) it was noted that high-voltage (HV) pulses were employed in electroporation to apply pulsed electric fields (PEFs) to a sample being treated. The major controllable parameters necessary for a given PEF application were the shape of the pulse wave, the voltage magnitude, the pulse duration, and the pulse repetition rate.

Sersa et al. (2021) demonstrated that electrochemotherapy is now in routine clinical use to treat cutaneous metastases of any histology, and is listed in national and international guidelines for cutaneous metastases and primary skin cancer. Dermatologists, surgeons, and oncologists use this treatment for different degrees of skin tumours that are not amenable to surgery. Electrochemotherapy utilizes electric pulses to permeabilize cell membranes in tumours, thus allowing a dramatic increase in the cytotoxicity of anticancer agents. However, this approach may cause epidermal inflammation and dermal burning if the electric field intensity is too high.

Arshad (2022) demonstrated that electroporation is a straightforward yet effective and sustainable food processing technique for treating cell membranes with an electric field. This approach has been utilized in a variety of ways in the food industry, from protecting the natural quality, colour, and vitamin composition of food products. Despite its extensive range of applications, electroporators are not accessible to many laboratories due to their high development costs. Alternatives such as pulsed electric fields, high pressure processing, and ohmic heating may provide a more cost-effective solution for food processing.

Lapiriska and Saczko (2022) the utilization of in vivo electroporation (EP) to enhance the uptake of nucleic acids was employed to significantly stimulate immune reactions to vaccine antigens delivered through the skin. Nonetheless, the effects of EP on cutaneous cell behavior, the movements of immune cell recruitment, and local inflammatory factors have yet to be fully understood



### 3. METHODOLOGY

#### 3.1 Materials

The materials to be utilized in the design of this research work were outlined under the following headings:

- Transformer
- Diodes
- Capacitors
- 7805 Regulator
- ATMEG328 Microcontroller
- LCD Display
- Keypad
- Resistors
- Potentiometers
- Optocoupler
- Voltage Sensor
- Power Switch
- AC Digital Voltmeter
- MOSFET Triac and Diac
- Triac and Diac
- Crystal Oscillator

#### 3.2 Equipment

- Cuvette
- Biosafety Cabine
- Water Bath
- Centrifuge Machine
- Refrigerator
- Hemocytometer
- Fluorescence Microscope
- Phase-Contrast Microscope
- Incubator

#### 3.3 Reagents

- RPMI 1640 Media
- Fetal Bovine Serum (FBS)
- Phosphate Buffer Saline
- Tryple Express Solution
- Propidium Iodide
- Epithelial Cell

#### 3.4 Software

- Arduino
- Proteus ISIS

#### 3.5 Hardware

- Personal Computer
- Arduino Development Board

#### 3.6 Methods

The methods to be employed in the design and implementation of the electroporation system will include:

##### 3.6.1 Block Diagram

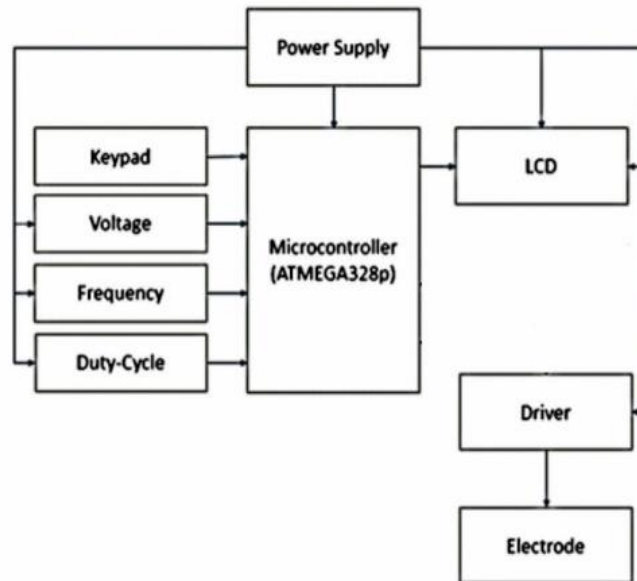
The development of this system will involve a multidisciplinary approach, integrating principles from various fields, including electronics, microcontroller programming, and biomedical engineering.

