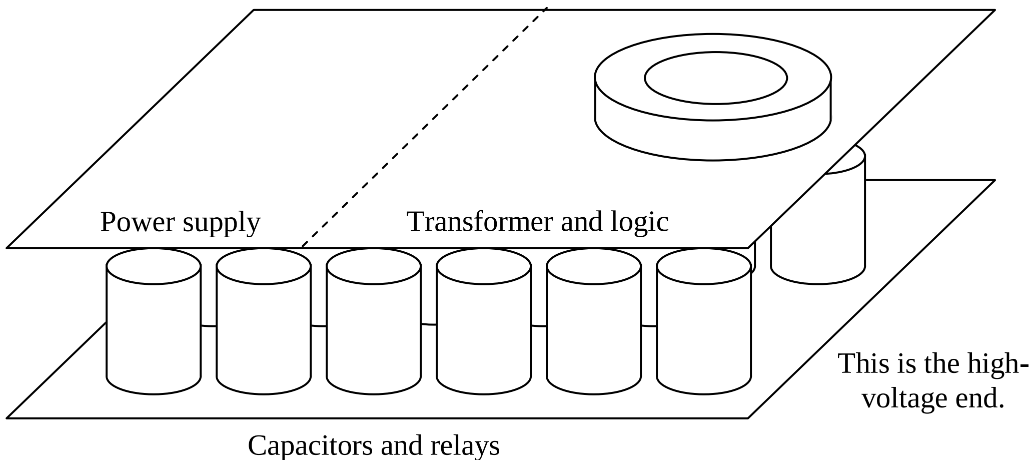
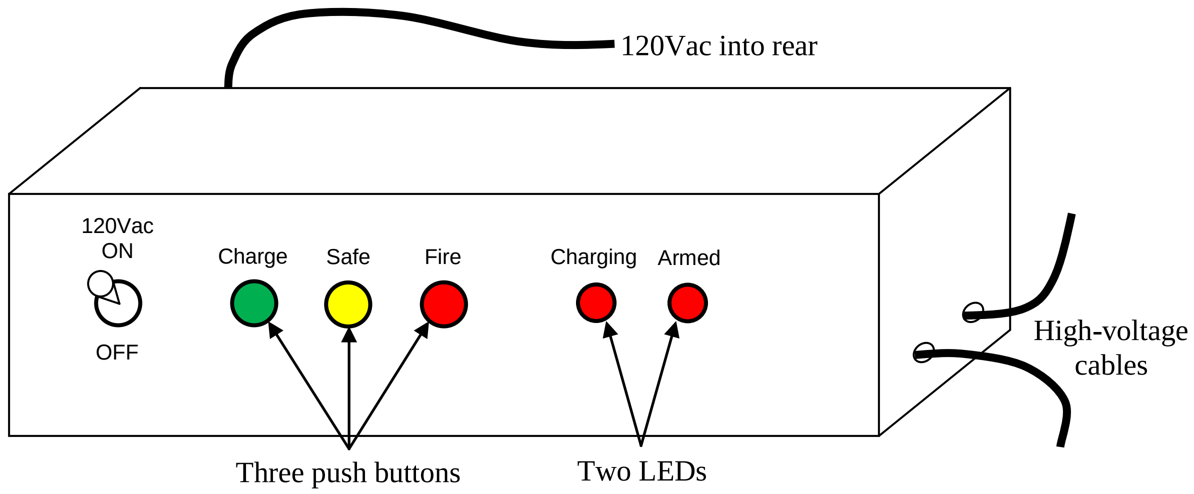
Construction of a high-voltage Buck-Boost capacitor charger

This paper describes the construction of the circuit described in the paper titled *A high-voltage Buck-Boost capacitor charger*. As described there, the load capacitor is built from 22 electrolytic capacitors wired in series. The capacitors are relatively large and 22 of them are sufficient to take up most of a large printed circuit board. For this reason, the device is constructed from two printed circuit boards (PCBs), mounted one atop the other. The PCBs are one-side copper and measure 8 inches by 10½ inches. The following figure shows roughly the overall layout. The components are arranged so that the "high-voltage" things take place near the right-hand side of the device, in the view shown.

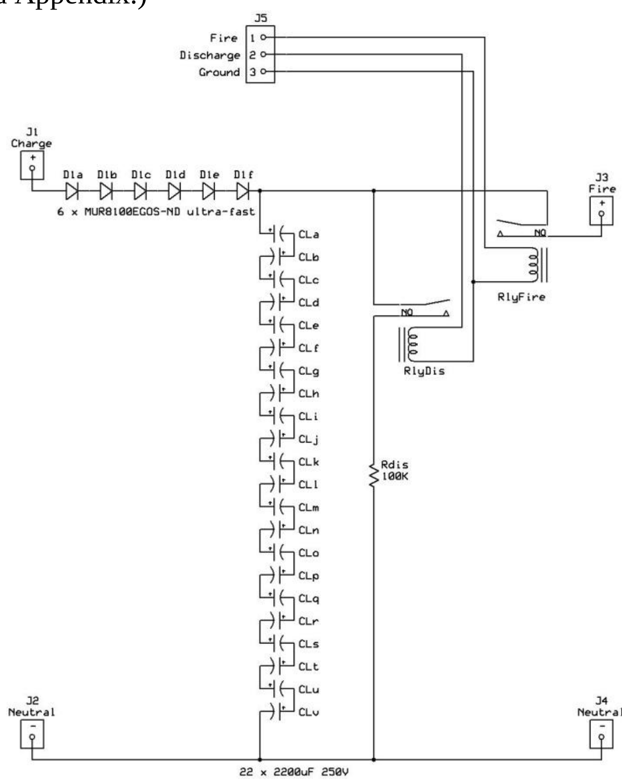


The toroidal transformer and the logic circuits are mounted on the right-hand end of the top PCB. The other end of the top PCB contains a 12V 2A power supply driven by the ac mains. If you plan to power your unit from a battery, then the power supply end of the top PCB will not be necessary. The following figure shows the front of the enclosure in which the two PCBs are mounted. The two cables which connect the load capacitor to an external circuit exit from the right-hand end. Since the external circuit will likely draw a substantial current, the cables should be heavy-duty in order to minimize their resistance. While not shown in the figure, the cables should be terminated with lugs. The 120Vac power cord exits from the rear of the device. I will describe the controls from left to right. A toggle switch turns the power supply on and off. There are three push buttons: (i) "Charge", which starts the 500-second period during which the load capacitor is charged up, (ii) "Safe", which discharges the load capacitor through an internal resistor, and (iii) "Fire", which discharges the load capacitor through whatever circuit is attached to the high-voltage cables. There are two LEDs: (i) "Charging", which is illuminated while the load capacitor is charging, and (ii) "Armed", which turns on when the load capacitor is charged up.



The first figure above shows that the bottom PCB holds the bank of load capacitors and the relays. You may ask: what are the relays all about? They were not mentioned in the paper titled *A high-voltage Buck-Boost capacitor charger*. When the capacitor bank is charged up to its design voltage of 4000V, the 800J of energy it contains is lethal. It is worth remembering that, in the early days of heart defibrillators, such devices were built with settings up to 400J. The maximum setting never got much use, since lower energies were usually sufficient to kill the patient. More modern defibrillators have settings up to about 160J, and are discharged by sending half the energy in one direction and the other half in the other direction. To avoid jolting oneself into a steady-state, the capacitor bank must be controlled using remote switches such as relays. There is no place here for loose wires, sloppy workmanship, lack of concentration or careless procedures.

The following schematic diagram (Schematic #1) shows all of the components which are mounted on the lower PCB. (All of the schematic diagrams referred herein, and the layout of the printed circuit boards, are set out in the attached Appendix.)



As described in the earlier paper, diode $D1$, through which current flows to charge up the load capacitor, is built up from six MUR8100 diodes wired in series. The load capacitor itself is comprised of twenty-two 2200μF 250V electrolytic capacitors also wired in series.

The two leads from the secondary winding on the toroidal transformer, which is mounted on the top PCB, are connected to this PCB by the two "connectors" $J1$ and $J2$. These connectors are simply brass bolts inserted through the PCB with their heads soldered to large round pads. The leads from the transformer should have lugs on their ends and the lugs should be securely fastened to these bolts. A similar pair of bolts, being connectors $J3$ and $J4$, are the means through which the load capacitor is connected to whatever external circuit it drives.

