



A Digital DC Power Supply (programmable bench power supply unit), hardware version 3.0



Abstract:

A good, reliable and easy to use bench power supply unit is probably the most important and most used device in every electronic lab.

A proper electronically stabilized bench power supply unit is an important but also expensive device. Using a microcontroller based design we can build a power supply which has a lot of extra features, is easy to build and very affordable.

The tuxgraphics digital DC power supply has been a very successful product and this is now the third generation. It is still based on the same idea as the first version but comes with a number of good improvements.

The components + PCB are available as a kit from our online shop: <http://shop.tuxgraphics.org/electronic/index-kits.html>



Introduction

This bench power supply unit is less complex than most other circuits but has a lot more features:

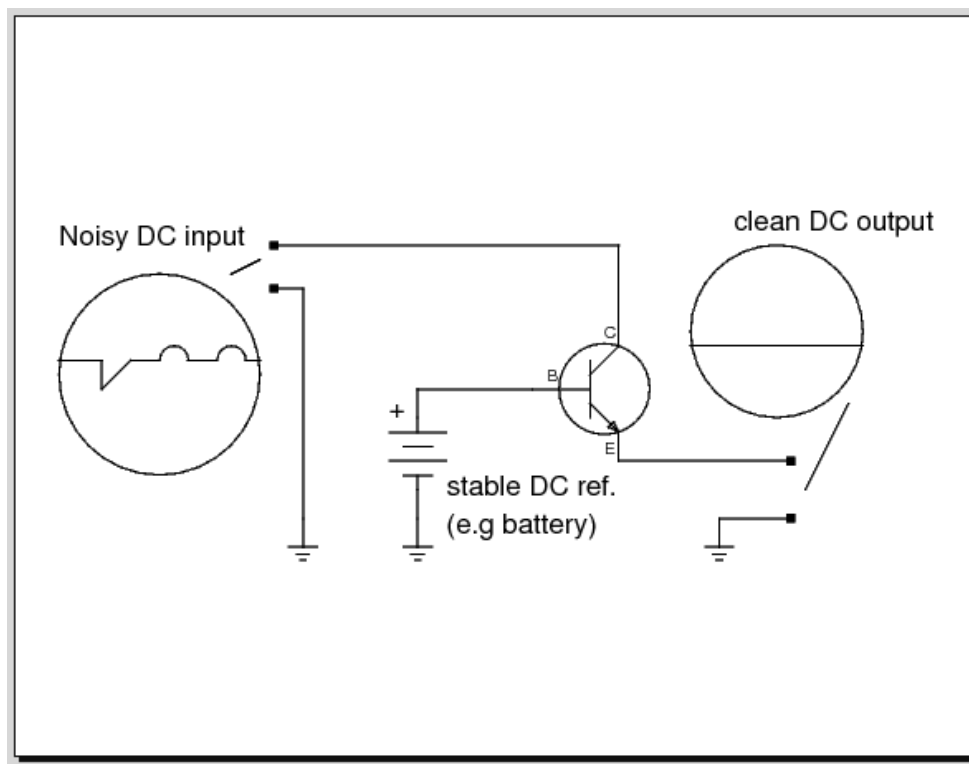
1. The display shows the actual measurement values for voltage and current.
2. The display shows the pre-set limits for voltage and current.
3. Only standard components are used (no special chips).
4. Only one power source is needed (no separate negative supply voltage for operational amplifiers or control logic)
5. You can control the power supply from a PC. You can read current and voltages and you can set them with simple commands. This is very useful for automated testing.
6. A small button pad is available to directly enter the desired voltage and max. current.
7. It is really small but powerful.

How was it possible to remove components and add more features? The trick is to move functionality which is normally based on analog components like operational amplifiers into the microcontroller. In other words the complexity of the software and algorithms is higher but hardware complexity is reduced. This reduces the overall complexity for you as the software can just be copied.

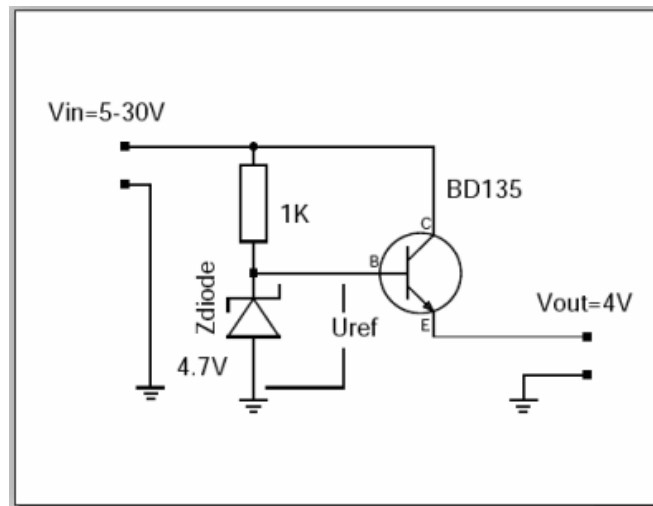
The basic electrical design idea

A common misconception about a digital power supply is that people assume everything to be digital and don't understand how this could possibly work with a circuit based on a microcontroller. We want a clean and stable analog voltage as output and for this we use analog components. Only analog components are fast enough to remove ripples due to load changes or any remaining 50/60Hz noise.

The emitter voltage on a transistor is related to the voltage on the base and not the input voltage on the collector. The main current flows however from C to E. This simple circuit produces a clean DC voltage. It removes noise coming in through the collector pin and controls load changes on the emitter side.