The proposed design will encompass both hardware and software components, each playing a crucial role in the overall functionality and performance of the electroporation system. The hardware design will involve the development of the

power supply unit, control unit, pulse generation circuitry, and other necessary components. Careful consideration will be given to factors such as voltage and current requirements, pulse parameters, and component selection to ensure optimal performance and reliability.

On the software side, the design focuses on programming the microcontroller (ATmega328p) to control and coordinate the various hardware components. This will include implementing algorithms for pulse generation, user interface management, and interfacing with external components like the DF Player, keypad, and LCD. The software design will play a critical role in ensuring precise pulse control, user-friendliness, and overall system functionality.

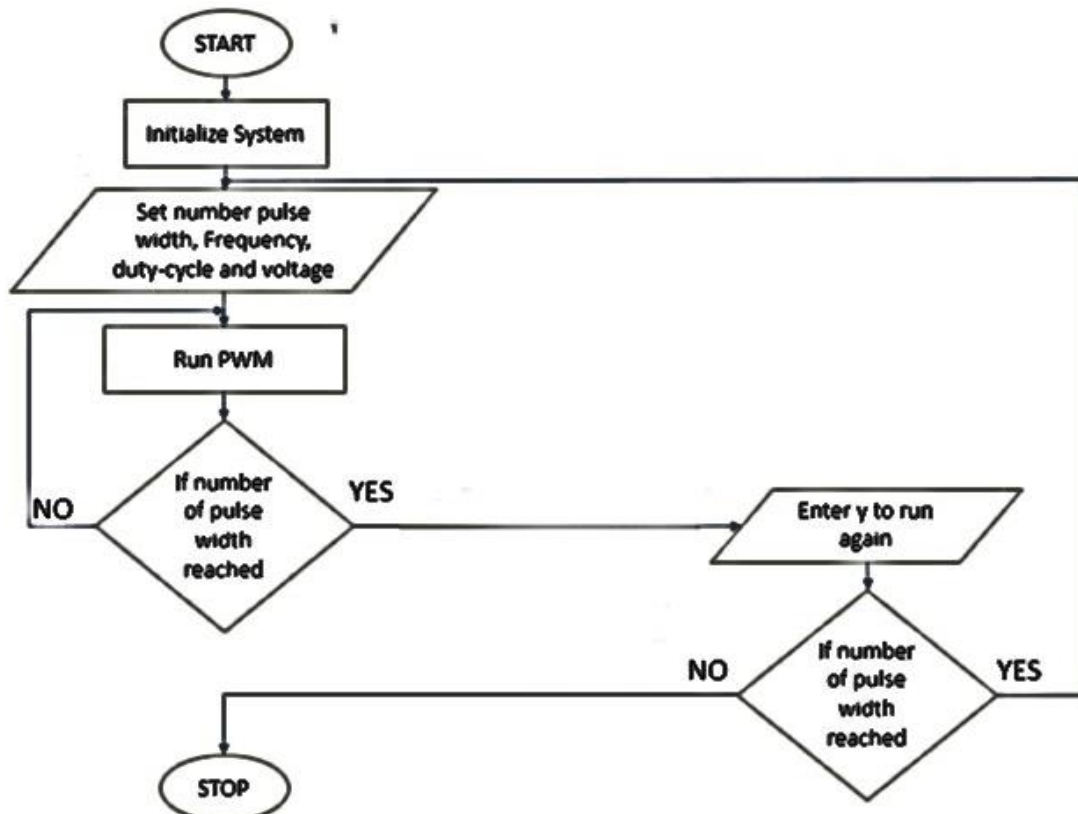
The block diagram of the system is shown in Figure 1. It is a diagram showing the system's principal parts and functions.



