Designing a Soft Start/Stop MOSFET circuit for a photomultiplier tube DAQ system

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Abstract

Sensitive electrical equipment can be prone to damage from inrush current, which is the maximum current that an electrical device draws when first turned on. Such current spikes can be roughly 10 to 30 times the actual current and could prove extremely disastrous when voltage amplifiers, such as the G30 XP Power, increase the voltage at a ratio of 1 to 250. Soft start circuits, meant to gradually raise the voltage over a period, are usually implemented to alleviate this issue. This paper covers the design and functionality of a soft start circuit that utilizes a N-Type MOSFET in a source-follower orientation. Though simulations on LT spice as well as physical demonstrations using the IRF510 MOSFET, the goal was to improve and better understand the mechanics behind this Soft Start circuit. It was concluded that designed soft start circuit does work as intended, gradually raising the voltage over a designated period, independent of the load. Future iterations of the design would improve upon this aspect, seeking to contain both a true soft stop and a soft start design function that works independent of the load, as well as any possible simplifications. Additionally, this paper will contain any major obstacles encountered and their solutions. The ideal circuit would contain minimal components, enabling students to create and solder their very own soft start & stop circuit, to which they can implement into their own designs at home.

Introduction

The Soft start circuit is designed for a Cosmic ray muon detector, a device that requires voltage to be fed through a DC-DC voltage converter (the G30 XP Power), a voltage regulator (the LM317) and into a scintillator photomultiplier tube device.

Resistor: A two- terminal component that provides impedance that limits current flow.

LM317: An adjustable voltage regulator. In the prototype it functions as R_{Load}.

Capacitors: A two-terminal component that stores electrical energy in an electrical field. Polarized capacitors have one terminal strictly designated to ground and one terminal strictly designated to power.

RC Circuit: A resistor-capacitor circuit dictates the charge time of the capacitor with the formula t = R * C, where resistance is in ohms Ω and capacitance in farads F. The time constant t represents how long it takes for a capacitor to charge to ~63.2% of its missing voltage and to discharge to ~32.8% of its current voltage. It takes roughly 5 time constants for a capacitor to be considered fully discharged or charged.

Voltage charge of the capacitor: $Voltage = V_{in}(1 - e^{-\frac{t}{RC}})$

Voltage discharge of the capacitor: $Voltage = V_{in}(e^{-\frac{t}{RC}})$

It is extremely important to recall that this Soft Start circuit hingers on a source-follower design. The voltage across the Gate relative to ground minus the voltage across the Source relative to Ground must be around 2-4V. This means that the desired voltage will always be 2V lower than the inputted voltage. The following series of equations represents minimum voltage needed at Gate relative to Ground for our intended design.

$V_{GGnd} - V_{SGnd} = V_{GS} \geq 2V$; $V_{SGnd} = V_{Load}$; $V_{GGnd} \geq V_{Load} + 2V$; $V_{GGnd} \geq V_{PMT} + V_{LM317} + V_{Voltage\ Regulator} + 2V$; $V_{GGnd} = 9.6V + 1V + 1V + 2V = 13.6V$

Methods and Materials

LT Spice was the primary program used to simulate the prototypes before they were tested physically. Prior to the creation of the circuit via soldering, the prototypes were constructed on a standard solderless breadboard of any size. Several reference documents provided by Professor Armendariz and Professor Stalerman were also of relevance in regards to the design.

