DRSSTC

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The DRSSTC is the perfected form of the Tesla Coil in the works for over a hundred years. It is also the most complicated of the many forms. In this experiment a small DRSSTC was built using a full bridge of high power IGBTs. The first DRSSTC was made by Jimmy Hynes. Since then it has become a popular project for anyone interested in high power electronics. The interrupter built is capable of BPS between 122 Hz and 918 Hz and pulse widths between 1ms and 100ms.

INTRODUCTION

The Dual Resonant Solid State Tesla Coil is the newest and most efficient form of the Tesla Coil. Nikola Tesla first applied for a patent for the high frequency transformer in 1891. Not much had been changed until in the past decade or so when the first DRSSTC was made by Jimmy Hynes. [1] High efficiency coupled with precise streamer control makes the DRSSTC attractive for any electronics project.

THEORETICAL BACKGROUND

By definition the Tesla Coil is an air-cored resonant transformer. The difference between the original spark gap and solid state coils only differ in the driving of the transformer. In order to understand of the modifications, one must first understand the original. The theory section is split into three parts: Spark Gap Tesla Coil, Solid State Tesla Coil (SSTC), and DRSSTC Modifications.

Spark Gap Tesla Coil

The most basic of Spark Gap Tesla Coil (SGTC) is shown schematically in Figure 1. It is essentialy a driven series RLC circuit. The circuit begins when the capacitor is charged with a high voltage power supply. When sufficient voltage accumulates, an arc is established across the spark gap discharging all the stored energy into the primary. The inductive coupling between the primary and secondary induces a charge at the topload torus. The charging and discharging of the capacitor through the primary coil has a certain resonant frequency given by

$$\omega = \sqrt{\frac{1}{LC}} \tag{1}$$

The secondary also has a resonant frequency governed by the inductance and self capacitance of the secondary/topload combination. A topload is not necessary but is often included to increase the capacitance and thus lower the resonant frequency of the secondary. The amazing thing about the Tesla Coil is that the output is not solely governed by the turns ratio as it is with a traditional transformer. The output is determined by resonance matching between the primary and secondary tank circuits as well as the Q-factor of the system. The voltage rise of a RLC circuit around resonance is shown for several Q values is shown in Figure 1. The voltage rise around resonance is limited only by the resistance of the tank circuit. Unfortunately the resistance of the spark gap can be very high on the order of 3 ohms when calibrated properly. Combined with the primary resistance and the internal resistance of the capacitor the total resistance can cause a relatively low Q. The output is still much much greater than a traditional transformer. The SSTC works to reduce the resistance of the tank circuit and increase the overall Q-factor resulting in a greater output and efficiency.

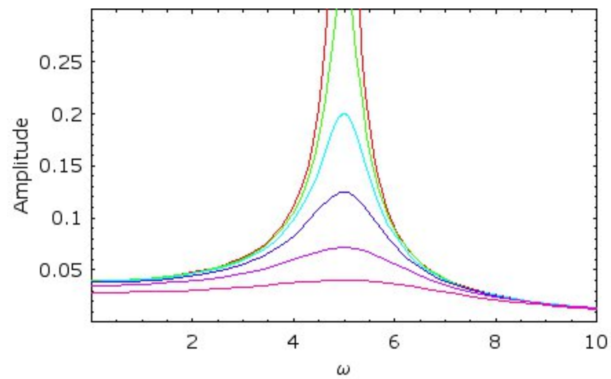

FIG. 1. Voltage across any element of an RLC circuit around resonance for increasing Q-factors. [2]

Solid State Tesla Coil

The Solid State Tesla Coil was a great milestone in coiling. The idea was to replace the messy and physically large tank circuit of the SGTC with a lighter solid state version. Most designs use a full bridge of MOSFETs to switch a large amount of power at the resonant frequency. The beauty of the SSTC is that the system is built to work continuous wave so very different arc effects can be shown. The SSTC is so called single-resonance because the primary coil does not necessarily have to be in tune

