TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Electrical Power Engineering and Mechatronics

FILM CAPACITOR ACCELERATED LIFETIME TEST SYSTEM AUTOMATION

KILEKONDENSAATORITE KIIRENDATUD ELUEA TESTSÜSTEEMI AUTOMATISEERIMINE

MASTER THESIS

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Tallinn, 2023

(*On the reverse side of title page*)

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ABSTRACT

Author: Daniil Dudenkov	*Type of the work:* Master Thesis
Title: Film Capacitor Accelerated Lifetime Test System Automation	
Date: 18.05.2023	69 *pages (the number of thesis pages including appendices)*
University: Tallinn University of Technology *School*: School of Engineering *Department:* Department of Electrical Power Engineering and Mechatronics	
Supervisor(s) of the thesis: Tarmo Korõtko, Sergey Kalashnikov	

Abstract:

Selecting the best type of component for serial production is a very common challenge. The selection of film capacitors is one such issue. The solution to this problem is reliability testing. Of all the testing methods, the ALT (accelerated lifetime testing) method is the most suitable to solve this problem. It gives an estimate of the lifetime of a product in a short period of time. But when testing capacitors there is a risk that they explode or ignite, which can damage both the test system and other test capacitors. In order to reduce the risk and to increase the efficiency of the system, work was done to automate the test system using a PLC (Programmable Logic Controller). The use of the PLC made it possible to check the measurements from the sensors on the limits and use the databases, which significantly improved the security of both the test system and the test data. A visualisation for the PLC software was also created, which allowed more complex tests to be carried out by setting up test steps and a much more efficient handling of the test system, since the PLC integrated all the devices. In order to handle the test data more efficiently, a program was written to automate the data processing. In the end, the result showed that all automation objectives had been achieved.

Keywords: film capacitors, automation, PLC, reliability testing, ALT, database, test system, programming, master thesis

LÕPUTÖÖ LÜHIKOKKUVÕTE

Autor: Daniil Dudenkov	*Lõputöö liik:* Magistritöö
Töö pealkiri: Kilekondensaatorite kiirendatud eluea testisüsteemi automatiseerimine	
Kuupäev: 18.05.2023	69 *lk (lõputöö lehekülgede arv koos lisadega)*
Ülikool: Tallinna Tehnikaülikool *Teaduskond:* Inseneriteaduskond *Instituut:* Elektroenergeetika ja mehhatroonika instituut	
Töö juhendaja(d): Tarmo Korõtko, Sergey Kalashnikov	

Sisu kirjeldus:

Parima komponenditüübi valimine seeriatootmiseks on väga levinud probleem. Kilekondensaatorite valik on üks selline probleem. Selle probleemi lahenduseks on töökindluse testimine. Kõikidest katsemeetoditest on ALT (Accelerated lifetime testing) meetod kõige sobivam selle probleemi lahendamiseks. See annab hinnangu toote eluea kohta lühikese aja jooksul. Kuid kondensaatorite testimisel on oht, et need plahvatavad või süttivad, mis võib kahjustada nii testisüsteemi kui ka teisi testikondensaatoreid. Selle riski vähendamiseks ja süsteemi tõhususe suurendamiseks tehti tööd testisüsteemi automatiseerimiseks PLC (programmeeritav loogiline kontroller) abil. PLC kasutamine võimaldas kontrollida andurite mõõtmisi piirväärtuste kohta ja kasutada andmebaase, mis parandas oluliselt nii katsesüsteemi kui ka katseandmete turvalisust. Samuti loodi PLC-tarkvara visualiseerimine, mis võimaldas keerukamaid katseid läbi viia katsesammude seadistamise ja palju tõhusama katsesüsteemi käsitsemise kaudu, kuna PLC integreeris kõik seadmed. Katseandmete tõhusamaks käsitlemiseks kirjutati programm andmete töötlemise automatiseerimiseks. Lõpptulemus näitas, et kõik automatiseerimise eesmärgid olid saavutatud.

Märksõnad: kilekondensaatorid, automaatika, PLC, töökindluse testimine, ALT, andmebaas, testisüsteem, programmeerimine, magistritöö

Form for thesis task for programs at Department of
Electrical Power Engineering and Mechatronics
Approved by the department board 17.06.2022

TALTECH
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THESIS TASK

Thesis title in English:	**Film Capacitor Accelerated Lifetime Test System Automation**
Thesis title in Estonian:	**Kilekondensaatorite kiirendatud eluea testisüsteemi automatiseerimine**
Student:	**Daniil Dudenkov, 212023**
Programme:	**MAHM**
Type of the work:	**Master Thesis**
Supervisor of the thesis:	**Tarmo Korõtko, Senior Researcher**
Co-supervisor of the thesis: (company, position and contact)	**Sergey Kalashnikov, Reliability Testing Manager, sergey.kalashnikov@ee.abb.com**
Validity period of the thesis task:	**Validity period is given by supervisor** 2022/2023 2022/2023 Autumn
Submission deadline of the thesis:	**18.05.2023**

____________________ ____________________ ______________________

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Co-supervisor (signature)

1. Reasons for choosing the topic

A very common difficulty is choosing an optimal type (price-quality relation) component for serial production. One such problem is the choice of film capacitors. Each supplier offers different type of capacitors, which have both disadvantages and advantages. Using the test programme, it is possible to estimate the lifetime of the capacitors, which helps to select the optimum batch based on the test results.

The test system was created to accelerate lifetime of the product, but it had its drawbacks. These disadvantages were the lack of automation, which made the operation labour-intensive, and the increased risk of an incident due to the lack of additional protection. It is important for the company to reduce the risk of incident, especially when working with capacitors that can damage the test equipment or even harm employees. In addition, more test data needs to be obtained from the test system to better know the behaviour of the test capacitors.

The new solution will provide more test data to analyse various types of film capacitors for further selection, will reduce the risk of incident and will save the company money by replacing human labour with automation than the previous solution.

2. Thesis objective

The thesis objective is to create safer solution that provides more test data through automation and requires less time to work with the test system and its data than the previous solution. Explore different methods of calculating the estimated lifetime of the test products to improve the test result.

3. List of sub-questions:

1. What is behind the product failure?
2. What test methods are used to test the product for quality?
3. What methods are used to calculate the estimated lifetime of a product?
4. How to avoid an incident when testing capacitors?
5. How to automate data acquisition and processing in the test system?

4. Basic data:

1. Company related technical specification for existed test systems.
2. Company documents and different articles about automation
3. Company documents and different articles about reliability testing.
4. Documentation of already existing similar test systems.
5. Different sources about reliability testing and automation.

5. Research methods

Based on a review of the literature, explore different ways of calculating the estimated lifetime of a test product to improve the test result. Automate the test system based on the analysis of the literature. Make a comparison of the new solution with the previous one, listing the changes and how they have affected the test system, and giving an assessment of how important these changes are.

6. Graphical material

1. PLC programme flowchart
2. PLC visualisation
3. Data processing software flowchart
4. Data processing software interface
5. Table of time savings through automation
6. Table of automation results

7. Thesis structure

1. Testing methods overview
2. Analysis of different ways of calculating the estimated lifetime of a product
3. Data structure and Database
4. Creation of a PLC programme with visualisation
5. Data handling software with interface
6. Overview of the automation result

8. References

[1] 'The embodiment of reliability for variable speed drives', *Drives*. https://new.abb.com/drives/highlights-and-references/reliability-for-speed-drives (accessed Mar. 25, 2023).

[2] 'Why do variable speed drives fail and how do we test them', *Drives*. https://new.abb.com/drives/highlights-and-references/why-do-variable-speed-drives-fail-and-how-do-we-test-them (accessed Mar. 25, 2023).

[3] A. Mueller, 'Reliability Test Methods'. ABB Switzserland Ltd, Jun. 02, 2021.

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9. Thesis consultants

10. Work stages and schedule

Date	**Work stages**
07.11.22	Writing the theoretical part
21.11.22	PLC programming
26.12.22	Sending the theoretical part to the supervisor
30.01.23	Sending the chapter on PLC programming to the supervisor
31.01.23	Data processing and calculations
06.03.23	Sending the chapter on data processing with calculations to the supervisor
07.03.23	Overview of the automated test system
17.04.23	Final draft of the thesis
18.04.23	Final corrections in the thesis work
01.05.23	Final version of the thesis

Terms of thesis closed defence and/or thesis restricted access conditions to be formulated on the reverse side.

CONTENTS

PREFACE

The topic of the thesis was suggested by ABB. The major thesis work was done at the ABB Drive Research Centre in Jüri, Estonia. I would like to express gratitude to the company for giving me the opportunity to work on the topic of this thesis. I would like to express special thanks to the supervisor from the company Sergey Kalashnikov and the supervisor from the university Tarmo Korõtko for the advice on issues related to this paper.

LIST OF ABBREVIATIONS AND SYMBOLS

AC	Alternating current
AF	Acceleration factor
ALT	Accelerated life testing
C	Capacitance
CPU	Central processing unit
DAQ	Data acquisition
DC	Direct current
E_a	Thermal activation energy
ESR	Equivalent series resistance
EUT	Equipment under test
FMEA	Failure Mode and Effects Analysis
FBA	Fieldbus adapter
GUI	Graphical user interface
HALT	Highly accelerated life testing
HASS	Highly accelerated stress screening
HMI	Human-machine interface
INU	Inverter unit
ISU	IGBT supply unit
K	Boltzmann's constant
LCL	Lower Control Limit
m	Humidity power constant
N	The total number of datapoints
n	Voltage power constant
ORT	On going reliability testing
PLC	Programmable logic controller
PoF	Physics of failure
RDT	Reliability demonstration testing
RPN	Risk Priority Number
RH_{stress}	Life test stress relative
T_{field}	Time in the field
T_{stress}	Life test stress temperature
T_t	Time in the test
T_{use}	Use temperature
RH_{use}	Use relative humidity
UCL	Upper control limit
x	The value of each data point

μ	The mean (average) of the datapoints
σ	Standard deviation
$\bar{X}$	The sample mean

INTRODUCTION

There are many different types of capacitors on the market today. It is sometimes difficult to choose the optimal type of capacitor (price-quality relation), because we do not know what percentage of defects the batch has, how much the lifetime of capacitors differs from that declared by the manufacturer (if the manufacturer indicates this) and so on.

This is important because when ordering an untested batch of capacitors to save money or to develop new product, it may turn out that the new batch of capacitors has a high percentage of defects. In this case, the company will lose not only money, but also reputation, which is worth a lot. However, according to the sources [1], [2] the capacitor is one of the most vulnerable components in power electronics.

Implementing a test system to accelerate the lifetime of capacitors will solve the problem raised above. The concept behind this approach is that by including stress factors, it is possible to quickly test the life of the capacitors. The collected test data will help understand which of the tested batches is optimal and which of them is not.

The product may break if additional stress factors are present. Capacitors have the potential to explode, which can damage the test equipment and even the personnel. Automating the test system allows additional safety protection to be used to prevent an incident. Even in the event of a failure, the likelihood of an incident involving employees or damage to the test system is minimised. Additionally, automating the test system can improve results and save time.

The business goal is to test and validate the component's designed life. Conduct standardized tests on various components and compare them. Search for weak links or quality problems in new designs and test second-source components.

The goal of the thesis is to develop a safer solution that uses automation to obtain more test data and requires less time to work with the test system and its data. To improve the test result, several techniques for calculating the estimated lifetime of the test products will be analysed.

1.RELIABILITY TESTING REVIEW

1.1 The physics behind product failure

It is important to understand when and why a product fails. This will help to prevent a possible incident or failure of the whole system. In reliability engineering, a bathtub curve diagram is often used to describe how failure rates behave as a function of time, as shown in figure 1.1. The bathtub curve is useful for planning spare parts logistics, making warranty provisions, etc. Unfortunately, this statistical bathtub model gives very little information about a new product [3], [4].

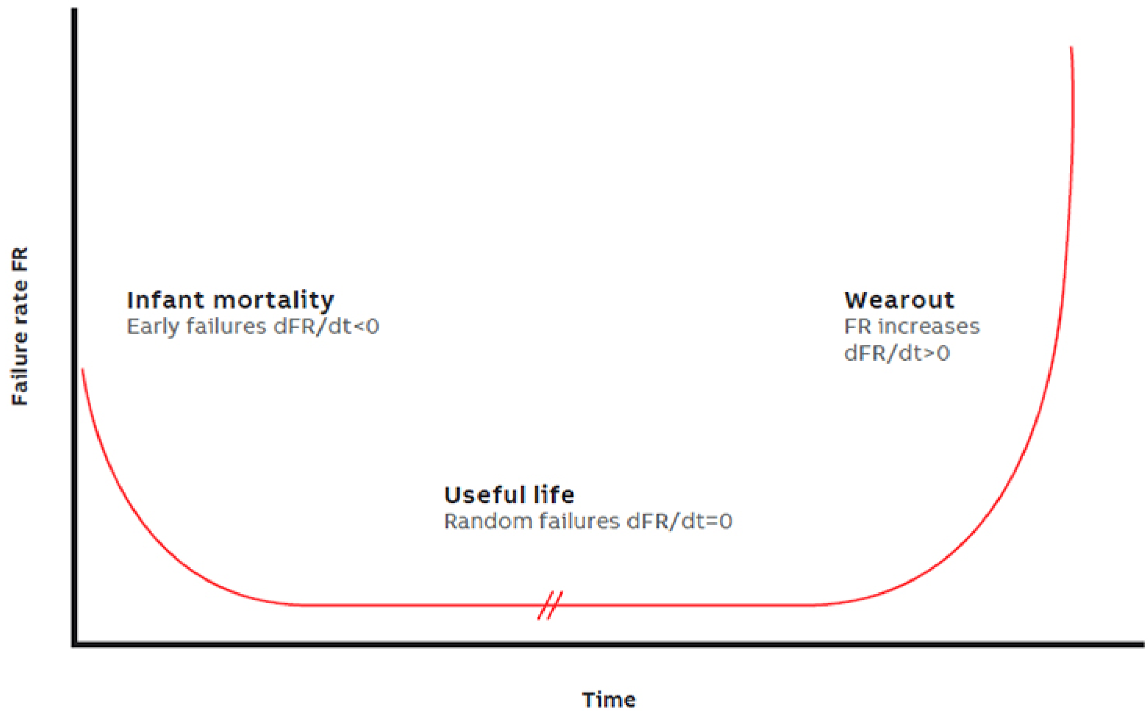

Figure 1.1 Bathtub curve diagram, where dFR/dt is change in failure rate over time [3]

Overstress and wear, two factors related to product toughness and durability, are the causes of product failure. When a product is stressed beyond its capacity, overstress failure occurs. Wear is a longer-term failure process: each time a product is subjected to stress it suffers some damage and the cumulative effect builds up and eventually causes failure when it exceeds the product's life. The shortest time before wear-out occurs is typically expressed in terms of durability. It refers to the ability of a product to continue to operate under typical operating conditions for the duration of its design life without significant maintenance or repair. The physics of failure (PoF) approach classifies products as either nominal or failing. Nominal products will withstand nominal stresses and last their entire design life if they are not subjected to stresses greater than those specified. If minimal stress is applied to a defective product, it will fail. This may lead consumers to believe that faulty products don't last very long once they are in use, but many continue to work. This is because defects don't lead to failure and products continue to operate without problems because the stress levels in most applications are below the nominal design limits. Figure 1.2 gives a general overview of why things fail, and the testing techniques that can be used to reduce the risk of failure and ensure the design that is currently in use [5]–[7].

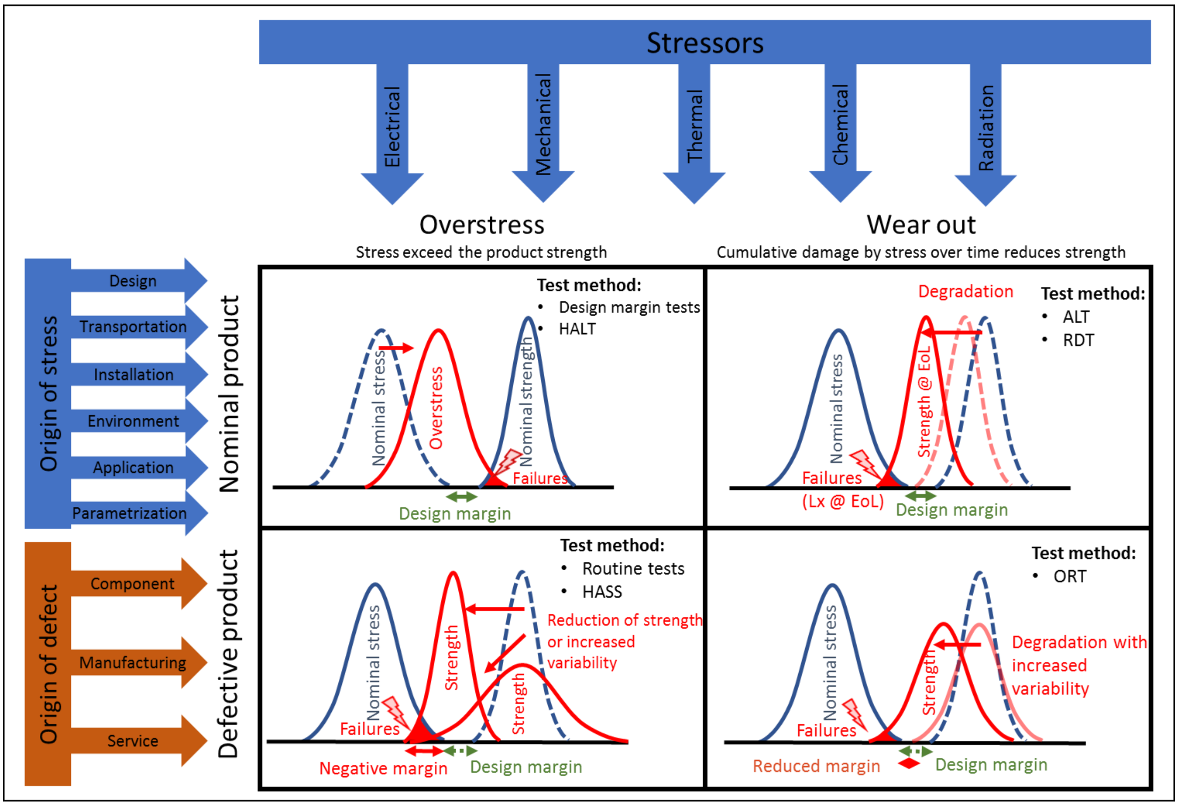

Figure 1.2 Things fail when stress exceeds strength. Defective products have less than nominal strength and fail already at nominal stress [6]

1.2 Reliability testing criteria

Testing is an essential part of any engineering development programme. The test programme becomes a significant part of the overall development effort in terms of time and other resources when the development risks are high. For example, a new type of electrical drive or a new component of existing equipment will typically undergo a series of rigorous tests to ensure that the design is reliable under the expected operating conditions and for the expected service life. Because designers often lack complete knowledge of all the potential reasons why their designs might fail, reliability testing is essential [8].

