

An Overview of Pulsed Power System Design and Applications

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Abstract

Pulsed power is the delivery of energy to a load in very short time frames. By reducing the time component, massive instantaneous power magnitudes are achieved, scaling up to the high terawatt range in some modern applications. The study of general system design and its applications have great academic merit. By analyzing the structure and breakdown of such a system, uses in various fields have been discovered, including cancer treatment and manufacturing. Liberty hopes to gain access to this research field by replicating two existing systems (with permission) and conducting tests to aid in societal progress. Results of high voltage pulse generators with nanosecond fall times can be expected in the future.

An Overview of Pulsed Power System Design and Applications

Introduction

The study of pulsed power and its applications is a growing topic of study within the scientific and engineering communities, with state-of-the-art technologies and systems revolutionizing processes in many different fields. The main goal behind the research conducted for this thesis is to show typical system design and application benefits with the hope of propagating interest in the field as well as bringing about a more advanced state of research at Liberty University.

Background

Scientific Background

Pulsed power involves the delivery of high amounts of energy within a condensed timeframe. This is delivered through high voltage or high-current pulses by a pulsed power generator. By condensing the time frame that it takes for the energy to be delivered, the generator is able to deliver a pulse with substantial instantaneous power [1]. The relationship between instantaneous power, time, voltage, current, and charge is shown below:

$$P = VI \quad (1)$$

$$V = \frac{E}{Q} \quad (2)$$

$$I = \frac{Q}{t} \quad (3)$$

By substituting equations (2) and (3) into equation (1), it is easily shown that:

$$P = \frac{E}{t} \quad (4)$$

This relationship shows how a decrease in time while maintaining constant energy would increase the instantaneous power delivered to a load (inverse relationship between time and instantaneous power). Another important thing to keep in mind when considering this relationship is average power. Average power is the time average of power for a given time unit. This shows that average power stays the same regardless of the delivery time (same total energy transferred).

Typical times for the delivery of these pulses range from milliseconds (1×10^{-3}) to picoseconds (1×10^{-12}) [2]. If one Watt of power is defined as 1 Joule per second, then that same Joule of energy delivered over one picosecond will produce 1 terawatt of instantaneous power, or 1000000000000 Watts. This level of power is being produced for an extremely small amount of time, but from this calculation we can see just how much these pulses can produce depending on the timeframe.

As the idea of pulsed power is centralized around releasing energy, components such as capacitors and inductors (energy stored in electric and magnetic fields respectively) are large parts of Pulsed Power design. Capacitors with the ability to discharge in the microsecond range have been developed for military purposes [3]. This is indicative of some of the current operations happening in this field. Other engineers have given examples of their designs in reports and journals. An example of a solid-state nanosecond pulse generator is shown in [4].

Historical Background

This section will cover a historical background of pulsed power, both its origins and development throughout time. This is important to the study of this topic as it helps identify the current state of work and what direction the work in this topic will take as research continues with time.

Beginnings

Sandia National Laboratories is considered by most to be the birthplace of pulsed power technology. This process, based on work done Marx Generators in the early 20th century, started in the 1950s with the intent to utilize it in military applications. Marx Generators are power generation systems developed by Professor Erwin Marx in 1923 (to be discussed in more detail at a later point).

Due to growing concern of the effect of Soviet atomic weapons and radiation on United States military equipment, Sandia was tasked with finding ways to test the vulnerability of this equipment (gamma radiation in particular). High voltage and very short pulses were needed to effectively test the potential weapon effects, and this is when pulsed power systems started to become heavily developed at Sandia, with scientists trying to find the most successful ways to implement these systems [5]

Atomic Weapons Research Establishment

J.C. Martin and other team members at Atomic Weapons Research Establishment (or AWRE) were among the first to develop systems capable of delivering pulses of megavolt levels if the time range was kept in the tens of nanoseconds. This was accomplished through use of electrodes of very small dimensions inside a suitable vacuum. The teams inside the United States

utilized much of this research to test the effects of X-Ray and gamma radiation on military equipment [6]. This collaboration was enabled by the Mutual Defense Agreement of 1958, which set the baseline for cooperation and work between the United States and Britain on the subject [5].

Bridge into Modern Day

According to [6], the most successful generators constructed in the United States in the early period were Marx Generators “charging a single liquid-dielectric transmission line system that was switched by liquid spark gaps.” A group called Physics International Company (PI) constructed the first of these systems in 1964, effectively scaling the output of pulsed power systems by a large factor, which led to an increased application range of pulsed power. The term pulsed power was first introduced by PI employees at this time to describe their work. Once the production of these systems was found to have such a revolutionary effect, research started to expand across the world and across many different fields, such as manufacturing, laser-beam technology, biological effects, and more. This brings us into the present-day era of research on pulsed power.

State of Work at LUSE Background

Liberty University’s School of Engineering (LUSE) has recognized the benefits and advantages of researching pulsed power system design and applications in the modern era of engineering. A brief background is given here of the work conducted at LUSE, while a more in-depth study of methodology and results is given further on in this thesis.