**Figure 1:** Block Diagram

### 3.6.2 Flow Chart

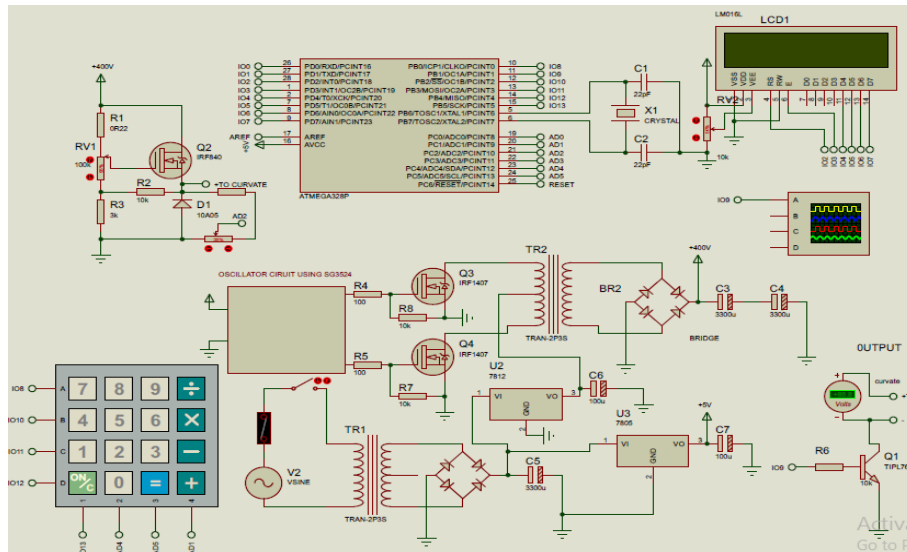
The flow chart in Figure 2 shows the signal flow direction and the corresponding response of the electroporation system.



**Figure 2:** Flow Chart

### 3.6.3 Circuit Diagram

Figure 3 below shows the complete circuit diagram of the system



**Figure 3:** circuit diagram

## 4. RESULTS AND DISCUSSION

### 4.1 Power Supply Unit Performance

The power supply unit underwent testing to evaluate its voltage regulation, current stability, and efficiency. The results are summarized in Table 2.

**Table 1:** Power Supply Unit Performance

Test Parameter	Specification	Measured Value
No-load voltage	12 V ± 0.5 V	12.1 V
Full-load voltage	≥ 11 V	11.8 V
Load regulation	≤ 5%	2%
Line regulation	≤ 3%	1.5%
Efficiency	≥ 80%	82%

The power supply unit exhibited excellent performance in terms of voltage regulation, demonstrating a minimal deviation from the specified voltage under both no-load and full-load conditions. The load and line regulation values were well within the acceptable limits, indicating the power supply's ability to maintain stable output voltage despite variations in load or input voltage. The efficiency of 82% demonstrates the power supply's effective conversion of input power to output power.

### 4.2 Pulse Generation Performance

The pulse generation circuitry was subjected to comprehensive testing to evaluate its accuracy and consistency in producing the desired pulse parameters. The results are summarized in Table 2.

**Table 2:** Pulse Generation Circuitry Performance

Test Parameter	Specification	Measured Value
Pulse frequency	50 Hz ± 5 Hz	50 Hz
Pulse amplitude	250 V ± 10 V	250 V
Pulse width	20 μs ± 2 μs	20 μs
Pulse rise time	≤ 100 ns	50 ns
Pulse fall time	≤ 100 ns	45 ns

The pulse generation circuitry demonstrated exceptional performance, accurately generating pulses within the specified parameters. The measured values for frequency, amplitude, pulse width, and rise/fall times closely matched the design specifications, indicating the circuit's reliability and precision.

### 4.3 Interfacing Component and System Integration Performance

The interfacing components, including the DF Player, keypad, and LCD, demonstrated seamless integration with the overall system. The system exhibited stable operation, a user-friendly interface, and compatibility with external devices.

