HORIZON EUROPE PROGRAMME – TOPIC HORIZON-CL5-2022-D2-01-06

Embedding smart functionalities into battery cells (embedding sensing and self-healing functionalities to monitor and self-repair battery cells)

(Batteries Partnership)

PHOENIX

Building more reliable and performant batteries by embedding sensors and self-healing functionalities to detect degradation and repair damage via advanced Battery Management System

Grant Agreement No. 101103702

Starting date: 1st May 2023 – Duration: 48 months

Deliverable D6.2
BMS v1 test

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4.0	28.06.2024	Inès BOURSOT (VUB)	Format review, version ready for submission

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SHORT ABSTRACT

Abstract

The goal of this deliverable is to show how the developed BMS were tested and document the obtained results. The results of this deliverable ensure that the BMSs operate as expected and can be used by partners for subsequent work.

For this purpose, various tests are conducted: integration tests with partner electronic, data reading acquisition and comparison with reference equipment, self-healing triggering, etc.
The obtained results are analysed. Based on the carried-out tests, the BMS are operational and can be used.

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LIST OF PARTNERS

N.	Logo	Name	Short Name	Country
1		VRIJE UNIVERSITEIT BRUSSEL	VUB	Belgium
2		FRAUNHOFER GESELLSCHAFT ZUR FORDERUNG DER ANGEWANDTEN FORSCHUNG EV	FhG	Germany
3		DEUTSCHES ZENTRUM FÜR LUFT- UND RAUMFAHRT	DLR	Germany
4		ENWAIR ENERJI TEKNOLOJILERI ANONIMSIRKETI	ENW	Turkey
5		DEEP BLUE SRL	DBL	Italy
6		FUNDACION CIDETEC	CID	Spain
7		LECLANCHÉ GMBH	LEC	Germany
8		ACCUREC-RECYCLING GMBH	ACC	Germany
9		CSEM CENTRE SUISSE D'ÉLECTRONIQUE ET DE MICROTECHNIQUE SA - RECHERCHE ET DEVELOPPEMENT	CSEM	Switzerland

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ABBREVIATIONS

Acronym	Description
BMS	Battery Management System
EIS	Electrochemical Impedance Spectroscopy
zBMS	Battery Management System developed by CSEM in the scope of PHOENIX
SH	Self-Healing
FW	Firmware

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EXECUTIVE SUMMARY

The aim of this deliverable is to show how the developed BMSs were tested and document the obtained results. The BMSs were designed and manufactured according to the requirements of D6.1 The results of this deliverable ensure that the BMSs operate as expected and can be used by partners for subsequent work. In particular for VUB for the analysis of WP4.

For this purpose, various tests are conducted: integration tests with partner electronic, data reading, self-healing triggering, etc.

The obtained results are analysed. Based on the carried-out tests, the BMS are operational and can be used.

It is worth pointing out that the deliverable was initially due at M12, however it was agreed to deliver it at M14.

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1. Introduction

The goal of this deliverable is to ensure that the developed BMS that will be used by WP4 partners operate as desired over a long period.
To demonstrate this, the document is divided in the following key chapters:

- Chapter 2 (High level test matrix): provides a high-level overview of the carried-out tests
- Chapters 3 to 7:
    - Test 1: EIS: tests the EIS between the cell tabs
    - Test 2: EIS on ref. electrode: assesses the EIS on the reference electrode
    - Test 3: BMS features: checks the BMS features (including voltage measurements)
    - Test 4: system test: connects several BMS and sensors over a long period
    - Test 5: BMS SH activation: ensure SH activation over a long period

Each test is composed of the same sections:

- Purpose of the test: to describe the purpose of the test
- Used hardware and software: gives details about the used hardware and software. A general overview of the used HW is provided in Table 2.
- Test results: provides the results
- Analysis and conclusion: assesses the results

Three points are to be mentioned:

1) The aim of this deliverable is not to validate the accuracy of the sensors provided by partners, but to ensure that the measured data is transmitted accordingly. The individual sensor functionality is assessed in D4.3.
2) Similarly, for self-healing (SH) actuation, this deliverable only assesses the communication between the laboratory PC and the SH. The functionality of the SH is assessed in D3.1
3) Only the equipment that was available during the tests could be validated. This excludes:
    a. optical fibre temperature sensing: that is directly connected to the PC
    b. ultrasonic sensing: Unavailable at time of testing
    c. gas sensors: that were not available at the time this work was carried out. In the first following tests, these sensors will be connected to the laboratory PC using standard off the shelf electronics.

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2. High level test matrix and used hardware

Table 1 provides an overview of the performed tests. As mentioned in the introduction, each test aims at validating certain features:

- Test 1: EIS: tests the EIS between the cell tabs and compare the results against a reference laboratory equipment.
- Test 2: EIS on ref. electrode: assesses the EIS on the reference electrode and compare the results against a reference laboratory equipment.
- Test 3: BMS features: checks the BMS features (such as over voltage). In this test key BMS features are validated. This test also includes the validation of the voltage measurements.
- Test 4: system test: connects several BMS and sensors over a long period. The goal of this test is to ensure that data is sent and collected correctly using several BMSs over a long period. KPI such as data loss and gaps are evaluated.
- Test 5: BMS SH activation: ensure SH activation over a long period. In this test the goal is to ensure that SH activations can be sent over a long period and that they are applied correctly.

Table 2 provides an overview of the hardware used in the various tests. If required details are provided in the various tests' chapters.

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Table 1: high level test matrix

Test #	Focus	Setup description	Purpose of test	Test description
1	EIS	Test on: monolyer cell + 21700 cylindrical cell.	Verify the EIS	Compare PHOENIX EIS with reference equipment
2	EIS reference electrode	Same as 1	Verify the EIS on reference electrode	Compare PHOENIX EIS with reference equipment
3	BMS	BMS feature tests: over/under voltage BMS voltage accuracy	Ensure that over/under voltage is detected fast enough Ensure that the voltage measurement is correct.	Do manually (with lab supply).
4	System sensing	Laboratory PC with Python test script WDC 3 BMSs: - Ppico temperature: real 1x - FHG temperature sensor: 1x - - FHG thermal trigger - BMS temperature - BMS voltages: emulated	Verify data acquisition validation over long duration	Assess that the data arrives reliably.
5	System SH	Laboratory PC with Python test script WDC 1 BMS: - Ppico temperature: real 1x - FHG temperature sensor: 1x - FHG thermal trigger	Send activations over a long duration.	Send heating activations to FHG thermal trigger, read back temperature using FHG temperature sensor.

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Table 2: used hardware

Item	HW number	FW tag	Comment
BMS1 (Wisenode 65)	B1	zbms_plus_ fw_baremetal	
BMS1 (Wisenode 66)	B2	zbms_plus_ fw_baremetal	
BMS1 (Wisenode 67)	B3	zbms_plus_ fw_baremetal	
BMS1 (Wisenode 68)	B4	zbms_plus_ fw_baremetal	
BMS1 (Wisenode 69)	B5	zbms_plus_ fw_baremetal	
Wireless data concentrator	V1	30 mai 2024 16:02	This is the wireless receiver inside the blue box on the PC side
Wisenode	V1	31 mai 2024	This is the wireless module present on each BMS. It's a small violet PCB
Raspberry pi	Raspberry PI 3B+	-	
Reference EIS Biologic BCS-815[1] Channel C8	Serial # 236	N/A	Low frequencies uncertainties as discussed Section 3.4
Cell 1: 21700	Internal: B.QEP-008	N/A	Standard cylindrical cell Samsung INR21700-50E recommended max C-rate of 1C
Cell 2: monolayer[2] with RE[3]		N/A	NMC622/Graphite mono-layer pouch cell (50.16 mAh cell) produced by CSEM with RE from

[1] https://www.biologic.net/

[2] NMC622 cathode (2 mAh/cm2), NEI graphite (2.4 mAh/cm2), LP71 + 10wt% FEC electrolyte and HPPE separator

[3] LFP on Al mesh from Cidetec (conditioned RE)

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			CIDETEC recommended max C-rate of 1C
Lab PC code (Python)	N/A	EIS_V1	
Laboratory power supply	Rigol DP832 S/N: DP8C234205586	N/A	
Multimeter	Fluke 289 S/N: 55370080	N/A	
FHG temperature sensor	V1Fluke 289 S/N: 55370080	Version 7 may 2024	Connected to BMS1
FHG SH temperature trigger	V1	Version 7 may 2024	Connected to BMS1
Handheld IR thermal gun	Fluke 62 maxV1	N/A	Connected to BMS1

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3. Test 1: EIS

3.1 Purpose of the test

The purpose of this test is to validate that EIS can be obtained in a standard configuration (i.e. between the cell tabs). The target KPI for EIS is summarized in Table 3.