Research done on pulsed power at LUSE has been conducted under Dr. Carl Pettiford, Associate Dean of LUSE. Joshua Zaiter (author) has been working under Dr. Pettiford to verify

and replicate two existing pulsed power systems to act as a foundation for work at Liberty University on the subject. Liberty University has been given permission by the original researchers to conduct this research.

The verification process involves simulation and testing of the systems provided, as well as their individual sections and components. The physical aspect of this includes printed circuit board design, physical construction, and physical verification of the generator. If properly completed, Liberty University will obtain one or more working pulsed power generators, available for research on different topics such as cancer treatment.

General System Design

There are a great deal of factors to consider when considering, designing, constructing, and implementing a pulsed power system or generator. As this subject is extremely expansive and requires a high level of understanding, this section will seek to give a fundamental basis to the major components and sections of such a system, as well as provide examples from various sources on the topic.

Dielectric Material Considerations

When designing a pulsed power system, one of the most important things to consider is the makeup of the devices that store electric or magnetic fields. Capacitors, which store electric fields, and inductors, which store magnetic fields, are the primary components regarding this discussion and will be the indicated components when mentioning these devices.

A dielectric material is an insulating material that is used in the capacitor to increase its capacitance without causing breakdown. Capacitors often consist of two parallel plates that have

a voltage applied across them. When the voltage is applied across the plates, the capacitor will accumulate charge (Q). The capacitance of a parallel plate capacitor is given by:

$$C = \epsilon_0 \frac{A}{d} \quad (5)$$

ϵ_0 is the dielectric permittivity of a vacuum, A is the surface area, and d is the distance between the plates [7]. When a dielectric material is added between the plates, the equation for capacitance is multiplied by the dielectric constant of the material, k . The larger k is, the more capacitance. These dielectrics are easily polarized and are poor conductors of current.

These dielectric components can exist in a gaseous, liquid, or solid form. They exist not only in capacitors, but in transmission lines and transformers as well [8]. Along with the dielectric constant, discussed above, the electric breakdown strength of a material is one of the deciding properties of such a dielectric. According to [8], the “electric strength of an insulant can be defined qualitatively as the maximum field stress that the material can withstand for a given time.” To further understand the idea of electric breakdown, we reference the previous claim that dielectrics are poor conductors of current. When a given material is subject to a sufficiently high voltage, it will lose that trait and start conducting current. In the field of pulsed power, where the objective is to produce large amounts of power, often through very high voltage values, the ability of a dielectric to maintain its properties is a vital trait to consider.

The breakdown strength of a ceramic capacitor for example was found by [9] to be heavily influenced by ϵ_r , or relative permittivity. To test the breakdown strength of certain capacitor samples under DC charging and pulse charging, [9] utilized a high voltage test scheme

as well as a circuit scheme shown in [9]. Results from this study showed that breakdown strength of the dielectrics used decreased with increasing thickness of dimensions. When the dielectric constant was the independent variable of testing, results showed a nonlinear decrease of breakdown strength with an increase in dielectric constant (under DC charging). This study gives useful parameters for the proper implementation of a dielectric into pulsed power system components.

One more important note in the study of dielectric choice is made by [8]. Solids, liquids, and gaseous materials have different uses and advantages in different systems. For example, a gas or liquid can self-repair following a high voltage induced breakdown, while a solid dielectric material is unable to self-repair, i.e., it is permanently destroyed. However, if a mechanical force is in play and the system must withstand this force, a solid dielectric is necessary. Liquid dielectrics are preferable in the case of large amounts of heat loss needing to be eliminated.

Energy Storage

Continuing our discussion of pulsed power system design is the study of energy storage devices. This is considered the first main section in a pulsed power system, with the energy storage device used determining system parameters such as discharge capabilities, power, electric/magnetic field strengths, and system resilience. Dielectrics, discussed previously, are a part of the discussion of energy storage units, but this section will aim to look at the incorporation of different techniques and methods used in pulsed power generators, not necessarily the component breakdowns themselves.

[8] gives a list of requirements that an energy storage device should meet for pulsed power applications: “1) High energy density; 2) High breakdown strength; 3) High discharge

current capability; 4) Long storage time; 5) High charging and discharging efficiency; 6) Large power multiplication; 7) Repetition rate capability/long lifetime; 8) Low Specific Cost.”

The author of this list does note that certain tradeoffs are required as some requirements conflict with others.

Capacitors for Pulse Applications

High voltage capacitors, to this day, are one of the most used energy storage devices in pulsed power applications. [8] claims this is because “reliable, repetitive, fast closing switches are easier to build than the opening switches necessary to realize generators based on inductive storage.” This meets the repetition requirement outlined above. The energy hold time of these capacitors is also greatly increased compared to the hold times of inductive devices (inductors, different coil methods, and devices that store energy in magnetic fields) [8]. This meets another requirement for a storage device.

