Active Power Factor Correction:

A Tesla Coil Power Supply

Steve Ward, 2009

Introduction

The modern Tesla Coil of the "Solid-State" variety requires a "DC Bus" or "DC link" for its bulk power feed for the high power inverter (half-bridge or full-bridge). In many instances this DC bus is satisfied by rectifying the AC line and using large electrolytic filtering capacitors. While quite simple and very robust, this solution can be troublesome as the power consumption of the system begins to exceed what is readily available (240V at 60A). The issue is that the rectifier/capacitor power supply has a poor power factor, typically around 0.6 to 0.7. By power factor I do not mean simply a phase shift between the line voltage and current that may be corrected with capacitors/inductors placed on the line. The problem is much worse and is caused by the inherent non-linear behavior of the input rectifier. For a rectifier to be forward biased, and thus passing appreciable current, the line voltage must exceed the DC bus voltage. This condition is met only at the very peaks of the AC line voltage, thus current is drawn from the AC line at only the very peaks. In order to make up for all the time spent not drawing current from the line, the current peaks are very large, making the RMS value accordingly very large. You can also explain the power factor issue from the spectral analysis of the line current, which large amounts of energy being present at harmonics of 60Hz, which implies poor power factor.

How can the power factor be improved? There are passive methods, basically that of a power filter on the line, in the form of a large inductor. The inductor will tend to drop voltage during the AC mains peak, and produce voltage for a short period afterward (as the current cannot stop flowing instantaneously). This will take the sharp current spikes and spread them out over a longer percentage of the AC line voltage. Some voltage will be lost, and the power factor might only get up to say 0.85 at best.

The most luxurious method of power factor correction in this scenario is "Active Power Factor Correction" also called "Active Rectification". I will limit my discussion to single phase active PFC as 3-phase PFC is indeed much more than just 3 single-phase PFCs!

Active PFC is essentially a boost converter that operates with raw DC input power. By raw I mean, the AC line is full-wave rectified but has only a very small amount of filter capacitance (enough to make the converter work). The brain of this converter is called a "PFC pre-regulator", and is a somewhat sophisticated control system. During the DC-DC conversion of a boost converter, the pre-regulator is constantly tweaking the converter duty cycle such that 2 conditions are met: 1) the DC bus voltage is close to the desired value, and 2) the current draw from the AC line is sinusoidal and in phase with the AC line voltage. This implies that there are 2 control loops implemented in the pre-regulator, one that watches the DC bus voltage and regulates that, and another that watches the AC line current (or rather, the current after the rectifier so its uni-polar). Classic controls theory corners us into a rather specific design. In order to regulate the input current, the control loop should be say 10 times faster than the 60Hz signal it is trying to track, so we set the current regulator bandwidth to 600Hz or so. To avoid conflict with the DC bus regulation loop, its bandwidth needs to be sufficiently less than 600Hz, in fact it should be sufficiently less than 120Hz (2x Fmains) so that it does not try to filter it out (this would increase line current THD). So the voltage control loop is generally set to a sluggish 20Hz bandwidth, and is often "compensated" by just adding more output capacitance to achieve acceptable ripple on the DC bus.   I would like to stress the fact that unlike other DC-DC converters, the voltage regulation of the Active PFC is sacrificed so that the current regulator loop can be more accurate, which improves the power factor by reducing the total harmonic content of the line current. If one wants both high power factor and tight DC regulation, then another stage of DC-DC converter must be added after the PFC stage. For this application (a Tesla Coil) we are often pleased to have 10% regulation + ripple error, and there is no need to further complicate things with more conversions.

For more information about active PFC design theory, I suggest visiting the Fairchild Semiconductor website at www.fairchildsemi.com.