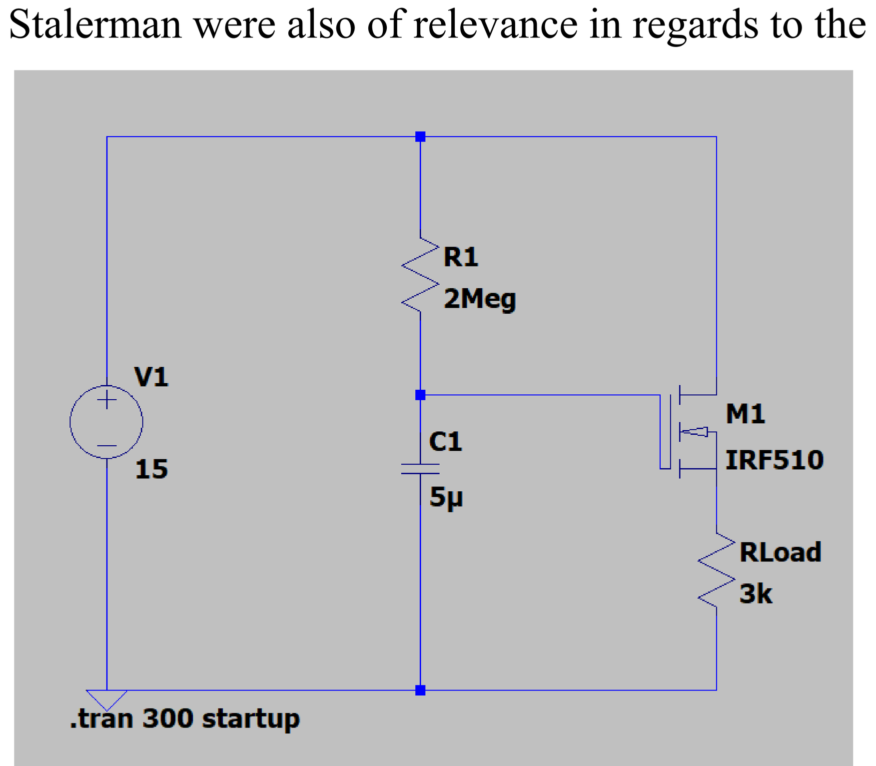

Figure 1 is the image to the left. This is the original design modeled in LT Spice before any changes were made to its design.

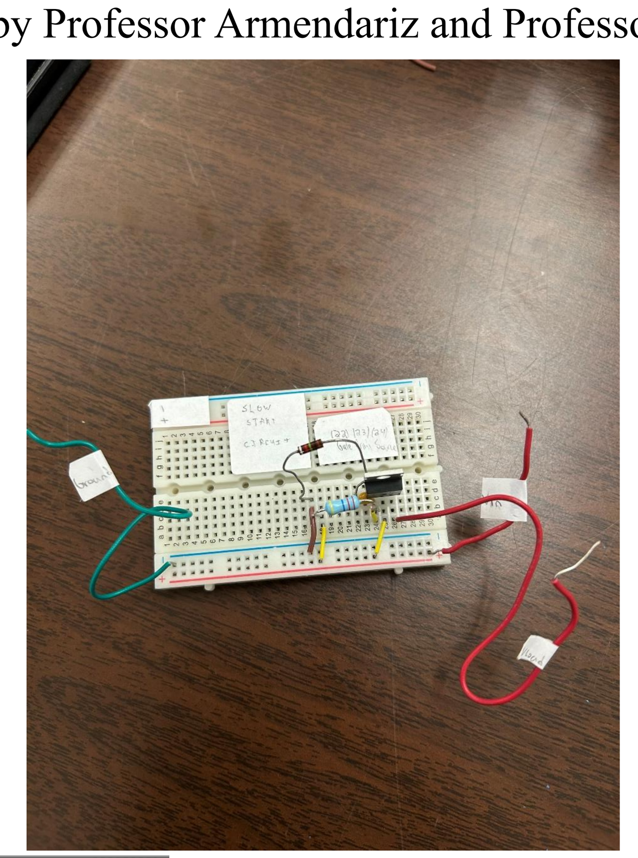

Figure 2 is the image to the left. This is the original design made on a bread board.