Reliability testing should be considered as part of an integrated test programme, which should include [6]:

1. Functional and margin testing, to confirm that the design meets the basic performance requirements expected limits;
2. Environmental testing, to ensure that the design is capable to operate under the expected range of environments;
3. Statistical tests, to optimize the design of the product and the production processes;
4. Durability testing, to ensure (as far as is practicable) that the product will operate without failure during its expected life;
5. Safety testing, when appropriate;

To provide the basis for a properly integrated development test programme, the design specification should cover all criteria to be tested (function, environment, reliability, safety) [9].

It is necessary to create failures to collect reliability information. Only then can safety margins be determined. Before the production phase, flaws in the design (or the way it was made) must be found and corrected. Realistically, the only way to do this is to deliberately create failures. Any failure mode that might otherwise occur in service will be uncovered by the test programme [9].

1.3 Testing methods

To improve the quality of the company's products, the testing programme has been established for components such as the film capacitors, which are the most commonly used in LCL filters. The aim of this programme is to improve the quality of the company's products by extending their life through the selection of higher quality product components. As the information on the lifetime of capacitors differs from that provided by the manufacturer, it is important to verify it through testing. As all capacitor suppliers used comply with the IEC 61071 standard, it is sufficient to use only the Durability test programme.

There are different ways of testing. Basically 5 different types of tests are used in the Durability testing [5]:

1. Highly Accelerated Life testing (HALT),
2. Reliability Demonstration Testing (RDT),
3. Accelerated Life Testing (ALT),
4. Highly Accelerated Stress Screening (HASS),
5. On Going Reliability Testing (ORT).

The authors of [5] divided them into 2 categories: accelerated test and operational test. The accelerated test category is divided into 2 types: Overstress and Wearout. The operational test category is divided into 2 types: Nominal and Defective. Testing methods and their classifications are shown in figure 1.3.

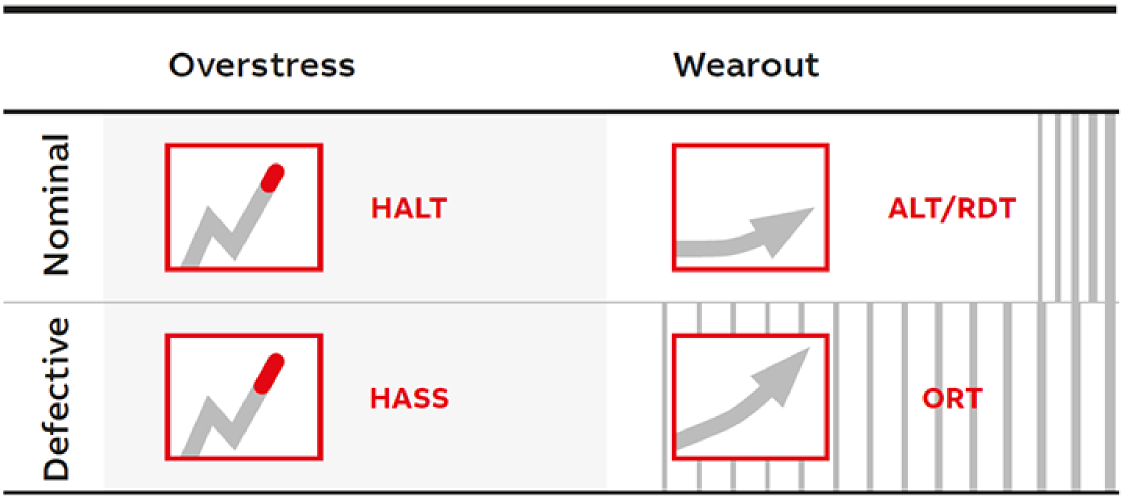

Figure 1.3 Testing methods and their classification [5]

Overstress refers to the conditions that cause a product or system to fail prematurely due to excessive stress or strain. In reliability testing, overstress testing is used to identify the point at which a product or system fails under extreme conditions and to determine the conditions under which it can be expected to fail. This information is used to design products or systems that can withstand the expected range of operating conditions and to establish safety margins for unexpected events.

Wearout refers to the conditions that cause a product or system to degrade over time, eventually leading to failure. In reliability testing, wearout testing is used to identify the point at which a product or system begins to degrade and to determine how long it can be expected to perform before it fails. This information is used to determine the product or system's expected lifetime and to design maintenance schedules and replacement strategies.

Nominal testing is used to evaluate the performance and reliability of a product or system under normal operating conditions. This testing is used to verify that the product or system meets the design specifications and that it can perform as expected in real-world applications. The aim of nominal testing is to identify any performance issues or defects that may occur under normal operating conditions so that they can be addressed before the product or system is released to the market.

Defective testing is used to evaluate the performance and reliability of a product or system under conditions that simulate defects or failures. This testing is used to identify the point at which a product or system fails and to determine the conditions under which it can be expected to fail. The objective of defective testing is to identify any weaknesses or vulnerabilities in the product or system so that they can be addressed before the product or system is released to the market.

When selecting a testing method, it is important to consider the lifetime of the product as a test result, i.e. how long it would have lasted if it had been in use. The ALT and RDT methods are suitable for these criteria. The RDT testing differs from the ALT testing in that it leaves us unsure of the real expected life, as the equipment is not supposed to fail. ALT testing will give us a real life assessment, which is exactly what is needed to solve the above problem [5].

1.4 Accelerated life testing method

ALT belongs to the category test to failure, i.e., to generate failures. According to the source [10], ALT is an expedient and cost-effective solution for determining the reliability and robustness of an electronic product or component. ALT uncovers potential failure risks and quantifies the lifetime characteristics of a product or component much faster than in the field - leading to improved product design and faster time to market.

An acceleration factor (AF), which is the ratio of time in the field to time in the test for a given failure mechanism, must be considered when establishing an effective ALT for lifetime prediction. The general AF formula 1.1 [10] is shown below:

$$AF = \frac{T_{field}}{T_t} \tag{1.1}$$

where AF - Acceleration Factor,

T_{field} - Time in the field,

T_t - Time in the test.

Adding stressors speeds up the test. Stressors are taken from the environment that increases product wear, such as: high temperature, humidity, high load (in the case of capacitors this is voltage), vibration, etc. There are special formulas and different ways to calculate the AF including different stressors.

The Arrhenius formula 1.2 [11] is designed to calculate AF using only temperature as a stressor:

$$AF = e^{\left(\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{use}}-\frac{1}{T_{stress}}\right)\right)} \tag{1.2}$$

where AF – Acceleration Factor,

E_a – Thermal activation energy,

K – Boltzmann's constant,

T_{use} – Use temperature,

T_{stress} – Life test stress temperature.

The thermal activation energy can be taken from the source [6].

The Peck formula of model 1.3 [12] is designed to calculate AF using temperature and humidity as stressors:

$$AF = \left(\frac{RH_{use}}{RH_{stress}}\right)^{-m} e^{\left(\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{use}}-\frac{1}{T_{stress}}\right)\right)} \tag{1.3}$$

where AF – Acceleration Factor,

RH_{use} – Use Relative Humidity,

RH_{stress} – Life test stress Relative Humidity,

m – Humidity power constant,

E_a – Thermal activation energy,

K – Boltzmann's constant,

T_{use} – Use temperature,

T_{stress} – Life test stress temperature.

The coefficient m depends on the material and can be taken from the [13]. This characteristic coefficient is derived from the historical collection of Coffin-Manson exponents.

The Hallberg-Peck formula 1.4 [14] is designed to calculate AF using temperature, humidity and load (voltage in the case of capacitors) as stress factors:

$$AF = \left(\frac{U_{use}}{U_{Strss}}\right)^{-n} \left(\frac{RH_{use}}{RH_{stress}}\right)^{-m} e^{\left(\left(\frac{E_a}{K}\right)\left(\frac{1}{T_{use}}-\frac{1}{T_{stress}}\right)\right)} \quad (1.4)$$

where AF – Acceleration Factor,
U_{use} – Use voltage,
U_{stress} – Life test stress voltage,
n - Voltage power constant,
RH_{use} – Use Relative Humidity,
RH_{stress} – Life test stress Relative Humidity,
m – Humidity power constant,
E_a – Thermal activation energy,
K – Boltzmann's constant,
T_{use} – Use temperature,
T_{stress} – Life test stress temperature.

The coefficient m is found in a similar way to formula 1.3. According to the [15], the coefficient n is 3.5 for a voltage ratio (ratio of U_{use} to U_{stress}) from 0.7 to 1.3. For other values of the voltage ratio, the n varies greatly from manufacturer to manufacturer, which can be explained by different manufacturing techniques. In such cases, the factor n can be found in the capacitor data sheet or empirically.

There are also methods for calculating AF using neural networks. Sources [14], [15] used neural networks to assume changes in capacitor parameters, which can be used to calculate AF. Of these two sources, [15] showed the best result. In the source [15], the principle is to train a neural network with test data until the accuracy of predicted capacitance (C) and equivalent series resistance (ESR) changes reaches at least 90%. The predicted ageing score is then calculated, and the test is stopped. A detailed flowchart is shown in figure 1.4.

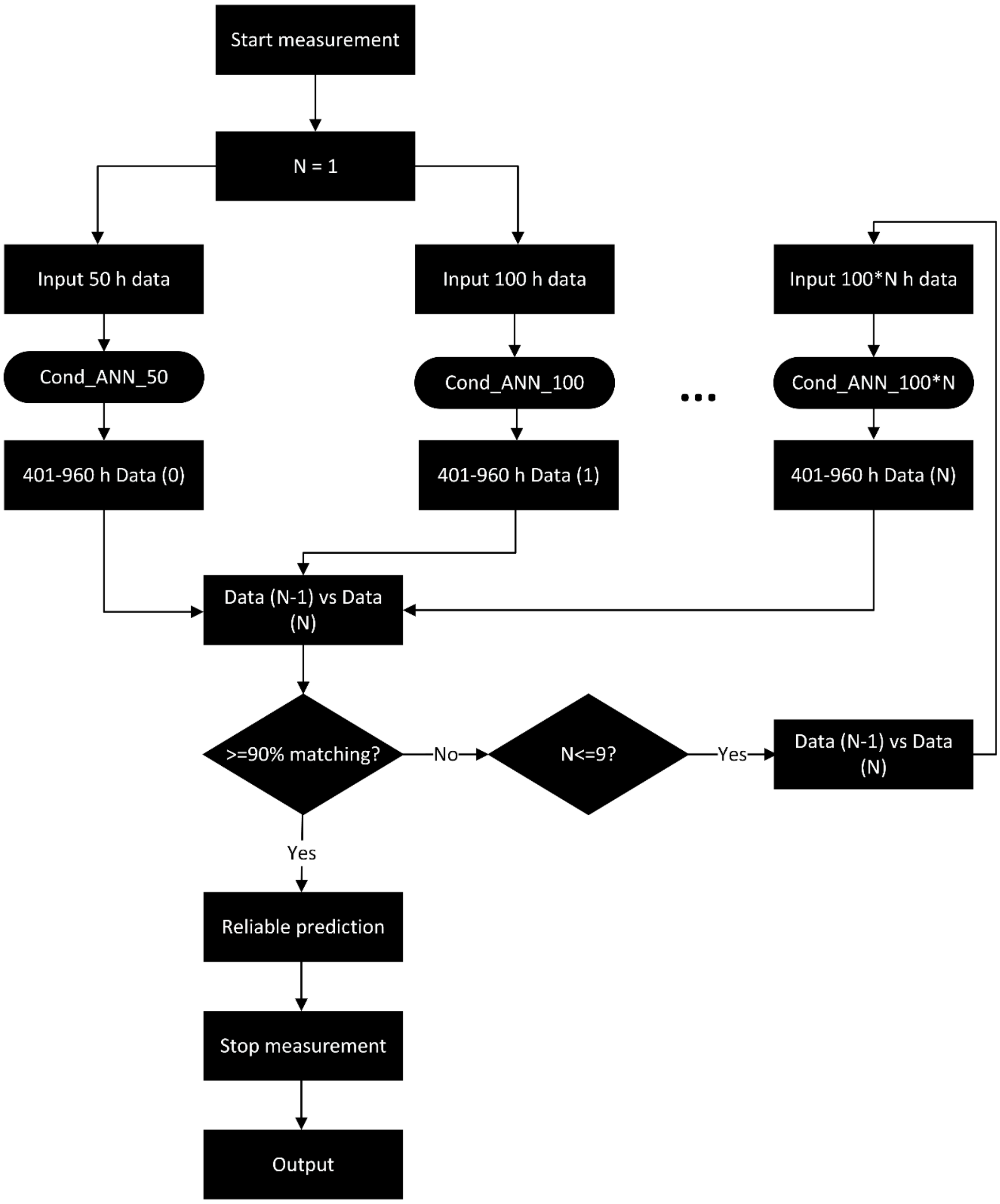

Figure 1.4 Flowchart of ageing prediction based on Deep Neural Networks [16]

The author achieved a prediction accuracy of 99 percents after 200 hours of testing. This is a very efficient method as it saves a lot of time, but it is also very complex and has not been tested for other types of capacitors, such as three-phase film capacitors, which are intended for the new test. According to the source [17], prolonged exposure to high temperatures can accelerate other ageing reactions, which can affect the accuracy of the neural network over a longer period of testing. It is also important to set up the neural network correctly, considering many factors. As the new test system intended for three-phase capacitors, which is different from the method described above, it is not clear how this neural network model will behave. This issue is the subject of further research beyond the scope of this paper.

The most suitable method for this problem is to use the formula 1.4 as it speeds up the test by using temperature, humidity and voltage as stress factors. However, the disadvantage of this method is that it works well for a voltage ratio of 0.7 to 1.3. For other values, it is necessary to find the n coefficient in the capacitor data sheet or empirically. If this data is not available, the formula 1.3 must be used.

1.5 Safety

Safety is a very important aspect of capacitor testing. The condition of the capacitor must always be monitored during the test, otherwise it could explode, causing damage to the test equipment and even to the operator. Figure 1.5 shows that one of the protective walls of the test fixture was ripped off when the capacitor exploded.

