Kullfallet Power Station

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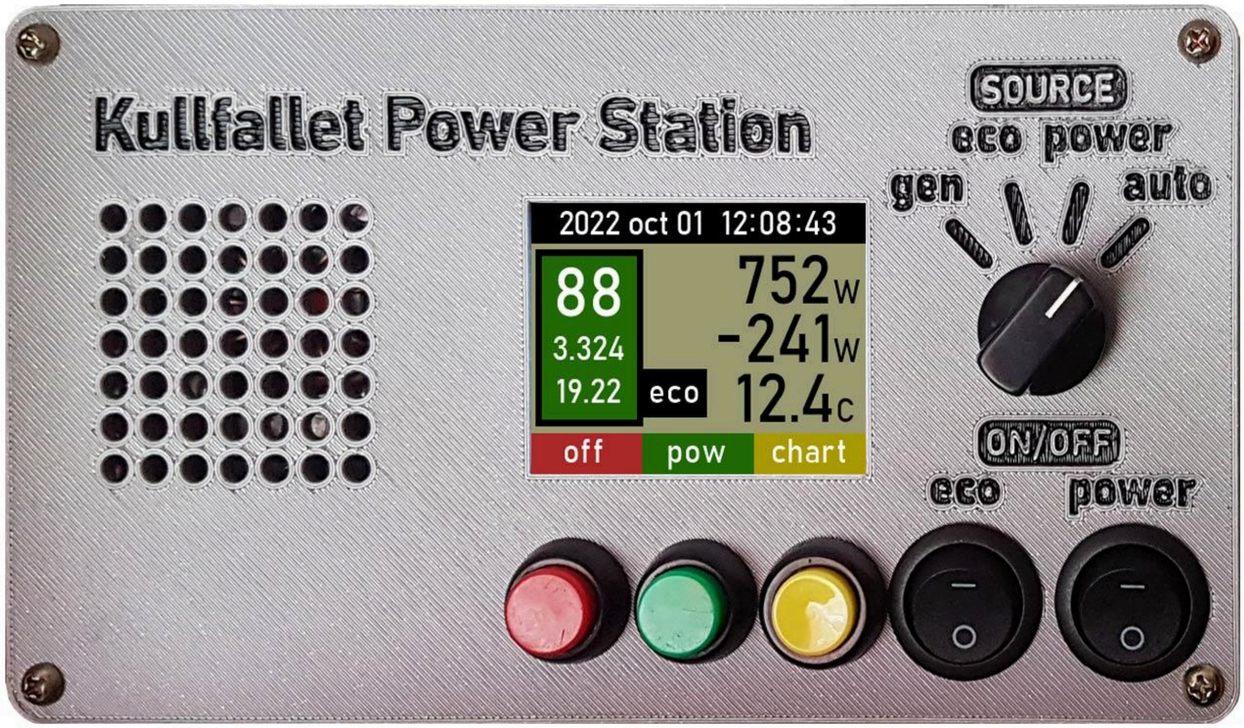
Summary

A monitor and control device for the solar powered energy system at Kullfallet.

- Monitors solar charge power and inverter power use
- Monitors battery voltage, battery charge current and temperature
- Monitors outdoor temperature
- Selects power source for the house (economical small inverter, large power inverter or gas powered generator
- Turns on/off the fridge depending on battery level
- Monitors fridge temperature, and turns on fridge fans during winter
- Senses water pressure and turns on/off the well pump
- Displays real time data on a small LCD screen, and also allows the user to change important parameters for control
- Saves real time data to a SD-card for later analysis on a PC
- Has a manual mode and an automatic mode

Based on an Arduino Uno microcontroller with a 2.4” color screen, two I2C current shunts, two I2C temperature sensors and four remotely controlled relays.

Control box



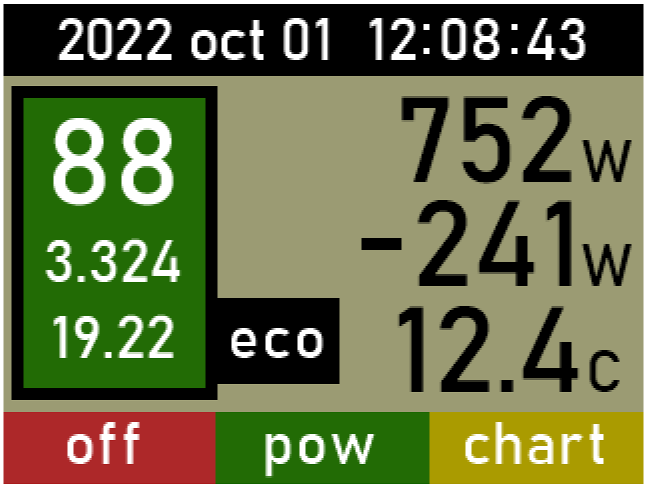
The control box allows you to turn on/off the two inverters with the buttons at the lower right, and to select what power source (petrol generator, eco inverter, power inverter or auto mode) to use for the house with the knob at the top right. It also has a display and three colored buttons to change control parameters.

