SPARKS

We are finally to the point of discussing the sparks or streamers produced by a Tesla coil. Results apply only to the case of a vertical coil above a ground plane, driven at the base with a square wave of voltage from a solid state driver. Spark lengths will be less than for a classical Tesla coil. We will hopefully see why that must be the case, at least for my specific configuration. Before continuing, let me present some definitions found in the IEEE Standard dictionary [1].

arc. (1) A discharge of electricity through a gas, normally characterized by a voltage drop in the immediate vicinity of the cathode approximately equal to the ionization potential of the gas. (2) A continuous luminous discharge of electricity across an insulating medium, usually accompanied by the partial volatilization of the electrodes.

corona. (1)(air) A luminous discharge due to ionization of the air surrounding a conductor caused by a voltage gradient exceeding a certain critical value. (2)(gas) A discharge with slight luminosity produced in the neighborhood of a conductor, without greatly heating it, and limited to the region surrounding the conductor in which the electric field exceeds a certain value.

spark. A brilliantly luminous phenomenon of short duration that characterizes a disruptive discharge. Note: A disruptive discharge is the sudden and large increase in current through an insulating medium due to the complete failure of the medium under electric stress.

streamer. An incomplete disruptive discharge in a gaseous or liquid dielectric that does not completely bridge the test piece or gap.

In general usage, *arc* is for big currents. An arc welder may run hundreds of amps through a welding rod to make a weld. It is possible for a power arc to develop across a spark gap in a conventional Tesla coil, a highly undesirable event. About the closest to an arc that occurs in my solid state drive is when all the IGBTs are turned on at the same time, forming a short across a large capacitor bank. This event includes a loud thump, smoke, and flying pieces of silicon. The traces on the printed circuit board volatilize. If not a real arc, it is a good enough imitation for me!

Corona is a common occurrence around Tesla coils. Leads and connections from the high voltage terminals may be in corona, although it may be difficult to see in the light produced by the spark gap and discharges from the toroid. It will be especially noticeable on the lead from the top of the secondary to the bottom of the extra coil in a magnifier connection. Corona is a violet or purple discharge extending out from the conductor a centimeter or two. Power losses are not excessive, but using larger diameter conductors to avoid corona will also reduce resistance losses and may help performance of the coil.

It would seem from these definitions that one could use either *spark* or *streamer* for the discharge from the top of a Tesla coil. I notice some coilers trying to be more specific and precise, which is good. There are some differences between discharges to air and discharges to a nearby ground rod, so separate nomenclature is appropriate. I think I hear some referring to discharges from a toroid as streamers, and the electrical phenomenon in a spark gap as sparks. I personally tend to be casual in this area, and will refer to the electrical phenomenon on and around a toroid as discharges, sparks, or streamers, more or less interchangeably. Those interested in more information about these terms should refer to one of the books on lightning by Uman [2], [3].

1 Waveforms

I apply a square wave of voltage at the bottom of a Tesla coil, which causes a sinusoidal current to flow, as shown in Fig. 1. These waveforms are for coil 12T operating at a voltage insufficient for a discharge to occur. (The variac was set at 30%). The oscilloscope is the HP54645D, which contains the capability to calculate quantities like rms voltage and frequency of a waveform, and also to print out the screen image to a printer.

