# Final report

## 1.1 Project details

| | |
|---|---|
| **Project title** | 12518-Grid Connected Flow Batteries |
| **Project identification (program abbrev. and file)** | GCFB |
| **Name of the programme which has funded the project** | EUDP17-1 |
| **Project managing company/institution (name and address)** | Eniig Holding A/S (Eniig Forsyning A/S)<br><br>Tietgensvej 4<br><br>8600 Silkeborg |
| **Project partners** | VisBlue A/S<br><br>Aarhus University |
| **CVR** (central business register) | 39072793 |
| **Date for submission** | September 6th 2016 |

# Indhold

## 1.2 Short description of project objective and results

### *1.2.1 Danish*

Formålet med Grid Connected Flow Batteries (GCFB) projektet var at undersøge mulighederne for at installere et redox flowbatteri i det offentlig elnet til at rebalancere spændings-frekvensubalancer forårsaget af ubalancer i belastningen på elnettets tre faser.
Projektets første fase gik ud på at definere systemkrav baseret på analyser af et typisk elnet med synlige ubalancer. Herefter startede systemudviklingen, hvor en egnet testlokation i Eniigs (nu Norlys) forsyningsområde blev valgt.
I projektet blev forskellige analyser af elnetkarakteristika og typiske elforbrugskomponenter ved en række elforbrugere udført. Undervejs blev batteriet udviklet og bygget, herunder inklusiv de specielle komponenter og batteristyring, der skulle til for at styre batteriet individuelt på elnettets tre faser.
Efterhånden viste det sig, at den planlagte installation på testlokationen ikke var mulig, fordi batteriets invertere ikke nåede at blive godkendt til brug på det danske elnet i tide. Derfor blev batteriet testet på VisBlues testlaboratorie med en forbindelse til det offentlige elnet. Testresultatet viste sig at være tilfredsstillende, da batteriet beviste, at det kan individuelt udkompensere en del af den ubalance, der blev simuleret på de tre faser.
I et opstillet scenarie, hvor en opgradering af elnettet vha. kabler og transformerstationer eller en installation af et batteri i elnettet sammenlignes økonomisk, blev det i projektet også bevist, at batteriløsningen er konkurrencedygtig, samt har den fordel, at den er fleksibel mht. muligheder indenfor effekt, placering og styring.

### *1.2.2 English*

The objective for the Grid Connected Flow Batteries (GCFB) project has been to investigate the possibility of installing a redox flow battery in the public grid to rebalance voltage and frequency imbalances caused by unbalanced load on the grid's three phases.
In the initial phase of the project, the system was defined based on analyses of a typical scenario with an unbalanced grid. Subsequently, development of the system started, and a suitable test site in Eniig's (now Norlys) distribution area was selected.
During the project, analyses of grid characteristics and load types of various consumer electrical appliances were completed at the selected test site. Underway, the battery system was developed and built, including its special components and battery control, which enabled individual control of the battery on each of the grid's three phases.
Gradually, it came to light that installation at the test site was not possible, because the battery inverters were not approved for use on the Danish grid. Instead, the battery was tested at VisBlue's test facility with a connection to the public grid. The test results were good, as the battery proved its ability to compensate imbalances caused by simulated unbalanced loads on the grid's three phases.
In the project it was proved in a scenario, where an upgrade of the grid via cables and transformer stations or an installation of a battery solution in the grid are compared in regards to economic feasibility, the battery solution is competitive and has the advantage of flexibility within possibilities of power output, placement, and control.

## 1.3 Executive summary

The project has ended based on laboratory tests at VisBlue's facilities. As a proof of concept, the results are promising in the sense that it was proven that the battery could be controlled independently on each of the three phases. Additionally, the battery was capable of automatically reacting to voltage changes and the compensation of these changes. Since the test was performed in a laboratory (VisBlue's test facilities) during a shorter period of time, further tests in the field with genuine imbalances must be completed, in order to tune the battery control. The results, however, prove a potential to utilise this configuration of the flow battery, as it can be configured and altered to fit the requirements of the particular site with an unbalanced grid. Another advantage of the flow battery is the fact that you can scale power output and capacity independently. Project results show that this characteristic is useful, when you have different objectives to solve in the grid, e.g. transformer overload, voltage fluctuations, or cable overload in the low voltage grid close to the consumer. Moreover, the flow battery can easily be moved to another site, which in comparison to upgrading cables and transformer stations provides a more flexible solution.