Design Goals

This power supply was intended to replace the variac stack that was used previously, which weighed about 120lbs and was housed in a box that was about 2'x2'x2'. Furthermore, we were already exceeding the VA capacity of the variacs, which were rated at 54A total, by almost 200% (partly because the poor power factor). So, these new power controllers needed to supply about 6kW on a continuous basis, and up to 12kW on a burst basis (say 10% duty cycle, but this is not exactly known). This meant that the components must be selected to handle the 12kW condition, but I could reduce my thermal load by assuming that we would not operate at 12kW for extended periods of time. So the basic specs are as follows:

Input Power: 190 – 280VAC, 60A max
Output Voltage: 350 – 650VDC, 18A max
Efficiency: 95% or better
Power Factor: 0.9 at <2kW; 0.98 at >6kW
Weight: < boat anchor (40lbs)

The Controller

I opted to use a generic PFC control chip that operates in continuous-conduction mode. The chip is the FAN4810 from Fairchild Semiconductor. I suggest thoroughly reading the datasheet to become familiar with how this chip works; from there my design should be mostly obvious. Wrapped around the FAN4810 is an ATMEGA88 micro-controller from Atmel. The micro-controller samples DC bus voltage and current with its ADC channels. It sends averaged

V and I, and resulting W data to a serial enabled character display, such as the one Sparkfun Electronics sells (note that my source code was for another display and would need to be updated to work with the sparkfun displays).

Output Voltage Control

The microcontroller also adjusts the target output voltage by changing the resistance of the bottom resistor in the bus voltage feedback network. This is accomplished by setting the I/O pins for either tri-stated (high impedance) or a low impedance to ground, thus effectively swapping 16 possible resistance values in for the divider. This gives "4-bit" voltage control. The micro receives its voltage set-point command from a potentiometer that feeds its ADC. In this round-about way, the PFC output voltage is digitally controlled. This may seem odd, but it was the only way that the micro-controller could "know" the set-point voltage without the use of another HV divider from the DC bus. The reason being: the FAN4810 always regulates until it sees 2.5V at its feedback input, and so the micro-controller also always sees these 2.5V signal (assuming perfect regulation, which is never the case).

Pre-Charge (Inrush Current Limiting)

The micro-controller also controls an inrush limiting circuit for pre-charging the output capacitance of the PFC. The micro samples the bus voltage and waits for 2 conditions to be met, 1) the bus voltage is over XX VDC, and 2) the voltage has stabilized, implying that the output capacitance is charged. At this point, the 50 ohm pre-charge resistance in series with the AC input power is bypassed with 2 x 30A contacts.

Input Rectification and Filtering

The input rectifier consists of 4 parallel 600V 25A bridge rectifiers. Generally, as you parallel more devices, you must de-rate them more so. The filter capacitor is small for the power level, just 40uF. The capacitors must tolerate 50A or more of 120Hz current, plus the high frequency ripple current generated by the boost switching, so the caps should be high quality poly-propylene film type.

The Inductor

The biggest component of this whole thing is the boost inductor. The inductor is critical in that it determines current loop compensation, and also determines the high-frequency ripple current presented to the AC line (generally about 20% of the peak current draw). In my design the inductor had to be about 1.2mH, and not saturate at up to 110A peak current. To handle this I obtained some cores from Micrometals, the mighty T650-34. This is the biggest powdered iron core I could find, and while it is not a more exotic material like "cool-mu" or other variants, it is a fairly low loss powdered iron, and the permeability is just right for the design. The toroid is wound with 85 turns of 8awg flexible cable.

As it turns out, the cores I got were surplus with 2 cores epoxied together. I had to cut them apart and then re-paint the exposed powdered iron with grey epoxy.