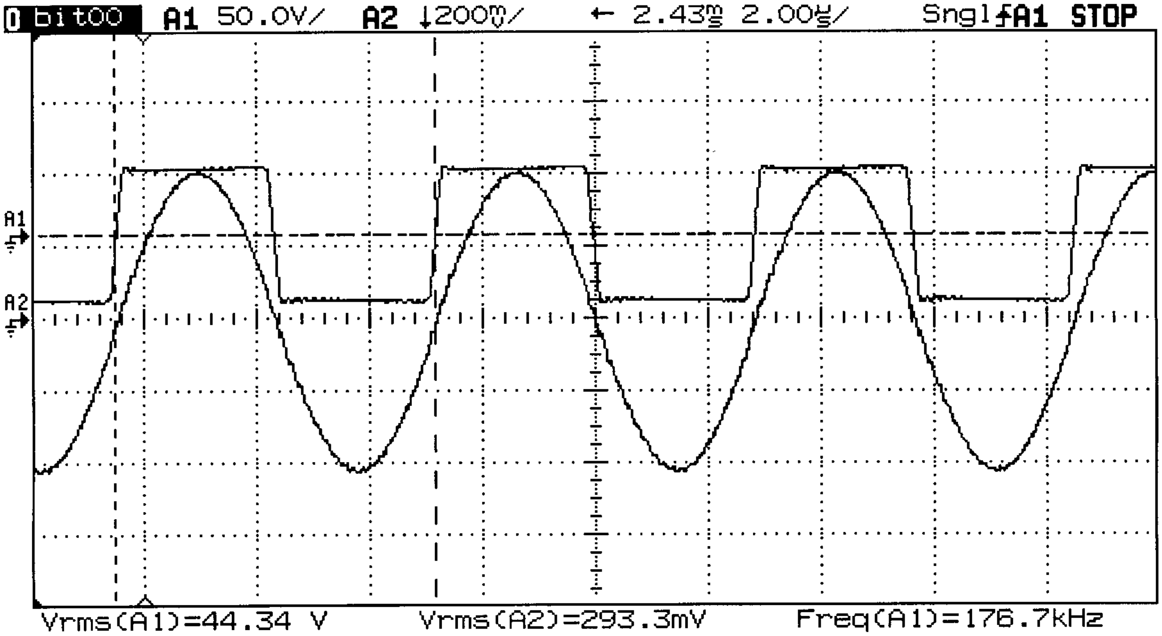

Figure 1: Square wave of voltage, sine wave of current at base of coil 12T below breakout.

Voltage is actually the voltage output of a 10:1 voltage divider. The vertical scale for channel A1 is thus 500 V/div rather than 50. At the lower left of the screen image we see Vrms(A1)=44.34 V. The rms value would actually be 443.4 V. The rms of a perfect square wave is the same as the peak value, so I am applying a voltage of approximately ±443.4 V to the coil.

The current waveform is the voltage across a 20 mΩ resistor. The current corresponding to a voltage of 293.3 mV is

$$I_{TC} = \frac{V_{TC}}{R} = \frac{393.3\text{mV}}{20\text{m}\Omega} = 19.66 \quad \text{A}$$

We also want the input power and the input impedance of the Tesla coil. The combination of a square wave voltage and a sinusoidal current is different from what we are used to, so we need to go back to circuit theory to make sure we have all the correct multiplying factors.

A voltage square wave of value $\pm V_p$ has the same heating capability when applied to a non-inductive resistor as a dc voltage V_p, hence is said to have an rms value of $V_{ac} = V_p$. The corresponding dc current in a resistor would have an rms value of $I_{ac} = I_p$. The average power delivered to the resistor is the product of the rms voltage and the rms current,

$$P_{ave} = V_p I_p = V_{ac} I_{ac} \tag{1}$$

Suppose now we apply a sinusoidal voltage $V_p \sin \omega t$ to a non-inductive resistor. The resulting current is $I_p \sin \omega t$. The average power is

$$P_{ave} = \frac{1}{\pi}\int_0^{\pi} V_p I_p \sin^2\theta d\theta = \frac{V_p}{\sqrt{2}}\frac{I_p}{\sqrt{2}} = \frac{V_p I_p}{2} = V_{ac} I_{ac} \tag{2}$$

When the voltage is square wave and the current is in phase with the voltage but is sinusoidal, the integral for average power becomes

$$P_{ave} = \frac{1}{\pi}\int_0^{\pi} V_p I_p \sin\theta d\theta = \frac{2}{\pi} V_p I_p = \frac{2}{\pi} V_p(\sqrt{2} I_{ac}) = 0.9 V_{ac} I_{ac} \tag{3}$$

For this case, the average power is no longer the simple product of rms voltage and rms current (as for dc and single frequency sinusoids), but has a 0.9 multiplying factor. The difference is due to the fact that the square wave voltage is composed of an infinite series of harmonics (fundamental, third, fifth, etc.). Each harmonic contributes to the rms value of the square wave. The current has no harmonics, so the higher voltage harmonics do not produce any contribution to the average power.

