Input

The input to the converter is a verticalled stacted Anderson Powerpole connector. This connector arrangement was chosen in order to prevent high voltage lines from being plugged into low voltage lines. The current rating of this connector is 45A.

Input Fuse

A 10A input fuse is used to protect the converter against over current. This fuse was chosen because of its small size and very low resistance. In converters designed for the highest efficiency, the losses in fuses is non-negligible.

Input Sensing

The input current is sensed using a unidirectional hall effect current sensor with a sub-milliohm resistance. shunt resistors would introduce unacceptable high losses in a converter like this.

The input voltage is sensed using a voltage divider bridge. There are two series resistors in the high voltage path so that the microcontroller is not destroyed in the event that one becomes shorted.

Input Filtering

A C-L-C pi filter is used to smooth the current of the input. If substantial current ripple is present at the input, the solar panel will not be able to operate exactly at its MPP over the course of a switching cycle. A second order filter such as this one allows for much smaller capacitors and inductors to be used to achieve the same filtering. The converter operates at 100kHz, but the addition of a second phase explained in the next section increases the effective frequency seen by the filter to 200 kHz. After the DC bias effect on the capacitors is taken into account, the effective model of the filter becomes 10uF-1uH-10uF. The ESR of the electrolytic cap is around three orders of magnitude higher than the ceramic capacitors, so it has little effect on the cutoff frequency of this filter, but it does act to reduce the Q of the filter which reduces ringing at the resonant frequency of the filter and reduces inrush voltage spikes when the panel is first connected. This filter reduces current ripple at the input by around 30dB. Because the converter is in continuous conduction mode, the unfiltered input ripple is only ~0.5A. With the addition of this filter the ripple brought down to ~1mA.

Large ceramic capacitors are susceptible to cracking under even mild board flexure to the extent that NASA imposes size limitations for non-leaded capacitors. J-leaded stacked capacitors are used in this converter because the leads absorb flexing and protect the capacitors from cracking. The leads also allow for more capacitance in a smaller land area.

The 1210 and 0805 package capacitors are used to improve the ability of the filter to handle high frequency noise since large capacitors have higher parasitic inductance. The actual effect of adding this capacitors is likely negligible, but they are cheap and including them has no downsides.

The reverse biased diode at the input to the converter is to protect against reverse polarity if the input being suddenly disconnected. Since the electrolytic capacitor was added, the inductors do not store enough energy to make that happen, but this diode does provide some short term input reversal protection. While the current rating of the diode is not high enough to carry the full short circuit current of a panel continuously, it can carry the current long enough for the inductors to charge in reverse and allow the body diodes of the power stage MOSFETs to take the brunt of the reverse current. The converter should be able to handle a reverse connected input indefinitely, but this has not been tested for.

Power Stage

The power stage consists of two identical boost converters driven with the same duty cycle. The MOSFETS charge up the inductor on the first part of the cycle, and then dump some of their energy into the output through an output diode. There are two extra MOSFET footprints present which can be used for synchronous rectification.

The MOSFETS were selected to have low gate charge and low on resistance. There is a tradeoff between gate charge and on resistance. Gate charge is responsible for a large part of switching losses which are constant regardless how much current the FET is carrying. On resistance is responsible for conduction losses which is proportional to the square of the current the FET is carrying. The FET used here represents the best compromise that could be found. On resistance has a positive temperature coefficient; the warmer a MOSFET gets, the higher its on resistance becomes. While the prototype converter never got close to its maximum temperature ratings, the efficiency suffered as the FETS warmed up. The production converter has a much larger heat sink area to combat this effect.

The output diode is an ultrafast diode. The faster a diode is, the lower its switching losses. This diode has a forward voltage of around 0.8V which is higher than the ~0.6V drop of high voltage Schottkys, but experiments showed less efficiency (likely due to switching losses) and much lower reliability (several devices failed, but none of the ultrafast diode devices failed even after as many as half a dozen 320 C reflow cycles). A common cathode single package diode is used here so that both diodes stay around the same temperature. Experiments showed a nasty thermal runaway phenomenon where one half of the power stage would begin to carry a majority of the current because its diode was warmer (lower forward voltage drop).

The output diode ia paralled with synchronous rectifier FETS so that the ~0.8V diode voltage drop can be negated. It is possible that these will actually end up consuming more power than the diode, but it is worth testing.

