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Smart Electrical Installation System with Power Management and Safety Features

I23 - Instytut Elektroniki

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Spis treści

Abstract

The project involves the development and implementation of a smart electrical installation system designed for home and office use. The system will enable real-time monitoring of energy consumption for individual devices, identification of high-energy-consuming appliances, and prediction of future power usage trends. Key features include scheduled switching of devices, detection of abnormal energy consumption, and monitoring of safety mechanisms. Additionally, users will have remote access to system parameters, alerts, and control functions. The demonstrator will include a prototype smart socket and a custom-designed control unit with supporting software to implement selected features of the system.

Keywords:

Power, Measurement, Accuracy, IoT, Socket

Streszczenie

Praca inżynierska obejmuje opracowanie i wdrożenie inteligentnej instalacji elektrycznej przeznaczonej do użytku domowego i biurowego. System umożliwi monitorowanie zużycia energii w czasie rzeczywistym dla poszczególnych urządzeń, identyfikację odbiorników o wysokim poborze mocy oraz przewidywanie przyszłego zużycia energii. Kluczowe funkcje obejmują harmonogramowane włączanie i wyłączanie urządzeń, wykrywanie nietypowego zużycia energii oraz monitorowanie mechanizmów zabezpieczających. Dodatkowo użytkownicy będą mieli możliwość zdalnego dostępu do parametrów systemu, alertów oraz funkcji sterowania. Demonstrator będzie zawierał prototyp inteligentnego gniazdka oraz zaprojektowany układ sterujący wraz z oprogramowaniem realizującym wybrane funkcje systemu.

Słowa Kluczowe:

Moc, Pomiary, Rozdzielczość, Internet Rzeczy, Gniazdko

Introduction

In today’s world, environmental concerns are becoming increasingly urgent. The rising consumption of electricity, growing greenhouse gas emissions, and depletion of natural resources necessitate the implementation of technologies that reduce environmental impact. Smart sockets are one such solution, enabling efficient energy use, minimizing waste, and reducing carbon footprints.

Many household appliances continue consuming electricity even when in standby mode. Smart sockets detect unused appliances, eliminating unnecessary power consumption and reducing overall electricity demand.

Additionally, these devices help balance electrical loads. By scheduling appliance usage outside peak hours, smart sockets prevent network overloads and reduce the risk of power failures.

Modern smart sockets come with real-time energy monitoring, advanced control of the load, allowing users to track power consumption through mobile applications. This feature helps identify energy-intensive devices and encourages consumers to switch to more efficient alternatives.

Frequent voltage fluctuations, overheating, and uncontrolled switching on and off can lead to premature appliance failure. Smart sockets help stabilize electricity supply and prevent overloads, ensuring a longer lifespan for household devices.

By extending the durability of electronics, smart sockets also contribute to reducing electronic waste, which remains a major environmental challenge due to the difficulties of recycling and disposal.

Addressing modern environmental challenges requires responsible energy consumption. Smart sockets play a vital role in reducing resource waste, lowering carbon emissions, easing the strain on power grids, and extending the lifespan of household appliances.

Thesis

Development and implementation of a smart electrical installation demonstrator for home/office applications with selected functions:

- Real-time monitoring of energy consumption for each connected device (power outlets, lighting, fixed appliances).
- Identification of the most energy-consuming devices, detection of unusually high/low energy consumption, and prediction of future energy usage.
- Scheduled switching on/off of devices.
- Detection of installation faults and monitoring of protective devices.
- Remote user access (reading parameters, fault statuses, configuring functions, and controlling the installation).
- Data collection related to the operation of the installation.

The demonstrator will consist of a section of the installation along with control electronics designed and implemented by the student, as well as its potential software. It will implement selected functions from the list above.

Cel i zakres pracy

Opracowanie i wykonanie demonstratora inteligentnej instalacji elektrycznej do zastosowań domowych/biurowych z uwzględnieniem wybranych funkcji:

- monitoring w czasie rzeczywistym zużycia energii przez każdy z odbiorników (gniazda wtyczkowe, oświetlenie, odbiorniki stałe) podłączonych do instalacji,
- identyfikacja odbiorników zużywających najwięcej energii, nietypowo dużego/małego zużycia, przewidywanie przyszłego zużycia energii,
- załączanie/wyłączanie odbiorników wg. harmonogramu,
- wykrywanie stanów awaryjnych instalacji, monitoring działania urządzeń zabezpieczających,
- zdalny dostęp dla użytkownika (odczyt parametrów, stanów awaryjnych, konfiguracja funkcji, sterowanie instalacją),
- gromadzenie danych związanych z pracą instalacji.

Demonstrator ma stanowić fragment instalacji wraz z zaprojektowaną i wykonaną przez dyplomanta elektroniką sterującą i jej ew. oprogramowaniem. Ma realizować wybrane z powyższych funkcji.

Theoretical background

Standards of power measuring devices

This part will cover the theory behind building a power measuring device: standards, requirements and general overview of the methods of electrical energy measurement.

Behind any of the electrical devices there are plenty production/capabilities standards. The design of SEIS was bound critically to the standards, particularly with the once from International Electrotechnical Commission (IEC). The standards that describe the power measuring station, hence, being taken in mind, are:

IEC standard	Brief description of what this standard covers
IEC 61000-4-30	Defines methods for measuring power quality parameters in AC power supply systems.
IEC 61850-9-2	Specifies communication service mapping for the transmission of sampled values in power utility automation.
IEC 61010	Safety Requirements for Electrical Equipment, including isolation guidelines.
IEC 60947	Relates to low-voltage switchgear and control gear.
IEC 61000	Focuses on electromagnetic compatibility (EMC).
IEC 62368-1	Combines safety standards for audio/video equipment into a single document.
IEC 62133	Specifies test methods for lithium-ion batteries used in portable devices
IEC 61558	Covers safety requirements for power transformers, power supplies, and similar products.

Table 1.1.1. Energy measurement and monitor related IEC standards list.

The IEC 61000-4-30 is the most important for development, because it actually defines the methods, accuracies, algorithms for measuring power quality parameters in AC power supply systems. The standard specifies different **"classes"** of measurement accuracy and performance for power quality instruments. The table below lists the IEC 61000-4-30 classes:

Class	Power measurement accuracy [%]	Measurement Purpose	Applications	Defined In IEC 61000-4-30
Class A	0.1	Compliance, legal, disputes	Utility, grid compliance, legal reporting	Fully defined
Class S	0.5	Surveys, analysis, planning	Network planning, benchmarking	Defined partially
Class B*	Not defined	Basic monitoring	Maintenance, general monitoring	Not defined under this standard

Table 1.1.2. IEC 61000-4-30 classes list.

* Although Class B is not officially defined in this standard, it is sometimes referenced informally

As for this task, the aim will be to construct the device, the Class A will be the main reference for development.

Measurement considerations taken from IEC 61000-4-30 Class A measuring device standard:

Parameter	Ranges	Uncertainty Tolerances
Frequency	For $50Hz$ system: $50Hz \pm 7.5Hz$ For $60Hz$ system: $60Hz \pm 9Hz$	$\pm 10mHz$
Voltage True RMS	$10 \sim 150\%\ of\ V_{in}$	$\pm 0.1\%$
Current	Acc. Transducer Range	$\pm 0.1\%$
Unbalance u2 y u0	$0 \sim 5\ \%$	$\pm 0.15\ \%$
Voltage harmonics	$0 \sim 200\%$	$\pm 5\%$

Table 1.1.3. IEC 61000-4-30 Class A instrument measurement requirements.

This means, that system must measure the voltage with the accuracy of

$\pm 0.1\%$ withing the range of $10 \sim 150\%\ of\ V_{in}$. As soon as there are different voltages across the word, the United States standards with European one is Being taken:

$$US\text{: } 120VAC,\ \ 60Hz \qquad EU\text{: } 240VAC,\ \ 50Hz \quad [1].$$

So, the widest range for the obtained voltages will be the 10% of American voltage, and 150% of European, resulting in the following numbers:

$$0.1 * 120 = 12VAC, \qquad 1.5 * 240 = 360VAC$$

The requirement for the current transducer actually says, that the current range can be chosen by developer. Thus, the 16A current was taken in mind, as being the nominal current for both regions [1].

The Unbalance u2 y u0 is not being treated as soon as the device will be measuring single phase power loop.

Besides these requirements, there are plenty other:

- Every Class A instrument should give the same results when connected to the same stimulus.
- Data aggregation intervals. measurement shall be 'contiguous non-overlapping' over a 10 – 12 periods (cycles) time interval for a 50 - 60 Hz power systems respectively. This means taking measurements for:

  $$\frac{1}{50Hz} * 10c = \frac{1}{60Hz} * 12c = 200ms$$

  and only after that processing them. This ensures that the measurements are taken in a consistent and systematic manner, providing accurate and reliable data for each specified time interval without any gaps or overlaps. This is crucial for precise power quality analysis and monitoring.
- RMS calculation. This must be calculated, having full cycle (1c), while the maximal time for detection of dips, swells, interruption is half of a cycle (0.5c).

  With this taken in mind, the system can achieve both high accuracy and quick responsiveness, ensuring reliable detection and analysis of power quality issues)

- The power parameters need to be calculated in such way:

    1. 10/12 Cycle (~ each 200 ms): Detailed waveforms, instant RMS, instantaneous power, harmonics,
    2. 10c-20c Cycle (~ each 200-400 ms): Calculation of Fast Furrier Transform,
    3. 150/180 Cycle (~ each 3 sec): long term RMS values, frequency, power quality events,
    4. 10-Minute Interval: Average values, power factor, energy consumption, voltage unbalance,
    5. 2-Hour Interval: Long-term flicker severity (Plt), voltage variations.

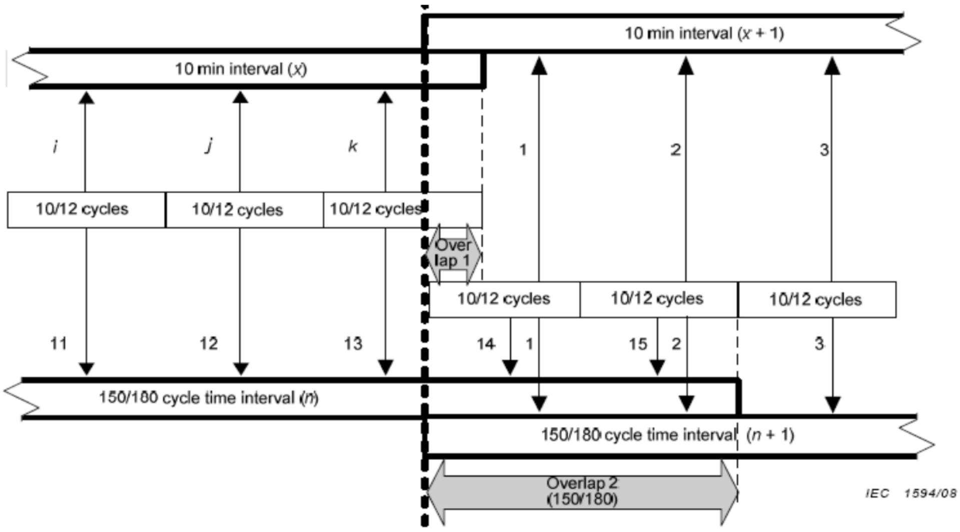

Fig. 1.1.4. Time aggregation scheme – (figure from IEC 61000-4-30 Ed.2 2008, Class A aggregation method)

An additional remark would be about using multiple instruments. The accuracy of measurement timestamps needs to be in the range of 1c:

$$\pm 20ms(for\ 50Hz\ system), \qquad and \quad \pm\ 16.7ms(for\ 60Hz\ system)$$

To achieve this, standard suggests: GPS clock, via a GPS receiver, or NTP (Network Time Protocol), via Ethernet.

Another standard to be considered is IEC 61850-9-2. This standard defines the process bus communication for sampled data, allowing digitalized analog measurements of power (in our case) to be transmitted and the sampling requirements. From this standard, the following requirement is taken in mind:

- ADC must be capable of sampling 256 samples per cycle. 80 samples for protection purposes and 256 samples for measurement purposes.

$$\frac{50Hz}{256} = 12.8\ kHz\ (for\ 50Hz\ system), and \pm \frac{60Hz}{256} = 15.36\ kHz(for\ 60Hz\ system)$$

And lastly the IEC 61010, which covers the isolation requirements for electrical equipment. This states that there must be an isolation layer between hi-voltage and low-voltage loops.

Power measurement

Signal conditioning with operational amplifier

Proper signal conditioning means the lowest possible conditioning error. In the operational amplifier stage, there are many factors to be considered, and proper signal propagation must be performed, to ensure that signal will not be corrupted at the ADC interfacing stage.

Consider the input signal, coming from current or voltage sensor with minimal and maximal possible values known:

$$V_{sig\_min} \ and \ V_{sig\_max}$$

Input voltage offset: this error applies at the very input of the amplifier. The input signal is being “shifted” by some offset voltage V_{OS}, defined in the datasheet, as shown in figure:

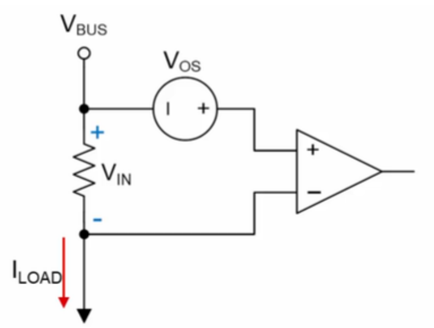

Fig. 1.2.1. Offset voltage equivalent scheme

From the datasheet, the maximal, typical and minimal offset voltages can be found. The interesting part will be the maximal possible voltage offset, to ensure worst case scenario for correct error calculation.

Offset voltage is also being affected by the temperature, and this change is being characterizes as an Offset Voltage Temperature Drift.

$$V_{os\_max}(T) = V_{os\_max} + \frac{\Delta V_{os}}{\Delta T} * \Delta T_A,$$

Where:

V_{OS_max} −maximal possible offset voltage

$\frac{\Delta V_{os}}{\Delta T}$ – offset voltage temperature drift

$\Delta T_A = (T - T_A)$ – difference to the room temperature

Then, we can calculate the offset error by defining it as a ratio of its influence on an output signal:

$$e_{os(max)} = \frac{V_{os\_\max}(T) \ * \ G}{V_{out\_min}} = \frac{V_{os\_max}(T) \ * \ G_i}{V_{sig\_min} * G_i} \rightarrow \quad \boldsymbol{e_{os(max)}(T) = \frac{V_{os\_max}\,(T)}{V_{sig\_min}}}$$

$V_{sig\ min}$- operational amplifier minimal differential input.

Important note is to see, that the smaller the signal magnitude is, the bigger is the error proportionally. The minimal signal magnitude is being taken, to ensure the biggest ratio and the worst possible case scenario.

Common mode voltage influence: the output signal furtherly is being affected by the common mode voltage. The common mode voltage amplification influences on the resulting output, and operational amplifier must reject is. The ability of an operational amplifier to reject the common mode signal is called common mode rejection ratio or CMRR. The CMRR is defines as the ratio of differential gain of an amplifier to common mode gain, and is represented in $\frac{V}{V}$:

$$CMRR_V = \frac{A_d}{A_c}$$

From the datasheet the minimal possible CMRR must be considered to ensure worst case possible influence of the common mode voltage. The CMRR is usually being represented as the value in decibels, and to convert it to $\frac{V}{V}$ the following equation is used:

$$CMRR_V = 10^{\frac{CMRR_{dB}}{20}}$$

The CMRR influence on the output voltage can be calculated with the following equation:

$$V_{CMRR} = \frac{V_{cm}}{CMRR_V} * G$$

Where

V_{cm} −common mode voltage

G −operational amplifier gain

And the error caused by the CMRR is calculated in this form:

$$e_{CMRR} = \frac{V_{CMRR}}{V_{sig\_min}} * 100\%$$

The minimal signal magnitude is being taken, to ensure the biggest ratio and the worst possible case scenario.

Power Supply Rejection Ratio (PSRR) is a measure of a circuit's ability (typically an amplifier or voltage reference) to reject variations in its power supply voltage and prevent them from affecting the output and is measured in $\frac{V}{V}$.

This value is being taken from the datasheet, and the lower quantity possible is preferred for eliminating the worst-case scenario. The PSRR influence on the output voltage can be calculated:

$$V_{PSRR} = \frac{\Delta V_{sup}}{PSRR_V}$$

Where:

ΔV_{sup} −fluctuations in the power supply line.

If the value is written in the decibels, the following conversion equation is used:

$$PSRR_V = 10^{-\frac{PSRR_{dB}}{20}}$$

The error, caused but the power source voltage fluctuations is calculated like this:

$$e_{PSRR} = \frac{V_{PSRR}}{V_{sig\_min}} * 100\%$$

The minimal signal magnitude is being taken, to ensure the biggest ratio and the worst possible case scenario.

The total gain error influence can be estimated by the use of gain error from the datasheet. Again, the biggest value must be considered, together with temperature drift.

$$e_G(T) = e_G + \frac{\Delta E_G}{\Delta °C} * \Delta T_A$$

e_G – gain error.