Actually the product $0.9V_{ac}I_{ac}$ is the apparent power S for these two waveforms, which happens to be equal to the average power when the waves are in phase. If there is a phase shift, P_{ave} will be less than S by a factor $\cos\theta$, where θ is the phase angle between the two wave. I can readily determine S from the product of rms voltage and rms current (and a 0.9 multiplying constant). However, P_{ave} requires either a wattmeter for measurement or an additional measurement of phase angle. Building an accurate wattmeter in the hundreds of kHz range is a challenge, and was not done for this research. My scope will estimate the phase angle between waveforms but the quality of the estimate is not very good when small amplitude signals have significant ripple, as is often my situation. Since I always try to operate in the in-phase condition, I will approximate or estimate the average power as the apparent power. It should be remembered that the actual average power will be slightly less than the numbers I calculate.

At resonance, when the input impedance is real, it can be defined as

$$Z_{in} = R_{TC} = \frac{P_{ave}}{I_{ac}^2} = \frac{2\sqrt{2}V_p I_{ac}}{\pi I_{ac}^2} = \frac{2\sqrt{2}V_p}{\pi I_{ac}} = 0.9\frac{V_{ac}}{I_{ac}} \qquad (4)$$

In the following, I will refer to the rms voltage applied to the coil as V_{TC} and the rms current as I_{TC}. The average power for Fig. 1 is approximately

$$P = 0.9 V_{TC} I_{TC} = (0.9)(443.4)(19.66) = 7846 \quad \mathrm{W}$$

The frequency is calculated from the time lapse between two adjacent leading edges of the voltage at the points indicated by the two vertical dashed lines. It is 176.7 kHz for this case.

The horizontal scale is 2 μs/div. The coil was driven at resonance for about 3 ms. The scope records the entire waveform. This particular screen is a section of that waveform at 2.43 ms after initiation.

When the variac is turned up to 40%, a spark occurs when the toroid reaches a sufficient voltage. Fig. 2 shows the current building up slowly until spark initiation at about 1.4 ms and then a more rapid decline. The jagged appearance of the wave envelope is due to the scope's algorithm to select representative points from the long waveform data set and does not imply that the current is experiencing rapid excursions. When one spreads out the waveform, it can be seen that the current looks as well behaved as the current in Fig. 1 except that it grows by a small amount each cycle.

One cycle at 176.7 kHz lasts for about 5.66 μs. If the spark starts at 1400 μs, then it took 1400/5.66 = 247 cycles to get to breakout.

As charge leaves the toroid in the streamer, the toroid effectively gets a little larger due to the space charge in the streamer. This increases the capacitance and lowers the resonant frequency. The solid state drive must be able to slew with this change in frequency to keep driving the coil at its (changing) resonant frequency. My driver will maintain a fixed resonant frequency to within 50 Hz and then slew at 50–100 Hz/μs to follow changes. These are nontrivial specifications, as is obvious from the many patches in the controller circuit described in the previous chapter.

Fig. 3 shows the voltage and current waveforms at 1.40 ms, just before breakout. They