From March to November put the power source knob in the "power" position and turn on the "power" switch. Nothing more is needed and you can ignore the rest of this document.

From December to February you need to be economical with the power consumption. The control box has support for this through the "auto" mode. Turn the control knob to "auto" and turn off the switches for "eco" and "power". Now the control box selects the power source automatically, as well as turning on the pump and fridge automatically.

Display views

The display cycles between three views: **Main view** (shows real time data, seen below), **Chart view** (shows logged data in a time graph) and **Setup view** (changeable configurations).



The red, green and yellow buttons control the power station. What action each button performs is shown by the corresponding label at the bottom of the display.

Press briefly to use a button once, press and hold to use a button multiple times, for example a large change to a setting.

The Power Station is designed to be constantly running. To turn it off, for example when closing down the house for the winter, pull out the power connector at the bottom.

At startup, the display shows the setting for time and date. It is important that you set the correct date and time, because it is used when the control box logs the data to the SD-card.

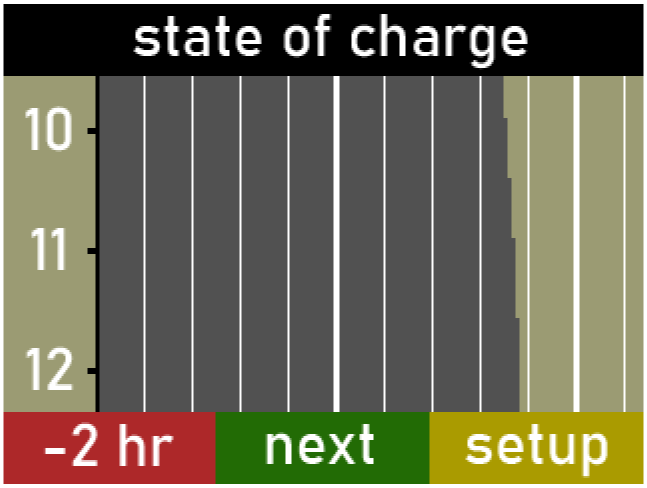
Main view

The main view (see example above) shows:

- **Date and time** at the top.
- **Charge level.** (88%). The background of the rectangle is color coded for charge level so that 50% or more is green, 49-25% is yellow, and 0-24% is red.
- **Average voltage per cell** (3.324 V)
- **Charge current** (19.22 A).
- **Current state.** Shown as a three letter symbol: **eco** (eco inverter), **pow** (power inverter), **gen** (generator), **pmp** (currently running a pump cycle) and **off** (turned off).
- **Solar power.** (752 W) This is the amount that is charging into the battery. It also includes the consumption of the charge controller and the control box. At night it will show a negative number.
- **Power inverter consumption.** (241 W). This also includes things that run directly on battery power, for example the emergency light. This is normally a negative number. When the generator is charging the batteries it will be a positive number.
- **Outdoor temperature.** (12.4 C).
- **Turn off.** Press the red button to turn off all inverters after a pause of 5 seconds (only works in auto mode).
- **Switch inverter.** Press the green button to switch between POW and ECO inverters (only works in auto mode).
- **Show charts.** Press the yellow button to switch to the chart view.

Chart view

Use the green button to switch between the charts. Each chart shows the last three hours. Use the red button to move back further in time. The values come from the logged values on the SD card.



State of charge. Shows the charge level of the battery. The first major line is at 50%, second major line is at 100%.

Sun power. Shows the charge power with major lines at 500, 1000 and 1500 W. Positive values (charging into the battery) with black, negative (discharging from the battery) with white.

Inverter. Shows the inverter power with major lines at 500, 1000 and 1500 W. Negative values (discharging from the battery) with black, positive values (using the generator to charge into the battery) with white.

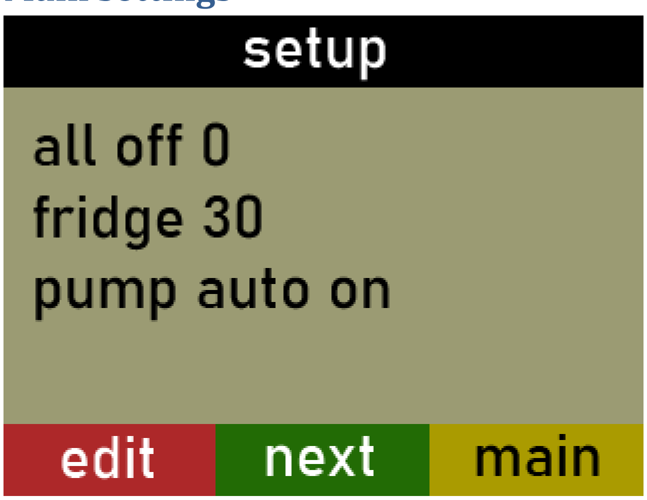
Cell. Average cell voltage with major lines at 3.0 V and 3.5 V.