Output Filtering

The output filter is similar to the input filter, but it has no film capacitor at its input. The higher bias voltage on the output capacitors reduces the effective circuit to 2uF-1uH-10uF which provides 28dB of attenuation at 400kHz. The ripple current is also higher than the input because the current falls to zero on every cycle, but fortunately it is also reduced by a factor of (1-D). Assuming a 2.4A at the output of the power stage, the output of the converter will see a current ripple of around ~5mA. The inductance of the wiring to the battery and the battery itself will add at least 2uH of inductance which forms in effect a three stage filter with a 200kHz attenuation of an astonishing 70dB, so the battery will not have much in the way of current ripple to deal with.

The smaller ceramic capacitors were added for the same reason as in the input filter, but the electrolytic capacitor serves a second purpose in the output filter aside from lower the Q of the filter; it slows the rise time of the output voltage when the battery is suddenly removed and provides a place for the current stored in the boost inductors to go so that the voltage does not spike when the microcontroller or analog safetys turn off the power stage MOSFETs.

Output Sensing

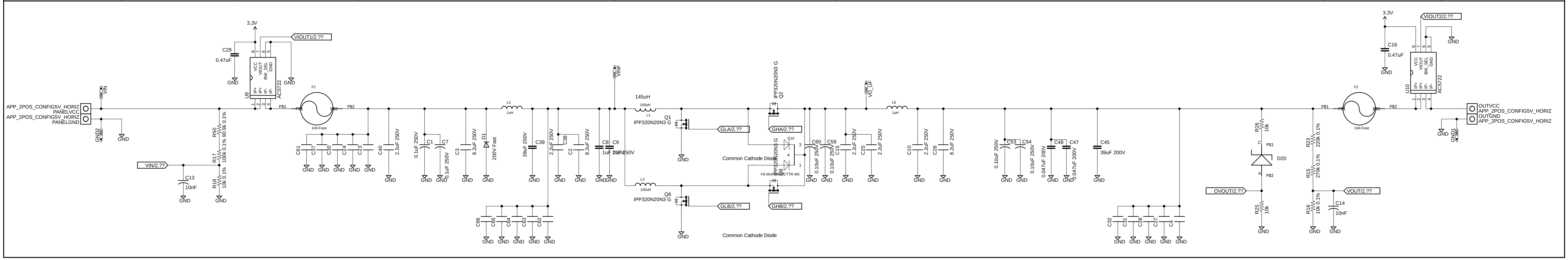
The output has the same voltage and current sensing arrangement as the input with the addition of an extra feedback mechanism which works as a kind of sloppy discrete comparator. When the output voltage is less than 160V, D20 (a 160V zener diode) conducts no current aside from uA range leakage and the R10 keeps the voltage of OVOUT at ground. When the output voltage exceeds 120V, D20 begins to conduct and it allows the voltage to rise to (Vout-120)/2 (1/2 due to the R26 / R10 voltage divider) until the voltage of OVOUT reaches 0.6V (output voltage of 121.2V). At that point the voltage of OVOUT is clamped to 0.6V by the base to emitter drip of Q7 in the analog protection block and current through D20 is limited by R26. When the OVOUT voltage reaches 0.6V the analog protection section of the circuit disables the PWM drive waveforms to the gate drivers.

Output Fuse

The output fuse prevents a fault in the output diode of the power stage from destroying, well, everything. If the output diode fails shorted with the fuse in place, the fuse will blow and the rest of the converter should survive unharmed. This fuse has a 10A rating because the failure modes that would cause it to blow are all catastrophic enough that currents many times higher than 10A will be present anyway.

Output

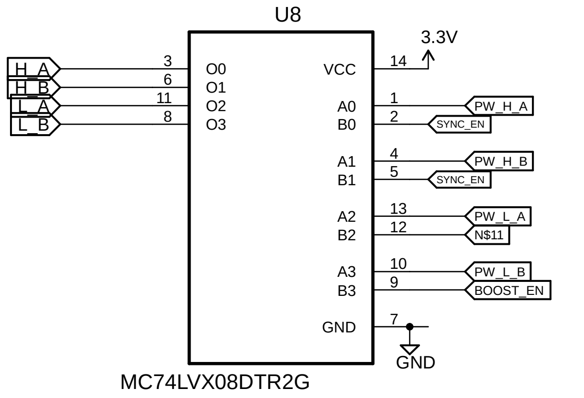
The output of the converter interfaces to the car through the same arrangement of Anderson Powerpole connectors as the input. Different colored cables and connectors should be used to prevent the output from being connected to the input. Nothing should be harmed if that happened, but color coding will remove the possibility of undesirable downtime from a simple wiring error.



