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Software and Hardware Testing of a Lithium-Ion Battery Controller

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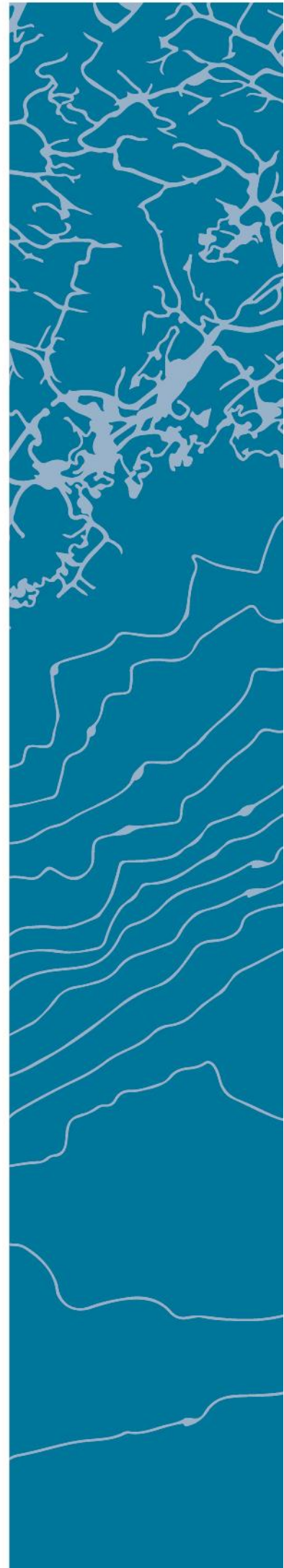
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Abstract

The Lithium-ion battery development has been very rapid in the last few years with respect to performance and safety. This has been the result of increasing development of battery management systems, which prolong the battery lifespan, optimize battery performance, provide with sensor data and apply of all these features to increase the safety of battery operation. Grenland Energy is a company that develops and supplies battery based power supply systems with batteries and battery management systems. Their battery controller unit called electronic and electric top (EE-Top) is a state-of-the-art product, providing with battery energy and power management, as well as battery statistics communication and safety.

During this thesis, software testing was developed by programming a simulation of the physical EE-Top and battery module equipment. This simulation will be used to test battery management system control logic with the EE-Top and batteries, without the need of physical equipment. The developed simulation was tested for a single EE-Top system and its functionality was verified by performing sequencing tests and data communication. The simulation was then expanded into a larger three EE-Top system, since most of the battery management systems consist of several EE-Tops. Also, hardware testing of the EE-Top was developed as end-of-line testing procedures. These tests were verified on a physical EE-Top and provided with component functionality and communication tests.

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Abbreviations

ΔT temperature gradient. 13

ΔV voltage difference. 13

AC alternating current. 13

BMS battery management systems. 1

CAN controller area network. 3

CFC continuous function chart. 25

CGM CAN group module. 9

CO₂ carbon dioxide. 30

CPU central processing unit. 15

DC direct current. 8

DCM dual cell module. 37

DUT device under test. 24

EE-Top electronic and electric top. i

EoL end-of-line. 3

GRE Grenland Energy. 2

GVL global variable list. 24

HMI human machine interface. 4

HV high voltage. 40

I/O input and output. 3

IEC international electrotechnical commission. 16

IP internet protocol. 11

Li-ion Lithium-ion. 1

MG Main goals. 4

O objectives. 4

OCM octo cell module. 9

PLC programmable logic controllers. 3

POU program organization unit. 25

RTU remote terminal unit. 18

S Seebeck. 13

SoC state of charge. 2

SR Set/Reset. 26

TCP transmission control protocol. 18

TON Timer On. 26

UiA University of Agder. 2

V volt. 8

Chapter 1

Introduction

1.1 Background

The Lithium-ion (Li-ion) battery development has been very rapid in the last few years with respect to performance and safety. This trend will most likely continue and maintain its progress in order to push the boundaries of battery energy/power density, safety, and cost [1]. The cost of Li-ion batteries and additional, needed electronics as battery management systems (BMS) are the main factors that restrain battery based energy storage systems from extensive renewable energy application. At present, the major factors that contribute to the cost of the Li-ion batteries are the processing cost of materials and BMS which prolong the lifespan of the batteries.

When it comes to the material costs, lithium contributes only a small amount in the cathode and anode, which does not make it the major contributor to the material cost of Li-ion batteries. The processing of other materials like cobalt which are used in larger quantities influence the end product costs greatly [2]. As mentioned, issue with prolonging the lifespan of Li-ion batteries also influences the costs greatly and one of the main factors that lead to batteries end of life is degradation. Degradation process of batteries is dictated by the operating temperatures, charge/discharge cycles and power, and state of charge management. Therefore, implementing a system that prevents the batteries from operating outside the threshold conditions is very beneficiary and decreases battery servicing costs.

Battery packs may consist of a variety of series and parallel connected Li-ion cells and the battery pack's performance is limited by the worst performing cell. It is known that each Li-ion battery cell has a slight difference in terminal voltage, charge capacity, degradation capacity and self-discharge rate [3]. The balance loss/differences between the batteries, which usually occurs during the charging and discharging cycles, leads to battery operating outside

the operating conditions and consequently increased battery degradation and higher chance for battery failures. Implementation of BMS in Li-ion batteries has become necessary due to the different Li-ion cell scenarios mentioned above.

A BMS plays an important role in ensuring safety and enhancing the service life of a battery. This includes real-time monitoring of temperatures, current and voltages, implementation of battery balancing, state of charge (SoC) calculations, alarms detection, failure prevention, communication to internal and external devices, data logging, etc [4]. It prevents battery packs from overcharging, discharging completely and operating outside the desirable temperature. Different batteries have their own normal operating conditions, thus, configuration and calibration of BMS for each battery specific application is necessary.

Grenland Energy (GRE) is a company providing with battery packs with BMS, consists of several components that together make it state-of-the-art system for marine applications. Today's GRE's available system is adaptable to many different operating conditions and is configurable and calibrated individually for each application. Their system consist of Li-ion battery cell modules, which are managed by a network of different sensors, controllers and equipment designed to optimize their performance and longevity. Nevertheless, their battery systems still benefit from further development and testing of the equipment and software used to program the equipment.

This project is given by Grenland Energy and will be a part of the ENE500 course at University of Agder (UiA) in the Renewable Energy specialization. The project will be supervized by Prof. Mohan Lal Kolhe, Bernhard Fäßler from UiA, and Rambabu Kandepu from GRE. It will be developed by master students Asther Nueva and Deividas Svaikauskas.

1.2 Problem Statement

GRE has developed a battery controller called EE-Top. It is a part of the state-of-art BMS and responsible of managing a battery string consisting of several battery modules with many battery cells inside. Due to its complexity and use of new technology, it still benefits from further software and hardware testing. These tests can be performed both, on control logic software for project specific applications and for end-of-line (EoL) product testing. The tests ensure that the equipment delivered to the customer are in perfect working condition and lower company's costs in on-site servicing of the equipment. This report describes the development of the earlier mentioned tests for the EE-Top and will be split into **two objectives**; development of a simulation of the EE-Top and battery module for software testing and development of EoL testing procedure for the EE-Top.

1) Simulation: First objective was to use two programmable logic controllers (PLC) to develop a simulation of the equipment which then could be implemented in future project testing, providing with control logic and sequencing verification without presence of physical equipment. In this simulation, the PLC-System Controller contains control logic of the equipment, while PLC-Simulator simulates physical EE-Top and battery module properties and functionalities. This way, a variety of different size systems can be simulated and tested for project specific applications.

2) End-of-Line: Second objective of the project was to develop an EoL testing procedure for the EE-Top. Since GRE outsources the assembly of this equipment, they require further testing of the assembled EE-Top before it is delivered to the customer. This involves physical component testing like switches and plugs, input and output (I/O) signal testing, communication via Modbus and controller area network (CAN) bus to other components in the system and general software and hardware interaction. If time permits, a testing station for the EoL testing is to be designed.

1.3 Specific Goals

Main goals (MG) associated with this projects two objectives (O) are outlined in table 1.1.

Objective	Goal	Explanation
Simulation	O1MG1	Develop a simulation with one EE-Top
	O1MG2	Develop a simulation with several EE-Tops
End-of-Line	O2MG1	Develop end-of-line testing procedure
	O2MG2	Design and build end-of-line test station

Table 1.1: Goals

1.3.1 O1MG1: Develop a Simulation with one EE-Top

Develop a simulation using PLC, consisting of both, battery module and EE-Top. Battery module voltages and temperatures are required and should be adjustable, together with the bus communication between the battery module and the EE-Top for simulated sensor data sharing. EE-Top has many switches that need to be simulated as I/Os and require correct simulation of real life operation like switching delays and switching sequences.

1.3.2 O1MG2: Develop a Simulation with Several EE-Tops

This task is similar to O1MG1, however the simulation is designed for several EE-Tops. It is crucial to test if the simulation is applicable to larger scale systems, since most of the projects of GRE involve several EE-Tops.

1.3.3 O2MG1: Develop End-of-Line Testing Procedure

Develop EoL test procedure concept for the EE-Top. Because the electronic assembly is outsourced, and the received finished product is in need of further testing before it is delivered to the customer. This requires software and hardware compatibility testing, component like switches and plugs testing, I/O module testing and communication check between the EE-Top and the rest of the BMS. The testing should be fast and easy to perform, by either using an external connection to a computer or a human machine interface (HMI) display.

1.3.4 O2MG2: Design and Build End-of-Line Test Station

To verify the EoL test procedure concept in O2MG1, a test station to perform these procedures should be designed and a prototype should be built. EE-Top testing require additional equipment and components from the BMS, which should be available and if possible a simplified version should be considered. That should help to test EE-Tops functionality to the fullest.

Chapter 2

Method

2.1 Grenland Energy's Battery Management System

2.1.1 System Component Overview

There are mainly three core equipment in the GRE's BMS: battery system controller, EE-Top, and battery strings as shown in Figure 2.1. These components consist of many smaller components and parts that need to be taken into consideration when upgrading system hardware or software and developing test procedures. Most of this information is based on GRE's product documentation [5].

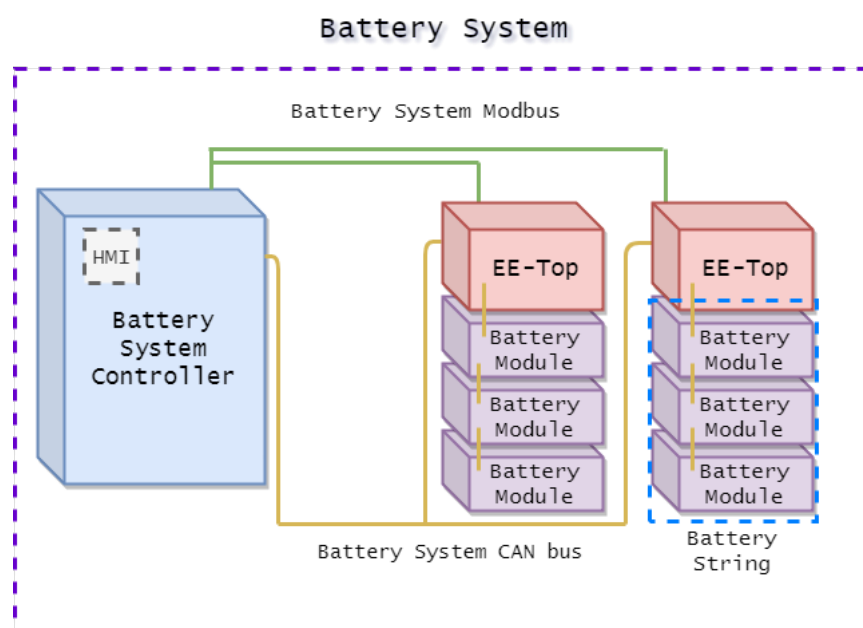


Figure 2.1: Grenland Energy's battery management system overview

2.1.1.1 Battery System Controller

Battery system controller is the interface between the EE-Top, the battery modules and the user as shown in Figure 2.1. Usually placed in high voltage/low voltage cabinet, it consists of PLC-System Controller, industrial Ethernet-switch for Modbus, HMI with local control, 24 volt (V) direct current (DC) supply, main fuse, main service breaker, relays and emergency stop. This PLC-System Controller is the main controller of the whole system.

PLC-System Controller stores and runs the software with programmed sequences of all the EE-Top actions. It also performs different system statistics like SoC, average cell volt-ages/temperatures and available power charge/discharge. The communication protocols for Modbus/CAN bus are also set up in the program. PLC-System has the I/O signals of the emergency stop, ground fault, fire alarm, door switches to the cabinet, etc. These I/O's are a safety measure and need to be in non-alarm state for the system to start.

2.1.1.2 Battery String

Battery strings consist of a set amount of battery modules which deliver voltage and current capacity required for the project application. These battery modules have four cell modules, which consist of a set amount of battery cells as shown in Figure 2.2. Each cell module have a cell module card that collect and transfers cell sensor data. The battery string has a EE-Top to ensure temperature and energy capacity management, for the sake of safety, battery longevity and system performance.

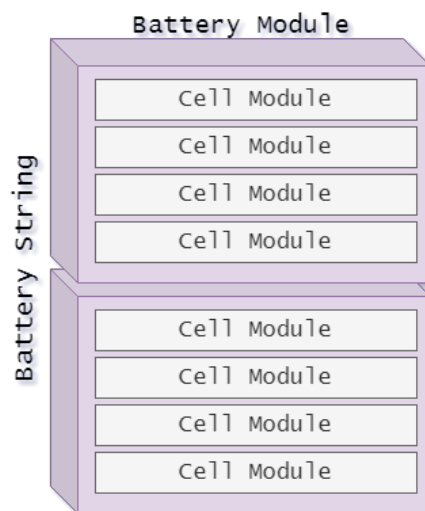


Figure 2.2: Battery string overview

2.1.1.3 EE-Top

EE-Top is a battery module management unit, that is responsible for battery state communication to the rest of the system. It has communication to the battery system controller, the battery string and other EE-Tops if a master/slave topology is applied as shown in Figure 2.1. It also connects the batteries to the electric device, working as a switch to turn on/off the current supply. EE-Top is responsible for the pre-charge sequence, which is meant to pre-charge the capacitors so that the sudden voltage and current supply would not damage the components. The control signals are sent from battery system controller to EE-Top. These signals are then transformed to I/O signals for the EE-Top components like the contactor switches. These contactors are responsible of managing the positive and negative terminals, which when connected transfer current through the EE-Top. Feedback is then sent back to the battery system controller, based on the I/O signals from the switches that are received by the EE-Tops.

2.1.2 Communication

There are two different communication protocols used in GRE's BMS, Modbus and CAN bus. These two buses are used to transfer different information, based on their data transfer capabilities. **CAN bus** is known for its ability to supply system nodes with data consistency. Being a popular choice for basic data transferring, in GRE's BMS it is responsible for transferring octo cell module (OCM) sensor data from battery modules to the CAN group module (CGM) card in the EE-Top. This information is then transferred to the battery system controller and used in battery statistics calculations. For bigger data transferring like program codes or control sequences, **Modbus** is used. This bus allows fast transferring rates as well as provide with dependent master/slave communication. Battery system controller is connected to the EE-Top via Modbus. Working as a master, battery system controller sends information to EE-Top and requests it back. Other BMS interfaces like an external PC or HMI are connected via Modbus.

2.1.3 Software

There are two different software used to manage and program the EE-Top - Emus BMS and e!Cockpit. **e!Cockpit** is used to run the control logic of the GE's BMS. The control logic is programmed using continuous function chart language, which is very alike the function block diagram. e!Cockpit will be used for development in the project and thus good understanding of the software and the system control logic of the BMS is required. Modbus and CAN bus

communication is also set up in this software, where different ID's and channels are created for the CAN bus cell statistic information and Modbus I/O signal transferring. **Emus BMS** is used for monitoring and accessing live battery information directly from the EE-Top. It allows battery cell management and a limited EE-Top parameter upgrading without the need of PLC connection. This software is connected to the CGM and CAN bus communication, receiving all of the battery cell information.

2.1.4 Battery Management System Function

GE's BMS has following functionalities:

- Monitor all cell voltages and temperatures in the entire battery system
- Balance all cell and string voltages individually
- Monitor all battery string currents individually
- Customizable charge protocol for BMS controlled charge cycle
- Internal diagnostics, fault handling and event logging
- Redundant Master-Slave topology
- Multiple configurable I/O ports
- High level functions and customizable interface in battery system controller
- Modbus for communication to external applications

The topology of the BMS is as follows; the entire battery system has one common Modbus and CAN bus communication system. Each battery system has one system controller in charge of monitoring and controlling the battery string. Each battery string consists of a set amount of battery modules and has one EE-Top, which is connected to the common bus communication. Each battery module has a CGM, which communicates with the EE-Top via string CAN bus. The battery module comprises four cell modules, which have an OCM each. These OCM cards are responsible of collecting battery cell temperature data.

2.1.5 EE-Top Components

Software and hardware testing of GRE's EE-Top is the main objective of this thesis. To better understand what is done during the developing phase of the thesis, an in depth explanation of which components are in the EE-Top, how these components work, their internal and external communication, and software to hardware interaction is required.

Programmable Logic Controller: The EE-Top houses a Wago I/O module, which is responsible to connect to Modbus communication, I/O management and relay controlling. Through the Ethernet connection, this I/O modules is connected to an Ethernet switch which

connects all of the BMS core components to the same internet protocol (IP) address. Through this connection, the I/O modules inside EE-Top receive command signals from PLC-System Controller inside battery system controller. These command signals are then used to control relays.

Relays: The relays work as switches and based on the received signal from the I/O module, the relays turn on or off. By controlling the switches, control logic performs activation or deactivation of the positive and negative contactors, pre-charge contactor and emergency shut down of the EE-Top.

CAN Group Module: This module communicates using CAN bus. It sends voltage and temperature data between battery modules, to the EE-Top and then on to the battery system controller.