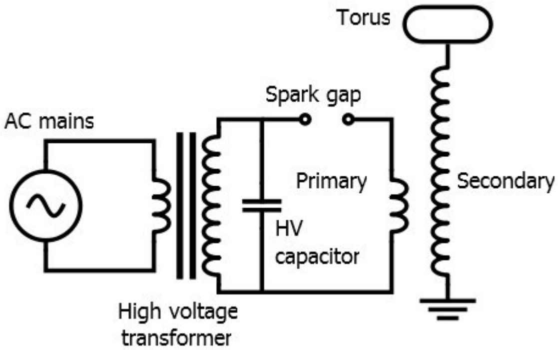

FIG. 2. Circuit diagram for a simple spark gap tesla coil.[3]

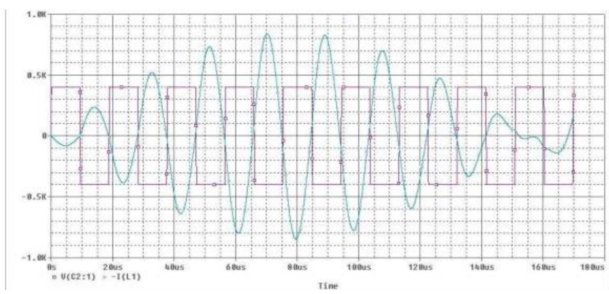

FIG. 3. The square wave voltage and current output from the H-Bridge. [4]

with the secondary.

DRSSTC Modifications

The DRSSTC combines the effectiveness of the Solid State Tesla Coil (SSTC) with the large resonance rise of the SGTC. The DRSSTC gets its name from the fact that the primary tank circuit is resonant as well as the secondary. The only modification to the SSTC is the addition of a primary tank capacitance. This minute addition causes some very large changes. The goal remains the same, however, to maximize Q and pump as much energy into the secondary in as little time as possible. Figure 3 shows the driving square wave voltage and current. The output from a signal like this is shown in Figure 4. The system starts when voltage is applied to the LC tank circuit through the H-Bridge. This quick voltage rise induces a current onto the secondary. The secondary naturally begins to ocscillate at its resonant frequency defined by its self-capacitance and inductance. If the H-Bridge and secondary are in resonance, as soon as the current in the primary oscillates to zero, the H-Bridge will switch and pull the current in the primary down which in turn pulls the secondary current down. This push-pull adds energy to the secondary each cycle as shown by the rise in peak current in Figure 4. Eventually an arc is established at the output of the secondary leading to a drain in the energy stored up. The sudden drop shown in Figure 4 is such a strike. Theretically one could run the entire system continuous wave but physical limitations mainly due to IGBT contruction keep that from happening. The biggest problem associated with the DRSSTC is overcurrent and overvoltage. Inductor voltage is proportional to the change in current. The faster the rise in current, the larger the voltage drop across the inductor. That is in fact what makes the DRSSTC so attractive. Combined with the large energy storage capabilities of the tank capacitance makes for a very complicated system. Peak voltages around 5 KV and currents up to 1000 Amps are typical. Any stray inductance or capacitance, even from the component themselves present a major problem. Many current and voltage protection circuits are included in DRSSTC design to compensate for this. The actual application of the DRSSTC can become very complicated.

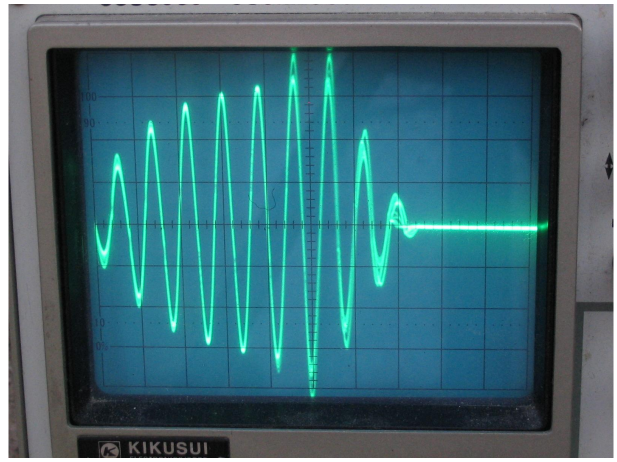

FIG. 4. Current output from the secondary coil during a ground strike. The output is oscillating as normal and then a ground stike occurs draining the system of energy. [5]

APPARATUS

The particular design that was used in this experiment includes three parts: an interrupter, controller, and H-Bridge.