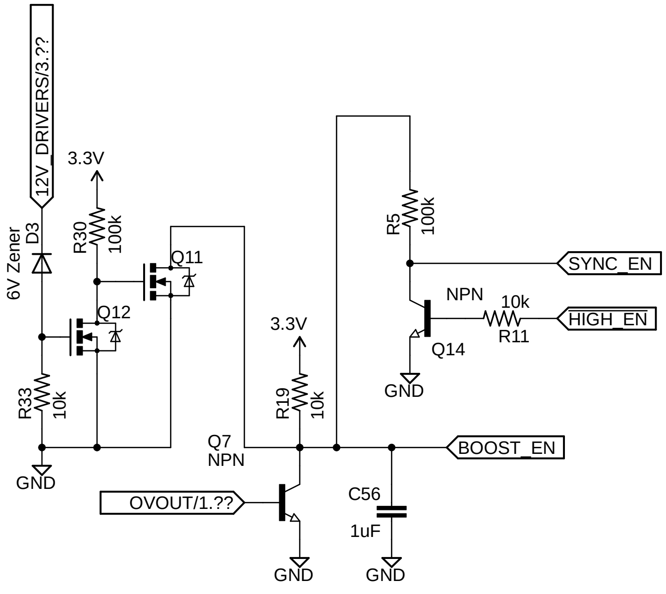
This is an AND gate which takes the enable signals from the previous two circuits and supplies the FET drivers with their input waveforms. In this implementation the AND gate only works to disable dive waveforms during over voltage events. If synchronous rectification were used, the capacitors attached to the PW_X_X nets would need to be populated in order to enable dead time.

This circuit inverts the signal from OVOUT in order to provide an active high enable signal to the AND gate at the top of this section. An IC logic inverter was not used because the input impedance would be high enough that the voltage from OVOUT would exceed the maximum rating of the gate input. Using a discrete BJT allows for the excess voltage and current to be handled by one $0.02 device. When the base exceeds its threshold voltage, the BJT conducts collector to emitter and brings the voltage of BOOST_EN low to disable the power stage.