$\frac{\Delta E_G}{\Delta °C}$ – gain error temperature drift

$\Delta T_A = (T - T_A)$ – difference to the room temperature

Then, the operational amplifier linearity must be taken into account. This effect is being described as a linearity of operational amplifier voltage transfer function. The elimination method of this quantity is shown in figure below:

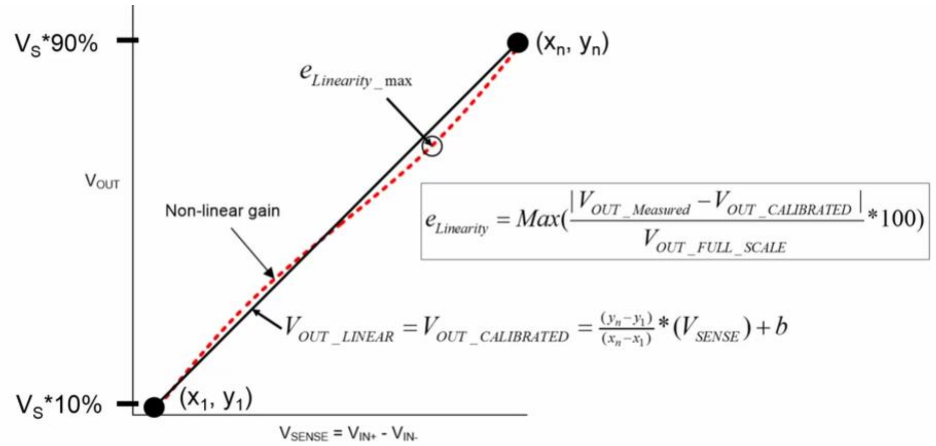

Fig. 1.2.2. Non-linearity elimination method.

The linearity error again can be found in datasheet, and the maximal value should be taken into account. This term is just being added to the gain error.

$$e_g = e_G(T) + e_{lin}$$

e_{lin}- linearity error.

The obtained e_g value characterises the possible misplacement of the gain transfer curve slope:

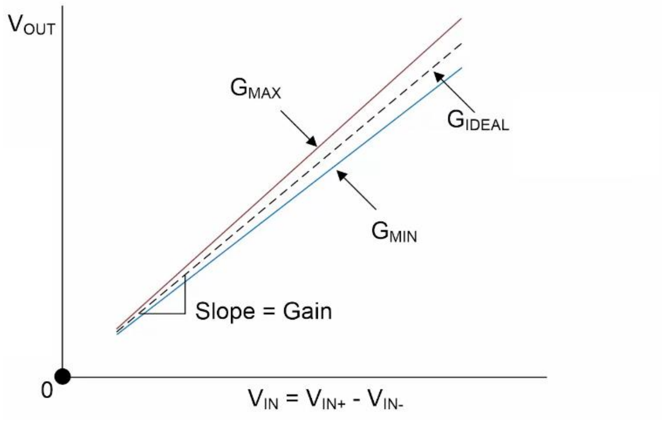

Fig. 1.2.3. Gain error example shift graph.

The actual or real gain is lately being calculated, taking in mind this misplacement quantity:

$$G_{min} = G_i * (1 - e_g)$$

$$G_{max} = G_i * (1 + e_g)$$

Where:

G_i – operational amplifier ideal gain.

Hence, this gains are more preferred to be used, when estimating the possible output ranges, to avoid overflows, and the most worst case output voltage, having all factors described is calculated as follows:

$$V_{out\_worst\_case\_max} = (V_{sig\_max}(T) + V_{os}(T) + V_{PSRR}) * G_{max} + V_{PSRR} + V_{ref}$$

$$V_{out\_worst\_case\_min} = (V_{sig\_min}(T) - V_{os}(T) + V_{CMRR}) * G_{min} + V_{PSRR} + V_{ref}$$

Regions of normal operation: during the design, very important note is to ensure the proper operational amplifier operating regions. The first of all is so called operational amplifier swing, that determines the margin, to which the output of the operational amplifier is bounded. However, there is also a good practice to add an additional safe margin (usually on the level of $10\ to\ 100\ mV$), to even more ensure linearity of the transfer function:

$$V_{sp} = V_s - S_p \qquad V_{in\_lin\_min} = \frac{\mathrm{V}_{\mathrm{out\_lin\_min}} - V_{CM}}{G_{max}}$$

$$V_{sn} = S_n \qquad V_{in\_lin\_max} = \frac{\mathrm{V}_{out\_lin\_max} - V_{CM}}{G_{min}}$$

V_s – operational amplifier positive supply voltage

S_p – operational amplifier positive swing

S_n – operational amplifier negative swing

V_m – linear region safe margin

Additionally, some operational amplifier manufacturers provide the region, for which the gain error was tested. This means, that the gain will remain linear within this specifier voltage range in the datasheet. This condition is being checked like this:

$$V_{out\_g\_test\_min} = G_{min} * V_{in\_g\_test\_min} + V_{CM}$$

$$V_{out\_g\_test\_max} = G_{max} * V_{out\_g\_test\_max} + V_{CM}$$

$V_{in\_g\_test\_min}$- lower border, for which the gain error was tested

$V_{in\_g\_test\_max}$- upper border, for which the gain error was tested

So, for operational amplifier to have a linear output without saturations and distortions, following conditions must be fulfilled:

Linearity condition:

- INPUT $\begin{cases} V_{sig\_max} < V_{in\_lin\_max} \\ V_{sig\_min} > V_{in\_lin\_min} \end{cases}$
- OUTPUT $\begin{cases} V_{out\_worst\_case\_max} < V_{\mathrm{out\_lin\_max}} \\ V_{out\_worst\_case\_\mathrm{min}} > V_{\mathrm{out\_lin\_min}} \end{cases}$

Gain error range test condition:

- INPUT: $\begin{cases} V_{sig\_max} < V_{in\_g\_test\_max} \\ V_{sig\_min} > V_{in\_g\_test\_min} \end{cases}$

- OUTPUT: $\begin{cases} V_{out\_worst\_case\_max} < V_{out\_g\_test\_max} \\ V_{out\_worst\_case\_\min} > V_{out\_g\_test\_min} \end{cases}$

The scheme of the operational amplifier transfer function is shown below:

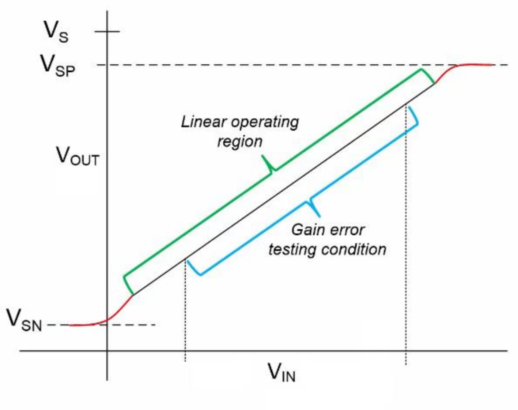

Fig. 1.2.4. Operational amplifier forward transfer characteristics

And, lastly, the total measurement error is being eliminated as the root square sum of all the errors present:

$$e = \sqrt{\sum_{i=1}^{n} (e_i^2)}$$

Current sensing: the instrument, that is suitable both for accurate measurement of big load currents and isolation requirements, is current transformer. It was chosen mainly because of the high voltage requirements, where the shunt resistor is not

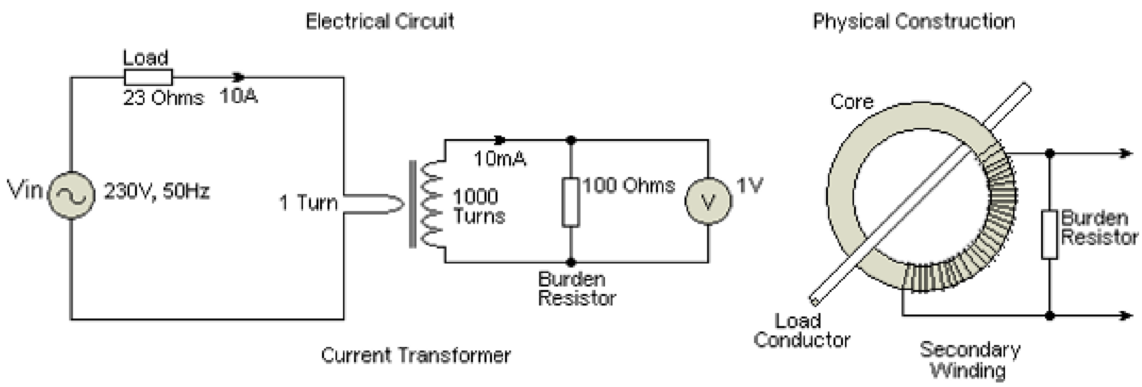

Fig. 1.2.5. Current sensing scheme with current transformer [18].

The idea of sensing with current transformer is based on the electromagnetic law of induction. The current in the AC current loop induces the alternating magnetic field around the wire, which passes through a coil with big amount of winding and a ferromagnetic core. This magnetic field induces a moderate current in the coil windings, which then passes through a burden resistor, to obtain the voltage. The sensing voltage equation is as follows:

$$V_{sense} = \frac{I_{load}}{N} * R_{burden}$$

The one disadvantage is the accuracy. Accuracy of measurement with current transformer relies on many factors, such as device accuracy class, and a burden resistor error. Also, the device has a problem of electromagnetic hysteresis, or so called residual magnetism, leading to measurement Errors, especially at low currents or during polarity changes, and a saturation Effects under high current surges, causing non-linear behaviour.

The one device which is similar to current transformer and does not have residual magnetism, is Rogowski Coil. It does not have the ferrite core at all, but it is not capable though to measure lower amplitude currents.

Another, more straightforward technique would be the shunt resistor, but it has one major disadvantage. The following connection allows to measure the current, passing through the shunt first, and then to the load.

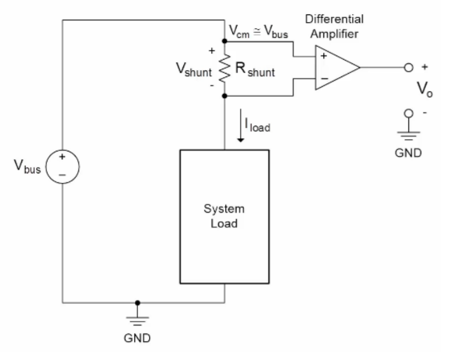

Fig. 1.2.6. TI Precision lab series. High-sided shunt current sensing block diagram

Here, we can see, that the common mode voltage of the operational amplifier will actually be equal to V_{bus}. In the case of the project, $V_{bus} =$

$120 \sim 240\,VAC$. Of course, there are special amplifier types, called current sensing amplifier with special biasing stage, that allows to have a high common mode voltage, but they are expensive. Having additionally high current and voltage magnitudes, requires a shunt with big power dissipation, which usually results in bigger shunt size, which is not good for a compact design of an instrument, together with missing isolation, makes shunt current sensing not suitable for our task.

improves accuracy and signal detail.

Calculation:

Voltage sensing with potential divider

This technique uses series connection of the resistors, which converts the high-magnitude voltage to a lower one. This technique allows for linear voltage transition but lacks the isolation requirements.

The divider output voltage can be calculated with the following equation:

$$V_{sense} = R_{d1} \frac{V_{in}}{R_{d1} + R_{d2}}$$

Where:

V_{sense} – divider output voltage

R_{d1} – resistor, from which the signal is being taken

R_{d2} – resistor, connected in series

The accuracy of this method relies on the tolerance of resistors.

Voltage transformer is not suitable because of the size of a transformer. By the way, it is actually a current transformer, and the voltage is firstly being converted to current, then passed through first coil, which induces the current in secondary coil, and this current is lately converted back to voltage using burdens. This requires complex calculations, and the tolerance of the method relies on many factors.

Analog to digital conversion and sampling.

This stage is done to interface the signal to a digital processing unit. The way it is done, it by the use of Analog to digital converter. The design involves signal integrity, accuracy, and performance requirements. The goal is to accurately convert an analog signal into a digital representation with minimal error.

Bits of Resolution, which determines the number of discrete levels the ADC can produce (e.g., 8-bit, 12-bit, 16-bit, 24-bit). This factor directly determines the resolution of ADC, together with the error. The error is also being estimated using this resolution, so called quantization error. This occurs due to the finite resolution of the ADC.

The error magnitude is ±0.5 of LSB

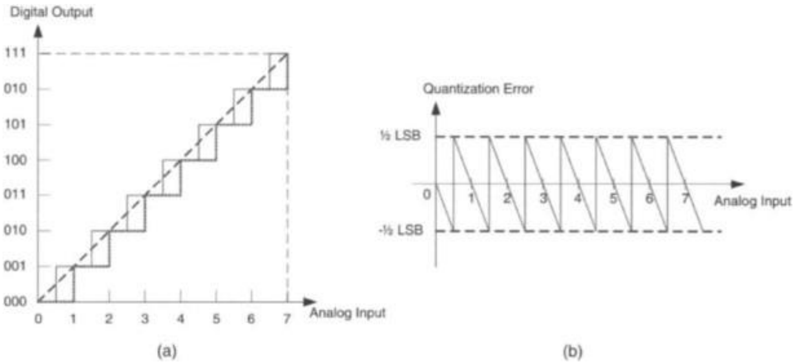

Fig. 1.2.7. Quantization error illustration [14].

Sampling rate. By Nyquist Criterion, sampling rate of ADC should be at least twice the highest frequency component of the input signal.

$$f_s \geq 2 * f_{highest}$$

This under sampling can cause unwanted aliasing effect, where high-frequency components appear as false low frequencies in the digital signal domain.

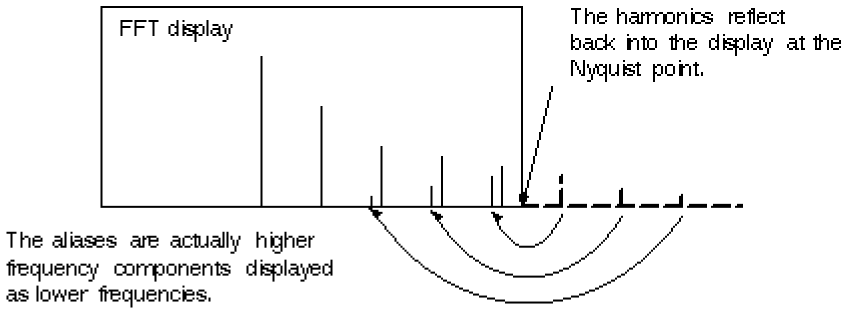

Fig. 1.2.8. Aliasing illustration [15].

as for the operational amplifier, the similar criteria are also applicable for the ADC, such as offset, gain error, linearity CMRR and PSRR.

Offset error: this is the difference between the actual output code and the ideal output code when the input voltage is zero (or at the lowest input range for bipolar ADCs).

Gain error refers to the discrepancy between the actual slope of the ADC's transfer function and the ideal slope, usually measured as a percentage of full-scale range (FSR).

Differential Non-Linearity (DNL). It quantifies the deviation of each digital code step size from the ideal 1 Least Significant Bit (LSB) step.

Integral Non-Linearity (INL). It is the maximum deviation of the ADC's actual transfer function from a straight line, which could be the ideal line or a best-fit line.

Power Supply Rejection Ratio (PSRR): it is similar to operational amplifier definition, and it is again the ability, now of an ADC to suppress variations in the power supply voltage and prevent them from appearing at the output.

Common mode rejection ratio (CMRR): it is similar to operational amplifier definition, and it is again the ability, now of an ADC, to reject common-mode signals while amplifying differential signals.

Power switching and dimming

Power switching can be performed in various methods. Referring to IEC 60947 standard requirements, we can outline main criterions of power switch:

- *ON state*: switching on the unit is electrically equal to just plugging the device to an outlet. The path from power line to device has no impedance.
- *OFF state*: switching off the unit ensures there is no power coming to device. The device does not have any voltage supplied to it. This means total energy blockage and isolation from power line with no leakage of currents and voltages.
- The controlled power loop is isolated from the controlling loop.
- During the short circuit, it must be able to switch off fast.

EMR: Switch, that fully fulfils these requirements is EMR, or Electro Mechanical Relay. They can conduct both DC and AC large currents and voltages. EMR "switched on" state has extremely low impedance, fulfilling ON-state requirement, and "switched off" state provides physically disconnected contacts, thus fulfil of "switch off", ensuring full isolation during OFF state. They also are able to disconnect themselves during short circuit, with fast enough speed, typically between 5 to 15 milliseconds.