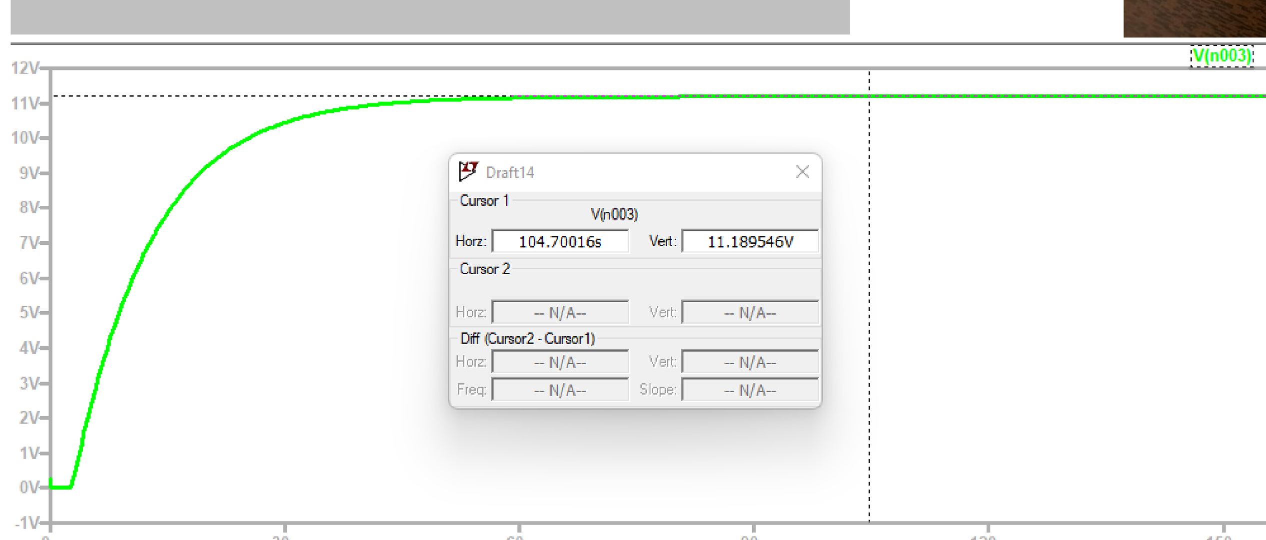

Figure 3 is the image to the left. This is the voltage across R_{Load} when measured in LT Spice. The measured circuit is the image in Figure 1. Note that the voltage drop is ~4V, this is a designated value in LT Spice.

Results

When testing various designs, two main issues surfaced. One was why certain capacitors, for instance electrolytic, did not work, while others such as ceramic did work. The second issue was how to get the circuit to 'soft stop'.

Result #1

Issues with using high resistance along side certain capacitors for an RC circuit: In the physical design, it was discovered that the maximum voltage across the some capacitors-especially aluminum electrolytic capacitors-were heavily limited. The leading suspect was found and proven to be leakage current in a capacitor. The maximum voltage across the capacitor is demonstrated by the following equation, a modified voltage divider equation:

$$V_{Max} = \frac{R_{Leak}}{R_1 + R_2 + R_{Leak}} * V_{in} \qquad R_{Leak} = \frac{V_{in}}{I_{Leak}}$$

Assuming the $I_{Leak} = 3\text{mA}$; $R_1 = 22M\Omega$; $R_2 = 1M\Omega$; $V_{in} = 15V$

In this case, the maximum voltage would be 15MΩ/(22MΩ + 15MΩ + 1MΩ) = **~5.921V**

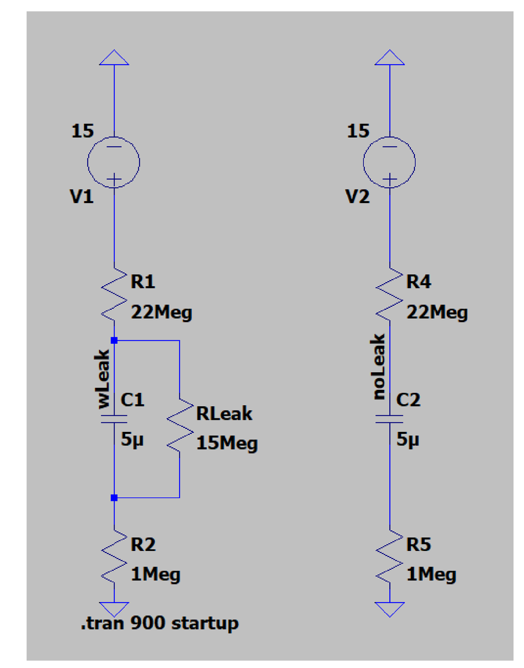

Figure 3 shows two RC circuits side by side. The circuit on the left, titled 'wLeak' represents a circuit that has a capacitor with 1µA of leakage current. The circuit on the right titled 'noLeak' has an ideal capacitor with no leakage.

