Bachelor assignment - Module design document

Diagnostic measurements on current transformers

Applied to 150/110/50kV oil-filled instrumentation transformers within the TenneT and Liander power grid.

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Abbreviation list

Abbreviation	Explanation
HV	High-Voltage
TCU	Temperature control unit
CT	Current transformer
VT	Voltage transformer
IT	Instrumentation Transformer
Moscow	Ideation method Must-Should-Could-Would
$tan\Delta$	Angle loss measurement
V_s	Voltage (secondary)
V_p	Voltage (primary)
N_s	Number of turns (secondary)
N_p	Number of turns (primary
ADC	Analog to digital converter
WWW	What went well
EBI	Even better if

Background

1.1 Introduction

The Netherlands is highly honored for its reliable energy grid. However, the increasing electricity demands pose risks to this reliability. Ensuring the reliability of high voltage components such as transformers is critical in maintaining the power grid's integrity.

This document focuses on monitoring the conditions of Current transformers (CT) to prevent failures that can affect the system's stability.

1.2 Company overview

As a company Qirion operates under Alliander, specializing in the management and maintenance of High-voltage (HV) installations across 70% of the Netherlands electrical grid, as part of Alliander commitment to providing reliable, affordable, and sustainable energy, Qirion focuses on innovative solutions and efficient operation of energy networks.

The vital role in designing, building and maintaining energy infrastructure ensuring continuity and safe distribution of electricity, Bellow the figure displays the activities of the Alliander group in an organogram, grid operator, network activities and the network activities in Germany.

Figure 1

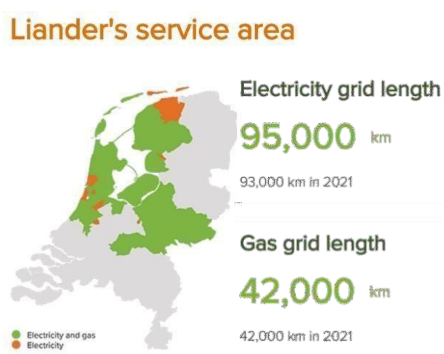


Figure 2 Service area (Al)Liander (Alliander, 2023)

1.3 Project description

The project will be carried out within Qirion's Quality and Maintenance Management (K&MM) department in the Maintenance and Management team (Team Onderhoud en Beheer in Dutch). Among other things, this department advises the TenneT and Liander asset management departments on maintenance and asset management. With its (technical) expertise, the department also supports the operational installation managers of TenneT and Liander. The Advisor Maintenance Engineer (AME) advises and supports various departments within TenneT and Liander based, among other things, on the condition data in the maintenancemanagement system.

1.4 The problem

When an CT fails due to, for example, internal short circuit because of excessive moisture content in the paper, huge damage to adjacent assets and potential human injury occurs.
Besides the asset exploding, porcelain shards fly around because of the insulator exploding resulting in huge risks. Figure 3 below shows the damage following a failure in the field. It is essential to monitor the condition of suspected designated assets regarding safety, operational management and maintenance (strategy).
Instruments in the HV grid are maintained and inspected as shown in figure 4 below, different condition codes are assigned to the asset and its subcomponents, which is used for planning corrective maintenance and replacement investments.

Figure 4 Ct inspection in the Lab

Figure 3 exploded CT (Internal source) - 150kV installation

Real-time condition monitoring and condition-based maintenance are not yet widely applied within Liander. The reasons for this are that assets in the past were generally loaded low and that redundancy in the network was much more secure than it is now and will be in the future.
There are several health modes by which a CT can be in.The failure modes depend on the type of component used and its environment, in this assignment, Realtime-based condition measurements are carried out on which a component is approved or rejected in accordance with temperature change. For this condition assessment, the component needs to be taken out of service or brought to the laboratory.
The aim of the project is to enable online condition assessment methods. This ‘circle’ starts with determining the health of the equipment and ends with the choices made in terms of management and maintenance strategy.
the use of a general assessment sheet which provides an index of whether the data being collected meets the requirements of healthy equipment, this is given by the company.

Table 1 Requirements

Health	Explanation
Good	Standard inspection program.
Sufficient	
Poor I	Work in high voltage stations can continue but replace components on medium-long term.
Poor II	Replace on short time, short time work in high voltage station is possible, applying additional protective measures during prolonged work is necessary.
Poor III	Directly switch off component, 100% shielding and replace component as soon as possible.

