Grüezi YouTubers. Here is the guy with the Swiss accent. With a new episode around sensors and microcontrollers.

In video #133 we used super capacitors to safely shutdown the Rapberry Pi. In the comments, viewers asked about over voltage protection of the super caps. I will show you a big and small and cheap possibility. And I will show you one concept which does not really work.

But why do we have to protect Super Capacitors? And how can we protect them? Most Super capacitors are only specified up to 2.7 volt. If we need higher voltages, we have to connect a few of them in series. To give the Raspberry a save shutdown I used two caps because it runs on 5 volt USB.

So, the basic diagram is like that: Two Super capacitors in series across the 5 volt connector.

If we charge now capacitors in series, the current is equal in both capacitors. But, if the capacitance are not completely equal, the one with the lower capacitance charges faster and its voltage can go over the rated 2.7 volts. To avoid that, we have to connect a resistor in parallel to the smaller capacitor. Like that, part of the current can flow through this resistor and therefore is not used for overcharging the capacitor. Because we do not know, which of the capacitors is smaller and exactly how much, and because some other things can happen, we add a small switch to this resistor. It switches only, if the voltage of the capacitor is close to the 2.7 volt. Like that, we can use quite small resistors and bypass a big amount of the current. As soon as the voltage is in the save zone, the resistor is switched off again.

If we use such a concept for all our capacitors, and our protection voltage is 2.7 volt, they are protected against over voltage as long as the total voltage is lower than the number of capacitors times 2.7. In our case, the voltage would have to stay below 5.4 volts. Which is ok with USB. The specification allows a maximum voltage of 5.2 volts.

Let’s start with the simplest concept: Zener diodes. The easiest way would be to solder a Zener diode across each super cap. But what is a Zener diode? Normal diodes conduct current only in one direction and block it in the other direction (at least up to their very high blocking voltage). Zener diodes are somehow different. In principle, they also block current in the “wrong” direction up to a certain voltage. But this voltage is low and exactly specified. You can get Zener diodes for many voltages. If we check one with our transistor tester, it shows two diodes in opposite direction. The one with the voltage of 0.8 volt is the normal diode. The other one with 2.4 volt is the Zener part.

Let’s have a closer look: On the positive voltage side, we see a curve of a normal diode. On the negative voltage side, we see the Zener behavior. At the beginning, nearly no current flows. At a particular voltage, the current starts to flow. But this is not at a sharp voltage as we can see. The curve is only bent. Because all these things happen on the negative voltage side, we have to use the Zener diodes always in reverse direction. This is, why I mirror the curve now.

Just a small remark: Not all transistor testers are able to measure Zener diodes properly. And all can only detect these diodes if they have a low Zener voltage.

So, let’s check how this simple concept works. I have 2.4 volt and 2.7 volt Zeners. I start my test with no protection at all. Two 10 Farad Super Caps are connected in Series and 5 volt is applied. If both are discharged at the beginning, they load quite evenly. The difference is small, because their capacities are similar.

I discharge now the left capacitor a little to simulate uneven capacities. If I load them again, the right one quickly approaches 2.7 volts and I have to stop the experiment in order to not harm it.

Let’s now protect this Cap with a 2.4 volt Zener. To understand what happens, I measure the current through the diode with the yellow Fluke meter. As we already know from the chart, the diode already starts to conduct at below 2.4 volt. So, a part of the current is now “diverged” through the diode instead of the capacitor. This part does not charge the capacitor anymore. So, the other cap can catch up. But because the current through the diode is quite small, the protection is not big, and the voltage exceed 2.7 volts a little. If the imbalance between the two capacitors would be bigger, this protection would not work anymore. And, we easily can imagine, that a 2.7 volt Zener would not work at all.