Table 3: EIS test KPI

KPI	Threshold
The EIS must look like the one obtained using a reference equipment (frequency range: 10mHz – 1kHz) and be repeatable.	N/A
The EIS must be repeatable (precision)	Average standard deviation over frequency range <2 [dB]

3.2 Used hardware and software

The used hardware for these tests is summarized in Table 2.

Note: with the current FW, the EIS computation (i.e. raw data to Nyquist) is done offline using a Python script. In future versions, the computation will be done in the BMS. This test validates the excitation signal generation capability.

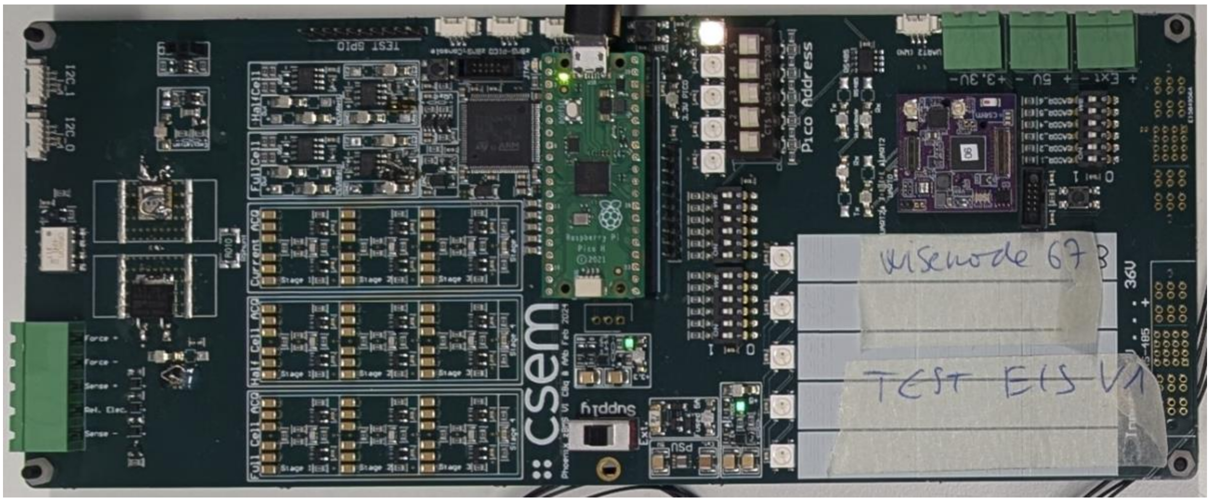

Figure 1: Figure of the BMS1 (Wisenode 67)

3.3 Test results

The tests have been performed on two distinct cells. A commercial 21700 and a pouch cell made in CSEM. Results for the commercial 21700 cell are highlighted in Figure 2 to Figure 4

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and Table 4. While results for the pouch cell are highlighted in Figure 5 to Figure 7 and Table 4: EIS test results.

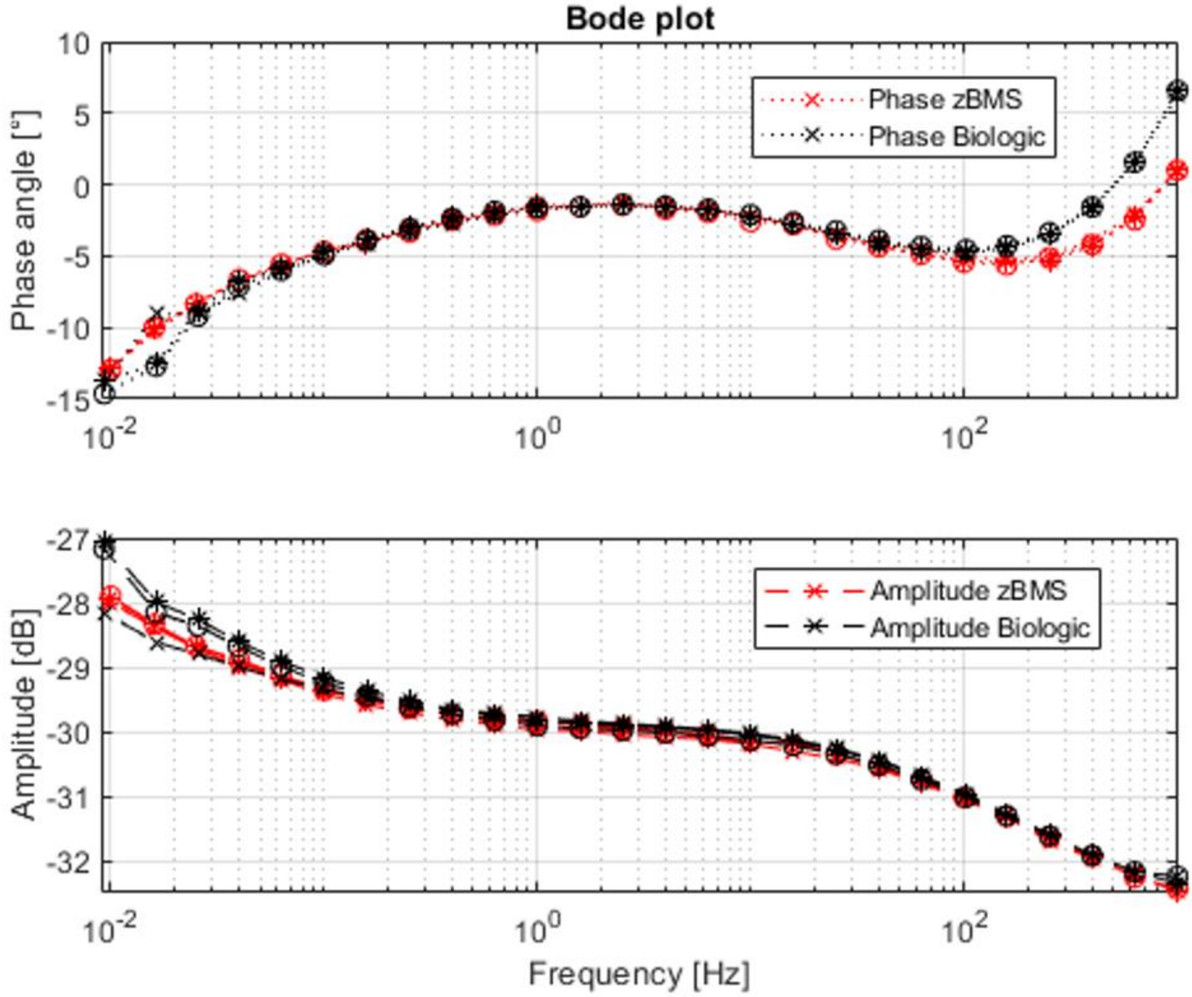

Figure 2: BMS n°1 EIS test result on cell 21700 (Bode plot) (red: BMS1, black: reference)

