ESD SIMULATOR

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Electrostatic discharges (ESD) are a common problem that circuit designers must address. ESD pulses can destroy electronic devices or cause system malfunctions so adequate protection against these events is mandatory.

Professional ESD simulators are expensive equipment, but a cheap high voltage generator, like the one proposed here, can be practical enough to be confident that those boards surviving its sparks would also pass any serious ESD test.

This circuit can be built using components already at hand. Its main component is just an small power transformer, and only two transistors and tree capacitors require a high voltage rating. When properly driven, this transformer can deliver pulses up to 3500 Volts instead of its nominal 230V. These pulses, when applied through a 100pF capacitor, simulate ESD discharges according to the commonly used Human-Body model. The pulses are generated in pairs with opposite polarities in each pulse. The circuit is powered by four AA cells and activated by a pushbutton.

The circuit is built around an 1.5VA, 230V to 2x6V, power transformer, and it uses the same working principle of an engine ignition coil. Indeed, a real ignition coil would be an ideal choice for this circuit if size is no concern. In our case the transformer is reversed, so the low voltage coils are the primaries and the high voltage coil the secondary (contrary to device marking). One primary, in parallel with a capacitor, is connected to a voltage source through a switch until the current in the coil saturates. Then the switch opens and the magnetic energy in the transformer core is converted into electrostatic energy in the dielectric between the capacitor plates, generating a high voltage pulse in the primary. Of course, in the secondary windings of the transformer the voltage is much higher, easily reaching the kilovolt range. Then the LC tank oscillates until the voltage fades away. But first lets find an estimate for the amplitude of the first pulse.

Using the law of conservation of energy we can write:

$$\frac{1}{2}I_{pk}^2 L = \frac{1}{2}V_{pk}^2 C$$

Where I_{pk} is the coil current when the switch opens, V_{pk} is the peak voltage that follows, L is the inductance of the primary winding, and C is the capacitance. Lets assume $L = 69mH$, $C = 100nF$, and $I_{pk} = 350mA$. The peak voltage will be:

$$V_{pk} = \sqrt{\frac{L}{C}} I_{pk} = 290V$$

And this is the primary. In the secondary the voltage is going to be: $V_{out} = V_{pk} \times \frac{230}{6} = 11kV$

Impressive, but we are assuming there are no losses in the LC tank. In practice the losses can be high enough to lower these figures to about 1/3 of their ideal values.