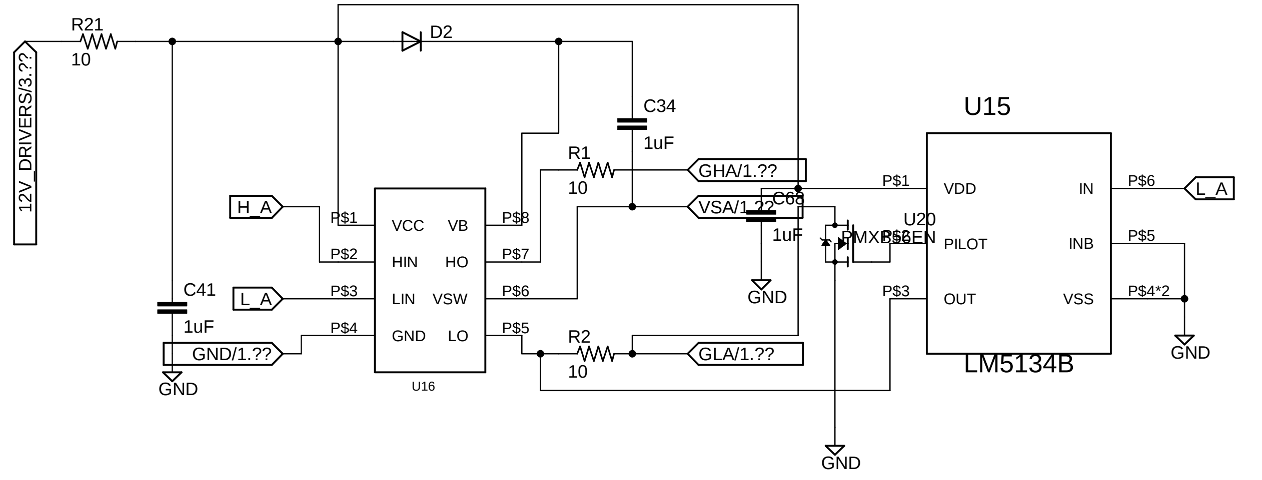
Analog Protection

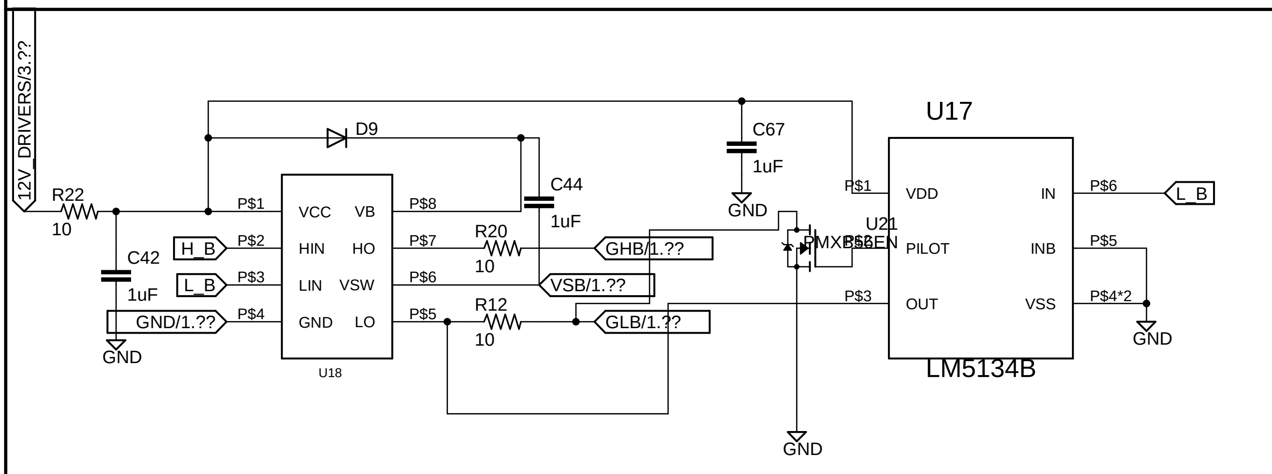


ADD HIGH SIDE ENABLE



FET Drivers





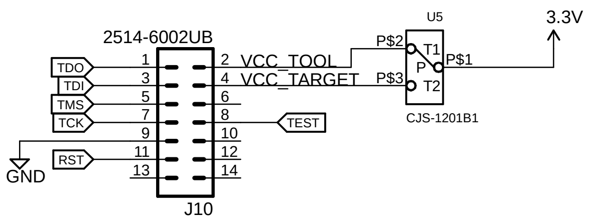
The FET drivers take the logic level signal from AND gate and shift it to a higher voltage level and a much higher current drive level in order to efficiently drive the gates.

The R1 gate drive resistor is needed to limit peak current out of the driver to a level below its maximum rating. Simulations show that this resistor has little effect on efficiency and experiments show that the inclusion of this resistor decreases driver heat dissipation.
The Power input to the gate driver is a 10 Ohm, 1uF low pass filter. This to some degree keeps switching noise from the chip but is mostly there to serve as an indicator that a driver has failed when the board is viewed with a thermal camera.

Non-rigerous testing has shown that the converter is less reliable when the gate drive resistors are 0 Ohm as opposed to 10 Ohm. So long as a fast driver is used (minimum rise time) efficiency is not greatly effected by drive resistance.

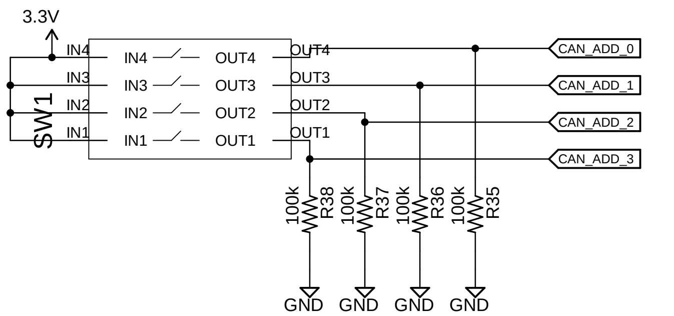
Programing Headder

This header allows the microcontroller to be connected to a TI programmer.