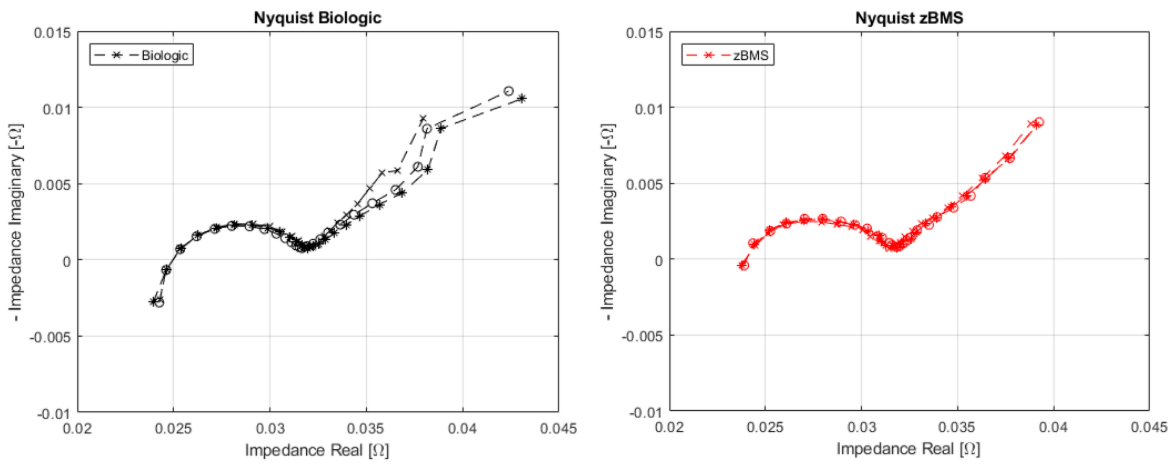

Figure 3: BMS 1 EIS test result on cell 21700 (Nyquist). Reference system (left), PHOENIX BMS (right)

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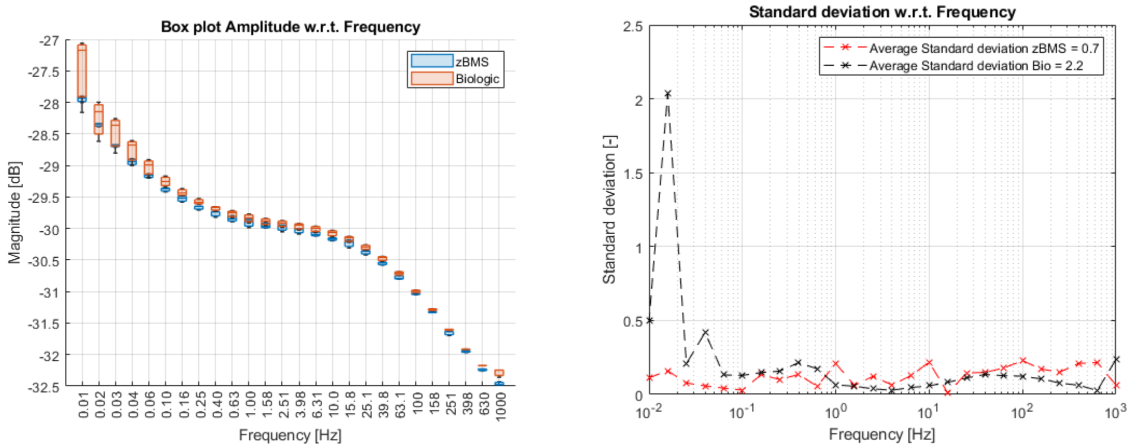

Figure 4: BMS n°1 EIS test result repeatability on cell 21700. Box plot (left), Standard deviation (right).

Table 4: EIS test results

Item	KPI	Result	Comment
BMS n°1 (cell: 21700)	Bode	The Bode is similar	High frequencies are discussed in Section 3.4
BMS n°1 (cell: 21700)	Nyquist	The Nyquist is similar	High frequencies are discussed in Section 3.4
BMS n°1 (cell: 21700)	Repeatability	Average standard deviation = 0.7	
BMS n°1 (cell: monolayer)	Bode	The Bode is similar	
BMS n°1 (cell: monolayer)	Nyquist	The Nyquist is unstable at lower frequencies	
BMS n°1 (cell: monolayer)	Repeatability	Average standard deviation = 1.4	

3.4 Analysis and conclusion

Tests on the cylindrical cell show that the EIS at low frequencies (i.e. below 200Hz) is equivalent to the reference equipment. The developed BMS is even more repeatable than the laboratory equipment. The reason for this is currently under investigation. At higher frequencies (i.e. above 200Hz) there is a deviation between the developed BMS and the reference equipment. This can be linked to the current generation and measurement part of the circuit that can have a slight impact on the measurement precision. More in detail, the precision choice for the measurement resistor (1%) and the parasitic capacitors of the MOSFET transistor have a bigger impact than expected on the measurement above 200Hz. This part is under analysis and will be corrected for the next version of the BMS.

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The tests on the pouch cell are highlighted in Figure 5 to Figure 7 and Table 4: EIS test results.

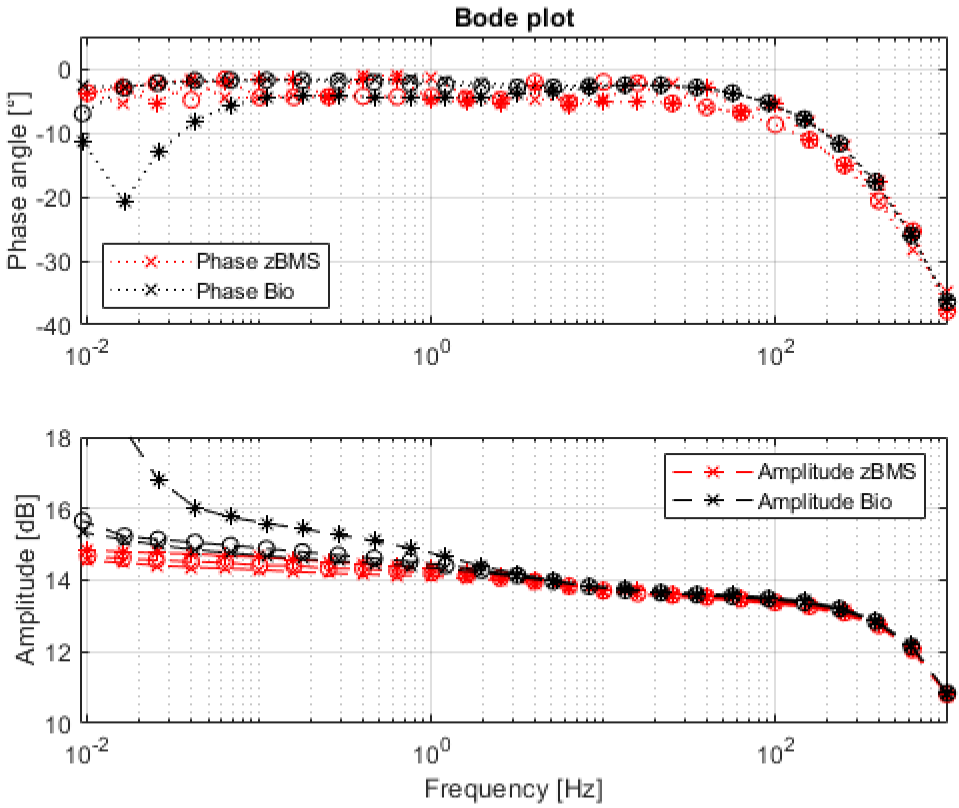

Figure 5: BMS n°1 EIS test result on pouch cell (Bode plot) (red:BMS1, black: reference)