The EMR is being controlled, by applying current to the coil inside the EMR. This will generate the magnetic field, due to which the contact connect/disconnect from each other.
EMR has different structures and variations, from single channel to multichannel and from normally-off to normally-on:

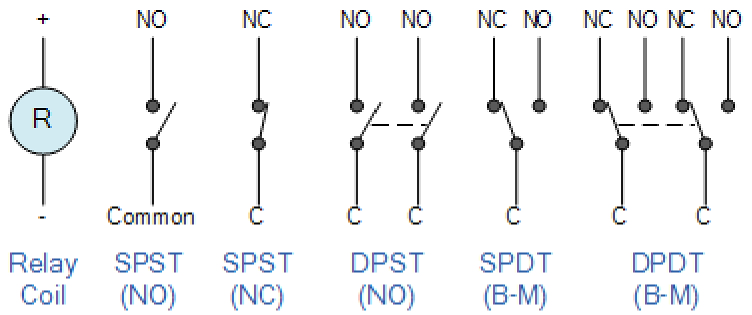

Fig. 1.2.1.1. Illustration of different types of EMR switch [4].

Talking about the reliability of this switch, it is worth mentioning that the mechanical components are subject to wear over time, which can affect performance and reliability. Also, detaching the contacts between each other, can generate the spikes in power line, which indeed need to be suppressed. Also, for the controlling stage, it is needed to keep the coil isolated from the controlling loop also, due to the spikes and de-energization or a coil, so called backward induction.

The control loop in this case must have Controller for rated for the coil requirements, able to keep the coil powered for long time. Isolation of relay control loop and MCU output. Usually performed by using the phototransistors. And, lastly adding fast, powerful diodes, which are required for de-energization of relay.

SSR: Another option would be a solid-state relay. This is a semiconductor device, usually a triac, which is being controlled by the voltage applied to it.

This is much faster option, having switching time in terms of micro second. But this overshoots the requirement of speed, so it is not really considered as an advantage. This type of switch does not fulfil several requirements. First of all, it is a semiconductor device, which has a leakage current. This leads to not fulfilling the OFF-state requirement of having full electrical isolation. Also, it has bigger ON state impedance, which leads to not fulfilling the ON state requirement of infinite impedance output and sufficient heat generation. This will require additional heat sink, for managing the heat generated.

SSRs can fail in short-circuit mode, which means they might not turn off the load when they fail. Therefore, it’s required to use additional safety mechanisms like circuit breakers or contactors for fail-safe operation.
Having discussed switches, several outcomes will be made for making the dimmer loop. The dimming technique is based on cancelling some part of a sinusoidal wave of a voltage, as shown on figure below:

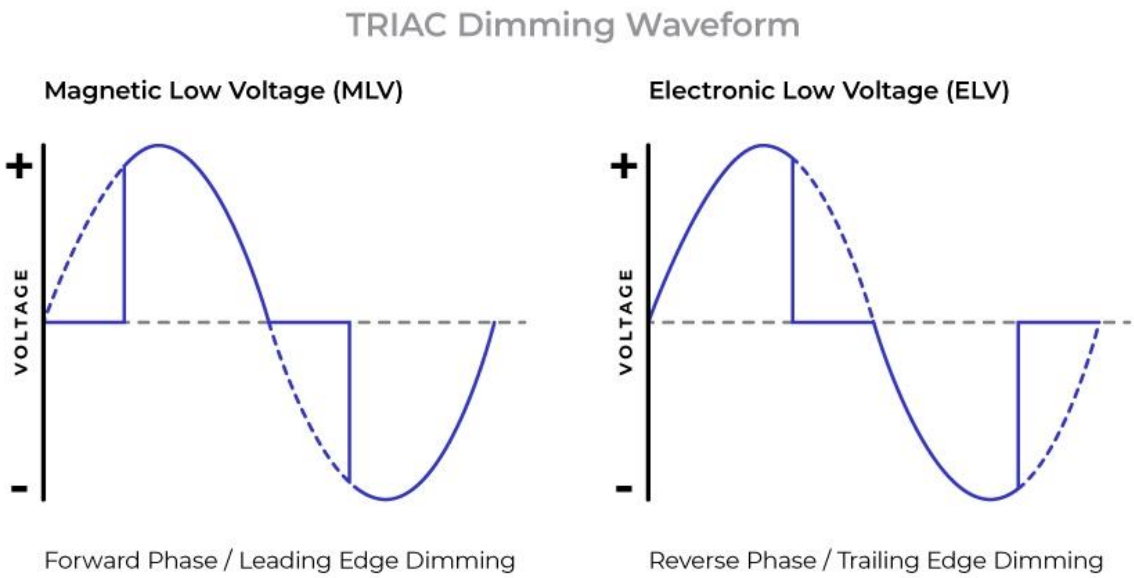

Fig. 1.2.1.2. Dimming technique, based on cancelling some part of sinusoidal wave [7].

For this task, the EMR is not applicable, because the duration of a single cycle of the waveform in the socket outlet is equal to (considering maximal frequency possible for worst case scenario):

$$\frac{1}{60\,Hz} = 16.7\,ms, \qquad so\ around\ 8\,ms\ for\ a\ half - cycle$$

This is on the level of the EMR switching speed, so it will not simply manage this speed. Moreover, this frequent switching will create buzzing, and will destroy the mechanical parts, together with the controller loop, destroyed by electromagnetic discharge of a coil. SSR can be ideally used for this task, for its fast reaction. But it is a costly solution, but it can be rather replaced by triac.
Triac is a type of semiconductor device, which can switch high magnitude currents flow in both directions. SSR is actually consisting of the triac and

photodiac loop, but with lower heat management capabilities and higher cost.
Schemes, based on the triac switch usually look like that:

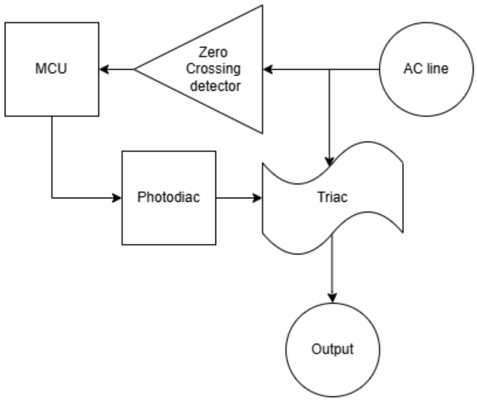

Fig. 1.2.1.3. Dimming technique, based on cancelling some part of sinusoidal wave with zero crossing detection.

The triac is triggered by the photodiac, which is triggered by the MCU, when there is zero cross detected and at a specific phase angle of the AC waveform, controlling the amount of power delivered to the load. The DIAC remains non-conductive until the voltage across it reaches the breakover voltage**.** Upon breakover, the DIAC switches on suddenly**,** delivering a sharp pulse of current to the gate of the triac **(**TRIAC or SCR), providing a sharp, well-defined trigger pulse, which ensures reliable and clean switching of the triac**.** It prevents partial triggering and gate misfiring**,** which could cause inefficient operation**.**

The power capabilities of a triac must fulfil the power capabilities of an instrument, by the way having additional switch for turning it off, to fulfil the IEC 60947 standard requirements.

Voltage spikes protection

As for the voltage spikes, nowadays the MOV or so-called varistors are typically used. This is a semiconductor device that changes its conductivity at different voltage levels.
The main function of the clamp is to absorb the overvoltage surge by

lowering its impedance to such a level that the voltage drops on an always-present series impedance that is significant enough to limit the overvoltage on “critical parts” to an acceptable level.

Varistor: One option would be using Varistor. They provide protection for low power, as well as for high power electronics. Varistors can absorb high transient energies (Devices can be built to withstand the current up to 70000A surge) and are able to suppress positive, as well as the negative transients. Varistor can react within a nanosecond.

Varistors have very long lifetime, and their failure mode results in a short circuit, preventing the device from overvoltage.

Zenner diodes: Another option is with Zenner diodes, or so-called TVS, because they can also “clamp” the voltage at specific levels. The advantage is that modern Zenner diodes are very effective and come closest to ideal constant voltage clamp. The disadvantage is that the avalanche voltage is maintained across a thin junction area, leading to huge heat dissipation. They are only suitable for low-power and low voltage applications.

The figure below illustrates the transient characteristics of those devices:

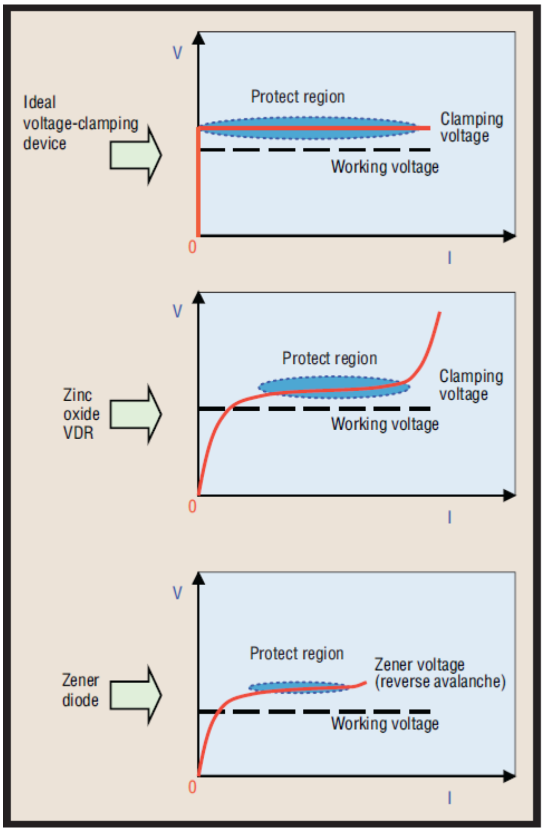

Fig. 1.2.2.1. Varistors: Ideal solution to surge protection: chart, showing clamping responses of Varistor and Zenner diodes.

The selection criteria of a varistor depends on the purpose of protection, type of waveform and of course the power. The figure below demonstrates an algorithm, which shows the varistor selection:

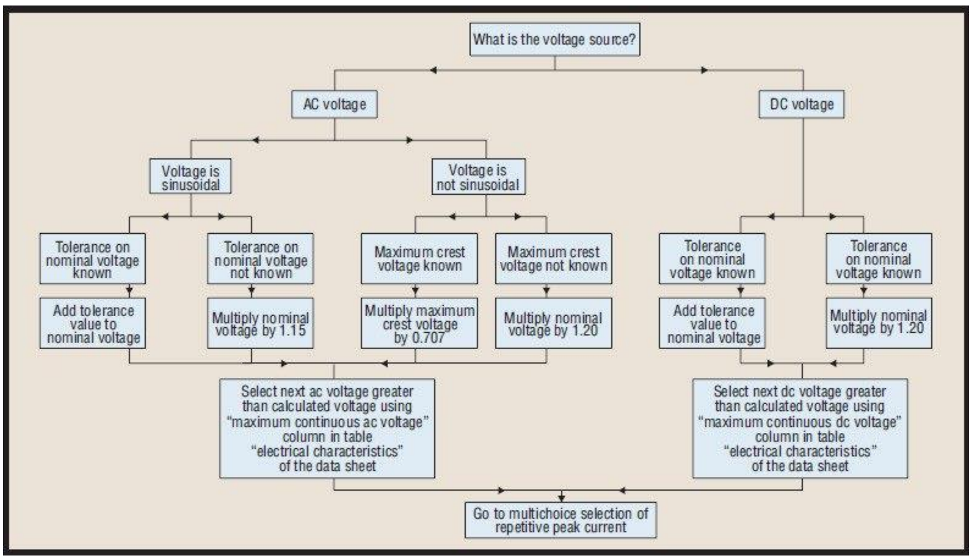

Fig. 1.2.2.2. Varistors: Ideal solution to surge protection: flowchart used to determine the necessary steady state voltage rating for a Varistor.

Websockets

Websockets is a TCP based full-duplex communication protocol, that allows for real-time communication between client and a server, where client and server can send messages to each other independently. It is persistent, which reduces the need of repeated handshakes. It accepts both the binary and text frames. The example of handshake GET request is shown here:

- GET /chat HTTP/1.1
- Host: some.domain.com
- Upgrade: websocket
- Connection: Upgrade
- Sec-WebSocket-Key: dGhlIHNhbXBsZSBub25jZQ==
- Sec-WebSocket-Version: 13
- Origin

And some optional fields:

- Sec-WebSocket-Protocol: chat, superchat
- Sec-WebSocket-Extensions: permessage-deflate; client_max_window_bits

The connection with the server starts with the HTTP/1.1 handshake, where the protocol switch from HTTP to websiockets is requested, target domain address, protocol version and base64-encoded random nonce(client generated), that is used to prevent replay attacks. Optional parameters include the subprotocols the client wishes to use. This allows for high-level protocols to run on websocket, such as STOMP and MQTT. Then, the extensions are listed.

Server response:

- HTTP/1.1 101 Switching Protocols
- Upgrade: websocket
- Connection: Upgrade
- Sec-WebSocket-Accept: s3pPLMBiTxaQ9kYGzzhZRbK+xOo=

- Sec-WebSocket-Protocol: chat Sec-WebSocket-Extensions: permessage-deflate

"101 switching protocols" indicates successful upgrade to websockets. Then, when the connection is upgraded, the client and server start sharing the websocket frames, meanwhile sending ping-pong frames to keep the connection alive.

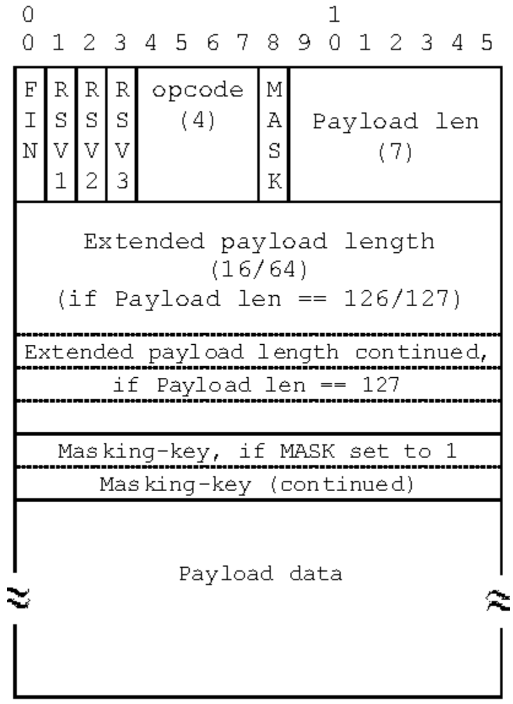

Fig. 1.3.1.1. Websocket frame [16].

WebSockets are the preferred communication protocol for IoT power monitoring and control systems due to their high-speed, full-duplex communication capabilities. They provide real-time data transmission and instantaneous control actions. Additionally, WebSockets offer high bandwidth, enabling the connection of numerous devices and facilitating simultaneous, efficient data transfer across the network.

Signal processing

Spectral analysis

The spectral analysis is performed in order to see the unwanted harmonics and for the power quality analysis. One of this algorithms is a furrier transform, particularly discrete digital fast furrier transform. It is used, to transform the discrete digital data from the time domain to the frequency domain.

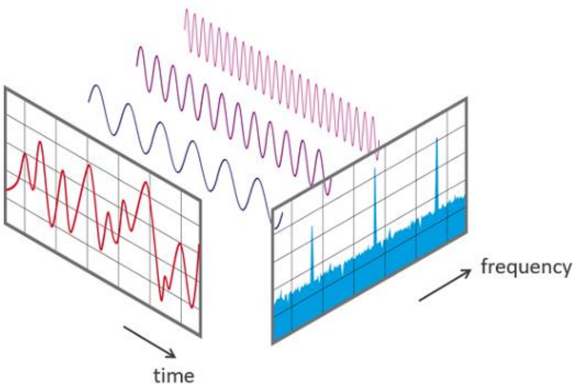

Fig. 1.4.1.1. Demonstration of time domain to frequency domain conversion [13].

Once doing the fast furrier transform, the frequency resolution should be on the level of desired frequency. The IEC 61000-4-30 standard tells, that the system must be capable of measuring 200% of the main frequency.
So:

$$50Hz \rightarrow \ 100Hz, \quad 60Hz \rightarrow 120$$

But, in terms of analysis of spikes for example or other disturbances, it is suggested to use 2 kHz bandwidth. So, the frequency resolution must be on the level of 10 Hz, and the number of samples would be 256. This results in a bandwidth of 2560Hz.

The number of samples should be taken as the power of 2 for the fast furrier transform. This is because of the Radix-2 algorithm, which recursively breaks down DFT computations into smaller DFTs of half the size, continuing this process until single-point DFTs are reached.

This divide-and-conquer approach is only possible when the number of samples is a power of 2, enabling Optimal use of butterfly operations, which are computationally inexpensive. Efficient memory access patterns, minimizing cache misses.

Power calculation

The power, that will be estimated is counted in this way:

1. Instant power:

$$P(t) = V(t)I(t)$$

This measurement is required for the spikes, drops detection

2. Voltage, current and power RMS for a n samples taken for 10-12c:

$$V_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i)} \qquad I_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(I_i)} \qquad P_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i I_i)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i)}$$

This term is needed for the evaluation of the instant RMS for power measurement monitoring

3. Voltage, current and power long term RMS for a k samples taken for 150-180c:

$$V_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i)} \qquad I_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(I_i)} \qquad P_{RMS} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(V_i I_i)} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(P_i)}$$

This term is needed for the evaluation of the long term RMS evaluation, for power quality assessment.