In addition to the breakdown strength of the dielectric, discussed previously, the geometry, surface area, and material used for the capacitor terminals all play a part in the high voltage strength of the capacitor. Other testing and environmental conditions such as temperature, pressure, humidity, and voltage reversal can affect the threshold for capacitor breakdown. [8] describes the effect of voltage reversal on capacitor breakdown models in this way: “If charge has been injected from the metallic-cathode side into the dielectric, the space charge field associated with it can add to the external field during voltage reversal...” This additional field placed upon the capacitor and dielectric causes the breakdown stress to be surpassed and potentially damage the component. Although capacitors are popular due to the

ease-of-use factor, it is important to keep in mind the factors that affect the lifespan of these energy storage devices as to not blindly utilize them. This is a tradeoff in the system design.

Marx Generators

Marx Generators, named after their inventor, Erwin Marx (patented in 1923), are very popular selections for energy storage devices in systems producing pulses with significantly larger amplitudes than those used on capacitor-only based systems, typically over 100 kV [8]. The transformers needed for high-power charging units become exceedingly large once the amplitudes reach 100 kV, so another method is required.

The principal idea of a Marx Generator is the storage of electrical energy in banks of capacitors, similar to how a battery operates [5]. These capacitors are connected in parallel and receive charge in parallel and are then discharged in series. This connection provides the Marx Generator with the ability to amplify a low-power signal to a sufficiently large high voltage as needed by the application. The output voltage of a Marx Generator is found by multiplying the input voltage, or charging voltage, by the number of stages in the generator circuit [10]. Conceptually, this is understood by analyzing the behavior of capacitors in parallel (connected to the same electrical node). When supplied by a voltage source, the capacitors accumulate charge at the same rate until they are fully charged and do not allow current to pass through. Once the capacitors are triggered by a high-speed switching action, the energy stored is discharged at the same time, resulting in a voltage directly proportional to the number of stages in the generator.

As implied by Ohm's Law, as impedance decreases, the available power increases for a constant voltage supply. This means that for each stage of a Marx Generator, the increased impedance makes increasing the voltage to extremely high levels (terawatt and higher) very

difficult. Although voltage is being multiplied across the stages, more and more power is being lost due to the increased impedance per stage. To solve this problem and access power needed for certain applications, Marx Generators in ultra-high-power generators must charge an intermediate capacitor used for storage [8]. By designing a system with an equivalent intermediate capacitance to the capacitance of the Marx Generator, total energy transfer is attainable. Water is often used as this intermediate capacitance. Given that water's breakdown is related to pulse duration, the transfer must occur very quickly to ensure that the system does not fail in its goal.

Other determining factors in Marx Generator design, such as stray capacitance, LC generators, variation in time constant of the load based on switching action, and synchronization of multiple Marx Generators are outside the scope of this discussion. For further information on these critical properties, see [8]. An example of simplistic Marx Generator with $n = 3$ stages and unipolar charging is shown in Figure 1.

Other Methods

Various other methods for energy storage exist for modern day pulsed power generators and systems. These include inductive storage, which utilizes inductors to store energy in magnetic fields. The advantage of this method of storage is the increase in magnitude of up to two orders in energy density as opposed to that of a capacitive system. An inductive storage amplifies voltage while a capacitive system can be viewed as a current amplifier [8]. For the sake of brevity, only this brief overview of the study is given.

Switching Methods

To properly receive high power pulses, pulsed power systems require specialized

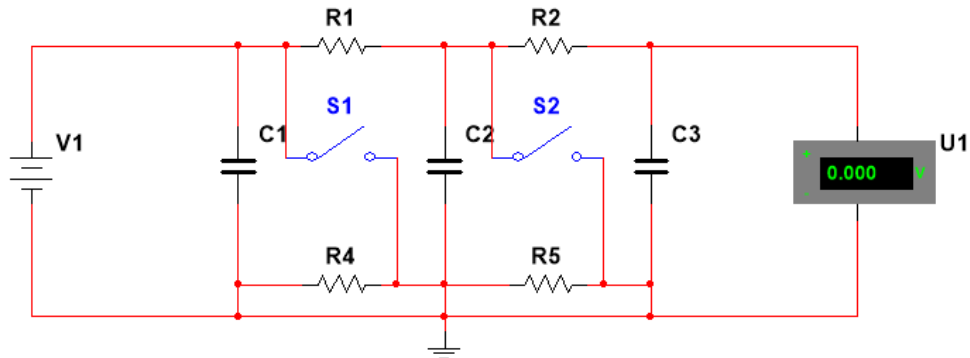


Fig. 1: Example of simplistic Marx Generator with $n = 3$ stages and unipolar charging (drawn by author). Switches in schematic represent triggers of Marx Generator. Based on [Fig. 3.9, 8].

switching methods that properly trigger discharge or stored energy. These are the next key element of a general system and lie in between the energy storage devices discussed above and the target load that receives the energy. Elements such as rise time, shape of pulse, and magnitude all depend on the implemented switching method. There are four primary stages that occur within the operation of any switching system, laid out by [8]. The first is the trigger phase, where the trigger discharge is accumulated. The second is the transition phase, where the transition between high-to-low switch impedance occurs. The stationary phase occurs when the switch has constant conductivity, and the last phase is the recovery phase where the prior electric strength is restored [8]. The major types of switching used in pulsed power systems are discussed now.