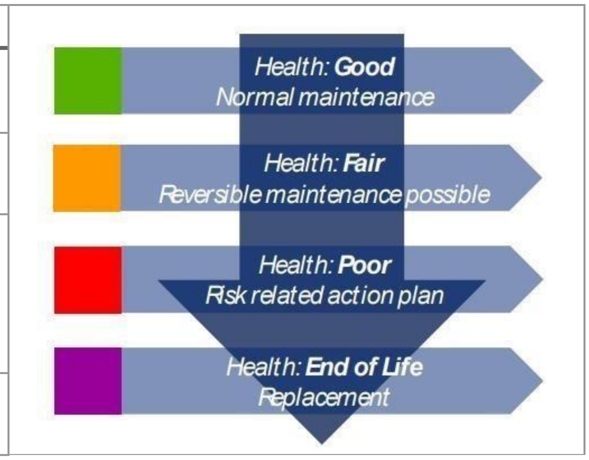


Table 2 Requirements

Method	Explanation
IDAX	IDAX measures based on frequency response and measures in a significantly wider frequency range (0.0001 - 1000 Hertz) than tangent delta (5 - 400 Hertz), making it a more comprehensive tangent delta measurement method. IDAX is not temperature dependent and determines the moisture content in the oil. When the temperature rises, the moisture extracts from the oil and reverses when the oil cools down. If this process occurs too quickly, moisture will accumulate, causing partial discharges that can lead to major failures. Another The advantage of IDAX is that the measured values can be calculated back to temperature.
Oil analysis	Often referred to as a reliable method of determining insulation ageing, but difficult to perform non-destructively on CTs. Oil analysis is considered risky due to the risk of moisture and air entering the CT and is therefore mainly used as a control method when other methods have shown that the condition may be severely deteriorated. Qirion does not use oil analysis in non-destructive measurements. However, oil samples are often used in destructive testing. Performing oil analysis with sensors may have potential.
Thermographic	Included in the TOR but not as one of the condition assessment methods for the insulation medium of the CT. In most cases, this technique also does not aim to determine condition but detect consequences of beginning failures such as links getting too hot because of increased contact resistance. For example, the thermographic inspection provided insight into the failure mechanisms of the CTs in Hemweg.
Partial discharge	Partial discharge measurements indicate the insulation quality of the worst part of the insulation. The variation in the number and energy level of partial discharges indicates the end of life of the oil/paper insulation. This method is specified in the TOR but is rarely used as a condition assessment. Unlike the tangent delta and oil quality assessment methods, no rejection criteria or standards have been established. Assessment by partial discharge has been included in the TOR by TenneT because they see potential in this form of condition assessment, but it has not yet been developed.

1.6 Reasoning of the Internship

This internship is part of my educational journey at Fontys University of Applied Science, aiming to bridge theoretical knowledge with practical skills acknowledged from the university in electrical engineering major, it focuses on addressing critical issues faced by Qirion in maintaining the integrity of HV components like current transformers.

1.7 Expectations

Qirion works with these transformers daily, the grid requires a more effective and efficient way to be able to acquire data and use it for research, in this research assignment the following is expected to meet the requirements of Fontys university of applied science and Qirion as a trainee.

The system can measure three-phase currents by using both *Model LB and Model CA* oil-insulated current transformers. The key processes involved are the measurement of leakage currents and the calculation of phase differences.
The company uses equipment from external providers to acquire real time data while testing these HV instruments either in the field or Labatory, my role as a trainee is to understand all the different methods and equipment's in use throughout the training process and to enhance a handheld measurement tool which can accomplish the following:

Table 3 Requirements

ID	REQUIRMENTS	PRIORITY	STATUS
U1	INPUTS: DESIRED TEMPERATURE $0-60°C$	MUST	PROPOSED
U2	GRID FREQUENCEY $50Hz$	MUST	PROPOSED
U3	INSTRUMENTATION AMPLIFIER	SHOULD	PROPOSED
U4	LED • RELAY STATUS • HEATER STATUS • TEMPERATURE READING • LEAKAGE CURRENT	MUST	PROPOSED
U5	USER INTERFACE	COULD	PROPOSED
U6	THERMOCOUPLES (TYPE-T)	MUST	PROPOSED
U7	LEAKAGE CURRENT MEASUREMENT $0-100\ mA$.	MUST	PROPOSED
U8	ADC CIRCUIT 24-BIT RESOLUTION FOR HIGH PRECISION DATA PROCESSING	SHOULD	PROPOSED
U9	UART RECEIVER TRANSMITTER MODULE	WOULD	PENDING
U10	MOTION SENSOR	COULD	PROPOSED
U11	PRESSURE SENSOR	COULD	PROPOSED
U12	PLASMA SENSOR	COULD	PROPOSED

Data Collection: Improve accuracy and reliability of leakage current measurements under varying temperature conditions.
Optimize Algorithms: Enhance the efficiency of data processing algorithms to provide real-time analysis.
Integrate Systems: Ensure seamless integration of the hardware and software components for continuous monitoring.
Reporting: documentation and provide detailed reports on findings and improvements.
These enhancements aim to optimize the transformer maintenance process, reduce downtime, and ensure the reliability of the power distribution network.

Research

1.1 Research questions

- What accuracy and resolution are needed in the measurements?
- Are there space or power constraints for the circuit within the test setup?
- What is the relationship between $\tan \Delta$ temperature inside a current transformer?
- What are design considerations for HV measurement instruments?

This research is based on general transformers. Figure 1 displays an example. A separate document has been written containing the research material.

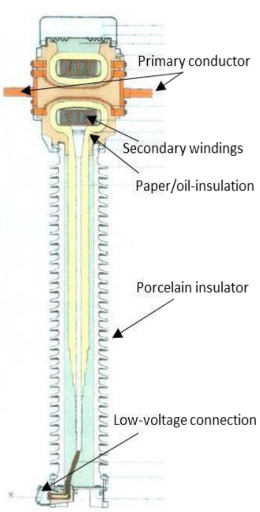
Further research on transformers

During my 20-week internship, our specialized team investigated ways in how to enhance the detection of leakage current, using real-time assessment techniques to improve maintenance, safety, and operational management. This project is supported by Qirion, providing all necessary resources. In this case we will be focusing on oil-paper immersed transformers **(Specifics are explained bellow in section 1.x)**

I used the Moscow method to prioritize essential requirements, drawing from expert advice and thorough research. This research focuses on asset performance of 150/110/50kV oil-filled CTs, which are widely used in the TenneT and Liander power grid. A 150kV oil filled current transformer in a high voltage installation is shown in 4, Figure 5 shows a cross- section of a similar type.

During the first couple of weeks the following questions were researched and documented to give a brief understanding.

1.2 Importance of Transformers



Current transformers are designed to provide a scaled down replica of the current in the HV line and isolate the measuring instruments, meters, relays, etc., from the high voltage power circuit, in this project we will be researching and finding different ways to effectively measure the effectiveness of a transformer and be able to optimize the maintenance procedure of the following HV equipment.

