Open Source Multimeter

Some notes on design, how stuff works, and component choices.

I go through the schematics pretty much in order, generally starting at the top-left. I don't show pictures of them here. Sub-pages are dealt with on their own.

Page 1 – Overview

The crystal oscillator (Y101, C101-102) is self-explanatory, but it does determine the accuracy of any frequency- or time-related measurements. So I'm using a crystal rather than ceramic resonator, although a temperature-compensated oscillator would be better.

JP101 and R104 control the microcontroller BOOT0 pin to determine whether to boot normally from the main flash memory or from system memory for programming via DFU.

U103 holds NRST low when the available voltage is below 3.5 V – the microcontroller's built-in reset circuitry acts at around 2 V, which is far too low for either the Li-Ion battery to be discharged to or for the voltage reference to be remotely accurate.

P101 provides access for any extensibility that anyone wants, e.g. a better ADC. Just remember that it isn't electrically isolated from the measurement terminals.

R101-103, R106-108 and C103-105 (which should be C0G / NP0 to avoid distortion) combine to provide a simple low-pass differential anti-aliasing filter. It supplies two ADCs: a 1 M/s 12-bit SAR ADC, and a 50 k/s (6 MHz) 16-bit delta-sigma ADC. It does allow some aliasing – it attenuates the voltage by 92% at the SAR ADC Nyquist of 500 kHz. With the delta-sigma ADC, things are different – the digital filter can deal with anti-aliasing around the data rate Nyquist at 25 kHz, we've only got to deal with the sampling rate Nyquist limit, so about 3 MHz. At this frequency it attenuates the voltage by over 98% – on top of any attenuation by the input section, and then the limited bandwidth of the ADC. On the other end, it only attenuates the voltage of a 10 kHz signal by about 5%. A second-order filter would be better, but it is more complex and probably unnecessary.

C114-115 are touch-sensing sampling capacitors. In accordance with relevant application notes for the microcontroller, they are C0G / NP0 ceramics, with roughly 10 nF capacitance. The exact value may need tuning depending on how things go.

All other capacitors are for decoupling. Some may be unnecessary, but I'd sooner have more than enough rather than the other way around. The ones on the microcontroller are as recommended by its datasheet. They all need to be low-leakage.

Q101 and R105 are to drive the LCD backlight. From what I've read, the LCD modules usually have the current-limit resistors built in for a current draw of about 60 – 70 mA, which is far too much for the STM32 to drive directly. It also has an SD card socket.

Q102 disconnects the LCD from the power. This sort of thing will pop up elsewhere.

Page 2 – Main I/O

Description and function

First we’ve got the current measurement terminals (P201-202), their fuses (F201-202), sense resistors (R201-202) and diodes to limit the current through the sense resistor (D201-204). The diodes are to prevent the resistors from cooking if the meter is connected to a voltage source when trying to measure current by limiting the voltage across them – and they also help the fuses blow faster with a moderate over-current. The choice of fuse and sense resistor needs to take voltage drop into account.

The voltage (P203) and common (P204) terminals both have two contacts. This is to allow Kelvin connections for resistance and similar measurements. The intended technique is to have the top half of the connector as contact 1 and the bottom half as 2. That way standard multimeter probes can plug in as normal. I have not bothered providing surge protection on each circuit separately, as there will never be a significant voltage differential between them when used with standard test leads.

The MOVs VR201-204 must clamp any transients coming in to about 1000 V (8/20 waveform, 4000 V peak voltage, 2 ohm source). The ones I’ve selected should survive at least 100 transients.

The group of resistors above the MOVs (10 in the range R217-230) are the input resistors for the main input voltage divider. I don’t like the long chain, but I didn’t find suitable resistors to replace them. The same applies to the group right of the MOVs (10 in the range R234-244, although R235 and R237 are smaller), which are for the lowest division.

After the main divider input resistors, the input connects to the buffer op-amp (U207C), and also to the groups of resistors to complete the divider (R232, R224-225, R219 and the second group mentioned above), selected by the analog switches U214, U211, U209 and U215. The voltage is limited by the input clamping diodes of the buffer op-amp – even at the maximum transient of 1000 V the maximum current is 0.1 mA, and the op-amp is allowed an input current of as much as 10 mA.

Above that is the low voltage input. It starts with R215, a single resistor because I did manage to find one suitable for here. Its purpose is to limit the current into the clamping diodes of U207A, the low-voltage buffer, in the event that the input voltage is too high. The buffer is there to handle leakage in the analog switch (which is up to 50 times higher than the op-amp input bias current). The Solid State Relay (U205) protects the buffer from high voltages. However, the SSR is only rated for 600 V so if there is a transient (1000 V) when it is off, the TVS diodes (D209-210) will conduct to protect it, forcing the op-amp to clamp the transient.

To the right of this we have the low voltage input multiplexer (U208, U210 and U212). This selects whether to feed the low voltage input, or which current input, to the low voltage amplifier (U207B). The amplifier’s gain is selected by R228, R231, R233, R238, U213, U215 and U217.

Of note is that one low-voltage ranges shares a control line with a voltage divider range. This is due to the different ranges needed depending on ADC resolution. And since the lowest voltage-divider range will almost always need a large portion of the resistor chain, it is also possible to configure the next division range to use that. Which ones are active is selected with JP201-204. The parts not selected would not be installed either.