Closing Switches

The use of closing switches is needed for systems with capacitive energy storage devices. There are various types of closing switches used in modern systems. Among these are gas switches and semiconductor switches. Gas switches have high ease-of-use and have very precise trigger values. This is useful for obtaining the quick switching action needed. Gas switches are

often utilized in systems of high power for their ability to handle large currents and charges. Types of gas switches include thyratrons, pseudospark switches, ignitrons, and many others. These lend themselves to different applications and uses [8].

Semiconductor closing switches carry inherent disadvantages not found in gas switches. The enlargement of the area of the channel that has current flow is the primary way to increase switching power due to “the relatively low mobility and density of charge carriers in the plasma...” [8]. Typical semiconductor switches include thyristors and insulated-gate bipolar transistors (IGBTs).

Opening Switches

In pulsed power systems that utilize inductive storage, opening switches are needed. As the name implies, opening switches see a sudden rise in impedance when triggered. This means that current is unable to flow and pass through the switch. There are many requirements for a usable opening switch, including long current conduction time, large current with small losses, high impedance when open, and short recovery time, allowing the switch to have high repeatability. Opening switches are designed using either resistive, capacitive, or inductive elements. A common example of a resistive fuse is a fuse, such as a melting fuse, that opens when a certain heat or current condition is met. Inductive opening is realized when the value of inductance increases with time, while a capacitive opening occurs when capacitance decreases with time. Typical types of opening switches include mechanical interrupters, plasma opening switches, and plasma flow switches [8].

Applications of Pulsed Power

Pulsed power has been developed for a wide array of applications since its inception in the early 20th century. The following discussion is not an exhaustive list of applications but rather some of the more well-known use-cases that may also be of interest to Liberty University from a future-research perspective. Each application's primary use will be examined as well as peripheral items such as how it works and the scientific background of the application.

Cancer Treatment Application

The treatment of tumors and cancer is a very relevant topic in the modern-day world, with the continual search for consistent safe treatments a very pressing burden on scientists of all kinds. High voltage pulsed power generation has shown the ability to treat cancerous cells and is a great topic of interest.

What Is It?

High voltage pulses delivered in a very short timeframe, typically in the nanosecond range in modern research, have shown the ability to induce cell death in tumorous or cancerous cells. Picosecond range pulses have been experimented with in recent years, however they are not commonplace. Nanosecond high voltage pulses reach up to 300 kV/cm in many experiments [2]. The application of the generated electric fields is known as nanosecond pulse electric fields, or nsPEFs. These nsPEFs, while delivering a large instantaneous power, only deliver a low amount of actual energy to the load (in this case the tumors). The amount of energy is determined by the time interval, and with a time interval in the nanosecond range, this total remains low enough to not play a part in the thermal reactions of the cells. This method induces

no health setbacks and is attractive as a potential treatment for the future [2]. Success has been found in treating cancer such as melanoma [2], oral cancer [11], and pancreatic cancer [12].

How Does It Work?

The key to the study of the effects of pulsed power on cancerous cells is a membrane behavior known as electroporation. Electroporation occurs when an increase in the permeability in the cell membrane is created because of the applied electric fields. This is possible due to the short pulse duration. When the cell encounters an external electric field of significance, it redistributes ions in the membrane to create an opposing electric field to cancel out the field. With short duration pulses, the field can affect the inside of the cell before the membrane is able to cancel out the field. When nanosecond pulses are applied, it has been found that intracellular organelles have been affected and undergo a similar process as the cell membrane. This is known as supra-electroporation [13]. When supra-electroporation occurs, the intracellular organelles are damaged, primarily the mitochondria and nucleus of the cell. It is speculated that the damage inflicted is responsible for the triggering of apoptosis in the cancerous cells [2]. Apoptosis is the natural programmed cell death resulting from growth and age. This cell death was found to occur in tests run with high voltage amplitude pulses. In tests run with lower pulse amplitudes, the cells did not undergo apoptosis immediately but were found to release calcium internally. This release is thought to be one of the initial triggers of apoptosis [2]. Another possible cause of the damage seen to the cells is the damage inflicted on DNA in the cell nucleus. This is a very plausible option but is unconfirmed as of current research [11]. The release of thermal energy has been shown to be a non-factor in the triggering of apoptosis, as the amount of energy delivered in the short pulses is not significant enough to change the temperature of the cell [14]. In-depth

information on the methodology, results, and justifications of a modern-day study into the effects of electroporation of cancerous cells can be found in [2], [11], and [14].

Electro-Plasticity

What Is It?

The electro-plastic effect, also known as electro-plasticity, is defined as “the reduction in flow stress of a material undergoing deformation on passing an electrical pulse through it” [15]. This application utilizes high-current pulses (greater than 10^3 A/cm²) to influence the plasticity or malleability of different materials, primarily metals [16]. When high-current pulses are applied to these materials, the plasticity is increased and a decrease in the flow stress is observed. It has also been found that these pulses give previously brittle metals the ability to undergo deformation and take other shapes. This has played an instrumental role in industries including the automotive industry, where shaping and forming metals is a key component to the production process.