A means is provided to discharge the load capacitor safely, without relying on any external circuit. Safety resistor R_{safe} is a large chassis-mount power resistor. The 100KΩ 50W resistor I used is Digikey's part number 850F100KE-ND. The load capacitor C_L has an equivalent capacitance of 100µF. It will discharge through resistor R_{dis} with a time-constant equal to $\tau = R_{dis}C_L = 10$ seconds. Resistor R_{dis} will have to burn off whatever energy is stored in the load capacitor. If the load capacitor is charged up to its design energy of 800J, the power burned off by the resistor will be in the order of 80W. However, the total discharge time is not so long that the resistor will over-heat.

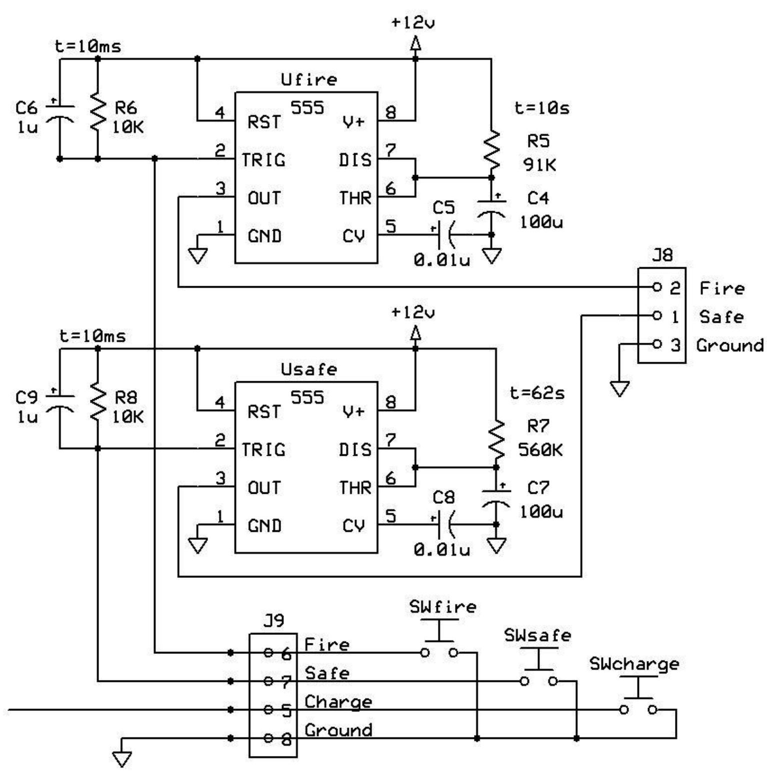
Discharge through the safety resistor is controlled by a single-pole single-throw (SPST) relay $RlySafe$. The relay I selected is sold by Digikey as its part number 374-1108-ND. It requires a coil voltage of 12V to close. Its contacts are rated for three amperes (3A) at 10KVdc. We will examine below the circuit which closes $RlySafe$ and keeps it closed long enough for the load capacitor to be substantially discharged.

A similar relay $RlyFire$ controls the discharge of the load capacitor into an external circuit.

The three lines which control the two relays are connected to a three-screw terminal block, shown in the schematic diagram as connector $J5$, from whence hookup wire can connect the lines to the top PCB.

The silkscreen side of the PCB on which the capacitors are mounted (called PCB #1) is set out in the Appendix. So is the copper trace side. The schematic diagrams and PCB layouts were drafted using the software from 123Express, which is available on the internet for free. Note that both printed circuit boards are exactly 8 inches wide and 10½ inches high.

The following schematic diagram is an extract from Schematic #2, which contains the toroidal transformer and the logic circuits. What is shown here are the two timers which control the relays $RlySafe$ and $RlyFire$ on the load capacitor's PCB. The two timers are common 555 timers, wired for single output pulses and activated by two off-momentary push button switches.



In fact, all three off-momentary push button switches are shown in the diagram: (i) SW_{fire} begins a discharge of the load capacitor through the external circuit, (ii) Sw_{safe} begins a discharge of the load capacitor through the internal resistor R_{safe}, and (iii) SW_{charge} begins the entire process of charging the load capacitor. The circuits for charging the load capacitor are not shown in the above extract.

The push button switches are mounted on the front panel of the unit. They connect to this PCB through a four-screw terminal block $J9$. The push button switches I used are Digikey part numbers EG4959-ND, EG4960-ND and EG4961-ND, respectively. They are identical except for the colour of the face of the button: SW_{fire} is red, SW_{safe} is yellow and SW_{charge} is green.

It can be seen that SW_{fire} is wired directly to the Trigger input pin of the 555 timer U_{fire}. Since SW_{fire} is normally open, the Trigger pin will normally be pulled high and kept high by resistor $R6$. When the switch is pressed closed, the voltage at the Trigger pin will be quickly pulled down to ground. (The power supply will provide the current to charge capacitor $C6$.) On the other hand, when the push button switch is released, capacitor $C6$ will discharge much more slowly. The only route available for current to flow out of this capacitor is through resistor $R6$. The time-constant of the $R6$-$C6$ resistor-capacitor pair is equal to $\tau = R6 \times C6 = 10\text{ms}$. It will take about five milliseconds before the voltage at the Trigger pin reaches a high enough voltage that U_{fire} can be triggered again. This delay "debounces" the switch, suppressing the multiple trigger pulses which would otherwise occur during the make-and-break cycles as the contacts of switch Sw_{fire} separate.

U_{fire} is wired as a monostable. The negative-going voltage edge at the Trigger pin will cause a single high-voltage pulse (in this case, "high-voltage" means the voltage of the power supply, 12V) on the Output pin. The length of the positive pulse is determined by the values of resistor $R5$ and capacitor $C4$. The formula given in the data sheet is $T_{on} = 1.1 \times R5 \times C4$ and, using the values shown, $T_{on} = 10.01$ seconds. Ten seconds is more than long enough for the load capacitor to discharge into the external circuit I used, but the values of $R5$ and $C4$ can easily be changed if your external circuit needs a longer discharge time.

The voltage pulse from U_{fire}'s Output pin is passed to the load capacitor's PCB through a three-screw terminal block $J8$. This signal is applied to the coil of relay Rly_{fire} and will keep the contacts of Rly_{fire} closed for ten seconds. During this period, the voltage over the load capacitor bank is connected to the output terminals of PCB #1 to which the high-voltage cables are attached.

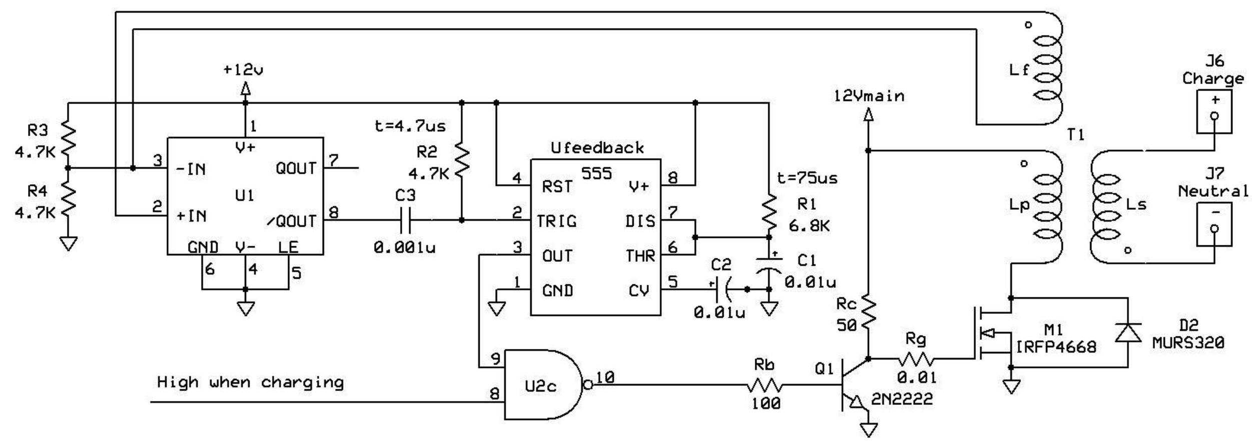
Incidentally, the small capacitor $C5$ which connects the Control Voltage pin of U_{fire} to ground is recommended by the timer's manufacturer for stability.