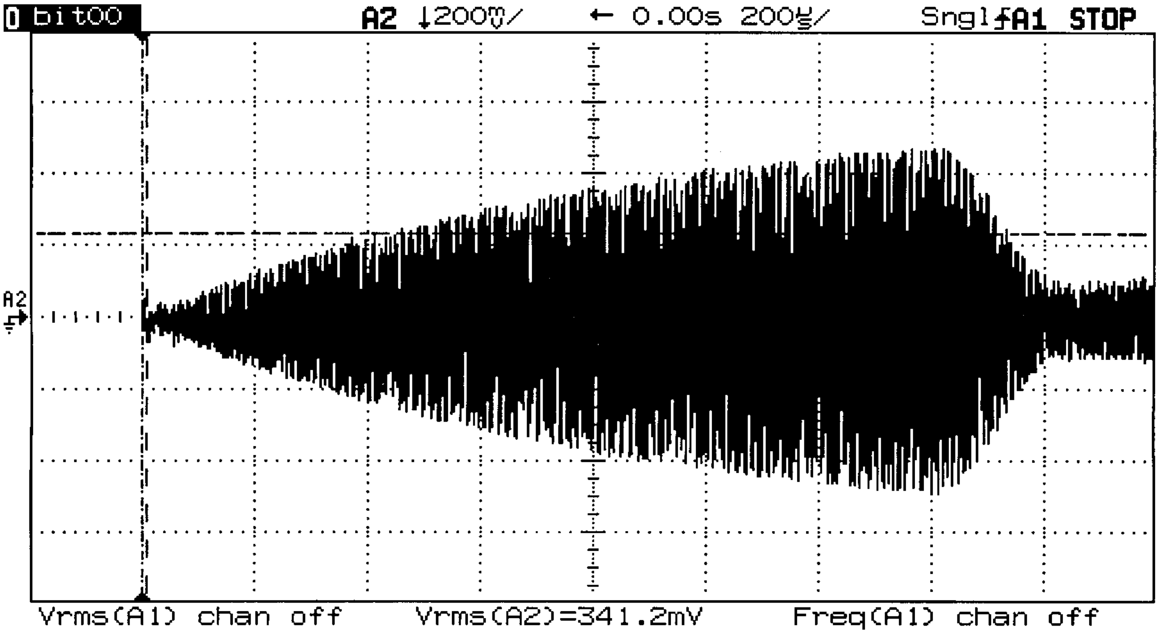

Figure 2: Current waveform at variac = 40%

look the same as in Fig. 1 except larger. The voltage is now 604.2 V, the current is 17.1 A, and the instantaneous power (the average power at this instant) is about 9.3 kW.

Fig. 4 shows the voltage and current waveforms during the spark. Voltage has increased slightly, as might be expected during lower current flow. Current is holding steady at 4.1 A. The controller is not holding the optimum phase angle between voltage and current, hence there is some ripple at the point of switching. If the phase angle were optimum, the current would be a little larger, perhaps in the 4.5 to 5 A range. Note that the frequency has dropped only slightly, to 176.1 kHz. People with classical spark gap coils will notice a greater frequency shift because they have bigger sparks for smaller coils and toroids than my case.

When the input voltage is increased, the current will build more rapidly, and spark initiation is sooner. The current waveform for a variac setting of 60% is shown in Fig. 5. The spark now starts at about 0.93 ms instead of 1.4 ms for the variac setting of 40%. Just before breakout the voltage is 913.5 V, and current is 21.5 A, and the instantaneous power is about 17.7 kW.

The voltage and current during the spark for the variac set to 60% are shown in Fig. 6. The voltage has rebounded slightly from 913.5 to 936.7 V. The spark current is still about 4 A.

The coil appears to operate as a constant-current device in breakout. Both the input dc current and the ac current into the coil stay about constant, perhaps even decreasing a little,