In other words our digital power supply has a completely analog control system for fast response to load and voltage changes and we overlay a second digital control system for the more fancy features that a bench top power supply needs. Let's remove the battery from that circuit and build the simplest possible electronically stabilized power supply. It consists of 2 basic parts: a transistor and a reference voltage generated with a Z-diode.



The output voltage of this circuit is $U_{ref} - 0.7V$. The 0.7V is approximately the voltage drop between B and E on the transistor. The Z-diode and the resistor generate a reference voltage which is stable, even if the input fluctuates and is noisy. The transistor is needed to handle higher currents than the Z-diode and resistor alone can provide. In this configuration the transistor just amplifies the current. The current which the resistor and Z-diode need to provide is the output current divided by h_{fe} (h_{fe} is a number which you can lookup in the datasheet of the transistor).

What are the problems with this circuit?

- The transistor will die when there is a short circuit on the output.
- It provides only a fixed output voltage.

These are quite severe limitations which make this circuit unusable but this circuit is still the basic building block of all electronically regulated power supplies.

To overcome those problems you need some "intelligence" which will regulate the current on the output and a variable reference voltage. That's all (... and this makes the circuit much more complex).

For the last few decades people have used operational amplifiers to provide this intelligence. Operational amplifiers can basically be used as analog calculators to add, subtract, multiply or logically "or" voltages and currents.

Today microcontrollers are so fast that all this can easily be done in software. The beauty is that you get as a side effect a voltmeter and an amperemeter for free. The control loop in the microcontrollers has to know voltage and current values anyhow. You just need to display them. What we need from the microcontroller are:

- A AD-converter to measure voltage and current all the time
- A DA-converter to drive our power transistor (provide the reference voltage)

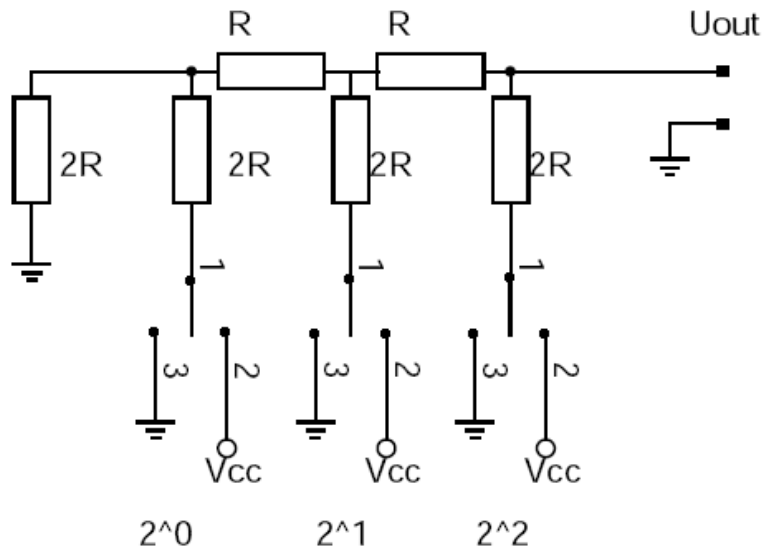
The problem is that the DA-converter needs to be very fast. If there is a short circuit detected on the output then we must immediately reduce the voltage on the basis of the transistor otherwise it will die. Fast means within milliseconds (as fast as an operational amplifier).

The ATmega8 has an AD-converter which is more than fast enough but it has at first glance no DA-converter. It is possible to use pulse width modulation (PWM) and an analog low pass filter to

get an DA-converter but PWM alone is much too slow to implement the short circuit protection in software. How to build a fast DA-converter?

The R-2R ladder

There are many ways to build a digital to analog converter but we need a fast and cheap one which can easily interface to our microcontroller. There is a DA-converter circuit known as "R-2R ladder". It consists of resistors and switches only. There are two types of resistors. One with the value R and one with twice the value of R.



$$U_{out} = Z * (V_{cc}/(Z_{max} + 1))$$

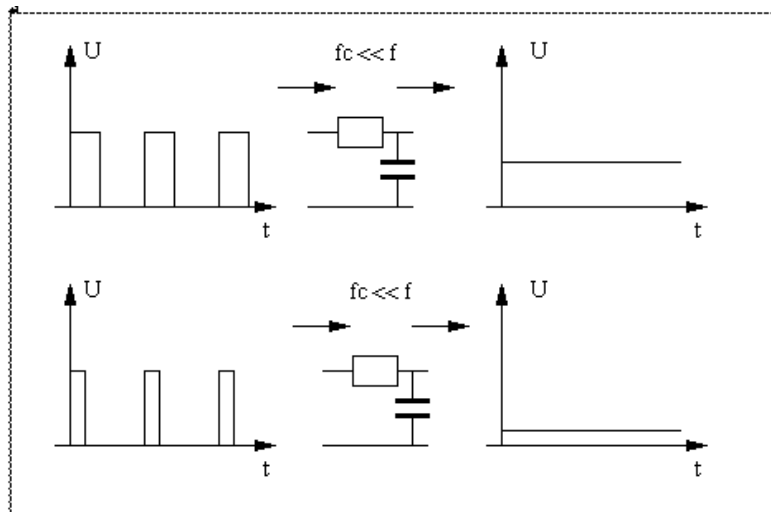
The above shows a 3 bit R2R-DA-converter. The control logic moves the switches between GND and Vcc. A digital "one" connects the switch to Vcc and a digital "zero" to GND. What does this circuit do? It provides voltages in steps of $V_{cc}/8$. In general the output voltage is $Z * (V_{cc}/(Z_{max}+1))$ where Z is the digital number. In the case of a 3 bit AD converter this is: 0-7.