The circuit for safely discharging the load capacitor is just the same. Resistor $R8$ and capacitor $C9$ debounce switch SW_{safe}, which they do with a time-constant of $\tau = R8 \times C9 = 10\text{K} \times 1\mu = 10\text{ms}$. When triggered, the output pulse from U_{safe} is much longer than the output pulse from U_{fire}. Components $R7$ and $C7$ set the duration of U_{safe}'s output pulse to $T_{on} = 1.1 \times R7 \times C7 = 1.1 \times 560\text{K} \times 100\mu = 61.6$ seconds. Recall that the load capacitor discharges through safety resistor R_{safe} with a time-constant of ten seconds. It will take about five such time-constants for the load capacitor to discharge "completely". To be conservative, and to allow for the capacitance of $C7$ to be somewhat less than its nominal value, I chose the combination of $R7$ and $C7$ to be slightly longer from fifty seconds. There are two points to note:

- The adverb "completely" is a misnomer. In theory, capacitor $C7$ can never be discharged entirely through resistor $R7$. The discharge will be an exponential decay which, strictly speaking, never comes to an end. After five time-constants, though. the load capacitor should hold less than one percent of its original voltage.

- However, the original voltage was very high. If the load capacitor was originally charged up to the design voltage of 4000V, it could still register 40V after five time-constants, and even more if the values of components $R7$ and $C7$ are less than nominal. It is worth your trouble to run a couple of tests, and explicitly measure the voltage over the load capacitor to ensure that it is at a safe level.

The following schematic diagram is another extract from Schematic #2. This extract shows the components of the charging circuit as described in the paper titled *A high-voltage Buck-Boost capacitor charger*. There are very few differences between the schematic shown here and the one described in the earlier paper.

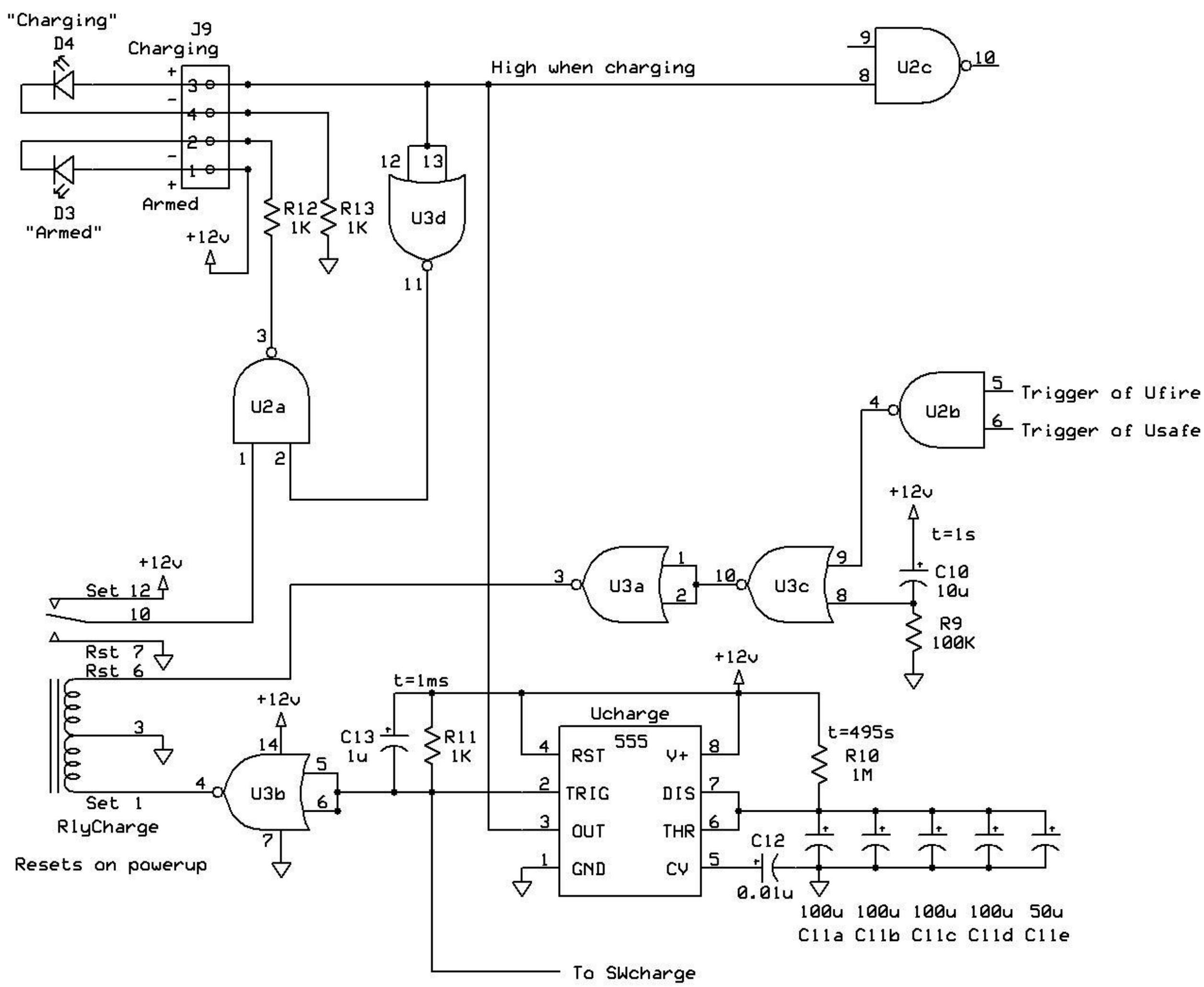


The two leads from the secondary winding of the toroidal transformer lead to two 1/8"-diameter brass bolts, inserted through the printed circuit board, with their heads soldered to the copper traces. These two bolts are shown as the "connectors" $J6$ and $J7$ and will be hooked up to their corresponding connectors / bolts $J1$ and $J2$ on the load capacitor's printed circuit board. Note that secondary circuit has no connection to the logic circuit's ground. The SPICE schematics shown in the earlier paper showed such a connection, but it was simply a requirement for the well-functioning of the SPICE program.

Secondly, a diode $D2$ is shown between the source and drain of the $M1$ hexfet. The hexfet has an internal diode between the same points. The one I have added is really just adding suspenders to a belt, as one says. This diode prevents the output leads of the hexfet from being reverse-biased to such an extent that the hexfet is damaged. The analysis in the earlier paper assumed that transformer $T1$ is perfect, in the sense that it does not suffer from leakage. If the transformer is leaky (and any real transformer will experience some loss), then it will experience voltage spikes at the start of the discharging cycle, when the magnetic field built up inside the transformer during the charging cycle begins to decay. Diode $D1$ will suppress these spikes. To make sure that it does, the diode I used is an ultra-fast diode. The datasheet for the MURS320 ultra-fast diode shows that it has a reverse breakdown voltage of 200V, the same as the output side of the hexfet.

The third and last difference is component $U2c$, one of four two-input NAND gates in a 4011B CMOS chip. In the earlier paper, this component was a simple inverter, inserted here to invert the positive pulse from the $U_{feedback}$ 555 timer when driver transistor $Q1$ is to be cut off. $U2c$ still performs the inversion, but does so only when permitted by the other input signal. We will look at the source of the signal "High when charging" below. But, as its name says, this signal is high (+12V) when the load capacitor is being charged. When the load capacitor is not being charged or, stated more precisely, when the charging process should be stopped, this line is brought low. When this control line is low, the output pin of $U2c$ will be kept high, driver transistor $Q1$ will remain in its saturation mode and hexfet $M1$ will stop cycling on and off. Hexfet $M1$ will be cut off and no current will flow in the primary circuit. Note that the power supply should not be turned off – even though it is no longer charging the load capacitor, it is providing the power needed to control the relays used to discharge the load capacitor.

Let us now look at the circuit which produces the "High when charging" signal. It is produced by the following circuit, which is yet another extract from Schematic #2. This circuit brings together the signals needed to charge and discharge the load capacitor and enables the user to control the process and see what is going on. The circuit is surprisingly complex given the supposedly limited functions it performs.



Let me first review the inputs and outputs of this circuit. We have already looked at two of the push button switches, SW_{fire} and SW_{safe}. The line to the third switch SW_{charge} is at the bottom of this sub-schematic diagram. That switch is connected to the Trigger input of the 555 timer U_{charge}. Pressing this third push button starts the process of charging up the load capacitor. The Trigger inputs of U_{fire} and U_{safe} are also needed by the circuit and are the two lines labeled "Trigger of Ufire" and "Trigger of Usafe", respectively. The control line we just looked at, "High when charging", is shown at the top of this sub-schematic diagram.