Interrupter

Some of the largest IGBTs available to the average consumer are capable of handling less than 70 amps RMS. The IGBTs must be run at a very low duty cycle to keep from overheating. The interrupter is usually designed with variable Pulse Width (PW) and Breaks Per Second (BPS) control. The PW is the amount of time the system is on and directly controls the power. The longer the system is turned on, the more power can be pumped into the secondary coil. A PW on the order of tens of microseconds is common. The typical DRSSTC runs at 120 BPS which results in a duty cycle of about 0.5%. the interrupter used in this experiment uses two 555 timers. One timer is wired in astable mode for BPS control and the other is wired in monostable mode to control the PW. An extra 555 timer is added for "Burst Mode" which sort of randomizes the output for a pretty spark effect. See Appendix A for the schematic diagram of the interrupter. The entire set up is run from a 9 Volt battery and placed inside a metal container to reduce interference. The output from the interrupter is then fed via a shielded wire into the controller. The BPS and PW can safely be adjusted from meters away while the coil is running.

Controller

The controller schematic is quite a bit more complicated (Appendix B). The easiest place to start is with the resonance detector section in the top left area. While operating the primary coil will oscillate at its resonant frequency. The induces a current onto two cascaded current transformers (T4 and T1). The current is reduced by 1:33:33 or about 1000 times. This also means that the voltage is increased by a factor of a thousand. Zener diodes D19 and D22 take care of that by clipping the voltage to 5V. Zeners tend to be rather slow so diodes D21 and D20 are added in to compensate. The output of these diodes is a clipped sine wave that highly resembles a square wave. Resistor R2 is added to limit the current and subsequently keep the zeners at the right voltage. C1 is just a filter capacitor. D1 and D2 clamp the voltage to the supply rail and ground. The output is then passed through two Hex-Inverting Schmitt Triggers (on the same chip) to clean up the square wave.

The second section is overcurrent protection. The same kind of cascaded current transformer set up is used. This time the output is full wave rectified and passed directly through a resistor. The voltage drop across the resistor can now be used (by Ohm's Law) to measure the current in the primary. This voltage is the compared to a variable voltage given by the R10 and R11 combination using the LM311 comparator Op-Amp. When the current in the primary reaches a defined value, the comparator goes low signally overcurrent. The output is then fed into a monostable 555 trigger. The pulse width on the 555 is set longer than the pulse width from the interrupter to ensure that all power is drained from the secondary. Overcurrent is also indicated visually on D4.

The interrupter signal is passed through another Schmitt Trigger to the Reset input of a JK Flip Flop. Whenever the interrupter goes high, the inteverter goes low making Q' go high. The RC combination after the interrupter acts to delay the signal to the Set input. Otherwise the output would never shut down. The Flip-Flop also takes the input from the resonance section as the clock thus synchronizing the shutdown at zero current (or thereabout) in the primary. Otherwise the H-Bridge could potentially be switching hundred of amps and suddenly stop inducing a huge voltage spike. The interrupter signal is also connected to a MOSFET controlled by the overcurrent detector. Whenever overcurrent is detected, the FET activates and pulls the interrupter signal to ground shutting down the system. The output from the Flip-Flop is then fed into the enable pin of two high current IGBT drivers. The enable pin pulls the output of the driver down whenever the pin is low. The resonance detector circuit is also fed into the drivers causing them to switch at resonance with the primary. The drivers are smoothed with capacitors C9 and C10. Any voltage transients from the H-Bridge are block with 40 volt schottky diodes D13-16. The drivers provide the signal to the H-Bridge through a gate drive transformer.

H-Bridge

The IGBTs used in this experiment are 40 Amp 600V. They are reported to be able to handle up to 500 Amps peak.[5] IGBTs are selected over MOSFETS because of their static voltage drop between the collector and emitter resulting in a loss proportional to current. MOSFETs have a saturation resistance with loss proportional to current squared. Obviously when handling several hundred amps, the square can become very important. The downside to the IGBT is that it is not capable of handling very high frequencies.

The power supply of the H-Bridge is simple mains voltage recitified and filtered. This is fed directly into a standard full bridge. The H-Bridge operates by turning on diagonal IGBTs at the same time. The power runs from the power supply through one IGBT, through C1 and L1 (the tank circuit) through the diagonal IGBT and then to ground. In the low cycle, the opposite two IGBTs are turn on allowing flow in the opposite direction. Dioded D6-13 are 33V zener diodes to catch any stray voltage transients from passing into the gate drive transformers and harming the controller. TVS diodes D14-17 are responsible for catching voltage transients on each of the IGBTs and D18 on the power rails. Capacitors C2 and C3 are decoupling capacitors to keep triggering of each IGBT from affecting another. The diode and resistor combination on the gate of each IGBT acts to protect the IGBTs from overcurrent.