Mathematically, the operation of a transformer is governed by the following relationships:

1. Voltage transformation ratio:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

Where V_s is the secondary voltage, V_p is the primary voltage, N_s is the number of turns in the secondary winding, and N_p is the number of turns in the primary winding.

2. Current transformation Ratio:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}$$

Where I_s is the secondary current and I_p is the primary current.

In the step-up transformer, the number of turns in the secondary winding (N_s) is greater than the number of turns in the primary winding (N_p), resulting in a higher secondary voltage $V_s > V_p$ and a lower secondary current ($I_S < I_p$). Vise-versa in a step-down transformer.

Transformers are also crucial, Insulation within transformers is vital for preventing electrical faults and ensuring safe operation. The insulation system in a transformer can have different orientations, Oilpaper, gas and dry insulation.

1.3 Leakage Current Measurement

Using a current sensor to measure the leakage currents in each phase, these sensors can be Rogowski coils, Hall effect sensors, or other suitable devices.

Collect real-time data using a data acquisition system (DAQ) connected to each phase, The following features make it ideal for this application:

Sensor in use:

FG-R05 Series Current Sensor

Why:

FG-R05 Series Current Sensor was chosen for this project due to its high sensitivity and precision in measuring leakage currents, which are critical parameters for assessing the condition of high-voltage current transformers (CTs). This sensor can detect small variations in leakage current, which can indicate issues such as insulation degradation or faults.

Why the MX3 board:

- **Versatility**: The MX3 board supports various sensors and peripheral devices, making it adaptable to different experimental setups.
- **High-Resolution ADC**: The 10-bit ADC on the MX3 board provides adequate resolution for precise measurement of leakage currents.
- **Processing Capability**: The PIC32 microcontroller's 80 MHz speed and ample memory allow for real-time data processing and analysis.
- **Connectivity**: Multiple communication interfaces (UART, SPI, I2C) facilitate integration with other devices and data logging systems.
- **User-Friendly**: Compatibility with development environments like MPLAB and Arduino IDE simplifies coding and debugging.

How using this kind of sensor, we can achieve the leakage current

The high precision/sensitivity with an analog signal which the sensor can produce as an output which is proportional to the current passing through it helping acquire the data which can then be read with the already existing ADCit through a processor which will be used in the software.

Phase Calculation

Measuring the time difference between the zero-crossing points of each phase current waveform allows us to be able to use the phase difference formula to display the difference in phase of in this case the three phase measurement of a current transformer.

Phase Difference Formula:

$$\Delta\phi = \phi 2 - \phi 1$$

where:

o ϕ Δϕ is the phase difference between the two waveforms.

ϕ 1 ϕ 1 is the phase angle of the first waveform.

ϕ 2 ϕ 2 is the phase angle of the second waveform.

Graph representation:

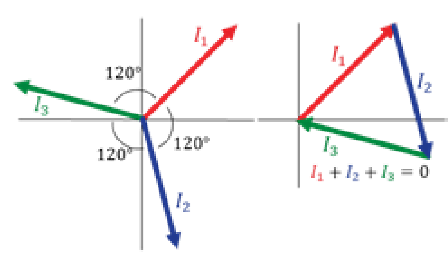


Figure 5 phase difference graph representation

ARTECHE HIGH VOLTAGE INSTRUMENT TRANSFORMERS.

Liquid Insulation: Oil-immersed transformers use mineral oil or other insulating liquids to provide cooling and additional insulation. The oil acts as a dielectric medium and helps in dissipating heat generated during operation.

Figure 1 model CA

Figure 2 model LB

Dielectric Strength: Excellent electrical insulation properties.
Effective Cooling: Efficient heat dissipation.
Moisture Management: Oil can absorb moisture, protecting solid insulation materials.
Disadvantages:
Leakage Risk: Potential for oil leaks.
Flammability: Some oils are flammable.
Requires periodic oil sampling and analysis.

Differences Between Model LB and Model CA
Model LB (Oilpaper Insulated Current Transformer)

- **Design**: Generally designed for outdoor applications, robust against environmental conditions.
- **Voltage Levels**: Suitable for high-voltage applications, commonly used in transmission networks.
- **Construction**: Typically, larger and more rugged, designed to withstand higher mechanical stresses.
- **Cooling**: Uses oil for both insulation and cooling, ensuring high performance under extreme conditions.