There are, in addition, two LEDs on the front panel of the device. $D4$ is the one labeled "Charging". It is illuminated when and only when the load capacitor is receiving charge. The other diode, $D3$, is labeled "Armed" and it will illuminate once the load capacitor has reached its full charge.

However, this circuit does not measure the voltage over the load capacitor to determine when it is fully charged. In fact, this circuit does not make any direct measurements at all. Instead, the load capacitor is allowed to charge for a fixed period of time, the duration of which is controlled by 555 timer U_{charge}. The Trigger pulse of U_{charge} is debounced by the same R-C circuit as the other two switches. Like them, a 1K resistor ($R11$) and 1μ capacitor ($C13$) provide the debounce with a time-constant equal to 10ms. Like U_{fire} and U_{safe}, U_{charge} is wired as a monostable. The duration of its output pulse is controlled by resistor $R10$ and capacitor $C11$. In the earlier paper, we found that the load capacitor reached its design voltage after 500 seconds of charging. The values of $R10$ and $C11$ have been selected here to give a pulse duration equal to $\tau = 1.1 \times 1\text{M} \times 450\mu = 495$ seconds.

A pulse duration of 495 seconds is relatively long for a 555 timer, and the values of $R10$ and $C11$ need to be high, as well. I used a single resistor and five capacitors in parallel to achieve the desired result. You will almost certainly have to do some testing, and perhaps try one or two different resistors or capacitors, in order to achieve the proper length of time. This testing should be done at an early stage of construction and with the charging circuit disconnected. It should be remembered that the load capacitor will charge up past 4000V quite easily and it is essential that it not be permitted to do so.

The Output pin of U_{charge} provides the signal "High when charging". This line also powers the "Charging" LED. The "Charging" LED and the "Armed" LED are common T1-3/4 LEDs, which are mounted on the front panel of the device using LED holders which are Digikey's part number 67-1332-ND. The 1K series resistors, $R13$ and $R12$, respectively, limit the current flowing through the LEDs to about 10mA.

Let us look now at the "Armed" LED, which should turn on once the load capacitor is fully charged. More precisely, it should turn on when the output pulse from U_{charge} comes to an end. Then, when either of the SW_{fire} or SW_{safe} push buttons is pressed to begin discharging the load capacitor, the "Armed" LED should turn off.

The "Armed" LED is controlled by several logic gates and relay $RlyCharge$. $RlyCharge$ is an interesting relay. It is a latching relay with two coils. When the Set coil is energized, the contact switch is pulled into the Set position, where it is latched. The contact will remain in the Set position even after current stops flowing through the Set coil. The contacts change state when the Reset coil is energized, which releases the contact into the Reset position. The contact will then remain in the Reset position, even with no current flowing through the Reset coil, until some later time when the Set coil is energized once again.

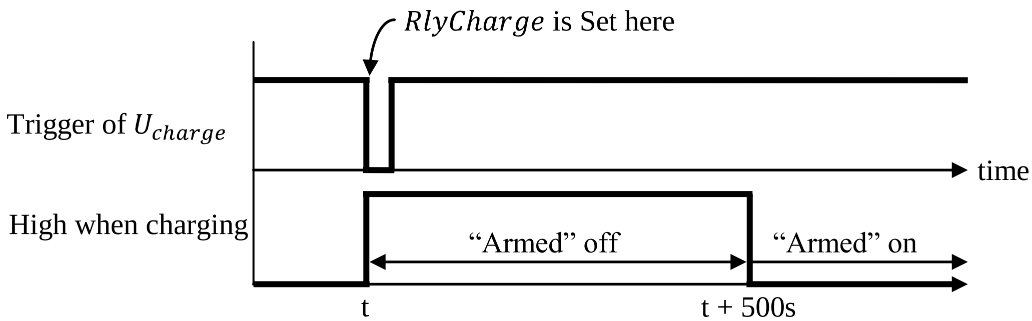
When $RlyCharge$'s contact is in the Reset position, the "Armed" LED will be off, regardless of anything else. In the Reset position, the contacts of $RlyCharge$ hold one of the input lines of NAND gate $U2a$ low. The output of $U2a$ will be high, there will be no voltage drop over the "Armed" LED and it will be off.

When in the Set position, on the other hand, the contacts of $RlyCharge$ hold that input high. In a sense, this "enables" $U2a$ so that its output voltage is controlled by the other input line. That other input line is the inverted version of the signal "High when charging". When the load capacitor is charging, "High when charging" will be high and the output voltage of $U2a$ again will be high, keeping the "Armed" LED off.

In short, the “Armed” LED will only be illuminated when: (i) $RlyCharge$ is in the Set position and (ii) the load capacitor is not being charged.

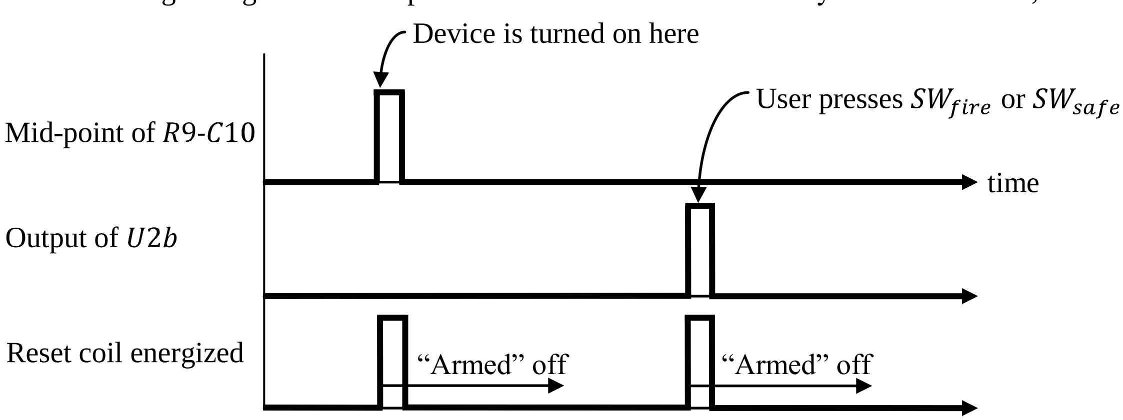
There is only one way by which $RlyCharge$ can be put into the Set position – pressing the SW_{charge} push button. Pressing the SW_{charge} push button will momentarily pull low the Trigger input of the 555 timer U_{charge}. NOR gate $U3b$ inverts that signal and energizes the Set coil. It should be noted that the low voltage on the Trigger input will remain low for as long as the user holds the button down, plus the debounce interval. We saw above that the time-constant of the debounce is 10ms, which means that the Trigger input will be low for an absolute minimum of 5ms or so. The datasheet for $RlyCharge$ shows that the Set and Reset coils need to be energized for 5ms in order for the contact to change state. The debounce time-constant was selected with this requirement in mind.

The following figure shows the timing of the process which Sets $RlyCharge$.