The inner resistance of the circuit as seen from the output is R.

Instead of using separate switches we can connect the R-2R ladder to the microcontroller output lines.

Generating a variable DC signal with PWM (pulse width modulation)

Puls width modulation is a method where you generate pulses and run them thru a low pass filter with a cut off frequency much lower than the pulse frequency. This results in a DC signal and the voltage depends on the width of those pulses.



Using PWM to generate a variable DC voltage.

The atmega8 provides in hardware 16bit PWM. That is: you could theoretically have a 16bit DAC with just very few components. In order to get a true DC signal out of a PWM signal one has to average it out using a filter and that can be a problem at high resolutions. The more accuracy you have the lower the frequency of the PWM signal. This again means you need big capacitors and the response time is very slow. The first and second generation of the digital DC power supply had a 10bit R2R-ladder DAC. That is: the output could be set in 1024 steps. If you run the atmega at 8MHz and use a 10bit PWM DAC then the PWM signal pulses have a frequency of $8\text{MHz}/1024=7.8\text{KHz}$. To get a somewhat good DC signal out of this you need to filter it with a second order low pass filter of 700Hz or less.

You can imagine what happens if you use 16bit PWM. $8\text{MHz}/65536=122\text{Hz}$. One would need a 12Hz low pass.

Combining R2R-ladder and PWM

It is possible to combine the idea of the PWM and the R2R-ladder. In this design we will use a 7bit R2R-ladder combined with a 5bit PWM signal. With a 8MHz system clock and 5bit resolution we will get a 250KHz signal. 250KHz can even be converted with small capacitors into a DC signal.

The original version of the tuxgraphics digital DC power supply had a 10bit DAC based on the R2R ladder. In this new design we use R2R-ladder and PWM with a total resolution of 12bit.

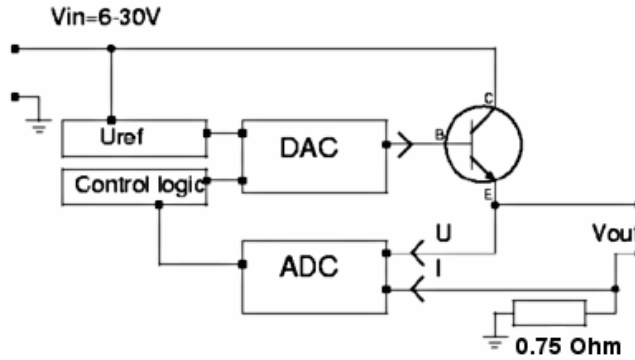
Oversampling

At the expense of some processing time one can increase the resolution of an analog to digital converter (ADC). This is called oversampling.

Four fold oversampling results in double resolution. That is: 4 consecutive samples can be used to get twice as many steps on the ADC. The theory behind oversampling is explained in the PDF document which you can find at the end of this article. We use oversampling for the voltage control loop. For the current control loop we use the original resolution of the ADC as fast response times are here more important than resolution.

A more detailed design

So here is now a more detailed design of the above circuit.



A few technical details are still missing:

- The DAC (digital to analog converter) can not provide the current to drive the power transistor
- The microcontroller operates at 5V so the maximum output of the DAC is 5V which means that the maximum output voltage behind the power transistor will be $5-0.7=4.3V$.

To fix this we must add amplifiers for current and voltage.

Adding an amplifier stage to the DAC

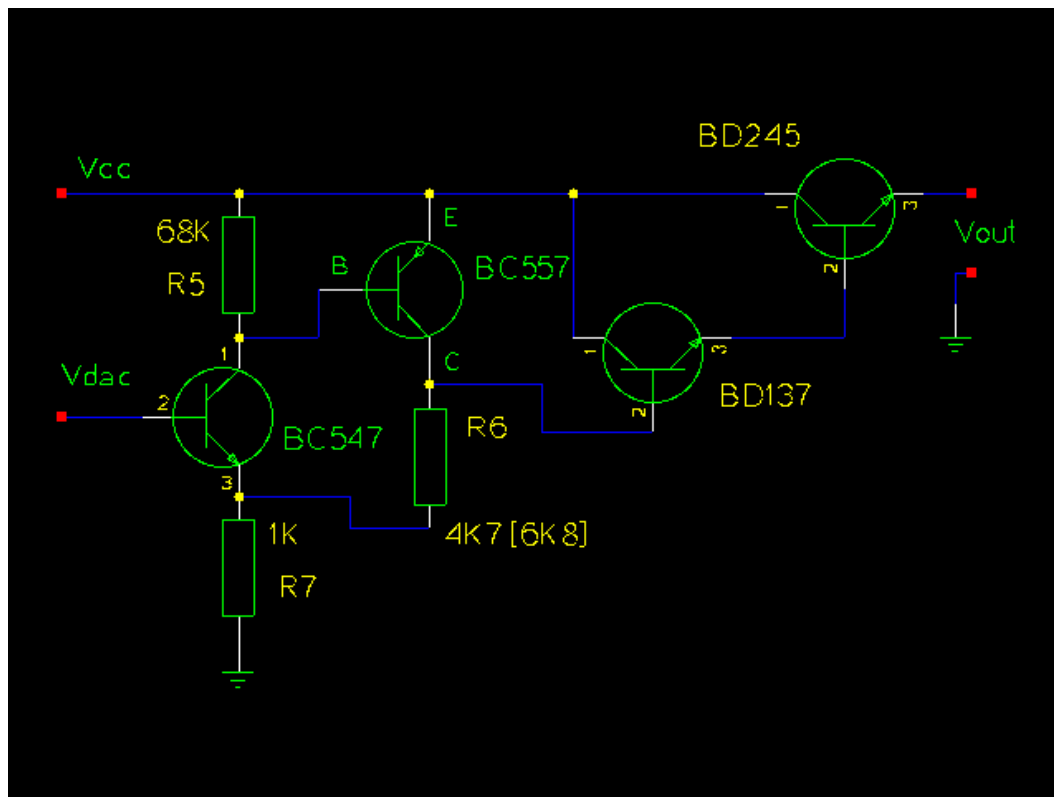
When adding amplifiers we must keep in mind that those must work with large signals. Most amplifier designs (e.g for audio) are done under the assumption that the signals will be small compared to the supply voltage. So forget all the classic books about transistor amplifier design.