Switches: EE-Top has two main contactor service switches, one for negative and one for positive terminals. These switches are designed for safety measure, providing physical control of the contactors inside the EE-Top. They work as a second layer of safety precaution, by requiring to be turned on for the EE-Top to be able to start the main contactors.

Connectors: There are three connector plugs to the EE-Top high voltage terminals, one for positive pre-charge contactor, one for positive main contactor and one for negative main contactor. These connectors connect the EE-Top to the rest of the grid and the electric devices to be powered.

2.2 Lithium-ion Batteries

Li-ion battery is a type of rechargeable battery that uses two electrodes (anode and cathode) and an electrolyte that acts as a conductor. During the discharging cycle, electrons are being released at the anode (negative electrode) where oxidation occurs. The electrons flow via external circuit to the cathode (positive electrode) which is reduced by receiving these electrons. For the charging cycle, the process of oxidation and reduction at the electrode is reversed [6]. The positive electrode is a metal oxide e.g. LiCoO_2 , LiMnO_2 , NMC, LiFePO_4 , LiTiO_2 and negative electrode consists of porous carbon, typically graphite.

Several types of battery exist and the most common are:

- Lithium Cobalt Oxide (LiCoO_2)
- Lithium Manganese Oxide (LiMnO_2)
- Lithium Nickel Manganese Cobalt Oxide (NMC)
- Lithium Iron Phosphate (LiFePO_4)
- Lithium Titanate (LiTiO_2)

The comparison of a battery is usually done by looking to its terminal voltage, service life, specific energy and power density. Terminal voltage is the measured voltage between two terminals during the charging and discharging process of a battery. The service life a battery is often referred to the number of charge/discharge cycles before the nominal capacity falls to 80%. With regards to the specific energy density of a battery, it can be defined as the electric energy per unit weight of the cell, while energy density is the electric energy per unit volume of a cell. Characteristics of different types of lithium-ion batteries are summarized and shown in table 2.1 [7].

Lithium-ion battery		
Operational Voltage	1.8-4.2	V
Specific energy	50-260	Wh/kg
Life cycles	500-7000	-
Thermal runaway	150-270	C°

Table 2.1: Characteristics of Lithium-ion batteries [5]

Safety and performance of a battery is crucial for having a good and reliable battery system. It is very important that Li-on battery is operating under the right conditions at all time. Improper use of Li-ion battery will decrease the performance and can even lead to destroying the cell. It only shows the importance of having a BMS that will ensure the safety while enhancing the performance of a battery.

2.3 Sensors

2.3.1 Temperature Sensor

Temperature sensor is a device that gathers temperature or heat information from a specific source. One common example of such electrical device is a thermocouple. It uses thermoelectric effect (direct temperature difference conversion to electric voltage) and consists of two dissimilar electric conductors that are joined together. The connection between the two conductors with different thermoelectric properties is called a junction. The difference in potential at the junction produces an electrical voltage, which is proportional to the temperature and is measured in micro-volt [8]. An illustration of a thermocouple is shown in Figure 2.3.

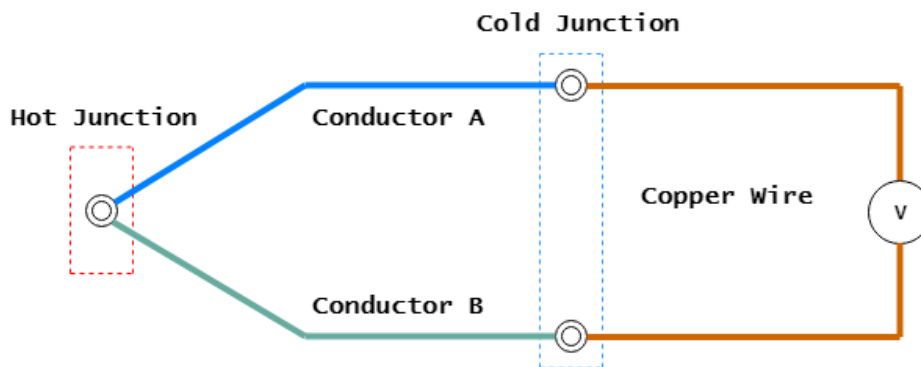


Figure 2.3: Thermocouple

The voltage difference can be measured by using Seebeck's principle [8], where voltage difference (ΔV) over the conductor is equal to the product of Seebeck (S) coefficient of a conductor and temperature gradient (ΔT).

$$\Delta V = -S \cdot \Delta T \quad (2.1)$$

2.3.2 Current Sensor

This sensor detects an electrical current from a source under either alternating current (AC) or DC conditions and converts this information into a signal proportional to the measured current. A flow of an electrical current through a wire or cable leads to a voltage drop and a magnetic field around the conductor. The measuring of current is divided into direct and indirect measuring.

Direct current sensors are purely based on Ohm's law. This principle works by placing a shunt resistor in a current path which leads to a voltage drop proportional to the measured current. A direct current sensor is shown in Figure 2.4 [9].

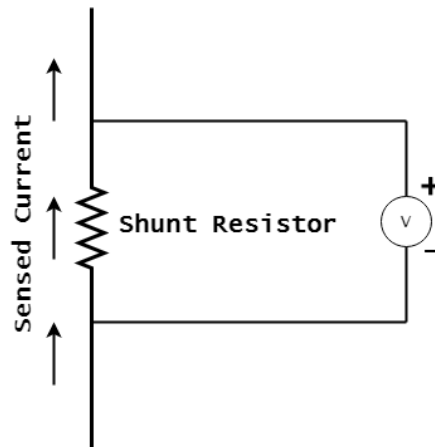


Figure 2.4: Direct sensor

Indirect current sensors based on Ampere's and Faraday's laws [10]. They detect the generated magnetic field around the conductor. As shown in Figure 2.5, it has a magnetic core that surrounds the current-carrying conductor and uses a hall element that detects the generated magnetic field and converts it into voltage [11]. These devices generate low voltage level and require an amplifier in order to produce a usable level output.

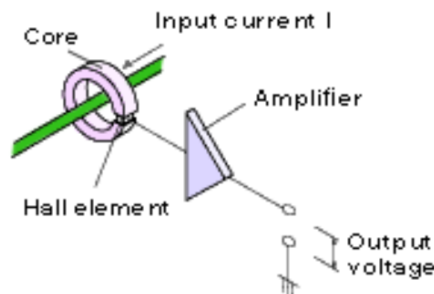


Figure 2.5: Hall effect. Adapted [reprinted] from [8]

2.3.3 Voltage Sensor

Voltage sensor is a device that uses voltage itself as an input to measure voltage between two points of an electrical circuit and turn it into an output signal that could be a human-readable data. It is applicable for detecting and measuring AC or/and DC voltage levels. Capacitive and resistive voltage sensors are the two main types of voltage sensors and are shown in Figure 2.6. In general, these type of voltage sensors have the same properties. The generated output signal for both cases is fairly low, have a high linearity and a large measurement range [12].

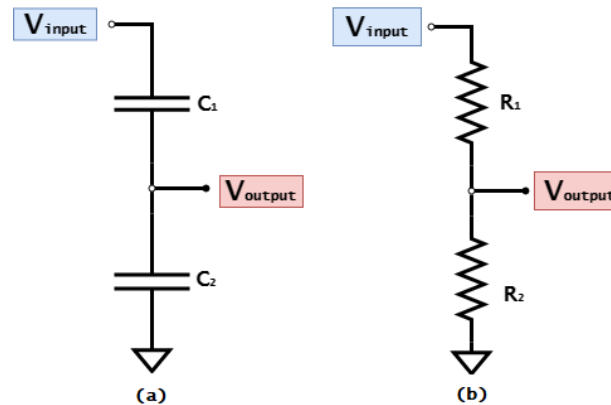


Figure 2.6: Voltage sensor types (a) capacitive (b) resistive

2.4 Programmable Logic Controller

2.4.1 Introduction of PLC

During the second part of the 20th Century, PLCs replaced mechanical relays when it comes to the control, sequencing and safety interlock logic of manufacturing processes [13]. The introduction of digital computers made this change possible, and the heavily complicated relay, timer, sequencer and closed-loop controller systems could be updated with simpler, much more robust PLC systems. PLC emulate electro-mechanical relay functions by analyzing the input device data, and then based on pre-programmed parameters, control the output devices. Based on the input and output devices, PLC can automate processes by controlling the start/stop functions, perform system analysis by monitoring and recording system run-time data, communicate with other digital computers and HMI, and much more. It has become a widely popular industrial digital computer, used in many different fields.

2.4.2 Structure

Figure 2.7 illustrates PLC features. The I/O signals can be either analog or digital and they provide information to the central processing unit (CPU) and trigger specific actions. The input signals are received from devices like sensors, meters and switches, while output signals are sent to devices like relays, valves and lights [14]. These I/O signals basically connect PLC to the rest of the machine and are communication between the logic controller and different equipment.

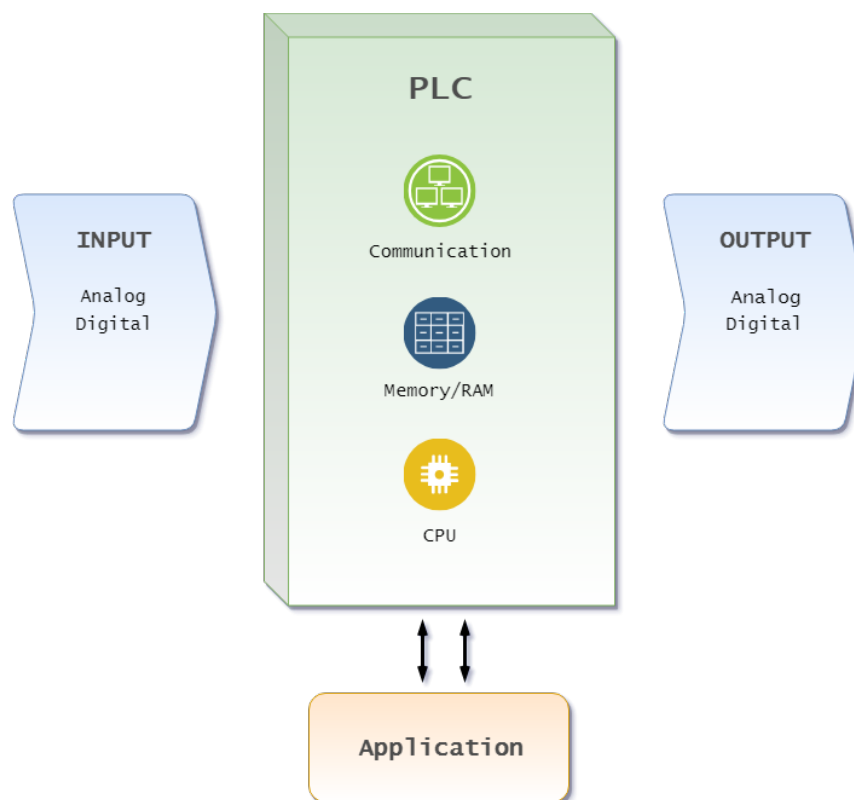


Figure 2.7: PLC Diagram

The CPU processes data received from input devices and then based on the programmed logic - executes the specific actions by sending signal to output devices. It is a processor that by performing logic, controlling, basic arithmetic and I/O operations carries out programmed instructions. It also stores selected data in the memory, either to log it or for later use.

PLC has a range of ports and communication protocols which provide different communication possibilities with users and other systems. The user can control and adjust the system functions in real time by using an HMI. This user interface can be a simple display with a keypad or a touchscreen, which provides with a possibility to review the information from PLC and adjust information if needed.

2.4.3 PLC Programming

The program that PLC runs is programmed on a computer and then downloaded to the controller. There are many different PLC programming software to choose from, and many PLC suppliers deliver their own. The available language or "logic" that the software use, is mostly the same for all of the companies and based on international electrotechnical commission (IEC) 61131-3 standards [13]. Based on the programmed logic, by completing

specific evaluations or step-by-step sequences, the controller performs actions. Some of the most used languages are ladder diagram, function block diagram, structured text, instruction list and sequential function chart. The languages used during the development of the project are:

Function block diagram: This graphical language, describes functions between input and output variables using elementary function blocks. The connection is oriented such that the data and sequences are ordered left to right. The blocks consist of simple functions like timers, delays, true/false statements, set/reset, etc. The variables are connected to these function blocks by connection lines, and can be connected to one or several blocks.

Structured text: It is one of the two textual languages in the IEC 61131-3 standard. It shares the common standard function elements alike the ones in free body diagram and also supports iteration loops (WHILE-DO, REPEAT-UNTIL), conditional execution (IF-THEN-ELSE) and trigonometric functions. As the name implies, this is a text form based programming language. It resembles Pascal programming language, which has a programming structure and syntax similar to that of the C programming language.

2.5 Communication Technology and Protocols

2.5.1 Controller Area Network

CAN is a digital network widely used in automotive, industrial, medical and scientific systems [15]. It was developed in 1980's to replace the existing serial buses in automotive industry. Due to new electronic functionality in vehicles - micro-controllers, sensors and devices required communication without a host computer.

This new message-based protocol has advantages like high resilience to noise, reliability, low cost, and ease of use. This serial bus became very popular for many basic data transfer applications. CAN bus is a network that provides every node of the system with data consistency, by broadcasting many short messages like sensor measured speed or temperature.

There are two CAN identifiers, the standard 11 bit (CAN 2.0A) and the extended 29 bit (CAN 2.0B) [16]. In a system with many nodes which are sharing information back and forth, a priority is established for more important messages by the identifiers. The lower the binary value, the higher priority the message has.

The CAN bus is usually connected to the nodes via a 9-pin D-sub plug. The cable pinout is shown in table 2.2 [15]. When transmitting a dominant (0) bit, CAN H wire is driven to 5V and the CAN L wire to 0V. Transmitting a recessive (1) bit, both CAN H and CAN L

wires are not driven and kept at 2.5V each. In a system with many nodes, ID's are sent and received at the same time. The nodes with the lowest number will always be prioritized and their message will be read first. This will put the other nodes on standby until the dominant node is done with its message. Then the nodes will try to re-transmit after the dominant node has finished its message.

Pin	Description
1	Reserved
2	CAN L, dominant low (CAN low or CAN-)
3	Optional ground
4	Reserved
5	Optional CAN shield
6	Optional ground
7	CAN H, dominant high (CAN high or CAN+)
8	Reserved
9	CAN V+, optional CAN external positive supply

Table 2.2: CAN bus 9-pin D-sub pinout [14]

2.5.2 Modbus

Modbus is a serial communication protocol which is based on master/slave or client/server architecture. It was published in 1979 by Modicon (now Schneider Electric) to be used with their PLCs and since then has become the open source communication structure [17]. It has many advantages like fast data transmitting via Ethernet connection, openly published and free to use, moves blocks of binary data without restrictions and is independent of technology and manufacturers. The master node will always initiate the communication to the slave node and only one Modbus transaction at the same time. The slave nodes will only transmit data and communicate with each other after a request is received for the master node.

The two most widely used data transmission operating protocol versions are Modbus transmission control protocol (TCP) and Modbus remote terminal unit (RTU) [18]. Modbus TCP has Ethernet based data transmission, establishes client/server communication and requires all of the nodes in a system to be connected to the same IP address range via 502 port. Modbus RTU uses RS-485, RS-422, RS-232 interfaces and establishes a serial master/slave communication. This is an older (the original) version of the Modbus protocol.

RTU might be cheaper than the TCP installation, however it has several drawbacks. Modbus RTU is more complex to install and troubleshoot. It is also somewhat limited to one polling (master) device, where all the information will have to be routed through the one master device. In Modbus TCP, several polling devices can be connected and share the information

directly without any unnecessary routing. It mostly comes down to the system and preference of the user.

Chapter 3

System Design

3.1 Battery and EE-Top Simulation

3.1.1 Battery and EE-Top Simulation Overview

The main goal with simulation of hardware equipment is to create an opportunity to test software/program aspects in correlation to the hardware equipment and components. GRE wished to have ability to test control logic of bigger projects with many equipment, without the need of having physical equipment present and assembled. For this project, a simulation was created to simulate a battery system, which could have one or more battery strings. Each battery string consist of one or more battery modules, each battery module consist of four cell module and two cell blocks for every cell module. The key objectives of the battery system simulation were:

- Create a EE-Top simulation
- Create a battery module simulation
- Connect the EE-Top and battery module simulation with the battery system controller
- Check if the simulation is stable over longer time and responds to parameter adjustment
- Apply the simulation to several EE-Tops and battery module simulations

3.1.2 Simulation Station Design

A simplified function block diagram of the simulation design is shown in Figure 3.1. The actual PLC-System Controller consists of more function blocks than the illustrated figure.

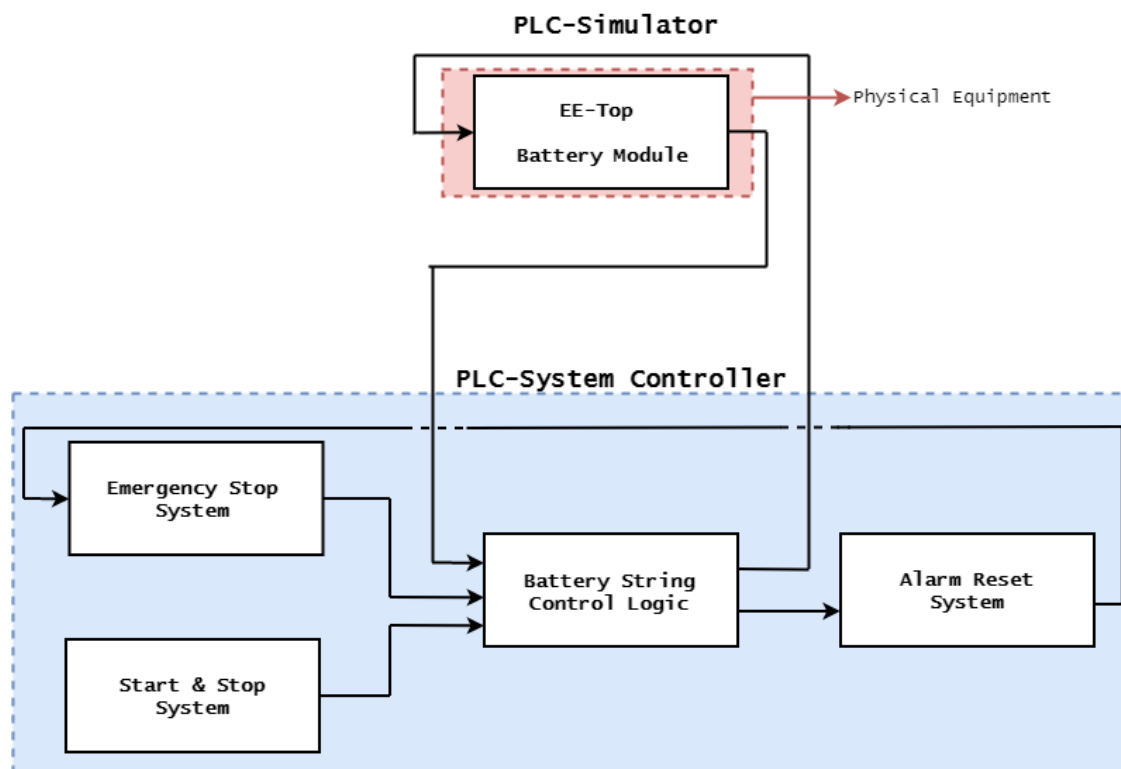


Figure 3.1: Simplified overview of the two PLCs application

Nevertheless, it is an illustration of how these two PLCs application works.