This effect was discovered in the work of O.A. Troitskii in the late 1960s, where increased elongation of metals was observed, and the effects of lowering flow stress were first noted [16]. Since then, researchers have delved into effects on different materials and their applications to industry [17]. Before the innovation of electro-plasticity methods, metals were deformed through the application of high temperature or constant DC currents. The disadvantages of the thermal method included a large amount of energy and time allocation to preheating, heating, and annealing. The high temperatures also lead to thermal stress and warping in the affected metals [18]. The application of DC current eliminated these negative

effects but did not retain the maximum elongation of the material. Pulsed power methods retain the maximum elongation while also avoiding the downsides of the thermal deformation process.

How Does It Work?

Engineers and physicists have not yet come to a complete consensus on the science behind the electro-plastic effect. However, many theories have been developed. One of these is the application of Joule-Heating. Joule-Heating occurs when energy passed through the material is converted to heat, increasing the deformation abilities. This is a tested concept with well-documented results, although it has been proven to not be the sole cause of the electro-plastic effect. Testing has occurred in which the pulse applied is short enough to not transfer enough energy to have a significant thermal effect. The electro-plastic effect was still observed in these materials, showing the need for another supporting explanation [19].

Another theory behind electro-plasticity is electron wind force. While working on Zn crystals, Troitskii noted an increase in ductility and a decrease in flow stress when electrons were directed along the slip plane of a material. After noting the electron behavior, Troitskii concluded that drift electrons could “exert a force (‘electron wind’) on dislocations and such force should occur during the passage of an electrical current through a metal being plastically deformed.” [18]. One other possible explanation for the phenomenon is depinning due to paramagnetic obstacles. Molotskii and Fleurov believed that the magnetic field generated from the induced current altered the bonds of the obstacles, leading to the depinning. This theory requires that the obstacles be paramagnetic [15].

Current State at Liberty University

One of the focuses of Liberty University's School of Engineering is to provide research opportunities in various fields, as well as advance the school's academic standing. This section details the research work done by Joshua Zaiter (author) under Dr. Carl Pettiford, Associate Dean of LUSE in the 2020-2021 academic year.

The goal of the conducted research is to effectively verify, replicate, and test two existing pulsed power generation systems. These systems are used with permission of the original research engineers. This section details descriptions of the systems, the current state of work (including process, expected results, and results), and goals for the future.

System Descriptions

Avalanche Transistor High Voltage Circuit

The first system is a high voltage nanosecond switching circuit utilizing avalanche transistors. This circuit was developed in [20]. The goal of this system is to generate high voltage pulses (in the kilovolt range) by switching a high voltage power supply connected to the load. The circuit was designed to drive a Pockels Cell for a Q-switched Nd:YAG laser within a 0-4.5 kV DC voltage [20].

The pulse circuit consists of three primary sections. These sections are the control unit, the trigger unit, and the high voltage power supply. The trigger unit, used to chop the high voltage power supply to ground (0 V), consists of 16 avalanche transistors connected in series. The avalanche transistor selected by [20] is the ZTX415. Avalanche mode transistors are capable of extremely fast switching speeds, ideal for use in a pulsed power system where a short falling time is required. They are defined by [21] as transistors with "a negative resistance region in

their V-I breakdown curve (usually called secondary breakdown).” This allows controlled switching of large currents when utilizing proper supporting circuitry (60 A with sub-20 ns pulse width) and has a maximum collector-emitter voltage of 260 V. A thorough discussion of ZTX415 characteristics and behaviors can be found in [21].

The control unit is the section of the system used to initiate the trigger unit. A PIC16F84A microcontroller with a single-push button was utilized by [20] to provide a single 10 μ s pulse to a BC547 transistor, which then connects to the trigger unit. This pulse is used to trigger Q1 (first avalanche transistor). The overvoltage in Q1 causes the avalanche overvoltage throughout the 16 transistors. [20] employed the use of a single push button to provide the pulse from the PIC16F84A.

The high voltage power supply provides a 0-4.5 kV signal to the load. The trigger unit is connected in series to the power supply and chops this signal to 0 V. The system was designed with 2 1-M Ω resistors directly connected to the power supply. An activity diagram with the flow of the system is shown in Figure 2.

The pulsed system is connected to a capacitor in series with the load resistor. The capacitor stores energy when connected to the high voltage supply, then discharges energy when the DC voltage is switched to zero. This creates the high voltage pulse seen at the load resistor.