Outdoor temp. Shows the outdoor temperature with major lines every 5 C. Positive temperatures are shown with black, negative with white.

Fridge temp. Shows the fridge temperature with major lines every 5 C. Positive temperatures are shown with black, negative with white.

Battery temp. Shows the battery cell temperature with major lines every 5 C. Positive temperatures are shown with black, negative with white.

Main settings



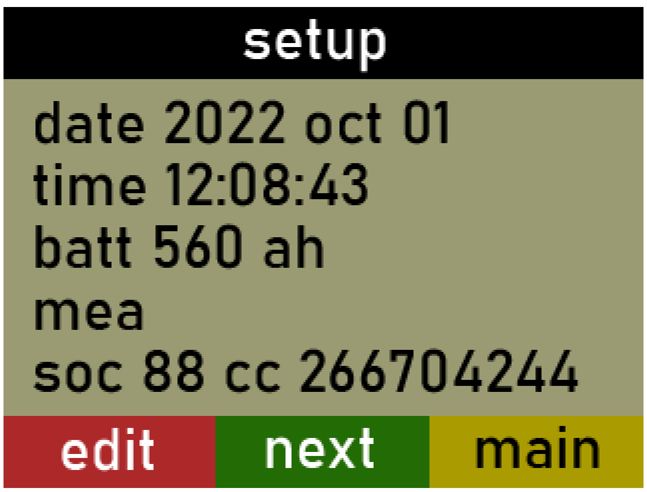
Press the red button to edit the values on this page. Then use the yellow button to cycle between fields, and the red and green buttons to change values.

All off: 0 – Turn off both power inverters when the charge level gets lower than a certain amount. Use this setting if you want to save a bit of charge in case of an emergency.

Fridge: 30 – If this value is 10 or higher then it indicates at what charge level to turn off the fridge. This is so the fridge's power consumption doesn't completely drain the battery. If the setting is below 10, then the fridge is put in low power mode. This means it is unplugged from the wall socket and instead cooled by fans that circulate cold air from the outside. The number is what temperature (Celsius) to aim for inside the fridge. You need to connect the air ducts to use this mode, and it needs to be freezing outside.

Pump auto: on – Run the pump automatically when the water pressure gets low and the current power consumption is less than 1000 W. This setting is off by default, so that the pump doesn't accidentally turn on when you start the system for the first time. After you have checked that nothing is wrong with the well water system, turn the setting to "on".

Date and battery settings



Press the red button to edit the values on this page. Then use the yellow button to cycle between fields, and the red and green buttons to change values.

Date. Current date.

Time. Current time.

Batt. The battery capacity in Ah. The value is used to calculate the charge level.

Mea. Shows measured battery capacity, in Ah, and how many days ago the measure was done. If the battery goes through a full charge cycle (from 95% SOC or higher down to 10% SOC or lower) within 10 days, the actual battery capacity is measured and shown here next to the mea label. If you adjust the battery capacity value to match the measured value, the charge level calculations will be more accurate.

SOC. (State of charge) The current charge level 0-100%. SOC is cleared when you turn off the Power Station, so you need to remember the current SOC and enter it again. Or you can simply wait for the battery to get fully charged and it will get an accurate SOC value automatically.

CC. The Coulomb counter value, which is the value that is used to calculate the SOC. This value can't be changed. It is there so you can verify that the Power Station works as intended.

Automatic mode

The Power Station can be in manual mode or automatic mode. This is controlled by rotating the main knob on the box. In manual mode you have to switch on/off the inverters manually and select one of them as the power input for the house. You also have to turn on/off the fridge and pump with their respective switches on the wall nearby. In automatic mode the Power Station controls all of this.

When you start the Power Station, and it is in automatic mode, all inverters will be turned off. Press the green button to start the ECO inverter. It now uses the following rules:

- If the charge level drops to 0%, all inverters will be turned off. You can change this value in the settings.
- When the charge level drops below 30% the fridge is turned off. You can change this value in the settings.
- If the water pressure is low and the current power consumption is less than 1000 W, the Power Station will enter a pump cycle: the POW inverter is temporarily turned on, the well pump is run to fill the hydrofor, and then the ECO inverter is turned back on.

You can also manually switch to the POW inverter by pressing the green button. You need to do this when you consume more than 375 W of power (max for the ECO inverter), for example when you run the microwave oven, the washing machine or use power tools. The reason for having two inverters is that the ECO inverter consumes a lot less power (saves battery charge) and the POW inverter is needed to temporarily run high power appliances.