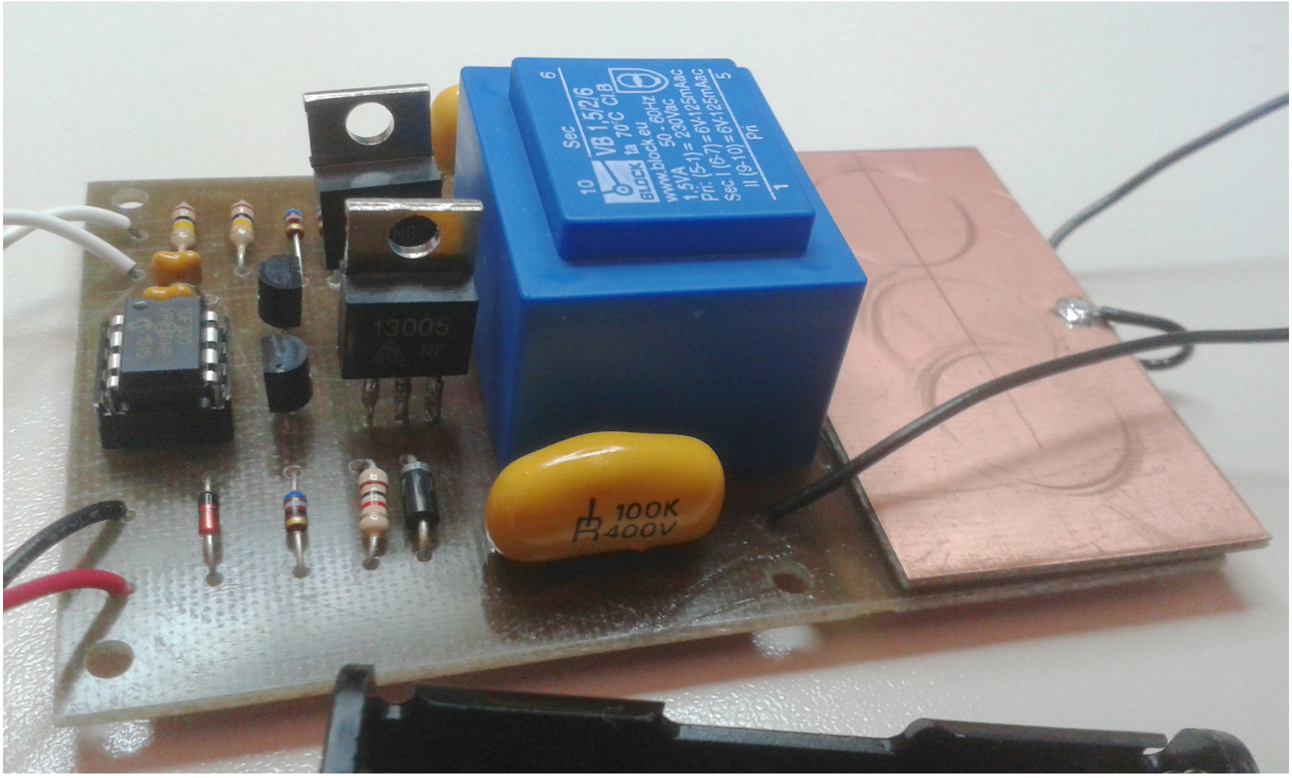

Figure 1: Snapshot of the simulator board. The blue box is the transformer and the bare PCB at the right is the homemade stacked high voltage capacitor.

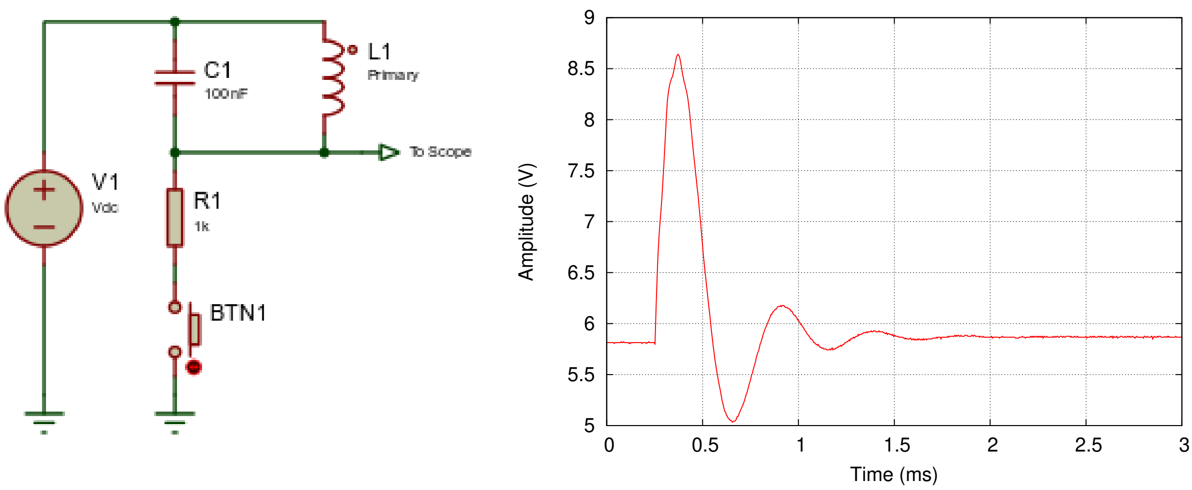

Figure 2: (a) Test circuit for measuring the transformer inductance. (b) Measured voltage transient.

Anyway, the first thing we have to do is to measure the inductance of the primary because the manufacturer gives no data about this parameter. All we can get from the datasheet is the turn ratio, $N = 230V/6V = 38.3$, and the saturation current: $I_{sat} = 2 \times 125mA \times \sqrt{2} = 353mA$. Also, using an ohmmeter we can measure the coil resistances, that were $R_{s,prim} = 11\Omega$, and $R_{s,sec} = 3k\Omega$. In order to get the inductance a $100nF$ capacitor was connected in parallel with the primary, and an small current ($5.8mA$) was switched, obtaining the voltage transient shown in Figure 2

Here we can see an strongly damped oscillation. From this curve, and knowing the capacitance value, we can derive the inductance of the primary:

A damped oscillation follows the curve:

$$v(t) = A \cdot e^{-\alpha t} \cdot sin(\omega_d t + \varphi)$$

Where $\omega_d^2 = \omega_0^2 - \alpha^2$, with $\omega_0^2 = 1/LC$

By means of a curve fitting we get $\omega_d = 2\pi \cdot 1.8kHz$ and $\alpha = 2\pi \cdot 637Hz$. These values results in an inductance, $L_{prim} = 69.6mH$, for the primary coils. The inductance is multiplied by the square of the turn ratio in the secondary, giving: $L_{sec} = L_{prim} \times N^2 = 102H$.