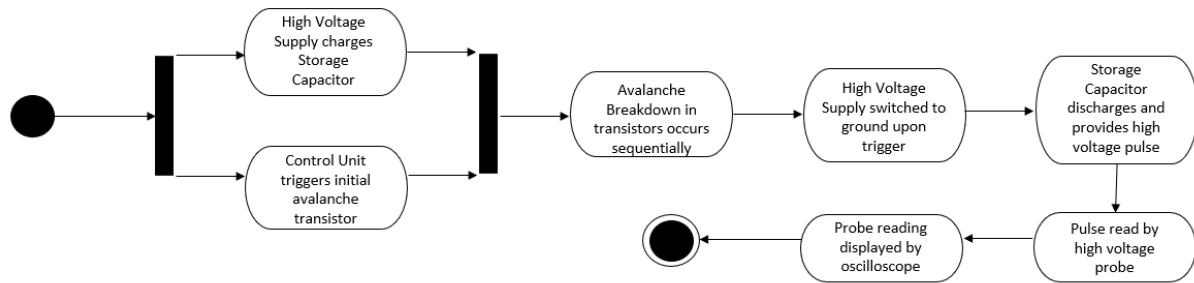


Fig. 2: Activity Diagram of Avalanche Transistor system (drawn by author). Based on [Fig. 2, 20].

Programmable Electroporation System

The second system of interest is a programmable electroporation for biological applications designed in [22]. Electroporation utilizes the application of electric fields to a cell membrane to infiltrate the cell and deliver foreign materials to the interior. The goal of this system is to be able to vary pulse duration, frequency, and total pulse number. The generator uses power MOSFETs to switch high voltages and can generate electric fields up to 1000 V/cm with pulse lengths between 10 μ s and 20 msec [22].

The electroporation design is divided into five major stages. These include a pulse generator programming, an inverter/driver, a high-power switch, a high voltage power supply, and a load. The load consists of an electroporation cuvette [22]. An activity diagram showing the flow of the electroporation system is seen in Figure 3.

The inverter was implemented using ZTX450 transistors and inverts the initial 5-volt signal. The driver converts the inverter output to a 15-volt signal. The driver is intended to switch the power MOSFET to control the high voltage. As described in the justification by [22], the ideal MOSFET in this scenario will quickly charge and discharge when the output of the

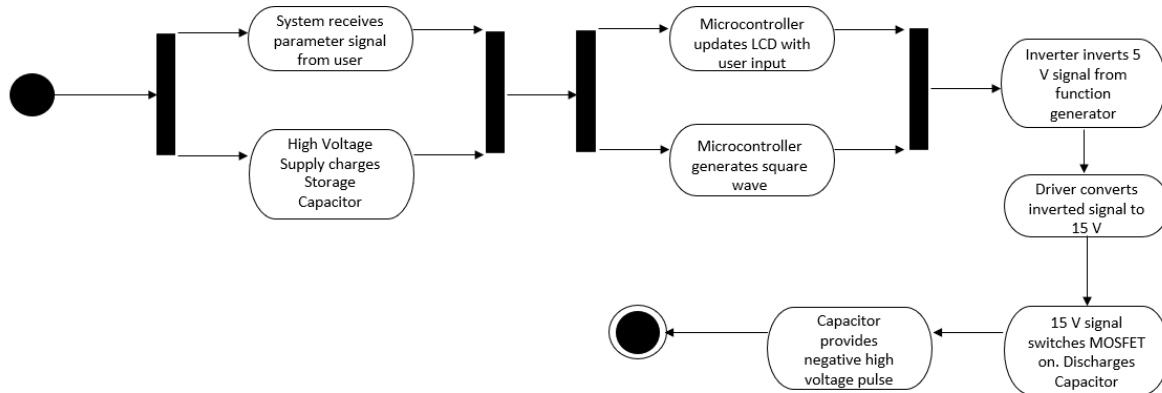


Fig. 3: Activity diagram of electroporation system (drawn by author). Based on [Fig. 3, 22].

driver reaches the gate of the MOSFET. When the MOSFET is switched off, the capacitor should charge (energy storage device). When the MOSFET is switched on, the capacitor discharges and produces a negative pulse voltage. A full schematic of the electroporation system can be found in [Fig. 4, 22].

State of Work

Avalanche Transistor Circuit Verification

The first step in the replication process of the avalanche system at Liberty is the verification process. This means constructing the system in simulation software, analyzing component choice and behavior, and comparing obtained results with the expected results given in the source. LTspice is the simulation software selected for this task. To construct a simulation schematic, all components utilized were gathered in LTspice and added to the library if not already contained as a preset. This included the ZTX415 avalanche transistors, where a SPICE model was obtained from the manufacturer with the proper parameters. To substitute the microcontroller in simulation, a pulse voltage source with similar parameters is used (for sake of

simplicity and ease-of-use). This pulse source provides a 10 μ s duration pulse to trigger the initial avalanche transistor (control unit).

The full LTspice schematic as it exists currently is shown in Figure 4. The control unit is on the left-most side of the schematic comprised of the pulse voltage source connected to a BC547C transistor. The trigger unit is in the middle of the figure, consisting of the 16 avalanche transistors. The high voltage power supply is on the right-most side, connected to a switch triggered by the trigger unit to chop the voltage down to zero. This is not the completed schematic for verification as modifications are still being made in an effort to consistently replicate expected results.