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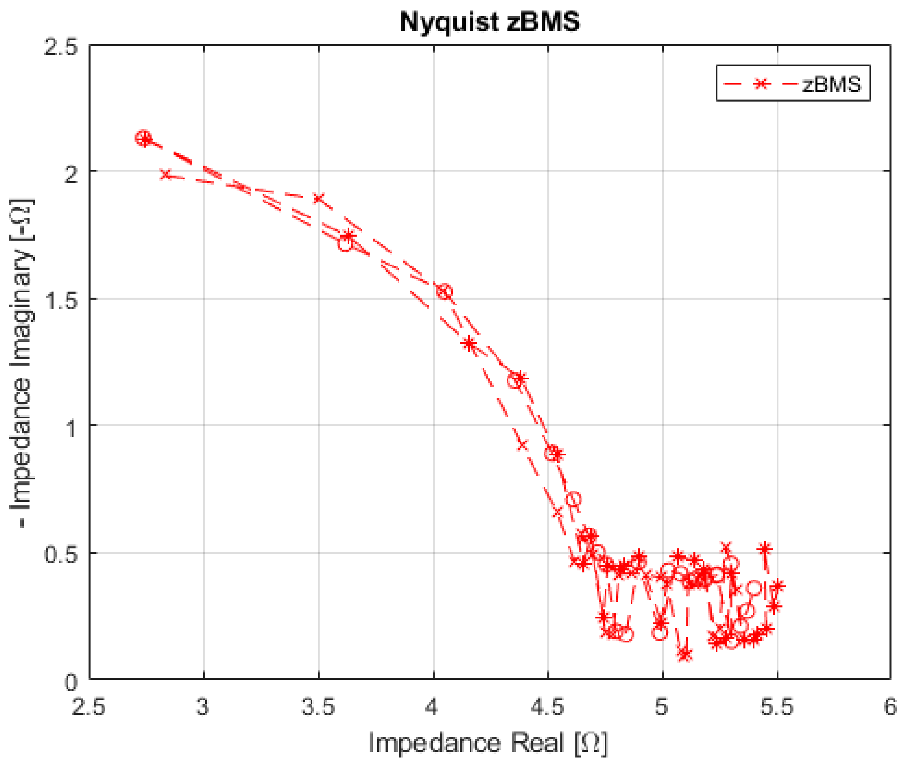

Figure 6 BMS 1 EIS test result on pouch cell (Nyquist) (red: BMS1)

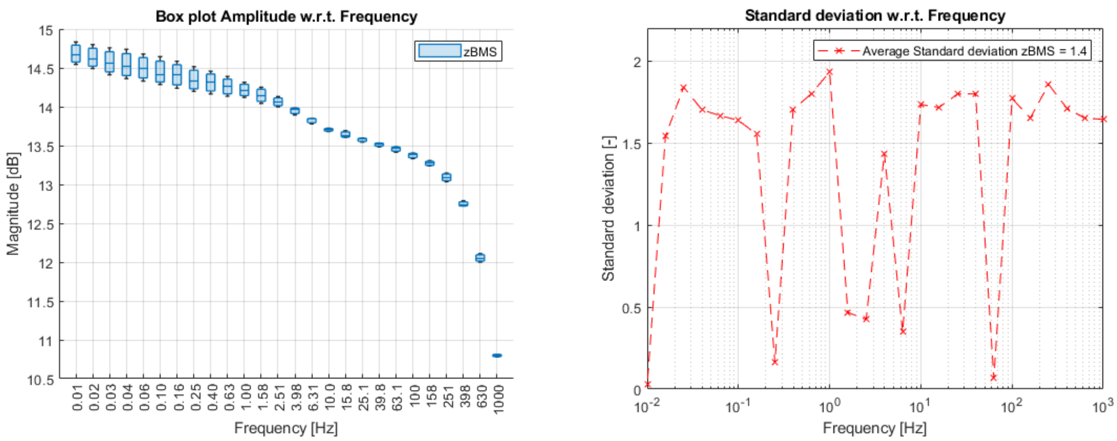

Figure 7 BMS n°1 EIS test result repeatability on pouch cell. Box plot (left), Standard deviation (right).

Contrary to the tests perform in the section above, the test on this cell have been performed on an uncontrolled voltage. In the previous section, prior to any EIS, the cell has been brought back to 3.6V and stabilized there. In this section, the EIS has been performed on the cell with a voltage between approximately 3.4V and 3.6V. This is due to a time constraint and is one of the reasons why the standard deviation is slightly higher as the voltage during the third EIS was significantly lower than during the first one.

Furthermore, due to current measurement uncertainties of the reference equipment, especially in the lower frequency range, the results have not been directly compared to the reference except for the bode plot.

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The EISs performed on the pouch cells are usable however their repeatability in the sub hertz frequency in the tests performed are not optimal. This creates especially noisy Nyquist plots as can be seen in Figure 6 BMS 1 EIS test result on pouch cell (Nyquist) (red: BMS1). This is due to uncontrolled voltages but also low input current (the pouch cell has been tested at an amplitude of 2.5 mA). This will be further investigated before the release of the 2nd version of the Phoenix BMS.

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4. Test 2: EIS on ref. electrode

4.1 Purpose of the test

The purpose of this test is to validate that EIS can be obtained with respect to the reference (RE) electrode. The target KPI for EIS is summarized in Table 3.

Table 5: EIS test KPI on RE

KPI	Threshold
The EIS must look like the one obtained using a reference equipment (frequency range: 10mHz – 1kHz) and be repeatable.	N/A
The EIS must be repeatable **(precision)**	Average standard deviation over frequency range <2 [dB]

4.2 Used hardware and software

The used hardware for these tests is summarized in Table 2. An illustration of the used pouch cell is provided in Figure 8.
For this test, the current is injected on the main tab of the pouch cell while the measurement is done between the negative and the reference electrode. Due to time constraints, this test has only been executed once with the BMS and three times with the reference equipment at uncontrolled voltage.
Note: with the current FW, the EIS computation (i.e. raw data to Nyquist) is done offline using a Python script. In future versions, the computation will be done in the BMS.

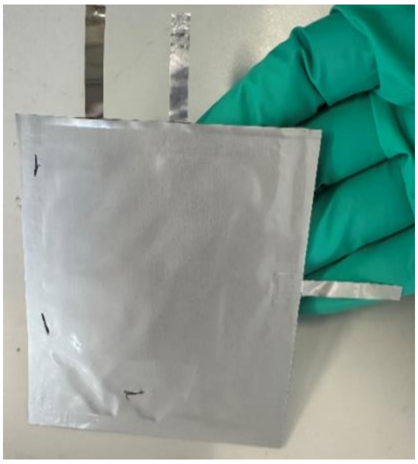

Figure 8: picture of the pouch cell with RE

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4.3 Test results

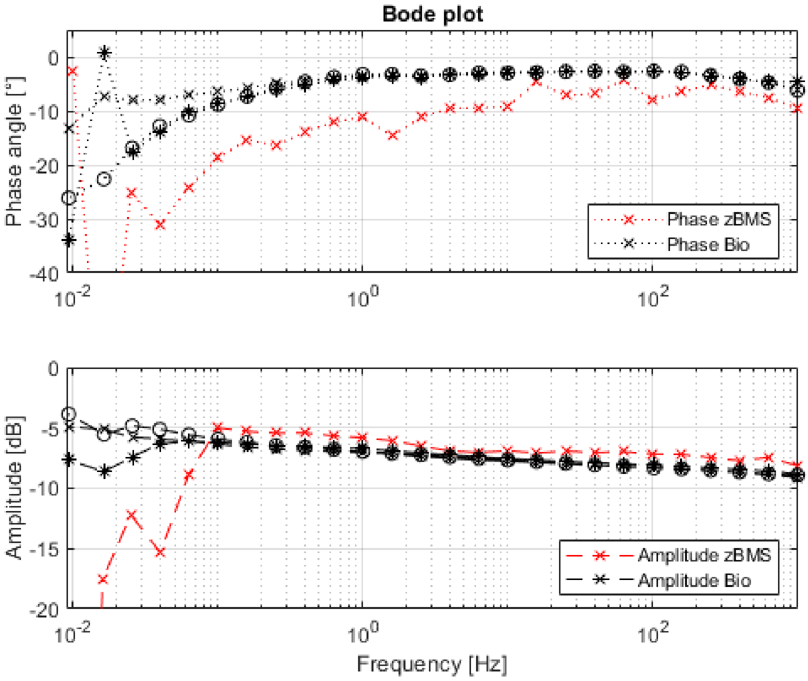

Figure 9 BMS n°1 EIS test result on reference electrode (Bode plot) (red: BMS1, black: reference)