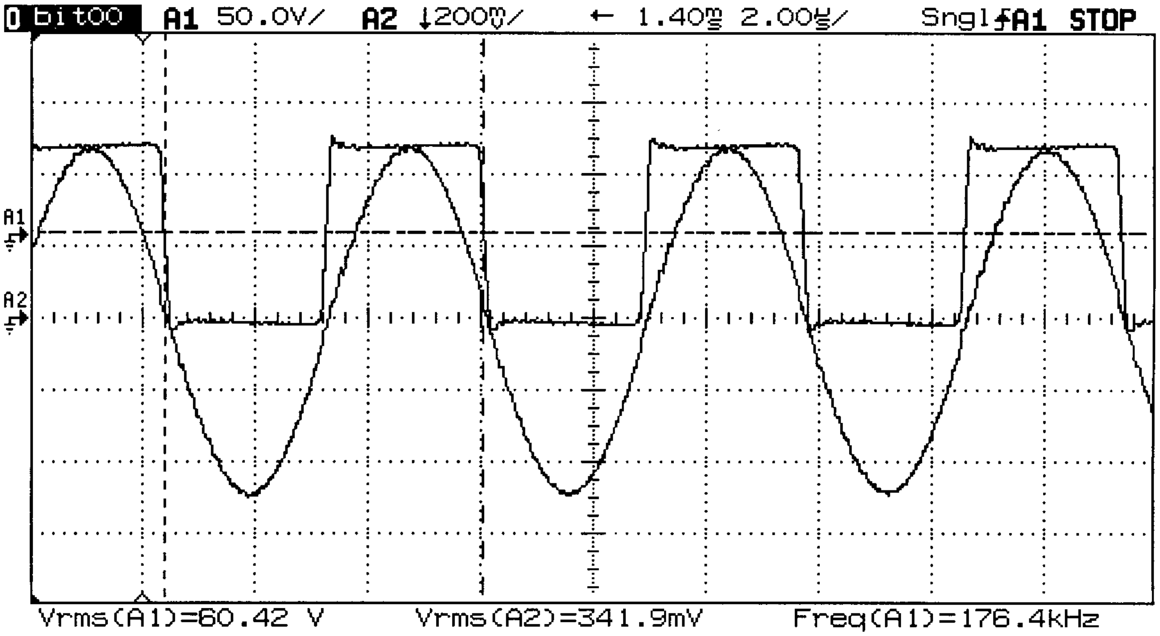

Figure 3: Voltage and current just before breakout at variac = 40%

as the variac is increased. The input impedance increases proportional to the input voltage, in order for the current to remain constant.

2 Spark Length

Estimating length of a streamer ending in air is a challenge, more than streamers to a ground point where the distance can be checked later with a tape measure. My record on distance to a ground point is 143 cm, in front of about 60 members and guests of the local ham club. For streamers to air, I put a piece of Styrofoam behind a bump on the toroid with a series of concentric circles drawn on it. I would get in a position to observe where the bump appeared to be in the center of the circles. My driver will operate either in CW or impulse mode. I would set it in CW or at several pulses per second and watch the sparks. An average observed distance would be recorded and corrected for parallax. The corresponding power just before breakout would also be recorded. I found the spark length to be related to the square root of power according to the formula

$$\ell_s = 0.17\sqrt{P} \qquad \text{inches} \tag{5}$$

where P is measured in watts. John Freau has measured spark lengths on his coils and determined the relationship should be $\ell_s = 1.7\sqrt{P_a}$ inches, where P_a is the average wattmeter