We could use operational amplifiers but those would require extra positive and negative supply voltages which we want to avoid.

There is also the additional requirement that the amplifier must go from zero voltage to a stable state without oscillating. In words there must not be any short oscillation or output peek when you switch on the power supply.

The below circuit shows an amplifier stage which is suitable for this purpose.

We start with the power transistor. We use a BD245 (Q1). According to the datasheet this transistor has a $h_{fe}=20$ at 3A output. It will therefore draw about 150mA on the basis. To amplify the current we use a configuration known as "Darlington transistor". For this we put a medium power transistor in front. Those have typically a h_{fe} value of 50-100. This will reduce the current needed to less than 3mA ($150\text{mA} / 50$). 3mA are manageable with small signal transistors like BC547/BC557. Those small signal transistors are then very good for building a voltage amplifier.



For 30V output we must at least amplify the 5V from the DAC by a factor of 6. For this we combine a PNP and an NPN transistor as shown above. The voltage amplification factor of this

circuit is:

$$V_{amp1} = (R6 + R7) / R7$$

The power supply shall be available in 2 version: Max 30 output and max 22V output. A combination of 1K and 6.8K gives a factor of 7.8 which is good for the 30V version and has some room for possible losses due to higher currents (our formula is linear. The reality is non-linear). For the 22V version we use 1K and 4.7K.

The inner resistance of the circuit as seen on the Basis of BC547 is:

$$R_{in} = h_{fe1} * S1 * R7 * R5 = 100 * 50 * 1K * 47K = 235 \text{ MOhm}$$

- h_{fe} is about 100 to 200 for a BC547 transistor
- S is the slope of the amplification curve of a transistor and is about 50 [unit=1/Ohm]

This is more than high enough for the connection to our DAC which has a inner resistance of 5K.

The inner equivalent output resistance is:

$$R_{out} = (R6 + R7) / (S1 + S2 * R5 * R7) = \text{about } 2 \text{ Ohm}$$

Low enough to drive the following transistor Q2.

R5 ties the basis of BC557 to the emitter which means "off" for the transistor until the DAC and BC547 come up. R7 and R6 tie the Basis of Q2 initially to ground which shuts the output darlington stage down.

In other words every component in this amplifier stage is initially off. This means we will not get from those transistors any oscillations or output peeks at power on or power off. A very important point. I have seen expensive industrial power supplies which produced a voltage peek at power off. Such a power supply is definitely to be avoided as it can easily kill sensitive circuits.

The limits

From previous experience I know that some readers would like to "customize" the circuit a bit. Here is a list of hardware limits and how to overcome them:

BD245B: 10A 80W. The 80W are however at a temperature of 25'C
In other words add a safety margin and calculate with 60W-70W:
(Max input voltage * Max current) < 65W

You can add a second BD245B to go up to 120W. To ensure that the current distributes equally add a 0.22 Ohm resistor into the Emitter line of each BD245B.
The same circuit and board can be used. Mount the transistors on a proper aluminum cooler and connect them with short wires to the board. The amplifier can drive a second power transistor (that's the maximum) but you might need to adjust the amplification factor.

Current measurement shunt:

We use a 0.75 Ohm resistor with 6W. This is good enough for about 2.5A of output ($I_{out}^2 * 0.75 \leq 6W$). Use a resistor with more watts for higher currents.

Power sources

You can either use a transformer, rectifier and big capacitors or you can try to get a 32/24V laptop power supply. I went for the later option. Those laptop power supply "bricks" are sometimes sold very cheap (over stock) and some of them provide 70W at 24V or even 32V DC.

Most people will probably go for a transformer because those are very easy to get.

22V 2.5A version: you need a 18V 3A transformer, a rectifier and a 2200uF or 3300uF capacitor. (reason: $18 * 1.4 = 25V$)

30V 2A version: you need a 24V 2.5A transformer, a rectifier and a 2200uF or 3300uF capacitor. (reason: $24 * 1.4 = 33.6V$)

It does not harm to buy a transformer which can provide more ampere.

A power diodes bridge with 4 diodes which are specified for a low voltage drop (e.g BYV29-500) gives a good rectifier.

You can also use a "heavier" transformer.

Check your circuit for proper insulation. Make sure that it is **not** possible to touch any part that may carry 110V/230V even when the case is open. Connect all metal parts of the chassis to earth (not to GND of the circuit).