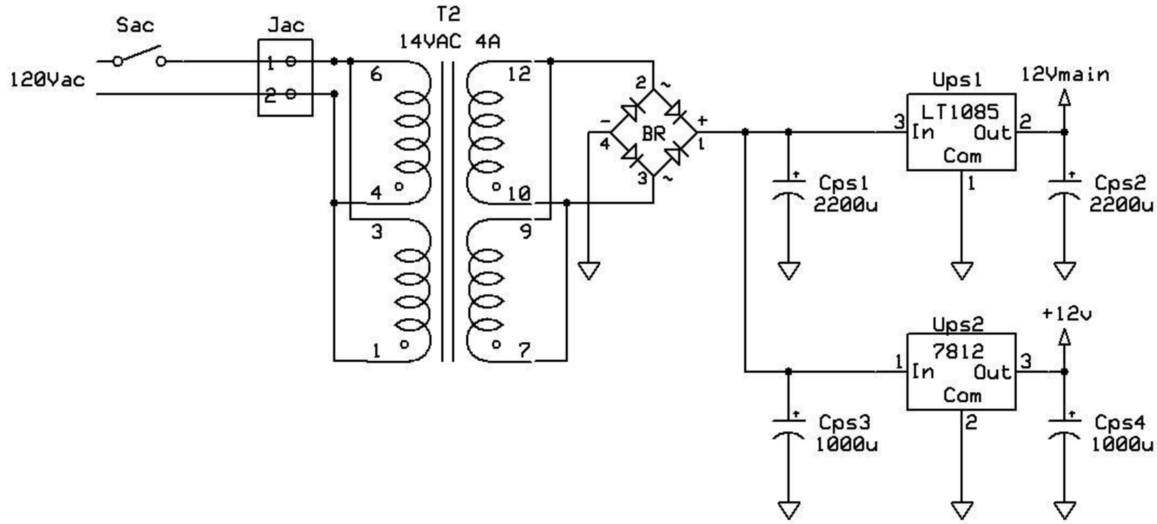


Now, let us look at what events can reset $RlyCharge$. There are three inputs to this decision. Two of them we have seen before. They are the Trigger inputs of the 555 timers U_{fire} and U_{safe}. These two signals are the two inputs to NAND gate $U2b$. In the normal state, when the user is not pushing either of the SW_{fire} or SW_{safe} push buttons, both Trigger lines are high and the output of $U2b$ is low. The output from $U2b$ will be high if and only if the user is pressing SW_{fire} or SW_{safe} (or both) and will be high as long as the user keeps the button(s) pressed, plus the debounce interval.

This combined signal is NORed with another signal by NOR gate $U3c$. This other signal is relevant only when the device is first powering up. Since the voltage over capacitor $C10$ cannot change instantaneously, the voltage at pin 8 of $U3c$ will go high immediately when power is applied. Resistor $R9$ will allow capacitor $C10$ to charge up gradually. The time-constant of the $R9$-$C10$ pair is equal to $\tau = R9 \times C10 = 100K \times 10\mu = 1$ second. This will ensure that the output from $U3c$ is low for the first one-half second or so after the device is first powered up. Thereafter, the voltage at pin 8 of $U3c$ will be below its switching voltage and the output from $U3c$ will be determined by the user’s action, as follows.



That completes the description of the logic circuits. Next, we will look at the power supply. If you intend to use a separate power supply or a battery to power your device, then you will not need to build this power supply.



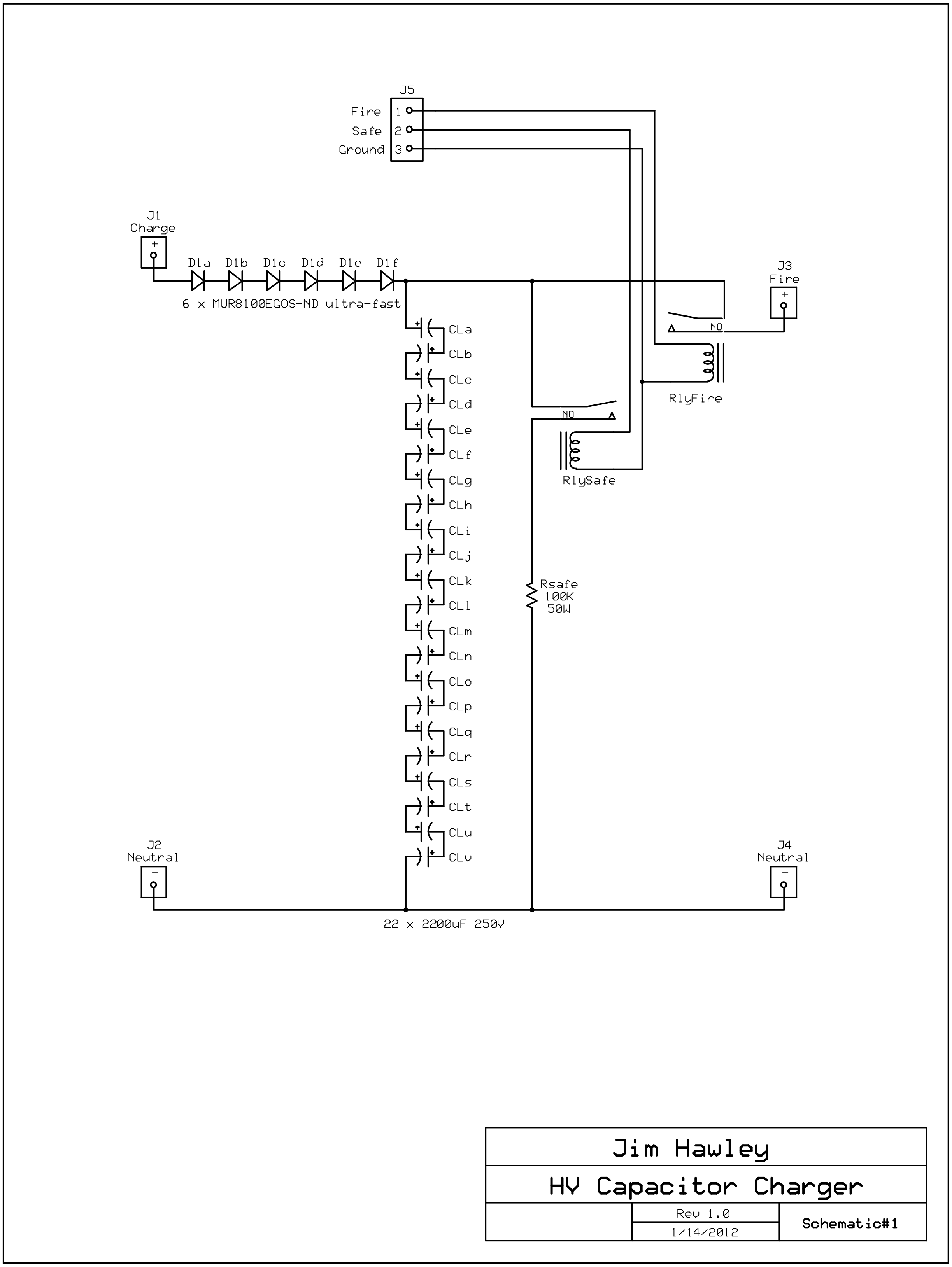
The transformer is a dual primary, dual secondary transformer, being Digikey's part number 237-1094-ND. It has pins so that it can be mounted on a printed circuit board. Both primary coils and both secondary coils are wired in parallel, in which configuration $T2$ provides 14Vac at four (4) amperes. The low voltage ac is rectified by a full wave rectifier and then fed to two different 12V regulators. One of the regulators (U_{ps1}) has a three (3) ampere capacity and provides power to the primary circuit of the toroidal transformer $T1$. A separate 12V regulator (U_{ps2}) provides power to the logic circuits. Relatively substantial capacitors are used to provide filtering of the inputs and outputs of both regulators.