## 1.4 Project objectives

The project has evolved as planned, according to the project plan, and there has been a rewarding cooperation between the project participants. One of the risks in the project proved to be the battery inverter used in VisBlue's battery system. The inverter is a key component, as it must support the required functionalities in order to fulfil the individual grid phase compensation. Additionally, the inverter must be approved for installation on the Danish public distribution grid. The first requirement was obtained during the process of the final tests, but the last requirement was not obtained until after the project's end.

## 1.5 Project results and dissemination of results

Throughout the project, the main activities have been to characterise an unbalanced grid, in-order to set up requirements and, subsequently, design and produce a redox flow battery that can solve/compensate the imbalances that are experienced in today's grid. These main activity steps are part of the original scope of the project, which is reflected in work packages and deliverables that have been completed as planned during the project.

### *1.5.1 The Danish grid[1]*

Historically, the electricity system have been dimensioned according to the supply to the local area. In step with the expansion of wind power, cogeneration and exchange between areas, the dimensioning takes place taking into account the requirements that this demands. With the current structure of the electricity system, the transmission network, international connections and the central facilities have a significant task of distributing and regulating the effect in the overall electricity system.

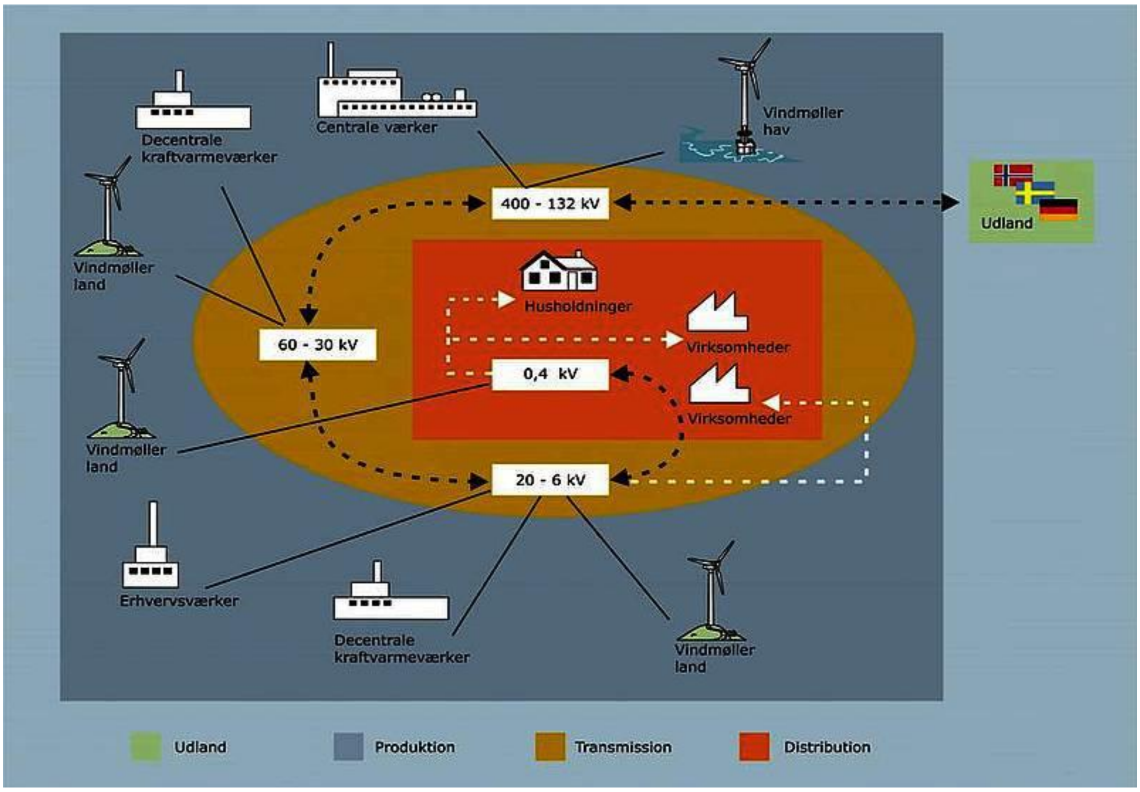



*Figure 1 the Danish grid*

### *1.5.2 Analysis of the low-woltage grid.*

In the report "Flowbatterier i distributionsnettet" by Dansk Energi (DE), the impact of batteries installed in the grid has been simulated and evaluated. Different installation locations of the battery have been simulated with two different goals: i) to prevent the selling of photovoltaic (PV) energy to the grid and ii) to assist the existing 10 kV/0.4 kV transformer stations