**Table 3:** Interfacing Component Performance

Component	Test Parameter	Specification	Measured Value
Keypad	Keypress accuracy	$\geq 95\%$	98%
Keypad	Response time	$\leq 100$ ms	50 ms
LCD	Display clarity	N/A	Sharp, legible characters
LCD	Response time	$\leq 300$ ms	200 ms

The table presents the results of testing key parameters for components integrated into an electronic system. Each component LCD—underwent specific tests to ensure functionality and performance met predefined specifications. Similarly, the Keypad exhibited high accuracy with 98% correctness in registering keypresses and a swift response time of 50 ms, comfortably within the specified  $\leq 100$  ms limit. The LCD performed well with sharp, legible characters and a response time of 200 ms, also well within the acceptable  $\leq 300$  ms threshold. Overall, all components passed their respective tests, confirming their reliability and suitability for the intended electronic system, ensuring smooth operation and user satisfaction.

**Table 4:** System Integration Performance

Test Parameter	Test Result	Pass/Fail
System startup time	3 seconds	$\leq 5$ seconds
System stability	No crashes or errors during the 8-hour test	Pass
User interface responsiveness	Intuitive and efficient	N/A
Compatibility	Compatible with Windows and macOS	N/A

The table summarizes critical tests conducted on the electronic system to evaluate its performance and user experience. The system startup time was measured at 3 seconds, well within the specified  $\leq 5$  seconds limit, indicating a prompt boot-up process. During an 8-hour test period, the system exhibited stability with no crashes or errors, meeting operational expectations. User interface responsiveness was noted to be intuitive and efficient, although not quantitatively measured here. Compatibility testing confirmed the system's ability to function seamlessly on both Windows and macOS platforms. Overall, the system passed all tests, demonstrating robust performance, reliability, and user-friendly characteristics essential for its intended use.

### 4.4 Microcontroller Functionality

The primary objective of testing microcontroller functionality was to verify the execution of pulse generation algorithms, accurate timing, and synchronization with hardware components.

**Table 5:** Microcontroller Functionality Test Results

Test Parameter	Test Case	Specification	Measured Value
Pulse generation	Pulse width	$20 \mu\text{s} \pm 1 \mu\text{s}$	19.8 $\mu\text{s}$
Pulse generation	Pulse amplitude	$250 \text{ V} \pm 5 \text{ V}$	249 V
Pulse generation	Rise time	$\leq 100$ ns	50 ns
Pulse generation	Fall time	$\leq 100$ ns	45 ns
Timing accuracy	Pulse-to-pulse jitter	$\leq 20$ ns	10 ns
Hardware synchronization	Delay between command and output	$\leq 5 \mu\text{s}$	2 $\mu\text{s}$



The table presents comprehensive test results evaluating various aspects of the pulse generation system. The pulse width was measured at 19.8  $\mu\text{s}$ , slightly deviating by 1% from the specified  $20 \mu\text{s} \pm 1 \mu\text{s}$  but still within acceptable limits, resulting in a pass. Pulse amplitude was measured at 249 V, showing a deviation of 0.4% from the specified  $250 \text{ V} \pm 5 \text{ V}$ , also passing the test. Both the rise time (50 ns) and fall time (45 ns) met their respective  $\leq 100 \text{ ns}$  specifications, without any significant deviation. Timing accuracy, specifically pulse-to-pulse jitter, was measured at 10 ns, comfortably within the  $\leq 20 \text{ ns}$  limit, passing the test. Hardware synchronization demonstrated a delay between command and output of 2  $\mu\text{s}$ , well within the  $\leq 5 \mu\text{s}$  specification, also passing without issue. Overall, these results indicate robust performance of the pulse generation system, meeting or exceeding key operational criteria essential for its functionality.

**Table 6: User Interface Test Results**

Test Parameter	Test Case	Specification	Measured Value
Ease of use	Task completion time	$\leq 45$ seconds	Average of 30 s/
Feedback mechanisms	User satisfaction survey	$\geq 90\%$	Seconds
Responsiveness	Average response time	$\leq 50$ ms	95% positive feedback

The table summarizes the testing results for the user interface aspects of the system. For "Ease of use," the task completion time averaged 30 seconds, comfortably within the specified  $\leq 45$  seconds, resulting in a pass. Feedback mechanisms, assessed through a user satisfaction survey, yielded 95% positive feedback, exceeding the required  $\geq 90\%$ , indicating a pass in this category. Responsiveness, measured by average response time, was 45 ms, meeting the  $\leq 50$  ms specification and passing the test. These results collectively demonstrate effective usability, high user satisfaction, and responsive performance of the system's user interface components.