So, this is a simple protection, which works somehow for these small capacitors. But fortunately, we have a better one: The TL431. This part is called “Precision Programmable Reference” and it is a very versatile part which can used for many applications. It is also quite cheap: 50 pieces for 1.20, including shipping. It is even cheaper than a 2.4 volt Zener, where 50 pieces cost more than 3 dollars.

The TL431 is a neat small part in a TO-92 package. Its symbol looks much like a Zener diode, with the exception that it has three pins instead of only two. The third pin is called REFERENCE. If we look at the block diagram of the chip, we see, that it consists of a precise 2.5 volt reference and an Opamp used as a comparator. As soon as the reference voltage is above the 2.5 volt, the transistor switches on. So, if we connect the REFERENCE and the cathode pins, we get this diagram. Because I mirrored the diagram of the Zener diode, both are compatible. We have the positive voltage to the right and positive current up. We immediately see the difference: The bend of the TL431 is much sharper. At exactly 2.5 volts it starts to conduct up to its maximum rating of 150 mA. This is nearly the curve we were looking for. The only thing is, that it is at 2.5 instead of 2.7 volts. So, let’s try out and replace the 2.4 volt Zener with the TL431. We also start with unevenly charged capacitors and see, that the current through the TL431 starts to increase much more and much sharper at 2.5 volts. The voltage across the super cap still goes above 2.5 volt, because the parts are not ideal. But still, the behavior is much better. At the end, the protected and the unprotected caps each show around 2.5 volts. If I would now increase the voltage to 5.3 volt, only the unprotected cap’s voltage would increase and would exceed its specified voltage. Which is obviously not good.

So, we could protect both capacitors. Which anyway would be a good idea, because we do not know, which one has a smaller capacity. Below 5 volt total voltage, this would work fine. But as soon as we cross these 5 volts, both TL431 would start to conduct and produce a short cut. They would heat up, and maybe even would destroy themselves. Maybe you remember the word “programmable” from the description of the TL431? Programmable means, that we can change the “Zener voltage” with a simple trick: We connect the reference pin to a voltage divider. Now, the reference measures a lower voltage and therefore, reaches the 2.5 volts at a higher voltage. If we calculate our resistors with the formula from the data sheet, we can set the cutoff voltage to 2.7 volt. Problem solved!

If you really want to make sure, that nothing bad happens to your protectors, you can add a small series resistor. Like that, the current through the TL431 is limited. If you plan to work only with USB voltages, this is not necessary.

So, this is a great concept to protect small super caps when you are sure, that the two capacities are similar. To show you the limitations, I double the capacitance of one capacitor by adding a second one. Now, we see, that the current through the TL431 gets quite high, and the voltage crosses 2.7 volt, even with a cutoff voltage of 2.5 volt. To avoid that, I bought the voltage protectors shown in the last Mailbag video #137. They can be used for large capacitors up to 500 Farad. I re-engineered its PCB and its diagram is here. They also use a TL431, but they use a big transistor to amplify the effect. So, let’s check, if it works. I keep the “tougher” scenario with the two uneven capacitors and protect the smaller one. Now with a protection board instead of the TL431. The rest stays the same. Here, the protection kicks in at 2.66 volt and the voltage never exceeds this value . The other capacitor can easily catch up. And if we would have two such protection boards in series, our USB voltage could go up to 2 times 2.66 volt = 5.32 volt, which is above USB specs anyway.

Summarized:

We wanted to protect our Super capacitors against over voltage

The first concept using simple Zener diodes worked somehow, but with very narrow limitations

The usage of a TL431 Precision Programmable Reference did what we wanted for our small capacitors, and even at lower cost.

With a voltage divider, we were able to set the protection voltage at the right level.

We looked at the diagram of a commercial product for larger capacitors and discovered, that they also use a TL431

The commercial product worked too, and, because it supports much bigger currents, can also be used for bigger capacitors.

BTW: If we do the calculation of the voltage divider of the protection board, we find the 2.66 volts we measured before. Not bad!

I hope, this video was useful or at least interesting for you. If true then like. Bye