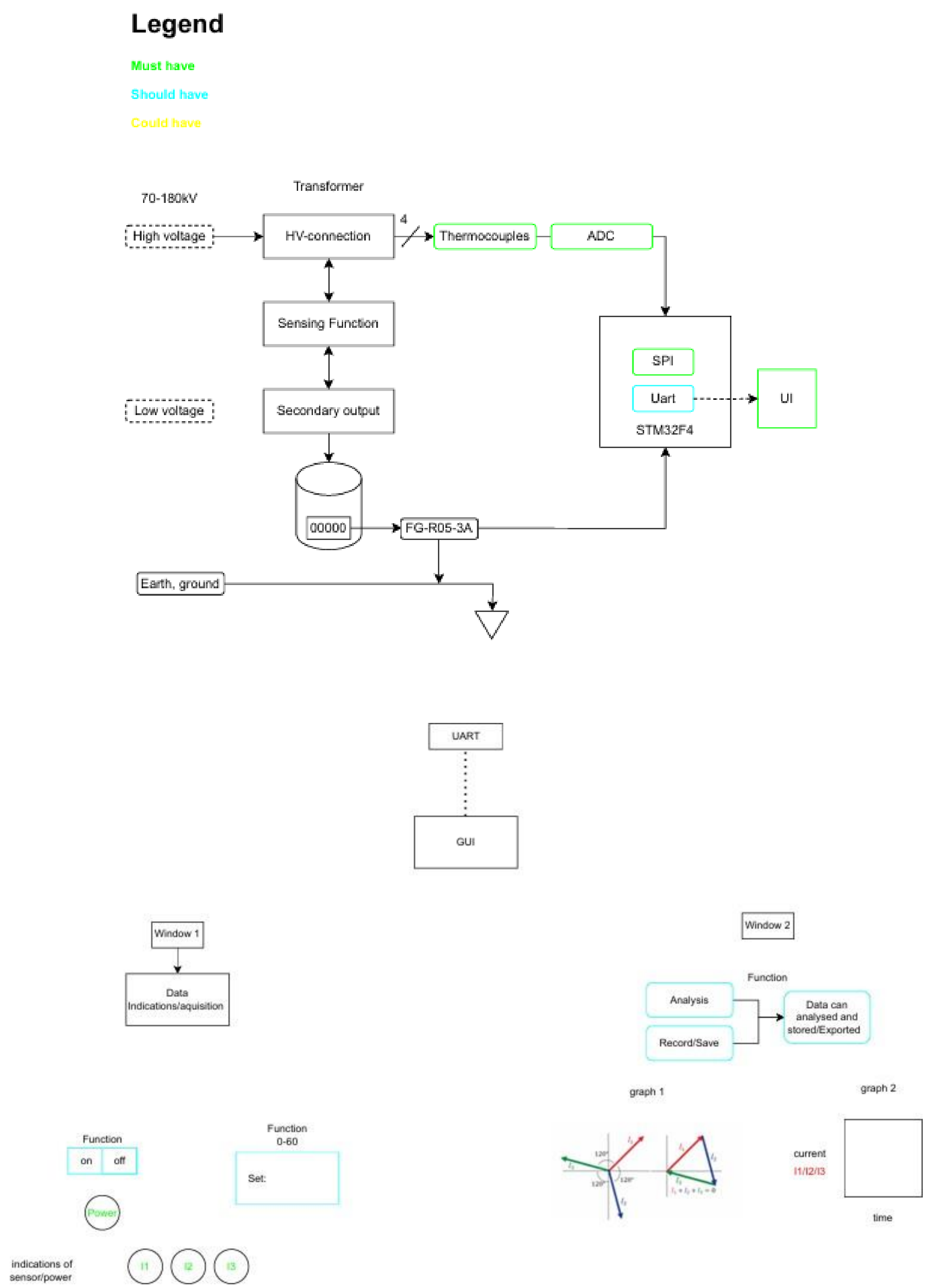
Model CA (Oilpaper Insulated Current Transformer)

- **Design**: Often used for both indoor and outdoor applications but might be more compact compared to Model LB.
- **Voltage Levels**: Suitable for medium to high-voltage applications, often used in distribution networks.
- **Construction**: May have a more compact design, suitable for spaces where larger transformers cannot be accommodated.
- **Cooling**: Like Model LB, it uses oil for insulation and cooling but may have design optimizations for specific installation environments.

Relevance to This Project
For this project, oil-paper insulation (CTs) is the primary focus, Monitoring the condition of the insulating oil, especially its dielectric strength and moisture content, is essential for assessing the health of the CTs and preventing failure.
In conclusion, after several weeks of attending lab sessions and understanding how the company likes to operate, a system requirement document has been designed and drawn, using ideas with an expert in the field, we were able to come up with specifications for a handheld measuring tool which can be used for data processing/analysis and of course compatible in there way of working making it accessible in the lab.
These requirements lists were assessed by the company and the university to continue with the research assignment.

System design documents

In this section, the requirement table is outlined with a drawing which is used to comprehend the overall system design comprehensive design of the system developed for leakage current measurement in high-voltage current transformers. This includes the integration of sensors, the microcontroller platform, and the system's overall architecture. Detailed schematics and design rationales will be provided to ensure clarity and reproducibility.



Testing/Verification

This chapter focuses on the testing and verification processes applied to ensure the accuracy, reliability, and efficiency of the leakage current measurement system. Different tools are used to validate both the hardware and software components. The results of these tests, along with any observed issues and their resolutions, will be documented to demonstrate the system's compliance with project requirements.