Transformers and laptop power supply bricks

If you want to use two or more power supplies in a chain to get positive and negative voltages for your circuit then it is important that the transformer is really insulated. Be careful with laptop power supply bricks. They are nice and small but some of them may connect the minus pin on the output to the earth pin on the input. This will then cause a short circuit via the earth wire if you use two power supplies in a chain.

Other voltages and current limits

The two provided configurations are 22V 2.5A and 30V 2A. If you want to build a version with other (lower) output voltages or current limits then just edit the `hardware_settings.h` file.

Example: To build a 18V 2.5A version you just edit the `hardware_settings.h` file and change the maximum output voltage to 18V.

You can then use a 20V 2.5A power source.

Example: To build a 18V 1.5A version you just edit the `hardware_settings.h` file and change the maximum output voltage to 18V and the max. current to 1.5A.

You can then use a 20V 1.5A power source.

Testing

The last component to solder to the board should be the microcontroller. Before you insert it I would recommend to do some basic hardware tests:

Test1: Connect some power supply (at least 10V) to the power input of the circuit and check that you get 5V DC behind the voltage regulator.

Test2: Measure the output voltage. It should be 0V (or near zero, e.g 0.15V, and it will go to zero if you put a "load" of 2K to 5K on the output.)

Test3: Solder the microcontroller to the board and load the LCD test software by running the commands in the directory of the unpacked digitaldcpower tar.gz package.

```
make test_lcd.hex  
make load_test_lcd
```

You should see "LCD works" on the display.

Now you can load the final software.

A word of warning for further testing with the final software: Be careful with short circuits until you have tested the current limitation function. A safe way to test the current limitation is to use a low Ohm resistor, e.g a car bulb.

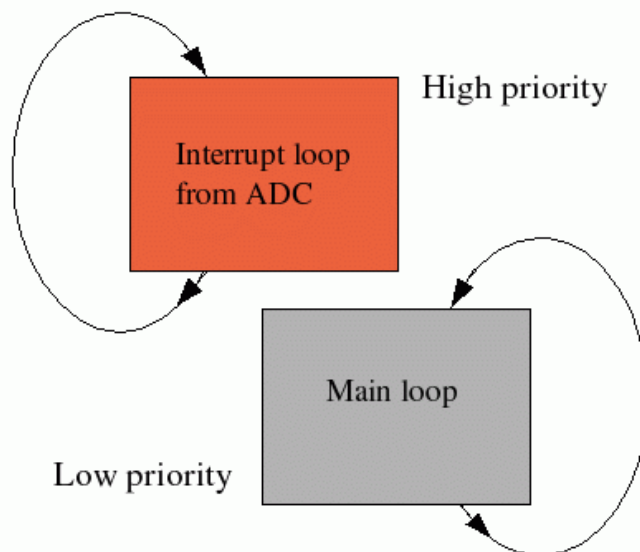
Set a low current limit, e.g 30mA at 10V. You should see the voltage go down immediately to almost zero once you connect the bulb on the output. There is still a fault in the circuit if it does not go down. The car bulb will protect the power supply circuit even if there is a fault as it is not a full short circuit.

The software

This section will give you insights as to how the software works and you can use the knowledge to do modifications. However be aware that the short circuit protection is also only software. If you make a mistake somewhere then this protection may not work. If you cause then a short circuit on the output your hardware may go off in a cloud of smoke. To avoid this you should use a 12V car bulb (see above) to test the short circuit protection.

Now a bit about the software structure. First look at the main program (file main.c, download at the end of this article) you will see that there are only a few lines of initialization code executed at power on and then the software enters an endless loop.

There are really 2 endless loops in this software. One is the main loop ("`while(1){ ...}`" in file main.c) and the other one is the periodic interrupt from the Analog the Digital Converter (function "`ISR(ADC_vect){...}`" in file analog.c). During initialization the interrupt is configured to execute every 104 μ Sec. All functions and code that is executed runs in the context of one of those tasks (task the name for a process or thread of execution in a real time OS, so I use this word here even if there is no OS).



The interrupt task can stop the execution of the main loop at any time. It will then execute without being interrupted and then execution continues again in the main loop at the place where it was interrupted. This has two consequences:

1. The code in the interrupt must not be too long as it must finish before the next interrupt comes. What counts here are the amount of instructions in machine code. A mathematical formula, which can be written as just one line of C-code may result in hundreds of lines of machine code.
2. Variables that you share between interrupt code and code in the main task may suddenly change in the middle of execution.

All this means that complex things like updating of the display, checking of push buttons,

conversion of ampere and volt values to internal units etc ... must be done in the main task. In the interrupt we execute only things that are time critical: Current and voltage control, overload protection and setting of the DAC. To avoid complex mathematics all calculations in the interrupt are done in ADC units. That is the same units that the ADC produces (integer values from 0...1023 for current and 0..2047 for voltages).

This is the basic idea of the software. I will also explain what you find in which files and then you should be able to understand the code (given that you are familiar with C).

Software: Which file contains what

```
main.c -- this file contains the main program. All initialization is
         done from here.here. The main loop is also implemented here.

analog.c -- the analog to digital converter and everything that
           runs in the context of the interrupt task can be found here.

dac.c -- the digital to analog converter. Initialized from ddc.c but
        used only from analog.c

kbd.c -- the keyboard code

lcd.c -- the LCD driver. This is a special version which will not need
        the RW pin of the display. It uses instead an internal timer
        which should be long enough for the display to finish its task.
```

Loading and using the software

To load the software into a microcontroller you need a programmer such as the avrusb500. You can download the zipped software archives at the end of the article.