Also, the damping frequency is related with the quality factor, Q, of the LC tank: $\alpha = \omega_0/2Q$. From this equation we get $Q = 1.41$

The series resistance of the primary windings can't explain the low value of Q measured ($Q = L\omega_d/R_{s,prim} = 71$). Of course, the skin effect in the wires is not taken into account but it is not expected to be significant for this low frequency ($1.8kHz$) and the Q discrepancy is way too big. The more plausible explanation is the eddy currents induced in the metallic iron of the transformer core. These losses can be modeled as a resistor in parallel with the primary: $R_{p,prim} = L\omega_d Q = 1110\Omega$.

With these data we can have a fairy accurate model for the transformer. In SPICE simulators transformers can be modeled as two or more coupled inductors. The coupling coefficient is going to be close to one, lets say 0.98. The primary and secondary inductances are the ones calculated before, $69.6mH$ and $102H$. In series with the inductances are the resistance of the windings, of 11Ω and $3k\Omega$ respectively. And, finally, In parallel with the primary we get the equivalent resistor of the core losses, of $1.11k\Omega$. The only important real effect not included here is the core saturation, but as long as the nominal peak current of $350mA$ is not exceeded it shouldn't be a problem.

Anyway, the measured transient shows that for $5.8mA$ of initial current the peak voltage obtained is $2.8V$ in the primary. If the current is increased up to $350mA$ this peak voltage can raise to $169V$, and the secondary can deliver about $6.5kV$

The magnitude of the maximum voltage transient in the primary sets the specs for both the capacitor and the switch. These devices should withstand more than $200V$. Transistors with max. V_{CE} in the $400V$ range are quite common. They are used by millions in compact fluorescent lamps. In fact, the transistors used in our prototype, (MJE13005), were salvaged from a broken CFL.

As it is shown in the schematic of Figure 3, two identical switches are connected to each primary coil of the transformer. With this arrangement we can change the polarity of the output pulse just by closing one switch or another. Each switch is made of an high voltage transistor, Q1, in series with a high voltage diode, D1, along with a driver circuit (Q3, R3, R1). The diode is needed because otherwise we can reach negative voltages in the collector of Q1 during transients, and these voltages would make the transistor to enter reverse conduction (collector acting as emitter). The driver circuit is needed because of the low h_{fe} of the Q1 transistor. It consist of an ordinary transistor, Q3, connected as emitter-follower, a base current limiting resistor, R3, and a base discharge resistor, R1.