Hardware

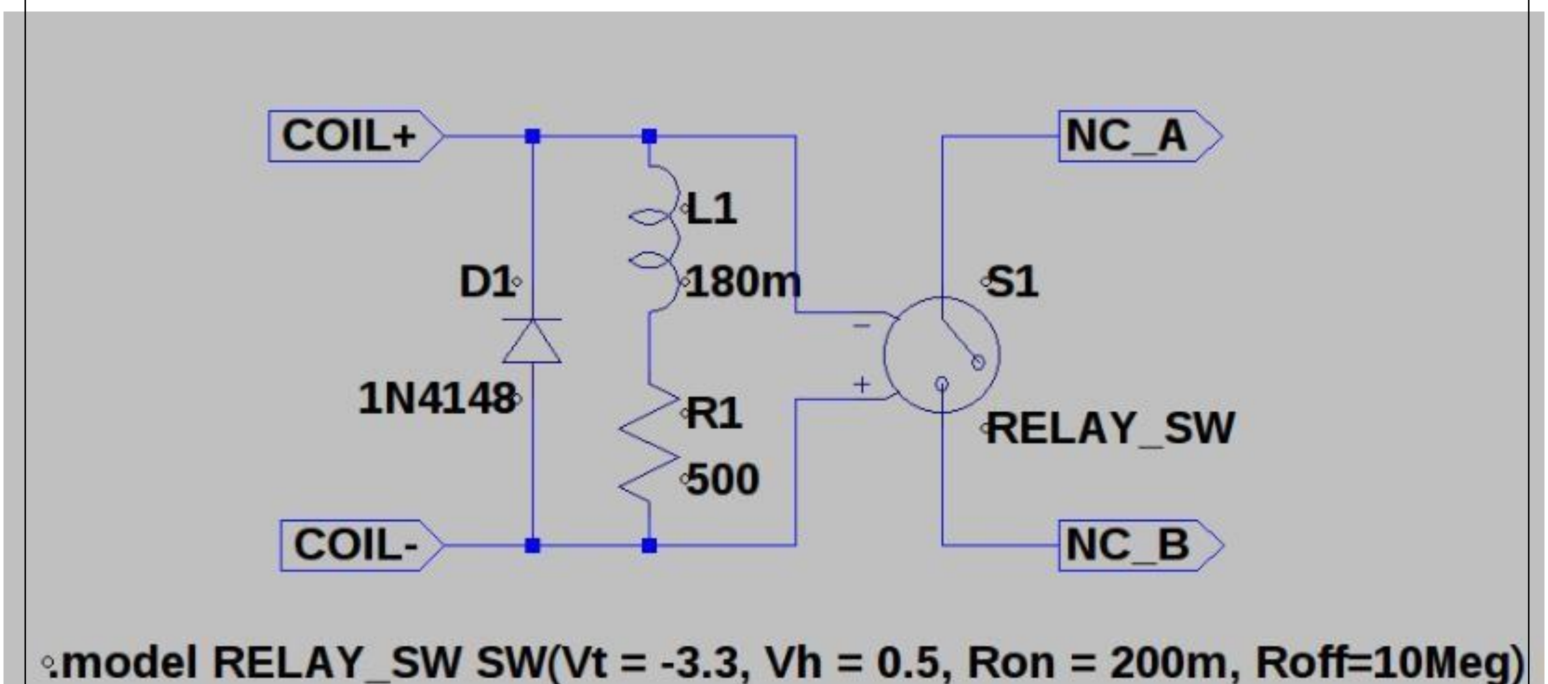
In the hardware section, we will explore the specific physical components that form the backbone of the leakage current measurement system. This includes detailed descriptions of each component's role, specifications, and I integration into the overall system.

- Relay module

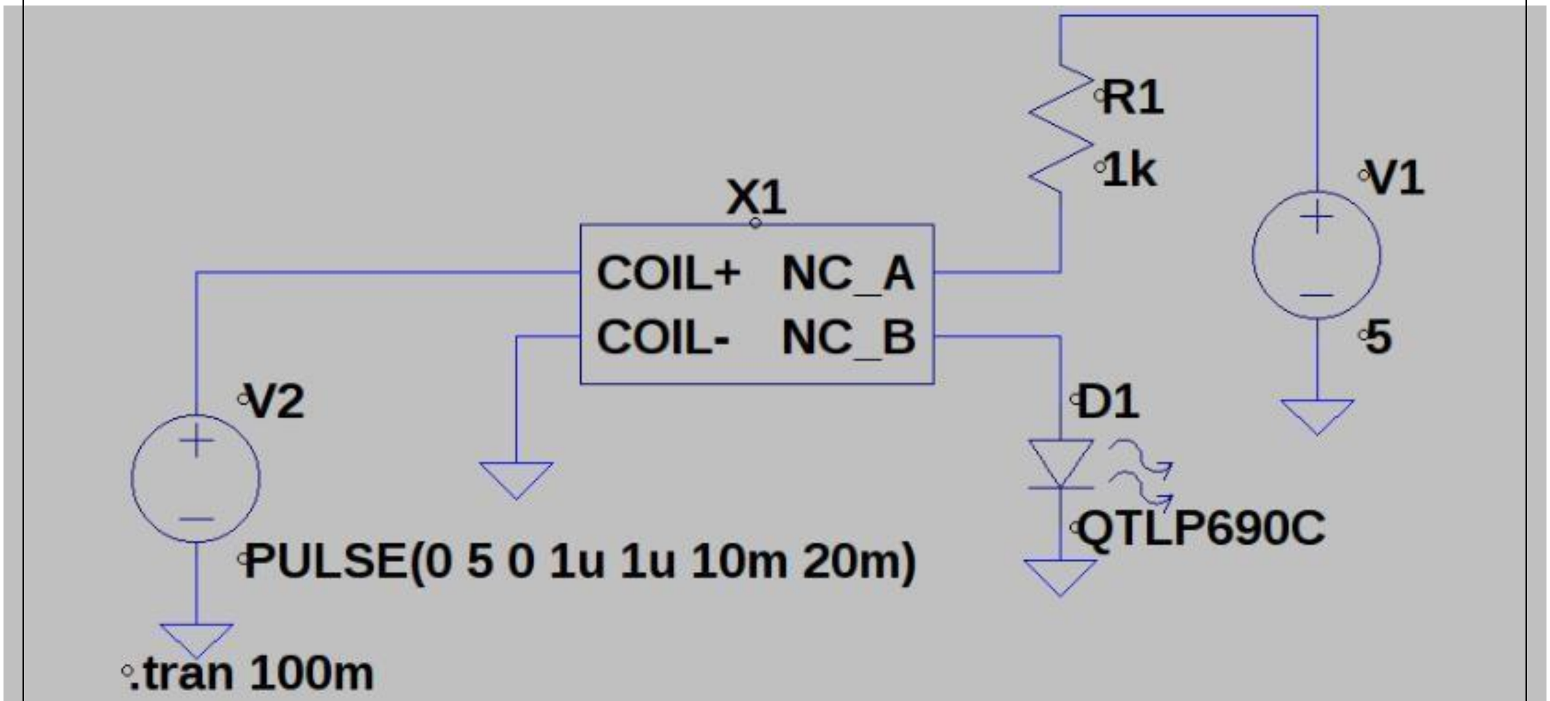
Here we used Lt spice to model a digital pin to control the SLA-12VDC-SL-C, since the parts were not acquired due to certain circumstances.