Edit the file `hardware_settings.h` and adjust it according to the hardware. Here you can also do calibrations of voltmeter and amperemeter. The file is well commented.

```
gedit hardware_settings.h
```

Connect the programmer cable and power on the circuit. Then run:

```
make fuse
```

This will set the clock frequency of the microcontroller to 8MHz. The software is designed for this frequency.

```
make
```

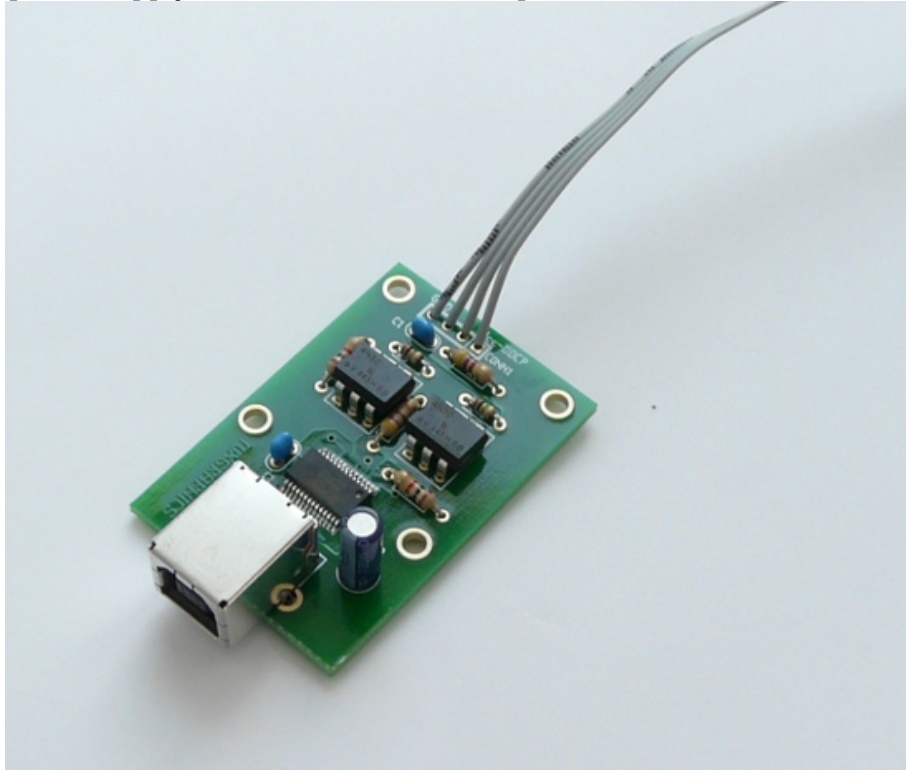
This will compile the software.

```
make load
```

This will load the software.

Control of the power supply unit from any PC (Win, Linux, Mac,...)

This power supply can be controlled by 5 buttons on the front pannel or via a USB connection from a PC. The power supply to USB interface is an optional add-on card.



Digital power supply USB interface with galvanic separation.

Note: we finally decided to use a USB-B socket. The power supply shown in the title image of this article has a different connector as it was built before that decision was made.

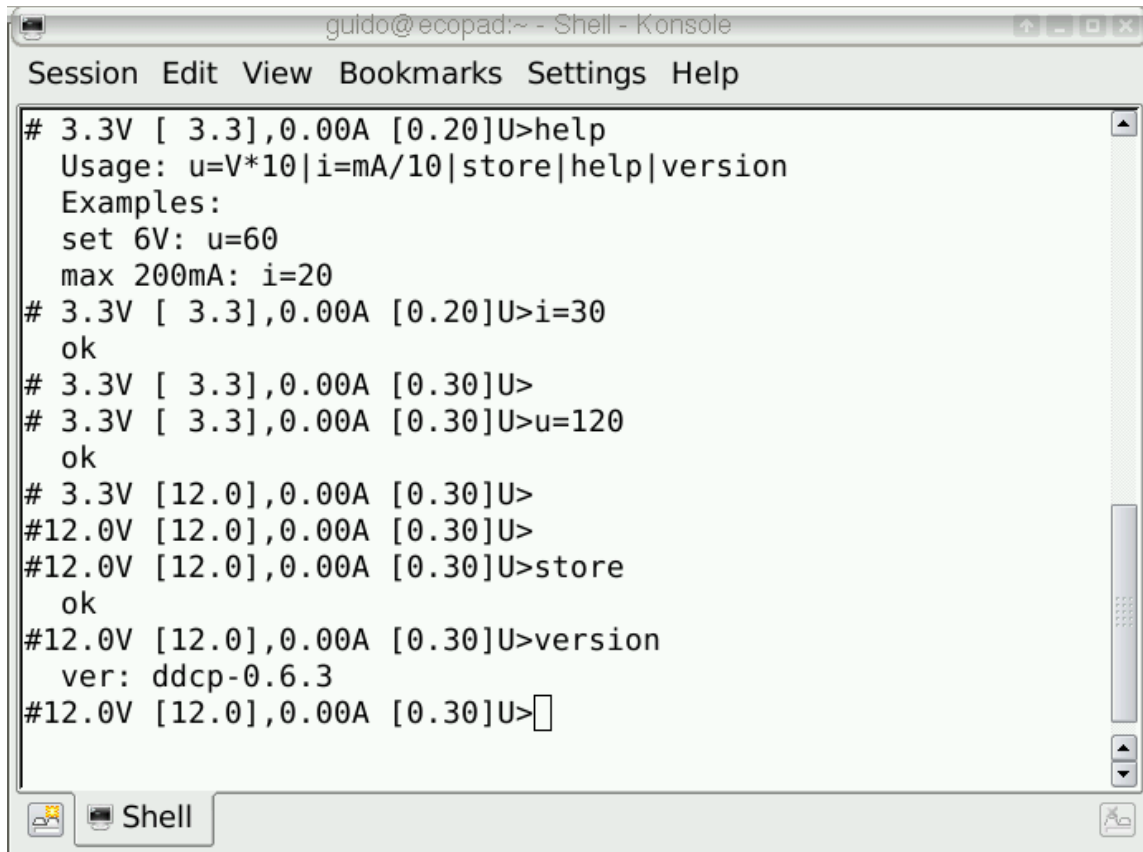
The card offers galvanic separation such that you can use this power supply relative to any reference point (e.g build two power supply units and use one as negative and one as positive power supply).