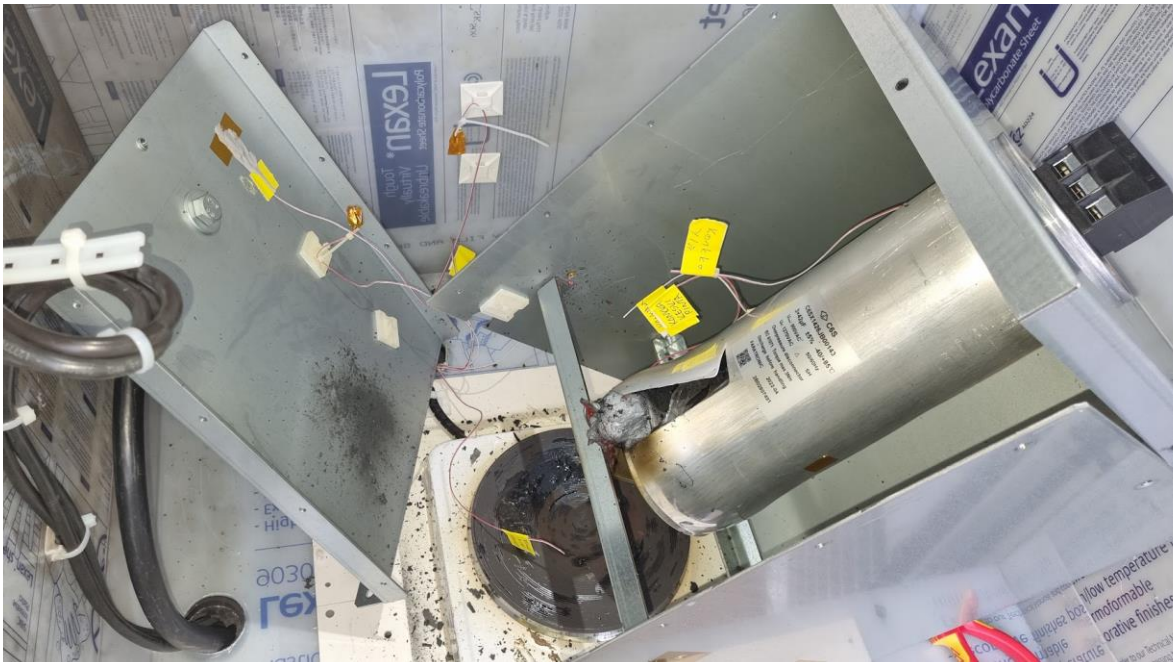

Figure 1.5 Exploded film capacitor from the HALT test

In the [15] an analysis was made of what causes capacitor failure and how it can be predicted. Figure 1.6 shows a diagram for film capacitors showing what causes the failure, how it occurs and what the consequences are. In total there are 3 consequences: loss of function, fire, explosion. In the case of a loss of function, nothing happens to the system or personnel. However, a fire or explosion is dangerous. The diagram in figure 1.6 shows that before a fire occurs, first the temperature rises and then the pressure rises, or only the temperature rises, or a chimney appears. Before an explosion occurs, the temperature rises, or a chimney appears. Therefore, monitoring the presence of smoke and monitoring the temperature is sufficient to prevent an incident.

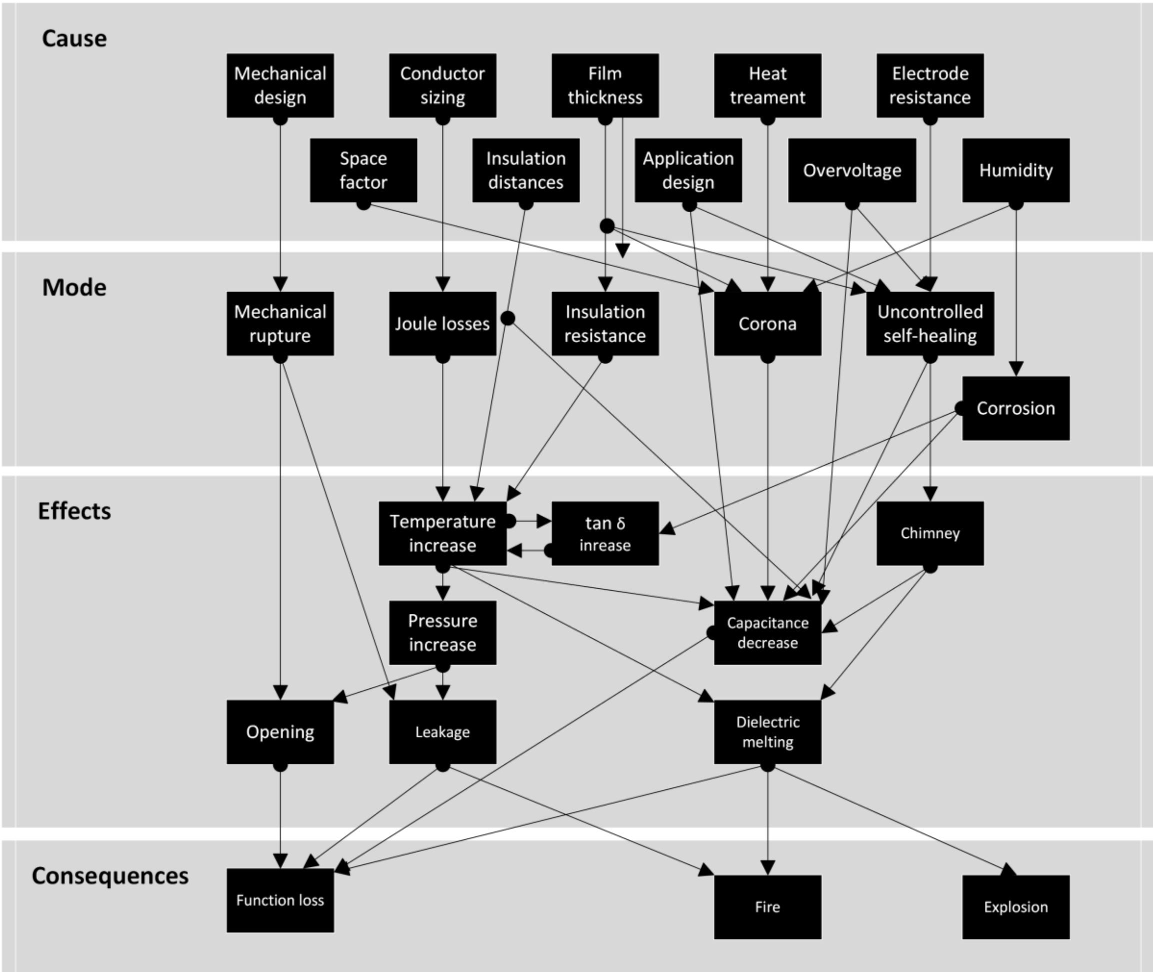

Figure 1.6 Film capacitor failure modes with their causes, effects, and consequences [15]

1.6 Conclusion

During the literature review it was considered that products fail mainly due to wear and tear. Knowing the life cycle of a product is useful for planning spare parts logistics, writing warranties, etc. Unfortunately, for new products, the lifetime stated by the manufacturer and the actual lifetime are not the same. Different types of tests are used to check products for defects. The most suitable solution to this problem is the ALT method. It allows to accelerate the life of the product by adding stress factors. By calculating the AF coefficient, which compares the lifetime under test conditions with the lifetime specified by the manufacturer, different methods can be used to determine the estimated lifetime of products. By including more stress factors, formula 2.5 gives a more accurate result. It is also important to consider safety when testing products such as capacitors, as they can ignite or even explode. To prevent an incident, the condition of capacitors should be monitored based on their temperature and the presence of smoke in their vicinity.

2. SOLUTION DEVELOPMENT

2.1 Overview of existing test system

At present, the test products are 3-phase alternative current (AC) delta connected film capacitors normally used in LCL filters. An example of testing sample is shown in figure 2.1.

Figure 2.1 An example of testing capacitor

The entire test system is housed in the sea container for safety purposes (figure 2.2). When the test system is in operation, it is locked with 2 locks: magnetic lock and mechanical lock. The magnetic lock is required to prevent access by personnel while the system is in operation. As there is a possibility that the magnetic lock can be opened by physical force, the mechanical lock is required to limit access to the system by unauthorised persons.

Figure 2.2 Sea container of the test system

Electricity flows from the substation through the LCL filter, actuators, 2X step-up transformer, fuses and only then to the test capacitors. The purpose of an LCL filter is to reduce harmonic distortion and improve the power factor of the load. The test system uses 2 drives: IGBT Supply Unit (ISU) and Inverter Unit (INU). ISU and INU are used to modulate the voltage load for the test product, where ISU and INU convert alternative current to direct current (DC) and DC to AC respectively. The 2X step-up transformer is used to increase the voltage of an AC power source by a factor of 2, enabling efficient power transfer and providing the required voltage for the test products. The fuses are designed to protect the test capacitors from overcurrent which could lead to a failure. Discharge resistors are required to discharge the capacitors in the test system when it is switched off. The principal circuit diagram is shown in figure 2.3.

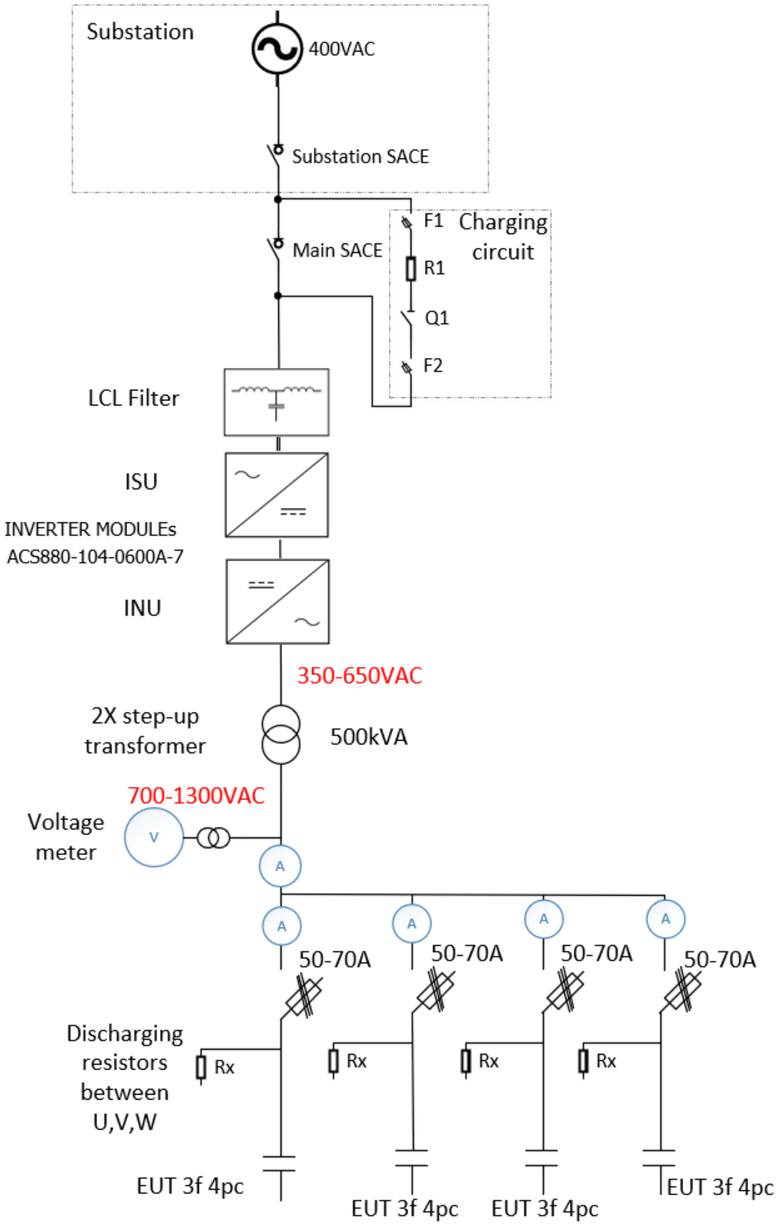

Figure 2.3 The principal circuit diagram

Environmental chamber is used to maintain the test temperature and humidity. Control is either via the web interface or the control panel on the chamber. J-type thermocouples are used for temperature sensing, HAL400 and HAL100 sensors for current sensing, and DVL2000 sensors for voltage sensing. The Keysight data acquisition (DAQ) device is used to record sensor data. LCR meter is used to measure capacitor parameters such as ESR and capacitance. Scales are used to measure the weight of the capacitor. The capacitors' parameters such as ESR, capacitance and weight are measured manually when the test system is stopped. The data from the DAQ device is written to an Excel file, the data from the LCR meter is written to a separate Excel file, as is the data from the capacitor weight measurements.

Safety is provided by smoke detectors located in the environmental chamber and the sea container, and stop buttons located inside and outside the sea container. If these are triggered, the safety relay cuts off power to the entire test system. There is also protection against high temperatures in the form of a thermal relay in the environmental chamber and transformer. If tripped, the drives will stop, switching off both the load generated by the drives on the test capacitors and the environmental chamber as it is powered by the drives. Opening the sea container door will also trip the drives. The device diagram before automation is shown in figure 2.4.

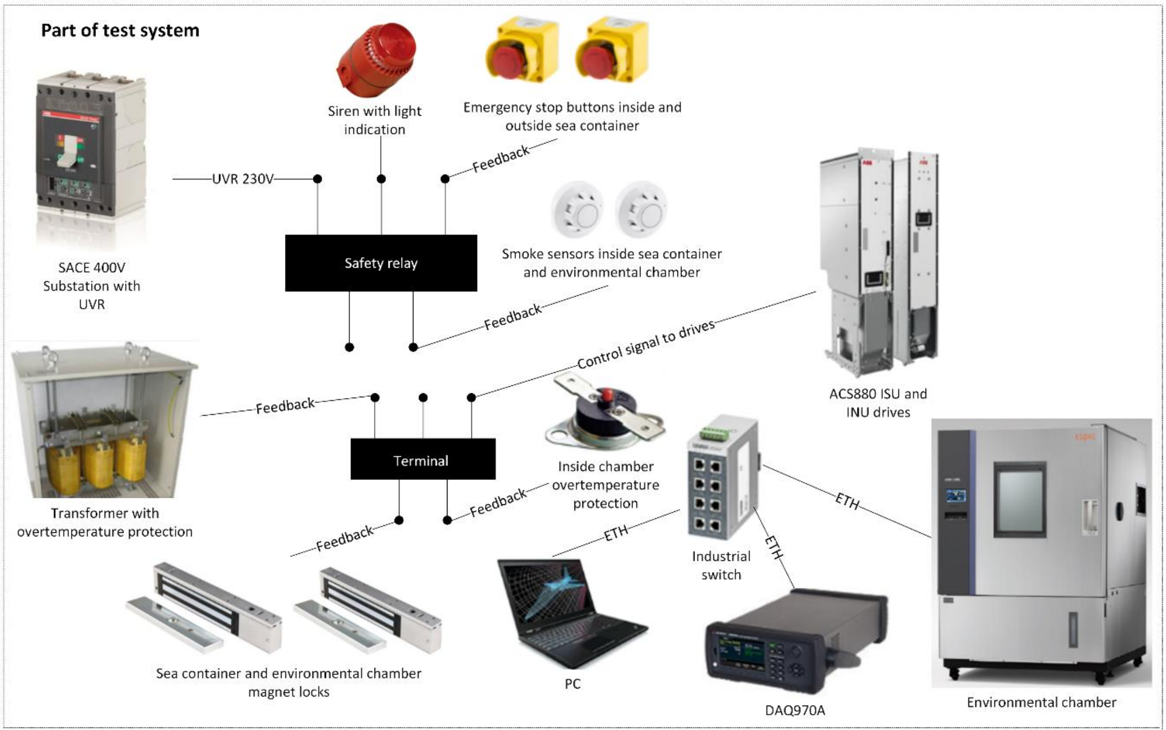

Figure 2.4 Device diagram before automation, where UVR – Undervoltage release

The capacitor is considered as failed if one of the following statements is fulfilled and the sample shall be removed from the setup:

- The capacitance value decreases more than 5 % of its initial value;
- ESR > 3× initial limit;
- Capacitor hotspot temperature (internal temperature) > maximum specified temperature;
- The capacitor should not sustain any damage or express any abnormal behaviour;
- Overpressure system is activated;

There are several problems with the previous solution:

1. No local database. All the data is stored in different Excel files, which makes it very difficult to work with the data. Also, the files can get corrupted, and some data can get lost.
2. Lack of a human-machine interface (HMI). Without an HMI, it is difficult to monitor the system. If an error occurs in the system, it is difficult to know what is wrong. It may even be that the problem is not critical, so the system will continue to work, but the operators will not know about it immediately.
3. There is no data structure. At this point there is no data structure as such because it is not clear to which phase of the test cycle the measurements belong. It is also not clear to which product the measurements belong. This makes it difficult to analyse the data, especially when trying to find the root cause of the problem.
4. Small amount of test data. Currently, measurements from the DAQ device and manually taken measurements are stored. Data from the drives, the environmental chamber and the power meter are missing.
5. Reduced safety. There is currently no parameter limit check. For example, if a capacitor has an increased temperature or current, the system does not react immediately. It also takes a long time to start up the system because a lot of things must be checked manually. This increases the risk of human error.
6. Difficult to use. As there is no connection device to the HMI, it is not only inconvenient but also difficult to work with the test system. For example, if a component fails, it may take a long time to diagnose. As mentioned, each device must be manually checked before starting, which makes it difficult to use the system.

2.2 Concept of the solution

The drawbacks in the existing solution make the system more difficult to operate and less safe. This has the potential to increase the risk of an incident, as well as wasting time, which is costly in the long run. The solution could be an HMI device that integrates all the devices. This could be a programmable logic controller (PLC) or a computer. According to the the authors of [18], a PLC is a fast and reliable solution that is compatible with drives and industrial sensors. It is also easy to set up an HMI on it. ABB AC500 V2 was chosen as the PLC model, mainly because of company policy.

The presence of a PLC will increase safety both by providing HMI and by checking the measurement limits. Some limits will be set by the operator before the test, some will be set in the software, as they will not be changed due to the technical characteristics of the test system (e.g. current limits). There are also plans to introduce limits for the rate of temperature change, but this has not yet been agreed upon as it requires further research.

It was decided to use databases to work with test data, because databases allow efficient and convenient handling of data [19]. The Microsoft structured query language (SQL) database, managed using the Microsoft Server Management Studio application, was chosen as the local database type. The reason for this choice was that a master database server was already in place. This environment was chosen to improve synchronisation. The database is located on a test computer that is connected to the master database.