Normally all switching between power sources is seamless and will not affect the appliances.

Generator

Start the generator when the charge level gets low.

- Select the POW inverter which has a built-in battery charger (press the green button if ECO is selected).
- Go to the generator. Make sure the charge cable is connected to it. Start the generator. It has a grounding fault sensor that sometimes triggers, and this shows as a blinking red light near the power socket. In that case, turn off the generator and start it again.
- The Power Station should now show around 1100 W of charge power on the display.
- A full tank of gas gives the generator around two hours of runtime.

Fridge

Because of its high energy consumption, the fridge can be configured into low power mode in the winter. Then its power is turned off, and two air ducts are mounted to lead cold air from the outside into the fridge, with two fans to blow this air. The fridge setting controls this (described above).

In normal mode, the fridge is only turned on if the charge level is above 30%. This enables the system to be turned on 24/7 without worrying that the fridge will completely drain the battery.

In low power mode, the fans are turned on if all of the following conditions are true: A) The charge level is 10% or higher, B) the outside temp is lower than the fridge temp, and C) the fridge temp is higher than the target temp in the setting. The fans run on battery current so they are also active when the inverters are turned off. They consume around 1 W.

Pump control

The Power Station keeps track of the total pump run time and checks if it is higher than 45 seconds to see if there is a problem in the system, such as a leak or frozen pipe. It then goes into error mode and turns off the pump completely.

The Power Station also prevents a pump cycle if the inverter is using more than 1000 W of power. This is to not overload the inverter.

Logged data

Historical data is logged on an SD card inside the Power Station. To access it, remove the four screws at the corners of the device, gently pull off the front, and you can see the card on the right edge of the display. Push it in and it bounces back out.

Transfer the files on the SD card to your PC and run the ChargeMonitorDiagram.exe program to view the data.

Electronics design

An DC-DC converter takes input from the 24V battery bank (22-31 V), and steps it down to 5V to power the Arduino. The screen is mounted directly to the Arduino.

The Arduino interfaces via I2C to peripheral devices: two digital I/O chips (PCF8574), two temp sensors (MCP9808) and two current/voltage sensors (INA226). The current/voltage sensors are mounted to shunts to measure current to the inverter and from the solar panels.

The Arduino is mounted in a 3D-printed box with switches to control the system, and a PCB with components.

Arduino Uno

Atmel Atmega328 microprocessor: 8-bit RISC, 32kB flash, 1kB EEPROM, 2 KB SRAM, 23 GPIO, 32 registers, USART/SPI, 6 x 10-bit A/D, 1.8-5.5 V. 16 MHz. Little Endian (least significant byte stored first in memory).

LCD screen

2.4" diagonal LCD TFT display (60.96 mm diagonal, 48.8 x 36.6 mm). 240x320 resolution, 18-bit (262,000) color. SPFD5408 controller with built in video RAM buffer. 8 bit digital interface, plus 4 control lines. MicroSD card reader. Piggy-backs on the Arduino and uses up all available pins, except for the I2C interface.

INA226

Uses a 16-bit ADC. Designed to measure two voltages very accurately: the battery voltage and the small voltage over a shunt resistor (200 A/75 mV shunt). Also calculates the resulting power. 6 mA shunt resolution @200A shunt. 1.25 mV voltage resolution @ max 36 V input. I2C addresses: 0x40 (solar charge), 0x41 (inverter). **NOTE: the PCBs have switched the DTA and CLK pins.**