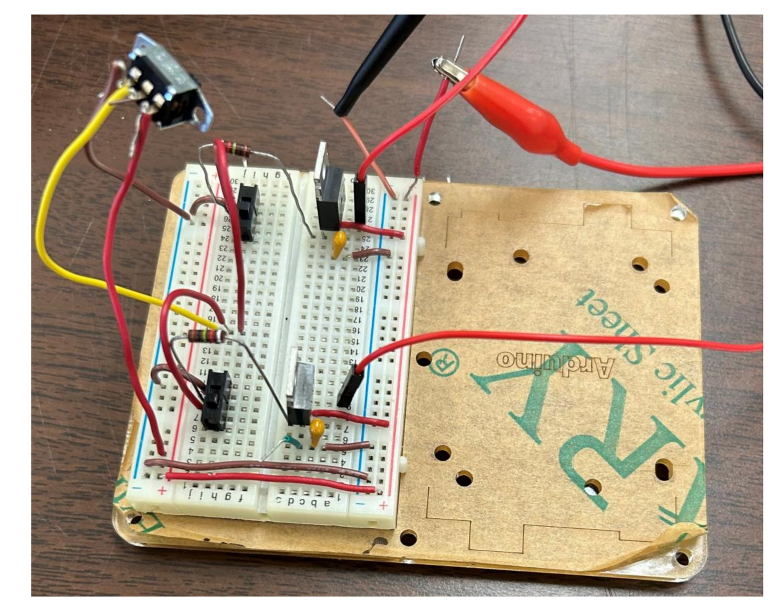

Figure 6 shows the second design. At the time of the prototype, there was no suitable relays available. SPDT switches were used as substitutes for Arduino-relay combinations and have extremely similar effects.

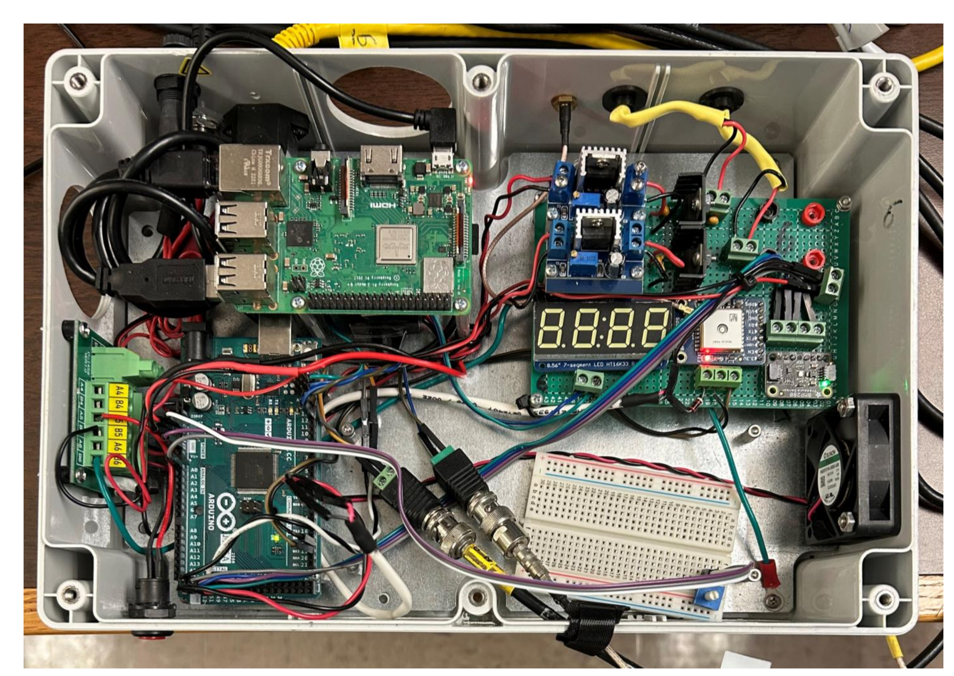

Figure 7 shows the completed DAQ box without the soft start. The soft start's intended location is going to be the top right of the box based on the top view.