The Profinet interface was chosen to control the ISU and INU drives since it is user friendly and well suited to drive control [20]. PLC and drives connected to the Profinet switch. In this case, use a Profinet switch rather than an industrial switch, as the Profinet switch is engineered to meet the stringent requirements of Profinet, including deterministic and real-time communication, low-latency transmission, and precise synchronization [21]. The test computer, DAQ device and environmental chamber are connected to an industrial switch, which is connected to the network with the main database. The device diagram is shown in figure 2.5.

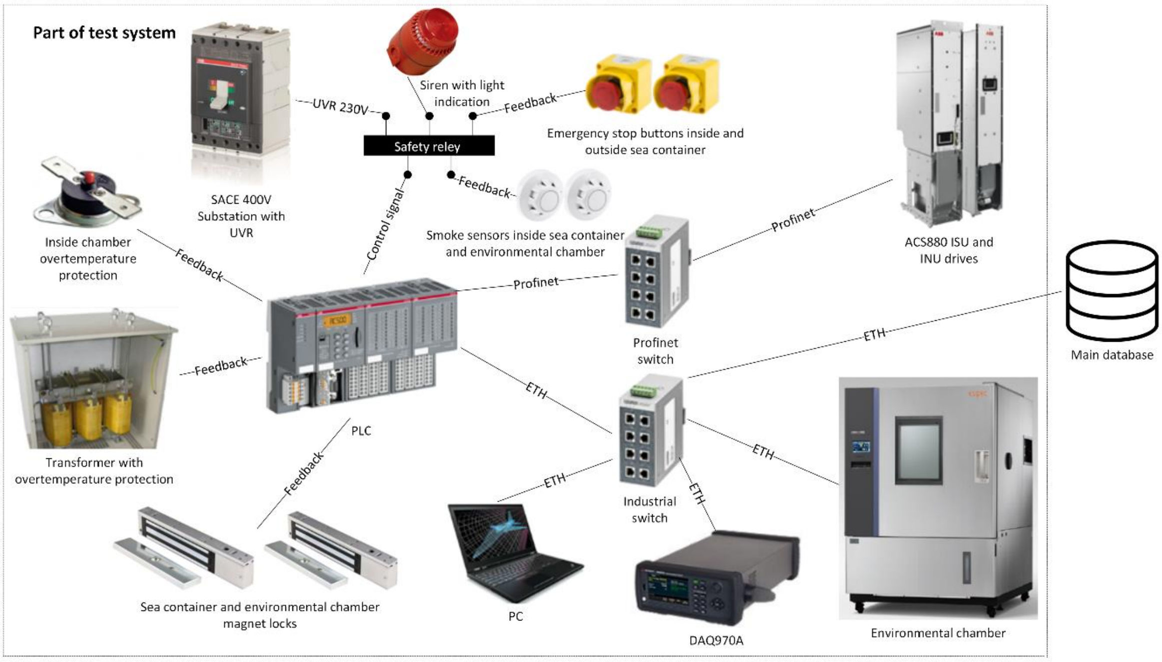

Figure 2.5 Device diagram

2.3 Data structure and Database

In the ALT testing, products can be tested for up to several years, depending on the test profile and the equipment under test (EUT). The test computer may run out of internal memory during the product testing period. A data structure is needed to make it easy to work with. The data can be grouped mainly by EUT and by cycle number.

A cycle is a repeated process. Since the load is constant in a new test and the key test factor is the number of hours, 1 cycle equals 1 hour. The higher cycles are the test steps or cycle steps. They are distinguished by different stress values and their duration. Below the cycles are the cycle savings. These indicate how many times per cycle the data will be saved. Therefore, after the end of the cycle or 1 hour, the cycle saving is reset.

The EUT is numbered with two numbers. The first number refers to the group to which it belongs. There are 4 groups, each group having a common 3-phase supply and common fuses. There can be up to 4 EUTs in a group. The sequence number in a group is indicated by the second number in the name. For example, EUT12 means that the test product is the second in the first group. Each EUT also has its own unique serial number. EUTs can be classified by type and project. The accelerated lifetime or target cycles are given in cycles.

There are measurements that cannot be assigned to an individual EUT. In this case they are written to the global parameter data structure. In the database they are identified by EUT number 0. For the global parameters, cycle indicates how much time has elapsed since the start of the test. Therefore, the cycle parameter for the global parameters is reset to zero at the start of the test. The structure of the data is shown in figure 2.6.

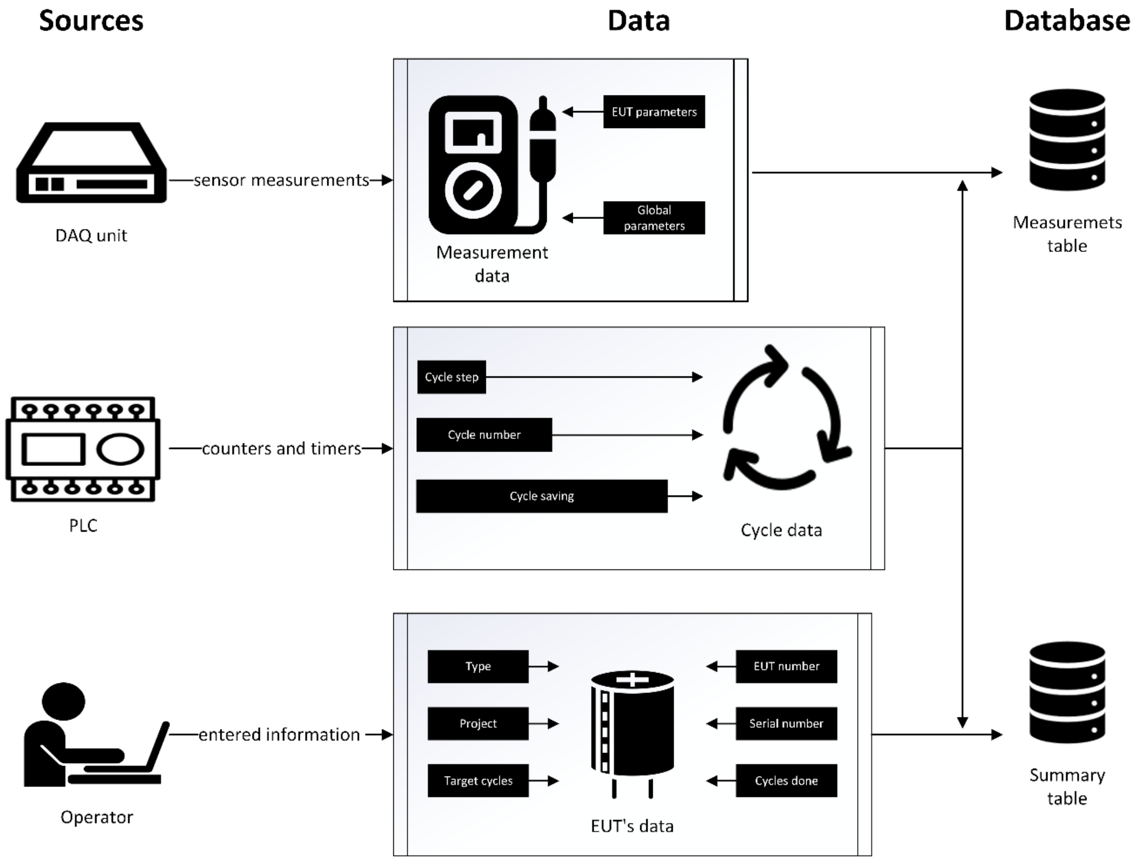

Figure 2.6 The data structure

The local SQL database consists of 2 tables: Measurements and Summary. The Measurements table records important measurements from the test system. In the table, the rows are measurements, and the columns are information about the measurements. Each column contains information about a measurement, making it easier to classify and analyse the information. There are 10 columns in the table, which are shown in table 2.1.

Table 2.1 Columns of the Measurements table

Nr	Column name	Description
1	Id	a unique number for each measurement
2	EUT_Place	EUT number in the test system
3	Cycle	cycle number
4	Cycle_step	cycle step number
5	Cycle_saving	number of saving in the cycle
6	Parameter_name	measurement parameter name
7	Parameter_value	measured value
8	Time_stamp	measurement time
9	Active_fault	the presence of a fault in the test system
10	User_modified	who was recorded the data

Detailed measurement information makes it easy to identify when and where a fault has occurred. Classification of the data makes it much easier to analyse the data to find the root cause of the problem.

The Summary table records important information about the test product. The rows in the table are the test product, and the columns are information about the product. Each column contains information about the product, making it easier to classify and analyse the information. There are 8 columns in the table, which are shown in table 2.2.

Table 2.2 Columns of the Summary table

Nr	Column name	Description
1	Id	a unique number for each test item
2	Serial_number	test item serial number
3	EUT_place	EUT number in the test system
4	Type	type of test item
5	Project	the name of the project to which this product belongs
6	Target_cycles	the number of cycles (hours) obtained by calculating the estimated life of the product under the test conditions
7	Added_on	the point in time at which the product began to be tested
8	Cycles_done	how many cycles (hours) the product has been tested

The tables are synchronised with the PLC programme. Thanks to the synchronisation, the cycle counter in the table is automatically updated, and the synchronisation with the table makes it easy to fill and overwrite it from the PLC visualisation, and the table serves as a backup in case of data loss in the PLC.

The main database is synchronised with the local database, with the main database retaining values from the local database. This is justified by the fact that the test computer has limited hard disk space and the old data will need to be deleted in the future. In addition, this solution helps to avoid data loss in the event of a test computer failure.

2.4 Drives configuration

Communication between the PLC and the drives is via the Profinet interface. The type of communication is synchronous, where parameters are read from the drives and references are sent to the drives. The ISU reference is the DC voltage parameter that goes to the INU, the INU reference is the Output frequency parameter that is responsible for the frequency of the current to the test capacitors. On the PLC side, only the Profinet channels need to be configured, by specifying the communication type, protocol, address and readable variables in the PLC programme. On the drive side, the parameters responsible for communication and control of the drive via the PLC must be configured. Drive control panels were used to set up the drives. Tables A1.1 and A1.2 show the parameters that have been modified to work with the PLC in Appendix 1.

The drive communication uses control and status words. The drive switches between its states according to the bit-coded instructions on the control word and returns status information to the master in the status word. The contents of the fieldbus control and status words can be found in the manual [22]. Tables A1.1 and A1.2 show that the FBA (Fieldbus Adapter) A data in channels are used to read the parameters and the FBA A data out2 channel is used to control the drive reference, where the parameters read from the drives and their purpose are shown in table 2.3.

Table 2.3 Drives parameters and their purpose

Group with index	Parameter name	Purpose
101.1	ISU DC voltage	To monitor the power supply on the INU
101.2	ISU Line current	To monitor the power supply to the ISU
101.9	ISU Grid voltage	To monitor the power supply to the ISU
1.6	INU Output frequency	To monitor the load on EUTs
1.7	INU Motor current	To monitor the load on EUTs
1.11	INU DC voltage	To monitor the power supply on the INU
1.13	INU Output voltage	To monitor the load on EUTs
5.11	INU Inverter temperature	To monitor the status of the INU

This can be used to monitor the power supplied to the drives, their status and the load on the EUT. As the INU drive is the key device for modulating the load on the EUT, this is the only place where the temperature is monitored.

3.PLC PROGRAMMING

3.1 PLC setup and programme

To operate the test system, both analogue and digital signals need to be read and written. As there are many signals, 2 DC532 modules were selected to read and write digital signals and 2 AI532 modules to read and write analogue signals. A communication module supporting the Profinet protocol is required to control the drives. The CM579PNIO module was chosen as it allows the actuators to be controlled via a Profinet protocol. The PM591 module was used as the central processing unit (CPU) module as it was available.

The DC532 modules are connected to LED lights, magnetic lock, thermal relay from transformer and environmental chamber, emergency stop buttons and fire detectors. The AI532 modules have HAL100, HAL400 and DVL2000 current and voltage sensors connected in parallel to the DAQ device. The CM579PNIO module is connected to the Profinet switch where the INU, ISU drives are connected.

Automation Builder and Codesys software were used to work with the PLC. The PLC with modules is shown in figure 3.1.

Figure 3.1 PLC setup in the test system

The original plan was to use a PLC to measure the current because it scans all the inputs faster than the DAQ device. However, it turned out that the HAL100, HAL400 and DVL2000 sensors produce an AC current output for which the AI532 module is not designed. To process an AC signal the FM502 module is required, which only works with the PM592 CPU module. It was decided not to pursue this idea, as there were problems with the delivery of the components. It was also decided to continue using the DAQ device for scanning current measurements, as the difference in speed was not critical.

The entire PLC programme consists of 6 processes that run in parallel:

1. Main programme loop,
2. Database programme loop,
3. Drives programme loop,
4. Environmental chamber programme loop,
5. DAQ device programme loop.

Test parameters and product data must be entered into the visualisation tables before the test starts. If the magnetic lock, DAQ device, environmental chamber or drives are not ready, a protection in the software prevents the test from starting. The test can be stopped manually via the visualisation or by pressing the emergency stop button. The visualisation displayed on the test computer in the Codesys environment allows the test to be monitored.

3.2 Main programme loop

The main cycle is the main process responsible for starting and stopping the test, updating the cycle counter, updating the cycle step parameters (voltage, temperature, humidity and cycle duration), checking and converting measurements. When the Init start button is pressed, the programme starts and checks the following devices:

1. Magnetic lock: activates the magnetic lock and uses feedback to check that it is closed;
2. DAQ device: starts reading data from the DAQ device unit and checks that the data is coming in;
3. Environmental chamber: switches the camera to manual mode and checks that the feedback has been received;
4. Drives: checks the drives for faults;

If all devices are OK, the Start test button will appear. When the button is pressed, the software starts the test. When the test starts, the cycle step data is read from the cycle step table in the visualisation and sent to the devices as setpoints. Finally, the drives are started and the LED indicator on the outside of the sea container shows that the test has started. Once the test is started, the cycle time timer starts, the measurement conversion and limit checking begin. During measurement conversion, the software converts and records the measurement results into the appropriate data structures (EUT or Global). The limit checking checks the measurement limits of the temperature, current and voltage sensors. The measurement limits are taken from the test specification. The limits are set in the code, except for the EUT temperature limit which is set by the operator as they vary depending on the test temperature. When the last step of the cycle is completed or a protection is activated (e.g. one of the measurements has exceeded the limit), the software stops the test. To stop the test, the software stops the drives and switches the chamber to cooling mode. Capacitors are considered cooled when their surface has cooled to room temperature (23 degrees Celsius). Experiments have shown that it takes 6 hours for capacitors to cool to room temperature. After 6 hours the software updates the number of cycles in the summary table, switches off the environmental chamber and opens the magnetic lock. Finally, an LED indicates that the test is complete. The logic of the main loop is shown in figure 3.2.

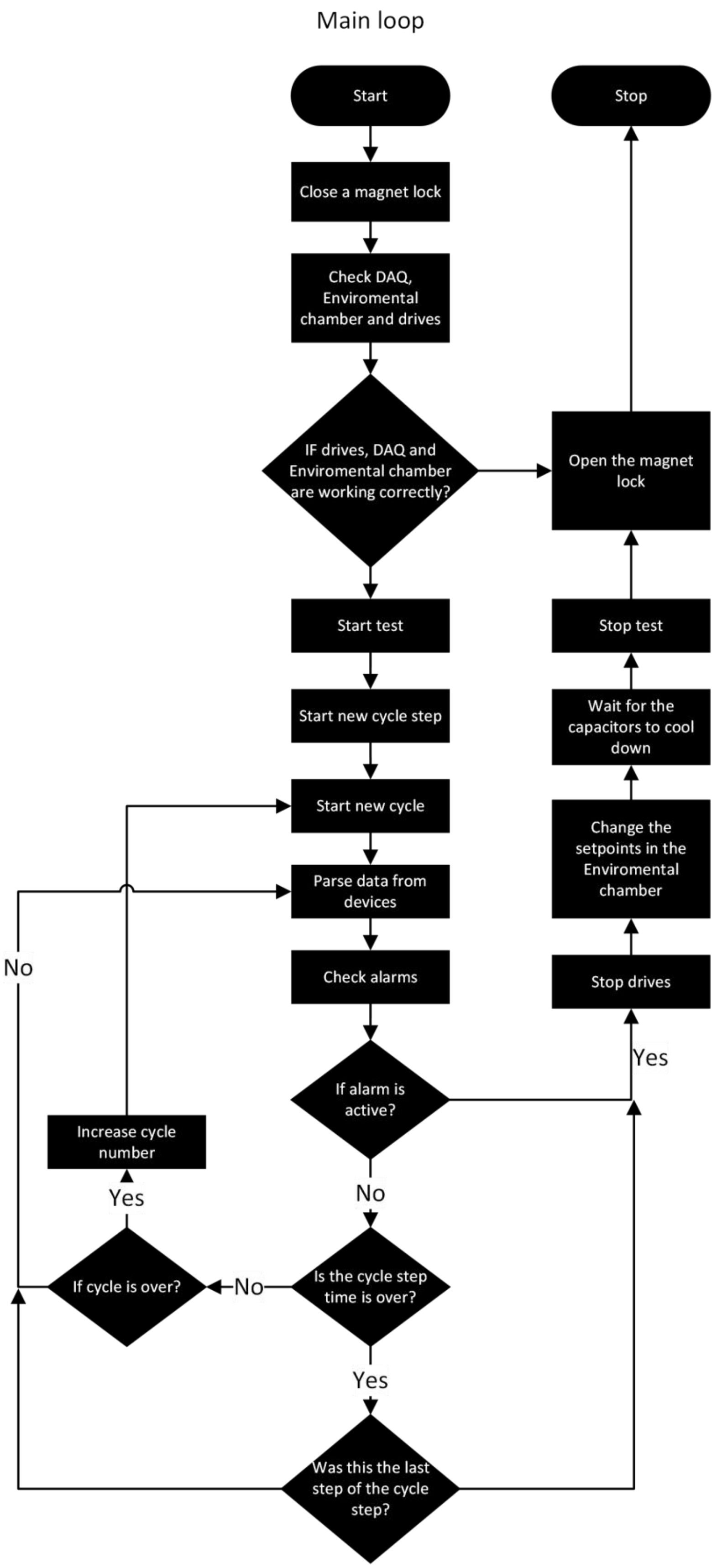

Figure 3.2 Main loop flowchart

3.3 Database programme loop

The Database programme loop is a parallel process in the PLC programme. The PLC programme uses a special MSSQL library to work with the database. In the visualisation there are 2 buttons related to this process: Summary write and Summary read. When the Summary write button is pressed, the programme sends data to the database in the Summary table all data about the EUTs, which is received during the test and entered by the user via the visualisation. If the serial number already exists in the database, the data of this item is updated, otherwise a new row is created in the table. By pressing the Summary read button, the software updates all information about the EUTs that it has received from the database. All the information received is visible in the programme visualisation. If the connection to the database is suddenly interrupted, a protection is triggered which raises an error flag preventing the test from starting or stopping the test if it is running. When the run flag is raised, the programme starts writing data to the database. The loop logic of the database programme is shown in figure 3.3.