[1] Source Experimentarium's website

during peak load situations. In both scenarios, the simulations show that batteries can help and alleviate possible complications in the grid. However, it is important to first define the purpose of the battery and then to install it, according to the purpose, in the right location in the grid.
Conclusions from this report are in short:
**No need for flow batteries now, but there will be in the year 2040.**

Given the current load and output, the current low voltage network is sufficient to supply the studied area. The most loaded component, the 10 / 0.4 kV transformer, is charged with 97% of its rated power for 1 hour of the year (17:00 Christmas Eve).
But with a projection to the year 2040, where both load and own production have increased, we see that there will be more hours where the transformer is overloaded. Furthermore, an aggressive roll-out of electric cars that are not controlled intelligently will aggravate the situation, so that both the transformer and certain cables will be damaged by the overload if nothing is done.
One (or more) flow battery (ies) could be used to prevent this overload. The rated power of the battery sets the ceiling for how much a reduction in overload the battery can deliver. In the worst case scenarios, a battery of at least 120 kW is required to avert overload.

#### 1.5.2.1 The location of the batteries is of great importance

Simulations of the low-voltage network show that the location of the batteries has a significant effect on voltage and component load. If the battery is placed at the mains station, only the transformer and the medium voltage grid will be relieved; the voltage and load of other components in the low voltage network remain almost unchanged. If, on the other hand, the battery capacity is split up and placed around the low-voltage grid, it will change the power flow so that the voltage profile is improved and the component load is lowered.

If the purpose of the battery is to stabilise the voltage in the grid, decentral batteries will have a larger impact within the grid compared with central batteries. A decentral battery will be able to compensate the power flow in the cables and, hereby, reduce voltage fluctuations. To exemplify, these situations could occur when PV panels produce a large amount of energy during the day-time, where a lot of power is injected into the grid with the result of the grid voltage increasing. An opposite situation could occur when electrical vehicles charge during the night, where a large amount of power is drawn from the grid and the grid voltage drops. Here, the battery can help in two ways: i) if the drawn/injected power is well-balanced over the three grid phases and the battery can absorb the PV energy by charging during the day, or ii) if the drawn/injected power is not well-balanced over the three grid phases, where the battery can both absorb and inject energy at the same time by charging on one phase and discharging on another phase(s).

If the goal is to assist the transformer stations in peak load situations, the battery should be larger and placed in a central location, close to the transformer station and the middle voltage distribution grid. This centrally located battery will be easier to control and maintain.

In relation to their total capacity, medium-sized "radial batteries" located in weak points in low-voltage radials support the network more efficiently than both large batteries at the mains station and small batteries distributed in households.

#### 1.5.2.2 Household batteries can postpone own production until later

The optimal battery size depends on whether you are looking at household batteries that are used to shift the household's own production to later, or batteries that are used to even out peaks in the load. An analysis of existing households with own production shows that a battery of 10 kWh will fulfill 50% of the theoretical potential to increase the degree of own consumption, and that a battery of 30 kWh will fulfill 95% of this potential.

### 1.5.2.3 Batteries in mains stations can reduce the peak load

In our analyzes, we see the potential for using station batteries, as they show that most substations can reduce their peak load by 15% with a battery that has only energy stored for one hour of delivery. Furthermore, the analyzes show that the battery's impact on the grid is limited by its rated power and not by the size of the energy store. Last but not least, larger energy stores, eg with energy for 1.3 hours of the station's peak load, can be used to lower the peak load by 35 - 45% in most cases.

### *1.5.3 The testsite*

As a part of the project, investigations to find a suitable site with issues of imbalance was completed, and a suitable site was found in a city in Jutland. The grid in this city was facing imbalance issues due to the closing of the district heating plant and a rise of heat pumps in the city’s grid. A large amount of the citizens has bought heat pumps and, in general, the energy that was previously bought from the district heating plant is now bought from the local electricity company. The additional disturbances of PV panels and electrical vehicles made the site optimal for the project to install the battery and perform real life tests.
In figure 1 is show the existing and new grid.