An overview of the actual simulation test design is shown in Figure 3.2. CAN bus acts as a communication interface between PLC-Simulator and PLC-System Controller while Modbus is used as a communication between the external PC and each individual PLCs. The list of components is shown in table 3.1

Components	Description
PLC controller	2x WAGO PFC200 (750-8204) controller
Ethernet switch	WAGO 852-1111 Industrial Ethernet switch
Ethernet cable	3x Cat 5 Ethernet cable
CAN bus cable	CAN bus cable with 9 pin plug
CAN bus connector	Phoenix contact, Subcon 9
Voltage power supply	24 output voltage supply
Human machine interface	Laptop with e!Cockpit and Emus BMS software

Table 3.1: List of components in software testing design

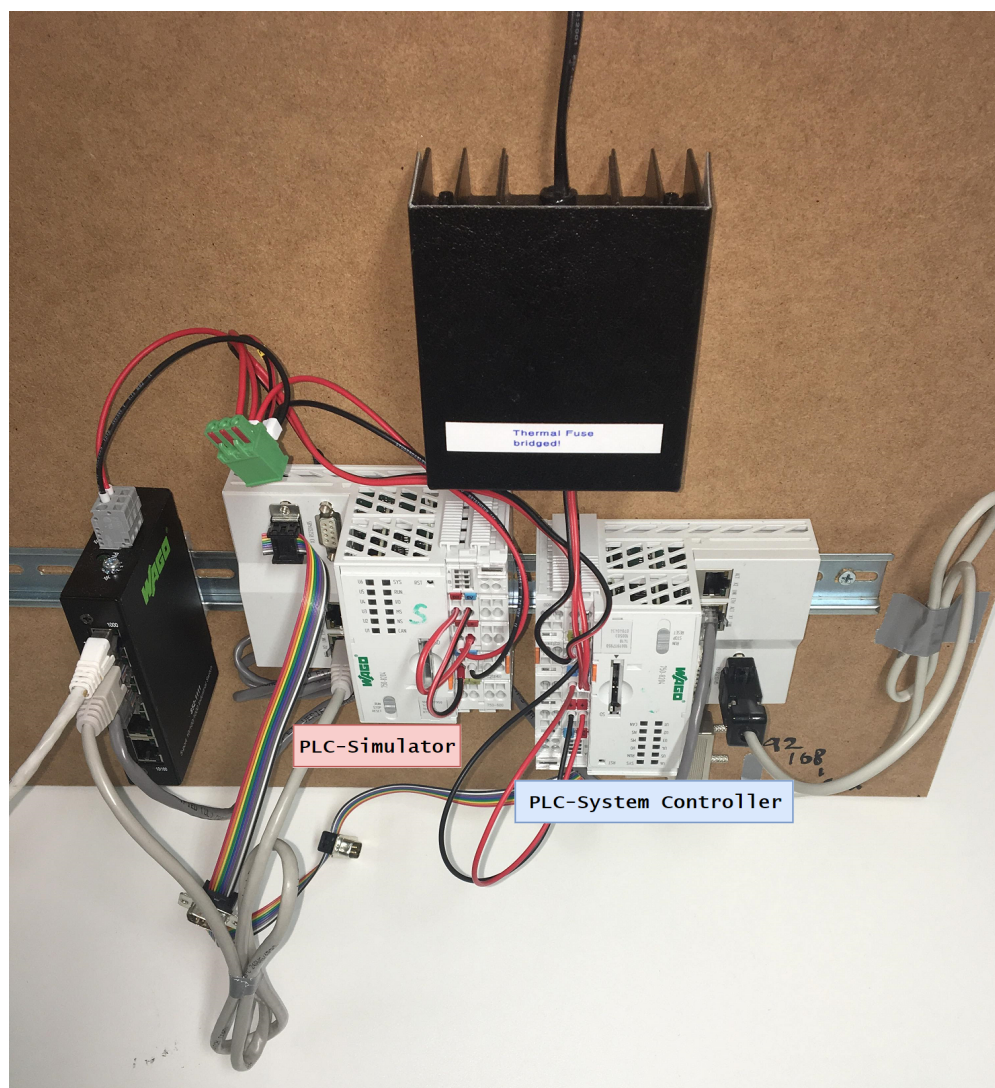


Figure 3.2: Simulation test station

3.1.3 Development of Hardware Simulation

3.1.3.1 PLC-Simulator

The main function of PLC-Simulator is used to simulate a physical EE-Top that can be configured to a specific application. An overview of all devices used in this application is shown in Figure 3.3. This already include a library manager that contains Io-Standard and WAGO standard libraries which follow the international standard for PLC programming (IEC 61131-3). The standard libraries contain all the functions required for I/O's configuration.

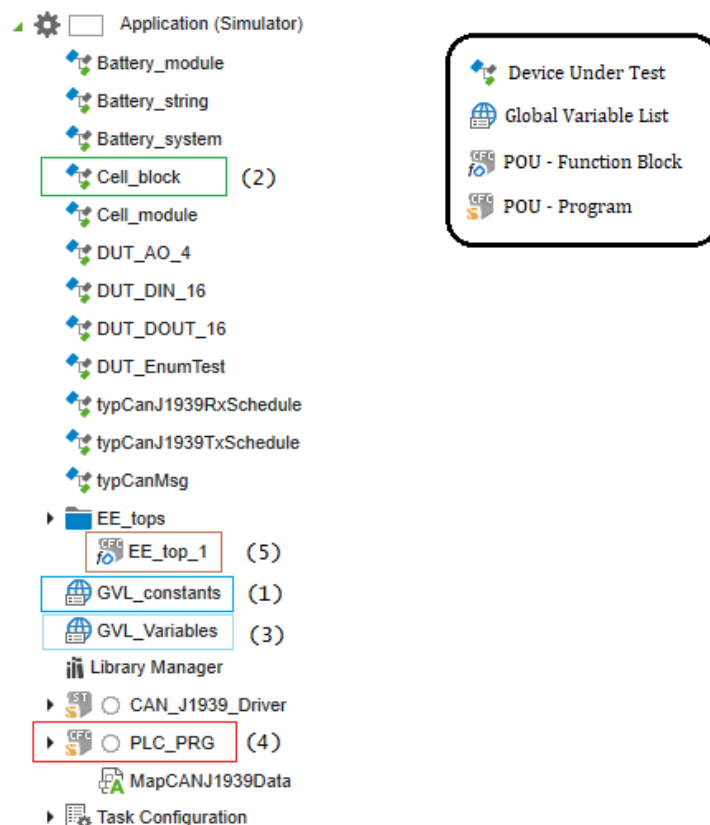


Figure 3.3: Device tree on PLC-Simulator application

Numbering on the following paragraphs refers to the numbering illustrated in Figure 3.3. The parameters of the battery for this application were declared using global variable list (GVL) - "GVL_constants" (1). As shown in Table 3.2, it included the number of strings, battery modules, cell modules and cell blocks. Other battery parameters such as voltage, resistance and temperature were specified in device under test (DUT) - "Cell_block" (2).

Parameters	Quantity
Battery module	1
Cell module	4
Cell block	8

Table 3.2: Battery string parameters

In the "GVL_Variables" device (3) lies an input and output array of ID number for CAN bus communication purposes. Every message that is sent or received through CAN bus communication has a unique ID number associated to a specific battery string that consists of one or more battery modules. Defining what information or variables these unique IDs would carry, were done in MAPCANJ1939Data under the "PLC_PRG" (4).

Signal	Description	Explanation
dIn 1	SC Main Contactor Start	Main contactors are ready
dIn 2	SC Pre Contactor Start	Pre-charge contactor is ready
dIn 3	SC Start Cooling	Battery cooling started
dIn 4	Main Contactor Pos Activated	Positive contactor has activated
dIn 5	Main Contactor Neg Activated	Negative contactor has activated
dIn 6	Pre Charge Contactor Activated	Pre-charge contactor has activated
dIn 7	Service Switch Neg	Negative contactor switch on/off
dIn 8	Service Switch Pos	Positive contactor switch on/off
dIn 9	HVIL Main Neg Connector In	Negative connector line in, in/out
dIn 10	HVIL Main Neg Connector Out	Negative connector line out, in/out
dIn 11	HVIL Main Pos Connector Out	Positive connector line out, in/out
dIn 16	Modbus IO Test IN	Modbus communication signal test
dOut 1	Emergency Stop Activated	Emergency from battery system controller
dOut 2	Main Contactor HV Pos Start	Start positive contactor
dOut 3	Main Contactor HV Neg Start	Start negative contactor
dOut 4	Pre Charge Contactor Start	Start pre-charge contactor
dOut 5	HVIL String Out	High voltage interlock for safety reasons
dOut 16	Modbus IO Test Out	Modbus communication signal test
aOut 1	Fan Control	Fan on/off

Table 3.3: EE-Top input and output signals

There are two I/O modules connected to the EE-Top PLC. First I/O module is connected to 12 digital inputs. The second I/O module is connected to six digital outputs and one analog output. These I/O's are depicted in table 3.3. The outputs are the signals that the EE-Top receives from the PLC-System Controller. Signals dOut 1 and dOut 5 are safety signals, while dOut 2, dOut 3 and dOut 4 are control logic signals from the PLC-System Controller.

The inputs are signals that the EE-Top sends back to the PLC-System Controller. Signals dIn 1 to dIn 6 are control logic signals to the PLC-System Controller, while signals dIn 7 to dIn 11 represent switching and plugs for the main and pre-charge contactors. Both dIn 16 and dOut 16 signals are Modbus communication test signals. aOut 1 signal controls the fan in battery modules.

The I/O signals of a EE-Top were defined by creating a program organization unit (POU) object "EE_top_1" (5) of function block type using continuous function chart (CFC). The POU typically consists of a declaration and implementation editor. Figure 3.4 shows the code used in the declaration editor.


```
FUNCTION_BLOCK EE_top_1

VAR_INPUT
dOut_1_Emergency_Stop_Activated: BOOL;
dOut_2_Main_Contactore_HV_Pos_Start: BOOL;
dOut_3_Main_Contactor_HV_Neg_Start: BOOL;
dOut_4_Pre_Charg_Contactor_Start: BOOL;
dOut_5_HVIL_String_Out: BOOL;

dOut_16_Modbus_IO_Test_Out: BOOL;
aOut_1_Fan_Control: WORD;
END_VAR

VAR_OUTPUT
dIn_1_SC_Main_Contactor_Start: BOOL;
dIn_2_SC_Pre_Contactor_Start: BOOL;
dIn_3_SC_Start_Cooling: BOOL;
dIn_4_Main_Contactor_Pos_Activated: BOOL;
dIn_5_Main_Contactor_Neg_Activated: BOOL;
dIn_6_Pre_Charg_Contactor_Activated: BOOL;
dIn_7_Service_Switch_Neg: BOOL;
dIn_8_Service_Switch_Pos: BOOL;
dIn_9_HVIL_Main_Neg_Connector_In: BOOL;
dIn_10_HVIL_Main_Neg_Conector_Out: BOOL;
dIn_11_HVIL_Main_Pos_Conector_Out: BOOL;
dIn_16_Modbus_IO_Test_IN: BOOL;
END_VAR
```

Figure 3.4: EE-Top declared input and output signals in the declaration editor

The function block diagram in the implementation editor is shown in Figure 3.5. The numbering used in the following paragraphs refers to Figure 3.5. The goal was to create a function block diagram that will start the pre-charge contactor (1) and negative contactor (2) as the system is manually started via HMI/external PC. The pre-charging time will take a set duration of 10 seconds and eventually stop after the time has run out. Afterwards, the positive contactor (3) will activate. This sequence was achieved by inserting a Timer On (TON) function block. TON_0's (4) function is to change a boolean true input signal into a true output signal after the 10 seconds delay time and goes to a NOT function block that turn the true input signal into a false output signal.

Set/Reset (SR) (5) function block was used to maintain the output signal dIn_1_SC_Main_Contactor_Start activated after signal dOut_4_Pre_Charg_Contactor_Start was deactivated. In reality, a very short delay occurs when sending or receiving a signal to turn on/off a switch. In order to replicate this situation, an addition of TON function block (6) (7) (8) were done with a preset timer values of 300 milliseconds.

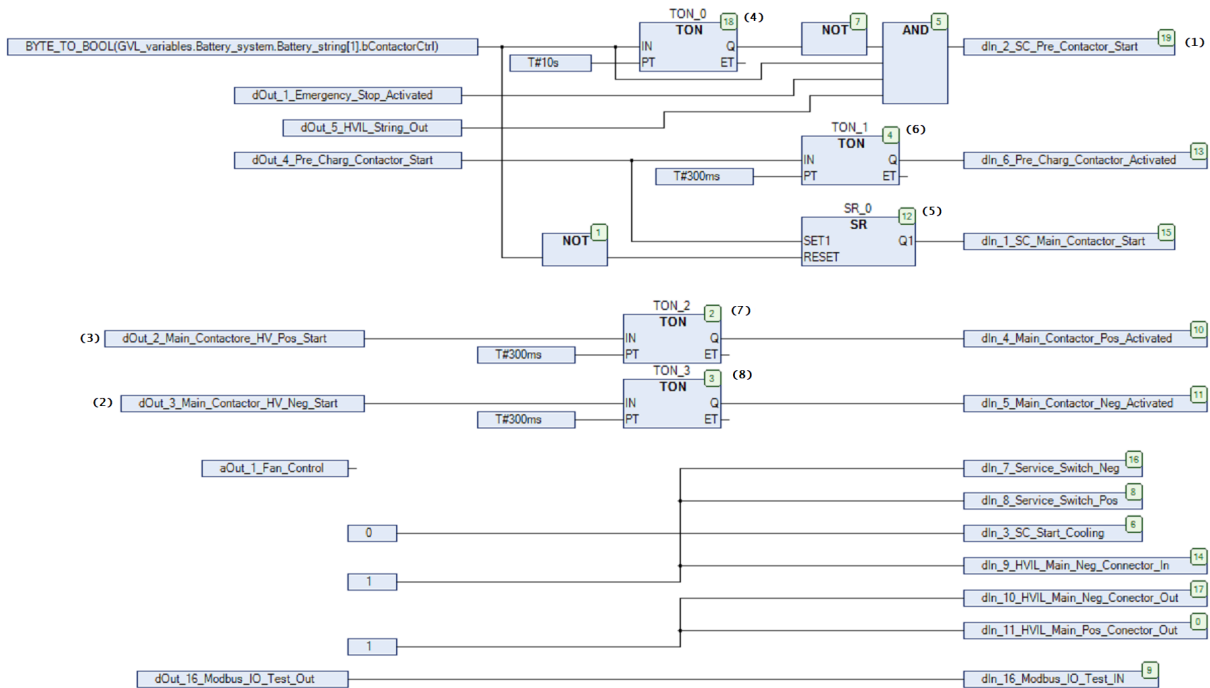


Figure 3.5: Function block diagram of the input and output signals in the EE-Top

For the PLC_PRG device ((4) in Figure 3.3), a POU object of program type using CFC implementation language was used. The main program PLC_PRG can call up to one or multiple function blocks for signal processing. When calling a function block, only the I/O variables are accessed and not the internal variables as shown in Figure 3.6. These were the signals that were being received from and sent back to battery string control logic in the PLC-System controller. The PLC_PRG is being controlled and executed in the task configuration where one or more program type of POU object can be configured.

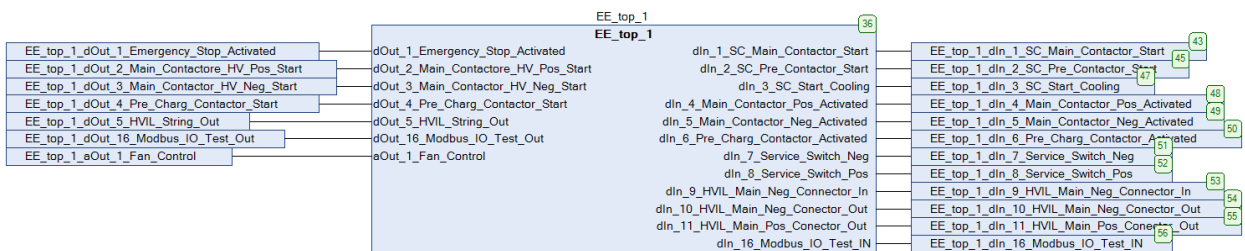


Figure 3.6: Input and output signals of EE-Top

3.1.3.2 PLC-System Controller

The PLC-System Controller is more complex when compared to the PLC-Simulator. This was designed to have all the control logic, sequencing and alarm configuration needed for

the whole BMS. It also included a visualization screen for testing of the simulation. The list of all devices in PLC-System Controller's System1 application is shown in Figure 3.7.