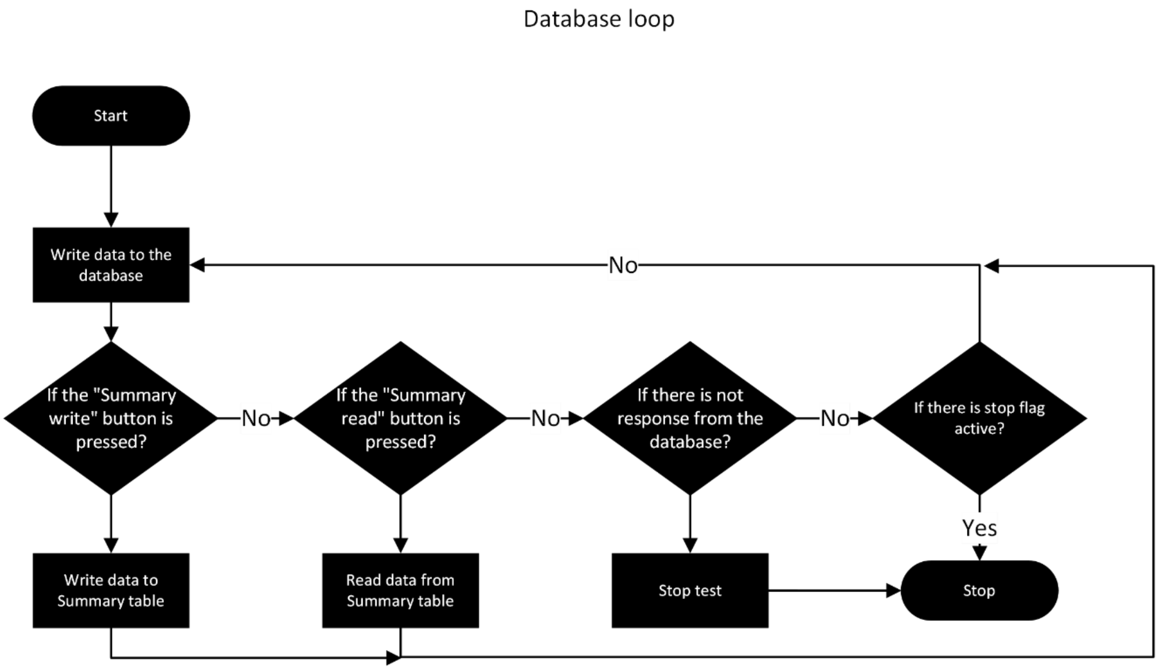

Figure 3.3 Database programme loop flowchart

3.4 Drives programme loop

The Drives programme loop is a parallel process in the PLC programme. When the PLC programme starts, the process starts to read data from the drives that the PLC receives via the Profinet interface. The programme reads the status of the drive by breaking the received numerical value into a bit value, where the 2nd bit shows if the drive works (value 1 on the bit means that the drive is working), the 3rd bit shows if the drive has an error. The parameters are read from the FBA data in channels. If at least one of the drives has a fault, a protection is triggered which sets a fault flag that does not allow the test to start or stops the test if it is working.

If a drive fails, the drive fault must be reset to allow the drive to restart. The software resets the faults when the test is started, or the alarm reset button is pressed. To reset a fault, the programme changes the 7th bit of the control word variable to 1, which is responsible for fault reset. When the start flag is raised, the control word 1151 is sent to the drives, in other cases the value 1150 is sent [14]. The control word bits and their function are shown in table 3.1. The Drives programme loop logic is shown in figure 3.4.

Table 3.1 Control word for starting the drives

Bit nr	Bit function	Bit value
0	OFF1 inactive	1
1	OFF1 inactive	1
2	OFF1 inactive	1
3	Enable operation	1
4	Enable ramp generator	1
5	Enable acceleration	1
6	Operating	1
7	Reset	0
8	Jogging 1	0
9	Jogging 2	0
10	Remote cmd	1

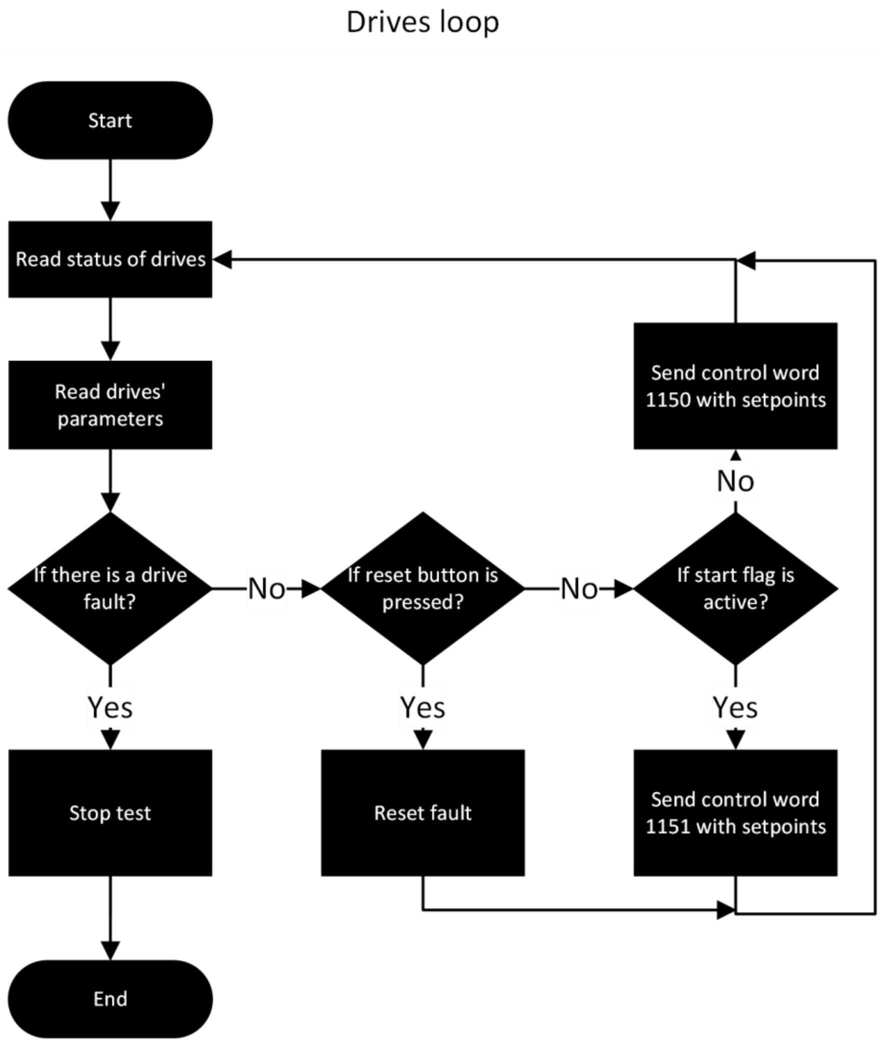

Figure 3.4 Drives programme loop flowchart

3.5 Environmental chamber programme loop

The environmental chamber programme loop is a parallel process in the PLC programme. A TCP/IP socket is used for communication between the environmental camera and the PLC. To control the chamber, it must be set to manual mode. Only then can setpoints for temperature and humidity be sent to the chamber. When the programme starts, it is set to manual mode and then the temperature and humidity in the chamber are read. When a new cycle step is started, the programme sends new setpoints to the environmental chamber. If the init stop flag has been raised, the software will send a setpoint of 20 degrees for temperature and 20 percent for humidity to cool the products. After sending, the flag is cleared, which means that the cooling process has started. When the stop flag is raised, the programme switches off the manual mode of the chamber, which means that the climate chamber programme stops regulating the climate in the chamber. The logic of the climate chamber is shown in figure 3.5.

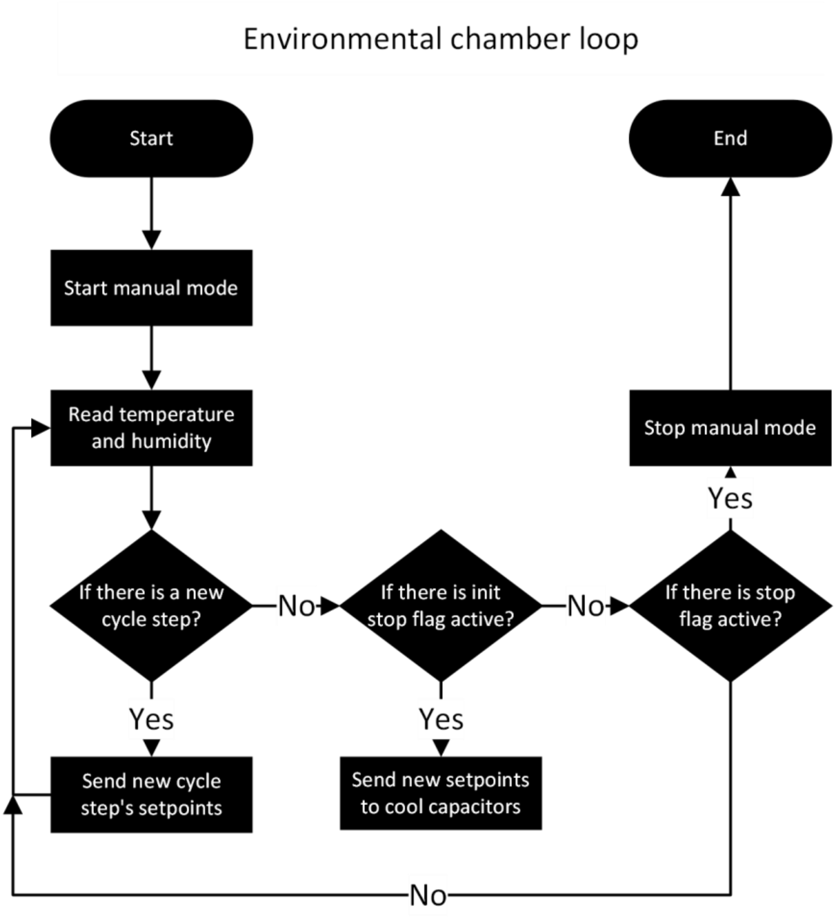

Figure 3.5 Environmental chamber loop flowchart

3.6 DAQ device programme loop

The DAQ device programme cycle is also a parallel process in the PLC programme. In this process, communication between the DAQ device and the PLC is established via a TCP/IP socket. Thermocouples, HAL400, HAL100 and DVL2000 sensors are connected to the DAQ device. The DAQ device is already configured to convert the sensor data from the previous solution. When the programme is started, the PLC sends a request to read the data from the DAQ device. If there is no response from the device, the stop flag is raised, stopping the test and communication with the DAQ device. The logic of the DAQ device programme cycle is shown in figure 3.7.

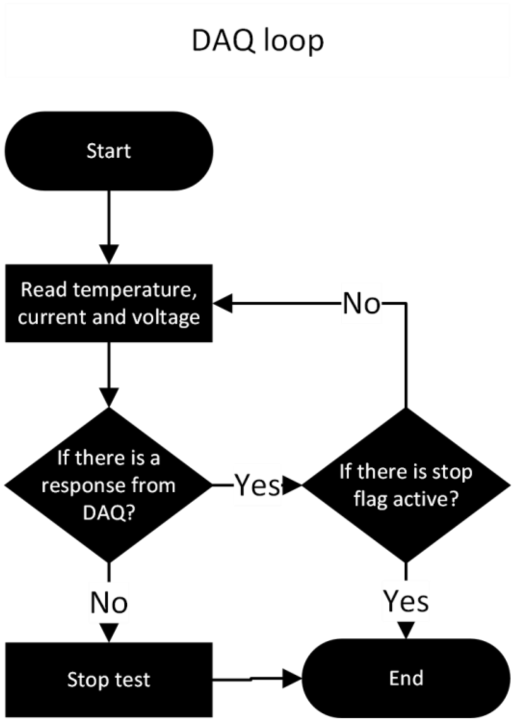

Figure 3.6 DAQ device loop logic flowchart

3.7 Alarm configuration

The Codesys programming environment allows alarms to be set via their environment. It is also possible to set them via a function in the code, but the main advantage of setting them via the Codesys environment is that if a fault occurs in the Codesys environment, the PLC reacts faster. The alarms are divided into two classes: Warning and Stop. Warning alarms warn the operator of a non-critical system fault via the visualisation, at which the system can continue to operate, e.g. an error when filling the Summary table. When alarms of class Stop occur, the programme stops the test due to a critical fault and informs the operator via the visualisation. All alarms and their classes are shown in table 3.2.

Table 3.2 Alarm table

Nr	Alarm name	Alarm class
1	Transformer overheat	Stop
2	Environmental chamber overheat	Stop
3	DAQ DEVICE Socket is dead	Stop
4	Sea container’s door is open	Stop
5	EUT Overheated	Stop
6	EUT's Current fault	Stop
7	Fire emergency stop	Stop
8	INU Fault	Stop
9	ISU Fault	Stop
10	Transformer's Current fault	Stop
11	Transformer's Voltage fault	Stop
12	Unable to connect to the database	Stop
13	Read from Summary error	Warning
14	Environmental chamber socket is dead	Warning
15	Write to Summary error	Warning

4. VISUALISATION

4.1 PLC visualisation

Visualisation for the PLC or HMI has been created for easy operation of the test system. Through the HMI, the operator must monitor the status of the test, set up the test, check the data received from the devices, see how the data has changed over time and what faults have occurred in the test system.

To make it easier to work with the HMI, the entire visualisation has been divided into pages, each with its own purpose. A total of 8 pages in the visualisation. All pages with their purpose are shown in figure 4.1.

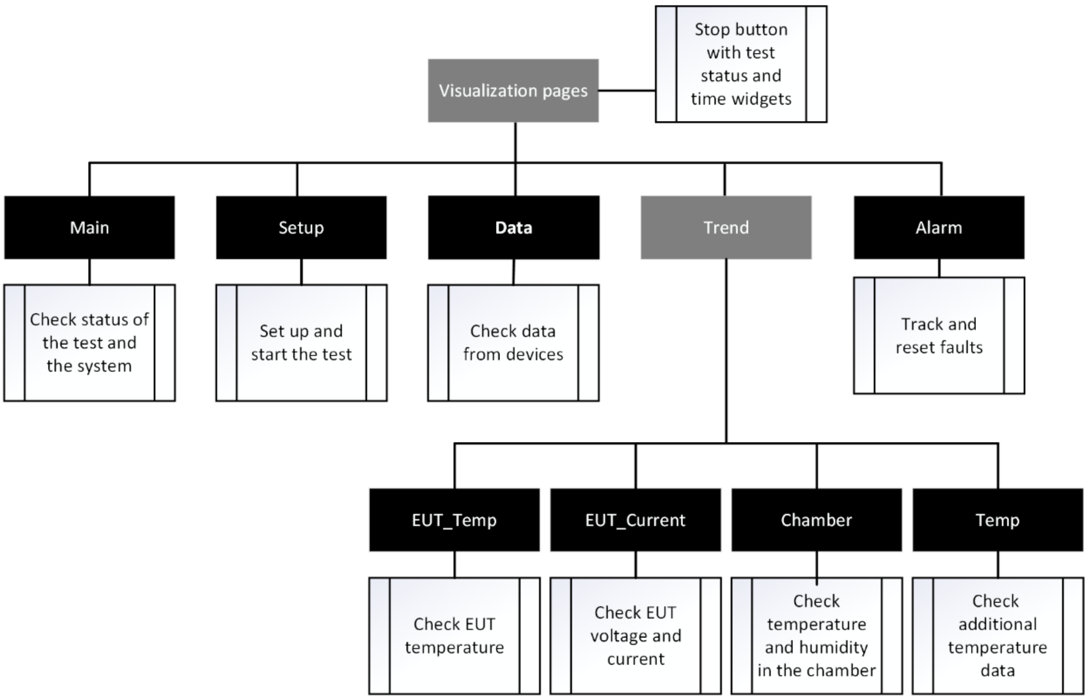

Figure 4.1 Visualisation pages with their purpose, where the black rectangles are the pages

When the test system is operating, a stop button for the test displays on each visualisation page's menu, allowing the operator to stop the test, see the system status, and navigate between the pages.