MCP9808

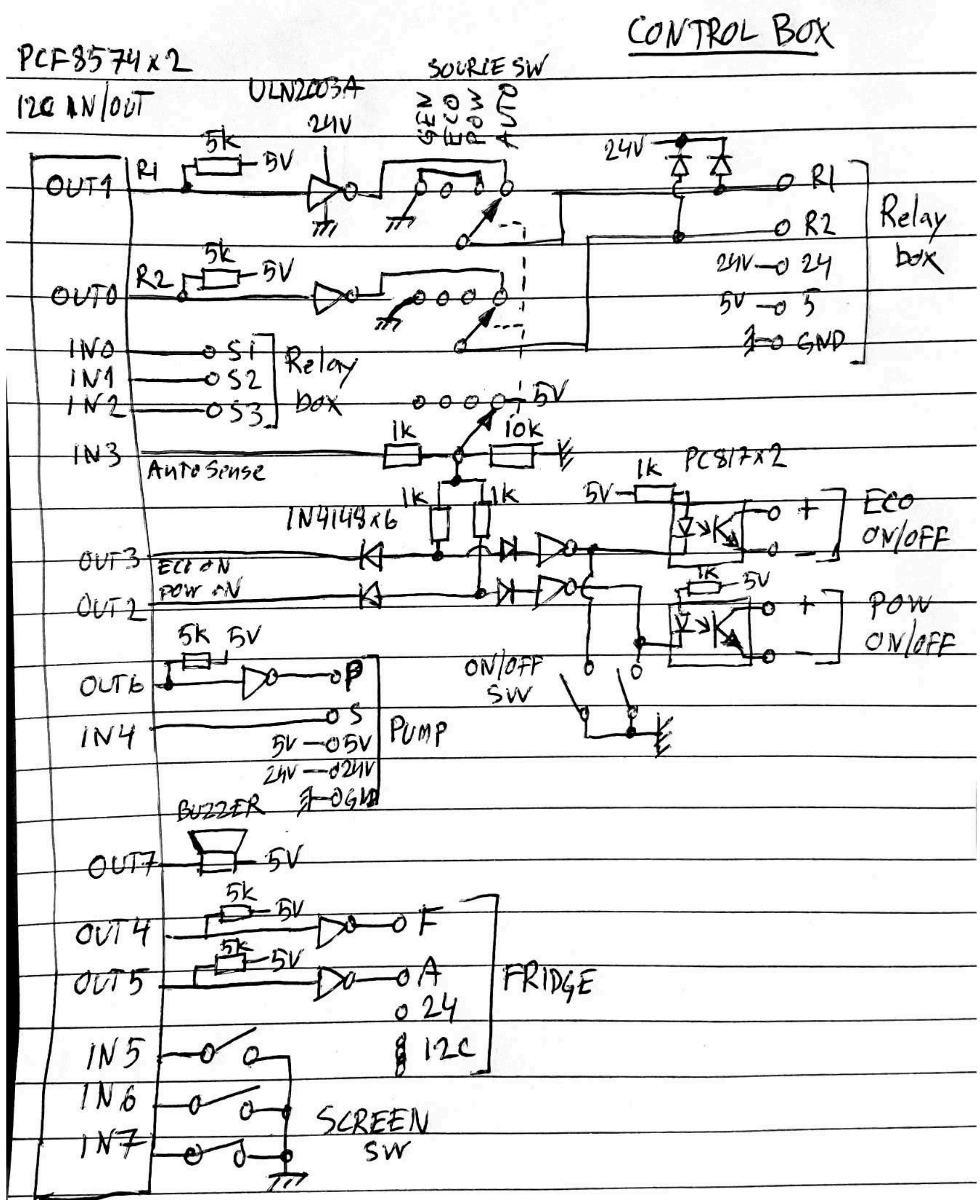
A 0.25 C accuracy temperature sensor, for the -40 C to +125 C range. I2C addresses: 0x18 (battery), 0x19 (outdoor), 0x1A (fridge).

PCF8574

An 8-bit digital I/O device, where each input can be either input or open collector output, with 10 mA