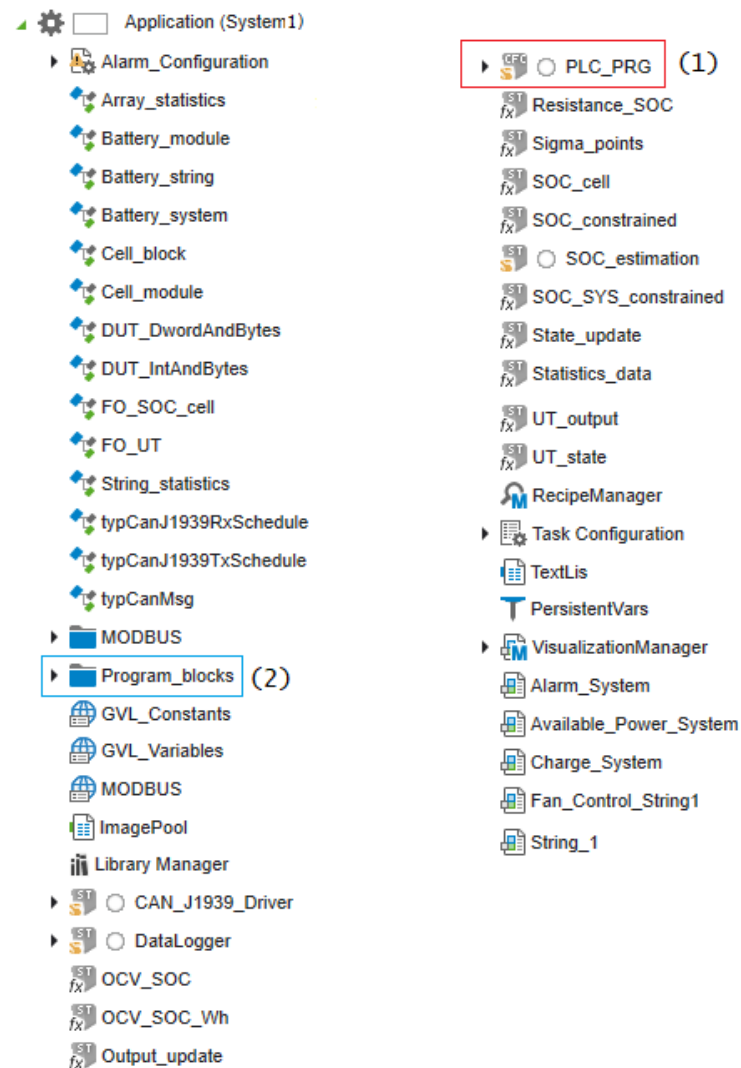


Figure 3.7: Device tree on PLC-System Controller

The I/O signals of PLC-System Controller together with their explanation is shown in Figure 3.4.

Signal	Description	Explanation
Digital input		
dIn 1	Emergency Stop	Emergency stop switch
dIn 2	Ground Fault Alarm	Ground fault in the system
dIn 3	HVIL System	HV equipment alarm
dIn 4	Drive Ready	Drive ready signal
dIn 5	Fire Alarm	Fire alarm in the room
dIn 6	Door Switch HV Cabinet	Cabinet door open
dIn 7	Door Switch Battery Room	Battery room door open
dIn 8	System Switch Extract Auto	Automatic system switch extraction
dIn 9	System Switch Extract Manuel	Manuel system switch extraction
dIn 10	Extractor Fan Alarm	Fan alarm
dIn 11	Extractor Fan Active	Fan is activated
dIn 12	Air Damper Feedback In	Air damper feedback
dIn 13	Air Damper Feedback Out	Air damper feedback
dIn 14	Gas Alarm In	Gas alarm connected
Digital output		
dOut 2	Gas Alarm Active	Gas alarm activated
dOut 3	Extractor Fan Start	Fan activated
dOut 4	Damper Close Open	Damper closed/open
dOut 5	Reset Emergency Stop Relay	Reset relay after emergency
Analog input		
aIn 1	Ambient Temp Battery Room	Temperature in battery room
aIn 2	CO2 Battery Room	CO2 amount in battery room

Table 3.4: PLC-System Controller input and output signals

The I/O signals of PLC-System controller were defined in the main program PLC_PRG ((1) in Figure 3.7) as shown in Figure 3.8. Data type boolean are designated for digital signals and data type word for analog signals. Digital I/Os receive and send fixed values of 1 for true signal and 0 for false signal. Analog I/Os receive and send values representing sensor data, but in this case only AI_2 received a fixed amount of 0 to simulate no carbon dioxide (CO2) gas in the room.

```
PROGRAM PLC_PRG

VAR_INPUT
  DI1_Emergency_Stop:BOOL:=1;
  DI2_Ground_Fault_Alarm:BOOL:=1;
  DI3_HVIL_System:BOOL:=1;
  DI4_Drive_Ready:BOOL:=1;
  DI5_Fire_Alarm:BOOL:=1;
  DI6_Door_Switch_HV_Cabinet:BOOL:=1;
  DI7_Door_Switch_Battery_Room:BOOL:=0;
  DI8_System_Switch_Extract_Auto:BOOL:=0;
  DI9_System_Switch_Extract_Manuel:BOOL:=0;
  DI10_Extractor_Fan_Alarm:BOOL;
  DI11_Extractor_Fan_Active:BOOL:=0;
  DI12_Air_Damper_Feedback_In:BOOL:=0;
  DI13_Air_Damper_Feedback_Out:BOOL:=0;
  DI14_Gas_Alarm_In:BOOL:=0;
  AI1_Ambient_Temp_Battery_Room:WORD;
  AI2_CO2_Battery_Rom:WORD:=0;

END_VAR
VAR_OUTPUT
  DO2_Gas_Alarm_Active:BOOL;
  DO3_Extractor_Fan_Start:BOOL:=0;
  DO4_Damper_Close_Open:BOOL:=1;
  DO5_Reset_Emergency_Stop_Relay:BOOL:=0;

END_VAR
```

Figure 3.8: PLC-System Controller simulated input and output signals

As shown in Figure 3.1, PLC-System Controller is composed of different function blocks. All the function blocks needed to build this system are located in the "Program_blocks" ((2) in Figure 3.7) folder.

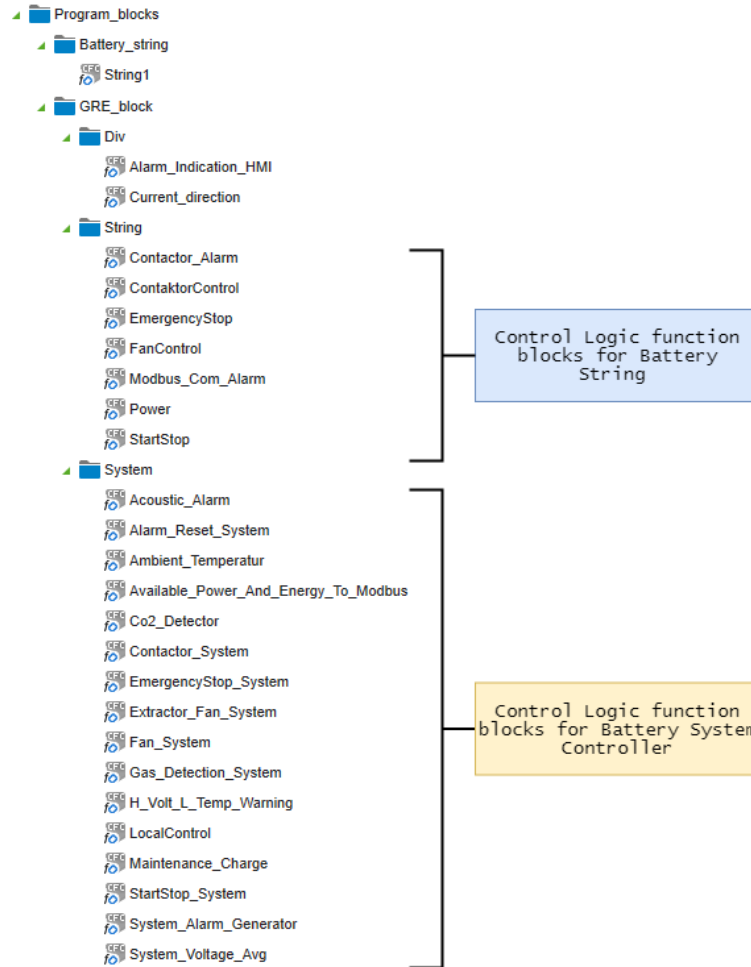


Figure 3.9: Function blocks overview in PLC-System Controller

Figure 3.10 shows the I/O signals of Start and Stop System function block. These input signals are manually triggered by a user via HMI. The internal variables of this function block requires the local control to be turned on before a start or stop sequence could be initiated.

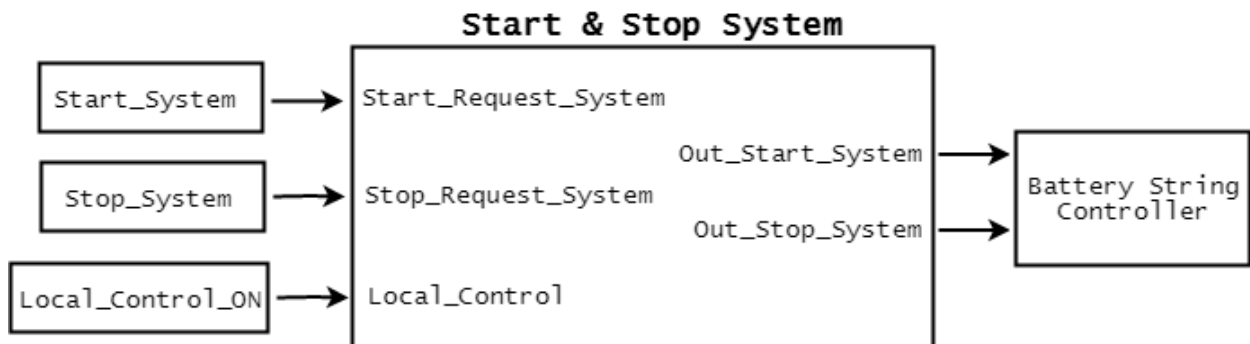


Figure 3.10: Inputs and outputs of Start and Stop System function block

An illustration of Emergency Stop System function block is shown in Figure 3.11. The

control logic inside this function block requires all input signal to be a true signal (no alarm) in order to have a true output signal. Occurrence of at least one alarm will trigger the system to stop functioning.

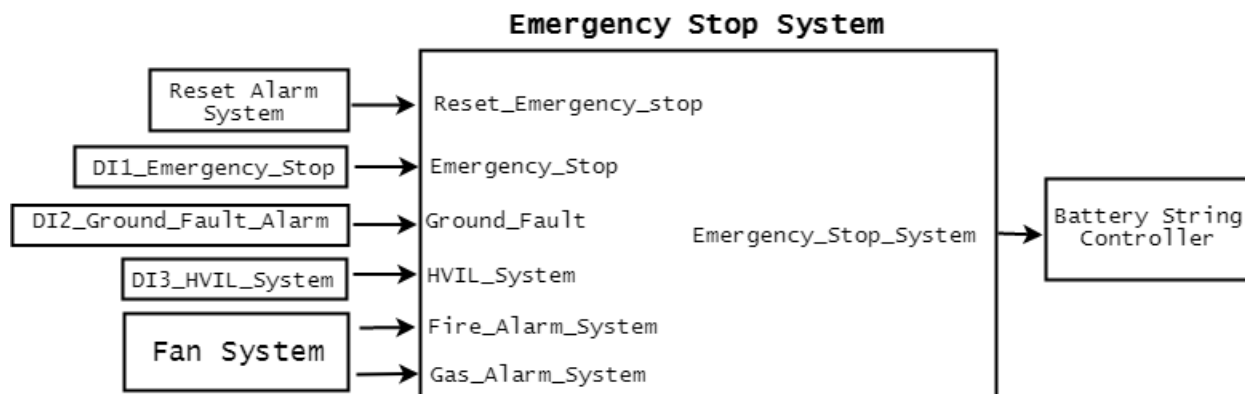


Figure 3.11: Inputs and outputs of Emergency Stop System function block

Battery String Control Logic function block consists of several function blocks such as contactor alarm, contactor control, emergency stop, start/stop, fan control, power calculation and Modbus communication alarm. However, a simplified function block diagram of a Battery String Control Logic together with its I/Os signal is shown in Figure 3.12.

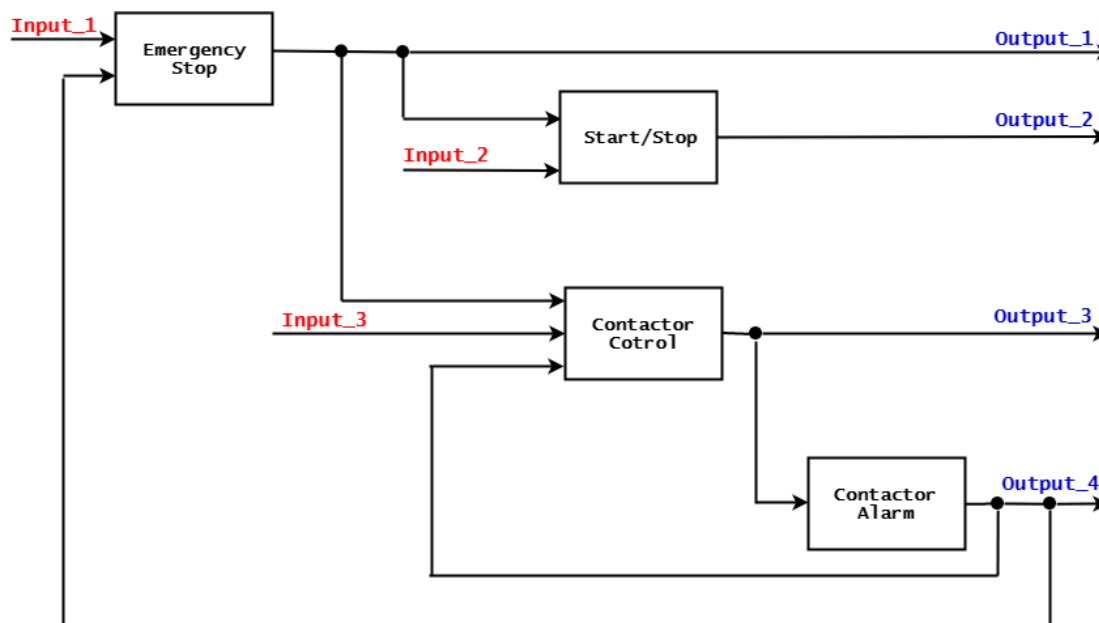


Figure 3.12: Simplified function block diagram of Battery String Control Logic function block

The list of I/O signals of the battery string controller associated to the figure above is shown in table 3.5 and 3.6. The digital input (dIn) and output (dOut) signals were the I/Os signal

of the PLC-Simulator. Other signals, such as Emergency_Stop_System, String_Alarm, etc., were I/Os signal of the system controller shown in Figure 3.8.

Signal	Description
Input_1	Emergency_Stop_System
	String_Alarm
	dIn_7_Service_Switch_Neg
	dIn_8_Service_Switch_Pos
	dIn_8_HVIL_Main_Neg_Connector_in
	dIn_10_HVIL_Main_Neg_Connector_Out
Input_2	dIn_11_HVIL_Main_Pos_Connector_Out
	Start_Request_System
	Stop_Request_System
Input_3	Local_Control_ON
	Drive_Ready_System
	dIn_1_SC_Pre_Main_Start
	dIn_2_SC_Pre_Contactor_Start
	dIn_4_Main_Pos_Contactor_Activated
	dIn_5_Main_Neg_Contactor_Activated
	dIn_6_Pre_Charg_Contactor_Activated

Table 3.5: Input signals of Battery String Control Logic function block

Signal	Description
Output_1	dOut_1_Emergency_Stop_Activated
	dOut_5_HVIL_String_Out
	Alarm_Ind_HMI
Output_2	bContactorCtrl_1
Output_3	Alarm_Drive_Ready
	Main_Cont_Pos_Alarm
	Main_Cont_Neg_Alarm
	Pre_Charge_Cont_Alarm
	dOut_2_Main_Contactore_HV_Pos_Start
Output_4	dOut_3_Main_Contactor_HV_Neg_Start
	dOut_4_Pre_Charg_Contactor_Start
	Contactor_Alarm_Out
	Reset_Contactor_Alarm_Out

Table 3.6: Output signals of Battery String Control Logic function block

The Alarm Reset System function block is shown in Figure 3.13. The control logic of this function block works as the Start and Stop system. Local Control must be turned in order to start the reset sequence of the system. Assuming that there is an alarm, the user must manually request a reset sequence via HMI.

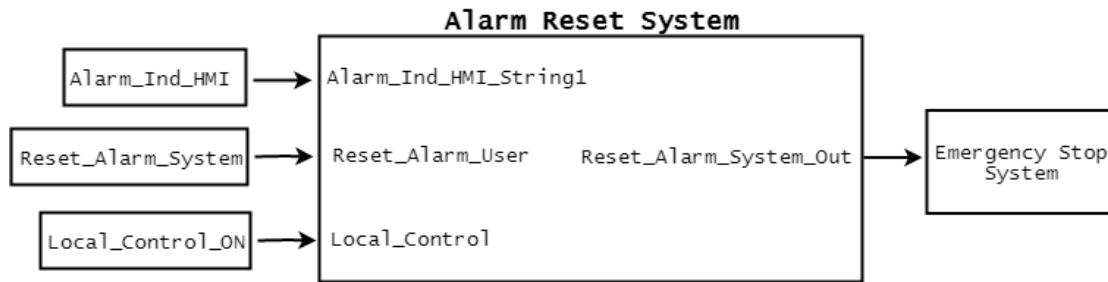


Figure 3.13: Alarm Reset System function block input and output signals

A developed visualization screen is going to be used to test the control logic sequencing of the system. Figure 3.14 shows the visualization screen on offline mode for one EE-Top simulation testing. The operation buttons (Start, Stop, Fan Control, Reset Alarm, and Local Control) should respond accordingly to which button is pressed. It also has graphic effects such as color changing background and switch movements that corresponds to a specific operation.