Above this is one part of the output signal generator. The other part is at the very bottom. The resistors (R205-208), SSR (U201) and TVS diodes (D207-208) serve exactly the same function as the analogous components in the low voltage input section, although with a much lower resistance to allow for a reasonable output current. Unfortunately that reasonable current means that if connected to a voltage source while on, the current is significantly higher – hence D205-206 on the top and D214-215 on the bottom to clamp it. R204 is the current shunt to measure the output current. The output voltage is measured by the normal voltage input circuitry – dependent on what is plugged in, and how things are configured. R247 (top) and R248 (bottom) protect the output op-amps (U202A and B) from excessive current – without them, when the voltage is being clamped, the input could forced past the power rail. The output op-amps buffer the output of the microcontroller's DAC – each is controlled separately. Q201 controls the output op-amp power to help battery life.

The voltage across the output current shunt (R204, mentioned above) is amplified by U203, an instrumentation amplifier. R209-210 protect it from excessive input voltages (especially R210 on the negative line, as it is before the 100 ohm shunt). The amplification ratio is chosen by R212-214, U204 and U206.

The common terminal is buffered by U207D for the ADC and also the reference voltage for the amplifiers. R245-246 give a return path for op-amp bias currents while also positioning COMMON at mid-rail.

All capacitors are for decoupling, and once again need to be low-leakage.

Component choices

As documented on the schematic, the unspecified resistors (R213-214, R219, R224-225, R231-233, R235, R237-238) should have their values (and even their existence, in fact) chosen according to the spreadsheet “voltage divider values.ods”. They will vary depending on the desired resolution of each range.

The above resistors don't need extremely tight tolerances, as it is possible to calibrate them in software. They should have reasonably low temperature coefficients, or at least be matched (within a group) so that temperature changes leave the ratio relatively constant.

All current sense resistors need a fairly low temperature coefficient, otherwise their tolerance over temperature will be poor – we can't play ratio tricks here. But we probably can play tricks with tolerances, by using the tightest tolerance one to measure the others – within limits. I recommend making the 100 ohm output current sense the one with the tight tolerance to measure others against, if only because it can have the lowest power rating.

The output signal current sense amplifier (U203) must be able to handle the necessary amplification ranges (some in-amps have minimum gain settings), and must also have an input range that includes both voltage rails, or at least close to them.

The analog switches need to be low leakage, and they also need a low enough on-resistance to not significantly influence the total resistance presented.

The op-amps need to be chosen according to the guidelines on the schematic.

Page 3 – Power Supply

D303 is mostly for my peace of mind, to ensure nothing other than the charger can try to charge the Li-ion battery.

Q301-302 and R301 switch the rail +V_int on and off. This is necessary for power saving. I chose to switch the positive rail rather than negative so that I didn't get a fourth ground rail. And seeing I'm switching a positive rail, I use a P-channel MOSFET (Q301). A resistor (R301) holds it switched off until pulled on by switching on Q302 – this also inverts the signal to give the same active-high that is needed for the voltage reference (U302).

D301 prevents clamping currents pushing the voltage rails up too far, while D302 prevents the increased voltage from influencing the rail +3.3VA from which +V_int derives.

R302-303 halves the battery voltage so that we can measure it. C302 lets us get an accurate reading despite the high resistance of the voltage divider, as long as we don't check it any more than about twice a second – which isn't a problem at all.

FB301 and C305-306 form the filtering to separate the analog rail from the digital rail. JP302 splits the corresponding ground rails for when laying out the PCB.

The rest of the capacitors are decoupling / filtering, and as always need to be low-leakage.

U301 regulates the battery voltage down to 3.3 V. It must have a fairly low power consumption, as it is on at all times. The worst-case efficiency is about 78%, so I'm not concerned about using a linear regulator.

U302 gives us our reference voltage. Its accuracy will limit the accuracy of the entire meter, so it needs to be fairly good. It is disabled when off to reduce power consumption. Noteworthy is that its output sense line (OUT_S on pin 5) connects very close to the primary ADC reference input, but this is not illustrated on the schematics.

Page 4 – Interface Inputs

i.e. The controls that the user interacts with.

The push-button switch (SW401) is required to wake up the microcontroller from low-power modes. It also acts as the OK button.

The other five (P401-405) are touch switches under the front cover – the sense pads themselves aren't on the PCB, hence the connectors P406-407. R401-405 are recommended by the STM32 touch-sensing guidelines for ESD protection.

Page 5 – USB and Charging

U501 protects against transients on both the USB power and data lines. I know that I have connected D- to pin 2, which is a no-connect, but this is actually the recommended layout from the datasheet of the part I have selected.

The USB connector (P501) should be inaccessible from outside while the terminals can be accessed, and vice versa. Otherwise the USB port could be floating far above earth ground in a circuit, and be dangerous.

U502 is a Li-Ion battery charging IC. R504-505 determine the battery temperature charge cutout point.

R503, R506 and Q501 regulate the charging current. R506 on its own regulates the charging current at 100 mA. When Q501 is enabled, R503 in parallel with R506 increases the charging current to 500 mA. This is needed to comply with USB specifications – these require the current to be no more than 100 mA unless the device has negotiated and been approved to draw more. Probably a non-issue, but I'll comply with it.

Q502 and R507-508 are to convert the two open-collector status outputs to a single tri-state signal – which we can monitor with a single GPIO.

Features

Unfortunately, the ability to measure voltage and current, provide an arbitrary output signal, a graphical display, SD card slot, and Li-ion battery with USB charging are the only hardware features. The choice of voltage reference, resistors and other components will dictate the accuracy. The rest is software, and that is only limited by what it can do with the hardware, and what the 72 MHz ARM Cortex-M4F microcontroller can handle.