The most effective systems utilize high peak currents with shorter on times. [5] The whole system must have as low resistance as possible. Any stray inductance or capacitance will at least hinder the performance if not

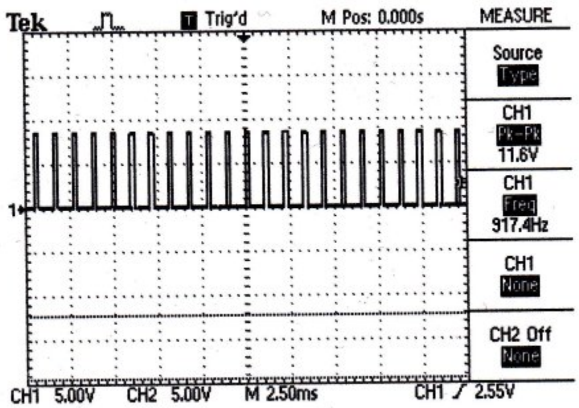

FIG. 5. Output from the interrupter as maximum BPS and PW.

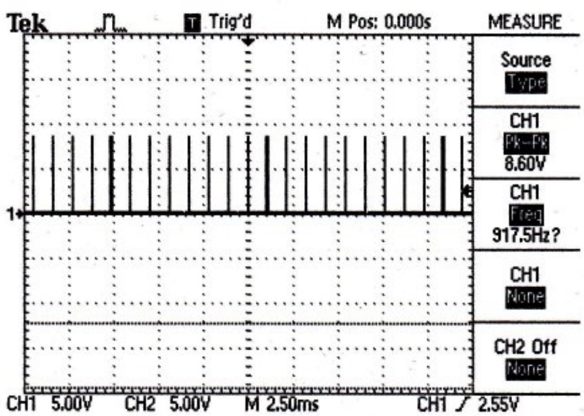

FIG. 6. Output from the interrupter as maximum BPS and minimum PW.

destroy the system itself. Even the inductance and self capacitance of the IGBTs themselves can present a problem.

RESULTS

The interrupter pulse width is variable from 1ms to 100ms. The BPS is fully adjustable between 122 Hz and 918 Hz. See Figure 5, 6 and 7 for the output waveforms from the interrupter. Most likely due to insufficient electrical isolation between adjacent IGBT heatsinks, the H-bridge experienced catastrophic failure three seconds or so into operation. Further testing of the device was not possible within the time contraints.

DISCUSSION & CONCLUSIONS

There is always more to learn. Especially in this case. Entire books have been written just on the design of the

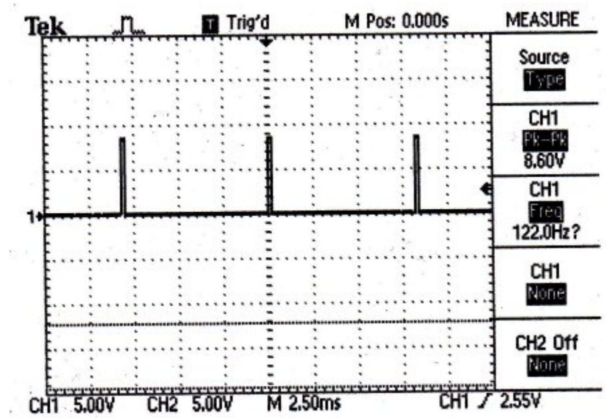

FIG. 7. Output from the interrupter as minimum BPS and maximum PW.

DRSSTC. [6] I discovered that the entire system runs in the transient state, so it was impossible to simulate in the lab. The only way to test it was to put everything together and turn it on. Definitely not the best system.