sink capability. I2C addresses: 0x20 (8 outputs), 0x21 (8 inputs).

Control box

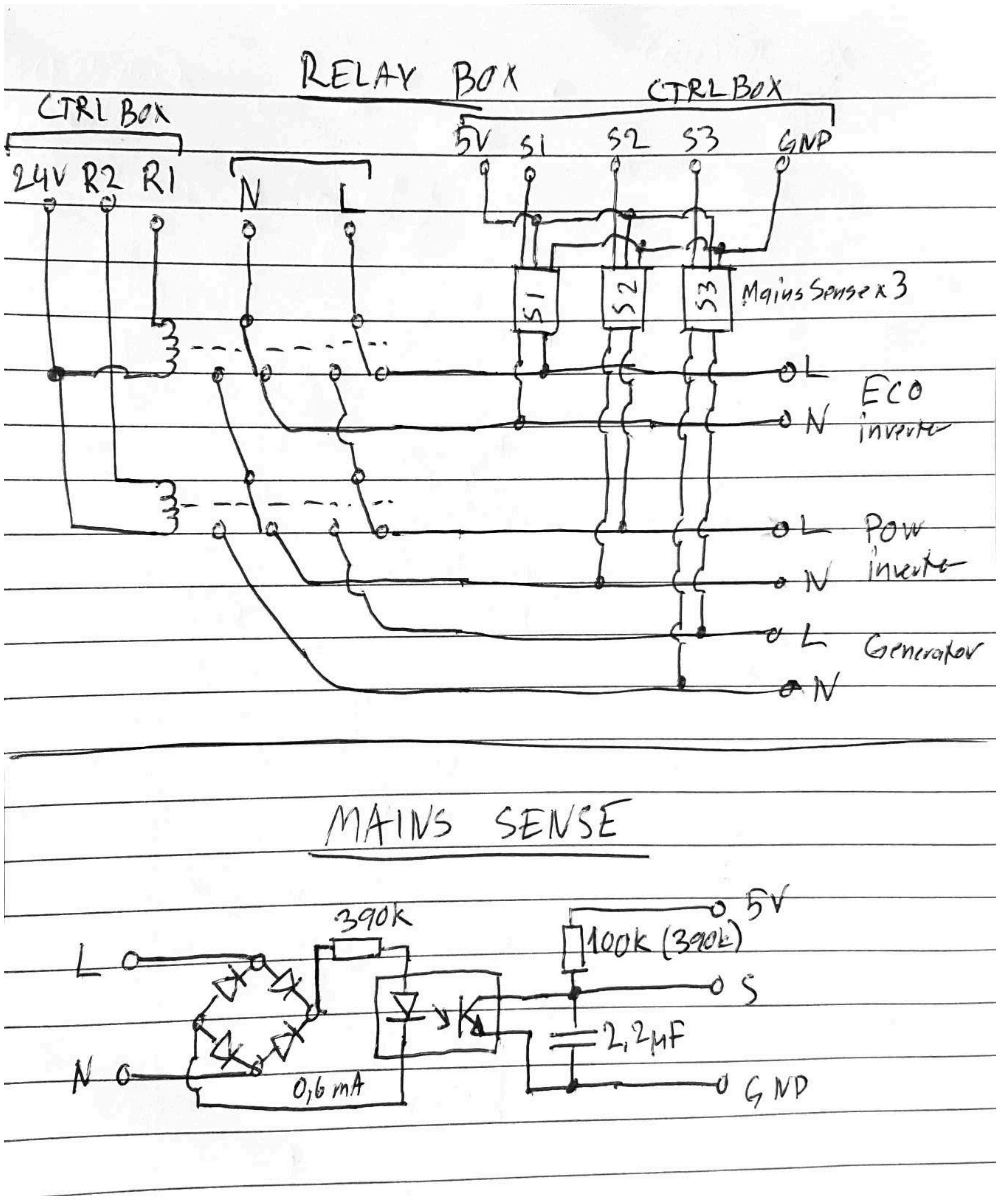
To enable control box functionality the Arduino interfaces to the devices using two PCF8574 I/O devices, connected to electronic components, as shown in the diagram below:



Things to note about the schematic:

- The PCF8574 can't drive relays directly, so a ULN2003 Darlington driver is used.
- The PCF8574 is open collector, so a pull-up resistor is required to drive the ULN2003 inputs.
- The relays require freewheeling diodes (1N4148) to protect the circuit from voltage spikes.
- The on/off for the inverters are done with opto-couplers to isolate the circuits. Only in the auto position will the PCF8574 influence their state.
- The fridge control cable also includes the I2C bus, so it can measure the fridge temperature. The same cable branches off to the outdoor temp sensor.
- This box connects to the power source relay box and the pump relay box, shown below.

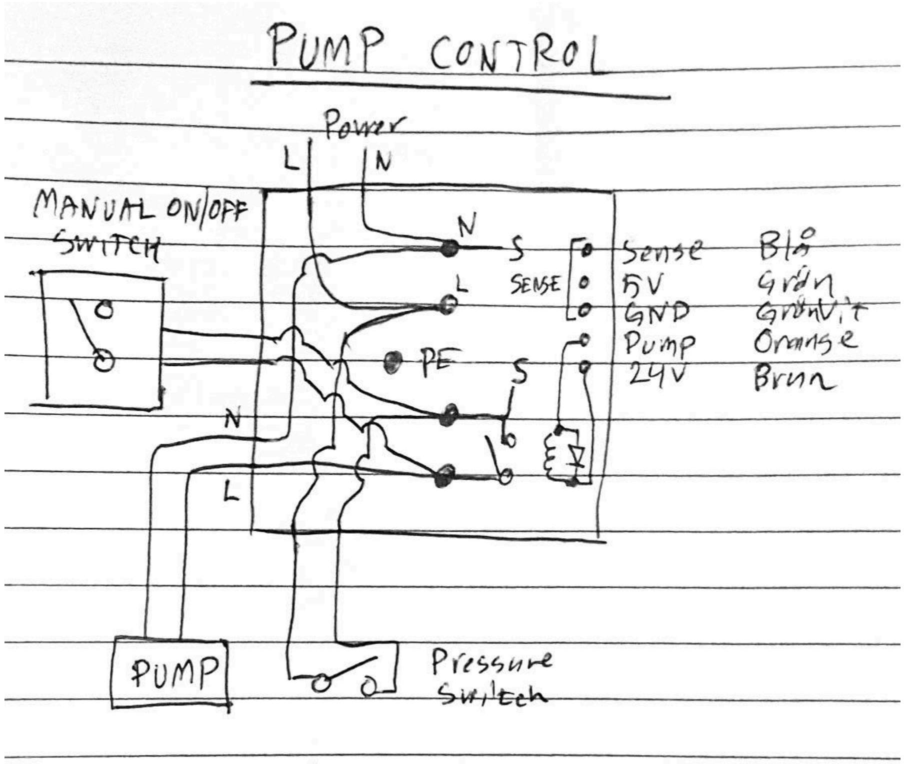
Power source relay box



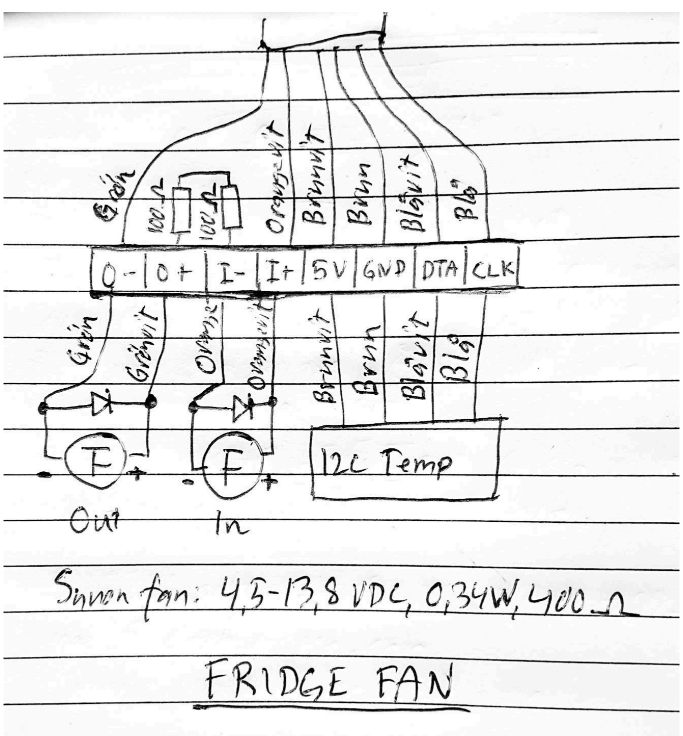
This box has two power relays that select what device will power the house; eco inverter, power inverter or the generator in the garage. The relays are Schrack RM222024, 240 VAC 16 A, 472 ohm/1.2W, 22-34 VDC.

It also has one mains 230 VAC voltage sense circuit per power source, so the control box can sense when a device delivers power, and switch accordingly. The circuits were tested with a 10k ohm resistor from the 5 V supply, but this turned out to be too low. Right now they are using 390 k resistors, but 100 k would have also been fine. 390 k/2.2 uF gives a time constant of 0.9 seconds, which is good enough for this circuit. It is active low (logical 0 when it senses a voltage, otherwise logical 1). **NOTE: Power sense is currently only used for the pressure switch on the hydrofor.**

Pump relay box



This box senses the state of the hydrofor pressure switch; if it delivers 230VAC then it means it is empty and the pump should run. It uses the same sense circuit as the Power source relay box. It also has a relay that can turn on the pump, and a manual switch to override the relay, in case the control box is in manual mode. The power comes in from the top, then through the pressure switch, then through the relay/manual switch, and finally to the pump. The relay is Shrack RZ03-1A3-D024, 250VAC 12A, 1440 ohm/0.4 W, 22-34 VDC.



Fridge fan

One fan at the bottom of the fridge sucks air from the outside into the fridge, and one fan at the top pushes air from the fridge to the outside.

NOTE: this is an old schematic. The fans are currently connected in parallel with a DC-DC converter taking down the 24 V to 12 V to drive them (small box mounted on the wall).

An I2C temperature sensor is also inside the fridge to monitor it. The temp is logged on the SD-card.

INA226 programming

Shunt data: 200 A/75 mV/0.000375 ohm. 200 A @ 24 V = 4800 W max.

The **CONFIG register (0x00)** controls capture timing: 1.1 ms capture time x 256 averages x 2 values = 563 ms. Continuous mode. Resulting value: 0x4B27. The register is read every 250 ms, so no samples will be missed.

The **CALIB register (0x05)** scales the measured value over the shunt, so it gets the best range for either precision or that the calculated power doesn't overflow. This register is not used, because the power is calculated from the measured voltage and current.

INA226 registers to read (all are based on averages, as specified in the config reg):

- **0x01 - SHUNT_REG** - the voltage of the shunt, LSB = 2.5 uV = 6.66 mA, this means 0.075 V = 30000, -0.075 = -30000
- **0x02 - BUS_REG** - the voltage of the bus (max 36 V), LSB = 1.25 mV, this means 36 V = 28800.
- **0x04 - CURRENT_REG** - Not used.
- **0x03 - POWER_REG** – Not used.

Coulomb counter

A LiFePO4 battery has extremely low losses during charge and discharge, and very low self discharge. For example a LF280K cell charged and discharged with 0.14C current has a round trip efficiency of 99.84%. This makes it possible to accurately predict SOC using a coulomb counter. This is actually the only way to keep track of SOC, because the voltage over a LiFePO4 cell is so flat in the middle part of the charge curve that cell voltage can't be used to estimate SOC.