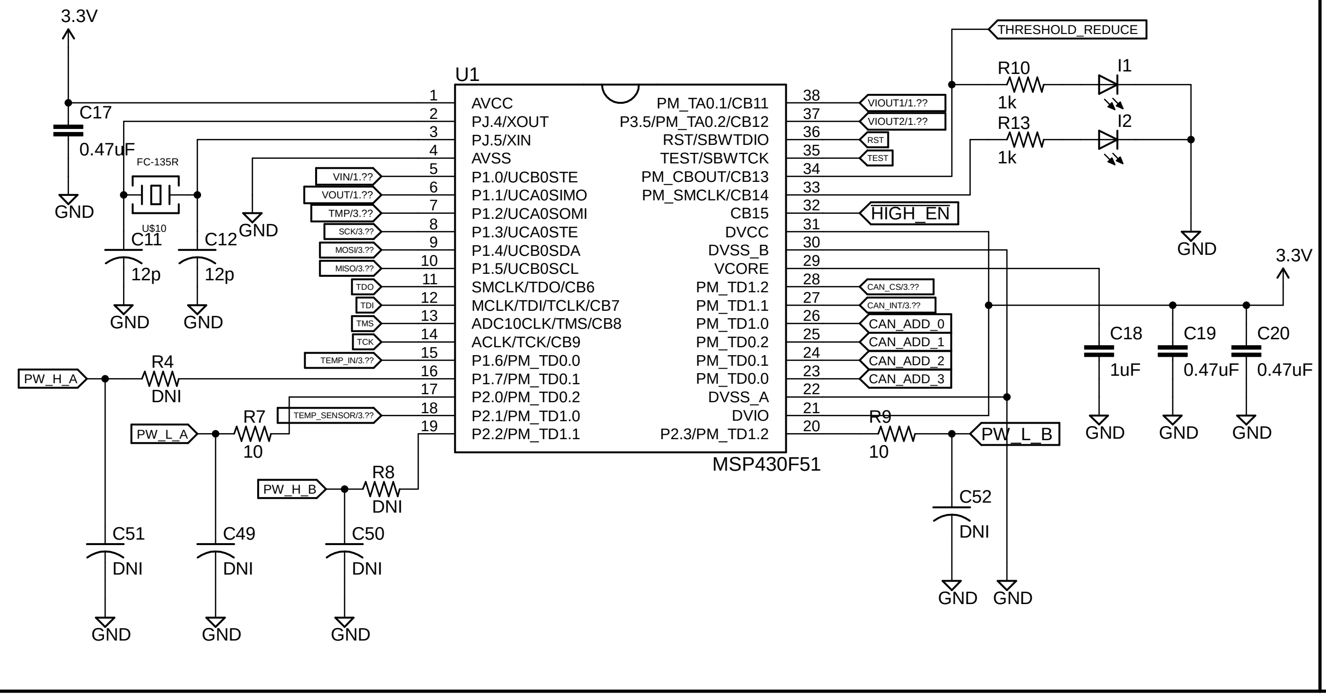


CAN Address Selector

A miniature DIP switch is used to select the CAN address of the board.



Microcontroller



The microcontroller used on the MPPT is a TI MSP430F5132IDAR. The MCU produces two PWM dive waveforms each 180 degrees out of phase with each other which are used to signal the boost MOSFETs. The MCU also produces two inverted versions which are used to signal the synchronous rectifier FETs. Resistors R4,R7-9 and Capacitors C49-52 are used to create dead time between the boost and sync drive signals which prevents shoot-though in the power stage. Since synchronous rectification is not used here, only the boost capacitors are populated and only the boost drive resistors are populated.

LEDs 1-3 are for displaying the status of the MPPT. Their functionality is configured in software.