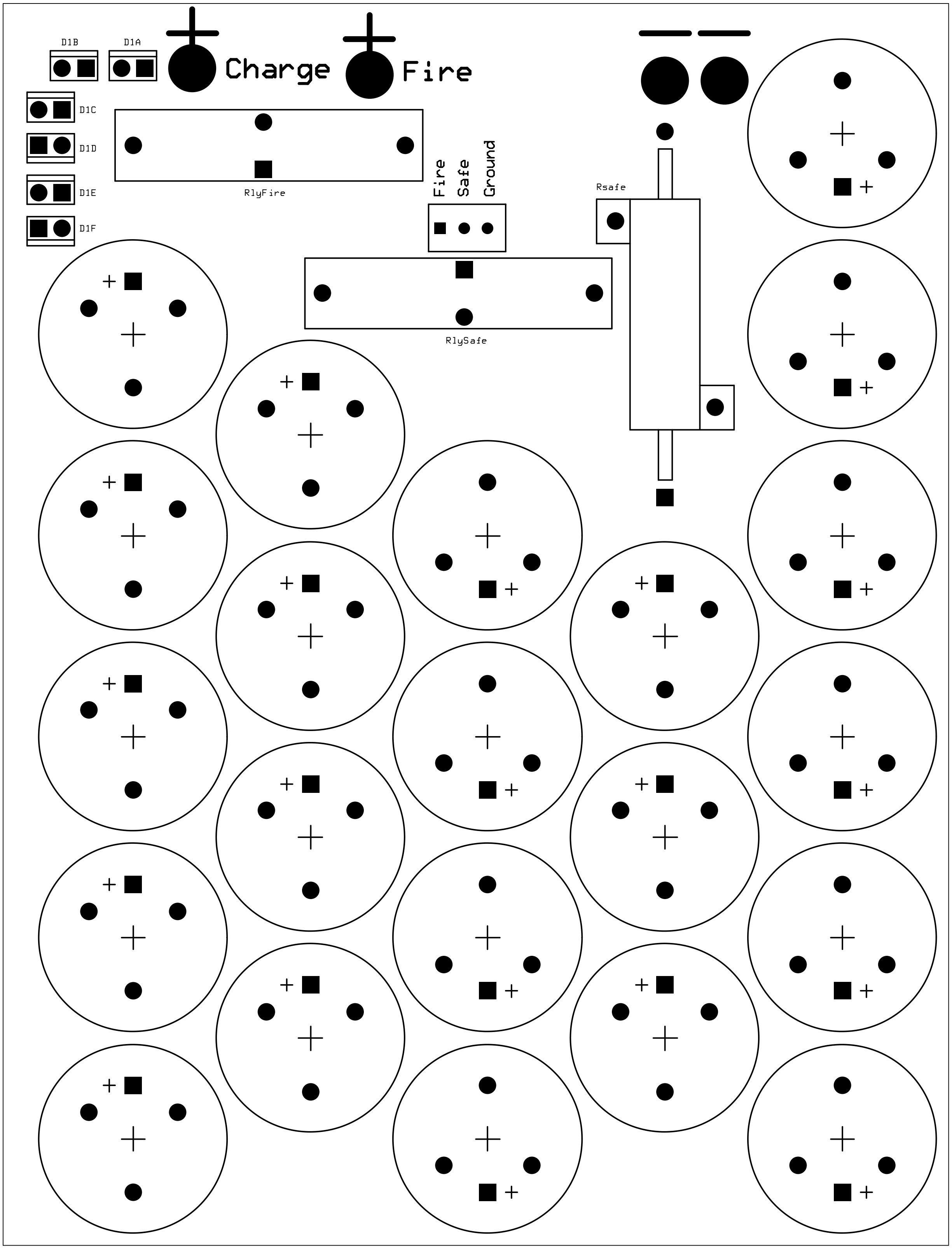
The last schedule in the Appendix is the list of parts required to build the device.

Jim Hawley
July 2012

An e-mail setting out errors and omissions would be appreciated.

Index of Appendices


J5
Fire
Safe
Ground
1
2
3
J1
Charge
+
D1a D1b D1c D1d D1e D1f
6 x MUR8100EGOS-ND ultra-fast
J3
Fire
+
NO
RlyFire
NO
RlySafe
CLa
CLb
CLc
CLd
CLe
CLf
CLg
CLh
CLi
CLj
CLk
CLl
CLm
CLn
CLo
CLp
CLq
CLr
CLs
CLt
CLu
CLv
Rsafe
100K
50W
J2
Neutral
−
J4
Neutral
−
22 x 2200uF 250V
Jim Hawley
HV Capacitor Charger
Rev 1.0
1/14/2012
Schematic#1



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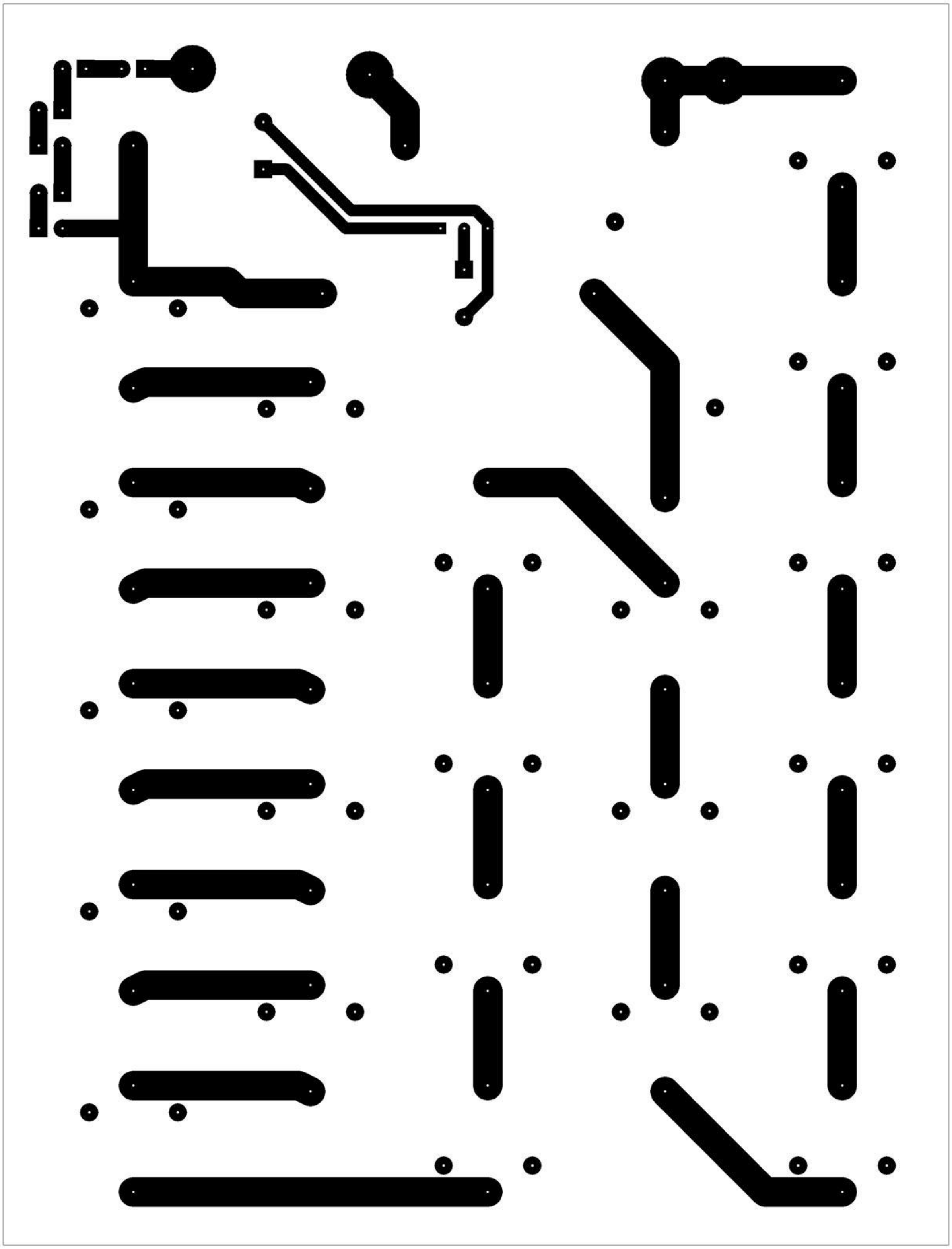