Result #2

Soft Stop addition to the circuit: In the user manual guide by Photek, the equal importance of gradually turning on AND off the PMT is greatly emphasized. Part of this reason is due to **outrush current,** which occurs when there is a surge of electrical flowing out of the capacitor bank or system when turning off a circuit. Three designs were created to counter this effect. The first design requires a much larger capacitor, around a milli-Farad, but can gradually lower the voltage across R_{Load} when power is cut to the ENTIRE circuit. The second and third design gradually lowers voltage across R_{Load} but requires voltage to always be sitting on the Drain of the soft start design. In other words, for the second design one cannot turn off the circuit by unplugging power. They must first lower the voltage across the gate by bleeding the capacitor to gradually lower the voltage across R_{Load} before unplugging power, lest they wish to risk damaging the circuit due to outrush current. The third design is extremely similar to the second design but differs in the way of activation. The second design uses relays while the third design uses additional MOSFETs to gradually lower the voltage across R_{Load}.
It was decided that designs two and three better suits the goals of this design.

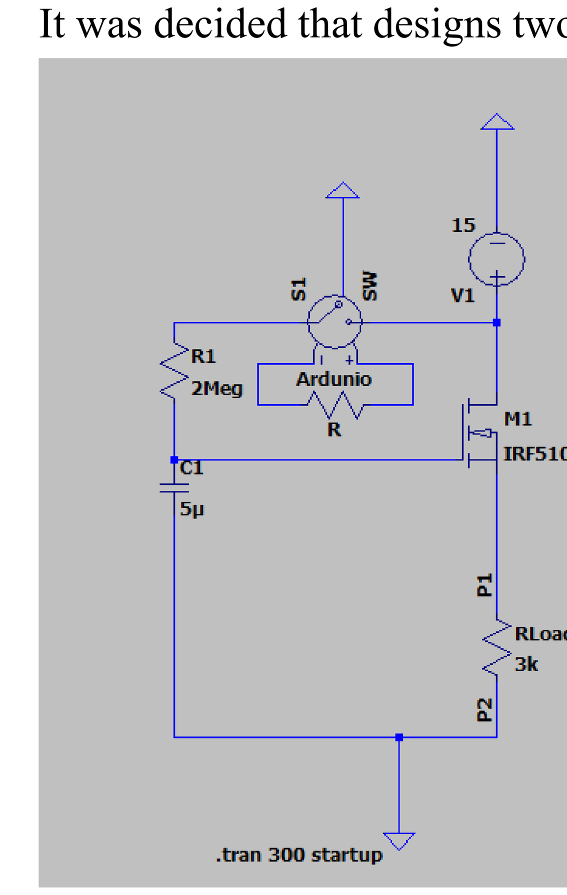

Figure 4 represents design 2. The resistor titled "Arduino" is a placeholder for the Arduino MEGA that will control the inductor on the SPDT relay