Device building

Component selection

Current transformer and voltage divider

The current transformer was chosen to be capable of measuring big currents, and by the same time being able to sense small current flows. The chosen device is AP-2000 from Talema.

Electrical Specifications at 20°C

Part No.	Turns	Burden Ohms	Rated Current in Amps	Max. Current in Amps	Resistance in Ohms Max.
AP-1000	1000	10	10	20	70
AP-1500	1500	15	10	20	120
AP-2000	2000	20	15	25	235
AP-2500	2500	50	15	25	330

Fig. 2.1.1.1. Talema current transformer specifications.

That amount of winding allows for high precision current sensing. This is accuracy class 0.2, which means that the measurement accuracy will be on the level of 0.2%.

This is really compact transformer, which is the most accurate transformer available on the chosen market of components, being the compromise of the price, accuracy and size.

The datasheet also suggests the burden resistor value. This is actually, the minimal resistor value, the lower values will not generate enough voltage to be sensed.

The values for the voltage divider series resistance were chosen to have big resistance and fulfil the power requirements. The chosen value is 3 connected in series resistances with the value of 330kΩ, and the Rd of the value 2kΩ. This allows for the divider ratio to be theoretically:

$$k \approx \frac{2k}{2k + 330k + 330k + 330k} \approx 0.002$$

Operational amplifier

The selection of an operational amplifier is the most important factor in this part. There are many types of an amplifiers available, together with possible configurations. As it was said in theory part, there are many error sources, but the most critical to my mind is the offset voltage error. Because, usually operational amplifiers have this voltage on the level of mV, which is the level of the measured sensing voltage.

So, the criterion of choosing the amplifier will be the cost, and the lowest possible offset voltage. The compromise of that two became the MCP6V27-E/SN operational amplifier.

This is the most affordable, two-channel fixed gain operational amplifier from Microchip, with the following characteristics:

Input Offset Voltage	V_{OS}	-2	—	+2	μV	T_A = +25°C (Note 1)
Input Offset Voltage Drift with Temperature (linear Temp. Co.)	TC_1	-50	—	+50	nV/°C	T_A = -40 to +125°C (Note 1)
Input Offset Voltage Quadratic Temperature Coefficient	TC_2	—	±0.2	—	nV/°C^2	T_A = -40 to +125°C
Power Supply Rejection	PSRR	125	142	—	dB	(Note 1)

Fig. 2.1.2.1. Information about input offset voltage, input offset voltage temperature drift and PSRR from MCP6V27-E/SN datasheet.

Common-Mode Rejection	CMRR	120	136	—	dB	V_{DD} = 2.3V, V_{CM} = -0.15V to 2.5V (Note 1, Note 2)
	CMRR	125	142	—	dB	V_{DD} = 5.5V, V_{CM} = -0.15V to 5.7V (Note 1, Note 2)

Fig. 2.1.2.2. Information about CMRR from MCP6V27-E/SN datasheet.

Minimum Output Voltage Swing	V_{OL}	—	V_{SS} + 5	V_{SS} + 15	mV	G = +2, 0.5V input overdrive
Maximum Output Voltage Swing	V_{OH}	V_{DD} – 15	V_{DD} – 5	—	mV	G = +2, 0.5V input overdrive

Fig. 2.1.2.3. Information about switching voltages from MCP6V27-E/SN datasheet.

The data obtained for the worst case scenario error calculation:

- $V_{os\_max} = 2uV,$
- $\frac{\Delta V_{os}}{\Delta T} = \pm 50 \frac{nV}{°C}$
- $PSRR_{min} = 125\ dB$
- $CMRR_{min} = 125\ dB\ (for\ power\ supply\ of\ 5V)$

- Supply voltage range: $2.3V - 5.5V$
- Bandwidth: $2MHz$
- Maximal swing to power rail: $15\ mV$
- Maximal swing to ground: $15mV$
- The total margin will be considered to be 50mV from ground, and 50mV from the rail.

This operational amplifier will be set in a differential mode, with a voltage reference of 2.5V, to make the output signal alternating across the midpoint of a measurement range.

According to the error estimation formulas shown in theory part, the minimal current the following conclusions were made:

- For the current transformer it will not be possible, to exceed the 0.2% measurement range. Thus, the minimal current for which the system does not exceed 0.2% is 300mA. This will be the system's minimal measuring current. The biggest burden value, for which those conditions fulfil is 80Ω.
- Having the minimal voltage of 12V, the resistor Rd corresponds the error on the level of 0.2% with fulfilment of linearity condition, when is equal to 2kΩ.

As it was said before, OPAMP is being configured in differential mode, show below:

Voltage part is shown on the figure below:

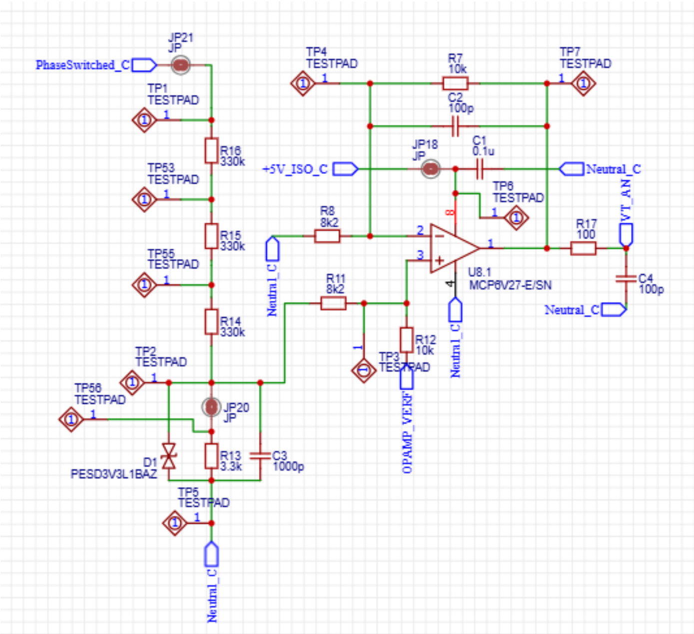

Fig. 2.1.2.4. Fragment from the SEIS schemas, voltage sensing and signal conditioning

Owing to the lack of the resistances with high accuracy on the shop, the value were measured, disconnecting the JP20, to stop the influence of nearby tvs and capacitor, the resistor R13 was measured by the use of TP56 and TP5 probes on PCB with the precise instrument BRYMEN BM 869s with the measurement error of 0.02%.

Fig. 2.1.2.5. BRYMEN BM 869s [5].

Thus, now the resistor value is known with 0.02% tolerance.

The voltage divider also has a noise filtering capacitor with a TVS diode, to supress the spikes, if they will appear. Operational amplier also has a noise filtering capacitor at the feedback resistor, and a low pass filter at the output stage of the OPAMP.

The value for the resistors, together with the other resistor measurements are listed below:

Voltage measurement	Value	Unit
R13 (Rd)	3.2993	kΩ
R16	327.50	kΩ
R15	325.92	kΩ
R14	327.40	kΩ
k Voltage divider ratio	$\frac{3.2993}{327.50 + 325.92 + 327.40 + 3.2993} = 0.0033$	-
R_f	10.244	kΩ
R_I(R11)	8.3471	kΩ
Gain	$\frac{10.244}{8.3471} = 1.227$	-
Sense voltage	$0.0033 * 12 = 0.0396$ $360 * 0.0033 = 1.186$	V
Total measurement error	0.112	%

Table 2.1.2.1. Voltage sensing calibration measurements

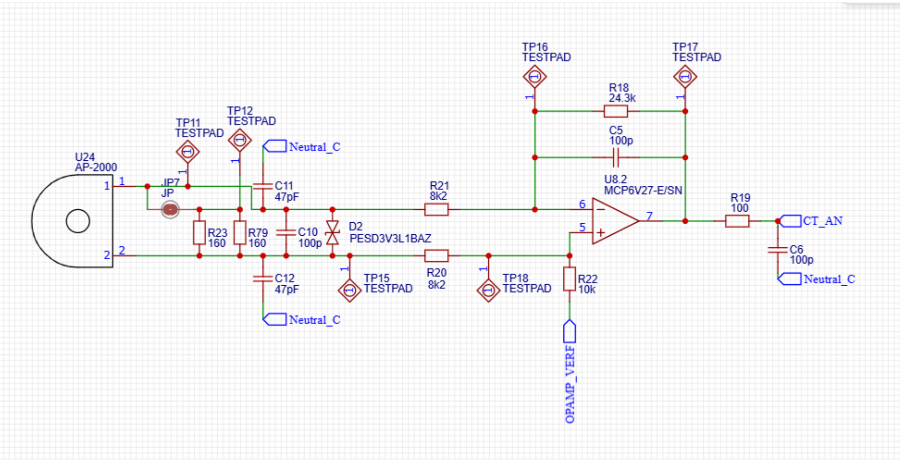

Fig. 2.1.2.6. Fragment from the SEIS schemas, current sensing and signal conditioning

Current part: The same technique was performed here. As soon as there were no resistors with the value of 80 Ω available in the shop, the two resistors in parallel were interconnected with each other, to get the desired 80 Ω. To measure the this resistance, the jumper JP7 was in soldered, and resistance between the pad number TP12 and TP15 was measured. The feedback resistor was measured with the use of the pads TP16 and TP17, and input resistance was measured with the use of pads TP11 and TP16.

The current transformer also has a noise filtering capacitors, and TVS diode, to supress the spikes, if they will appear. Operational amplier also has noise filtering capacitor at the feedback resistor, and a low pass filter at the output stage of the OPAMP.

Current measurement	Value	Unit
R13 (Rd)	3.2993	kΩ
R_{burden}	80.100	Ω
R_f	24.598	kΩ
R_I(R11)	8.3471	kΩ
Gain	$\frac{24.598}{8.3471} = 2.946$	-
Current sensing range	0.3 – 16	A
Transducer induced current range	$\frac{16}{2000} = 8 \quad \frac{0.3}{2000} = 0.15$	mA
Sensing voltage (across burden)	$0.00015 * 80 = 0.012$ $0.008 * 80 = 0.640$	V
Total measurement error	0.207	%

Table 2.1.2.2. Current sensing calibration measurements

The voltage reference is taken by the use of potential divider, with the operational amplifier as a buffer, with high frequency filtering capacitor:

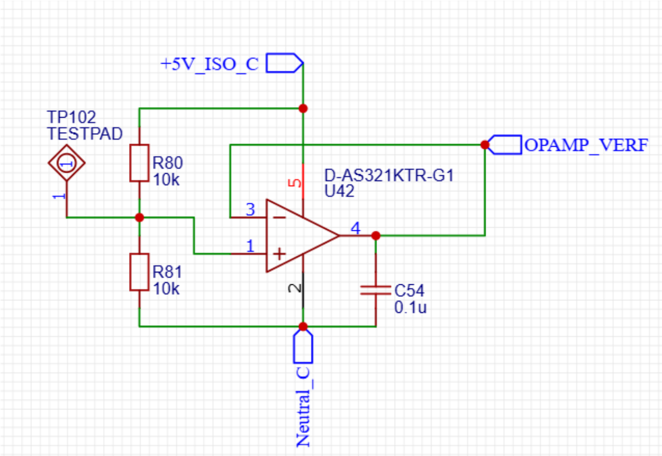

Fig. 2.1.2.7. Voltage reference of 2.5 volts

Resistor	Value
R80	10.792 kΩ
R81	9.9981 kΩ
Reference voltage	$5 * \frac{9.9981}{9.9981 + 10.792} = 2.404$ V

Table 2.1.2.2. Calibration of voltage reference

Choosing the ADC was performed also basing on the standard requirements and the affordability. The one that fulfils the requirements is MCP3911A0-E/SS, which is 24-bit delta sigma ADC, with the sampling rate of 100kHz and SPI interfacing. This works by requesting the specific register in the memory (particularly 0x0 for the channel 3 bytes, and 0x03 for the channel 1). This fulfilled the requirements of standards about the resolution and sampling rate.

The full schema also uses digital isolation for the whole power measuring loop, using п141E30S logic buffer:

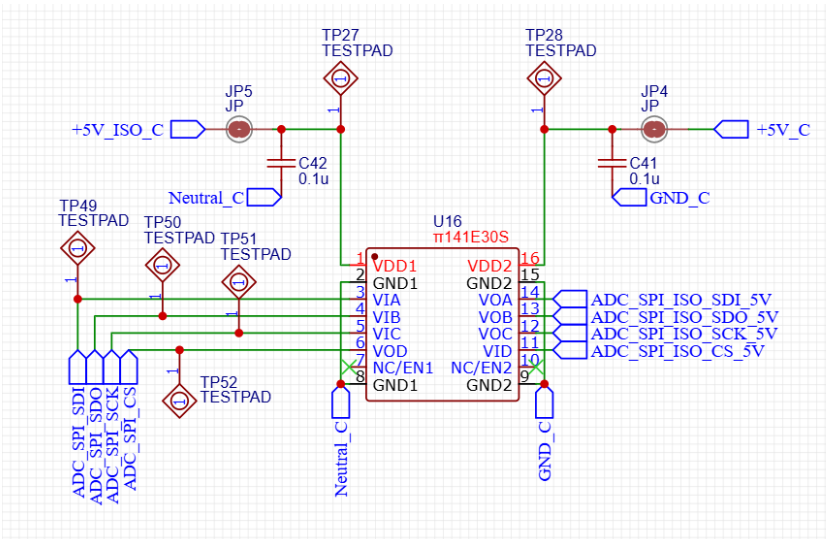

Fig. 2.1.2.8. Digital isolator from SEIS schema

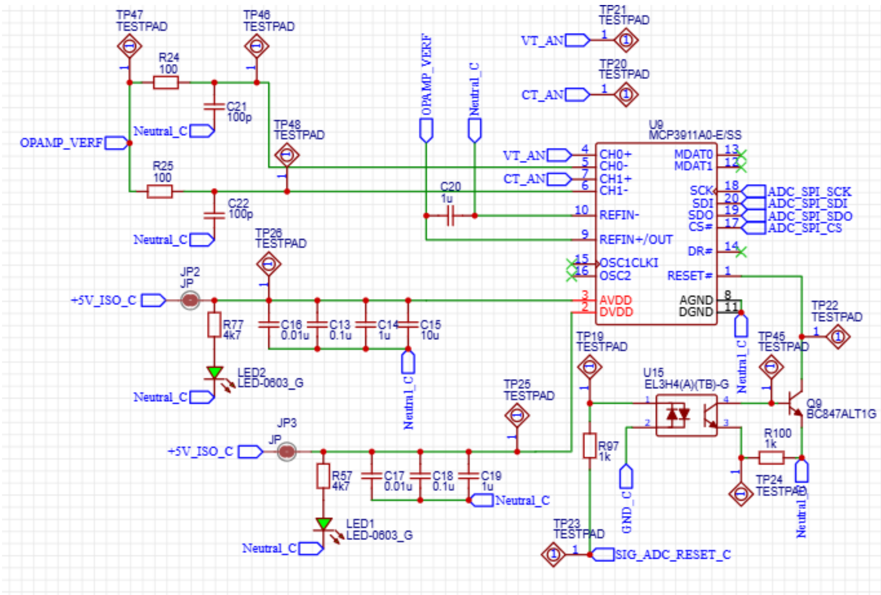

Fig. 2.1.2.9. The ADC schema

The ADC schema also contains the isolated ADC reset. After being isolated, the signal passes through the voltage level shifters from 5 to 3.3V and vice versa. The full block diagram looks like this:

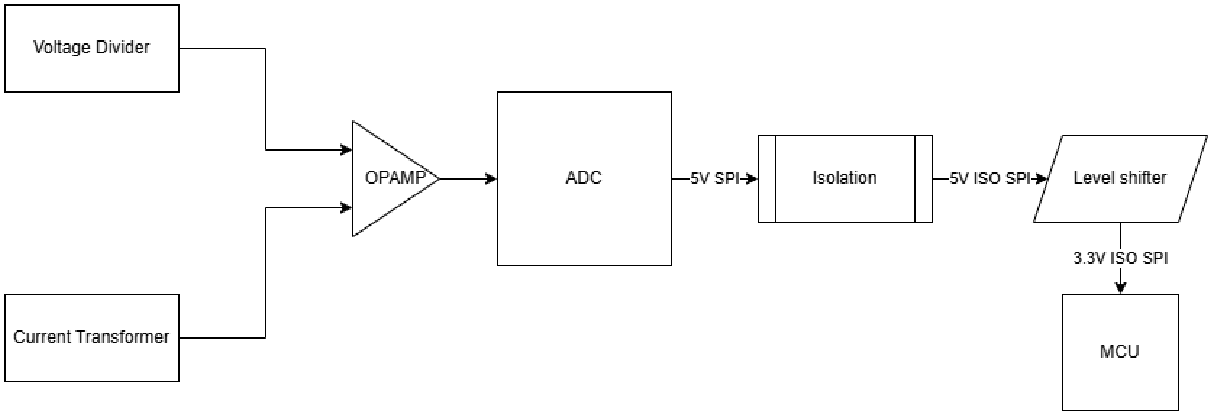

Fig. 2.1.2.9. Block diagram of power measuring loop with MCU interfacing and isolation

Output switch with dimming and surge protection

Main criteria for the EMR switch are its voltage and current capabilities. The preferred configuration is “SPST NO”. The one, that suits both power, and contact types and, being the most affordable is LMR1HA-5D.