The charge calculation is done once every minute, as part of the SD card logging, since there are already accumulated values for the currents over the shunts. To get the charge in Coulombs, the sum of the currents over the two shunts is multiplied by the time (60 seconds). This is added to the coulomb counter. The coulomb counter has a resolution of 0.00667 As, which is equivalent to 0.17 Ws/0.17 J.

The coulomb counter value is then divided by the overall charge capacity (Ah) entered in the settings to get the SOC value (1-100%).

Small measurement errors will over time make the coulomb counter lose precision. It needs a way to reset to a known value, and this is done at very high and very low voltages, where the voltage curve is steep. When the cell voltage reaches 3.43 V the coulomb counter is set to a fixed value that depends on the charge current. This fixed value corresponds to a SOC between 85% (0.5C) and 100% (0.033C). In other words, it is assumed that a LiFePO4 cell reaches 100% SOC at 3.43 V if the charge rate is 0.033C.

Very low charge rates can result in a full cell at a lower voltage. When the charge rate is 0.025C or lower and 3.40 V is reached, it triggers a resets of the coulomb counter to 100%.

The same happens when the cell voltage drops to 3.05 V: The coulomb counter is set to between 1.7% SOC (0.1C) and 4.5% SOC (0.5C). At a cell voltage of 2.80 V the coulomb counter has a hard lower limit of 0. There is also a forced lower adjustment so that if the cell voltage is higher than 3.05V, the SOC value can never get below 1%. This adjustment exists to prevent faulty low values when the rated capacity (Ah) is wrong.

The above three voltage threshold resets happen only once per charge cycle. Immediately after each reset regular coulomb counting is resumed.

The coulomb counter is allowed to get above the rated battery capacity, and this will show as a SOC higher than 100%. This way you can detect if the battery is getting overcharged. Values over 100% will immediately be lowered to 100% as soon as cell voltage drops to 3.37 V, which is the resting voltage of a fully charged cell.

If the manually entered battery capacity (Ah) does not match actual capacity, the SOC value will be off. This will be evident when the voltage thresholds are passed. If all thresholds have a smooth SOC value transition, the entered capacity is correct. To measure actual capacity, let the battery pass the upper threshold (fully charged) and then within 10 days pass the lower threshold (fully discharged). The measured capacity is shown at the settings page. Optionally adjust the rated capacity to match the measured capacity.

Log file format

The CPU stores real time values to the SD card. Each year has its own file, for example SAMP2022.bin.

Each entry is a struct of the raw 16-bit values read from the sensors, but averaged over a period of one minute (4 Hz read speed, means 240 values per minute to create the average from). Eight values make each struct in total 16 bytes. The year-files must be created ahead of time and filled with null data. There is a routine for this in the Arduino. When logging, the CPU does a simple file seek operation to find the correct position and overwrites the data there. The files are 842640 bytes to have enough space to handle leap years (366 days).

Each entry is as follows:

- Dummy – Not used, because a bug in the file system driver corrupts this value
- Unused – Currently unused.
- Inverter current – The raw value of the shunt register (0x01) of the INA226 inverter shunt
- Solar current – The raw value of the shunt register (0x01) of the INA226 solar shunt
- Outdoor temp – The raw value of the MCP9808 temperature register
- Fridge temp – The raw value of the MCP9808 temperature register
- Battery voltage – The raw value of the bus register (0x02) of the INA226 solar shunt
- Battery temp - The raw value of the MCP9808 temperature register

Links

https://www.instructables.com/id/How-to-use-24-inch-TFT-LCD-SPFD5408-with-Arduino-U/

https://www.instructables.com/id/ARDUINO-SPFD5408-TFT-LCD-2-4-TEMP-and-HUMIDiTY-Mon/

https://www.youtube.com/watch?v=yKUVNqLtj-Q

https://www.arduinolibraries.info/libraries/spfd5408-tft-library

https://forum.arduino.cc/index.php?topic=215334.15

Arduino programming and libraries

https://www.arduino.cc/en/Reference/Libraries

http://www.nongnu.org/avr-libc/user-manual/modules.html

SD card

https://arduino.stackexchange.com/questions/28540/how-to-increase-sd-card-write-speed-in-arduino

https://hackingmajenkoblog.wordpress.com/2016/03/25/fast-efficient-data-storage-on-an-arduino/

Arduino development

https://www.visualmicro.com/

https://devblogs.microsoft.com/iotdev/debug-your-arduino-code-with-visual-studio-code/

https://marketplace.visualstudio.com/items?itemName=vsciot-vscode.vscode-arduino

Battery charging

https://batteryuniversity.com/learn/article/how_to_measure_state_of_charge

https://www.mpoweruk.com/soc.htm

Battery State of Charge

https://footprinthero.com/lead-acid-battery-voltage-charts