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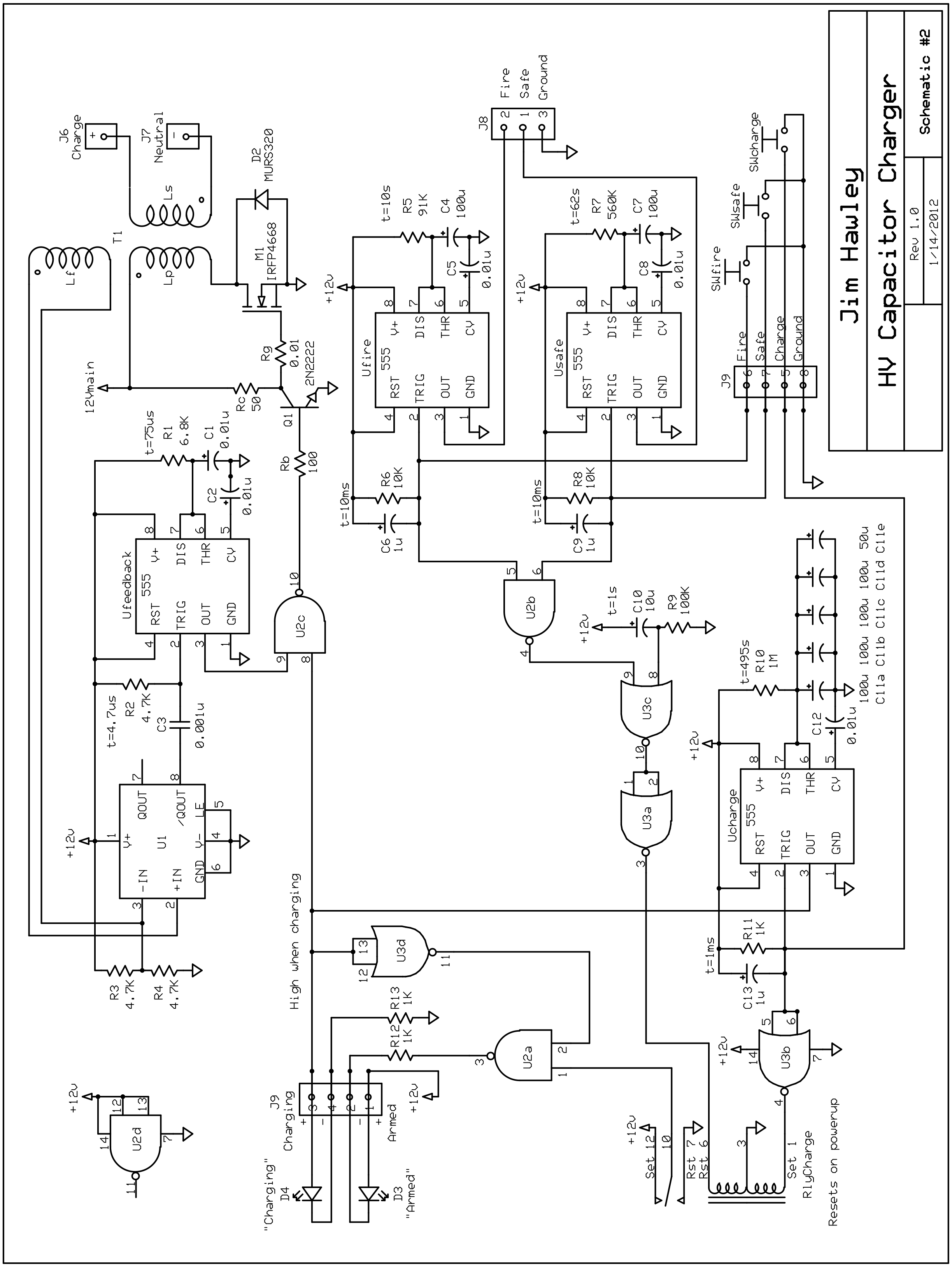
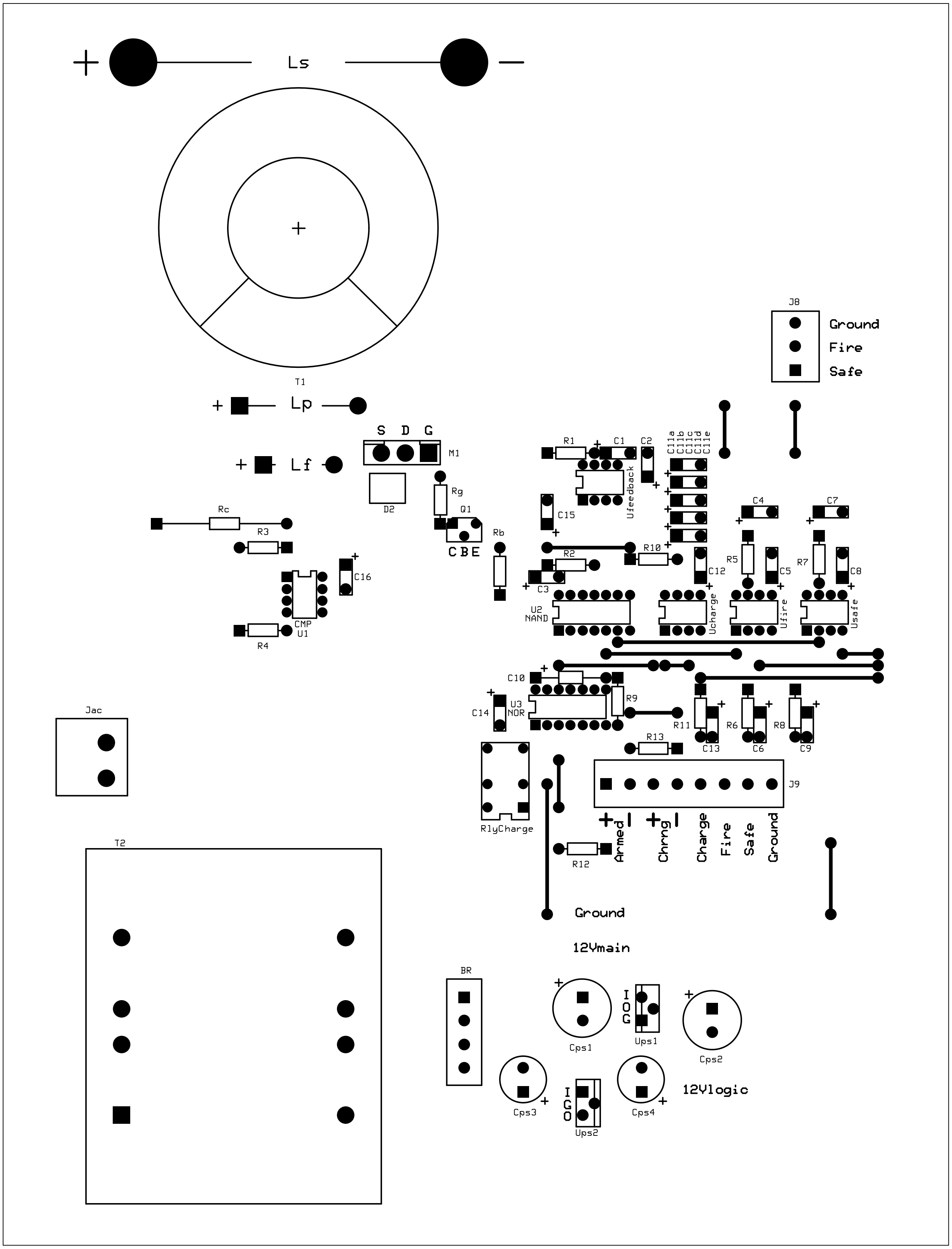