The expected result across the load of this system is a high voltage pulse (up to 4.5 kilovolts) with an average of switching falling time of 2.89 ns. The circuit should produce negative voltage values that are in a linear relationship with the applied voltage from the power supply. Expected high voltage switching signal results are found in [Fig. 4, 20] and typical nanosecond pulse results are found in [Fig. 5, 20].

As of February 7, 2021, the obtained results of simulation are not entirely consistent with expected results. A signal shape has been obtained across the load resistor (Figure 5). This signal has a similar shape to the one found in the expected high voltage switching signal [Fig. 4, 20]. However, there is indication for continued analysis and modification. The voltage values obtained via simulation max at magnitudes less than 5 volts. The expected magnitude should be corresponding to the high voltage supply, reaching the kilovolt range. The falling time of this pulse, shown in Figure 6, is within the nanosecond range, but is much larger than the expected value of \sim 3 ns, reaching its max value in 50 ns.

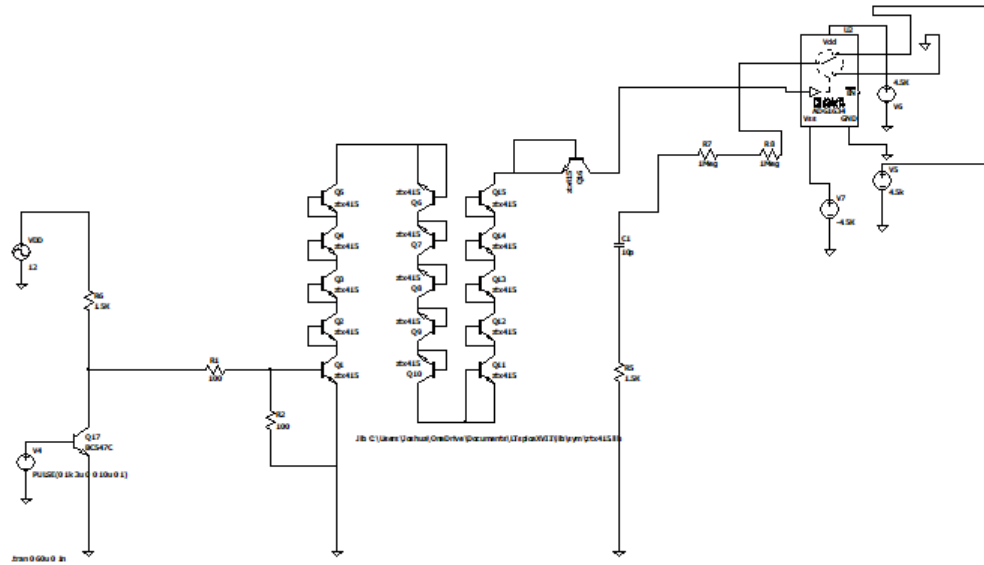


Fig. 4: Current LTspice schematic for avalanche transistor system (2/7/21)