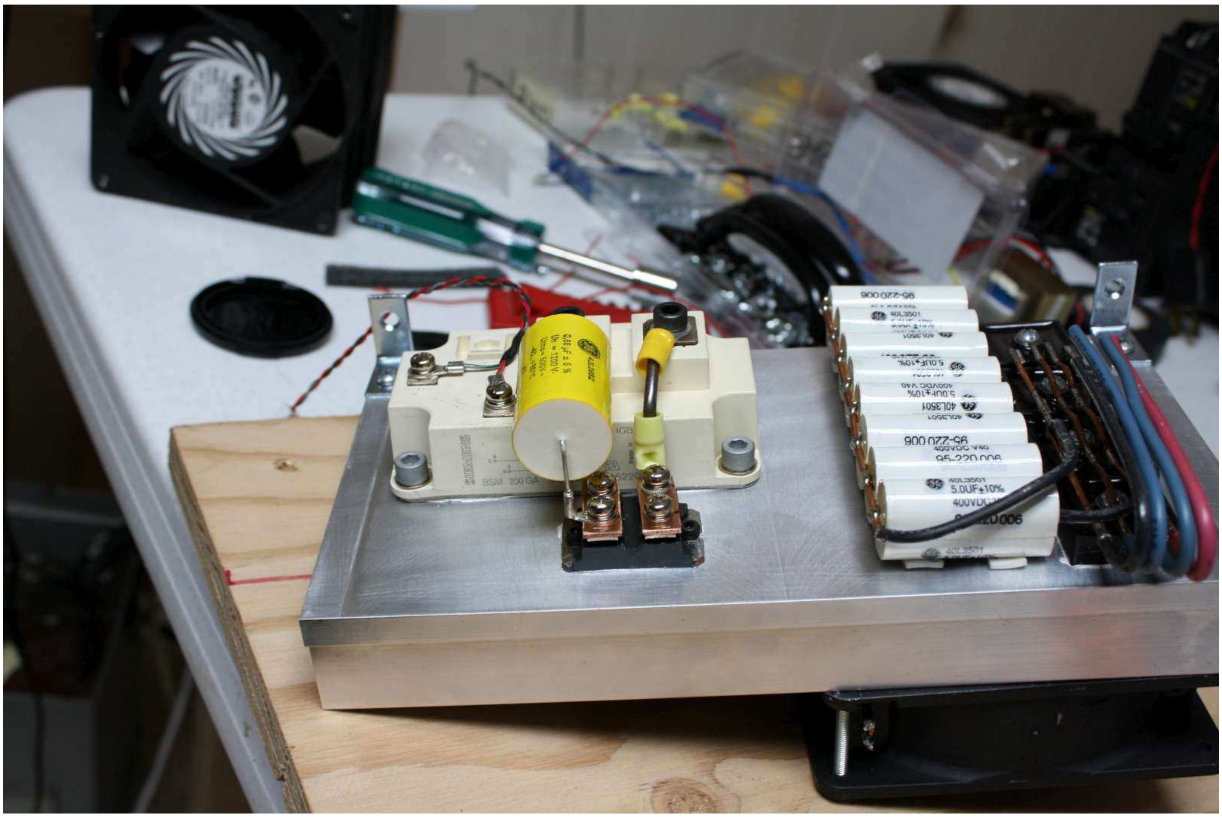
Cores for the boost inductors.