From its datasheet, we can find useful data about the coilin this EMR:

- Coil resistance – 47Ω
- Coild power consumption during switch on - $530\ mW$

Coil current calculation:

$$I_{coid} = \sqrt{\frac{P_{coil}}{R_{coil}}} \rightarrow \sqrt{\frac{0.530}{47}} = 0.106\ A$$

This means, that the minimal collector current of switching transistor is 0.106 A. The transistor, that is affordable the most, and which exceeds the collector-emitter voltage of 5V, and has collector current rating grater than 0.106A is BC817-25-TP.

- Maximal collector-emitter voltage - $45V$
- Maximal collector current - $500\ mA$

The current amplification coefficient β for this transistor varies,

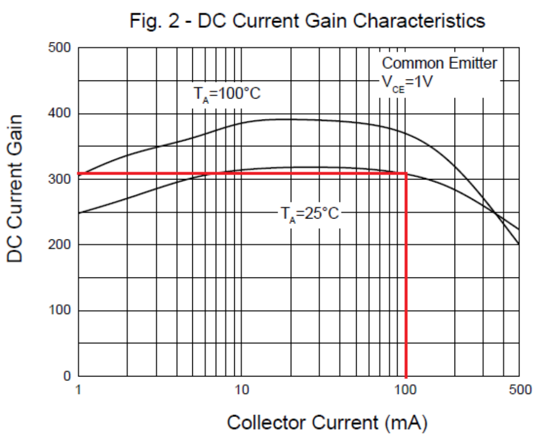

Fig. 2.1.3.1. BC817-25-TP current gain characteristics.

Taking $\beta = 300$ to consider the lowest value, to make sure the base current will produce sufficient collector current during possible high temperature work.

EMR switching transistor base current:

$$I_b = \frac{0.110A}{300} = 0.000367mA = 367uA$$

Maximal base resistance, that will allow the transistor to go into saturation mode:

Base-Emitter Saturation Voltage	$V_{BE(sat)}$			1.2	V	I_C=500mA, I_B=50mA

Fig. 2.1.3.2. BC817-25-TP base emitter saturation from the datasheet.

$$V_{BE(sat)} = 1.2V$$

$$R_{b\_max} = \frac{V_{sys} - V_{BE(sat)}}{I_B} \rightarrow \frac{5V - 1.2V}{0.000367} = 10363\Omega = 10k\Omega$$

For the safe margin to be sure that the transistor will be fully open, the 1kΩ resistor will be taken, just because it is popular choice for bjt gate resistance

$$R_b\ nominal\ power \rightarrow P_{Rb} = I_b^2 R_b = (0.000367)^2 * 1000 = 0.00013\ W = 0.13\ mW$$

Optocoupler: Talking about the optocoupler, the only requirement is to be able to drive the base current, which is already really small. Taking the most affordable one, which is EL3H4(A)(TB)-G.

From the current chart, we can see, that optocoupler truncates the 5mA for 5V V_{ce} and $I_c = 33mA$. That means, the only consideration will be to keep this current in terms of transoptor nominal forward collector current.

$$I_{transoptor\_c} \geq 367uA$$

$$R_{opto} = \frac{V_{sys}}{I_f} = \frac{3.3}{33mA} = 100\Omega$$

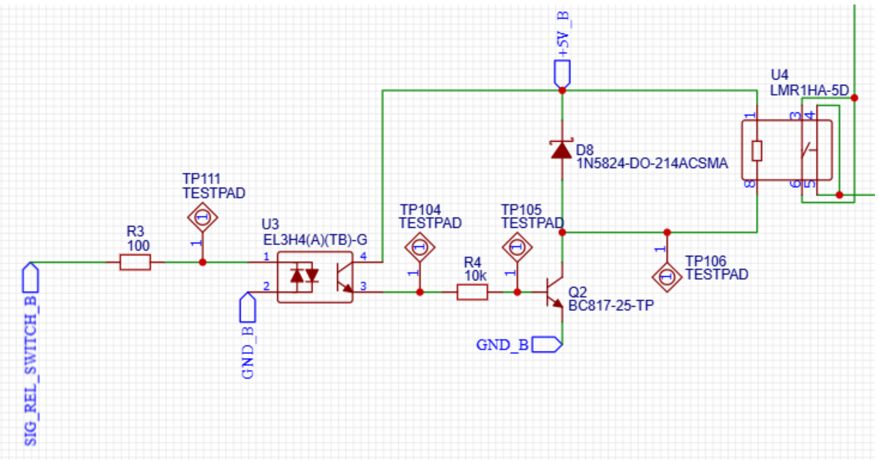

Fig. 2.1.3.3. Single switch from the SEIS schemas

The flyback diode BAT54-AQ was chosen as fast, and able to conduct big forward currents. Some data from the datasheet:

- Max forward current $I_{F\_max} = 200mA$
- Peak reverse voltage $V_{RRM} = 30V$
- Peak forward current (< 1s) $I_{PP} = 600mA$
- Recovery time $t_r < 5ns$

Dimmer: The requirements for the dimming loop mostly concerns the triac. This must fulfil the passing current requirements and voltage requirements. Thus, the most affordable one with the capability to conduct high power loads is MAC223A6,127.

Here is some data listed from the datasheet:

- The maximal forward voltage: 400V
- The maximal forward current: 25A
- The gate current: 50-75mA

The zero-crossing is done with the already chosen EL3H4(A)(TB)-G. As soon as it has bi-directional input, it is suitable for zero-crossing detection in AC line. The only this is to connect the current limiting resistors, chosen to be 30kΩ.

Additionally a photodiac was added to the triac, with the diac current ration, capable of opening chosen triac. The compromise of the affordability and rated current diac is MOC3021S-TA1.

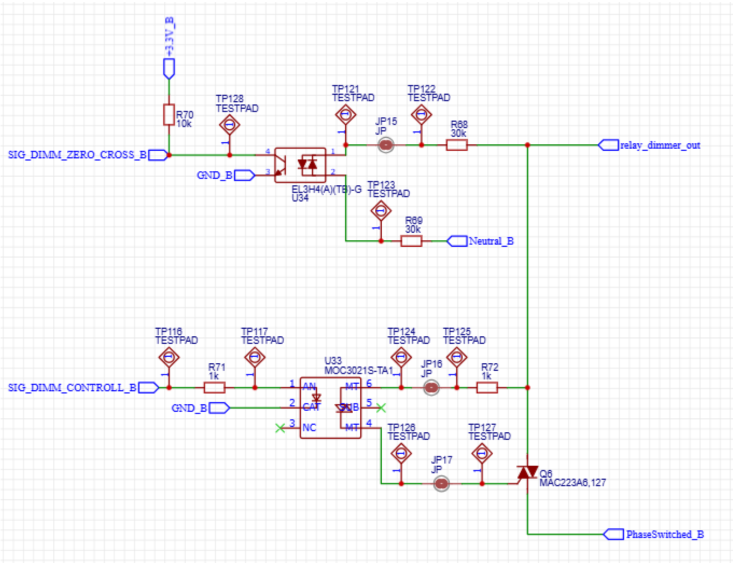

Fig. 2.1.3.4. The dimmer circuit from SEIS schemas.

Varistor: the selection of a varistor was done on the basis of the method, described in the theoretical part. As soon as the we have an AC sinusoidal signal, with the known tolerance, the required value needs to be at least 1.15 times higher than the voltage rating, that actually needs to be protected:

- For $120V: 120 * 1.15 = 138V, chosing\ the\ varistor\ of\ value\ 140V\ AC$
- For $240V: 240 * 1.15 = 275V, chosing\ the\ varistor\ of\ value\ 275VAC$

As for the diameter, origins of pulses are not known, short circuit value is considered to be 16A (then the circuit breaker must disconnect), then the repetitive peak current is equal to 50A, and the corresponding diameter is 5mm for both varistors.

The most affordable once are:

- For $120V: ERZV05D221$
- For $240V: JVR05N431K65PU5$

The switch complete look is shown in the diagram below:

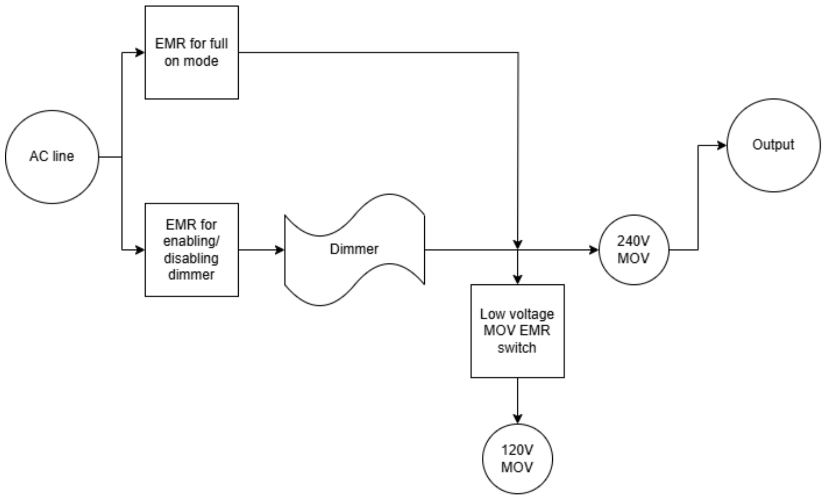

Fig. 2.1.3.5. Complete diagram of a switch with dimmer and surge protection

As we can see, as for the IEC 60947 standard requirements, the system has fully turned on state, when upper EMR is enabled. There is no leakage current during turn-off, with the help of the lower EMR, that disables or enables the dimming loop.

Interesting solution is also provided with lower voltage varistor. As soon as it has lower operating voltage(120V), when being connected to higher voltage AC line (240V), it will just start to conduct and result in leakage current. That is why there is additional EMR, that turns it on, when the system detects the lower voltage AC structure. Higher voltage MOV will not jut be influencing on the signal, when connected to lower AC line. It will just refuse to conduct, so there is no need to “unplug it”.

MCU and GPRS chip

The MCU is being chosen on the basis of the requirements. As for the TI TIDA-00835 instrument, the ARM® Cortex®-M4F Based MCU. For the scope of this project, the MCU was chosen to have the ability to connect to the Wi-Fi network, and being from the similar series, so that it will have a great performance power.

The very popular type of such microcontrollers are ESP32. However, they have many other, for this case not required at all features, like Bluetooth for instance. So, using the official ESP product list, to check the ESP32 with the same processing power, and with minimal peripherals, but with WiFi and TCP stack present, and being by the same time the most affordable.

The compromise of all of those is a ESP32-S2-WROOM-I4 module. At the core of this module is ESP32-S2, an Xtensa® 32-bit LX7 CPU that operates at up to 240 MHz. The chip has a low-power co-processor that can be used instead of the CPU to save power while performing tasks that do not require much computing power, such as monitoring of peripherals.

This MCU allows to run a RTOS in it, thus is capable of multiprocessing.

GPRS: This chip purpose is to maintain the Internet gateway, even during power breakdowns. The selection was performed in the way, that the chips that have the capabilities to connect to 4G, 4G and NB-IoT or LTE networks are more preferable. The one chip, which is suitable for such a task, and is affordable the most is SIM7022. This chip is being operated as a GSM modem, through UART, by sending “AT” commands. Another solution is to establish the PPPoS (Point-to-point protocol over serial). This allows for interfacing the ESP32 to use the SIM7022 as an Internet gateway, or a cellular modem for an internet access, both modules support that.

The MCU also has following characteristics, taken from the espressif product selector:

- Memories:
  - 128 KB of ROM
  - 320 KB of SRAM
  - 16 KB of RTCSRAM
  - 4, 8, 16 MB of Flash memory
- 3 V to 3.6 V operating voltage
- Big amount of GPIOs, up to 37:
  - 3 strapping GPIOs
  - 6 GPIOs need for flash/PSRAM
- Many communication interfaces
  - 2 I2C interfaces
  - 1 I2S interface
  - 4 SPI interfaces
  - 2 UART interfaces
  - 1 USB OTG interface
- Security features:
  - 4096 bit OTP
  - AES, SHA, RSA, ECC, RNG
  - Secure Boot, Flash Encryption, Digital signature, HMAC module

Power sources

The system has 3 power converters:

- AC/DC converter, that converts the AC line voltage (240/120VAC) to 5V 10W
- DC/DC buck converter, that converts the 5V into 3.3V 2A
- Isolation DC/DC converter that converts the 5V not isolated to 5V isolated, 200mA load

AC/DC converter: AMEL10-5S277HAVZ

DC/DC buck converter: TLV62569PDDCR, it supports the wide input voltage range, and keeps the output voltage stable at specific value. The calculation was performed in the following way:

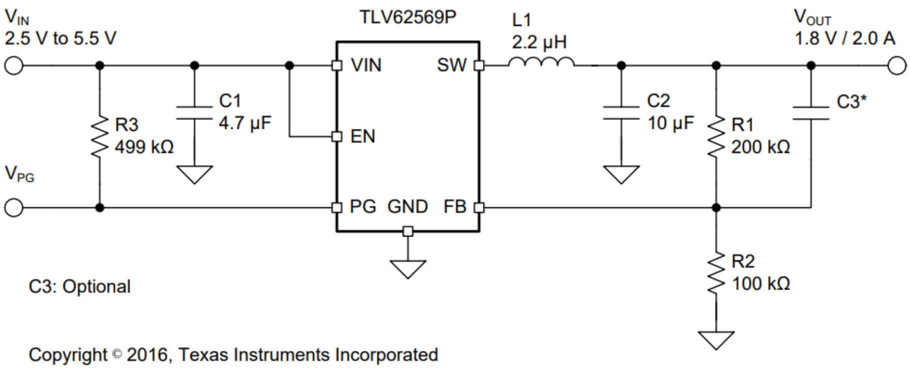

Fig. 2.1.6.1. Typical application of TLV62569

Output voltage:

$$V_{out} = V_{fb}\left(1+\frac{R_1}{R_2}\right) = 0.6V\left(1+\frac{R_1}{R_2}\right)$$

From the datasheet, R_2 should be equal to 100kΩ

Thus: $V_{out} = V_{FB}\left(1+\frac{R_1}{R_2}\right) \rightarrow \quad R_1 = R_2\left(\frac{V_{out}}{V_{fb}} - 1\right) \rightarrow R_1 = 100k * \left(\frac{3.3}{0.6} - 1\right) = 450k\Omega$

From the datasheet, $C_3$of 6.8pF capacitance is recommended for R_2 of $100k\Omega$ resistance of R_1.

From the datasheet output filter design, there is a table, that helps to find the output filter circuit values:

V_{OUT} [V]	L [μH] (1)	C_{OUT} [μF] (2)				
		4.7	10	22	2 x 22	100
$0.6 \le V_{OUT} < 1.2$	1				+	
	2.2				++ (3)	
$1.2 \le V_{OUT} < 1.8$	1			+	+	
	2.2			++ (3)	+	
$1.8 \le V_{OUT}$	1		+	+	+	
	2.2		++ (3)	+	+	

Fig. 2.1.6.2. Metrix of output capacitor and inductor combination for output filtering

To obtain the voltage of 3.3V, the combination of 2.2uH inductance and 10uF output capacitance it recommended the most.

Then, there is a need to calculate the maximum possible (worst case) inductor current, basing on the inductor current ripple:

$$I_{L\_max} = I_{out\_max} + \frac{\Delta I_L}{2}$$

$$\Delta I_L = V_{out} * \frac{1 - \frac{V_{out}}{V_{in}}}{L f_{sw}}$$

From the datasheet, the switching frequency is 1.5 MHz.

$$dI_L = 3.3 * \frac{1 - \frac{3.3}{5}}{2.2 * 10^{-6} * 1.5 * 10^{6}} = \frac{1.122}{3.3} = 0.34A$$

$$I_{L\_max} = 2 + \frac{0.34}{2} = 2.17A$$

It is recommended to choose the inductor of current capabilities of 20% higher that the needed, so:

$$I_L = 1.2 * I_{L\_max} = 2.17 * 1.2 = 2.6A$$

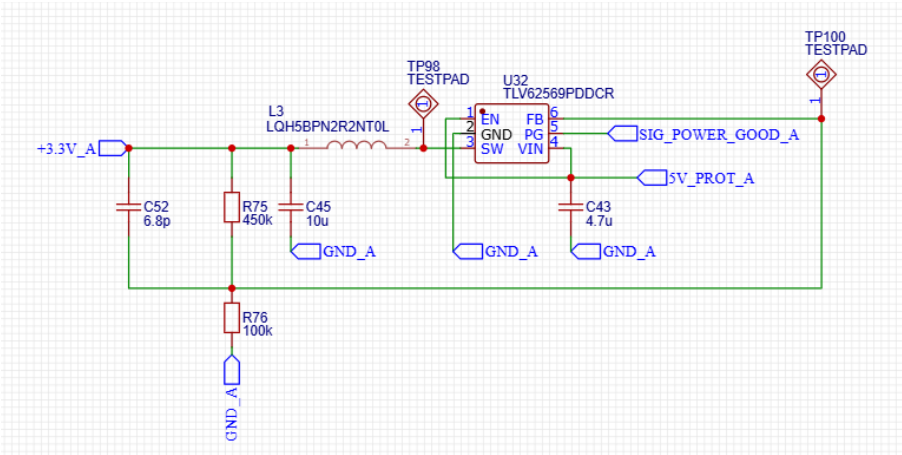

Fig. 2.1.6.3. DC/DC TLV62569PDDCR buck converter scheme.