The coil resistance is specified by the manufacturer, as are the pull-in and drop-out voltages (modeled here as a threshold and hysteresis value). What they don't tell you is the coil inductance.

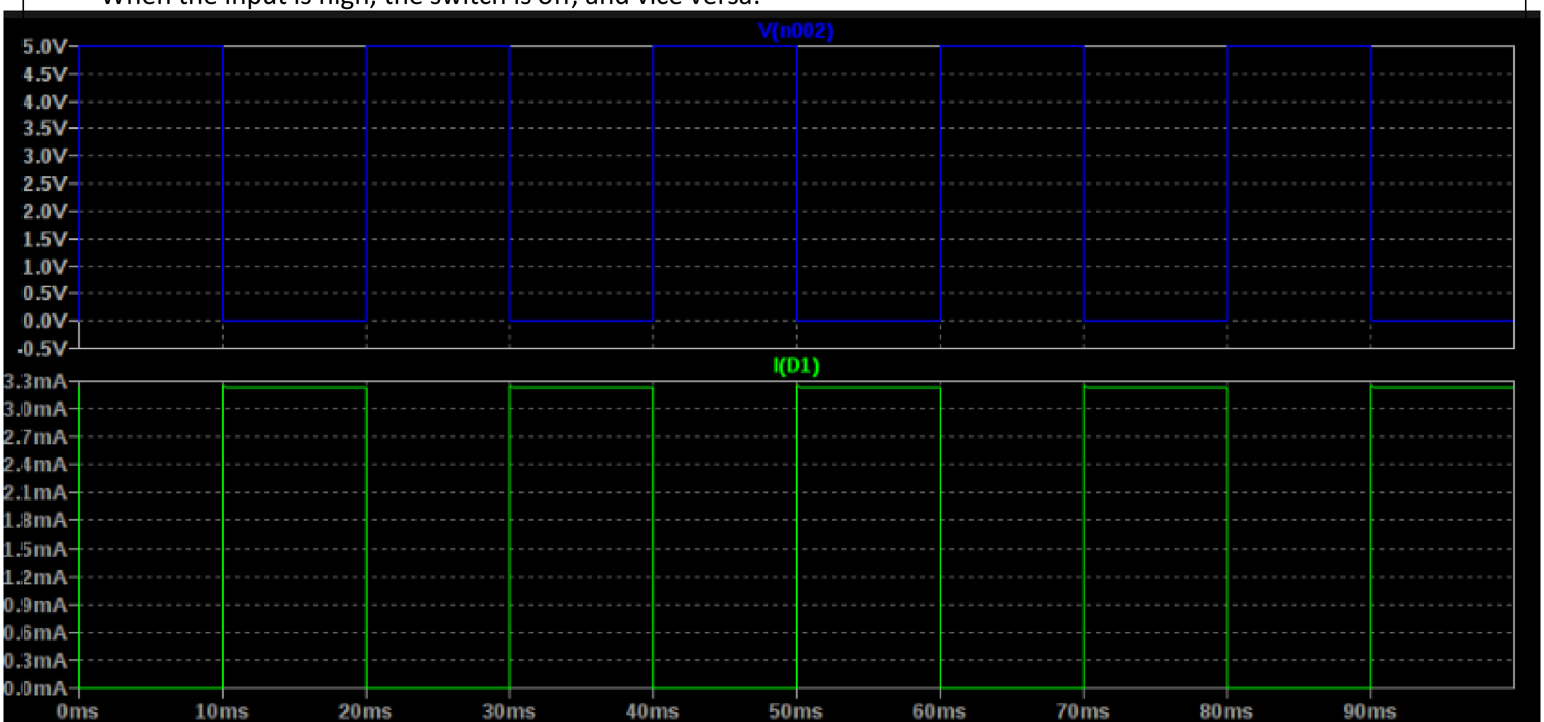
I guessed at a value based on the pull-in and dropout times and the voltage thresholds. With a 180m inductor, the switch in this model has similar timing to the published relay specs.



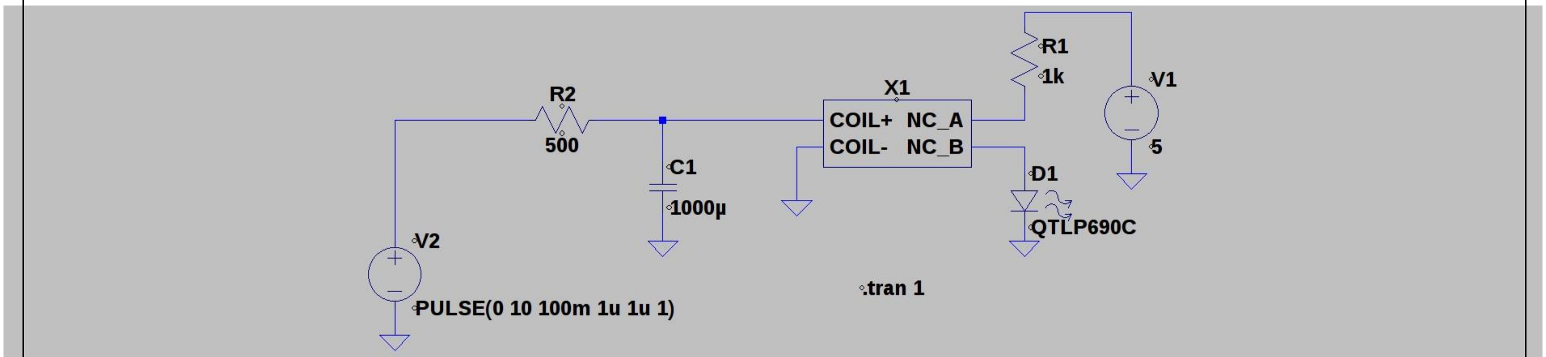
To get a normally closed output, I reversed the connections to the voltage-controlled switch component and used a negative threshold voltage. This whole circuit can be encapsulated in an LTspice symbol, shown here switching an LED:



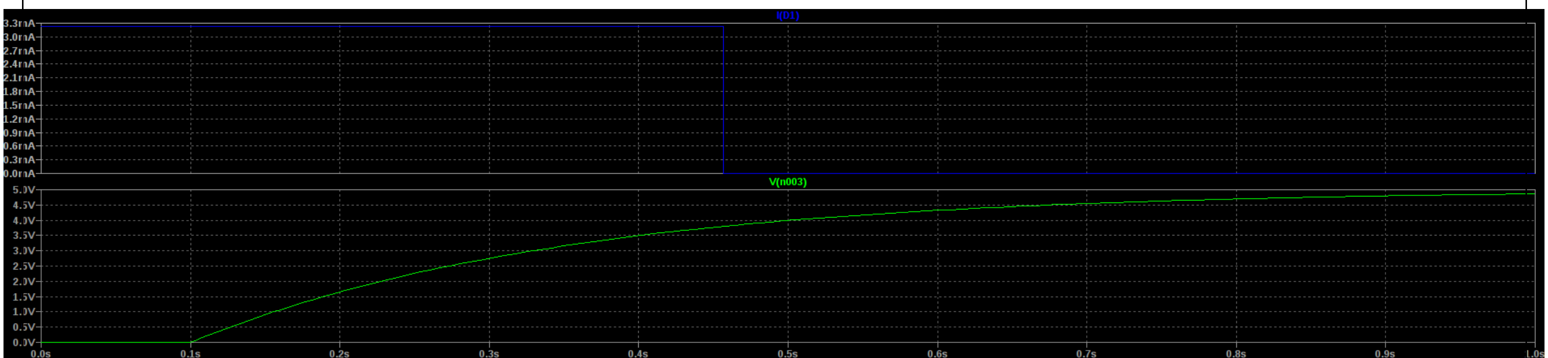
When the input is high, the switch is off, and vice versa:



Which isn't that impressive, but that's not why I made the model.
Slightly more interesting is the power-on reset circuit:



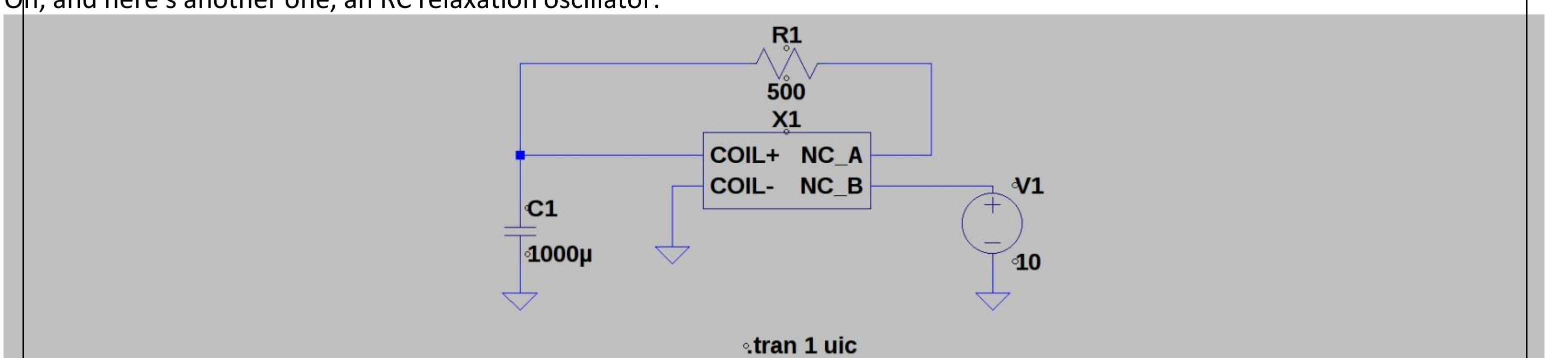
The supply starts at 0V and comes up to 10V at 100ms. R2 charges C1 slowly, delaying the opening of the relay contacts. With these values, the delay is about 350ms:



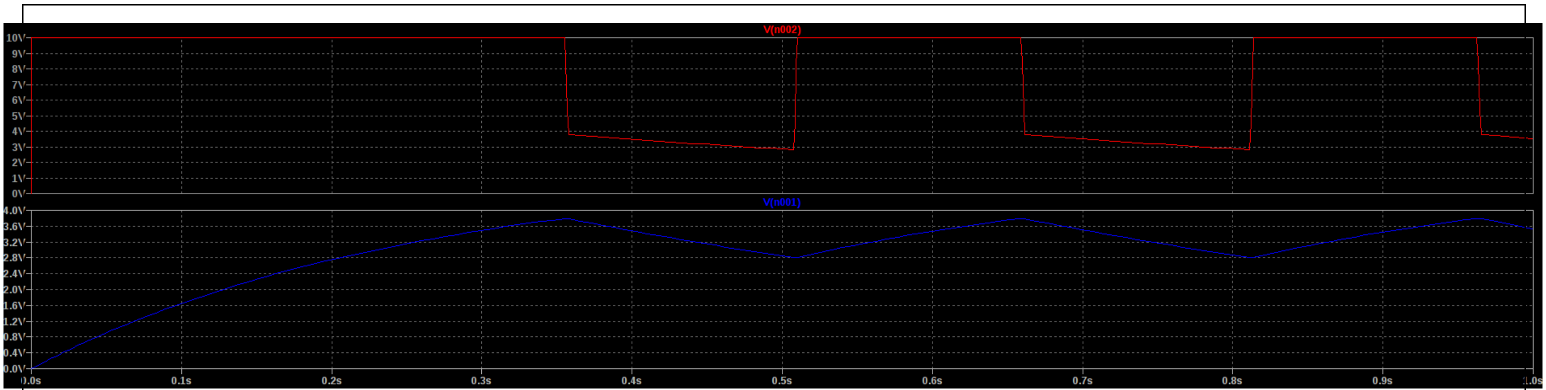
You can see the linear ramp (bottom; green) and the LED current (top; blue). The LED here represents the reset line for all the flip-flops. They'll be held in reset for those initial 350ms, ensuring they start in a known and stable state.

Is this a perfect simulation? Probably not - some values will need to be tweaked when I move to the real hardware, but I can get a qualitative feel for how things will work.

Oh, and here's another one, an RC relaxation oscillator:



It's the same thing you might see made with a Schmitt-trigger inverter and relies on the hysteresis of the relay to switch on and off, charging and discharging the capacitor. Here's the output:



The bottom trace (blue) is the voltage on the capacitor charging and discharging, with the output shown in the top trace in red. It oscillates at about 3Hz with these component values.

Software

The software section provides an in-depth look at the programming and code development that powers the leakage current measurement system, most of the data sheets and details of the board that is used can be seen in the references bellow and aswell as the requirements table.

Algorithm

Here is a short brief subsection describes the algorithms used for processing the data collected by the FG-R05 Series Current Sensor,
Here is a short brief,

Firmware for PIC32MX370F512L:

The firmware starts from main function which initializes clock and the peripherals like, UART for GUI, SPI for ADC, and timer for stamping time and regulating firmware into time-loop by calling function ***SYS_Initialize ( )***. This function also prepares timer1 to interrupt every 100ms.

The firmware has two main tasks, one is to interact with ADC through SPI and other is to interact with GUI by UART1. For GUI custom protocol is implemented on UART, it has 16 bytes of packet, specified and mutually agreed header and data integrity check by calculating checksum and appending this checksum in the packet. This will ensure error free and authentic data sharing between GUI and this firmware.

Then firmware enters while(1) loop, which means it will stay in this loop till power up. On the other hand, timer1 is configured to interrupt every 100ms, it means every 500ms the controller will pause main loop to entertain interrupt. Interrupt service routine (ISR) will Read SPI data from ADC, then prepare the packet for GUI and will send it to GUI. ISR will also synchronise main loop by setting a flag.

In main loop It requests UART to receive data of 16 bytes from GUI. Data integrity is checked, and command is scan. Then it waits for synchronization flag set by timer1 to start next iteration.

GUI:

GUI can be run by executing exe file in ***"..\AdcHmiFinal\AdcHmiFinal\AdcHmiFinal\bin\Release\net8.0-windows"***. To compile this code, you need to install latest visual studio and then can open ***"AdcHmiFinal.sln"***

Conclusion

In this project, we developed a comprehensive system for measuring leakage current in high-voltage current transformers using the FG-R05 Series Current Sensor and the MX3 board. The software was integrated to ensure precise and reliable measurements, the hardware was not yet completed but included details of the hardware can still be used to finish the section, The firmware for the PIC32MX370F512L microcontroller played a crucial role in managing the data acquisition and communication processes, interfacing with the ADC via SPI and the GUI via UART.

Working with Qirion as a company allowed me to understand and grasp skills that were not aquired during school years having more hands-on experience in the field, this is a very important skill to aquire since we come across grids in our everyday lives.

Overall, this project successfully demonstrated the integration of advanced sensor technology with microcontroller-based data processing and user-friendly interfaces, providing a reliable solution for condition monitoring and predictive maintenance of high-voltage current transformers.

WWW

- **Firmware Development**: The firmware for the PIC32MX370F512L was successfully developed and integrated, initializing the clock, peripherals, and managing data acquisition and communication efficiently.
- **Data Acquisition**: Accurate and reliable data acquisition was achieved through the SPI interface with the ADC, ensuring precise leakage current measurements.
- **UART Communication**: A robust custom protocol for UART communication was implemented, enabling error-free data exchange between the microcontroller and the GUI.
- **User Interface (UI)**: The GUI was effectively developed using Visual Studio, providing a user-friendly interface for real-time data monitoring and interaction.
- **Data Save and Display**: The system was designed to save acquired data and display it in a meaningful way on the GUI, facilitating easy analysis and interpretation.

EBI

- Ordering the necessary equipment earlier in the project would have prevented delays and ensured that all components were available when needed, facilitating smoother progress.
- If the phase difference calculation was included in the software
- A visual representation of the phase difference in the UI as shown in figure 4 above
- Acquiring system requirements at an earlier stage would have provided a clearer understanding of the project scope and needs, allowing for better planning and execution.
- Conducting meetings with Qirion and Fontys supervisors earlier in the project would have helped in aligning goals and expectations from the beginning, ensuring that all stakeholders were on the same page and any potential issues were addressed promptly

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