The Switch, Diode and Snubber

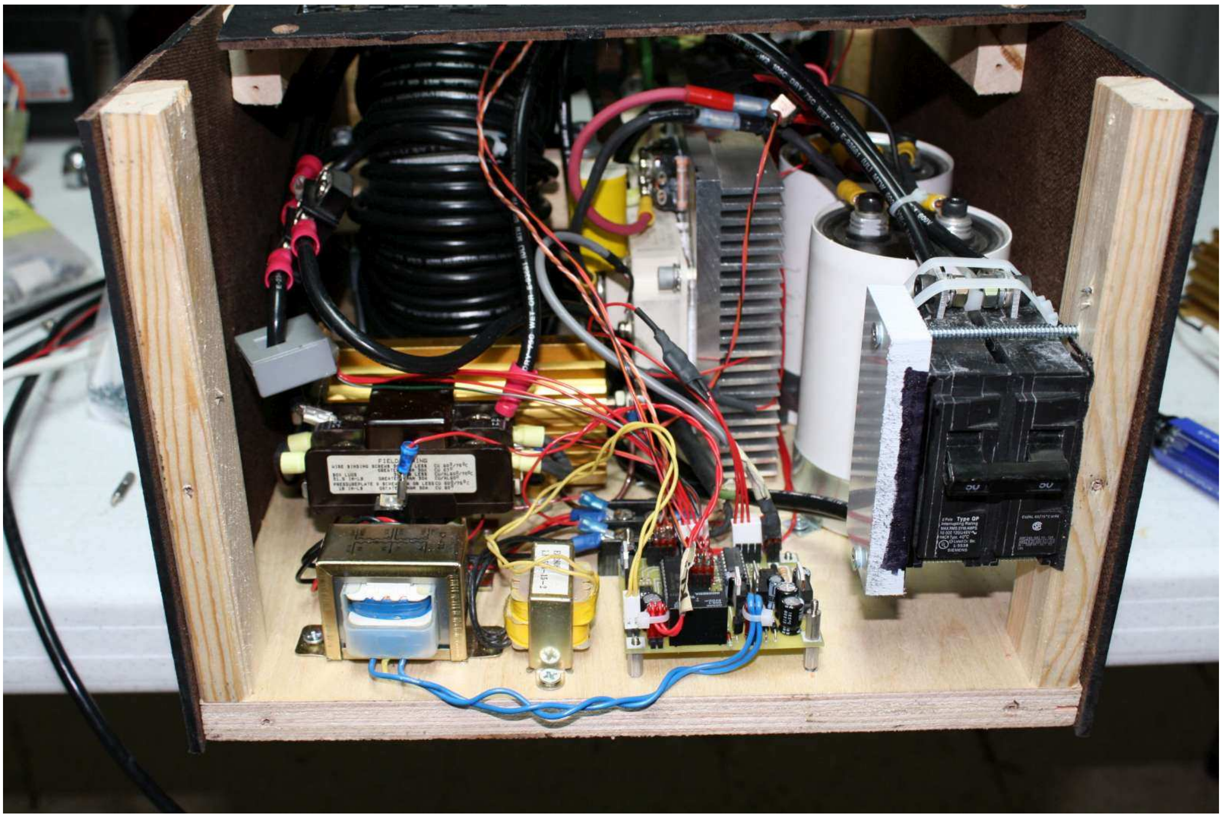
The switch is an IGBT (BSM200GA120DN2) rated at 200A and 1200V nominal. IGBTs have nice low conduction losses in high-voltage applications like this, but they suffer tremendously from switching losses, particularly turning the IGBT off. Diodes also dislike being turned off for the same reasons (charges stored in the device are wasted). Because of the hard-switched nature of this boost converter, I decided to keep the switching frequency as low as possible, about 8kHz in this situation.

The diode is an ultra-fast type, DSEI 2x61-12B from IXYS Corp. Generally you want a diode with a fast recovery time and as low of recovery charge (Qrr) as possible. This diode is pretty good, and often found on the surplus market. I parallel both diodes to handle the current.

The output of the diode feeds straight into a snubber capacitor. The loop between IGBT, diode and capacitor must be kept as low of inductance as possible. The reason being, that the energy stored in the switch inductance will drive whatever voltage necessary to maintain it's current. If there is significant inductance in this loop, there will be significant voltage according to L*di/dt (the di/dt being the IGBT rate of turn-off). Keeping the L small prevents destruction of the IGBT switch from voltage transients.



Power IGBT, Diode, Snubber as well as input rectification and filtering.