Jim Hawley
HV Capacitor Charger
Schematic #2
Rev 1.0
1/14/2012



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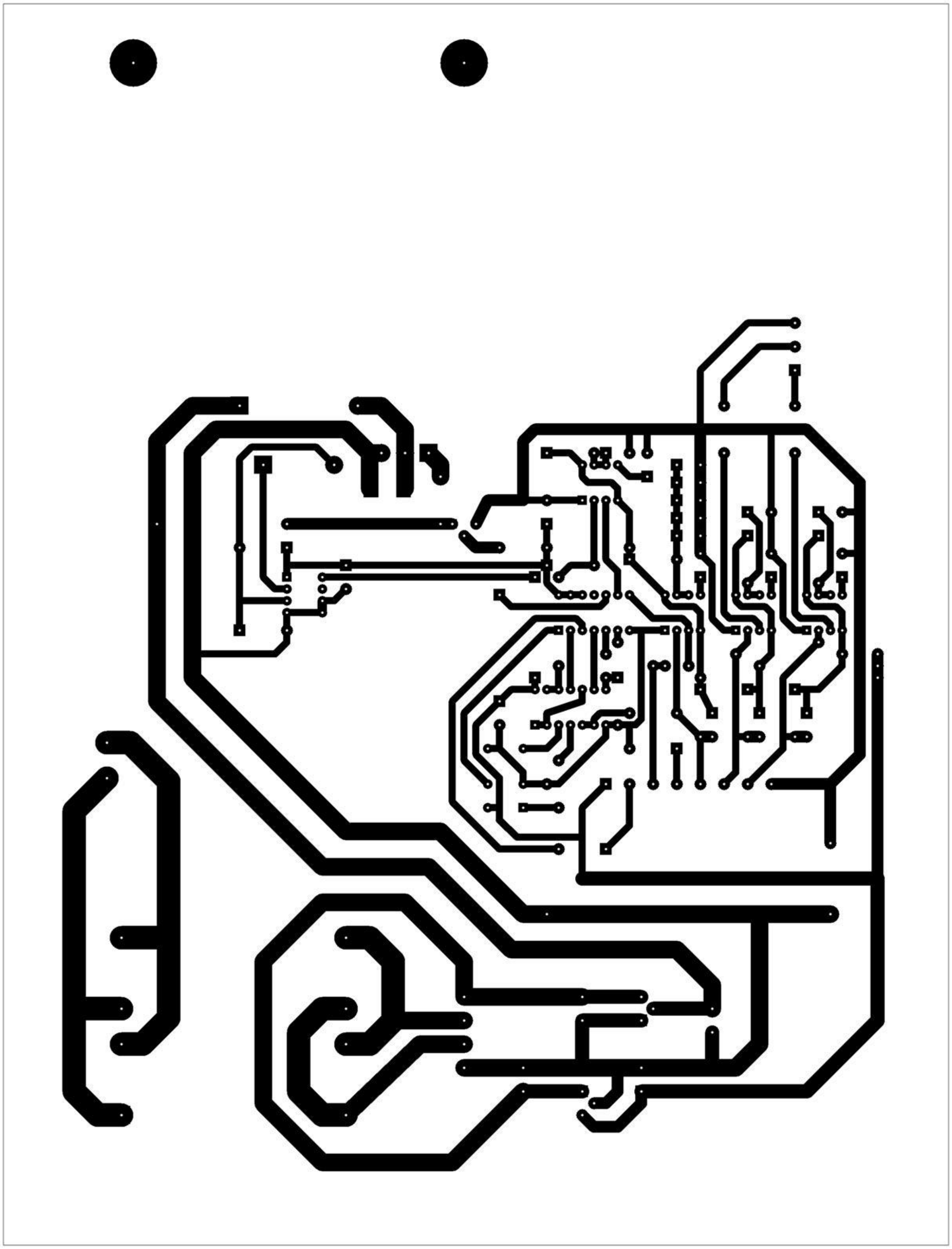
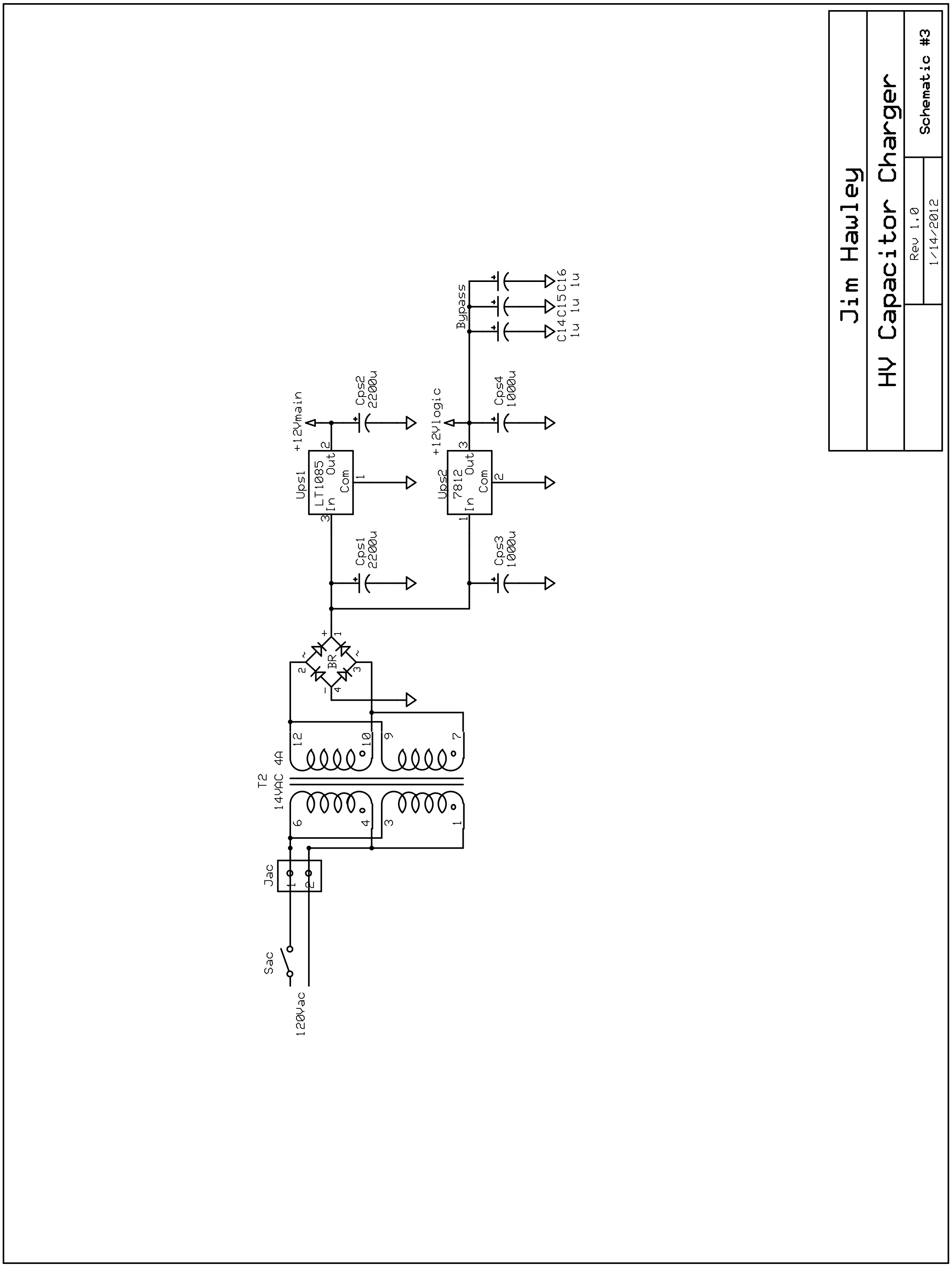


(Scale to 8” wide by 10½“ high.)


Jim Hawley
HV Capacitor Charger
Rev 1.0
1/14/2012
Schematic #3
120Vac
Sac
Jac
T2
14VAC 4A
BR
Cps1
2200u
Ups1
LT1085
In
Out
Com
+12Vmain
Cps2
2200u
Cps3
1000u
Ups2
7812
+12Vlogic
Cps4
1000u
Bypass
C14 C15 C16
1u 1u 1u

Parts List (Digikey except where noted)

Schematic #1 (Load capacitorand relays)

C1a-C1u = P10052-ND 2200uF 20% 250V
D1a-D1f = MUR8100EGOS-ND 8A 1000V TO220AC ultra-fast diode
RlyFire, RlyDis = 374-1108-ND 3A 12V SPST relay (MEDER HE12-1A83-03)
Rdis = 850F100KE-ND 100K 20% 50W chassis-mount resistor
J1-J4 = 1/8" brass bolts, through PCB, and soldered to trace
J5 = 281-1436-ND 3-screw terminal strip 0.2" spacing

Schematic #2 (Toroidal transformer and logic circuits)

SWfire = EG4959-ND panel mount Off-Mom red pushbutton switch
SWsafe = EG4960-ND panel mount Off-Mom yellow pushbutton switch
SWcharge = EG4961-ND panel mount Off-Mom green pushbutton switch
Ufire, Usafe, Ucharge, Ufeedback = 497-1963-5ND 555 timer
U1 = LT1016CN8#PBF-ND ultra-high speed 10ns comparator 8DIP
U2 = 568-1683-5-ND Quad 2-input 4011B CMOS NAND
U3 = 568-3070-5-ND Quad 2-input 4001B CMOS NOR
M1 = IRFP4668-ND hexfet
D2 = MURS320 ultra-fast diode
Q1 = P2N2222AGOS-ND NPN silicon transistor
RlyCharge = Z834-ND 12V dual coil latching SPDT relay
(Omron G6EK-134P-ST-US-DC12)
Panel mount T-1 3/4 LED holder = 67-1332-ND
Core for T1 = Newark part number 07R5397
(EPCOS B64290L40x830)

Schematic #3 (Power supply)

Jac = 5-1437648-7-ND 2-pin tri-barrier strip
T2 = 237-1094-ND 14Vac 4A PCB-mount transformer
BR = GBU6B-BPMS-ND 6A bridge rectifier
Cps1, Cps2 = P5157-ND 2200uF 25V electrolytic
Cps3-Cps5 = P5156-ND 1000uF 25V electrolytic
Ups1 = LT1085CT-12#PBF-ND 12V 3A voltage regulator
Ups2 = LM7812ACT-ND 12V 1A voltage regulator
Ups3 = LM7809ACT-ND 9V 1A voltage regulator
SWac = S1A-ND SPST panel mount toggle switch

Jim Hawley		
HV Capacitor Charger		
	Rev 1.0 1/14/2012	Parts List