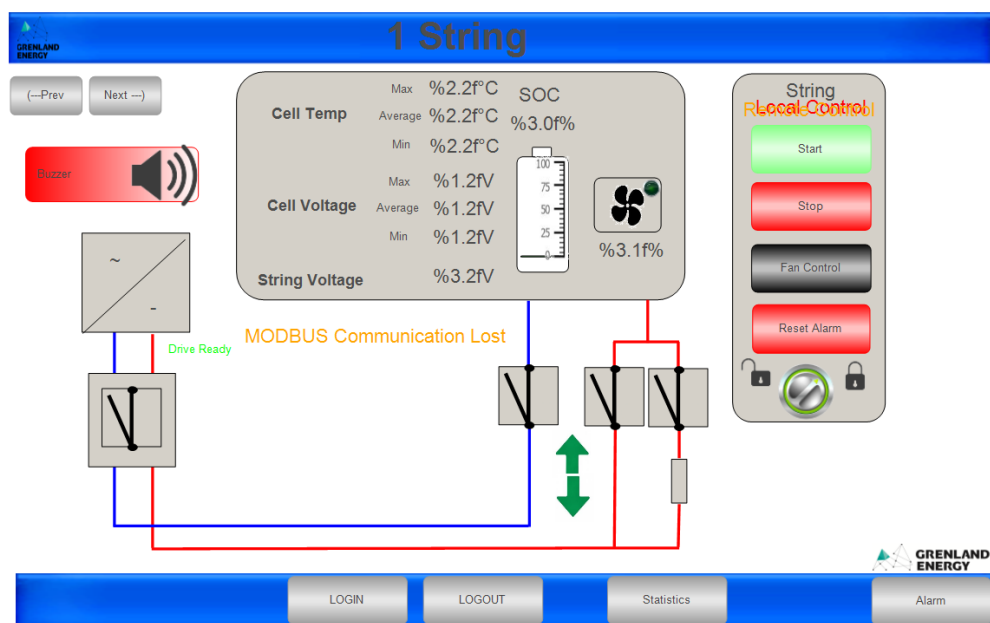


Figure 3.14: One string simulation visualization screen (offline mode)

After developing a system and visualization screen for one EE-Top, it was further developed into a system with three EE-Top. Figure 3.15 is an overview of a system with three EE-Top. This has almost the same features of the visualization screen shown in Figure 3.14. This provides the highest and lowest voltage and temperature, and total string voltage of the whole system. The visualization graphics of the main contactor will stay active as long as there is at least one of three strings is active.

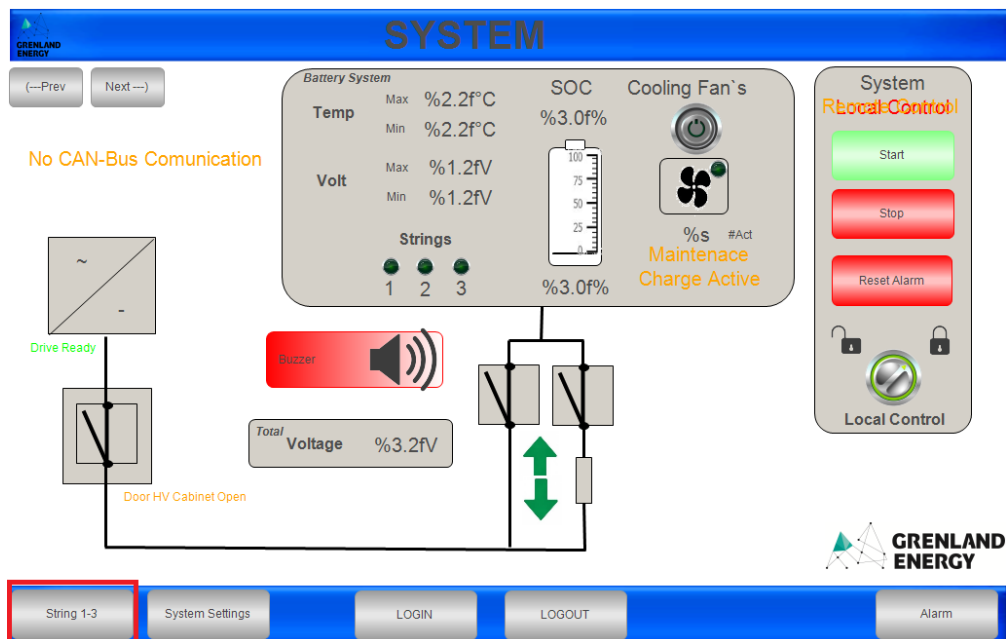


Figure 3.15: System simulation visualization screen (offline mode)

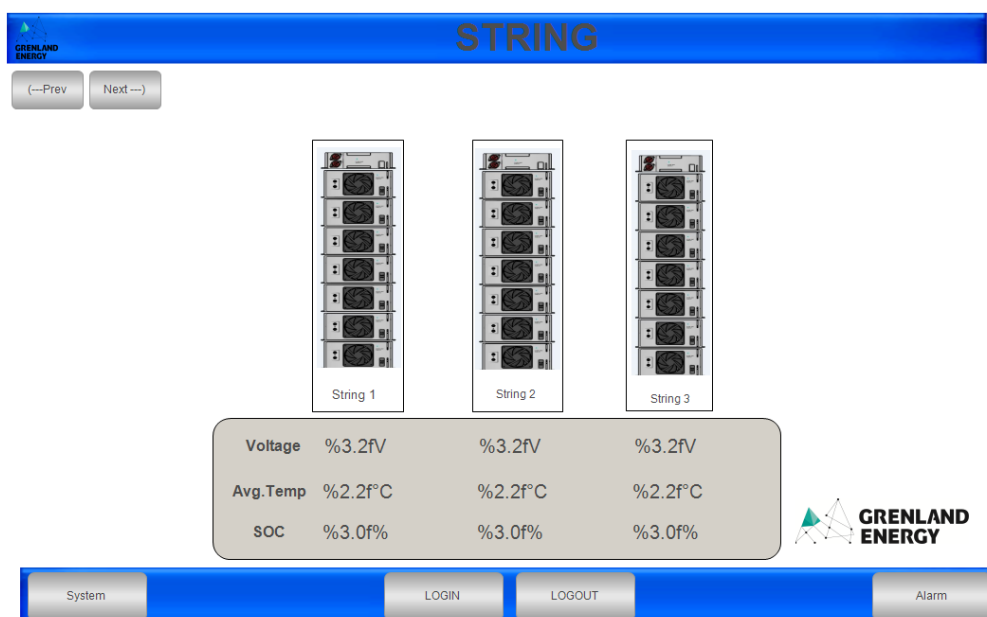


Figure 3.16: Three strings overview (offline mode)

The "String 1-3" tab (marked red) on the bottom left screen allows the user to open a new visualization. This new visualization is shown in Figure 3.16. It provides the voltage, temperature and SoC information of each individual battery string, consisting of several battery modules. The background color of a battery string will change from white to green when the string is activated as shown in Figure 3.17. By double clicking the battery string image of a specific string, it will open a new visualization that has the same functionalities

of the visualization screen shown in Figure 3.14. With this feature, the user can specifically start and stop a string that corresponds to which battery string is opened.



Figure 3.17: Inactive (white) and active (green) string

3.2 EE-Top End-of-Line Testing

3.2.1 End of Line Test Overview

The main goal for EoL testing is to check a product for faults and inconsistencies after it has been assembled. For this project, a testing procedure for the EE-Top was designed. The testing was developed to be easy and quick to perform, to test one EE-Top at a time, to have a designated testing station and to be simple to adjust in relation to future development. The key objectives of the testing procedure were:

- Check the contactor switches
- Check the connector plugs
- Check the CAN group module
- Check CAN bus communication
- Check Modbus communication
- Check the control functions of EE-Top (start/stop/emergency)
- Check if visualization screens (HMI) respond to hardware
- Check fan functionality

3.2.2 Test Station Design

To perform tests of the EE-Top, the test station design needed to resemble a normal GRE's BMS. This required all three core components of the system; battery system controller, EE-Top (to be tested) and a battery module as shown in Figure 3.18. However, to simplify the test station design, both battery system controller and battery module complex equipment were replaced with simplified versions. The component list is shown in table 3.7.

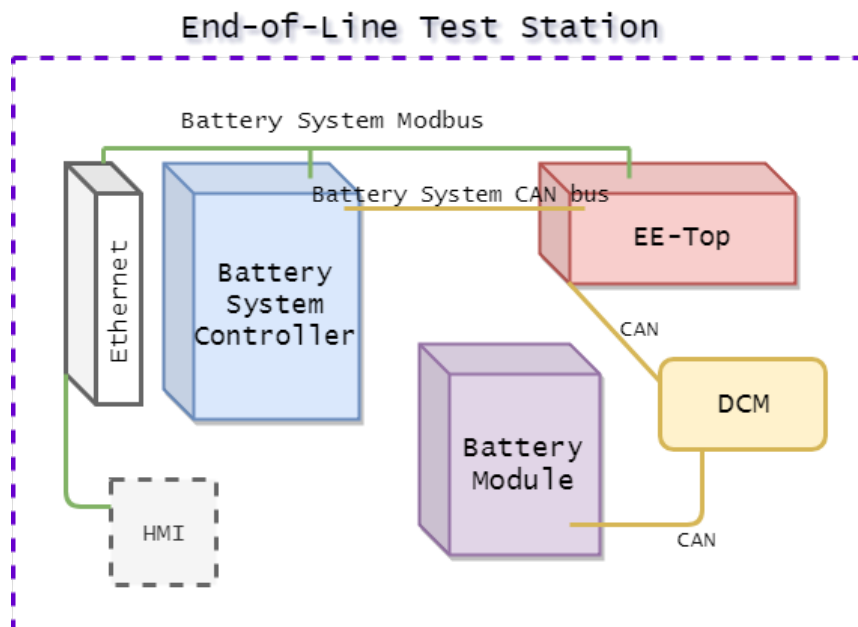


Figure 3.18: End-of-line test station design

Components	Description
PLC controller	WAGO PFC200 (750-8204) controller
Ethernet switch	WAGO 852-1111 Industrial Ethernet Switch
Battery module	Battery pack with 3 in parallel and 8 in series cells
Sensor module	A module for collecting temperature and voltage data
Ethernet cable	3x Cat 5 Ethernet cable
CAN bus cable	CAN bus cable with 9 pin plug
CAN bus cable	CAN bus cable for connecting sensor module
Voltage power supply	24 output voltage supply
Human machine interface	Laptop with e!Cockpit and Emus BMS software

Table 3.7: List of components for end-of-line test design

A simple test battery pack was chosen to replace a battery module, which would provide sensor data of the temperature and voltage. This battery pack was not an assembly of four cell modules with an OCM cards like a normal battery module, but rather a simpler, smaller battery pack with four dual cell module (DCM) cards and capability to connect to EE-Top.

Test station also required a battery system controller, with Modbus and CAN bus communication. To minimize space use and complexity of the test station, only the main components of battery system controller were chosen to be applied. A PLC-System Controller had to be available to initiate the control logic tests, an Ethernet switch for Modbus connection and a 24V DC power supply. A laptop or a tablet is required to connect to PLC-System Controller and be used as an HMI.

This test station design provided with the needed equipment and components to perform an elemental test procedure of EE-Top. Due to adjustment to the original BMS structure, adjustment were also performed in software and control logic of the PLC-System Controller. These changes will be discussed in software section of the end-of-line testing.

3.2.3 Software for End-of-Line Testing in e!Cockpit

The program that was used for EoL testing procedures was an adjusted version of the one EE-Top program described in Chapter 3.1. System1 application for the PLC-System Controller was used, with same simplification of the System1 application as shown in table 3.4. Instead of a simulated EE-Top, a connection to a real one was made.

In the network view, both System1 (PLC-System Controller) and String1 (EE-Top) can be found through scanning the IP address range. All of the equipment were connected to Modbus private IPv4 16-bit block, 256 class C block address range (e.g. 192.168.1.xxx).

To connect the equipment in e!Cockpit, Modbus UDP connection was made between the System1 and the String1 as seen in Figure 3.19. A Master/slave topology was selected, selecting System1 as the Master and String1 as the slave. A HMI display was also featured in the network but not connected. This can be connected to the Modbus communication later, if the user wishes to use a tablet for HMI.

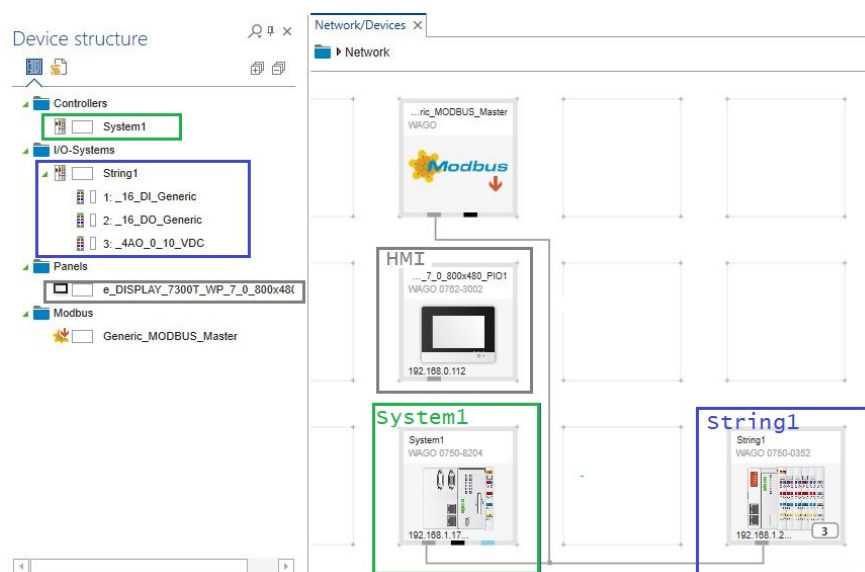


Figure 3.19: End-of-line network view

String1 I/O modules are also available in network view to be selected and viewed as shown in Figure 3.20. This allows the status check of the digital inputs, analog inputs and digital outputs without the need of checking the PLC inside the EE-Top.

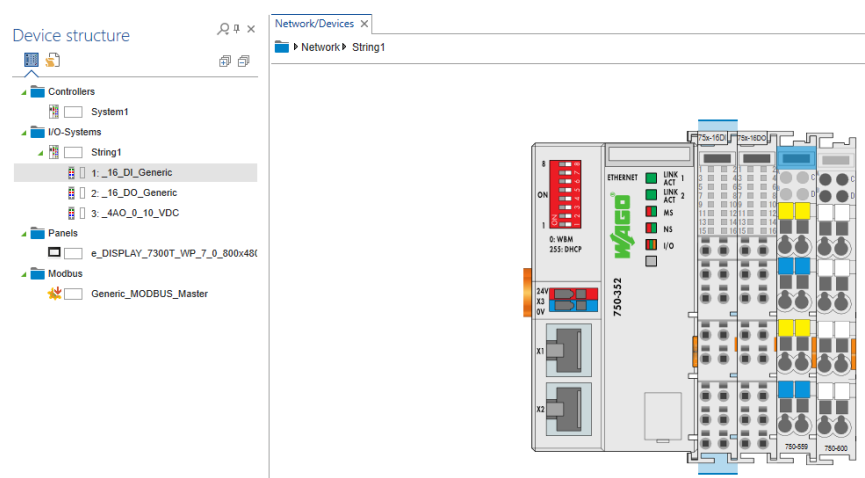


Figure 3.20: End-of-line String1 input and output selection in network view

3.2.4 Alarm Generator

The alarm generator messages in the System1 application in e!Cockpit are based on the signal inputs received from EE-Top by CAN bus and Modbus communication. These messages provide with information of which component or communication is not working and is a crucial part of the testing procedures of the EE-Top. The messages have their own ID's and are described by their signal type and class. The signals used to generate our messages are

all digital, however the classes are divided into four groups and range between information, error, warning and alarm. The classes are there to distinguish between the severity of the message, where the lowest class provides with general information and the highest class stops the system and prevents it from starting until the alarm is solved. It is also shown if true or false form of the signal that activates the alarm generated message.

CAN bus messages are used to alert for loss in CAN bus communication. In Figure 3.21 the alarms are depicted with classes and messages. In details, the message source is shown and the ones starting with GVL_Variables.xCan or GVL_Variables.xProt_flag are all messages located in global variable list GVL_Variables shown in Figure 3.7.

ID	Observ...	Details	Class	Message
46	Digital	GVL_Variables.xCanRxMonitorAlarm = TRUE	Warning_System	System Warning, CAN-Bus communication lost
24	Digital	GVL_Variables.xProt_flag_HVIL_1 = TRUE	Info	String 1 Alarm, Protection HVIL
31	Digital	GVL_Variables.xProt_flag_HVIL_sys = TRUE	Error	System Alarm, Protection HVIL
25	Digital	GVL_Variables.xProt_flag_no_comm_1 = TRUE	Alarm_String1	String 1 Alarm, Protection No Communication
32	Digital	GVL_Variables.xProt_flag_no_comm_sys = TRUE	Error	System Alarm, Protection No Communication

Figure 3.21: CAN bus alarm generator messages

In Figure 3.22 both contactor switch and all three connector plug messages are shown. These messages are received via Modbus and are defined as the alarm class. Since the switches and plugs are connected to high voltage (HV) components, it is necessary to treat these messages as very high severity and priority. A fault or a bad connection of these components could lead to serious consequences where equipment could be damaged or personnel could be hurt and therefore any alarm related to these HV components need to be solved before the EE-Top is started.