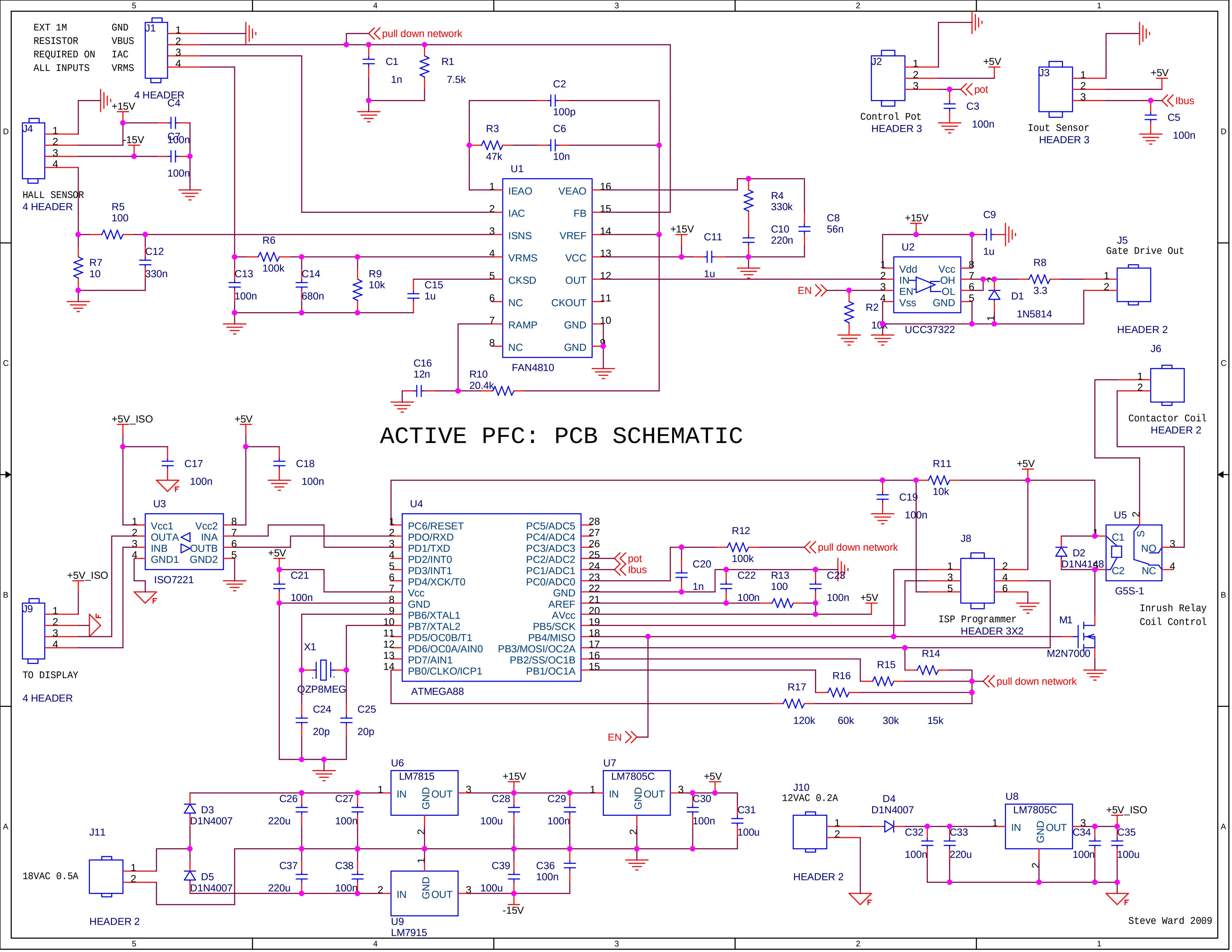
(nearly) The whole thing. Notice the inductor with black wire, the large white electrolytic filter caps on the output, and the golden inrush resistor with brown bypass contact in front.

The front of the PFC has the back-lit display showing Output voltage, Output current, Target voltage and Output Power. The knob is for the POT that tells the micro-controller what the target voltage should be. The big screen in front allows for air to flow in from the rear and out the front.

The Rear showing 2 large fans to bring in cool air. Also seen are the Anderson Power Pole Connectors used for the high current AC input and DC output.

Schematics:

There are 2 schematics for the PFC unit. The first is only for the PCB which has all the smarts on it. The second is for all the components that are located off of the PCB.