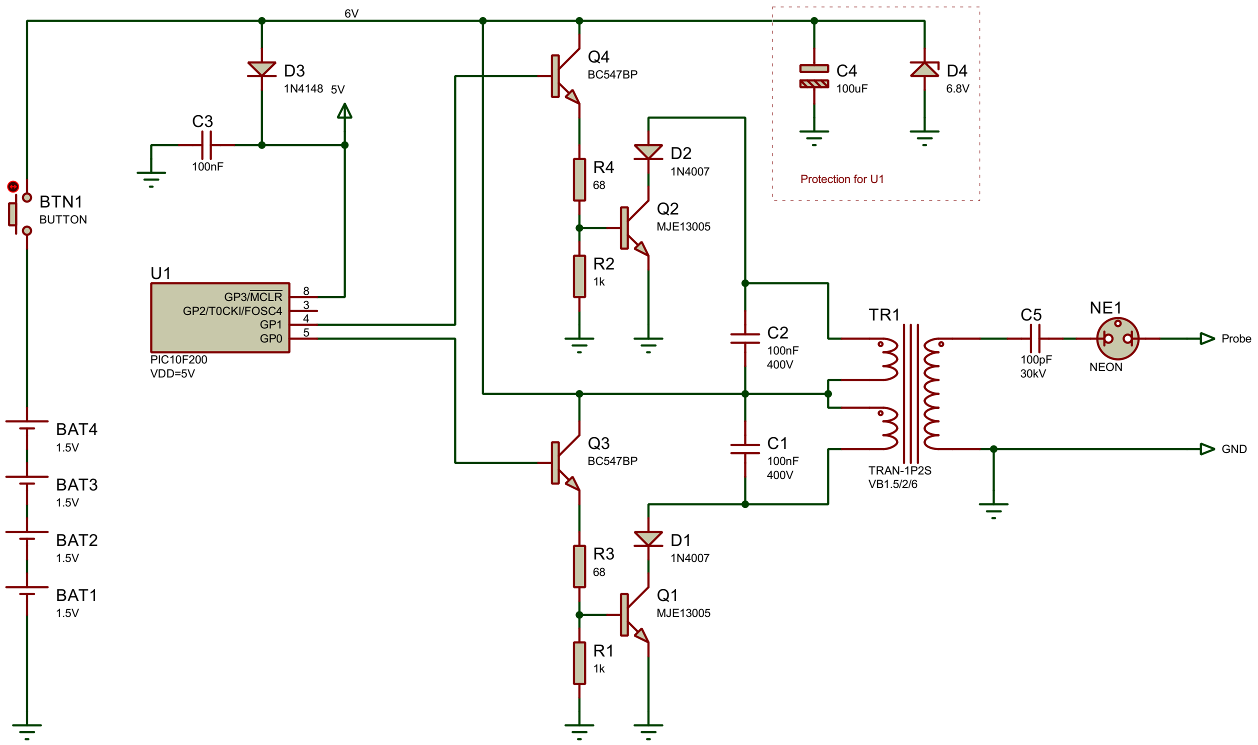

Figure 3: Schematic of the ESD simulator

The switches are driven from an small microcontroller, U1. In order to get the time each switch has to be turned on a simulation was carried out and the current entering the center-tap of the primaries was recorded (Figure 4). A 25*ms* pulse was applied to each switch, and the current reached about 380*mA* at the end of the pulse. This value reaches the saturation current of the core. Therefore, the firmware of the microcontroller was programmed to generate a slightly shorter pulses of 16*ms*. A sequence of two pulses (one per output) separated by 5*ms* results in two pulses with reverse polarity at the secondary of the transformer. Then, the whole sequence is repeated at a rate of 5 double polarity pulses per second.

The nominal supply voltage of the microcontroller is 5*V*, so the D3 diode was included to reduce the voltage form 6*V* to a more relaxed 5.3*V*

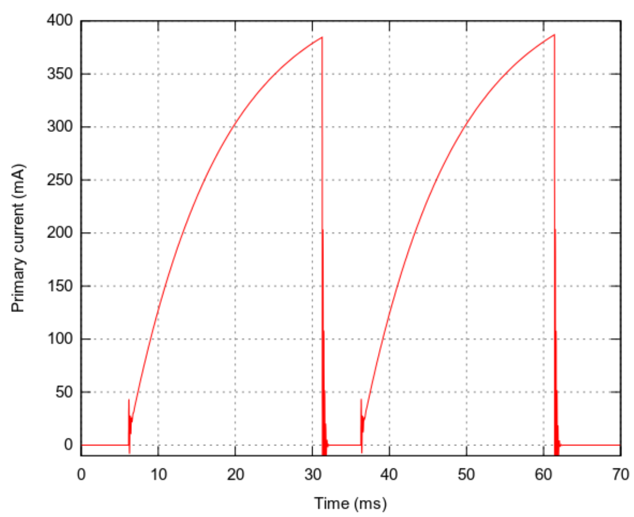

Figure 4: Simulated current entering the center-tap of the transformer primaries

In the secondary side of the transformer a high voltage, $100pF$, capacitor is needed. We had none with this rating at hand, so we made one ourselves using a raw, double sided, PCB board. It turned out that the area needed for this capacitance value was around $35cm^2$, not too much, and the PCB can be cut into several smaller pieces and stacked in order to save space. It is also a good idea to apply an insulation paint on the PCB borders to prevent arcing.

The neon lamp serves a dual purpose. It can be used as an indicator for discharges but it also acts as a switch, isolating the probe from the circuit under test until a discharge is applied. Once lit by a discharge the voltage drop in the lamp is so small that can be ignored. Without the lamp the impedance of the probe could be a problem when connected to some sensitive nodes like those found in oscillators.

It is ironic that the first device damaged by this ESD simulator was its own microcontroller. This problem wasn't found until some arcing was generated at the output. With the output open or shorted there is no problem, but arcing seems to be rather destructive. We suspected a high frequency and voltage transient was coupled to the supply of the microcontroller and we tried to attenuate it by means of a $100\mu F$ capacitor and a $6.8V$ zener diode connected in parallel with the supply. This protection was found to be effective and no more microcontrollers were broken after its installation.

Finally, the output pulses of the circuit were recorded and shown in Figure 5. There we can see the dual polarity of the pulses and also some detail of a single pulse with a peak voltage aroung $3500V$.