Galvanic separation is achieved buy using two opto-coupler chips. The information is transmitted with light pulses inside the chip but there is no electrical connection between the receiving and transmitting side.

The power supply shows then up as a virtual com-port on your computer and you can connect to it with any serial terminal. HyperTerminal is a popular windows serial terminal software but it is a bit complicated to use. I prefer putty (<http://www.chiark.greenend.org.uk/~sgtatham/putty/>). For Linux I can recommend picocom (<http://code.google.com/p/picocom/>) It is simple and straight forward to use. Just run the command "picocom -l -b 9600 /dev/ttyUSB0" and to disconnect you type Ctrl-a Ctrl-x.

The port settings are as follows:

```
baudrate   : 9600
parity     : none
flowcontrol: none
stopbits   : 1
databits   : 8
```



```
guido@ecopad:~ - Shell - Konsole
Session Edit View Bookmarks Settings Help
# 3.3V [ 3.3],0.00A [0.20]U>help
Usage: u=V*10|i=mA/10|store|help|version
Examples:
set 6V: u=60
max 200mA: i=20
# 3.3V [ 3.3],0.00A [0.20]U>i=30
ok
# 3.3V [ 3.3],0.00A [0.30]U>
# 3.3V [ 3.3],0.00A [0.30]U>u=120
ok
# 3.3V [12.0],0.00A [0.30]U>
#12.0V [12.0],0.00A [0.30]U>
#12.0V [12.0],0.00A [0.30]U>store
ok
#12.0V [12.0],0.00A [0.30]U>version
ver: ddcp-0.6.3
#12.0V [12.0],0.00A [0.30]U>
```

Command interface for the power supply

The power supply accepts simple commands like "u=.." to set the voltage or "i=.." to set the current. There is as well a "help" command which explains all commands and the syntax. The command prompt shows the same information that can be seen on the LCD display of the power supply.

You can control the digital power supply by commands. A number of commands are provided for this purpose. They are at the moment available for Linux, Mac and Windows:

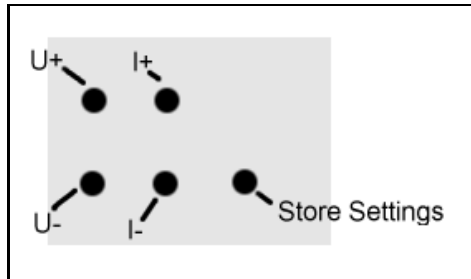
```
ddcp-script-ttyinit - initialize the COM port (run this once at
                    at the beginning)
ddcp-script-getval  - get current values (same as you see on the LCD)
ddcp-script-setval  - send a command to the power supply
```

With this you can write a shell script or batch file to control the power supply or print current values for current and voltage:


```
#!/bin/sh
dev="/dev/ttyUSB1"
# initialize the com port
ddcpc-script-ttyinit "$dev"
#
echo "current settings are:"
ddcpc-script-getval "$dev"
#
echo "setting voltage to 3.3 V"
ddcpc-script-setval "u=33" "$dev"
#
echo "wait a bit, it takes a moment for the display values"
echo "to adjust as they are polled in intervals by the avr software."
sleep 1
echo "the new settings are:"
ddcpc-script-getval "$dev"
```

The buttons

The power supply has 4 buttons for local control of voltage and max. current. The 5-th button is to store the settings permanently in an eeprom such that it will come up with identical settings the next time you power it on.

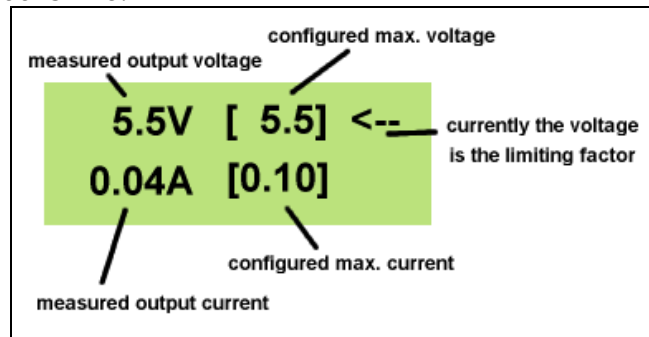


The local control button pad.

With U+ you can increase the voltage and with U- you decrease it. When you hold the button then it will step and after a while "run" faster to make it easy to change the voltage in large steps. The I+ and I- buttons work the same way.