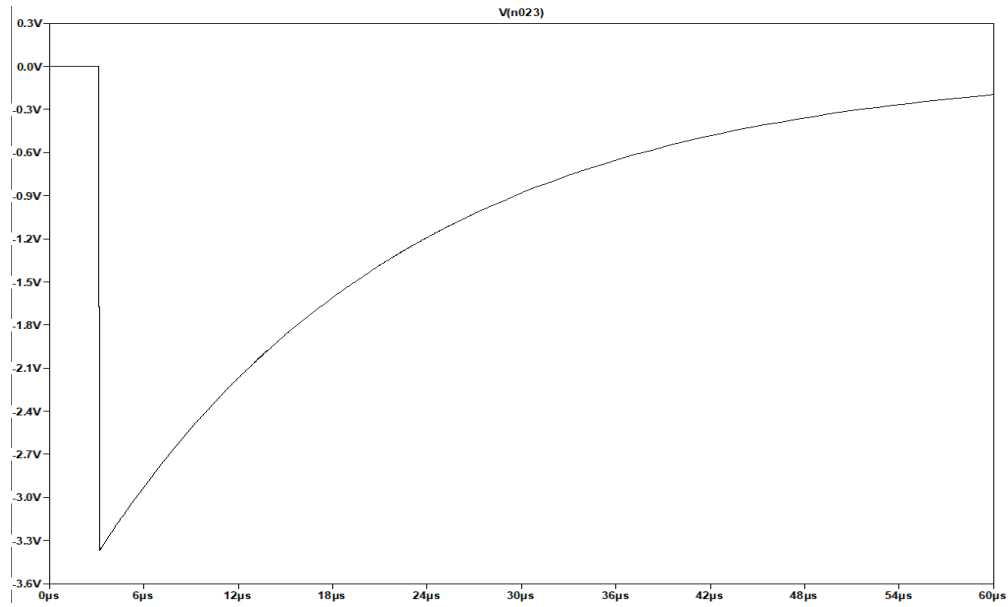


Fig. 5: Signal Shape across Load Resistor

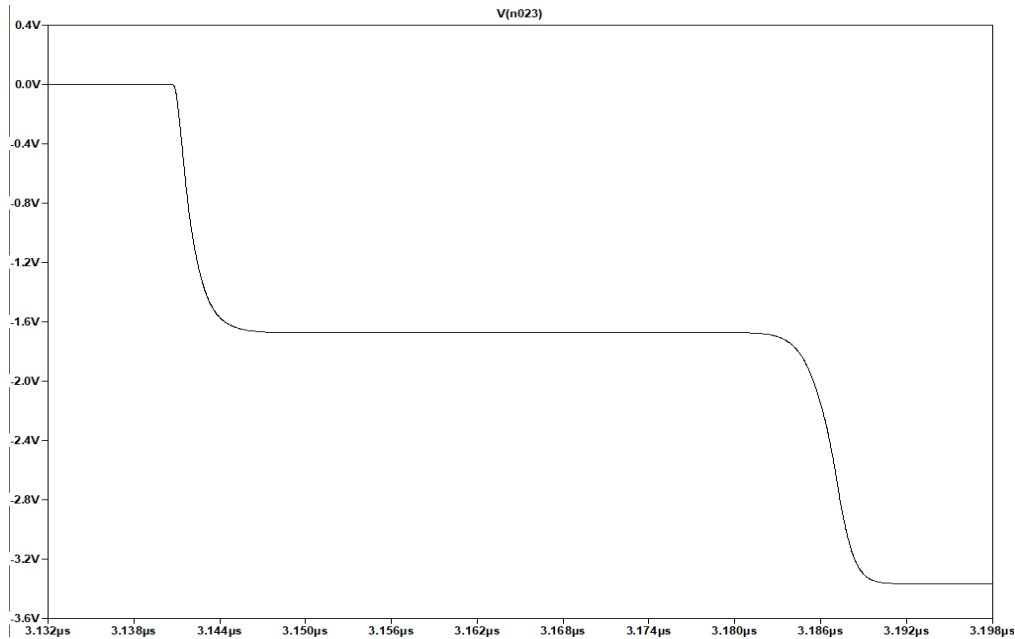


Fig. 6: Enhanced View of Load Signal showing pulse fall time

The trigger unit results also indicate faulty simulation. Ideally, the triggering of the first transistor should initiate an avalanche of overvoltage resulting in shorter and shorter switching falling time for following transistors. In current simulation results, the output of each transistor sees a decrease in voltage into the next transistor. With the current control unit pulse value set to 1 kV, a strong enough pulse is provided at the output of Q16 to trigger the switch that chops the DC voltage, but this is not the intended value of the control unit. When run with a pulse value of 5 V, the signal was not strong enough to trigger the switch. This implies the need for further testing of the ZTX415, the BC547, and the currently implemented switch in the LTspice schematic.

Goals for the Future

Short-Term Goals (2020-2021)

Regarding the avalanche transistor circuit replication, the first goal is to conclusively verify the results of the system as compared to the expected results laid out in [20]. This involves

testing the behaviors of all major components and then verifying the avalanche system. The next goal moving forward is to identify the analogous components purchased by Liberty University for use in this system. Not every component used in the source was purchased according to exact model number, but rather by behavior. This means that the non-source components require testing to ensure that the behavior is the same as their original counterparts.

Once the verification process is complete, the goal is to replicate the avalanche transistor system in the physical domain. This involves designing a printed circuit board (PCB), assembling the system, and testing the system behavior utilizing equipment purchased by LUSE. Currently the selected PCB design software is KiCAD.

Regarding the electroporation system, this system has not been analyzed or verified as of early Spring 2021. However, the short-term goal for this system, once the other has been completed, is to replicate the process. This means verifying through simulation and replicating in the physical domain as described for the avalanche transistor system.

Long-Term Goals

One long-term goal for pulsed power research at LUSE is to lay a foundation for system design and applications. By obtaining a working in-house pulsed power system, Liberty will be able to conduct research on a wide array of applications, such as cancer treatment. This would likely require cooperation between LUSE and Liberty University College of Osteopathic Medicine (LUCOM). This would bring great societal and educational benefit to both the school and external communities. Once a working system is introduced, it would be very plausible for the school to continue work on a unique system designed by Liberty faculty and students.

Another long-term goal for this work is to involve students in the research process at LUSE. Work in a high-level field such as pulsed power holds great academic value for students and provides an avenue to pursue graduate research and education. Work of this level at the undergraduate level also provides a useful experience for students when pursuing opportunities in the engineering field.

Conclusions

The study of pulsed power system design and its applications is an extremely useful research topic for Liberty University. The design of a general system has been well-documented since its inception in the 20th century and continues to be improved upon by engineers across the world. By analyzing the major sections of a general system, a better grasp on actual implementation is gained.

The process of replicating existing pulsed power system gives Liberty University the ability to conduct research and testing on various applications. The biological applications of such a system are of particular interest, as physical health is a common goal shared by society across the globe. The ability to aid in bacterial decontamination, cancer treatment, gene therapy, and other issues is a great humanitarian need and aids in Liberty University's mission to show the love of Christ while training Champions for Christ. We hope to complete the verification of these systems and implementation into the physical domain soon, providing the baseline for work on pulsed power at LUSE.

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