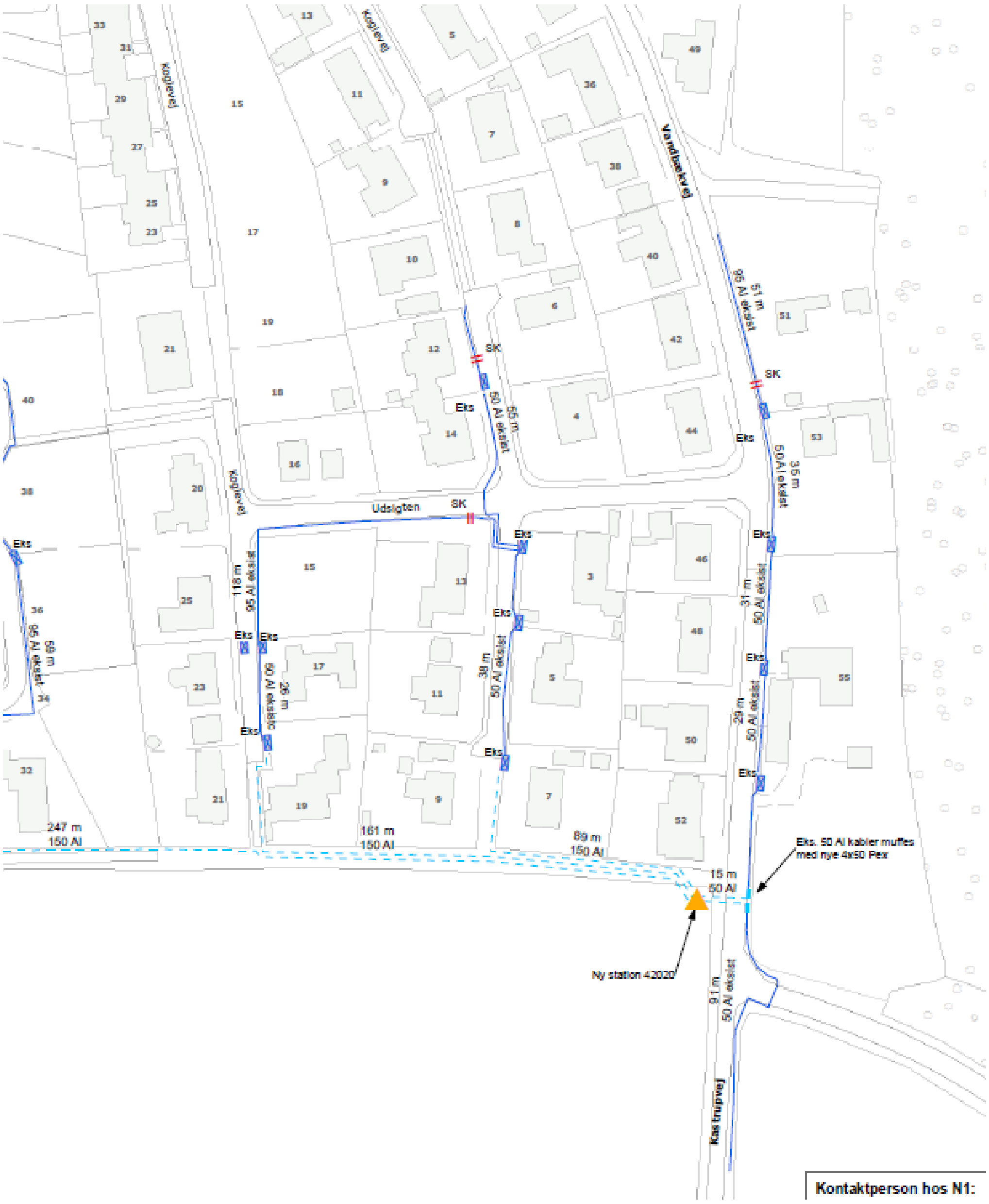



*Figure 2 Blue lines are the original grid, doddet lines are the added grid with a new transformer due til Heat-pumps*

### 1.5.4 *Business Models*

This section describes some different potential business cases for a flow-battery in the distribution grid.

Through discussions with several network companies in Denmark and simple abroad, VisBlue has concluded that the following challenges, such as a battery in the distribution network, can remedy the network companies with:

- Extend the life of the installed transformer station so that it is not necessary to install a larger one due to the possibility of
    - distribute the load between the phases
    - Avoid overloading the station.
- Possibility to scale / upgrade according to the need at the station.