The display

This is how the display looks like:

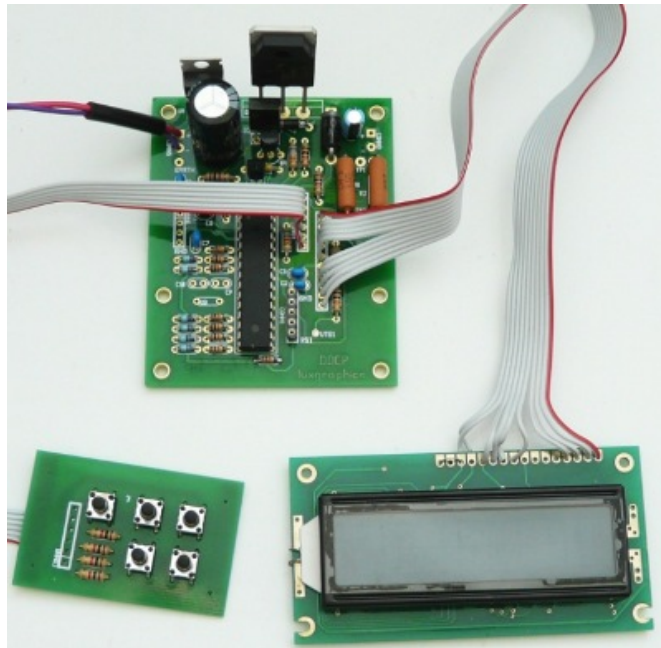


The fields in the LCD display area. The real measured values and the set values are always shown at the same time.

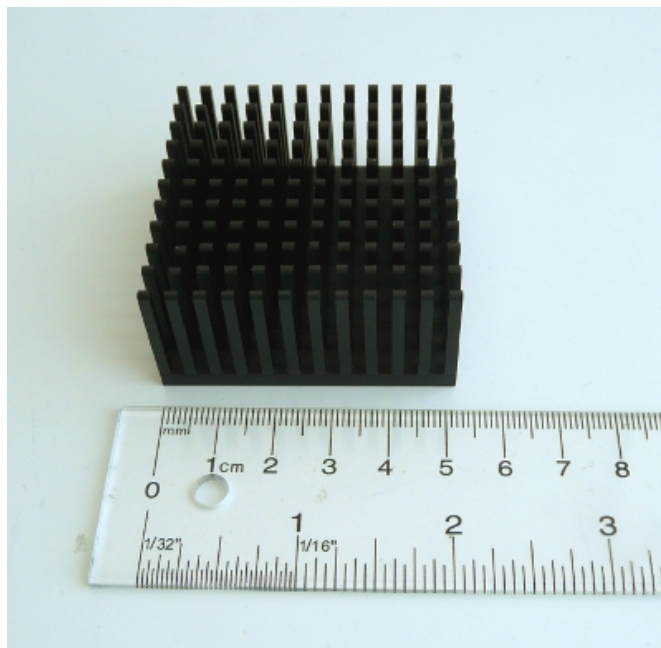
The arrow on the right indicates that currently the configured voltage is the limiting factor. Should a short circuit occur on the output or the connected device draws more current then the arrow will flip to the bottom line and indicate that the configured max. current has become the limiting factor.

Some pictures and ideas

Here are some pictures from the power supplies which I have build.

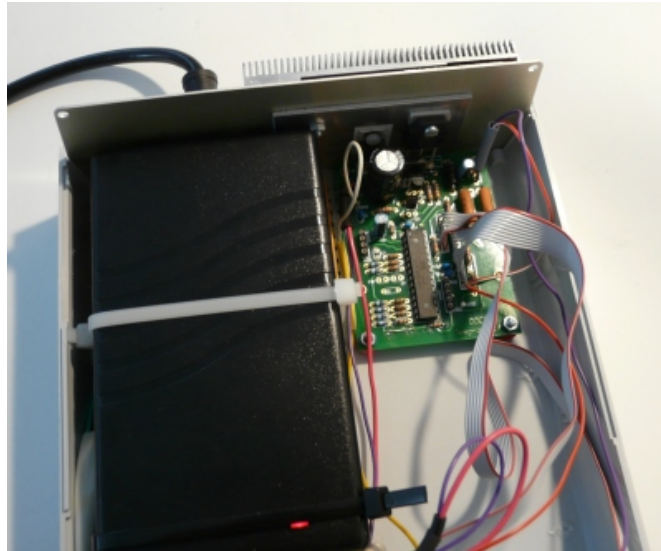


The circuit. Very small but with more features and more powerful than many other power supply circuits.



An old Pentium5 aluminium cooler is a good choice for this

power supply. It is compact and very efficient. A cooler that provides about 1K/W is sufficient. You might as well consider to under dimension it a bit. It will normally be very rare that you operate it permanently at maximum current with a low output voltage.



Installing the components in a case



The final power supply unit.



The final power supply unit. -With a green display-



... and with a blue display in a different case. Blue displays are bit difficult to photograph. It looks even better in reality than here on the photo.

Have fun! I am sure you will like this power supply unit. I use it a lot and every day.

References/Download

- [Download page](#) for this article (firmware updates and corrections will also be available from here).
- [Enhancing ADC resolution by oversampling \[PDF\]](#)
- Datasheet for the ATmega8: go to <http://www.atmel.com/> or http://shop.tuxgraphics.org/electronic/detail_atmega8.html
- [Tuxgraphics online shop](#), You can order this power supply unit as a kit from here. The kit includes not only the parts but also additional documentation and the circuit diagram.