Isolation DC/DC converter: RFM-0505S is needed for supplying the operational amplifier and the ADC of a measuring loop. This is needed for the isolation requirements of a standard, and this provide the isolated ground and 5V supply, with the 200mA response.

From its datasheet there is also an information about the output voltage range, which is bounded by $\pm 10\%$, which is actually the value, that was considered as a PSRR error source:

$$V_{PSRR} = \frac{1.1 * \mathrm{V}_{\mathrm{in\_iso}} - 0.9 * V_{in\_iso}}{PSRR_V}$$

Specifications (measured @ Ta= 25°C, nominal input voltage, full load and after warm-up)

BASIC CHARACTERISTICS				
Parameter	Condition	Min.	Typ.	Max.
Internal Input Filter				capacitor
Input Voltage Range			±10%	

Fig. 2.1.6.4. Table from the RFM-0505S datasheet, showing the voltage range.

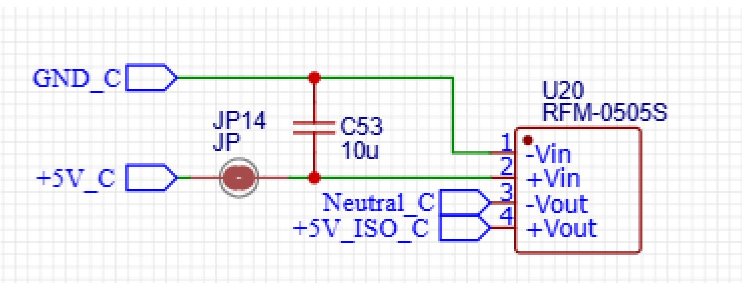

Fig. 2.1.6.5. DC/DC converter for supplying the power measuring part.

Internal emergency power source

Emergency power source, is made in terms of a using a supercapacitor, that is being charged during the presence of AC line, and keeps the system working for one-more minute, to notify the user about the breakdown.

The capacitor charge and discharge circuit was made:

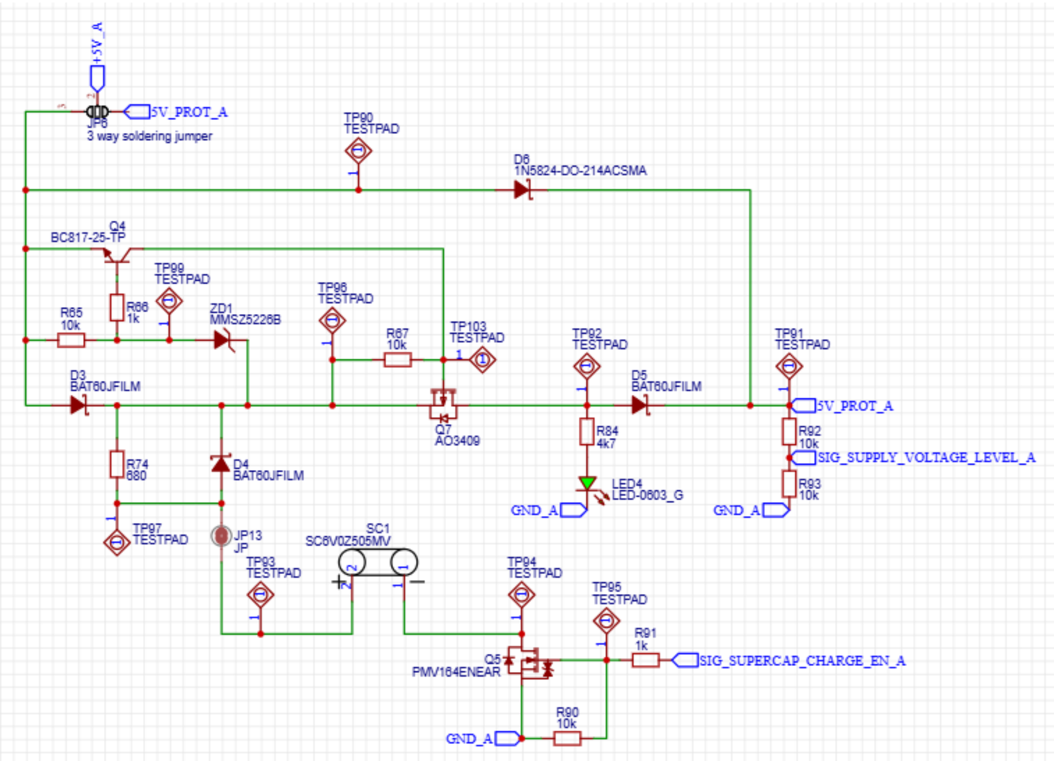

Fig. 2.1.7.1. Supercapacitor charging and discharging loop schema.

The schema works in the way, that when there is the voltage present from AC/DC converter, it passes through D3 Schottky diode, and goes to the capacitor through a charge current limiting resistor, and charges it (of course if the supercapacitor charge is enabled by passing the signal to the Q5 NMOS). Then, the supply voltage also goes through the D6 Schottky diode, which just forwards it to the output. Q5 Schottky diode prevents this voltage to go through the capacitor charging loop, charging the capacitor to the level of 4.7 volts (D3 and D4 and D5 have the forward voltage drop on the level of 0.3V).

When the voltage from AC/DC disappears, the current from supercapacitor starts to flow through the D4, and the voltage concentrates on D3 diode.

The ZD1 Zenner diode has the breakdown voltage of 3.3V. It breaks, the current starts to flow through the base of the Q4 transistor (R65 is used for pulling the anode of the ZD1 to the source voltage, to ensure the voltage drop on ZD1). The Q4 opens, passing the current flow from the capacitor to go through the R67, which opens a PMOS, which in this case, allows for the current to flow out. When the voltage on the ZD1 drops lower than its breakdown, diode stops conduction current and thus the loop closes at around 3V.

When voltage appears again, the potential difference on ZD1 changes its sign, and the loop closes, and capacitor begins charging again.

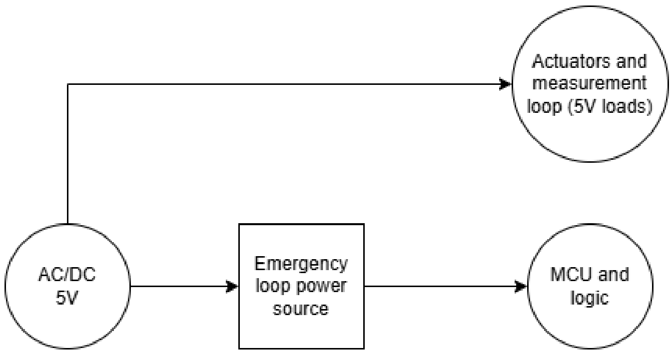

Fig. 2.1.7.2. Power sourcing schema

Component placing

In the PCB design, some parts require additional rules for placing, such as:

DC/DC power converter from 5 to 3.3V : It requires some parts to be big enough to conduct the high current flows, and isolate the inductor from the sensitive parts by the use of ground layer under it.

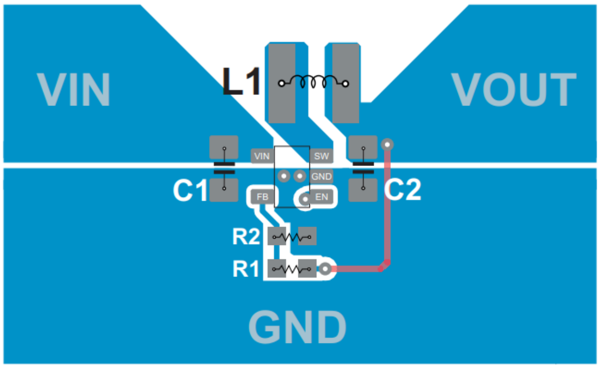

Fig. 2.2.1. TLV62569PDDCR datasheet example component placing.

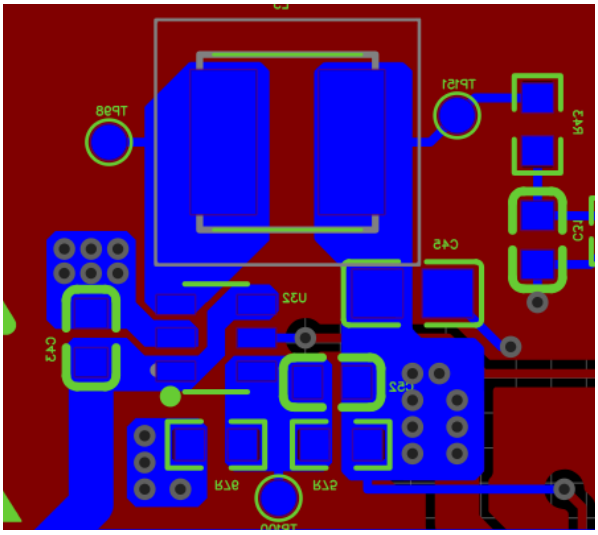

Fig. 2.2.2. SEIS component placing.

Sensors, operational amplifier and analog to digital converter interfacing: The main criteria of routing this part was to obtain as small paths as possible, to reduce electromagnetic induction on the long wires.

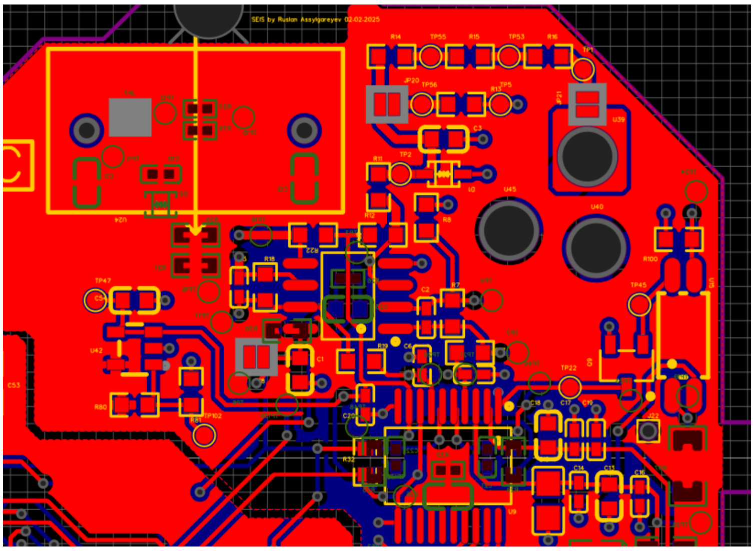

Fig. 2.2.3. Power measuring loop part.

Integrated circuits: Each integrated circuit requires a decoupling capacitors to be please as close to the power as possible.

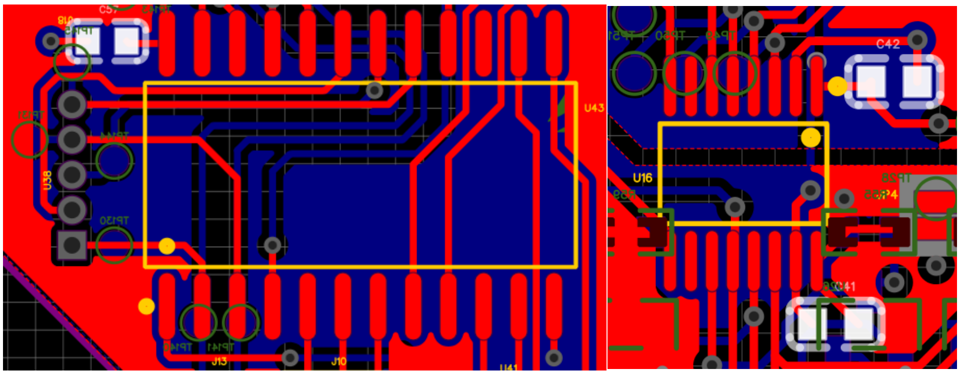

Fig. 2.2.4. Examples of adding decoupler capacitors to each of the integrated circuit power pin.

Power lines and through-holes: There must be multiple through holes on the power lines.

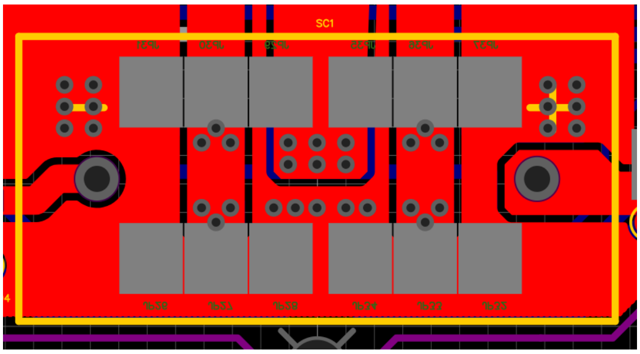

Fig. 2.2.5. Power line and though holes.

ESP and GPRS antennas: The ESP was mounted in the way, that the antenna is not being shielded by the copper areas. Although, the RF connector on ESP is more preferably to be used, because being mounted in a wall results in a problem of a signal propagation, requiring external (PCB) antenna. The RF connector for the SIM7022 was passed as far as possible from other parts of the circuitry, and additional impedance loop we added at the connector connection with the chip.

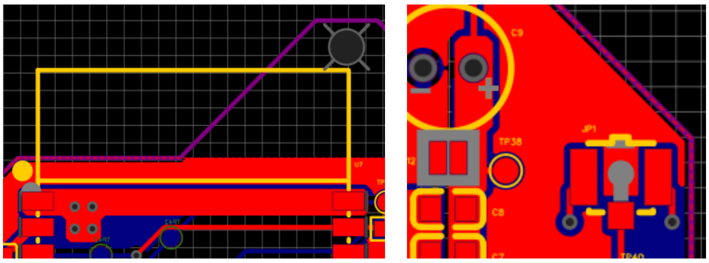

Fig. 2.2.6. Antenna of the ESP and the RF connector of a SIM7022 chip.

Flags and led indicators: The PCB is also has some flags, that help the MCU to get to know what is happening in the circuitry, for instance:

- POWER_SUPPLY_PRESENT – this flag is being pulled low, when there is not AC line power present.
- SUPERCAPACITOR_CHARGE – this flag can be converted to see the voltage on the supercapacitor.

LEDs are mainly placed at each power stage of any integrate circuit. These are actually power supply visual indicator for debugging purposes.

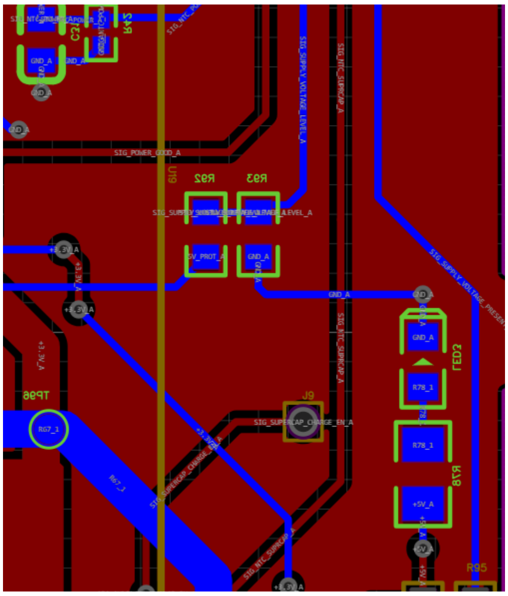

Fig. 2.2.7. Power present signal, and the LED, that emits the light when it is present.

Individual component temperature sensing

The PCB also has 9 NTC temperature sensors, populated in PCB. Those are required to measure the temperature of critical parts of a PCB, such as Varistor, dimmer or power source temperature measurements for safety issues, and operational amplifier, analog to digital converter for precise power measurement. Accuracy here is not a cruitial factor, because the accuracy of the measuring method should be on the level of a single degree Celsius.