The Main page displays information about the status of the system. The window is divided into modules which turn red when an error occurs. On the page, the operator can see the status and basic data of each item in the test system, making it easier to monitor the status of the system. The Main page is shown in figure 4.2.

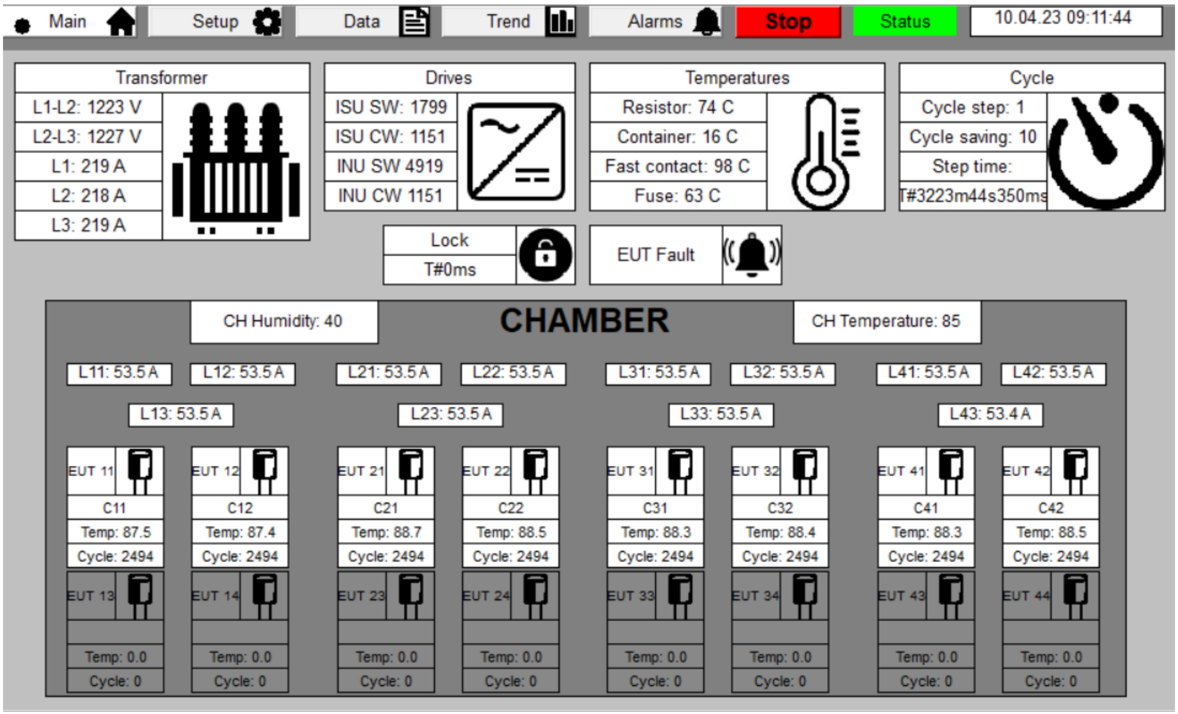

Figure 4.2 Main page in visualisation

The Setup page is created to start the test, view and edit test product data. There are two tables on this page: Summary and Cycle steps. The Summary table contains information about the EUTs that can be filled in manually by the operator or with information from the database. Each row has a button which, when clicked, changes the status of the EUT. Green means the EUT is active, red means it is inactive. At the bottom of the table there are 2 buttons: Read from DB and Write to DB. The Read from DB button retrieves information from the database and fills the table with it. The Write to DB button writes all the information from the table to the database. The Cycle steps table contains information about the test steps. The operator must fill this in manually before starting the test. The only thing left untouched in the table is the dt (rate of temperature change) limit (C) column, as it has not yet been determined what its value should be and for how long the dt will be calculated. At the bottom of the table there are circular device widgets that show the status of the device (green - ready to use, red - not ready to use) and the Init start button that checks if the system is ready to start. When each device widget turns green, the Start test button appears. When the Start test button is pressed, the buttons and device widgets disappear and the round green Running indicator appears, symbolising that the system is running. The system status widget will turn green, and the Stop button will appear in the page menu. This indicates that the test is now running. The setup page is shown in figure 4.3.

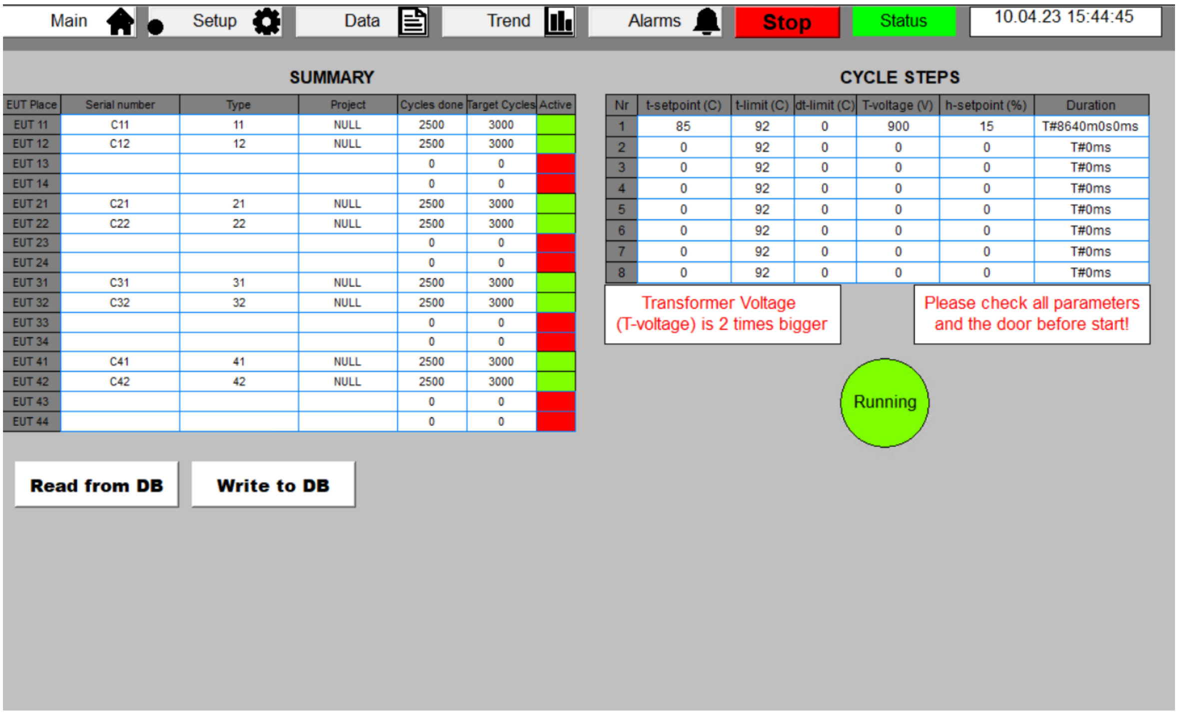

Figure 4.3 Setup page in visualisation

The Data page shows all parameters collected from the devices. Sometimes additional parameters are used to check the test system, which can only be found on this page. The Data page is shown in figure 4.4.

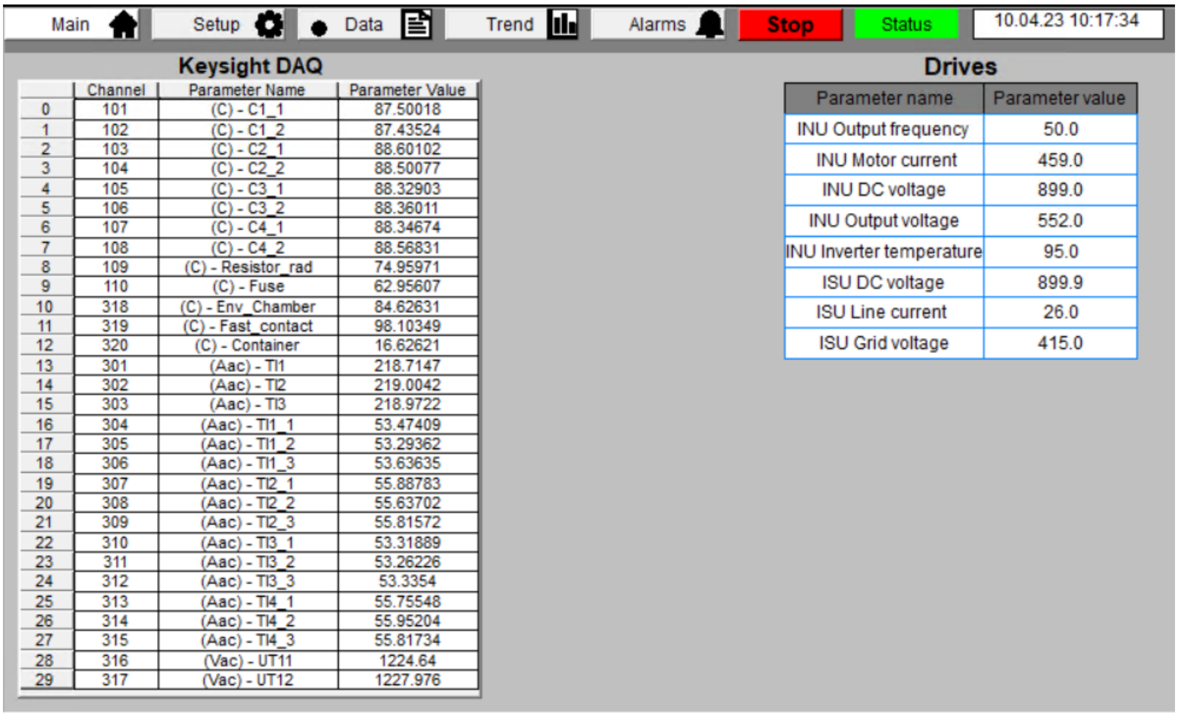

Figure 4.4 Data page in visualisation

Pressing the Trend button from the menu takes the user to the EUT_temp (EUT Temperature) page. The EUT_temp page shows a temperature chart for each EUT and its numerical value on the right. There is also a menu on the page to switch between the different charts:

1. EUT_temp – test capacitors temperature;
2. EUT_Curr – currents and voltages of test capacitors and transformers;
3. Chamber – environmental chamber temperature and humidity;
4. Temp – additional temperature data;

All the charts are similar except for EUT_Curr. The charts there show the range in which the values must remain. If the value is outside the chart, the protection is tripped, and the test is stopped. All charts are shown in Appendix 2.

The alarms page shows the active alarms and their history. There is the Reset alarms button which resets all alarms and removes all faults from the drives. This is needed to restart the system, as some faults need to be reset manually. The alarms page is shown in figure 4.5.

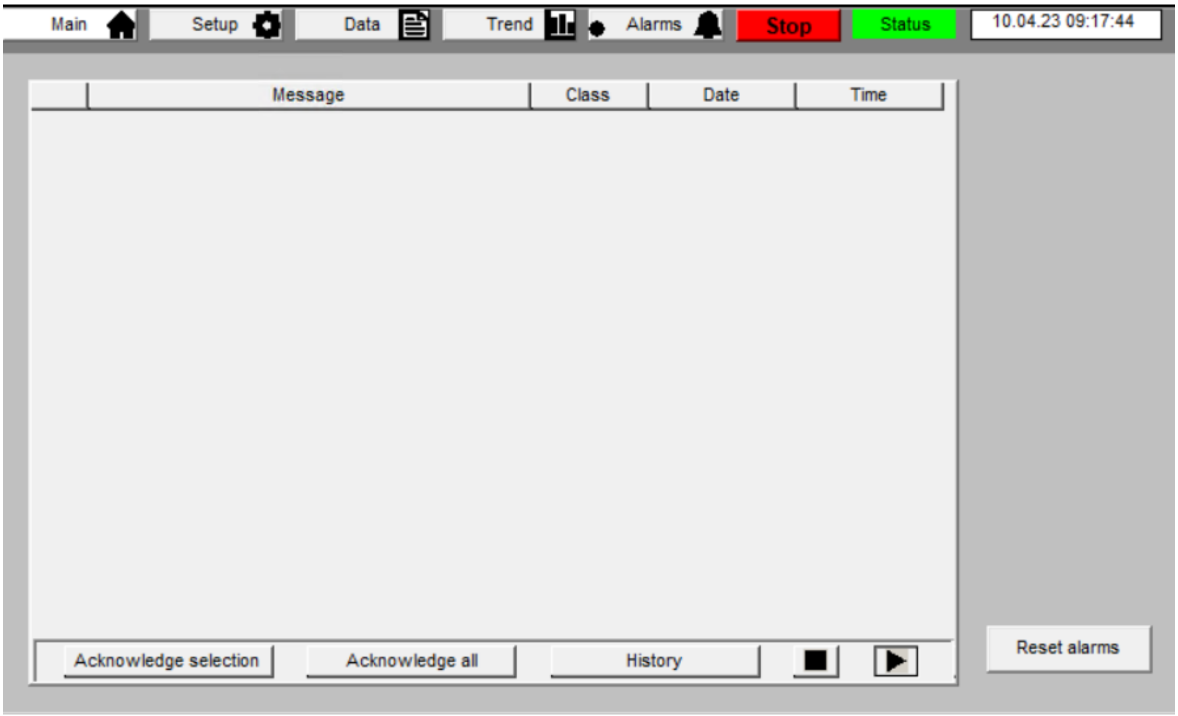

Figure 4.5 Alarm page in visualisation

4.2 Data processing software

The analysis of test data is an important process in both maintenance and product quality determination. Software written in the Python programming language has been created specifically for this purpose. The working principle of the software is that the user selects a test product, its test parameter (e.g. EUT temperature), time period and function (e.g. plot chart) using the graphical user interface (GUI) widgets. The software forms an SQL query and sends it to the database. After receiving the data, it builds a chart or table and displays it in the GUI. The logic of the programme is shown in figure 4.6.

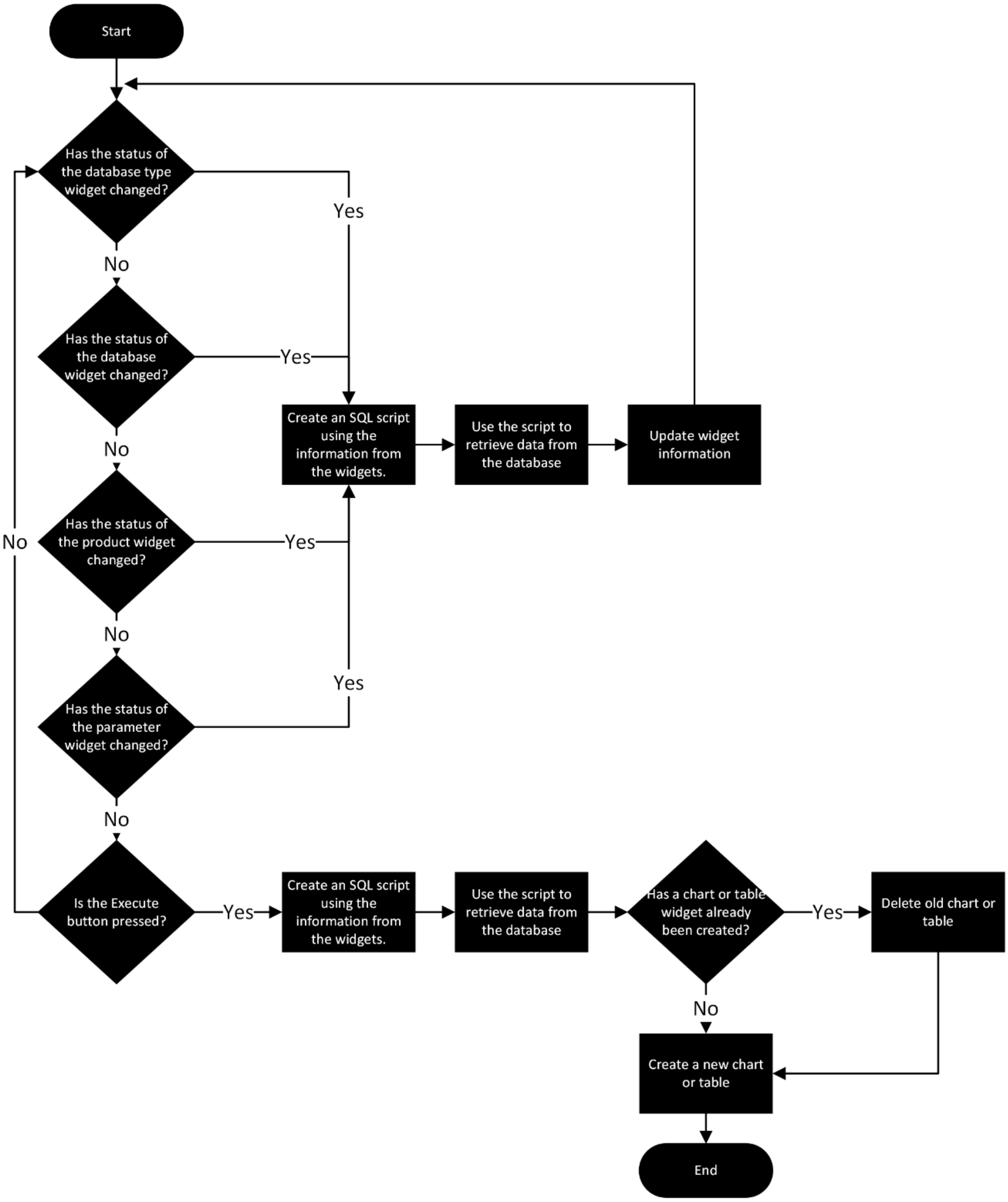

Figure 4.6 Data processing software logic flowchart

The software can be used to analyse data from both new and existing test systems. When the software is started, a window opens in the Main tab where a user first selects a type and name of database, which is presented as a list retrieved from the main database. User then selects a table name from the database. When a test system is chosen, the software sends a SQL query to the database to retrieve all the tested products' serial numbers. The Product widget can handle both serial numbers and the number of EUT place. There are some parameters that cannot be assigned to a single product. To select them it is necessary to select that the product has name Global or EUT place number is 0. Once the product has been selected, the programme sends an SQL query to obtain all the parameters of the product being tested. After selecting a parameter, the programme sends SQL query to the database to get the time interval when this product was tested. The user then selects the time interval he wants to see and a function. There are 4 functions in total:

1. Plot or Plot chart, where the function is represented as a line;
2. Scatter or Scatter chart, where the function is represented as points corresponding to individual data points;
3. Histogram;
4. Table;

Once a function has been selected, the Execute button must be pressed to display the data. When the Append button is pressed, the data is plotted on the existing chart. The GUI in the Main tab is shown in figure 4.7.