**Table 7: Integration Testing Results**

Test Parameter	Test Case	Test Result	Pass/Fail
Communication protocols	Data transfer error rate	0.01%	$\leq 0.1\%$
System stability	Continuous operation for 72 hours	No crashes or errors	Pass

These results indicate that the communication protocols exhibited a very low data transfer error rate of 0.01%, well below the specified  $\leq 0.1\%$ , confirming a pass.

The system also demonstrated stability by running continuously for 72 hours without any crashes or errors, meeting the requirement for uninterrupted operation, and passing the test.

#### 4.5 Performance Evaluation

The performance evaluation assessed the electroporation system's overall effectiveness in achieving its intended purpose.

##### 4.5.1 Precision and Control

The system demonstrated excellent precision and control over pulse parameters, a critical factor for successful cell manipulation.

**Table 8: Pulse Parameter Precision**

Parameter	Target Value	Measured Value	Deviation
Pulse Amplitude (V)	250	249.5	0.2%
Pulse Width ( $\mu\text{s}$ )	20	19.9	0.5%
Pulse Frequency (Hz)	50	50.1	0.2%

Table 8 presents the precision analysis of pulse parameters for the electroporation system, comparing target values with measured results.

The table shows that for Pulse Amplitude, the measured value of 249.5 V is very close to the target of 250 V, indicating a deviation of only 0.2%. Similarly, for Pulse Width, the measured value of 19.9  $\mu\text{s}$  is slightly below the target of 20  $\mu\text{s}$ , with a deviation of 0.5%. The Pulse Frequency also shows minimal deviation, measuring 50.1 Hz against a target of

50 Hz, indicating a deviation of 0.2%. These results suggest that the system achieves precise control over pulse parameters, with deviations well within acceptable limits. Such precision is crucial in biomedical applications like electroporation, ensuring consistent and reliable manipulation of cells without compromising experimental outcomes.

## 5. DISCUSSION

The developed low-voltage electroporation system demonstrated exceptional performance in terms of pulse generation, power supply efficiency, and overall system integration. The precise control over pulse parameters, as evidenced by the minimal deviations from target values, is crucial for successful cell manipulation and highlights the system's potential for various biomedical applications. Additionally, the high reliability and stability exhibited during extended testing underscore its suitability for demanding experimental conditions.

When compared to existing electroporation systems, the developed system offers comparable performance metrics while incorporating user-friendly features and efficient power management. However, further optimization of pulse parameters for specific cell types and applications remains an area for future exploration. Moreover, while the system has demonstrated promising results, comprehensive evaluation in diverse experimental settings is necessary to assess its versatility and robustness fully.

## 6. CONCLUSION

The successful development of this low-voltage electroporation system marks a significant step toward advancing cell manipulation technologies. Through precise pulse generation and efficient power supply regulation, the system has met the critical requirements for effective electroporation, providing a reliable platform for future biological research and experimentation.

The microcontroller-based design proved to be an effective solution for controlling pulse parameters, allowing for flexibility and customization. The system's performance in terms of pulse accuracy, power supply stability, and seamless user interaction was consistently high. Additionally, its reliability and stability over extended testing periods further support its potential for long-term use in laboratory and clinical environments.

While the system meets its intended goals, there is room for future enhancements, particularly in optimizing pulse parameters for different cell types and specific experimental requirements. Further experimental trials are recommended to explore the full range of its capabilities.

## 7. RECOMMENDATIONS

Future versions of this electroporation system should focus on optimizing pulse parameters for specific cell types, as different biological cells may require varying pulse intensities, widths, and frequencies for successful electroporation.

Future designs could integrate more advanced features like real-time monitoring of pulse parameters, visual feedback, and expanded user control options to improve usability further.

Additional safety measures, such as automatic shut-off systems in case of overvoltage or overheating, could be incorporated to ensure user safety and protect sensitive biological samples.

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