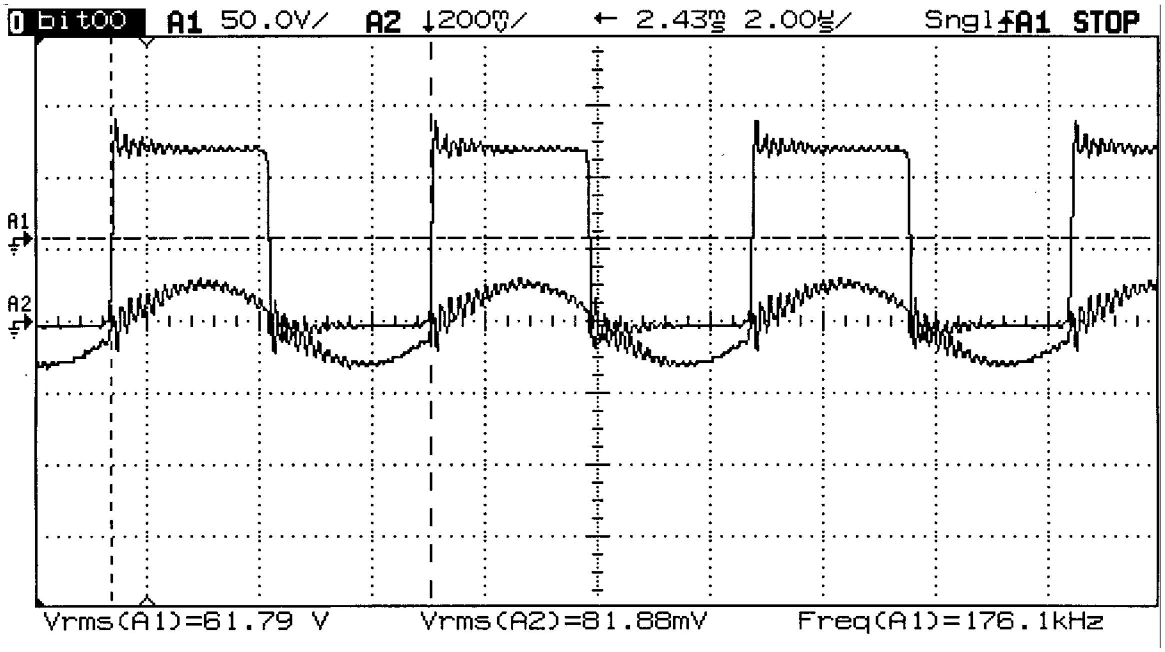

Figure 4: Voltage and current during spark at variac = 40%

reading on the 60 Hz, 120/240 V side of his circuit. There is obviously a factor of 10 difference between the two formulas. I have watched his videos and am convinced his equation is valid. I think the difference is in the definition of power. Suppose John supplies 1 kW to his capacitor for 1 cycle of the 60 Hz waveform, then dumps all this stored energy to the secondary in 1/100 of the 60 Hz waveform or 1/6000th of a second. The power during this impulse would then be 100 kW. Take the square root and we have the factor of 10.

A classical disruptive coil operates at very high power levels when the spark gap fires. The capacitor may be charged to 15 kV and it is connected to the input of a step-up transformer which raises the effective applied voltage to the secondary even more. The toroid voltage rings up to its firing voltage in a few cycles (at most) of the coil resonant frequency, so the energy supplied to the capacitor over a relatively long time period will be dumped to the spark quickly. Ionization of air requires some time, so the quicker the power is applied, the higher the voltage can rise, and the longer the spark.

I have checked my formula to about 30 kW, with spark lengths about 30 inches. Even modest classical coils can reach 54 inches of spark, which would require 100 kW peak according to my formula. A coil with a 14 ft spark (big by my standards) would require a peak power of 1 MW. Reaching these power levels at Tesla coil frequencies with silicon devices will be a challenge. I suppose it could be done, but not by some old geezer puttering in his shop. It will require more than bailing wire, duct tape, and chewing gum!