6	Digital	MODBUS.String1_udp.dln_10_HVIL_Main_Neg_Conector_Out = FALSE	Alarm_String1	String 1 Alarm. HVIL Negative Connector Output
7	Digital	MODBUS.String1_udp.dln_11_HVIL_Main_Pos_Conector_Out = FALSE	Alarm_String1	String 1 Alarm. HVIL Positive Connector Output
12	Digital	MODBUS.String1_udp.dln_7_Service_Switch_Neg = FALSE	Alarm_String1	String 1 Alarm. Service Switch Negative Terminal Activated
13	Digital	MODBUS.String1_udp.dln_8_Service_Switch_Pos = FALSE	Alarm_String1	String 1 Alarm. Service Switch Positive Terminal Activated
5	Digital	MODBUS.String1_udp.dln_9_HVIL_Main_Neg_Conector_In = FALSE	Alarm_String1	String 1 Alarm. HVIL Negative Connector Input

Figure 3.22: Modbus alarm generator messages

The alarm generator messages shown in Figure 3.23 are received from the system alarm generator block inside PLC_PRG program ((1) in Figure 3.7), where the messages are generated based on inputs and outputs from control logic or other type of input. These messages are less crucial and are only shown as error or warning class.

76	Digital	PLC_PRG.Alarm_Modbus_Communication_Lost_With_IO_Unit_System = TRUE	Warning_System	Warning System, Modbus Communication lost with IO-unit
41	Digital	PLC_PRG.Alarm_String_Contactor_Fault_System = TRUE	Error	System Alarm, Contactor Fault String
42	Digital	PLC_PRG.Alarm_String_HVIL_Connector_System = TRUE	Error	System Alarm, HVIL Connector String
43	Digital	PLC_PRG.Alarm_String_Service_Switch_System = TRUE	Error	System Alarm, Service Switch String

Figure 3.23: System alarm generator messages

In Figure 3.24 the alarm generator messages are received from String1 block inside PLC_PRG program, where messages are generated based from the control logic inputs which correspond to the Modbus signals. These messages relate to physical HV components and therefore alike the Modbus generated messages are defined as alarm class.











11	 Digital	PLC_PRG.String1_0.ContaktorControl_0.Drive_Ready_Alarm = TRUE	<input type="checkbox"/>  Alarm_String1	String 1 Alarm , No Drive Ready Feedback
8	 Digital	PLC_PRG.String1_0.ContaktorControl_0.Main_Cont_Neg_Alarm = TRUE	<input type="checkbox"/>  Alarm_String1	String 1 Alarm, Main Contactor Negative Fault
9	 Digital	PLC_PRG.String1_0.ContaktorControl_0.Main_Cont_Pos_Alarm = TRUE	<input type="checkbox"/>  Alarm_String1	String 1 Alarm, Main Contactor Positive Fault
10	 Digital	PLC_PRG.String1_0.ContaktorControl_0.Pre_Charge_Cont_Alarm = TRUE	<input type="checkbox"/>  Alarm_String1	String 1 Alarm, Pre Charge Contactor Fault
75	 Digital	PLC_PRG.String1_0.Modbus_String_Alarm = TRUE	<input type="checkbox"/>  Alarm_String1	String 1 Warning, MODBUS Communication lost with I/O unit

Figure 3.24: String1 alarm generator messages

Other alarm generator messages are also available for the current testing components. These alarm messages can be activated if the testing procedures will include current measurement and other equipment connected to the EE-Top. Since these messages are irrelevant within this work, they are excluded yet available for future applications.

3.2.5 Visualization Screen

Visualization screen developed for the testing of EE-Top is shown in Figure 3.25. It features the key controls and information display of the testing procedures. The screen shown in the figure is in offline mode. The sensor data values that are shown are just software indication for value print location. On the right side of the screen (marked green), a string control menu with local or remote control option is available, as well as start, stop, reset alarm and fan control buttons.

At the top, middle part of the string test visualization (marked orange), there is a big display of battery cell temperature, voltage, SoC and SoH. There is also a fan control indicator. Below this display (marked blue), a visual representation of the contactors are shown. Blue is for negative terminal and red for positive one. These contactors lead to HVIL System indicator. Current battery charge/discharge is displayed in the middle of visualization. The green arrows represent the current flow direction, with the direction up representing charging of the batteries.

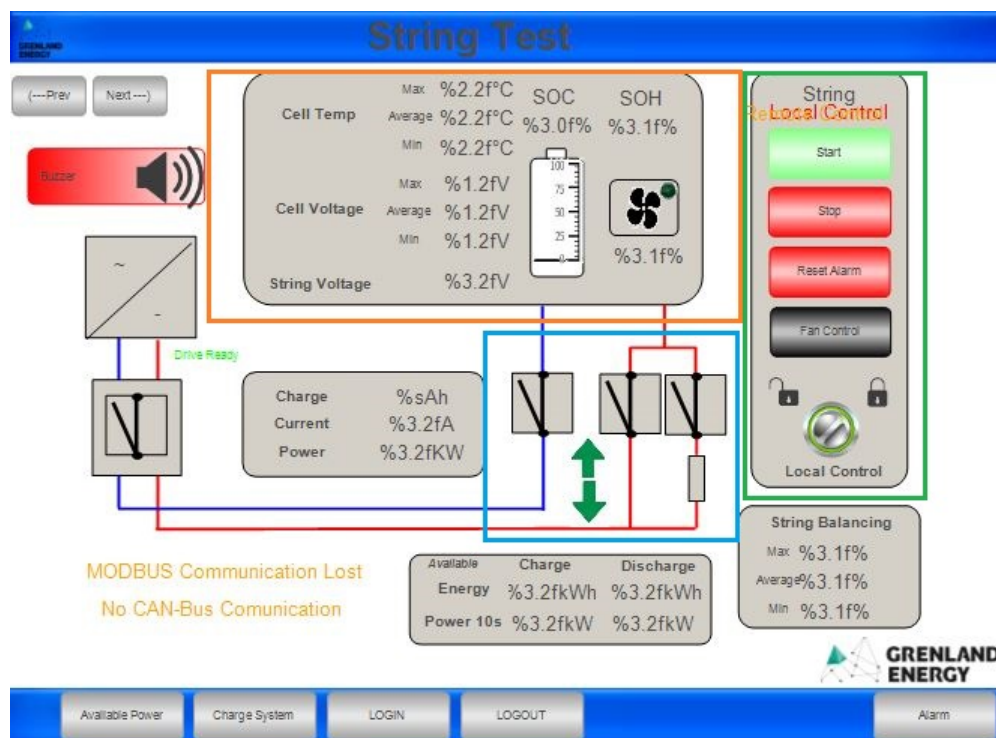


Figure 3.25: End-of-line String Test visualization screen

At the bottom there are indicators for Modbus and CAN bus connection loss, as well as available charge/discharge energy and power. On the blue bar at the bottom, several options are provided for the user. Options to check the available power, charge system, log in and log out visualizations are available. Also, the alarm window can be opened by the Alarm button.

The current related information and displays are present in the visualization for the future current testing procedures that GRE will apply to this testing program. Also, the Fan Control, Available Power, Charge System, LOGIN and LOGOUT are stock visualizations from GRE. These are required to be available during the testing procedure. However, since they are not developed during this project and are made available for future work, they are not included in the project.

3.2.6 Testing Procedures

3.2.6.1 Connecting the Equipment

To start the EoL testing of the EE-Top, the equipment are connected. Figure 3.26 shows a prototype test set-up used during the project.

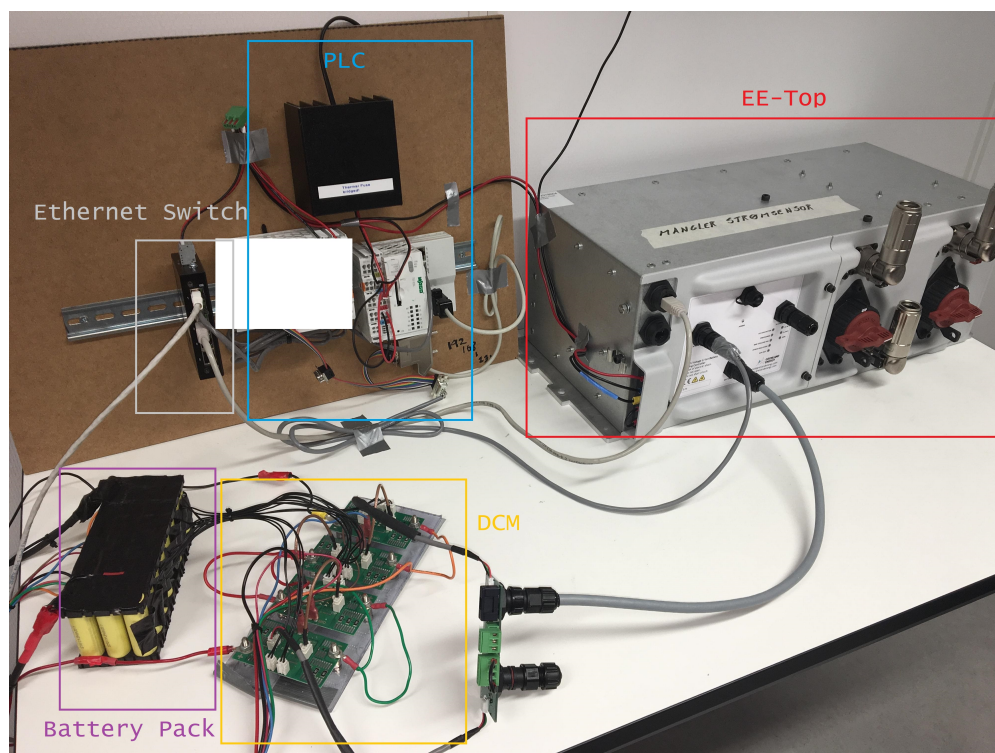


Figure 3.26: Prototype end of line test station

The equipment are to be connected in the following order:

1. Laptop, PLC-System Controller and EE-Top are connected to Ethernet switch by Ethernet cables.
2. Battery module is connected to the DCM sensor module and then to the string controller card in the EE-Top via CAN bus cable. The CGM CAN bus is also connected to the PLC-System Controller.
3. EE-Top and the PLCs are connected to a 24V DC power supply and ground.
4. Connector plugs are plugged in.
5. Contactor switches are turned on.
6. In e!Cockpit, the IP address is scanned for the EE-Top. When the EE-Top is connected to the software, the program is started.

If everything is connected correctly and there are no faults with the equipment, there should not be any alarms. In the visualization of the EE-Top testing, no alarm notification should be present. This means that the EE-Top is ready to move to further testing procedures, where we check different components one by one.

In Figure 3.27, the different switches and plugs are marked with different colour codes. This

figure will be used later to refer to different switches and plugs used for the EoL testing procedures. The two switches marked in red circles are the main contactor switches. The three green circles mark the connectors plugs. The black connectors and the left main contactor switch are connected to the negative terminal of the system, while the red connector and the right main contactor switch are connected to the positive terminal. The blue rectangle marks the CAN bus communication ports, with the bottom one connecting to the battery com and the two upper ones to either battery system controller or other EE-Tops. The yellow rectangle marks Ethernet cable port, which provides the Modbus communication.



Figure 3.27: Marked EE-Top switches and plugs

3.2.6.2 Contactor Switch Procedure

The contactor switches (red circles in Figure 3.27) should be switched on and off to see if the action will be registered by the EE-Top. The order of which contactor is tested does not matter, as long both contactors are checked. When the contactors are switched off, an alarm should appear in the visualization screen. The alarm should be reset after the contactor switch is turned back on. This sequence should be repeated 5 times to ensure the functionality of the switches. It is crucial that the alarm messages are observed to check if the messages match to the right contactor switch.

If the contactor alarm is active while the contactor switch is turned on, there is a problem with the switch. The problem should be investigated and both the signal to PLC and relay

inside the EE-Top should be checked. If there is a problem with the signal, the contactor switch component should be reconnected and replaced if needed.

3.2.6.3 Connector Plug Procedure

The connector plugs (green circles in Figure 3.27) should be detached and reattached to the female plug in the EE-Top to see if the action will be registered. The order of which connector is tested does not matter, as long all three connectors are checked. When the connectors are detached, an alarm should appear in the visualization screen. The alarm should be reset after the connector plug is reattached. Alike the contactor switches, this sequence should be repeated 5 times to ensure the functionality of the plugs. It is crucial that the alarm messages are observed to check if the messages match to the right contactor plug.

If the connector alarm is active while the connector plug is attached, there is a problem with the connector. The problem should be investigated and both the signal to PLC and relay inside the EE-Top should be checked. If there is a problem with the signal, the female connector component should be reconnected and replaced if needed.

3.2.6.4 CAN Group Module Procedure

CAN bus cable (blue circle in Figure 3.27) from EE-Top (battery com) to battery modules CGM should be disconnected and reconnected to see if the EE-Top will register loss of communication. The cable should be disconnected and an alarm should appear in the visualization screen. The alarm should reset when the cable is reconnected. If the alarm is active when the cable is connected, there is a problem with either the string controller card connections inside EE-Top or the CAN bus connection plugs. The components should be checked for faulty connection and reconnected or components replaced.

3.2.6.5 Modbus Communication Procedure

Ethernet cable (yellow circle in Figure 3.27) should be disconnected and reconnected to see if the EE-Top will register loss of Modbus communication. If the alarm is active when the cable is connected, there is a problem with either Ethernet cable or the Ethernet connection. The Modbus plugs outside the EE-Top have extension cables inside the EE-Top and their connection should be checked. The components should be reconnected and replaced if needed.

3.2.6.6 EE-Top Function Procedure

If the EE-Top has had no problems up to this point, then it is ready for the next round of testing. This test will check if the EE-Top is able to start (turn on contactors, pre-charge, show live data of temperature and voltage of the batteries) as it should. The EE-Top should be started through the "Start" button in the visualization. The contactor connection should be observed and the pre-charge sequence timed. The pre-charge starts with negative and pre-charge contactors turning on and after a set 10 seconds, the pre-charge contactor should turn off and the positive contactor should turn on. If the system does not start due to any hardware malfunction, an alarm should notify which component caused it.

The fan function should also be tested by entering the fan control visualization and turning the fan on/off. The fan control is quite important feature, since the fan cools the battery modules. If the fan control is faulty, it could lead to rise in battery temperature to the point of maximum temperature. The result in temperature would be system shut down and possibly component damage or increase in battery cell degradation. If the fan does not respond to the on/off control commands, there is a problem with connection inside the EE-Top. String controller card should be checked for correct connections and if any wires are faulty, they should be replaced.

3.2.6.7 Main Contactor Connection Procedure

The last test to be performed is the physical contactor connection test. These contactors are designed to be connected to battery modules with high voltages. If the contactors inside EE-Top are connected wrong (positive terminal to negative and negative terminal to positive), it could result in ruined equipment when the EE-Top is connected to a battery module and drives. Therefore checking for correct main contactor connection is one of the main testing requirements from GRE.

The connection should be checked using a multimeter or a "multitester" for resistance values in the contactors. During the pre-charge sequence, the positive terminal is connected to the pre-charge contactor with much higher resistance than the main positive contactor. Therefore, during this sequence the contactor resistance should be observed. This is the only way to check if the contactors are actually activating in correct order, without physically opening the EE-Top and seeing the process itself.

Chapter 4

Results

4.1 Simulation Results

4.1.1 Simulation of one EE-Top

To test the developed program of hardware simulation, both application Simulator and application System1 were connected and started. The program was tested for sequences, control functions and communication. The visualization screen of the started 1 String simulation is shown in Figure 4.1. The visualization was in remote control mode and to access control menu functions of the EE-Top, the local control must be activated. The temperature and cell voltage values were simulated to be 25°C and 3.8V respectively in the application Simulator. The values seen in Figure 4.1 are the values application System1 received via CAN bus from application Simulator.

Figures 4.2 and 4.3 show the start sequence, where the pre-charge was activated (marked in orange). During pre-charge duration, the pre-charge contactor and negative contactor were activated. At the end of the pre-charge duration, pre-charge contactor was deactivated while the positive contactor activated. To test the stability of the simulation, it was left active for 45 minutes and it did not have any errors.