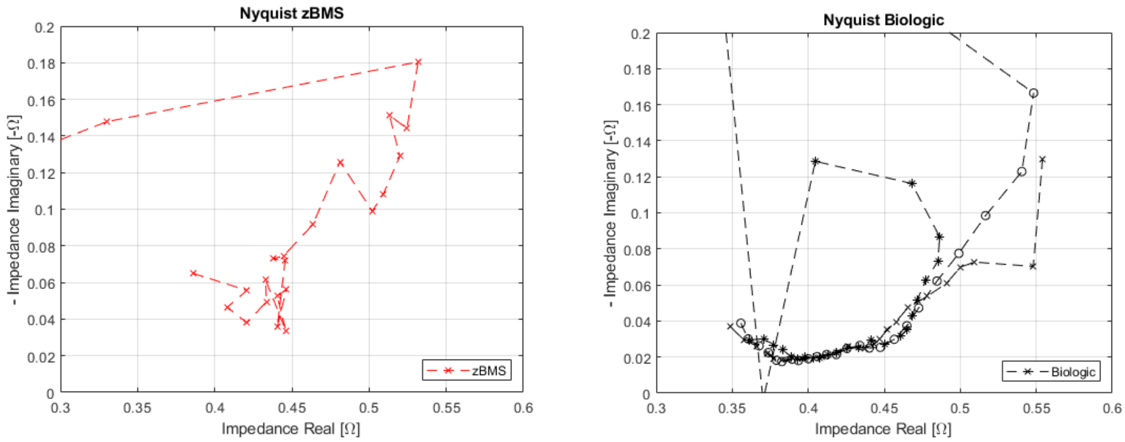

Figure 10 BMS 1 EIS test result on reference electrode (Nyquist) (red: BMS1, black: reference)

Table 6: RE EIS test results

Item	KPI	Result	Comment
BMS n°1 (cell: monolayer)	Bode	Similar	Above 100mHz
BMS n°1 (cell: monolayer)	Nyquist	Not similar	
BMS n°1 (cell: monolayer)	Repeatability	N/A	Only one measurement was performed

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4.4 Analysis and conclusion

The measurements on this setup are less good than the one performed on the 21700 and the pouch cell main tab. The measurements stay somewhat similar to the reference equipment above 100mHz but large outliner have been measured under this threshold. This greatly affected the readability of the Nyquist plot.
Furthermore, due to time constraints, only one measurement was done with the BMS hence no analysis on repeatability can be performed.
Further research and improvements will be performed on performing EIS on a reference electrode before delivering BMS V2.

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5. Test 3: BMS features

5.1 Purpose of the test

The objective of this test is to validate the BMS features that are listed in Table 7, in particular the voltage readings.

Table 7: BMS feature test KPI

KPI	Threshold
Time for over/under voltage reaction	< 1s
Voltage RMS	1mV

5.2 Used hardware and software

The material used for the BMS feature test is summarized in Table 2.

5.3 Test results

The test results are highlighted in Table 8 and Table 9.

The BMSs were tested at 3 set voltages: 2.5, 3.6 and 4.2. The BMSs were able to read those voltages with the following precision and accuracy:

Table 8: BMS voltage masurement results

BMS #	Set voltage	Measured voltage	Δ Voltage [mV]
B1	2.506 [V]	2.499 ± 0.000 [V]	7
B1	3.605 [V]	3.601 ± 0.000 [V]	4
B1	4.205 [V]	4.183 ± 0.000 [V]	22
B2	2.506 [V]	2.509 ± 0.001 [V]	3
B2	3.605 [V]	3.610 ± 0.001 [V]	5
B2	4.205 [V]	4.212 ± 0.001 [V]	7
B3	2.506 [V]	2.493 ± 0.005 [V]	13
B3	3.605 [V]	3.581 ± 0.000 [V]	24
B3	4.205 [V]	4.177 ± 0.001 [V]	28
B4	2.506 [V]	2.486 ± 0.000 [V]	20
B4	3.605 [V]	3.577 ± 0.001 [V]	28
B4	4.205 [V]	4.172 ± 0.001 [V]	33
B5	2.506 [V]	2.494 ± 0.001 [V]	12
B5	3.605 [V]	3.583 ± 0.002 [V]	22
B5	4.205 [V]	4.161 ± 0.001 [V]	44

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Table 9: BMS feature test results

Item	KPI	Result	Comment
BMS 1	RMS voltage precision	< 2mV	Expect B3 at 3.6 [V] which has a voltage precision of 5[mV]
BMS 1	RMS voltage accuracy	Above 99%	
BMS 1	Over/under voltage detection	Detected	

5.4 Analysis and conclusion

The BMS is able to consistently detect voltages with a precision under 2mV. However, it has a voltage dependent inaccuracy up to -44mV.
Both results do not fit the set KPIs.
Part of the problem come from the installed resistances that have too high tolerances, this will be fixed in the next iteration of the BMS.
The over/under voltage can be locally monitored accurately at the sub-hertz frequence.

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6. Test 4: system test

6.1 Purpose of the test

The objective of this test was to validate the whole system over a long duration. The goal was to connect the available sensors and self-healing actuators (see Section 6.3) and save the data. The test is conclusive if the KPIs of Table 10 are reached.

Table 10: system test KPI

KPI	Threshold
Data gap	Gap smaller than 5 points (**sampled at a minute basis**)
Data availability	90% of data available daily

6.2 Methodology

This test has been performed in two parts, 4a and 4b.
In test 4a, 5 zBMS and one raspberry pi pico are connected to the data aggregator with data pushed **every 10 seconds** (for the final application a 1-minute rate is used). This variation of the test with higher frequency than required has the goal to stress test the system. The zBMSs sends measured (temperature, sensors from Fraunhofer…) and simulated values (repeated ramps). This test focuses on the reliability of the reception of the data more than the data itself. This test has been performed for a period of over 7 days.
Test 4b repeats conditions of test 4a but the subsystem send message every minute as requested for the PHOENIX application.

6.3 Used hardware and software

The hardware listed in Table 2 is in use. Its interconnections can be seen in Figure 12.