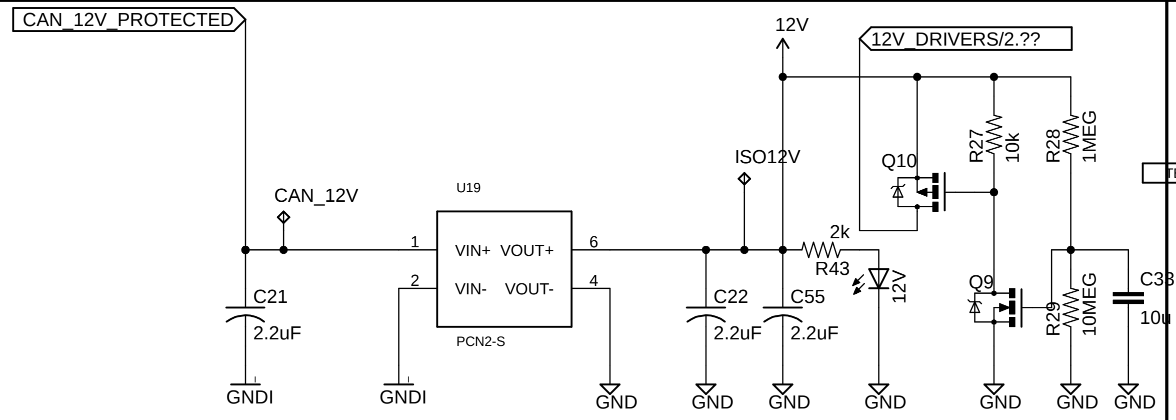
The MCU makes analog measurements of the input and output current and voltage as well as temperature.

The MCU communicates with a one wire serial temperature sensor external to the board using drive circuitry shown on the next page. The MCU also communicates telemetry over CAN bus using isolation and controller circuitry also shown on the next page.

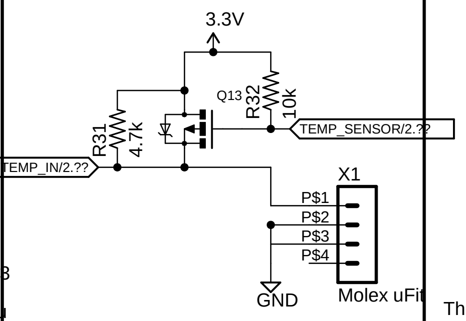
CAN 12V to Low Voltage 3V3 and Isolated 12V

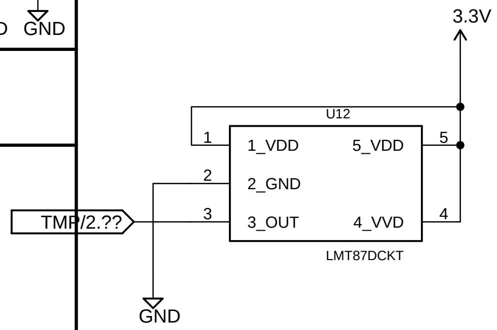
The MPPT is powered over the 12V CAN bus power line. A 12V to 12V isolator separates the high voltage ground from the low voltage ground which is necessary in order to prevent ground loops. The MCU sits on the high voltage side of this isolation bridge. A mistake was make when creating the 12V isolator part and in ordering as well. The +/- 12V version of this part was used instead of the +12V version. Fortunately the footprint for the part is still valid because the -12V pin is designated a no connect. The bipolar part should still work since its current rating will not be exceeded, but the mistake should be corrected in future ordering.

Non-isolated 12V power is used to power the CAN bus controller circuitry. Either a 5V or a 3.3V switched mode regulator can be used here



Temperature Sensors



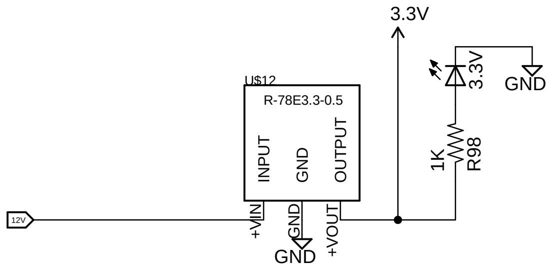


There is a linear analog output temperature sensor placed near one of the boost MOSFETS in order to get an idea of the operating temperature of the converter.

The other circuit allows for an off board one wire serial temperature sensor to be interfaced with.