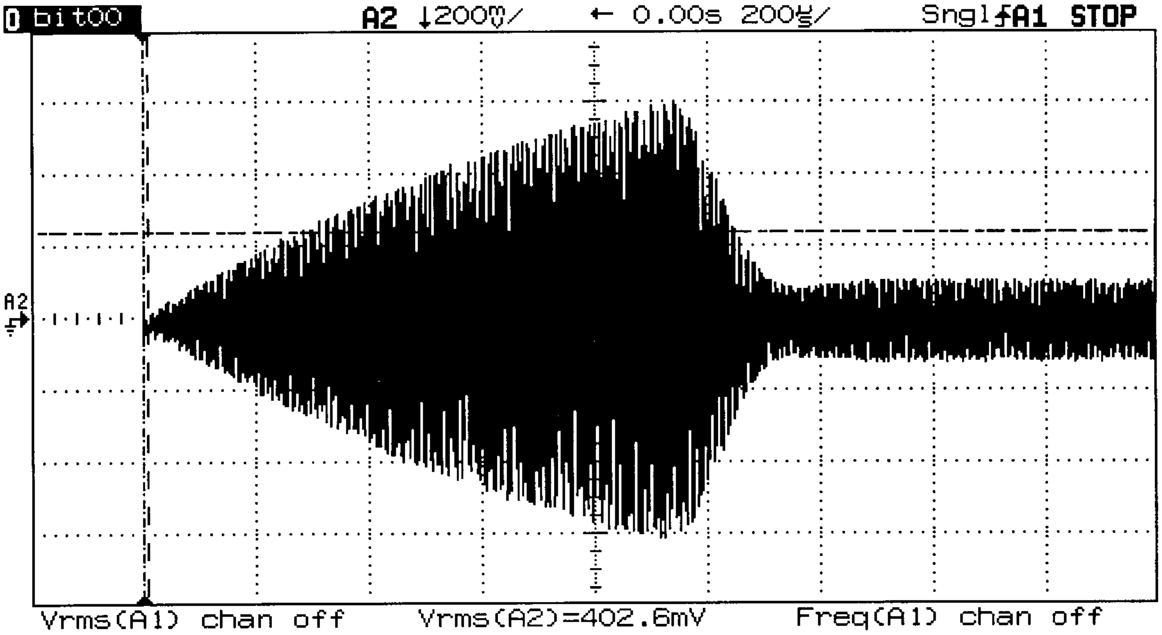

Figure 5: Current buildup for variac at 60%

3 Conclusions

It has been demonstrated that a Tesla coil secondary can be driven with IGBTs to produce sparks up to a meter in length. Sparks look the same as those from classical coils. Sparks get fatter the longer the coil is driven after spark initiation. A spark initiated at 1 ms and terminated at 2 ms will be much thinner and weaker looking than one terminated at 10 ms.

Once the system is adjusted, it will produce say 10 sparks per second for 24 hours per day and 7 days per week. No fan is necessary and there is no spark gap to get hot and corroded.

This chapter in particular needs to be rewritten and expanded. Please forward comments and suggestions to gjohnson@ksu.edu.

References

[1] *IEEE Standard Dictionary of Electrical and Electronics Terms*, Institute of Electrical and Electronics Engineers, IEEE Std 100–1977, 1977.

[2] Uman, Martin A., *Lightning*, Dover, 1969, 1984.

[3] Uman, Martin A., *All About Lightning*, Dover, 1971, 1986. This book is shorter and less technical than *Lightning.*

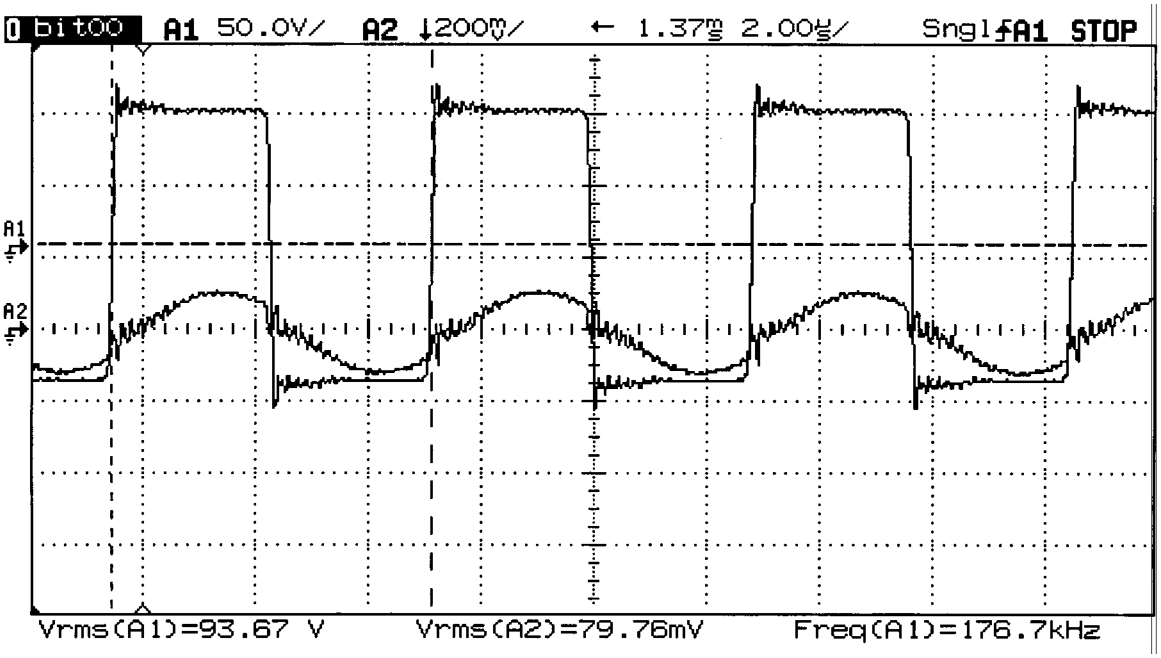

Figure 6: Voltage and current during spark for variac at 60%