ACTIVE PFC: PCB SCHEMATIC
EXT 1M RESISTOR REQUIRED ON ALL INPUTS
GND VBUS IAC VRMS
J1 4 HEADER
J4 HALL SENSOR 4 HEADER
J2 Control Pot HEADER 3
J3 Iout Sensor HEADER 3
J5 Gate Drive Out HEADER 2
J6 Contactor Coil HEADER 2
J8 ISP Programmer HEADER 3X2
J9 TO DISPLAY 4 HEADER
J10 12VAC 0.2A HEADER 2
J11 18VAC 0.5A HEADER 2
U1 FAN4810
IEAO IAC ISNS VRMS CKSD NC RAMP NC
VEAO FB VREF VCC OUT CKOUT GND GND
U2 UCC37322
Vdd IN EN Vss Vcc OH OL GND
U3 ISO7221
Vcc1 OUTA INB GND1 Vcc2 INA OUTB GND2
U4 ATMEGA88
PC6/RESET PDO/RXD PD1/TXD PD2/INT0 PD3/INT1 PD4/XCK/T0 Vcc GND PB6/XTAL1 PB7/XTAL2 PD5/OC0B/T1 PD6/OC0A/AIN0 PD7/AIN1 PB0/CLKO/ICP1
PC5/ADC5 PC4/ADC4 PC3/ADC3 PC2/ADC2 PC1/ADC1 PC0/ADC0 GND AREF AVcc PB5/SCK PB4/MISO PB3/MOSI/OC2A PB2/SS/OC1B PB1/OC1A
U5 G5S-1 Inrush Relay Coil Control
M1 M2N7000
U6 LM7815
U7 LM7805C
U8 LM7805C
U9 LM7915
IN GND OUT
X1 QZP8MEG
D1 1N5814
D2 D1N4148
D3 D1N4007
D4 D1N4007
D5 D1N4007
R1 7.5k
R2 10k
R3 47k
R4 330k
R5 100
R6 100k
R7 10
R8 3.3
R9 10k
R10 20.4k
R11 10k
R12 100k
R13 100
R14 15k
R15 30k
R16 60k
R17 120k
C1 1n
C2 100p
C3 100n
C4 100n
C5 100n
C6 10n
C7 100n
C8 56n
C9 1u
C10 220n
C11 1u
C12 330n
C13 100n
C14 680n
C15 1u
C16 12n
C17 100n
C18 100n
C19 100n
C20 1n
C21 100n
C22 100n
C23 100n
C24 20p
C25 20p
C26 220u
C27 100n
C28 100u
C29 100n
C30 100n
C31 100u
C32 100n
C33 220u
C34 100n
C35 100u
C36 100n
C37 220u
C38 100n
C39 100u
+5V
+15V
-15V
+5V_ISO
pull down network
pot
Ibus
EN
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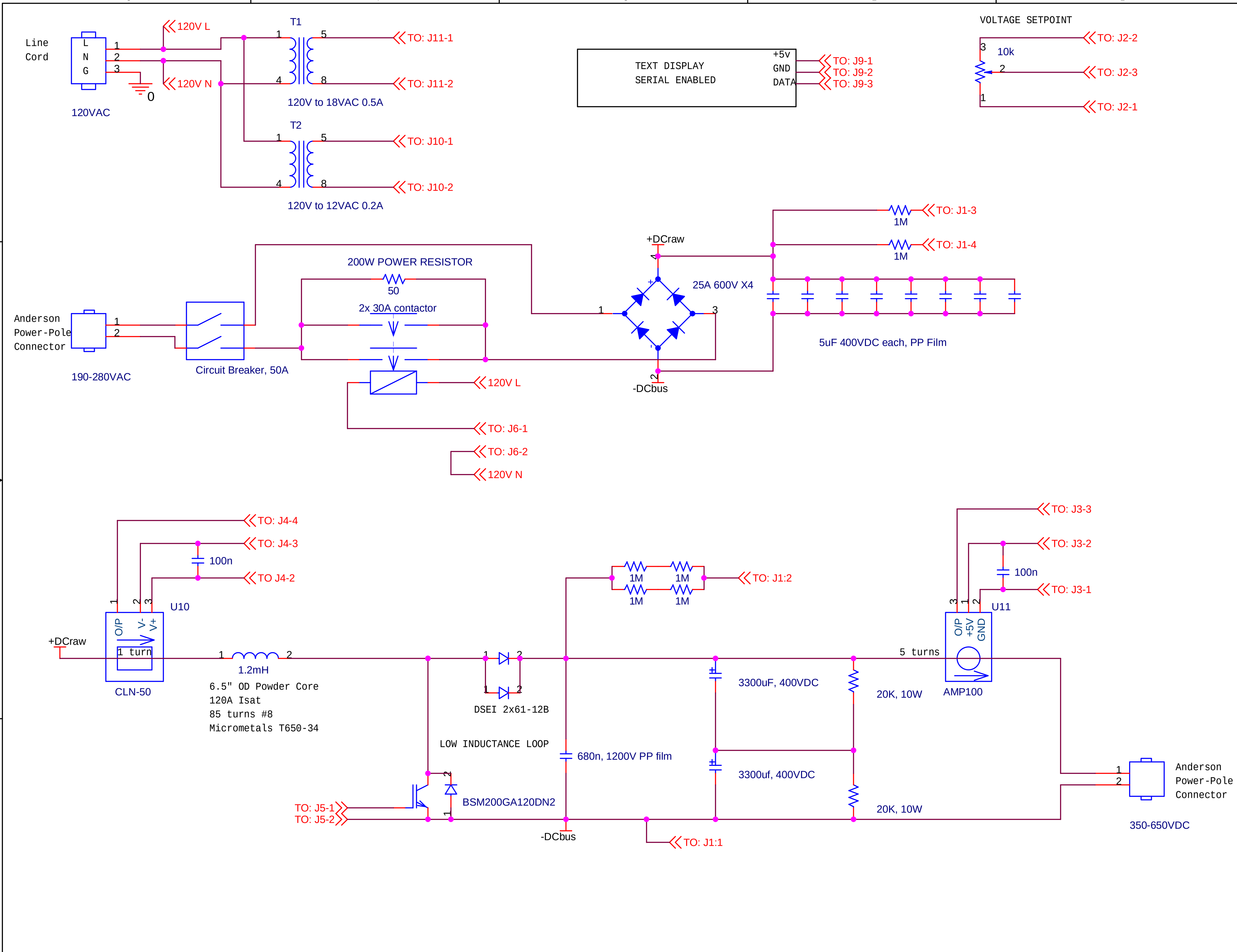