The full list of what part of the PCB temperature is measured:

- Triac temperature
- High voltage MOV temperature
- Low voltage MOV temperature
- DC/DC 5-3.3V converter temperature
- Operational amplifier temperature
- Analog to digital converter temperature
- Isolation DC/DC converter temperature
- Supercapacitor charge current limiting resistor temperature
- GPRS chip temperature

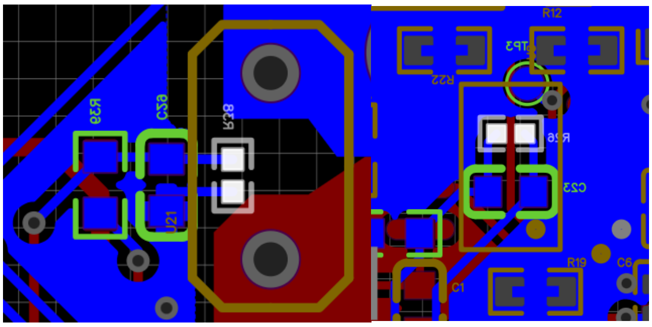

Fig. 2.3.1. Examples of NTC thermistors placing under critical parts of the PCB

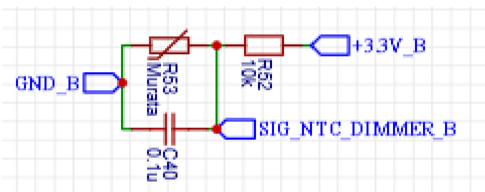

Fig. 2.3.2. Shema of the NTC temperature sensor.

Signal multuiplexing

The huge amount of signals is being lately multiplexed by a 4 bit (thus 16 channel) multiplexor CD74HC4067M96, which allows for passing the analog signlas in the level of the MCU 3.3V logic.

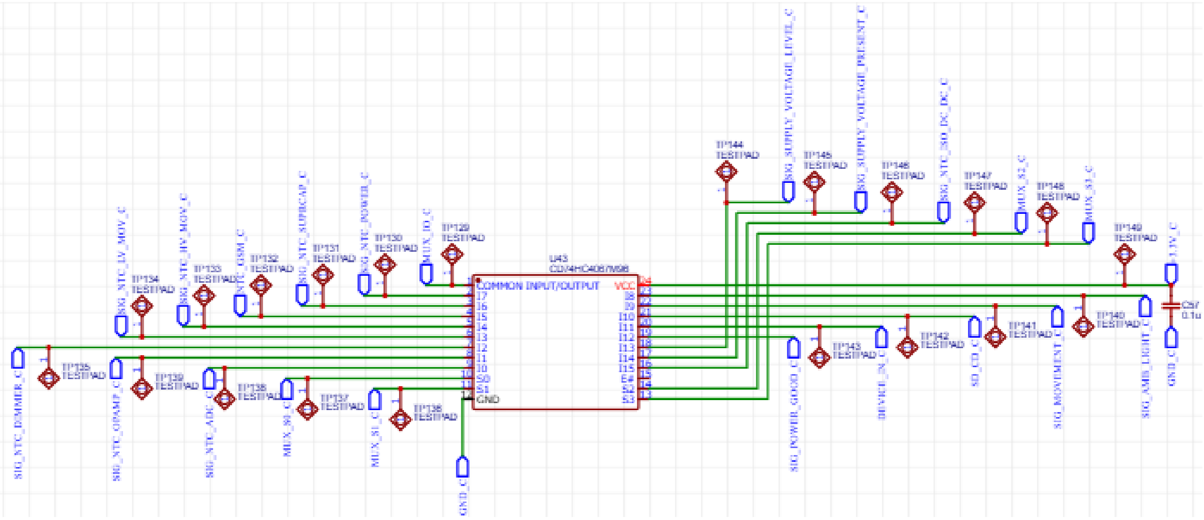

Fig. 2.4.1. Signal connection to multiplexor.

The multiplexor oi is being connected to MCU ADC, to measure the incoming signals, by applying address mask on a select line. Temperature will be measured as analog value, and then lately converted to readable temperature, and digital reading just will list full scale ADC output or complete 0 or value close to it.

PCB, Test pads and Soldering joints for debugging

The PCB design was made in EasyEDA editor, which also allowed for Gerber file generation, and was fabricated by JLCPCB. The complete PCB contains 5 separated layers:

- Layer A – it contains AC/DC converter, DC/DC 5-3.3V converter, supercapacitor and supercapacitor charging circuitry, together with connectors for the wires.
- Layer B –fully designed for output switch circuitry (dimmer, EMR, MOV, etc).
- Layer C – it contains power measuring loop, with the isolation DC/DC converter and a signal multiplexor(it was placed here, due to lack of the space in Main Layer)
- Main Layer – this layer is used for placing the MCU and GPRS chip, together with micro SD card holder and nano sim jack.
- Layer D – the layer, responsible for interaction with the user: it has several indication LEDs, motion detector, temperature and humidity sensor and ambient light sensor.

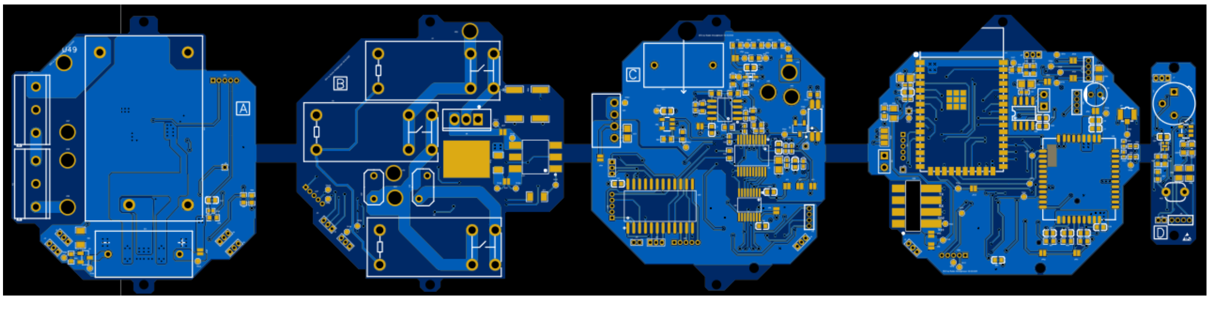

Fig. 2.5.1. Layers demonstration, PCB top side

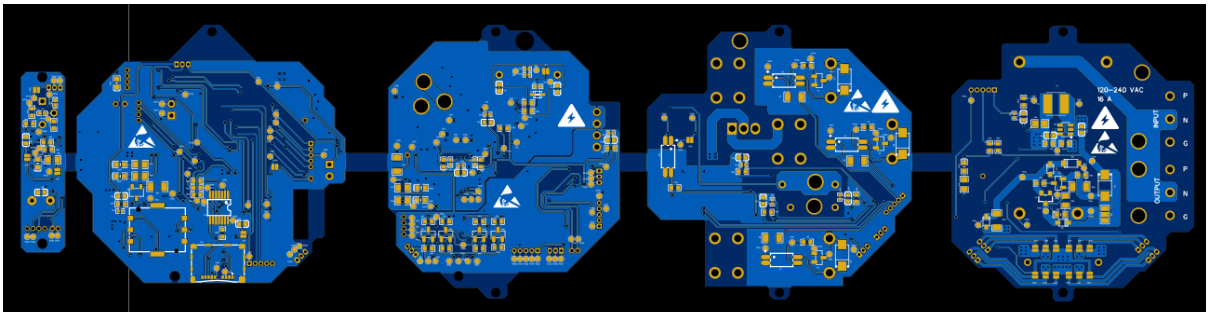

Fig. 2.5.2. Layers demonstration, PCB bottom side

Each of the layers have the holes for mounting to each other in so called "stack". The Layer D has the holes for it to be mounted on the reverse side of a socket outlet.

PCB also have some interconnection holes, because some signals are needed to be transferred between the layers (each signal has a letter at the end, indicating where it is "located"). Interconnections are also made for a power lines, where one of the goes directly through the current transformer, actually allowing for current measurement. Each PCB with a high voltage component present on it has special designator of a high voltage warning, and all of the plates have a designator of electrostatic discharge sensitivity.

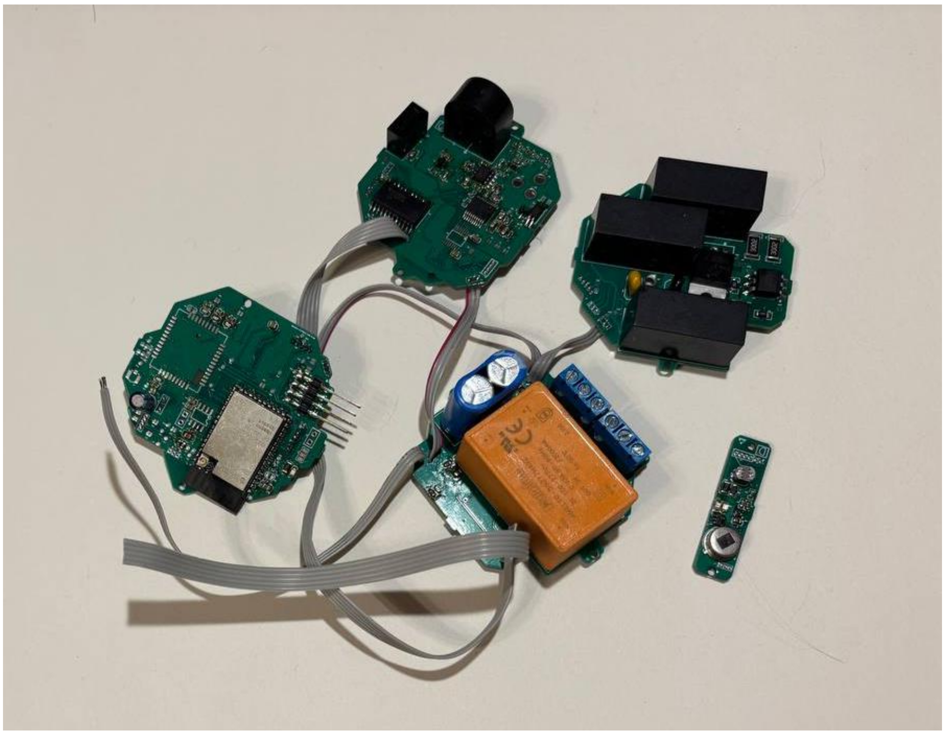

Fig. 2.5.3. Image of a SEIS during the assembly process, before being assembled in single unit. Top side.

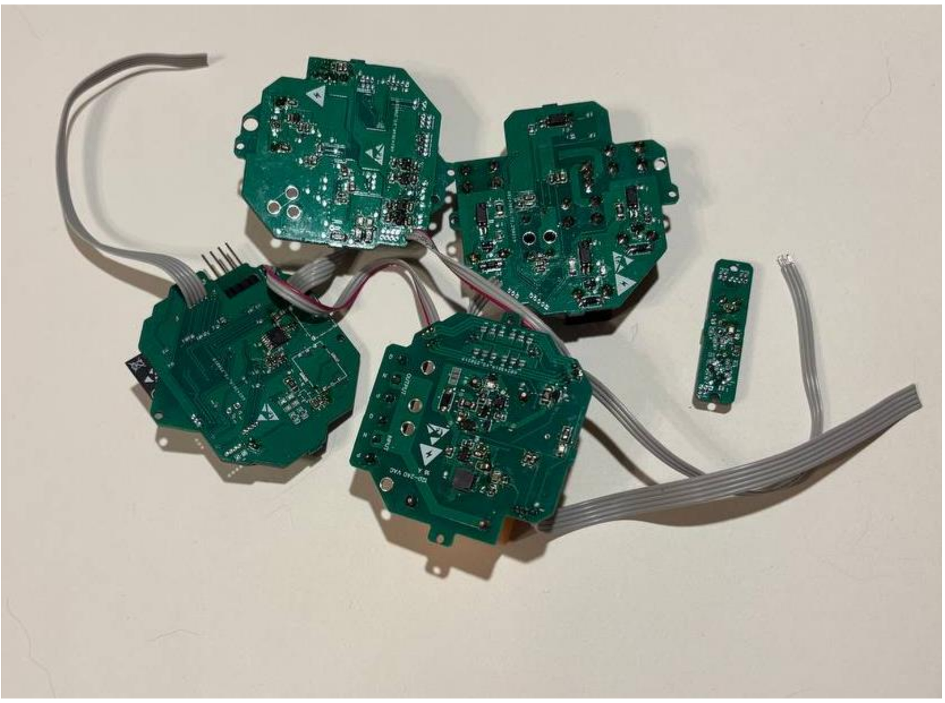

Fig. 2.5.4. Image of a SEIS during the assembly process, before being assembled in single unit. Bottom side.

Each PCB has a test point n each of the routes, which allows for easier debugging if needed, or, for instance, they were used for burden resistor and divider calibrations and measurements.

Also, another important feature of this PCB are the soldering jumpers. These are used for several purposes:

- Disconnecting power supply for each of the layer.

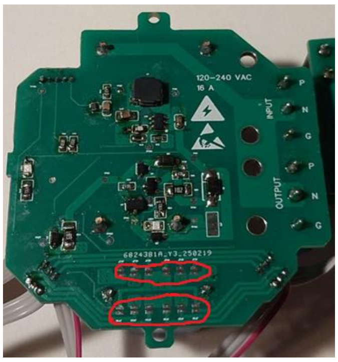

Fig. 2.5.5. Layer A power supply for each 4 remain layers jumpers

- Disconnecting and connecting expensive and sensitive electronics, only after everything was tested.

Fig. 2.5.6. Analog to digital converter pads, to disable the power supply

- Switching the device operation states. For instance, in Main layer there is a holes for a button, which is used as a device physical presence indicator in the outlet. The output of this buttons is connected to the 3-way jumper. Soldering one way make it a presence indicator, and soldering another pair makes it a reset button for board flashing.

Fig. 2.5.7. 3-way jumper used for the button action change.

Board also contains gold-pins for the UART flashing, mounted on the main layer, which allows for easy connection of a USB-TTL converter.

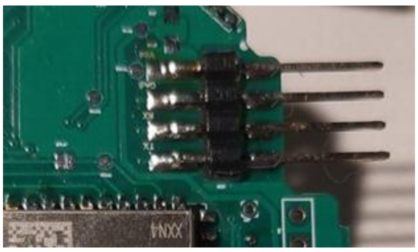

Fig. 2.5.8. Flashing pins.

Firmware

The firmware for the instrument was written using official ESP-IDF (Espressif IoT Development Framework), dedicated to ESP32 microcontrollers. This allows to run the Real Time Operating System, or RTOS, which provides grate performance and a capability of multitasking.

Particularly with this instrument, the FreeRTOS real time operating system was used. The firmware structure looks like this:

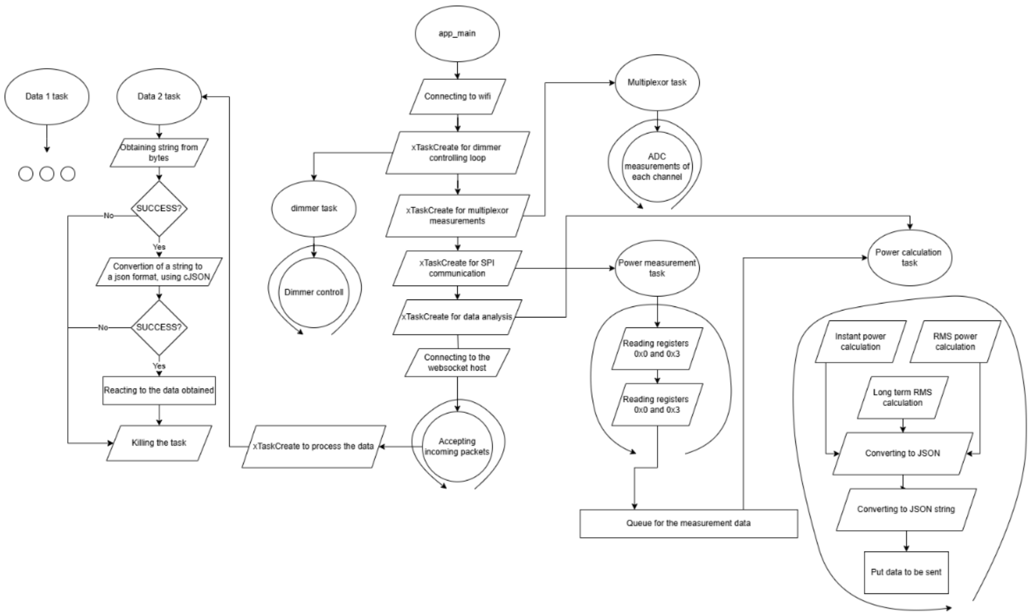

Fig. 2.6.1. Firmware task structure block diagram

As we can see, the program has a app_main. This is a task, that being created just when the program is launched. There, ESP first of all connects to Wi-Fi, and then starts to create tasks for different processes, using FreeRTOS xTaskCreate function.

Power measuring task(void power_measuring_task(void)):

- Priority: 3
- Memory heap size: 4096 bytes (2 - 3 measurement cycles)

Establishes the SPI connection and then continuously runs the infinite loop to read the information from the ADC registers, using SPI. The infinite loop is being repeated each 250 us (using vTaskDelay, together with), to have the 4kHz sampling frequency. This needs to have the higher priority to interrupt other tasks, when the new measurement needs to be taken, Then, obtained result is put into a Queue, to be shared and read by power processing task

Power processing task(void power_processing_task(void)):

- Priority: 2
- Memory heap size: 4096 bytes (mainly used by the FFT algorithm)

This task does the RMS, long term RMS calculation and the FFT. The result is being lately converted to a cJSON, stringified and putted to be sent from websockets. cJSON object then deletes.