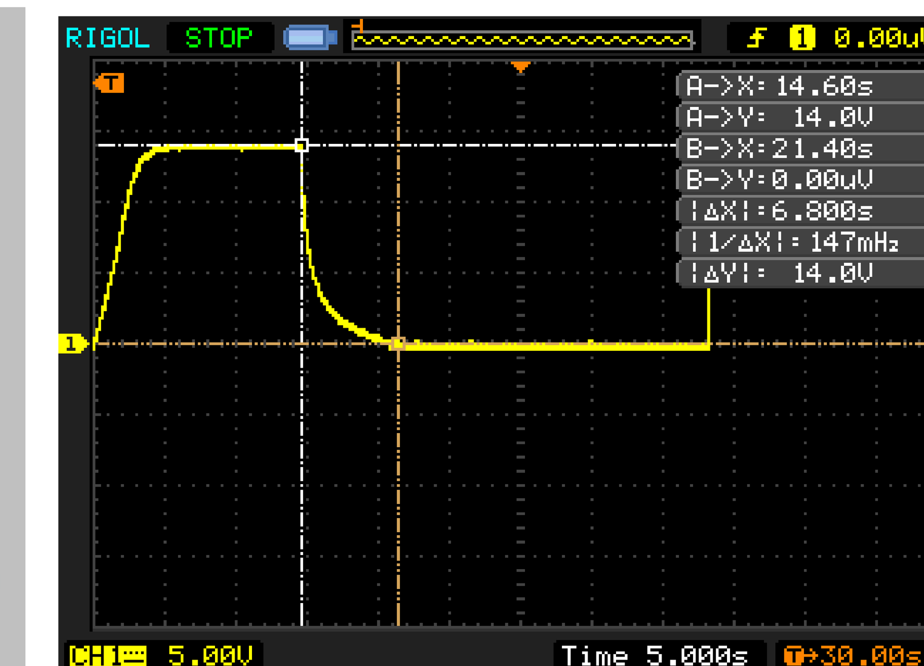

Figure 5 is the graph for the voltage across R_{Load} over time. Due to LT spice's difficulty with simulating the Arduino MEGA and the SPDT, the graph here was taken from an oscilloscope that recorded the voltage across the LM317 with a physical prototype of the circuit. The LM317 is the otherwise would be R_{Load}. The resistor is 1M Ω.

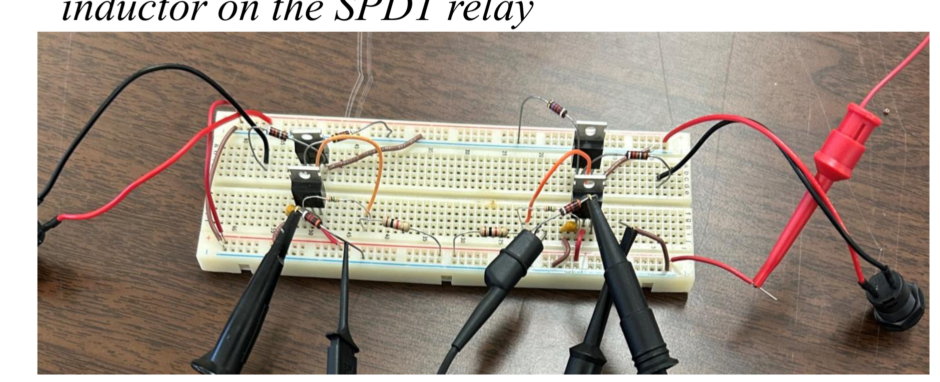

Figure 6 shows the third design. The two resistors that are being probed are the simulated R_{Load}. The two toggle buttons branching off the left and right simulate the Arduino channeling power to the MOSFET's Gate.

Discussions and Conclusions

Discussion and conclusion: The Soft Start circuit works as intended, providing a gradual voltage rise and drop across the desired circuit, independent of the resistance of the load. Additionally, the circuit can be easily modified to add more ways of turning on and off the circuit. Again, it is extremely important to note the impact of I_{Leak} of the capacitor, as for source-follower designs the voltage across the load will always be 2-4V lower than the voltage across the Gate. In other words the greater the leakage current is, the lower the voltage across the Gate and the lower the voltage across the load will be.

Limitations to the final design is that if voltage is unplugged at the source, ex pulling the plug, then the soft stop aspect does not work. Additionally, the function of the circuit under higher frequencies was not tested thoroughly and may have further implications. Lastly it was found that the relay that was chosen requires a current of ~30mA, where as the Arduino can only pump out a maximum of 20-40mA. This strain can damage the Arduino if left on for extended periods of time, meaning that either a new design that does not require relays must be found, or a more compatible relay is found.

Future designs would aim at fixing the aforementioned issue while retaining simplification if possible, or creating a more universal design, or enabling a soft stop when 'pulling the plug' among other things.

The MOSFET design which better suits the Arduino MEGA for a remote controlled turn on/off requires more components. This takes away from the simplification of the circuit, as well as making it more difficult to fit the entire circuit on the perf board, as well as replicate the circuit on the perf board.

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Acknowledgements