Future Plans

I plan on completing the DRSSTC created in this lab over the summer. My goal is to achieve arcs longer than I am tall. It is definitely possible using the driver and H-Bridge that I have now. That is once I replace the blown IGBT. Also I would like to replace the almost analog version of the interrupter with a microcontrolled system. That way, I can program in audio modulation and have complete control over the spark. I believe that the primary current feedback used in Steve Ward's design adds to much delay. Each time the signal is passed through a gate, it gets delayed by tens of nanoseconds. When passed through three or four gates, plus a few transformers, the delay can be significant. I think a better option would be to use a variable crystal oscillator located inside the interrupter box external to the system. The frequency can be adjusted in real time and resonance found. I certainly learned a lot even by building a broken system.

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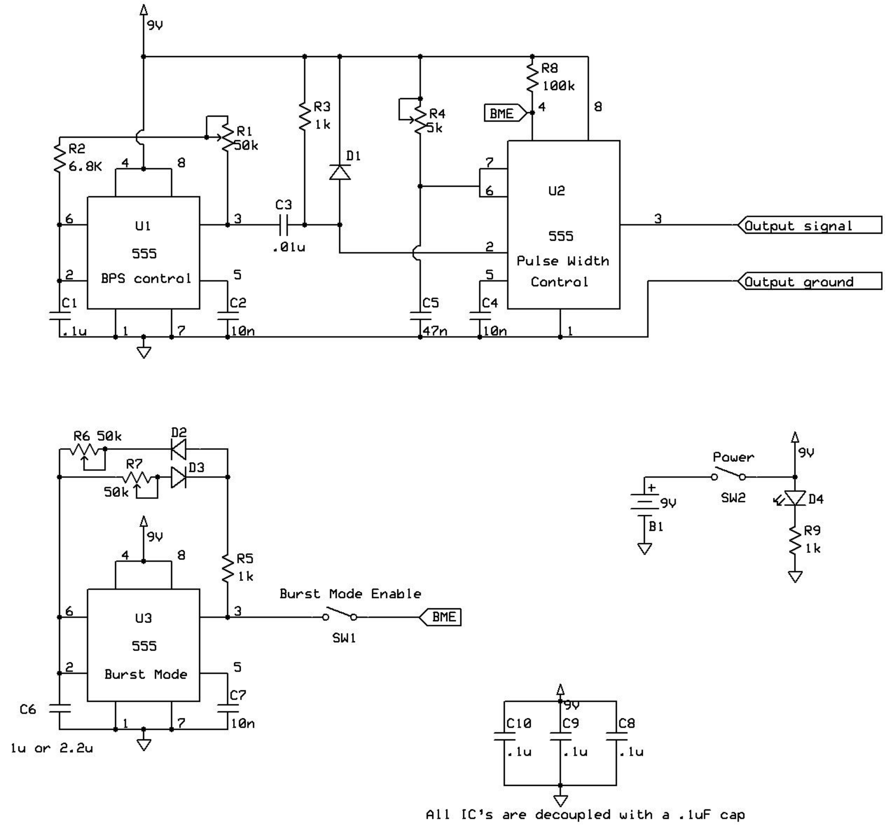
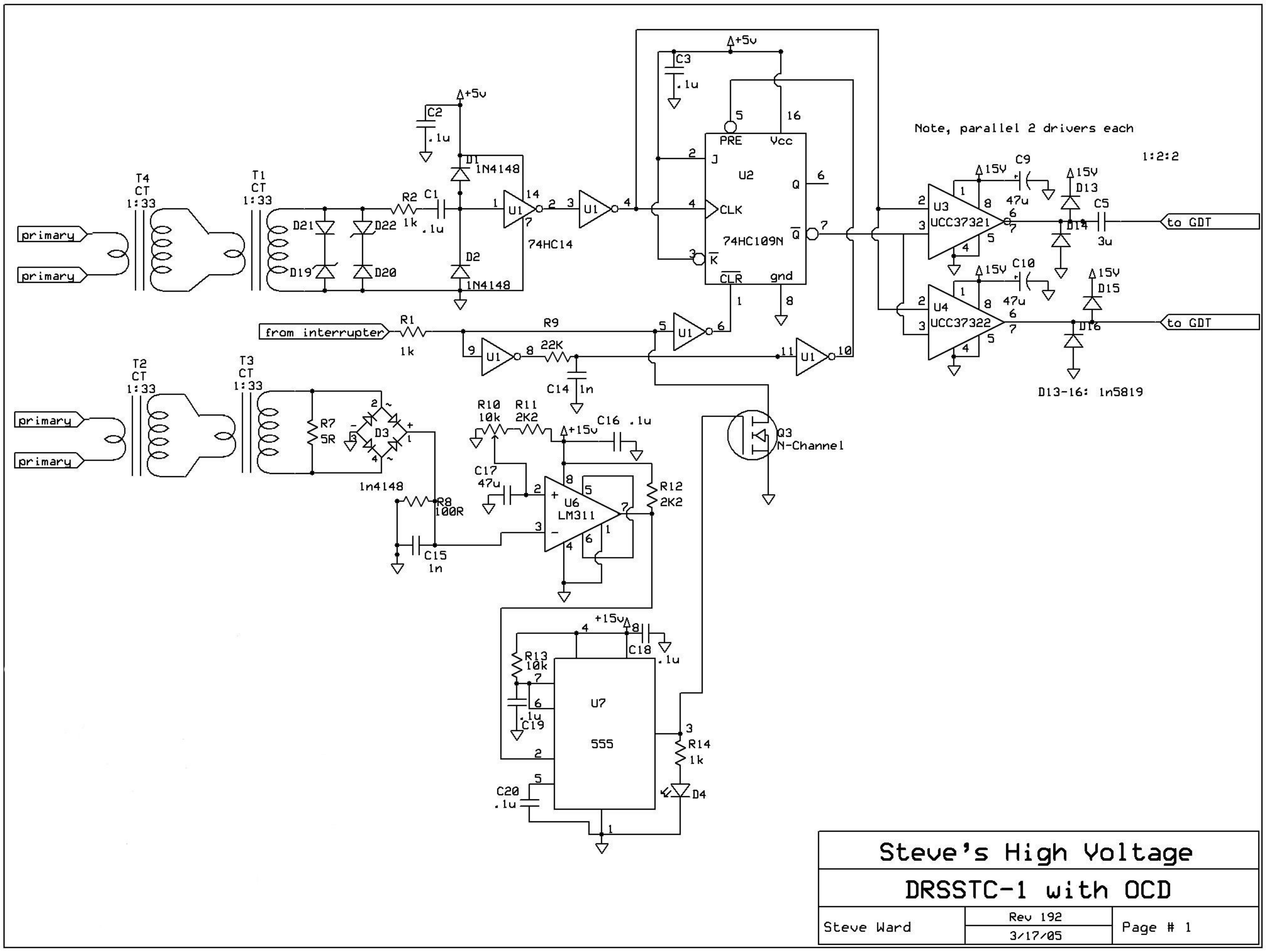
[1] *Dual Resonant Solid State Tesla Coil.* 4hv Forum. 2008.
[2] *Forced/Driven Oscillations.* Splung Physics. 2012
[3] *Tesla coil 4.jpg.* Wikimedia Commons. 17 April 2007.
[4] *A little info about DRSSTCs.* Jimmy Hynes. Mirrored by www.capturedlightning.com.
[5] *Steve's High Voltage.* Steve Ward. Nov 2008
[6] *DRSSTC: Building the Modern Day Tesla Coil.* Eastern Volt Research, LLC. 2010.