With this peak voltage is difficult to create sparks in open air but it is quite easy to make them over a dielectric surface. This generator was able to make sparks up to 4mm long over a PCB, to perforate its insulation resist and also a two layer coating of insulating paint, and to induce a catastrophic failure on a power supply after discharging into the gate of its weakly protected switching MOSFET. This last "achievement" was precisely the intended kind of use for this circuit.

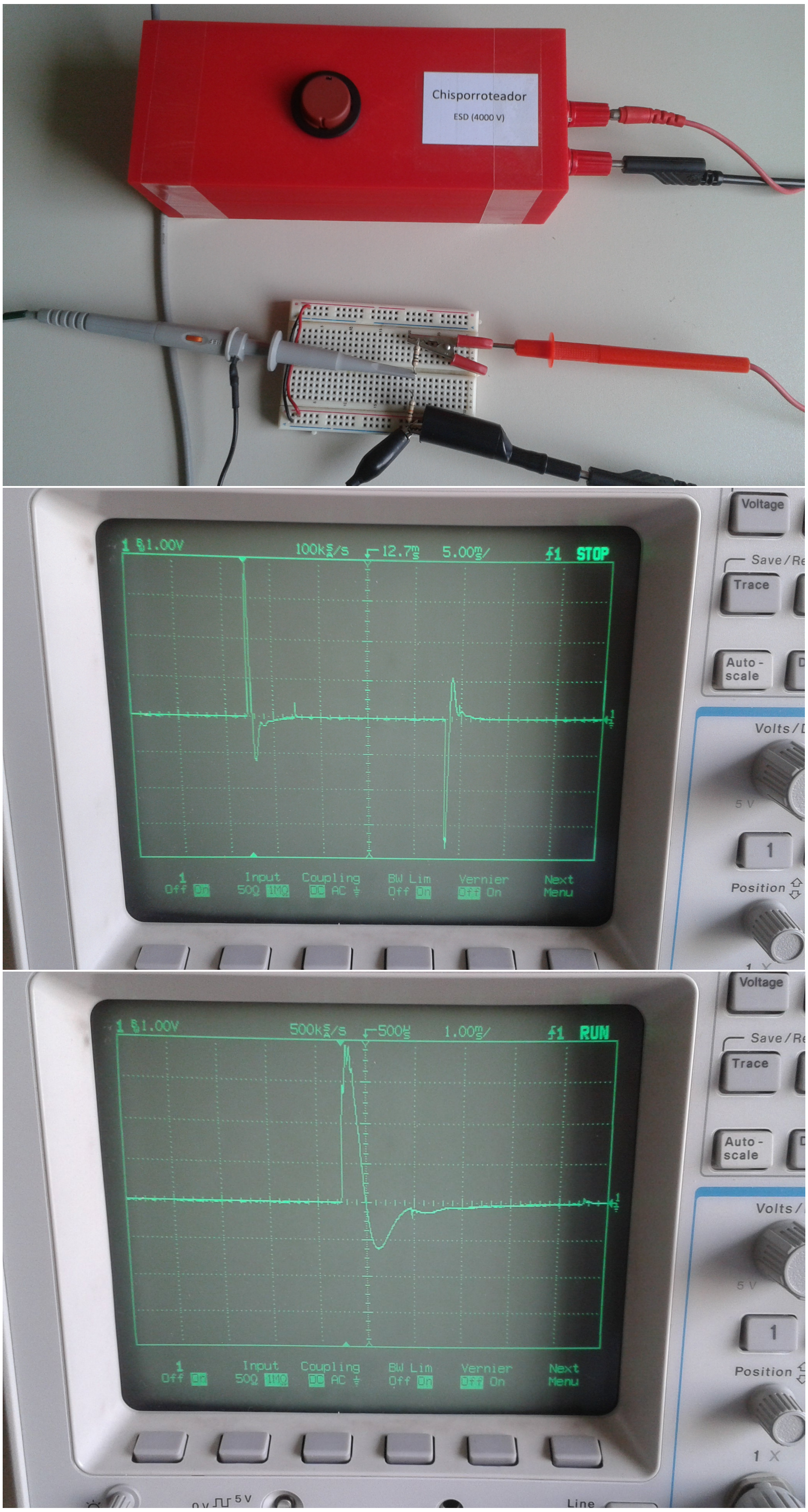

Figure 5: (a) ESD generator connected to a 1/1000 voltage divider. (b) Measured voltage pulses at the output. (c) Detail of the positive pulse.