Line Cord
L
N
G
120VAC
120V L
120V N
0
T1
120V to 18VAC 0.5A
TO: J11-1
TO: J11-2
T2
120V to 12VAC 0.2A
TO: J10-1
TO: J10-2
TEXT DISPLAY
SERIAL ENABLED
+5v
GND
DATA
TO: J9-1
TO: J9-2
TO: J9-3
VOLTAGE SETPOINT
10k
TO: J2-2
TO: J2-3
TO: J2-1
Anderson Power-Pole Connector
190-280VAC
Circuit Breaker, 50A
200W POWER RESISTOR
50
2x 30A contactor
120V L
TO: J6-1
TO: J6-2
120V N
+DCraw
-DCbus
25A 600V X4
1M
TO: J1-3
TO: J1-4
5uF 400VDC each, PP Film
TO: J4-4
TO: J4-3
TO J4-2
100n
U10
O/P
V-
V+
1 turn
CLN-50
+DCraw
1.2mH
6.5" OD Powder Core
120A Isat
85 turns #8
Micrometals T650-34
DSEI 2x61-12B
LOW INDUCTANCE LOOP
BSM200GA120DN2
TO: J5-1
TO: J5-2
-DCbus
680n, 1200V PP film
TO: J1:2
TO: J1:1
3300uF, 400VDC
3300uf, 400VDC
20K, 10W
20K, 10W
5 turns
U11
O/P
+5V
GND
AMP100
TO: J3-3
TO: J3-2
TO: J3-1
100n
Anderson Power-Pole Connector
350-650VDC