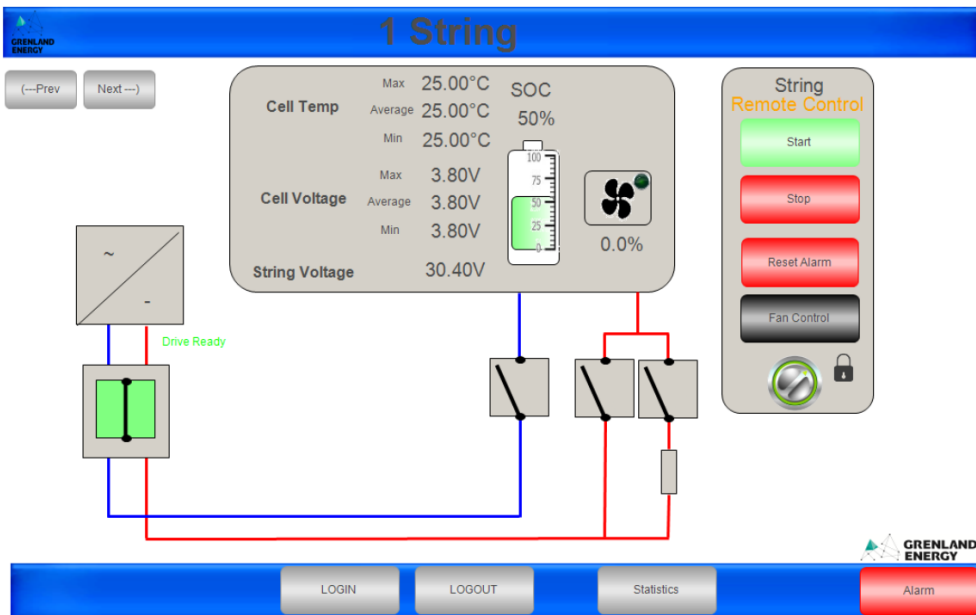


Figure 4.1: Visualization screen before start sequence

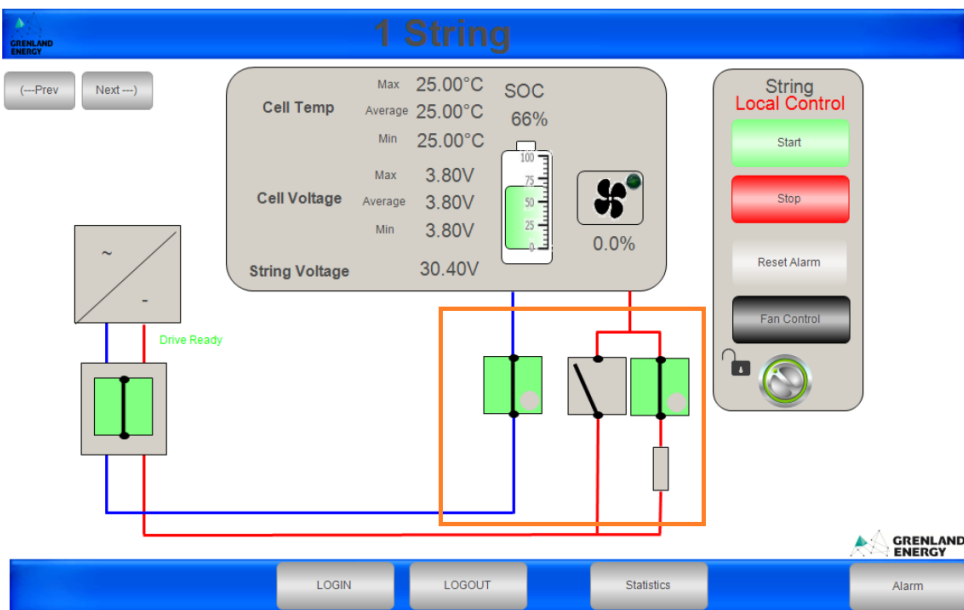


Figure 4.2: Pre-charge contactor

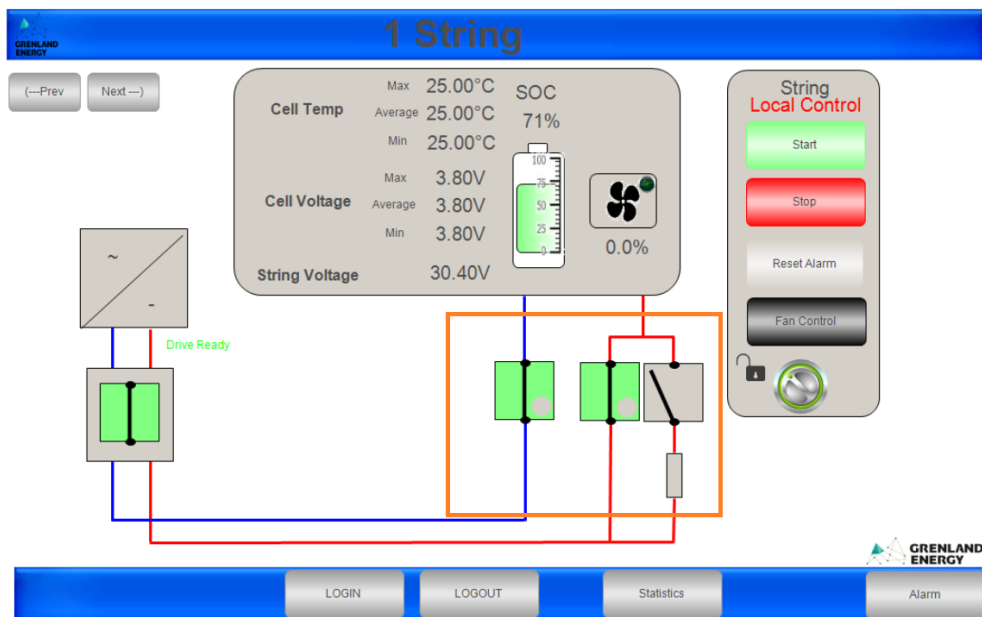


Figure 4.3: Main contactor activated

4.1.2 Three EE-Top Test Simulation

The program for three EE-Top simulation was also tested for sequences, control functions and communication. The started visualization of the System is shown in Figure 4.4. This visualization was used to start the simulation of all three EE-Tops at the same time.

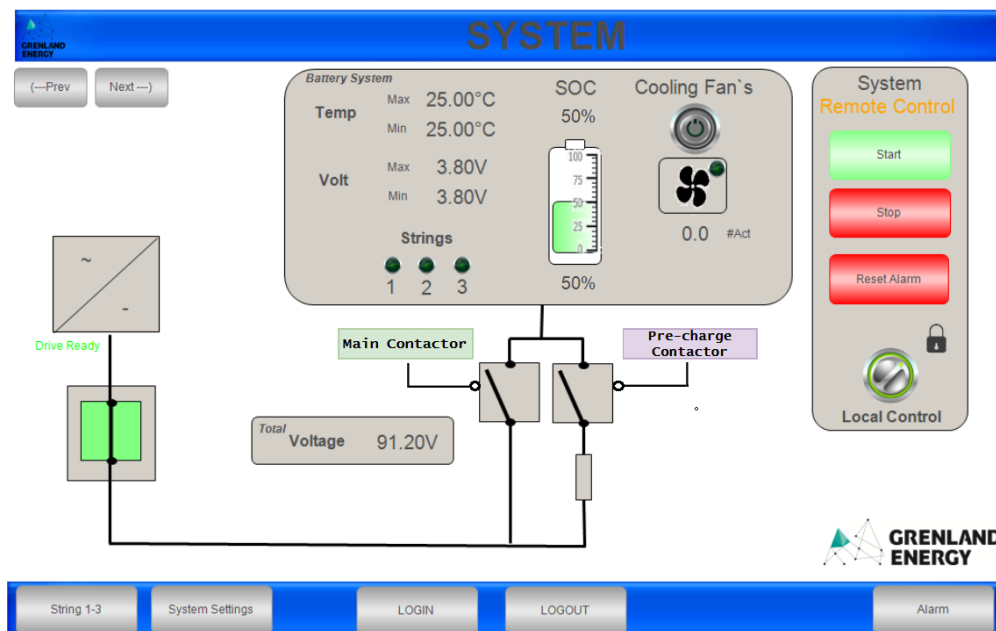


Figure 4.4: System overview before start sequence

When the start sequence had started, pre-charge contactor was activated as shown in Figure 4.5. After the pre-charge time of 10 seconds, pre-charge contactor would be deactivated. It triggered the activation of main contactor (changes from grey to green) and three strings in the system (marked red) as shown in Figure 4.6.

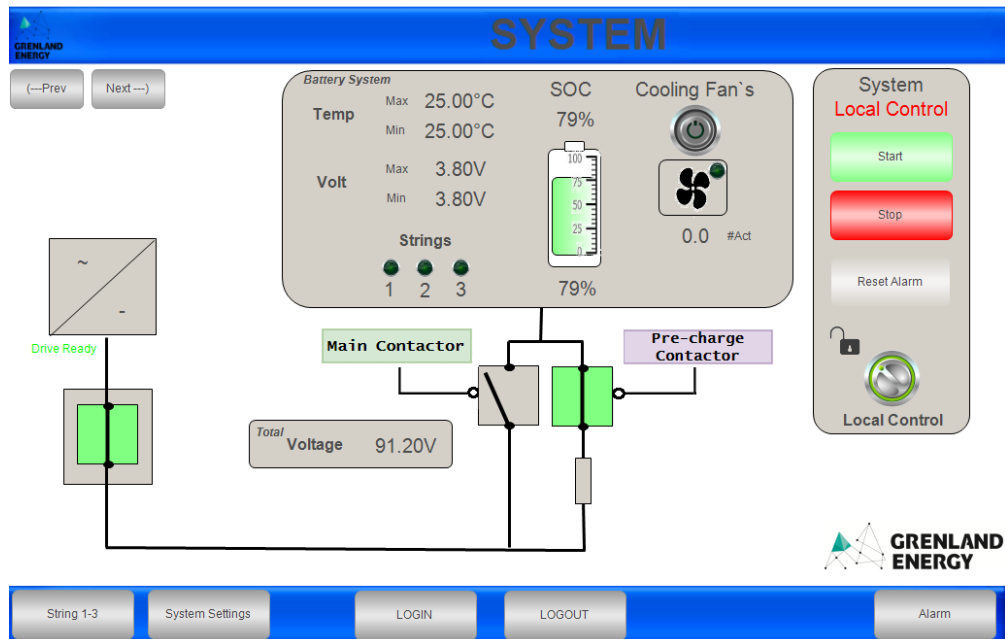


Figure 4.5: System overview during pre-charge

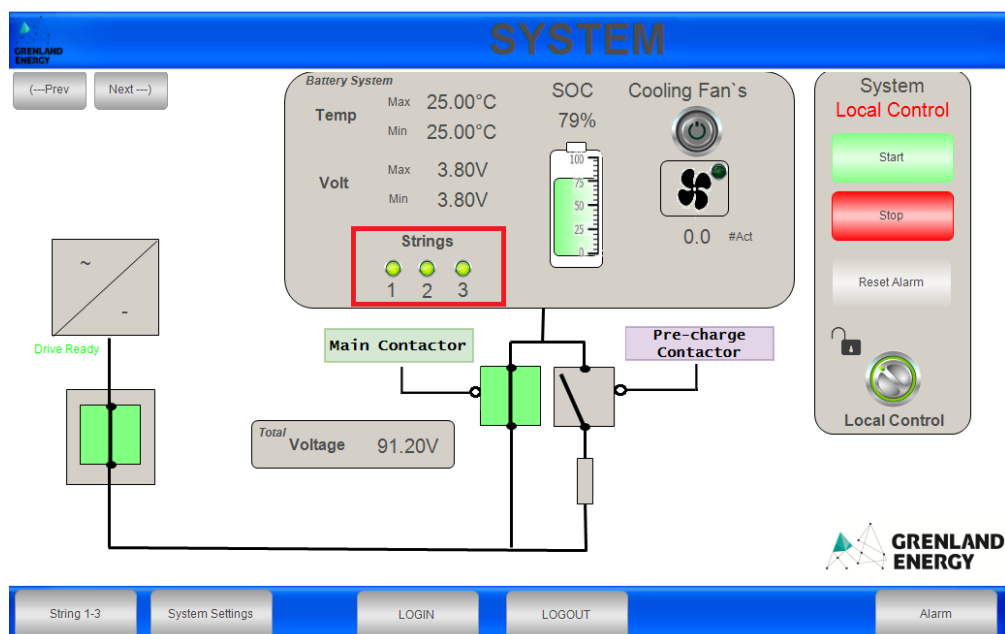


Figure 4.6: System overview main contactors activated

The String visualization was tested for responsivity to active strings. In Figure 4.7 the visualization is shown while all three strings are offline. As the simulation is started in

the System visualization screen, the strings shown in Figure 4.8 are active when the main contactors of the EE-Tops are activated.

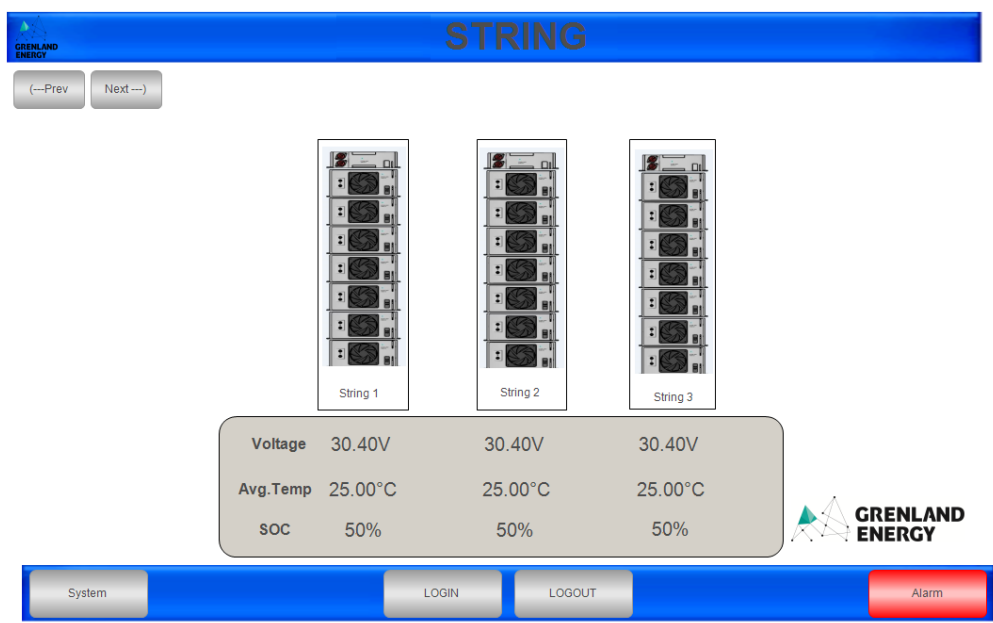


Figure 4.7: Three strings overview before start

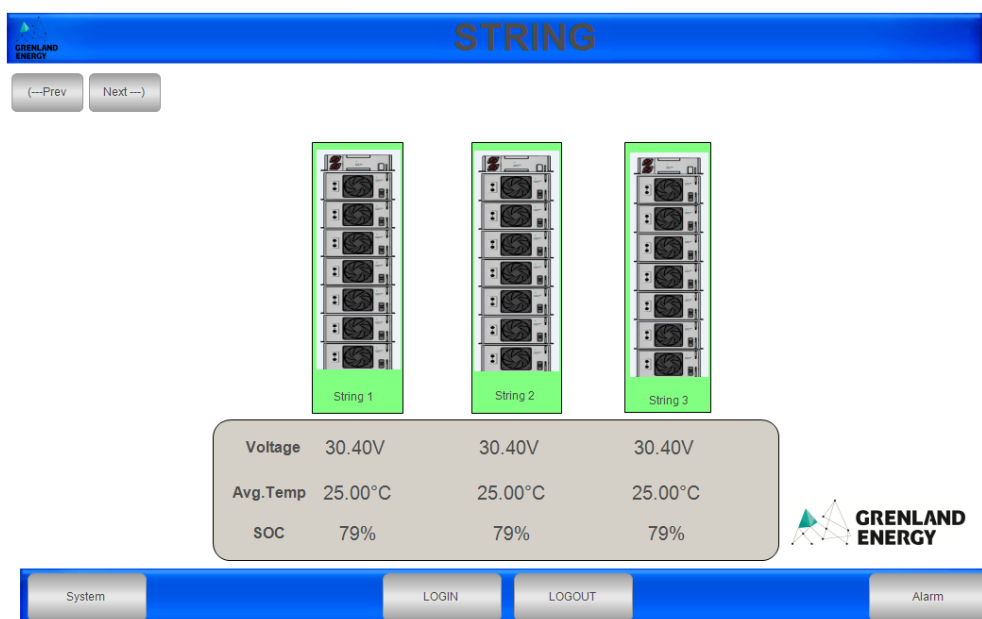


Figure 4.8: Three strings overview main contactor activated

A test to check if the simulation program is capable of running individual strings separately without stopping and displaying that in visualization was performed. In the System visualization the system was started and then the String2 was stopped. Figures 4.9 and 4.10 show both String and System visualization response to the performed test.

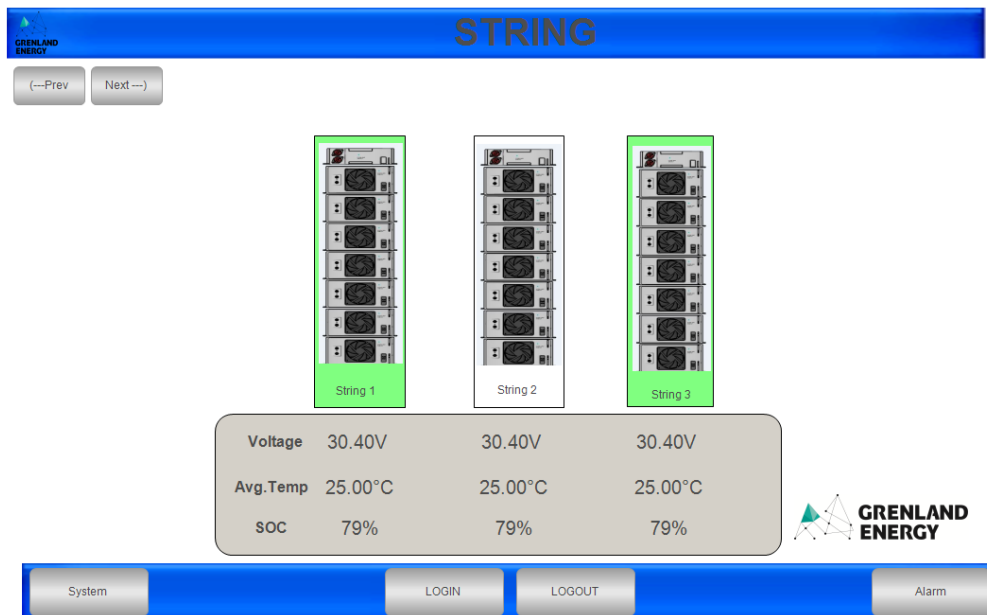


Figure 4.9: String2 deactivated

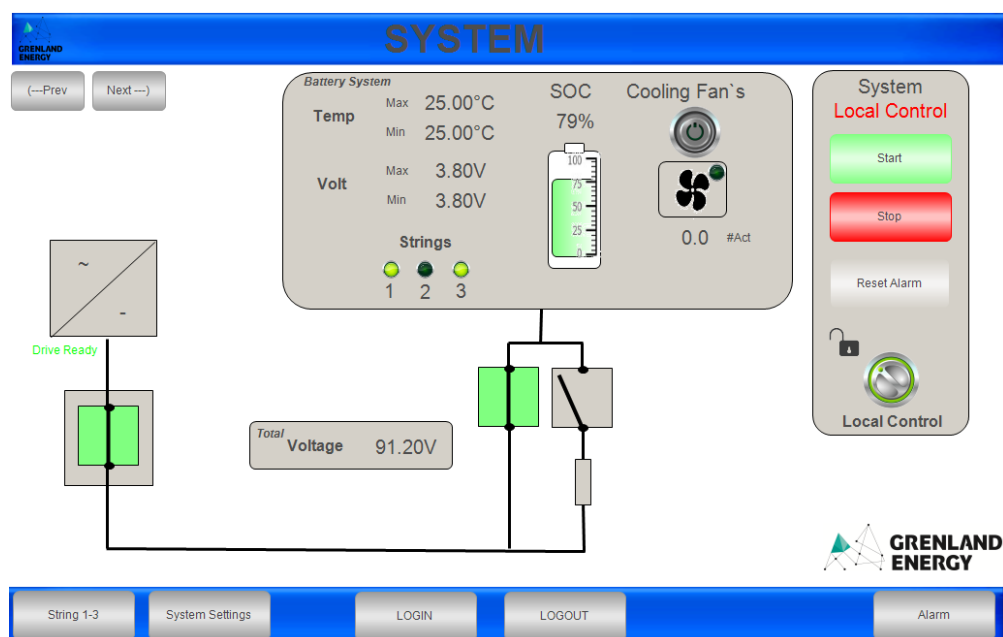


Figure 4.10: System overview String2 deactivated

4.2 End-of-Line Test Procedure Results

Tests were performed to check alarm generation and program responsivity to the different test procedures. The equipment were connected as explained in the start of Chapter 3.6.6. The testing procedures followed the guidelines described in Chapter 3.6.6 and the results

shown in the chapters below are the program response to the testing.