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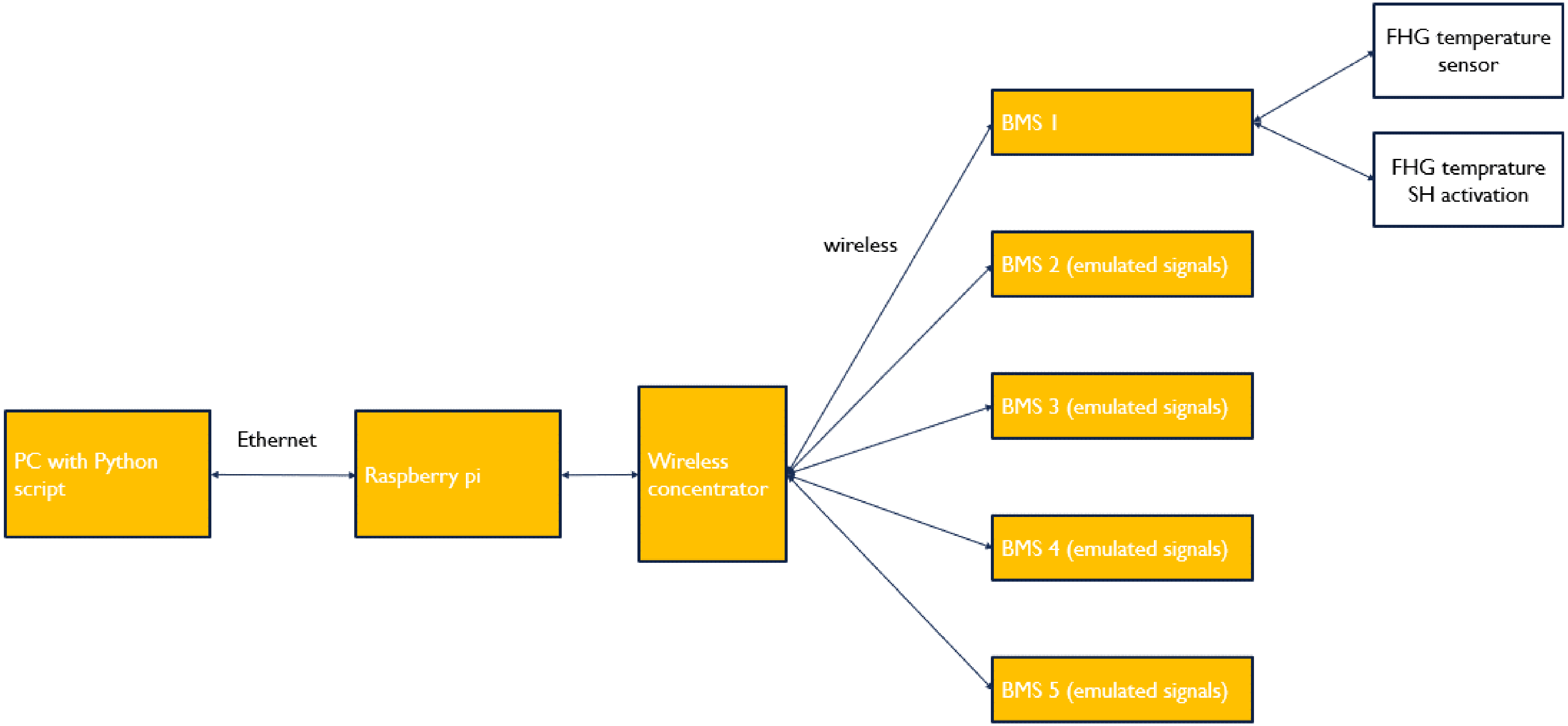

Figure 11: high level layout

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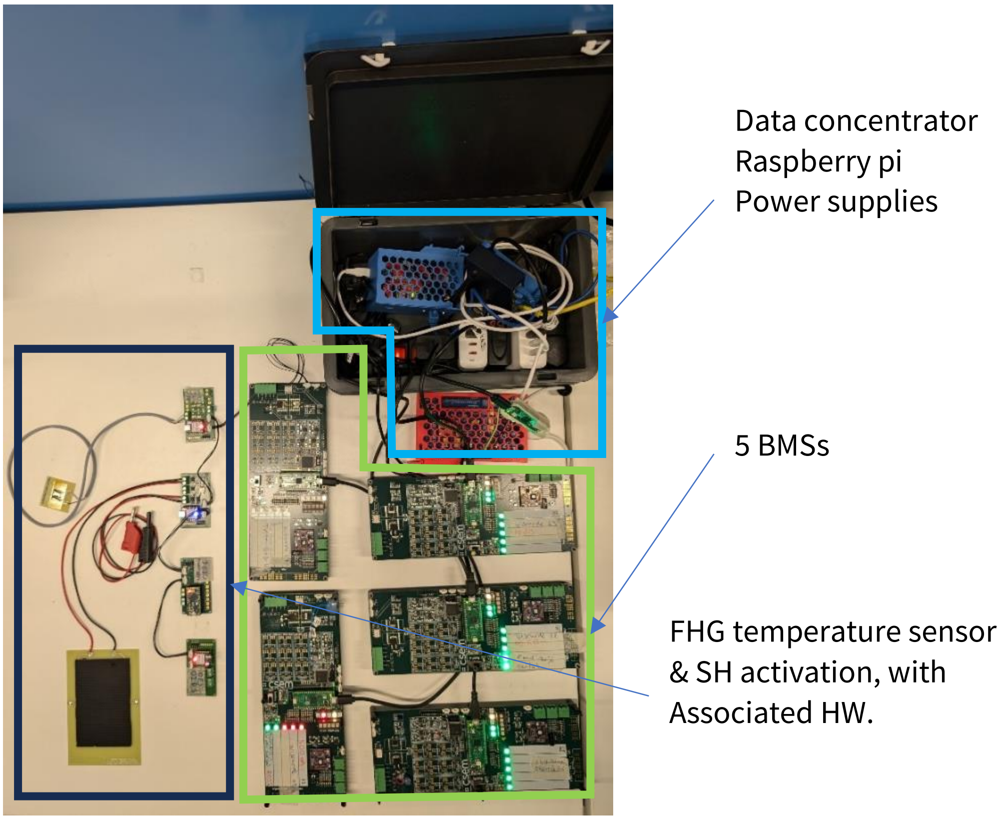

Figure 12: hardware layout overview for system test

Note: on BMS2 to BMS5:

1. the following sensors/actuators were emulated:
   - BMS Temperature
   - BMS Voltage
   - Dielectric Elastomer Sensor
   - NTC Sensor
   - Ultrasonic sensor

2. While the following values were created: BMS Status

3. And the following was measured: Pico temperature sensor[4]

These values were be emulated to transmit as many messages as possible in order to stress the communication subsystem.

[4] Temperature measured by the BMS via a temperature sensor embedded on the embedded electronics

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6.4 Test results

6.4.1 Test 4a: Messages sent at 10 seconds interval

The results for the stress test at 10 second interval are highlighted in Figure 13 to Figure 16.

Figure 13: One hour window of all the messages received from all cards displays an example of the messages received from multiple cards simultaneously over the span of one hour.

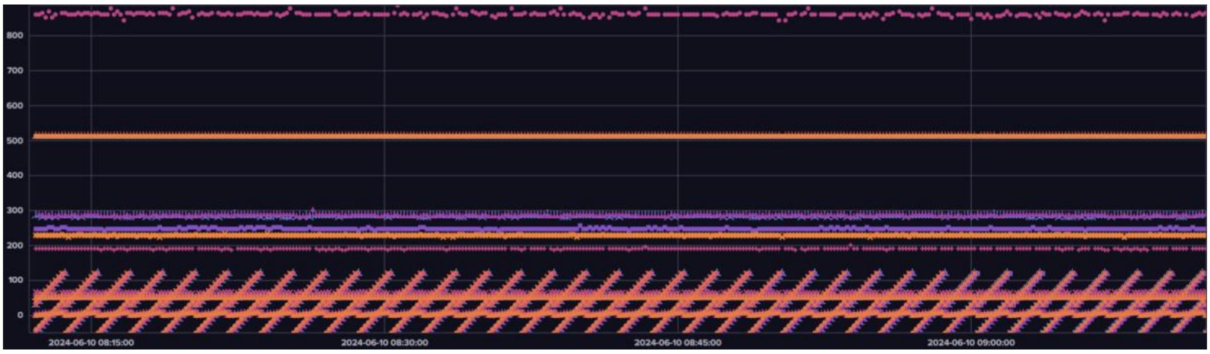

Figure 13: One hour window of all the messages received from all cards

Figure 14: Reception of 100% messages displays an example where 100% of a specific signal from one card is received every 10 seconds.