Based on the above challenges, there are four different business cases

- A stationary battery
- A mobile battery
- Rental of a battery
- Battery for charging electric cars in holiday home areas

**A stationary battery:** A flow battery cost the same as a new transformer station (approx. DKK 300,000 for a 5kW @ 40kWh battery), therefore it will only be a long-term solution to replace a transformer station with a battery, if it is very expensive to establish a new transformation due to the location. This can be, if the area is very far out, so a lot of kilometers of cable have to be dug down. Another parameter that is also included in the business case is the life of the battery and transformer station, respectively. The life of a battery is 20-25 years, where for a transformer station it is 50-60 years. This ratio is also not to the advantage of the battery, as the simple business case for the battery is more than twice as expensive as for ordinary reinforcements, incl. transformer station.

**A mobile battery:** If an area is suddenly overloaded due to a large number of new photovoltaic systems being installed within a short period of time, or many electric cars being purchased in the same area, such changes can create a sudden congestion, both as a result of increasing consumption and production. By installing a temporary (mobile) battery, the installation of new cables or a transformation can be postponed to a later date.

Below is a comparison between the two solutions

| **Battery**<br>**Over 15,000 cycles** | **Cost [DKK]** | **Features** |
|---|---|---|
| **A stationary battery**<br>**(5kW @ 40kWh)** | 300,000 | - Remote monitoring<br>- Outdoor cabinet<br>- ModBus interface for controlling the battery remotely<br>- 48Vdc<br>- 400Vac as add on<br>- Module built |
| **A mobile battery**<br>**(40kW @ 200kWh)** | 1,800,000 | as above plus<br>- AC installed<br>- 20 'container<br>- 400Vac |

The depreciation time of a battery is very dependent on the application in which the battery is used. If the battery is used in an application where the purpose is to utilize the current that will otherwise be injected into the network, the depreciation time can be calculated quite accurately. If the battery is used in a service function for the network company, one should look at the depreciation period for the network is made better by installing the battery.

The business case summarizes the ROI when it will be cheaper to invest in a battery solution rather than strengthening the electricity grid.

**Renting a battery:** The above example of a mobile battery can also be conceived as a business case, so a DSO rent a battery for a period of time. However, it will probably increase the cost of the businesscase overall, as there will be a fee for renting a battery.

**Battery for charging electric cars in areas with summerhouses**: When a private person buys an electric car, they have control of how to get their new car charged, but what happens when they go out in their summerhouse. Or what about the tourists who come to a cottage area. How should they get their electric car charged?
Here, there could be a business opportunity in having a larger battery installed, which could be charged by green power during the day and then discharged at night. By installing a battery for this task, it will not load the normal distribution network, which during this period is quite loaded.

As the above brief review shows, there are many opportunities to use flow batteries in the grid, which is "simply" needed partly for further market maturation and partly for prices to fall. Since with a very simple price calculation it is well twice as expensive to establish batteries rather than mains expansions.

### *1.5.5 The BusinessCase*

This project is looking at the possibility of installing a battery on the low voltage side of the network ie. on the 0.4 kV side
The network companies have a delivery obligation to the customers, ie they must supply electricity within certain quality requirements, e.g. 230 v +/-10%. The test site shows an example where two cities have decided to shut down their private CHP plants and get electric individual heat pumps.
To ensure security of supply, the local DSO chose to upgrade the network. As heat pumps at each consumer increase the electricity consumption in the electricity grid, compared to a locally located CHP plant, the local distribution company foresaw challenges with the local electricity grid, and thus challenges in maintaining the required voltage level at all times. As the consumption increases locally, the voltage will decrease, and thus there would be a risk that the voltage could not be kept above 207 V (230 V -10%).
The DSO has calculated the cost of the expansion of the electricity grid. The price of this expansion can be very difficult to compare from one locality to another, as there can be very different physical situations. In this situation, the electricity grid was expanded with a new transformer and a new division of the electricity grid.
There may be several ways to ensure security of supply. One way could be to strengthen the existing grid, which is what is common practice today, but in the example from the testcase, they chose to establish a new transformer and change the interfaces.

- In the testcase, the costs for the DSO to ensure security of supply in the future are DKK 570,000 (Capex cost), which is distributed with DKK 370,000 for transformers and DKK 200,000 for cables and cabling.
- The depreciation period is typically 40 years for electrical equipment.
- This means an annual cost of DKK 14,250
- There will be very limited maintenance costs (Opex Cost).