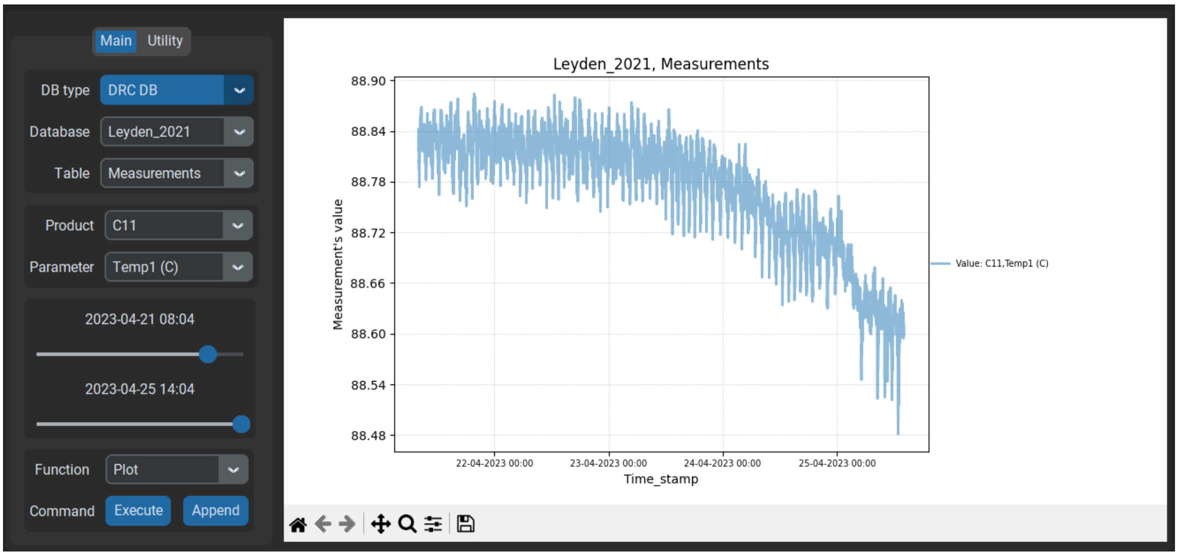

Figure 4.7 Main tab GUI with Plot function for the Measurements table

The Utility tab allows the user to change programme settings. There are 4 sections in total: Additional search criteria, Measurements, MinMax, Time format, Settings. The Additional search criteria section allows the user to add additional search parameters, e.g. to display the data from cycle 200. If the first cell in the row is empty, the software will not add any additional search criteria from that row. The Measurements and MinMax sections contain different functions for these tables. In the Measurements section it is possible to enable the display of the cycle steps in different colours. For the MinMax table, the Max and Min sliders enable or disable the display of the maximum and minimum values of the parameter in the cycle. The Time format section allows changing the time format of the X-axis. In the Settings section it is possible to enable or disable the display of outliers (unusual data points) in the test data, calculated according to the 3σ (three sigma) rule. If the 3σ function is enabled, the software calculates and displays the upper and lower limits beyond which outliers are located using the test data. The standard deviation formula 4.1 and the 3σ rule formula 4.2 are used for this purpose [23]. The 3σ rule is used because a high level of confidence is required in data analysis.

$$\sigma = \sqrt{[\Sigma(x-\mu)^2/N]} \tag{4.1}$$

where σ - standard deviation,

x - the value of each data point,

μ - the mean (average) of the data points,

N - the total number of data points.

$$\begin{aligned} Upper\ Control\ Limit\ (UCL) &= \bar{X} + 3\sigma \\ Lower\ Control\ Limit\ (LCL) &= \bar{X} - 3\sigma \end{aligned} \tag{4.2}$$

where $\bar{X}$ - the sample mean,

σ - the sample standard deviation.

The user can also change the GUI themes. The GUI in the Utility tab is shown in figure 4.8.

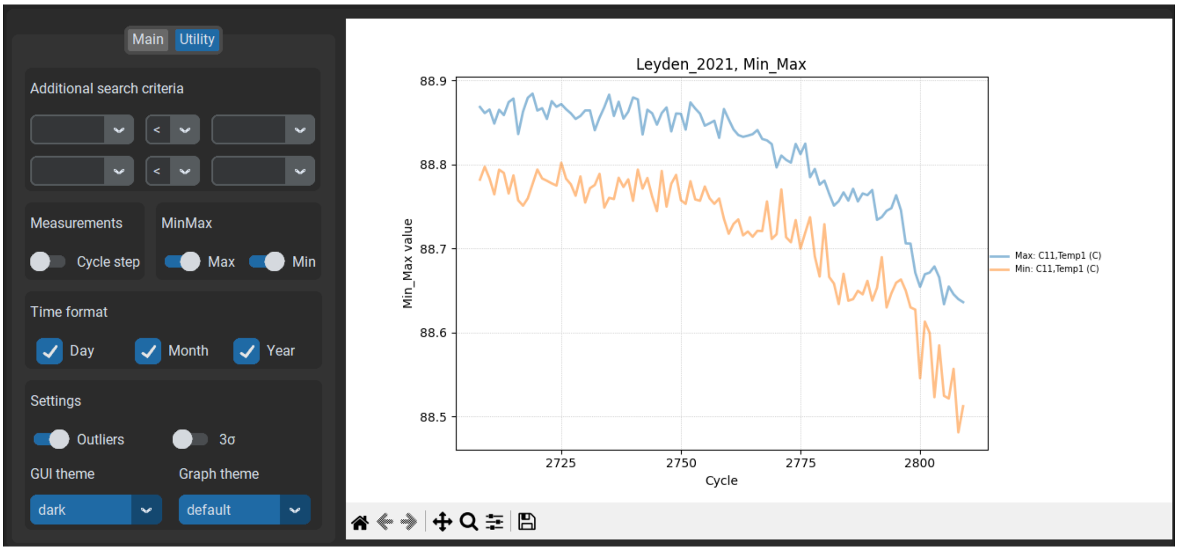

Figure 4.8 GUI in Utility tab with Plot function for MinMax table

5. RESULTS

5.1 Solution validation

In order to know how to evaluate the work done, it is necessary to know whether the solution is fit for purpose. To do this, a validation of the new solution was carried out, which is divided into 3 parts:

1. Risk analysis,
2. Time saving analysis,
3. General analysis of work.

Risk analysis shows the extent to which automation has reduced risk. Only those risks that have been affected by automation have been taken into account. Time saving analysis calculates how much time and money are saved per year when working with the test system and its data, allowing to see how important the new changes have become. In the General analysis of work, the author assesses the work he has done by analysing each change in the test system. If all the objectives have been achieved, the automation can be considered to have fulfilled its purpose.

5.2 Risk analysis

In assessing the results of automation, it is important to understand the extent to which risks have been reduced after automation. For this purpose, the risks whose probability decreased after automation were taken. FMEA (Failure Mode and Effects Analysis) [24] was used as a method because it also allows the evaluation of protective mechanisms for risk avoidance. The results are calculated based on the evaluation of three key factors for each failure mode: Severity (S), Occurrence (O), and Detection (D). These factors are rated on a scale from 1 to 10 or from low to high. The ratings for each factor are then multiplied together to determine the Risk Priority Number (RPN) for each failure mode. Severity refers to the seriousness of the potential consequences or effects of a failure mode. Occurrence represents the likelihood or frequency of the failure mode occurring. Detection evaluates the ability to detect the failure mode before it reaches the end-user or causes significant consequences. The detection rating is assigned based on a scale, with higher values indicating a lower probability of failure mode detection.

The following risks have been mitigated after automation:

1. Test capacitor explosion,
2. Test capacitor fire,
3. Data loss.

A test capacitor explosion can damage both the test system and the other test capacitors. This is the worst thing that can happen, of the risks taken for analysis, because the test system fails, and the test results of the other capacitors are spoiled. Therefore, the Severity has a score of 10. The probability of explosion is extremely low, with a higher probability the capacitor can catch fire. But when considering that the products are tested under stressful conditions, the probability of risk is higher. Therefore, the Occurrence has 2 points. The previous solution used a smoke detector and a thermal relay to prevent an incident. For the smoke detector to be triggered, the smoke must reach the detector. This can be problematic in an environmental chamber because of the operating fans in the environmental chamber. As for the thermal relay, it only reacts to the total temperature of the environmental chamber. The fuses will only trip at high current, but it is not clear whether the current will be high enough before the incident. Because of this, the protection system may or may not respond, which requires additional research that is beyond the scope of this paper. The Detection therefore received a score of 5 points. In the new solution, protection has been added in the form of a limit measurement check. If one of the parameters (e.g. temperature) exceeds the limits, the protection should be triggered immediately. Therefore, the New Detection received 1 point.

If not reacted to in time, a capacitor fire will have the same consequences as an explosion, which can damage the test system and capacitors. In this case the Severity is 10 points. According to [15], the number of factors that can cause a film capacitor to catch fire is greater than that of an explosion. Taking also into account that the probability of ignition is low because the ageing of the capacitor mainly results in a loss of function, the Occurrence is given a score of 3. The same means are used for protection as in the case of an explosion. In a fire, it is much easier to react before the incident as there is more smoke and higher temperature in a fire. The Detection receives a score of 3. If additional protection in the form of a measurement limit check is used, then the New Detection received 1 point.

If data is lost, the test result becomes inaccurate. It all depends on the amount of data. In this case the Severity scored 3, because usually a small amount of data is lost due to loss of power or file corruption. This happens occasionally so Occurrence scores 5. Backups help in this case, as they keep a copy of the data on the computer and in the event of an incident, a small amount of data is lost. But in the event of damage to the computer this will not help. Detection therefore has a score of 5. With databases, data is saved first in the local database, and then in the main database. This guarantees the security of the data. The New Detection therefore scores 1. The results of the analysis before and after automation are shown in table 5.1, 5.2.

Table 5.1 Failure Mode and Effects Analysis before automation, where S – Severity, O – Occurrence, D – Detection, RPN – Risk priority number

Failure Mode	**Failure Effect**	**S**	**Potential Causes**	**O**	**Current Process Controls**	**D**	**RPN**
Test capacitor explosion	Damage to the test system, damage to other test capacitors	10	Wear out	2	Smoke detector, fuses, thermal relay	5	100
Test capacitor fire	Damage to the test system, damage to other test capacitors	10	Wear out	3	Smoke detector, fuses, thermal relay	3	90
Data loss	Inaccurate test result	3	Loss of electricity, damaged test computer, corrupted file	5	Backup	5	75
					Total:		**265**

Table 5.2 Failure Mode and Effects Analysis after automation, where S – Severity, O – Occurrence, D – Detection, RPN – Risk priority number

Failure Mode	**Failure Effect**	**S**	**Potential Causes**	**O**	**Current Process Controls**	**D**	**RPN**
Test capacitor explosion	Damage to the test system, damage to other test capacitors	10	Wear out	2	Smoke detector, fuses, thermal relay	1	20
Test capacitor fire	Damage to the test system, damage to other test capacitors	10	Wear out	3	Smoke detector, fuses, thermal relay	1	30
Data loss	Inaccurate test result	3	Loss of electricity, damaged test computer, corrupted file	5	Backup	1	15
					Total:		**65**

The aim is to understand how well the automation has dealt with the potential risks. As a result, we can see that the RPN has decreased by about 4 times. Based on the analysis presented, it can be said that the new system is safer than the previous one, as the probability of serious accidents has been reduced by a factor of 4.

5.3 Time saving analysis

The presence of the PLC in the test system played a key role in the new solution. The PLC has made the use and maintenance of the test system more convenient and faster, which has reduced the time and minimised the possibility of an incident caused by human error. Because the PLC is connected to other devices, the amount of data has increased, improving the quality of data analysis. The HMI has made it easier and quicker to get the test system up and running. Previously, each device had to be configured separately, which took much longer to start up and maintain in the event of a fault. The flexibility of the PLC programme also makes it possible to run more complex tests with variable stressors, which are set at system startup when using the HMI. The presence of a PLC has made it possible to implement additional protection by checking the measurement limits. The presence of charts and an alarm table in the HMI has made it possible to find faults in the test system more quickly and to monitor the status of the test better, speeding up the maintenance and operation of the test system.

Having a data structure makes it easier to work with large amounts of data, which saves time when analysing the data. Previously, the data was stored in Excel files that had to be moved from the test computer to cloud storage. The new solution stores the data in the local SQL database, where it is much easier to find the required measurements. Having the local SQL database synchronised with the main SQL database makes the test data more accessible and prevents data loss if the test computer fails. Previously, limited space on the test computer was an issue, as the hard drive would become clogged up after a while, but by synchronising with the main database, old test data can now be deleted from the test computer.

The data processing software is designed to make analysis faster and better through its built-in features. The software allows interaction with other test systems, making it flexible. The charts obtained from the programme allow better analysis of various parameters not only in the new test system, but also in older test systems. These charts can also be used in test result reports. They can also be used to monitor the status of the test system at different time intervals and for any test parameter, reducing the time and improving the quality of test system monitoring. To find out how much time has been saved by automation, the time taken per week for the specific processes before and after automation was taken. In order to calculate how much money can be saved through automation, the average salary of an electrical engineer was taken from the source [25]. Considering all the costs to the employer per employee, the employer pays about 20 euros per hour. Table 5.3 shows how much time per year was gained by automating the processes.

Table 5.3 Time savings through automation

Activities	Weekly time spent before automation (min)	Weekly time spent after automation (min)	Annual savings (h)	Annual savings (euro)
Monitoring the status of the test	60	25	30	600
Working with test data	80	30	78	1560
Setting up and starting a test system	15	5	9	180
Total:	**155**	**60**	**82**	**1640**

The results show that the new solution is about three times faster and saves 1640 euros per year.

5.4 General analysis of work

The objective of the thesis is to create a safer solution that uses automation to collect more test data and reduce time spent working with the test system and its data. In order to check whether the objectives have been achieved, an analysis of change was made.

The use of PLCs has made it possible to use measurement limits which prevent a potential incident (e.g. explosion of a test capacitor) which can damage both other test capacitors and the test system. This can lead to premature failure of the test products, making the test results inaccurate, not to mention the cost of restoring the test system in the event of failure.

Local database has made the test data more accessible, as it is all in one place, and by synchronising with the main database it can be accessed remotely, making it much easier to work with. Synchronisation also removes the problem of limited test computer memory, increasing the volume of test data. If the test computer is damaged, there is no risk of losing a lot of data because the test data is transferred to the main database.

HMI makes it possible to react more quickly in the event of abnormal system behaviour or failure. HMI also allows the operator to see all measurements and faults in real time, so that the system can be better maintained, and less time spent on it. All of this improves operational efficiency and reduces the likelihood of incidents.

Data processing software reduces data handling time through features built into the software that reduce handling time many times over. The software allows the user to access data remotely, so the system can be monitored remotely. This software also makes it easier to work with test data, which saves a great deal of time, and partially takes over the function of the HMI, but does not change the operation of the system itself.

Data structure allows more detailed information to be obtained about the test product and what happened in the test at a particular time by classifying the data. The data structure is important for faster handling of the data, but this is where its functionality ends.

PLC has made it possible to collect data from devices other than the DAQ device and LCR meter. The database has also increased the volume of data. All this improves the quality of data analysis, but not significantly.

The use of PLCs has allowed more complex tests with variable stressors. This is currently not required for this test programme as the stress factors remain unchanged over a long period of time. However, it may be useful in the future when the test programme is changed. The result of the automation is shown in table 5.4.