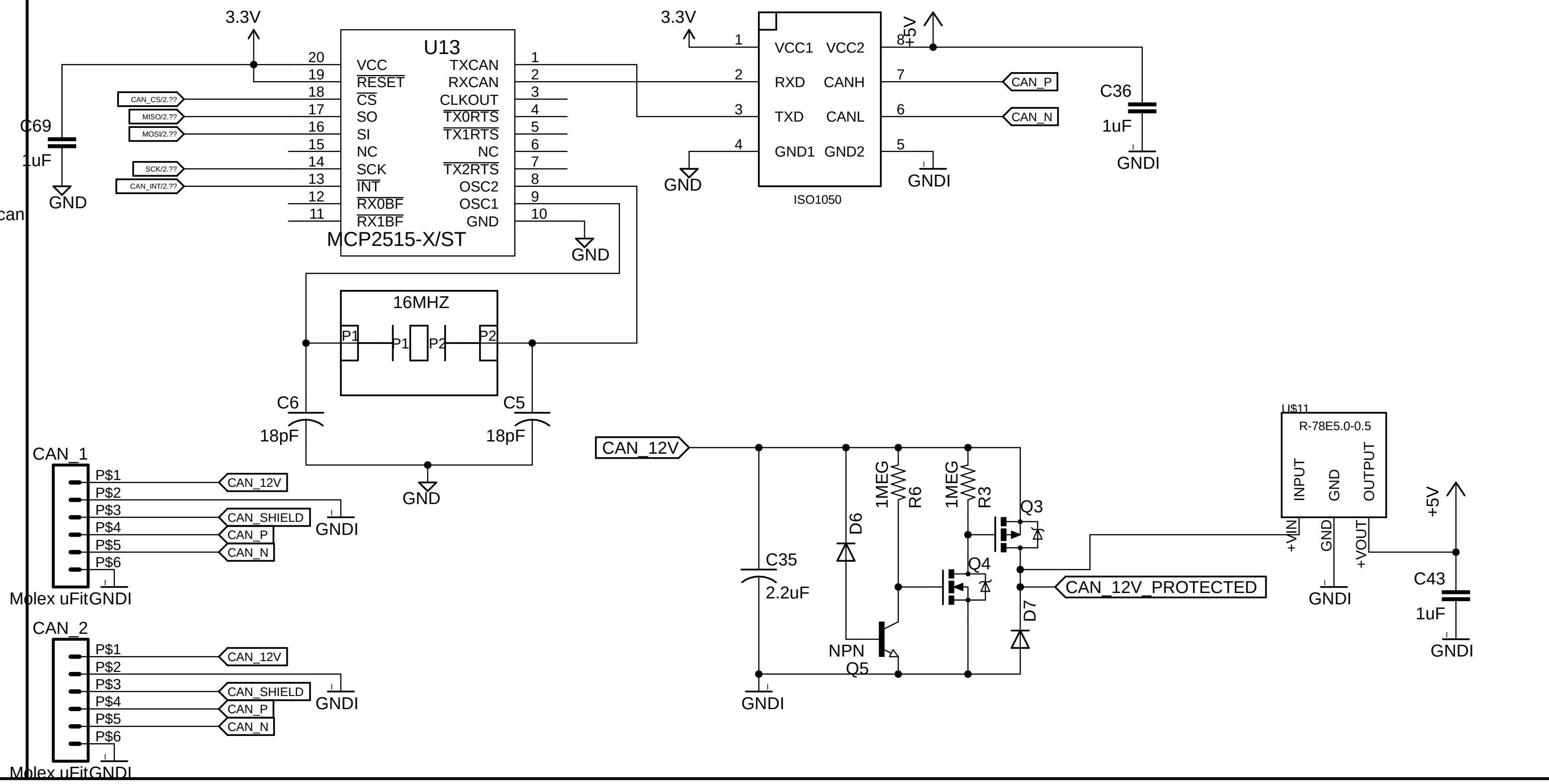
Isolated 12V to Isolated 3V3

The MCU requires 3.3V for its core power. This is provided by a Linear Technologies integrated switch buck converter. There is a footprint for a 3.3V LDO as well. This is intended for use on test boards to reduce cost and assembly time when efficiency is not important. Using the LDO instead of the switching regulator adds an additional 250mW of loss.



CAN Controller

This section shows the circuitry used by the can controller including the digital isolator.



S&T SCT Logo