- By installing a battery, the cost is DKK 300,000 (Capex Cost).
- The depreciation period / lifetime of the battery is set to 10 years.
- This means an annual cost of DKK 30,000
- 3 times more must be reinvested to achieve the same effect / service life as traditional cable reinforcement.

The assumptions for the calculation are a 5 kW / 40 kWh flow battery (it can be discussed whether it is large enough to have an effect in the chosen grid). Costs for changing topologies vary greatly from place to place, so in each case it should be assessed whether the battery can be justified. Especially since the battery can also have other functions than voltage regulation.

### *1.5.6 Workshop*

It was the expectation of the project to test the designed battery at the city in Jutland. This goal was not succeeded due to the lack of approval of the battery inverter for the Danish grid. Therefore, the tests of the designed battery were executed in a simulated setup that matched that of the city in Jutland, where the battery design concept was proven to work. The battery inverters were approved for operation on the Danish grid close to the project's end.

In May 2020 experiments were performed in the workshop of Visblue, to test the performance of a new control algorithm. The control algorithm had the goal of reducing differences between phase RMS voltage, and thus contributing to phase balancing.
The tests were performed in a workshop environment located in a small industrial park, using the public AC grid. The test was with 3 similar 10kWdcpeak VRFB systems BAT1, BAT2 & BAT3. DCAC inverters installed in all 3 systems is 3x5kVA Victron Multiplus II giving each system an AC power capacity of 10kWacpeak.

The test results show that the modulating active power on each phase of a 3-phase battery can have a positive impact in reducing RMS phase magnitude unbalance.

During May 2020 four tests were performed with the goal of the testing a new control algorithm to reduce the phase RMS voltage unbalance. The primary metric to quantify voltage unbalance was the PVUR (Phase Voltage Unbalance Ratio), which is a measure of the maximum phase voltage deviation from the mean of the three phases.
Two tests were performed to characterize the voltage of the public network and to calculate the observed Thevenin equivalent impedance. The measurements from the tests showed that there was a rather high variance in voltage, and consequently, the calculated Thevenin impedance. However, the impedance is high enough so that the battery creates measurable changes to RMS voltage when charging and discharging.
The next test was a series of unbalance scenarios, where two batteries created a voltage unbalance, while one battery was running the new control algorithm. The series of tests showed promising results, and a fall in PVUR could be seen, not only on the bus of the battery running the control algorithm, but also in some cases also on the bus of the battery creating the unbalance.

### *1.5.7 Experimental Set-Up*

A control algorithm has been developed by Visblue, to modulate active power of a VFB to contribute to improving voltage imbalance [1]. The algorithm uses measurements of RMS voltage at the battery's terminals as input to a PI controller. The response of the controller to a voltage level below a refence value will be to increase delivery of active power (or reduce consumption); if voltage is above the reference, the controller will increase power consumption (or reduce production).
The performance of this control algorithm was tested in a workshop setting [2]. The tests were conducted in a semi-controlled environment, in the sense that the battery loads were controlled for the tests, but the public low voltage AC mains power supply was shared with others network users, and therefore subject to unpredictable disturbances. 5