Dimming task (void dimmer_task(void)):

- Priority: 2
- Memory heap size: 512 bytes

Dimming runs a conditional loop, where it detects the zero crossing point, and turns the signal on, after some time.

Main loop itself polls the websocket, to receive the incoming messages from the peers or the server. When something like that is received, the new task is being created:

Data processing task(void websocket_data_processing_task(void * *pvParameters*)):

- Priority: 3
- Memory heap size: 1024 bytes (for a cJSON convertions)

This task takes the data_ptr, and the length of the received packet. It then converts them into the char array, which is lately being parsed to a cJSON. If somewhere occurs the error, the task will immediately kill itself by vTaskDelete(NULL), to not to disturb other tasks from working.

When the object is being successfully converted, the specified actions in the command are done.

Flashing: Flashing the firmware and its compilation is done by the use of idf.py programm:

idf.py build

The project contains the cMakeFile.txt, in which there is a need to specify the files to be included and compiled.

For the scope of this exercise I used 2 external libraries, so called:

“cJSON.c”, “esp_websocket_client.c”.
Other, like drivers for GPIO and SPI line are built in libraries.
To upload the sketch, this command is used:
idf.py -p PORT flash
Where I need to specify the FTDI programmer port.
To make the instrument go to boot mode, there is a need to unplug it from the power supply, solder the JP19, to make the button go to a boot mode (what it is doing, is pulling IO0 of the esp32 to ground), and power it on, keeping it pressed, and flash.
The flashing procedure is done with the use of FTDI USB-UART converter, shown below:

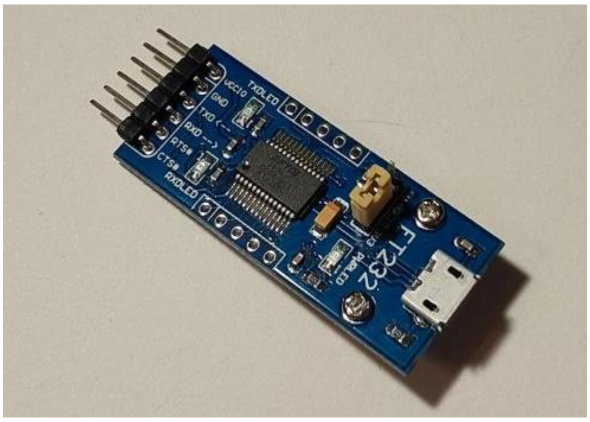

Fig. 2.6.1. FT232 USB-UART converter.

Communication with a server

The server for this instrument works in the way, that when it accepts a new client, it saves the instance of the websocket client to a class object, called NetworkPeer. This class has a static member – set of NetworkPeers. In this class, there will be an additional field, so called network_id, by using which, the server can distinguish between the peers.

Peers send the message to the server in form of the JSON format. The packet must have the task id, which is defined everywhere: in the instrument, mobile app and a server.

{"task": …, ...}

Here are some examples of a task id defines, taken from the firmware:

- #define TASK_USER_GET_NET_ID 0
- #define TASK_SET_NET_ID 1
- #define TASK_CREATE_TUNNEL 2
- #define TASK_TUNNEL_CREATED 3
- #define TASK_SET_EMR_STATE 4
- #define TASK_GET_CURRENT_TIME 5

This approach helps to reduce misspelling, and also add standardization to the data frames.

When peer is connected to the server, and it requesting TASK_SET_NET_ID, the server setts the id, requested by the user.

Then, the user receives positive response in the form of JSON with the task asked, and {"result":RESULT_OK}

response.

The user now can make a connection between itself and other users. Because, NetworkPeer has also the property of paired_users, which is a dictionary of type:

{id: <NetworkPeer instance>, …}

it makes it possible to save the instances of communication peers, and thus reducing the need of simultaneous search of pear with network id. The messages are just being forwarded to the peers directly, and peer can add or delete these references, and share the data directly with those references, that peer saved.

The user search is done by the static function get_peer_by_id(id : int) -> NetworkPeer.

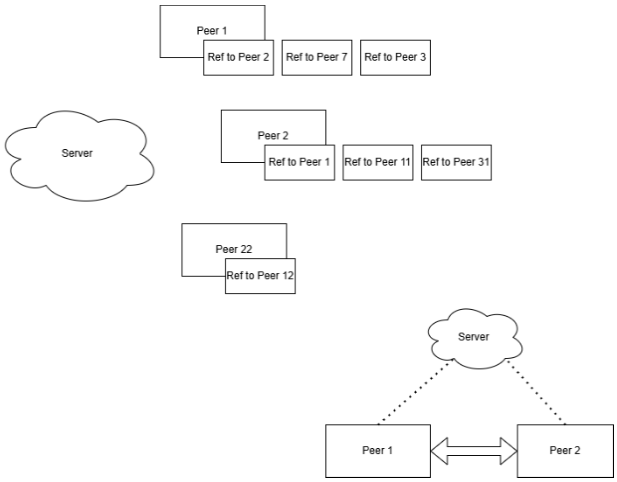

Fig. 3.1.1. Block diagram on how the communication works

The power monitors can also update their local times, as specified in IEC 61000-4-30 standard.

Server can be accessed globally, with the help of TCP tunnelling, made with Ngok tunnelling service.

The target server machine is the Raspberry Pi 4, on which there is 64-bit Raspbian lite version installed, with the SSH enabled.

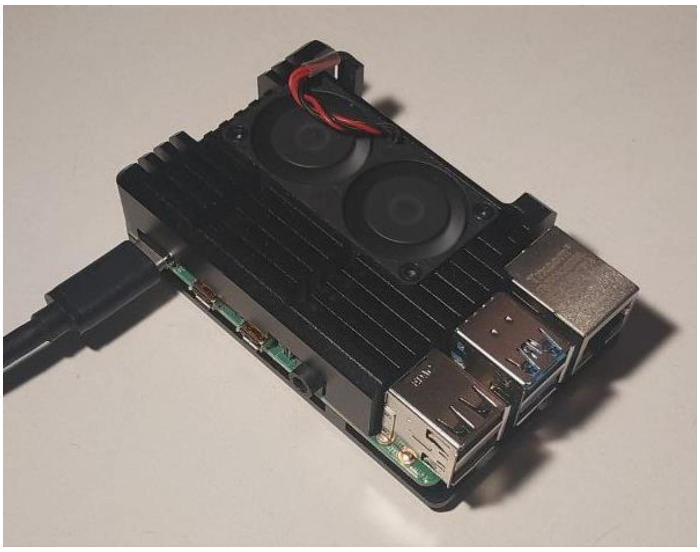

Fig. 3.1.1. Raspberry Pi 4 with the radiator.

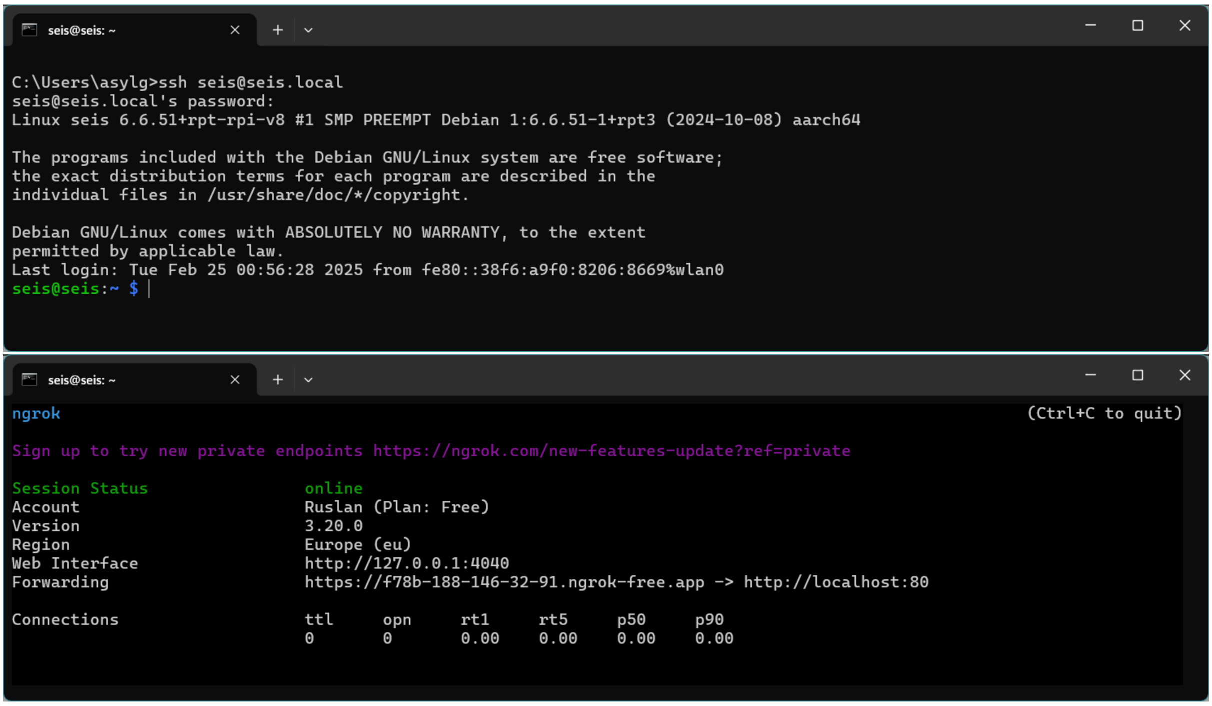

Fig. 3.1.1. The ssh service running, to have a remote console

After launching, the following command opens the tunnel for http:

ngrok http 80

The http word is used instead of TCP, because in ngrok documentation, it is written, that the websocket endpoints work through ngrok's HTTP tunnels. Now, the device can be connected to the server with the use of obtained domain, but with the wss at the beginning:

wss://f78b-188-146-32-91.ngrok-free.app

Device controlling application

Development Environment: The development environment, where the application was made is Godot Game Engine 4.3.0. This game engine provides nice GUI development interface, is being programmed as on the GD-script and as on the Java, and is compatible with Android .aar plugins made in Android studio with Gradle, or IOS plugins, written on Objective-C, and even exported to Windows, Linux, Mac OS or Web. The project creates in itself the websocket client, and as the unit, starts by sending the request for the id. Then the request for pairing, and it is ready to send the packets to paired devices.

The socket management application is quite intuitive. Users can configure and monitor the Energy Monitor, Control, Schedule, User, and Statistics sections. The Energy Monitor displays the amount of electricity currently being used; Control is the socket management menu; Schedule shows data statistics for the day, week, and month; Statistics analyzes energy consumption, makes forecasts, and sends notifications if there are system issues.

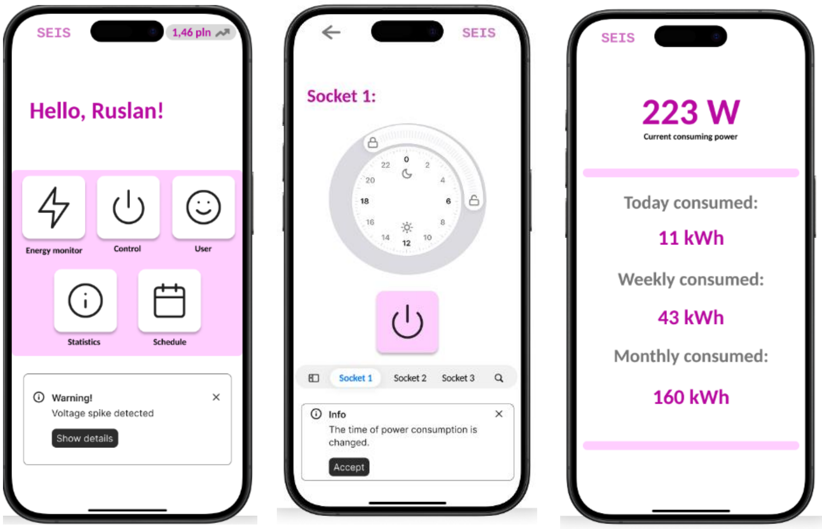

Fig. 4.1.1. The demonstration of the GUI of the application.

Engineering problems

PCB boot issue: This issue was caused by the misplacing the route. It was accidentally connected to the enable pin of the ESP.

The issue was tried to be resolved firstly by just connecting the IO0 with EN, but the board wasn't flashing then the button is pressed. So, last thing that was done is by sharping the route, and soldering the thin wire from the boot option on the JP19, to the IO0 f the ESP.

No GSM chip: Unfortunately, on the market the SIM7022 was not available just in time of the order. This issue could be resolved by connecting another one, but first it is a problem of voltage, because the modules that were available (mainly SIM800), they work at the level of 4V, while SIM7022 can operate even at the voltage levels of 2V

Not realized functions: Due to the lack of time, some of the function were not realised, like sockets grouping, user access privileges, sound emission, movement detection and socket physical blockage.

Current transformer measurement accuracy: The problem at this stage is that it was not possible to achieve the error at the desired 0.1% level, due to the lack of such component and by the way affordable current transducers. The best option was of class 0.2. Error without this transformer issue would be at most 0.1%.

Conclusions

Building the electrical energy measuring instrument is a challenging task, where there is a need to follow the criteria about isolation, measurement error, power supply stability and many other factors. The power measuring equipment can be of any type, and any accuracy. However, once designing an industrial-standard energy measuring device it is mandatory to fulfil the selected class of a measuring device from International Electrotechnical Commission standards.

The SEIS was designed to fulfil the Class A IEC 61000-4-30. The theoretical calculation with the selected components resulted in the total error to be on the level of 0.2% for the current and 0.11% for the voltage sensing. This does not fulfil the requirement of a Class A amplifier, but it is the maximal possible precision level with the available components present in the market.

The lack of the precise measurement burdens was compromised by the PCB structure, and existence of Test Pads and jumpers, that allow for no-influence measurement and testing of different parts of PCB.

The firmware requirements are fulfilled, the esp32s2-wroom-i4 is capable of running RTOS, that allows for multithreading and thus continuous measurements with all the tasks executed in parallel. External ADC allowed for cancelling the need of MCU to process the analog to digital conversion, but rather being interfaced by the fast SPI communication interface and reading the output reading registers of an ADC.

The communication protocol worked well, the server architecture allows for devices pairing and instant access from the paired devices, which provides high speed responses, allowing for low latencies. The server Itself is being run on a separated machine, and is capable to be reached from any part of the world.

The circuitry emergency power loop provides the power, supplied to the MCU and GPRS chip for a quite enough time to notice the lack of the incoming power, and notify the user about it.

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List of figures

List of tables

List of Abbreviations

AC – Alternating current

ADC – Analog to Digital Converter

AES – Advanced Encryption Standard

CMRR – Common Mode Rejection Ratio

COM – Communication

CPU – Central Processing Unit

DC – Direct current

DFT – Digital Fourier Transform

DIAC – Diode For Alternating Current

DNL – Differential Non-Linearity

ECC – Elliptic-Curve Cryptography

EMC – Electromagnetic Compatibility

EMR – Electromechanical Relay

FFT – Fast Fourier Transform

FSR – Full-Scale Range

FTDI – Future Technology Devices International Limited

GPIO – General Purpose Input/Output

GPRS – General Packet Radio Service

GSM – Global System For Mobile Communication

HMAC – Hash-Based Message Authentication Code

HTTP – Hyper Text Transfer Protocol

I2C – Inter-Integrated Circuit

I2S – Inter-Integrated Circuit Sound

IEC – International Electrotechnical Commission

INL – Integral Non-Linearity

IoT – Internet of Things

JP – Jumper

JSON – JavaScript Object Notation

LED – Light Emitting Diode

LSB – Least Significant Bit

LTE – Long-Term Evolution
MCU – Microcontroller Unit
MOV – Metal Oxide Varistor
MQTT – Message Queuing Telemetry Transport
NB-IoT – Narrow-Band Internet of Things
NCT – Negative Temperature Coefficient
OPAMP – Operational Amplifier
OS – Operating System
OTG – On-The-Go
OTP – One-Time Password
PCB – Printed Circuit Board
PPPoS – Point-to-Point Protocol over Serial
PSRAM – Pseudostatic Random Access Memory
PSRR – Power Supply Rejection Ratio
RF – Radio Frequency
RNG – Random Number Generator
RMS – Root Mean Square
ROM – Read Only Memory
RSA – Rivest-Shamir-Adleman
RTCSRAM – Real Time Clock Static Random Access Memory
RTOS – Real Time Operating System
SCR – Silicone Controlled Rectifier
SEIS – Smart Electrical Installation System
SHA – Secure Hash Algorithm
SPI – Serial Peripheral Interface
SRAM – Static Random Access Memory
SSH – Secure Shell
SSR – Solid State Relay
STOMP – Streaming Text Oriented Messaging Protocol
TCP – Transmission Control Protocol
TP – Test Pad
TRIAC – Triode For Alternating Current

TVS – Transient Voltage Suppression

UART – Universal Asynchronous Receiver/Transmitter

USB – Universal Serial Bus

USB-TTL – Transistor-Transistor Logic

ZD – Zener Diode