The generated messages are also color coded, distinguishing the message severity by the color. The yellow background color is used for information messages only. For these messages, no action is taken by the PLC-System Controller and the system does not stop when these messages are generated. The orange background color is used for inactive alarm or warning messages. These messages alike the yellow ones and do not stop the system. Red background color is used for active alarm and warning messages and stop the system/prevent it from starting.

4.2.1 Contactor Switch Test

The positive and negative contactor switches were switched off. These were the two switches with red circle shown in Figure 3.27. The messages shown in Figure 4.11 appeared for the positive contactor switch and in Figure 4.12 for the negative contactor switch. These alarms automatically reset when the contactor switches were turned back on. This switching sequence was repeated three times in total and the alarms were generated and reset.

ALARM AND WARNING	
Timestamp	Message
13.05.2019 16:58:43	System Alarm, Protection HVIL
13.05.2019 16:58:43	System Alarm, Service Switch String
13.05.2019 16:58:09	Warning System, Local control activated
13.05.2019 16:57:45	String 1 Alarm, Protection HVIL
13.05.2019 16:57:28	System Warning, High Cell Voltage System
13.05.2019 16:57:23	String 1 Alarm, Service Switch Positive Terminal Activated
13.05.2019 16:57:23	System Info, Door Battery Space Open

Figure 4.11: Alarm positive contactor

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:01:41	System Alarm, Service Switch String
13.05.2019 17:01:41	String 1 Alarm, Service Switch Negative Terminal Activated
13.05.2019 17:01:38	String 1 Alarm, Service Switch Positive Terminal Activated
13.05.2019 17:01:29	System Alarm, Protection HVIL
13.05.2019 17:01:24	String 1 Alarm, Protection HVIL
13.05.2019 16:58:09	Warning System, Local control activated
13.05.2019 16:57:28	System Warning, High Cell Voltage System
13.05.2019 16:57:23	System Info, Door Battery Space Open

Figure 4.12: Alarm negative contactor

4.2.2 Connector Plug Test

For the testing of the connector plugs shown marked with green circles in Figure 3.27, the positive connector plug out, negative connector plug out and negative connector plug in were detached. The messages shown in Figure 4.13 appeared for the positive connector plug out, Figure 4.14 for negative connector plug out and Figure 4.15 for negative connector plug in. These alarms automatically reset when the connector plug were reattached. This sequence was repeated three times in total and the alarms were generated and reset.

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:04:36	String 1 Alarm, Protection HVIL
13.05.2019 17:04:36	System Alarm, Protection HVIL
13.05.2019 17:04:35	System Alarm, HVIL Connector String
13.05.2019 17:04:35	String 1 Alarm, HVIL Positive Connector Output
13.05.2019 16:58:09	Warning System, Local control activated
13.05.2019 16:57:28	System Warning, High Cell Voltage System
13.05.2019 16:57:23	System Info, Door Battery Space Open

Figure 4.13: Alarm positive connector out

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:02:40	String 1 Alarm, Protection HVIL
13.05.2019 17:02:39	System Alarm, Protection HVIL
13.05.2019 17:02:39	System Alarm, HVIL Connector String
13.05.2019 17:02:39	String 1 Alarm, HVIL Negative Connector Output
13.05.2019 16:58:09	Warning System, Local control activated
13.05.2019 16:57:28	System Warning, High Cell Voltage System
13.05.2019 16:57:23	System Info, Door Battery Space Open

Figure 4.14: Alarm negative connector out

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:05:38	String 1 Alarm, Protection HVIL
13.05.2019 17:05:38	System Alarm, Protection HVIL
13.05.2019 17:05:38	System Alarm, HVIL Connector String
13.05.2019 17:05:37	String 1 Alarm, HVIL Negative Connector Input
13.05.2019 16:58:09	Warning System, Local control activated
13.05.2019 16:57:28	System Warning, High Cell Voltage System
13.05.2019 16:57:23	System Info, Door Battery Space Open

Figure 4.15: Alarm negative connector in

4.2.3 CAN Group Module Test

The cable was disconnected from plug outlet marked with blue in Figure 3.27. The results were the messages shown in Figure 4.16. The alarms reset when the cable was reconnected. This process was repeated three times in total and the alarms were generated and reset.

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:29:01	String 1 Alarm, Protection No Communication
13.05.2019 17:29:01	System Alarm, Protection No Communication
13.05.2019 17:28:55	String 1 Alarm, Protection HVIL
13.05.2019 17:28:54	System Alarm, Protection HVIL
13.05.2019 17:28:02	Warning System, Local control activated
13.05.2019 17:27:53	System Warning, High Cell Voltage System
13.05.2019 17:27:48	System Info, Door Battery Space Open

Figure 4.16: Alarm CAN bus

4.2.4 Modbus Communication Test

When the cable was disconnected from the plug outlet marked with yellow in Figure 3.27, it resulted to the messages shown in Figure 4.17. The alarms automatically reset when the cable was manually reconnected. This process was repeated three times in total and the alarms were generated and reset.

ALARM AND WARNING	
Timestamp	Message
13.05.2019 17:36:18	String 1 Warning, MODBUS Communication lost with I/O unit
13.05.2019 17:36:18	Warning System, Modbus Communication lost with IO-unit
13.05.2019 17:36:07	Warning System, Local control activated
13.05.2019 17:36:01	System Warning, High Cell Voltage System
13.05.2019 17:35:55	System Info, Door Battery Space Open

Figure 4.17: Alarm Modbus

4.2.5 EE-Top Functionality Test

The EE-Top was started by activating the "Start" function in the visualization screen. The pre-charge sequence was started and after 10 seconds the main positive and negative contactors started. In the Figure 4.18 the contactor sequence is shown during stopped, pre-charge and running modes. This procedure was repeated three times, showing the same results.

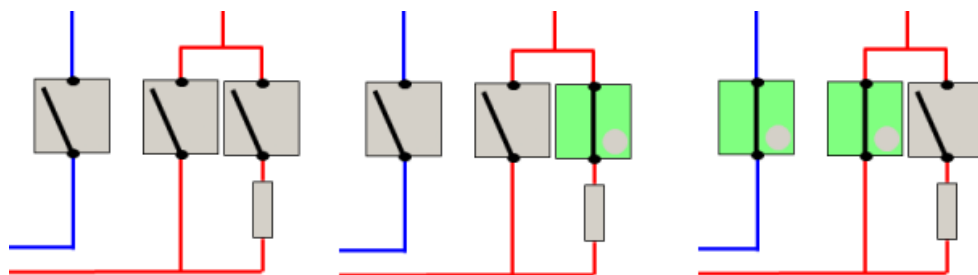


Figure 4.18: EE-Top contactor switch sequence test visualizing stopped, pre-charging and running contactors

In Figure 4.19, the started String Test visualization is shown. The EE-Top is easily controlled through this control menu. A test of CAN bus communication is performed by increasing the temperature of one thermocouple by introducing it to a warmer object as shown in Figure 4.20.

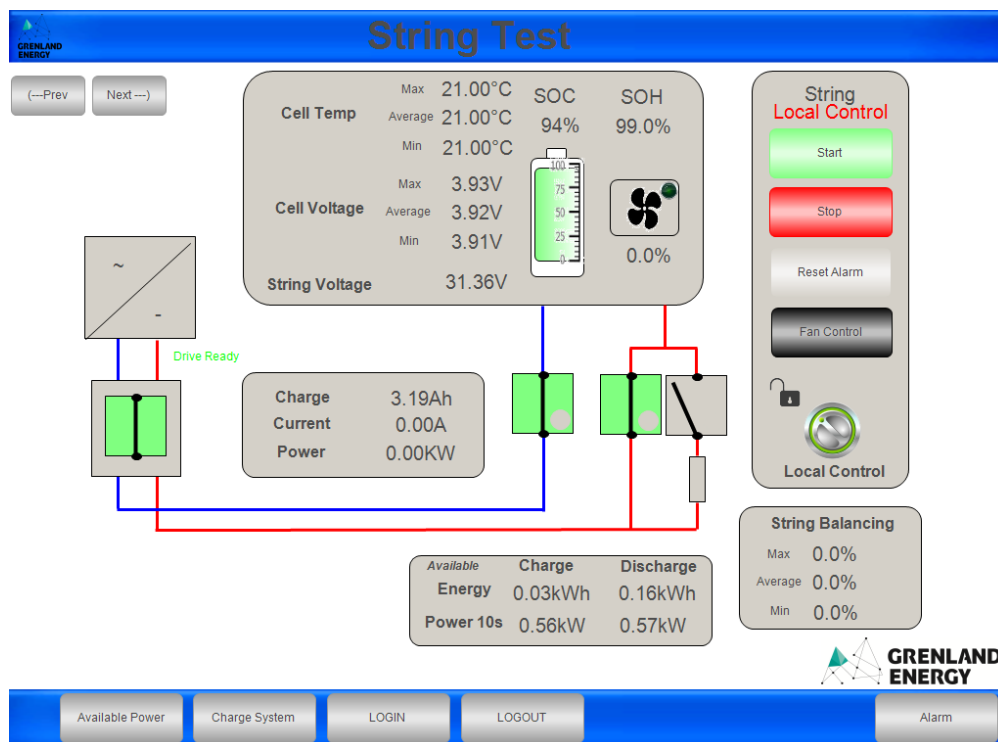


Figure 4.19: Visualization of a started EE-Top

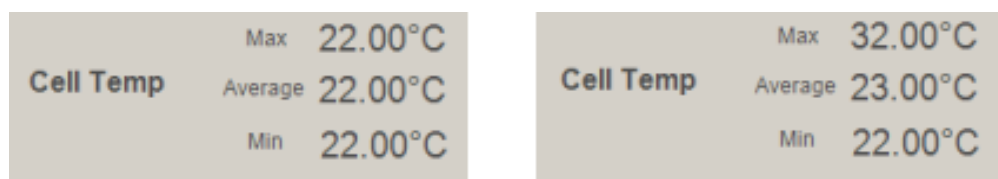


Figure 4.20: Visualization cell temperature test

Chapter 5

Discussion

5.1 Simulation

5.1.1 O1MG1: Develop a Simulation with one EE-Top

The developed simulation for one EE-Top showed excellent results with regards to control logic, process sequencing, and responsiveness of visualization screen. The two PLCs were connected and simulated without presence of any alarms and communication faults. The local control switch, start, stop and reset alarm buttons were tested and their functionality verified. In Simulation results of Chapter 4.1, Figures 4.2 and 4.3 showed the correct switching processes of the contactors during the simulation. Adjustable parameters such as voltages and temperature indicated that the visualization screen provides the right information based on battery parameters given to the system.

5.1.2 O1MG2: Develop a Simulation with Several EE-Tops

The results from the developed simulation for one EE-Top were implemented and modified in order to make a test simulation of three EE-Top. Same procedure was done to test all the functionalities and resulted to a working and stable simulation model. The System visualization panel was made to have an overview of all the strings. Figure 4.6 shows that when the start sequence was initiated, the three EE-Tops would be activated at the same time. Figure 4.8 provided us the information about the string parameters and which string was active. As shown in Figure 4.9 starting and stopping each string individually was tested and responded accordingly without causing any conflicts, such as stopping other string or causing an alarm. This was important when testing real life application which prevent

stopping the whole system during maintenance check.

5.2 End-of-Line

5.2.1 O2MG1: Develop End-of-Line Testing Procedure

The developed testing procedure for end-of-line testing provides with the EE-Top main component and their connection verification as required by the Grenland Energy. In Chapter 4, the results show that the developed program provides with necessary control logic, sequencing, control and feedback when running the tests. The program responds to contactor switching control as shown in Figure 4.11 and Figure 4.12 and provides correct alarms when the switches are turned off. The same can be observed for the contactor connector plugs and Figures 4.13, 4.14 and 4.15 show that correct alarms are generated when the plugs are detached. The testing of these two switches and three plugs is critical, since they are connected to the high voltage contactors inside the EE-Top. A fault with these components is a big safety risk and could lead to severe personnel injury or damaged components.

The communication test results of both CAN bus and Modbus in Figures 4.16 and 4.17 show that the program provides with necessary feedback during the tests. The CAN bus communication was further tested by increasing one thermocouple temperature by placing it in contact with a warm object. The increase in the temperature was registered by the equipment and the program and displayed in the visualization as shown in Figure 4.20. Both CAN bus and Modbus provide with control logic communication, therefore these components need to be functioning at all times and in case of loss connection, alarms should be present. Loss in control logic communication could prevent the user from performing necessary control actions. Loss in control of the equipment is a safety risk, and when high voltage equipment are involved, could lead to severe consequences.

During the functionality test procedures, an error in contactor switching sequence was observed as shown in Figure 4.18. When the start sequence was initiated in control menu, the EE-Top started by activating pre-charge mode. During this mode, the negative contactor and the pre-charge contactors should be activated. When the pre-charge duration is over, the pre-charge contactor should be turned off and the positive contactor turned on. However, during the testing, both negative and positive contactors did not turn on until the pre-charge duration was over. This produced alarms in the system and the cause of this was investigated. It was noticed that the Modbus commands for contactor activation were sent to the EE-Top from battery system controller, but the contactors did not start until the pre-charge duration was over. After further testing, a conclusion was made that there was

a wiring problem in the relays or the PLC connection. Due to complex EE-Top assembly and limited access to the internal components, this wiring problem was not solved during this project. However, this EE-Top component malfunction was an important result of the testing by verifying how important the end-of-line testing is. This ensures that the developed end-of-line testing procedure is capable of identifying faults in the components.

In general, the developed end-of-line testing program showed excellent visualization and control logic response to the EE-Top and testing procedures. Figure 4.19 shows that the program runs fine and the results in Chapter 4 correspond to the expectations. The step-by-step testing procedures explained in Chapter 3.6.6 provide with thorough walkthrough of the components used, connection of these components and test execution. Due to lack of current sensor inside the EE-Top, no current test procedure was developed during this project. However, the program has underlying framework for implementation of the current test of Grenland Energy wants to apply it in the future.

During the early stage of the project, there was a lot of time invested in simulation part of the project. There was lack of available information on this topic, therefore the learning outcome was solely based on self-taught knowledge based on the equipment and software, and assistance from the supervisors. The report authors had to get familiar with both software and hardware of the Grenland Energy's sophisticated battery management system, which required good understanding of the internal and external components, connections and communication to be able to develop end-of-line testing procedures. It was very beneficial that most of the programs and control logic from application System1 in Chapter 3.1 could be reused for the end-of-line testing procedure program, since it saved on time in an already tight schedule.

5.2.2 O2MG2: Design and Build End-of-Line Test Station

The prototype test station design used during this project provided with the necessary equipment to run end-of-line testing procedures on the EE-Top. A similar design station is to be built in the Grenland Energy's facility with simple adjustments. In case there are other tests added to the procedures, like a current test, some adjustment would potentially be made to the battery module and EE-Top connection. An human machine interface tablet could also be connected, but that is all up to the personnel running the test procedures.

In our prototype station, a problem related to the CAN bus wire plugs, connecting EE-Top to the PLC-System Controller was observed. This problem originated from a bad connection of CAN bus wire to the male plug. The result was loss of connection, which would prevent the EE-Top from responding to inputs from visualization and even freeze the program. The

cables should be inspected thoroughly when the test station is built in Grenland Energy's facility.

Chapter 6

Conclusion

The Lithium-ion battery development has been very rapid in the last few years and the cost of Lithium-ion batteries and complex battery management systems are the main factors that restrain battery based energy storage systems from extensive renewable energy application. These battery management systems require extensive software and hardware testing. The objectives of this thesis were to develop software and hardware testing of Lithium-ion battery controller that is one of the main components in Grenland Energy's state-of-the-art battery management system.

The developed simulation of Grenland Energy's EE-Top responded well with their battery system controller program. The EE-Top simulation functionality was tested for both one EE-Top and three EE-Top systems and both simulations proved to be stable and ran without any problems. The simulations included CAN bus and Modbus control logic communication, program sequencing and sensor data communication. The developed simulation can be implemented in future projects to test battery management system control logic for errors, providing with software testing without the need of physical equipment. Next step would be to simulate current transfer in the simulator, so that state of charge and current measurement statistics could be tested.

When it comes to the end-of-line testing of the EE-Top, both the program for the testing, testing station design and testing procedures were developed. The testing procedures were designed to perform tests on the EE-Top hardware components, providing with an elementary test of the equipment. Based on these procedures, the testing station design was made with all of the equipment needed to perform the tests. A program was also developed to be used during the end-of-line testing. It provided with verification that the components work and that the EE-top is receiving all of the necessary inputs, outputs and sensor data, and communicates it to the rest of the battery management system.

During the project, the project group did stumble upon several small obstacles, which were expected based on the complexity of Grenland Energy's battery management system. It was a steep learning curve to get to know their system and master component understanding, different communication protocols and programmable logic controller programming. Nevertheless, the project was a success, providing the project group members with great knowledge of state-of-the-art battery management system and Grenland Energy with software and hardware testing of their EE-Top product.

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