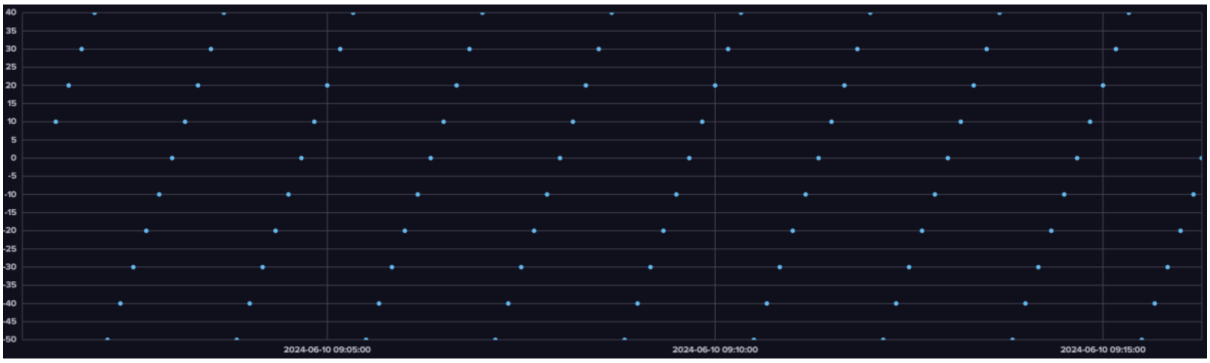

Figure 14: Reception of 100% messages

Figure 15: Reception of approx. 90% messages displays and example where the same specific signal from another card is not received at a 100% during the same time period. The issue has been identified and linked to software issues in the python code. However, the new version has not yet been tested.

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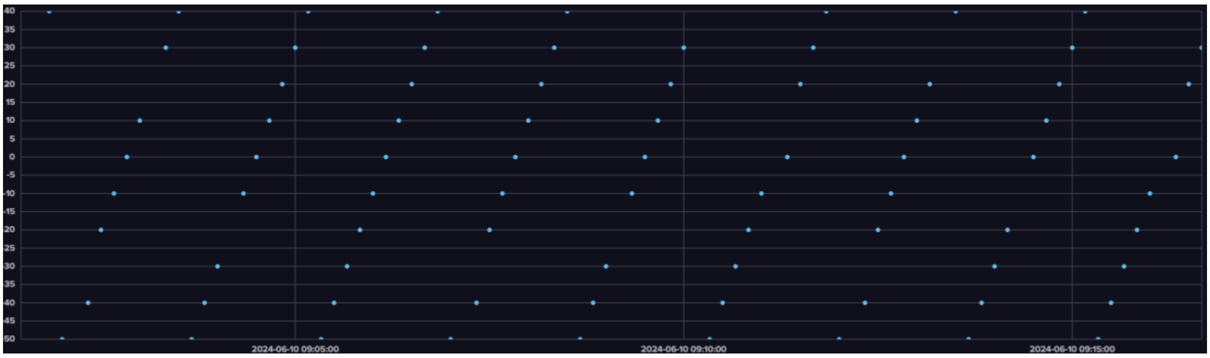

Figure 15: Reception of approx. 90% messages

Figure 16: 5 Days period for one BMS displays the real and simulated messages received for one BMS over a 5 days period. As it can be observed, no gap or outliners are present.

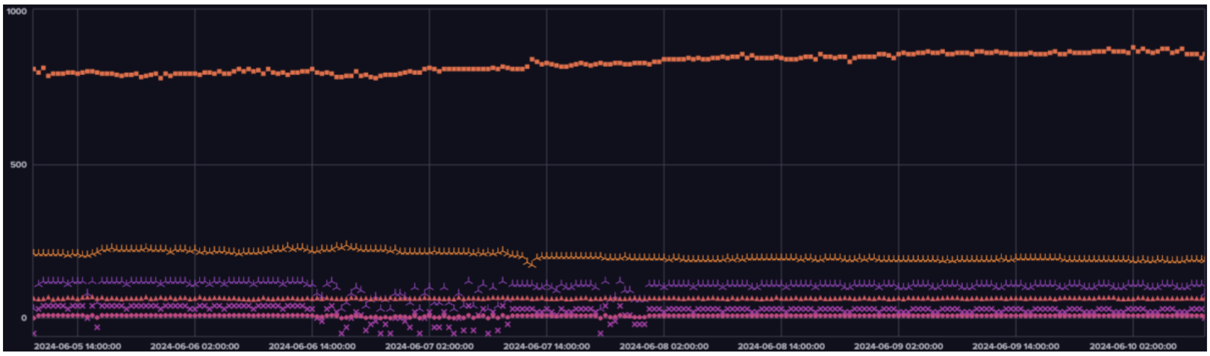

Figure 16: 5 Days period for one BMS

6.4.2 Test 4b: Messages sent at 60 seconds interval

At 60 seconds intervals, all the messages are received successfully without gaps.

Figure 17: 10h period for one BMS with one set of messages per minutedisplays the messages (mostly simulated) received by one BMS during the span of 10h.

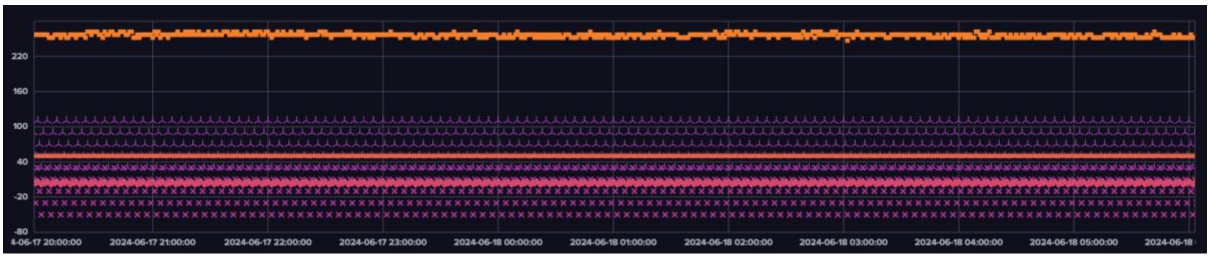

Figure 17: 10h period for one BMS with one set of messages per minute

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6.4.3 Results of Test 4a (10 seconds interval) and 4b (60 seconds interval)

Table 11: BMS data reading test results

Item	KPI	Result	Comment
BMS 1-5 (test 4a)	Data gap (at 10 second sampling)	At most 1 value missed	
BMS 1-5 (test 4a)	Data quantity (at 10 second sampling)	Above 90%	Linked to a problem with the python software
BMS 1-5 (test 4b)	Data gap (at 1 minute sampling)	At most 1 value delayed for a few seconds	
BMS 1-5 (test 4b)	Data quantity (at 1 minute sampling)	Above 99%	

6.5 Analysis and conclusion

The test 4a (i.e. communication stress test with 10 second intervals instead of 1 minute as requested) has been running continuously for more than a week reliably. Not data gap has been witnessed. Sporadically, for period of few minutes as depicted in Figure 15: Reception of approx. 90% messages, approximately 10% of messages are lost. This is linked to an issue with the python code on how the messages are sent to the external database. The database has been primarily used for debug and won't be implemented in the final code, removing the risk of lost messages. Test 4b (i.e. with the requested 1-minute interval) has been run for over 24 hours with no data gap witnessed. The quantity of messages received was expected. Test 4b has been running over a shorter period of time due to time limitations.

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7. Test 5: BMS SH activation

7.1 Purpose of the test

The objective of this test is to ensure that self-healing activations can be reliably triggered over a long duration. The goal of the test is to trigger SH (heating provided by FGH) and sense it using the NTC sensor (also provided by FHG). The KPI of Table 12 is used for validation.

Table 12: system SH activation test KPI

KPI	Threshold
SH gets activated as expected.	The actuator can be reliably activated and de-activated with a reaction time under 1 minute.

7.2 Used hardware and software

For the test the material listed in Table 2 is used, an illustration is provided in Figure 18.