Steve's High Voltage		
Interrupter with Burst Mode		
Steve Ward	Rev 1.0 9/20/2005	Page # 1


primary
primary
T4 CT 1:33
T1 CT 1:33
D21
D22
D19
D20
R2 1k
C1 .1u
C2 .1u
+5v
D1 1N4148
D2 1N4148
U1
74HC14
C3 .1u
PRE
Vcc
J
CLK
K
CLR
gnd
Q
U2
74HC109N
Note, parallel 2 drivers each
1:2:2
U3 UCC37321
U4 UCC37322
15V
C9 47u
C10 47u
D13
D14
D15
D16
C5 3u
to GDT
to GDT
D13-16: 1n5819
from interrupter
R1 1k
R9
22K
C14 1n
T2 CT 1:33
T3 CT 1:33
R7 5R
D3
1n4148
R8 100R
C15 1n
R10 10k
R11 2K2
+15v
C16 .1u
C17 47u
U6 LM311
R12 2K2
Q3 N-Channel
R13 10k
C18 .1u
C19 .1u
U7
555
R14 1k
D4
C20 .1u
Steve's High Voltage
DRSSTC-1 with OCD
Steve Ward
Rev 192
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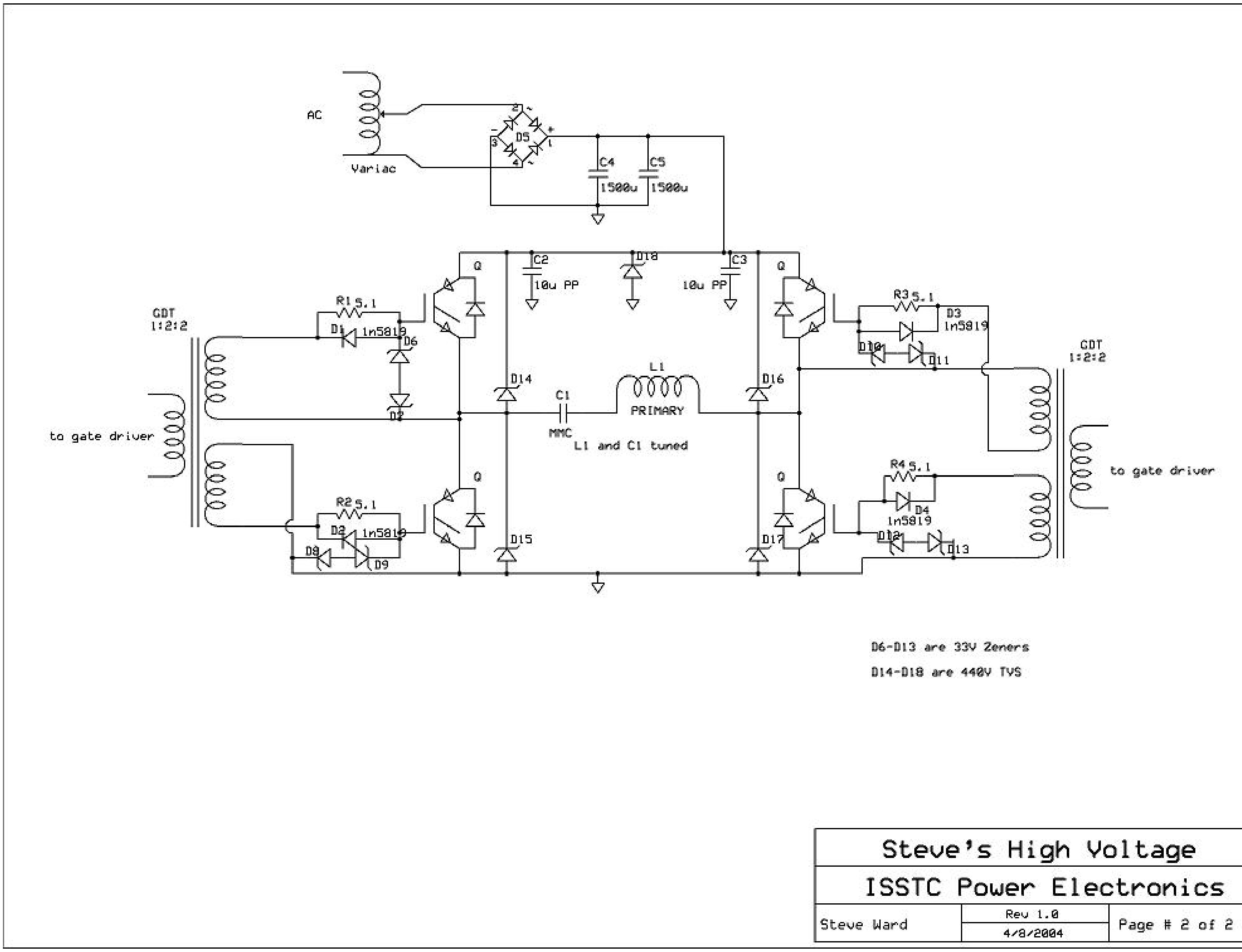
AC
Variac
D5
C4
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D18
C3
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1:2:2
R1 5.1
D1 1n5819
D6
D7
D14
C1
MMC
L1
PRIMARY
L1 and C1 tuned
D16
R3 5.1
D3
1n5819
D10
D11
to gate driver
R2 5.1
D2 1n5819
D8
D9
D15
D17
R4 5.1
D4
1n5819
D12
D13
D6-D13 are 33V Zeners
D14-D18 are 440V TVS
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