Table 5.4 Automation result

Improvements	**Impact**
Measurement limits	Prevent damage to test products, test system
Database	Makes data more accessible, increase the volume of test data and prevent loss of test data
HMI	Quicker response times, more detailed monitoring, easier maintenance
Data handling programme	Reduced data handling time, remote monitoring capability
Data structure	Reduced data handling time
More test data	Better data analysis
Cycle steps setting	The possibility of running a more complex test

The results show that automation has made important changes to the testing system, increasing safety, adding more functionality, generating more test data, reduced the time for working with the test system and its data. The objectives of the automation have been met.

SUMMARY

According to the literature review, wear and tear is the main reason why products fail. The problem is that the manufacturer's stated lifetime and the actual lifetime for new products are not the same. For this reason, there are various reliability test methods that can be used to check the quality of products. The ALT test method is the best way to estimate the lifetime of a product. Of all the methods for estimating the life of test capacitors, formula 2.4 is the most appropriate for this case, as it incorporates the greatest number of stress factors used, making the calculation result more accurate. When testing capacitors, it is important to monitor their condition to avoid the risk of explosion or fire. It has been found that it is sufficient to monitor their temperature and the presence of smoke to avoid an incident.

The ALT test system for capacitors was created to solve the problem. The previous solution had many disadvantages. A literature review was carried out to find out what formula should be used to calculate the estimated lifetime of the test capacitors and what should be considered to prevent an incident with the capacitors under test. To improve the test system, a PLC was used to integrate all the equipment in the test system. The implementation of additional protection in the form of measurement limit checking, the simplification of the test system using an HMI, and the simplification of test data handling through the use of a database, data processing software, and data structure have all been made possible by the use of the PLC. The PLC has also made it possible to receive data from devices other than the DAQ device, allowing better analysis of the test data. With the HMI it is now possible to run more complex tests by configuring the cycle steps.

Analysing the results, it is fair to say that it was worth it. It is now clearer which formula to use to calculate the estimated lifetime of the test capacitor and what causes it to fail. It is estimated that the automation will save 82 hours of work per year, or 1640 euros per year. Analysis of the results showed that all the objectives of automation, namely increased safety, generation of more test data and reduced time spent working with the test system and its data, were achieved.

KOKKUVÕTE

Kirjanduse ülevaate põhjal on kulumine peamine põhjus, miks tooted ebaõnnestuvad. Probleem on selles, et tootja poolt märgitud eluiga ja uute toodete tegelik eluiga ei ole sama. Seetõttu on olemas erinevad töökindluse testimise meetodid, mida saab kasutada toodete kvaliteedi kontrollimiseks. ALT-testimeetod on parim viis toote eluea hindamiseks. Testkondensaatorite eluea hindamise meetoditest on valem 2.4 antud juhul kõige sobivam, kuna see sisaldab kõige rohkem kasutatud stressitegureid, mis muudab arvutustulemuse täpsemaks. Kondensaatorite testimisel on oluline jälgida nende seisundit, et vältida plahvatuse või tulekahju ohtu. On leitud, et piisab nende temperatuuri ja suitsu olemasolu jälgimisest, et vältida vahejuhtumit.

Probleemi lahendamiseks loodi kondensaatorite testimise ALT-süsteem. Varasemal lahendusel oli palju puudusi. Teostati kirjanduse ülevaade, et selgitada välja, millist valemit tuleks kasutada katsekondensaatorite hinnangulise eluea arvutamiseks ja mida tuleks arvestada, et vältida õnnetusjuhtumit katsetatavate kondensaatoritega. Katsesüsteemi täiustamiseks kasutati PLC-d, et integreerida kõik testsüsteemi seadmed. Täiendava kaitse rakendamine mõõtmispiiride kontrollimise näol, katsesüsteemi lihtsustamine HMI kasutamise kaudu ning katseandmete käitlemise lihtsustamine andmebaasi, andmetöötlustarkvara ja andmestruktuuri kasutamise kaudu on kõik saanud võimalikuks tänu PLC kasutamisele. PLC on võimaldanud saada andmeid ka muudest seadmetest kui DAQ-seade, mis võimaldab testandmete paremat analüüsimist. HMI abil on nüüd võimalik teha keerulisemaid katseid, kasutades tsükli etappide konfigureerimist.

Tulemusi analüüsides on põhjust öelda, et see oli seda väärt. Nüüd on selgem, millist valemit kasutada testkondensaatori hinnangulise eluea arvutamiseks ja mis põhjustab selle ebaõnnestumise. Hinnanguliselt automatiseerimine säästab 82 töötundi aastas või 1640 eurot aastas. Tulemuste analüüs näitas, et kõik automatiseerimise eesmärgid, nimelt suurem ohutus, rohkemate katseandmete genereerimine ning testsüsteemi ja selle andmetega seotud ajakulu vähendamine, on saavutatud.

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APPENDICES

Appendix 1 Modified drive parameter tables

Table A1.1 ISU modified parameters

Parameter group nr	Parameter index number	Parameter name	Parameter value
120	1	Ext1 commands	Fieldbus A
123	2	DC voltage ref selection	FB A ref1
150	1	FBA A enable	Option slot 2
150	2	FBA A comm loss func	Fault
151	1	FBA A type	PROFInet IO
151	2	Protocol/Profile	PNIO ABB Pro
151	20	Telegram type	PPO7
152	1	FBA A data in1	SW 16 bit
152	2	FBA A data in2	101.1[16]
152	3	FBA A data in3	101.2[16]
52	4	FBA A data in4	101.9[16]
153	1	FBA A data out1	CW 16bit
153	2	FBA A data out2	Ref1 16bit

Table A1.2 INU modified parameters

Parameter group nr	Parameter index number	Parameter name	Parameter value
20	1	Ext1 commands	Fieldbus A
28	11	Frequency ref1 source	FB A ref1
50	1	FBA A enable	Option slot 2
50	2	FBA A comm loss func	Fault
51	1	FBA A type	PROFInet IO
51	2	Protocol/Profile	PNIO ABB Pro
51	20	Telegram type	PPO7
52	1	FBA A data in1	SW 16 bit
52	2	FBA A data in2	1.6[16]
52	3	FBA A data in3	1.7[16]
52	4	FBA A data in4	1.11[16]
52	5	FBA A data in5	1.13[16]
52	6	FBA A data in6	5.11[16]
53	1	FBA A data out1	CW 16bit
53	2	FBA A data out2	Ref1 16bit

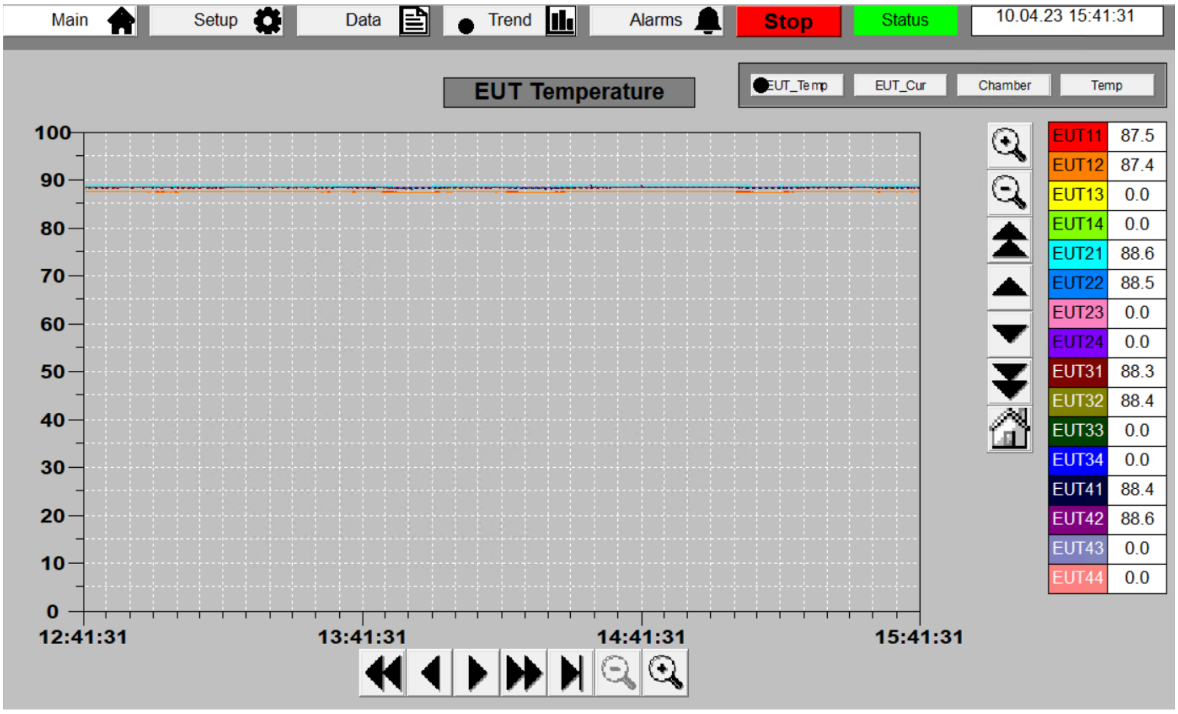

Figure A2.1 EUT_temp page in visualisation

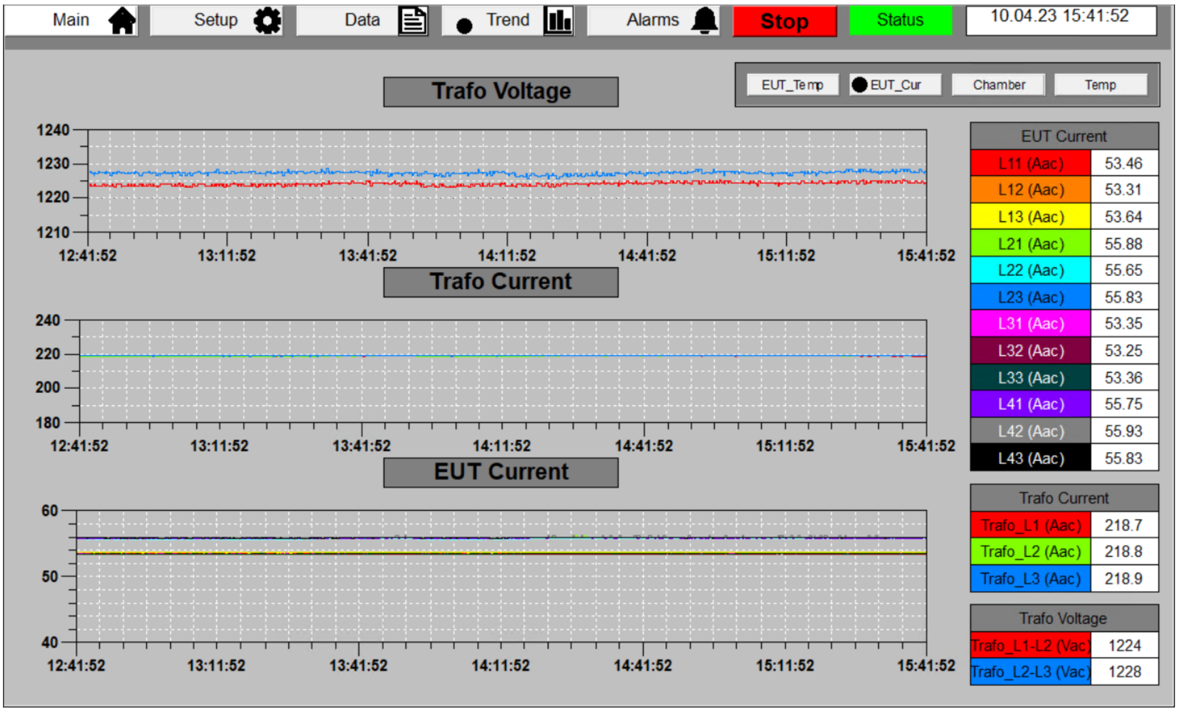

Figure A2.2 EUT_Cur page in visualisation

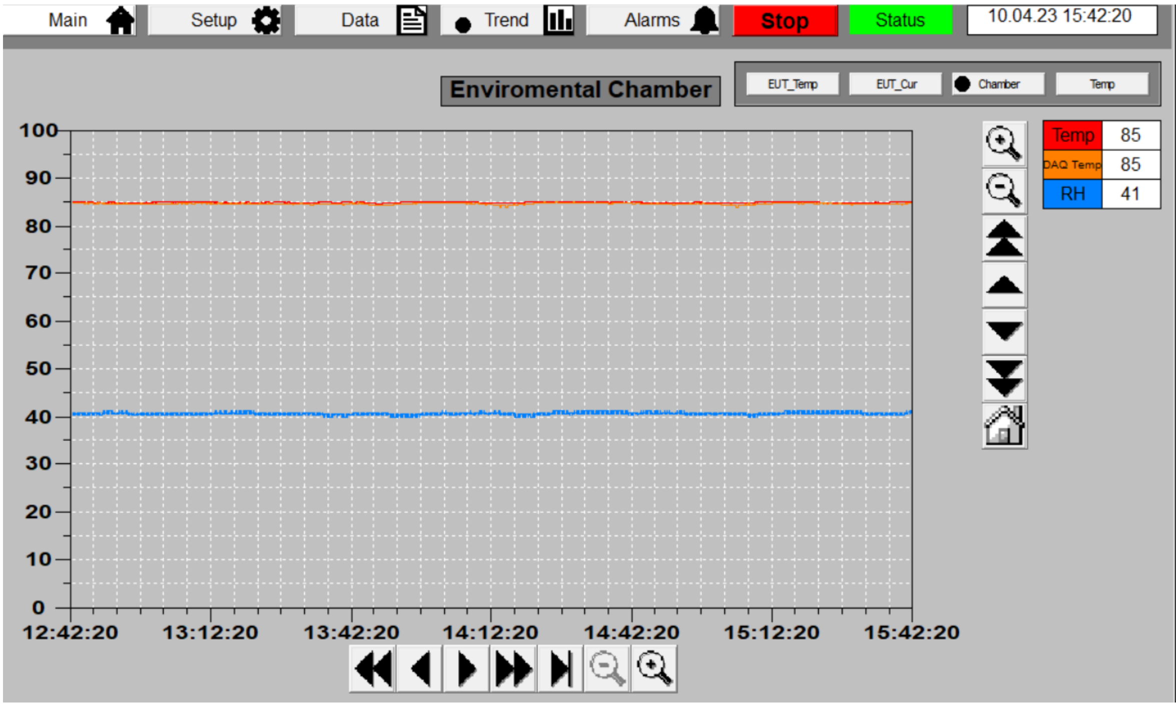

Figure A2.3 Chamber page in visualisation

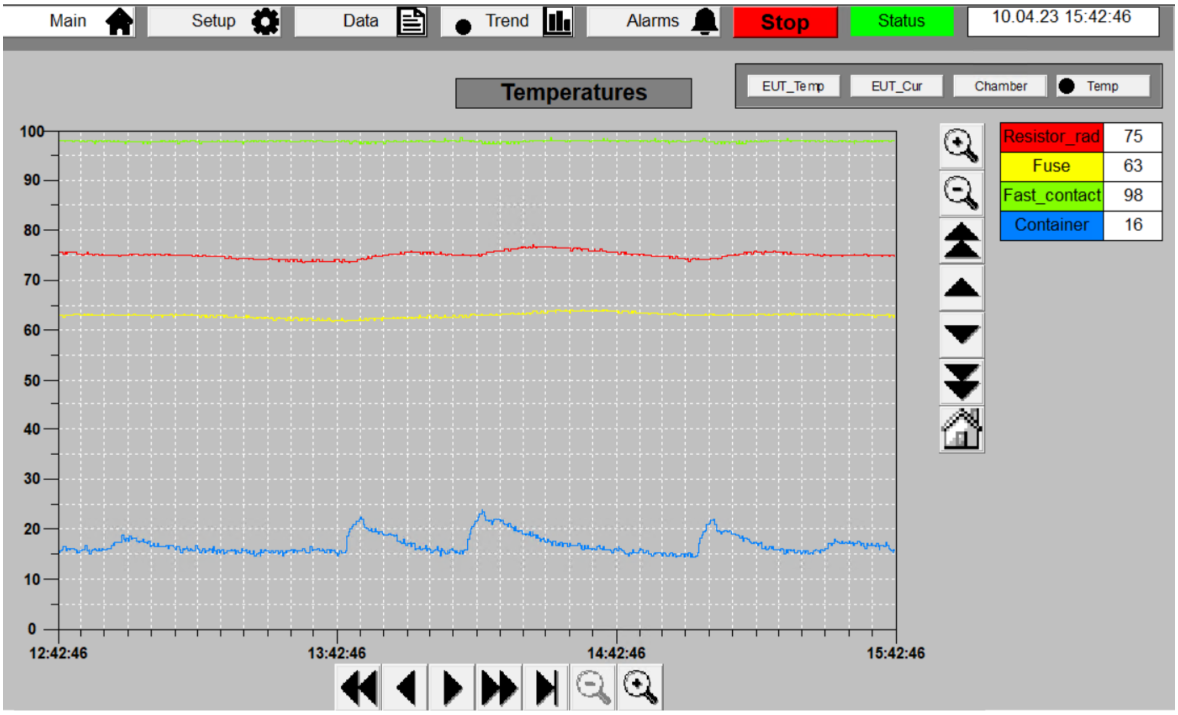

Figure A2.4 Temp page in visualisation

GRAPHICAL MATERIAL