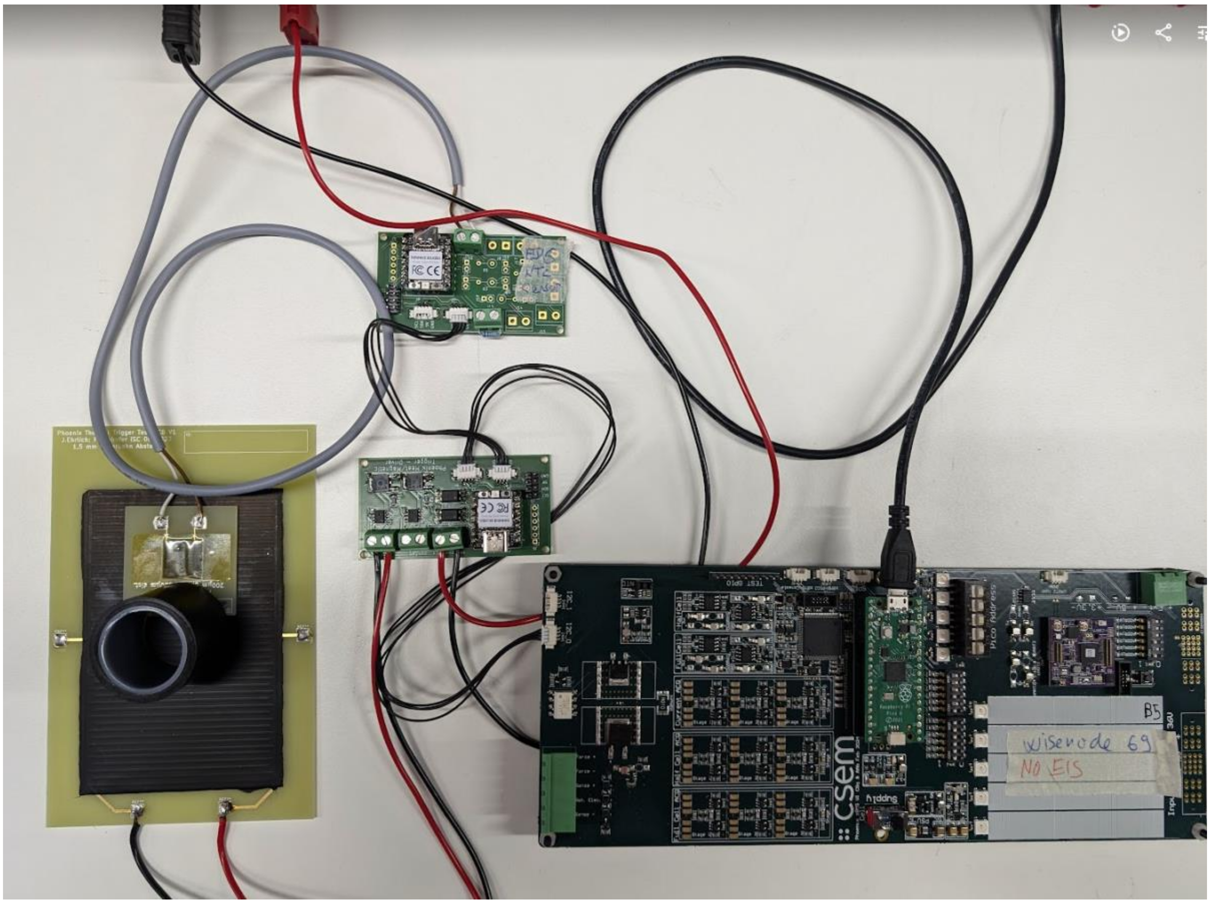

Figure 18: hardware layout for the SH test

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7.3 Test results

The following parameters have been used for the results displayed in Figure 19 Output of FG NTC sensor thermally linked to the thermal triggering, activation of 150 seconds (2min30) every 300 seconds (5 minutes).

The values displayed on the y-axis of Figure 19 Output of FG NTC sensor thermally linked to the thermal triggering is the value read from the FG NTC sensor, lower values represent higher temperature.
The variation of temperature was cross checked with an infrared thermal gun and correlated accordingly to the reading of the NTC sensor.
The state of the activation of the actuator (meaning the acknowledgement from the SH actuator to the BMS) was unfortunately not monitored during this test.

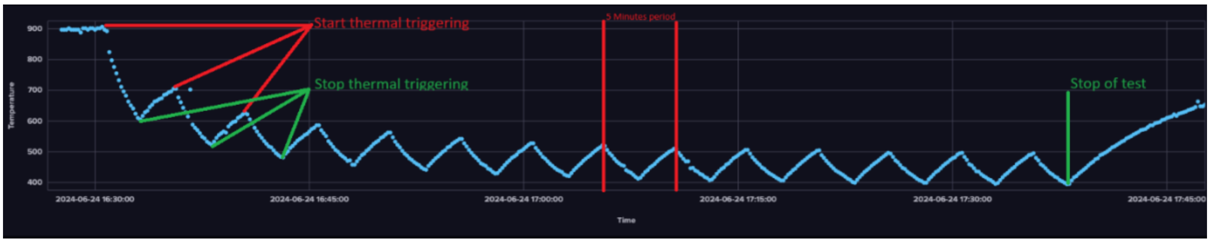

Figure 19 Output of FG NTC sensor thermally linked to the thermal triggering full test

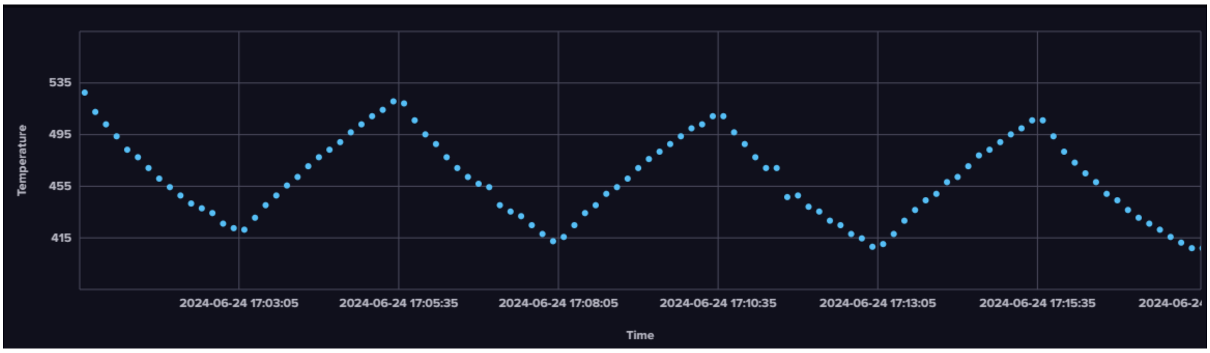

Figure 20 Output of FG NTC sensor thermally linked to the thermal triggering zoomed in

7.4 Analysis and conclusion

The system can successfully activate actuators at given interval and parallelly the external temperature sensor can reliably monitor temperature.

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8. Conclusions

This document tested the key features of the PHOENIX BMS v1. The following results were obtained:

- Test 1: EIS: the EIS performs as expected, some improvements at higher frequencies are to be done. This is foreseen in the BMS V2
- Test 2: reference electrode EIS: The EIS performs in a satisfactory manner above 100mHz. Results are overall less good than in test 1. Improvement are foreseen for BMS V2.
- Test 3: BMS features: the BMS detects over/under voltages as expected. The voltage measurement accuracy needs to be improved. This is included in the BMS V2
- Test 4: system test: the communication with several BMSs is stable, even under higher communication rate that required.
- Test 5: self healing activation: the test performed on the thermal heating activation was conclusive.

In summary, the BMS V1 can be used, the identified limitations will be corrected for the BMS V2.

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ANNEX (not applicable)

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