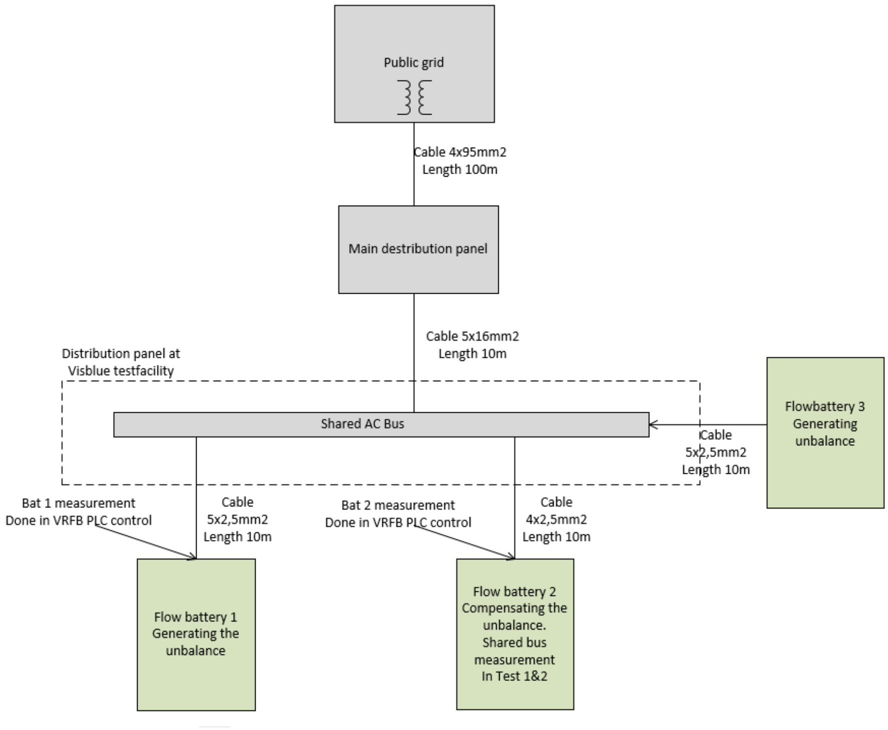



*Figure 3 Schematic diagram of test setup*

In this analysis, voltage unbalance will be quantified using the "Phase Voltage Unbalance Rate" (PVUR). PVUR is calculated by finding the maximum deviation of one phase from the average RMS voltage [3]:
$PVUR = \max\left((Ui - \bar{U})/\bar{U}\right) \times 100\ \%$

Where *Ui* is the RMS phase voltage for *i* = {A,B,C}, and $\bar{U}$ is the mean value of RMS voltage of all three phases.
In this analysis, the steady state PVUR before compensation is defined as the PVUR from the point in time when battery 1 starts making the unbalance until the compensation algorithm starts to ramp up/down the power. Then after a transition period when battery 2 compensates the unbalance, the system reaches a new steady state, and the PVUR is measured again to evaluate the effect of the compensation algorithm. By looking at the PVUR this way, one can quantify the PVUR before and after compensation.

### *1.5.8 Results*

This section presents the results of the experiments. In total 4 scenarios were tested, with one test having three subtests. These tests are summarized in Table 1. As can be seen, the first two tests are performed to characterizes different aspects of the public network. Test 3.1 to 3.3 are unbalance tests where one battery creates an unbalance, while another runs the compensation algorithm. Power P1, P2 and P3 indicates the power of the batteries generating unbalance in the different scenarios.

| **Test no.** | **Test description** | **Time testing** | **Power P1 [kWac]** | **Power P2 [kWac]** | **Power P3 [kWac]** |
|---|---|---|---|---|---|
| 1 | Characterize voltage variation in public network | 6-8th. June | - | - | - |
| 2 | Characterize impedance in public network | 9th. June 13:24 to 17:05 | - | - | - |
| 3.1 | Test unbalance compensation - fixed setpoints | 16-17th. June 22.02 to 22.23 | 5,31 | 0 | 0 |
| 3.2 | Test unbalance compensation - fixed setpoints | 16-17th. June 23.19 to 23.48 | 5,3 | 5,3 | 0 |
| 3.3 | Test unbalance compensation - fixed setpoints | 16-17th. June 00.09 to 00.18 | 0 | -5,3 | 5,3 |

| | | | | | |
|---|---|---|---|---|---|
| 4 | Test unbalance compensation – compensate public network | 16-17th. June 23.48 to 00.09 | 0 | 0 | 0 |

The next sections analyse the results of the performed tests. Section 1.5.8.1 and 1.5.8.2 analyses the results from test 1 and 2 respectively, with the objective of characterizing the voltage of the public network and characterizing the impedance in the public network. In Sections 1.5.8.3, 1.5.8.4 and 1.5.8.5 the results from subtests of the 3 are presented. Section 1.5.8.6 covers the analysis of test 4. Lastly in section 1.5.9 the results are summarized.

#### 1.5.8.1 Test 1: Characterize the voltage in the public network

The objective of test 1 was to characterize the voltage variation in the public network.

In this test the batteries are performing balanced AC Power charge and discharge cycles over a period of three days (Figure 4 below).

The noise levels in test are high, and therefore a high variance is seen in the results. During the test there are several voltage drops and rises, that approximately correspond to the charge and discharge cycles of the battery. However, in most cases there are a time shift between the change in power and the voltage drop/rise, which indicates that there is something happening in the public grid, that affects the voltage. This could be changes in tap position of a transformer.

When analyzing the graphs and taking the above-mentioned behavior into account, it is found that the impedance of the grid is high enough, for the voltage to be influenced by the changes in the charge/discharge pattern.

The PVUR is relatively stable between 0,5 and 1%, with a mean over the whole period of 0,93% and maximum of 2,5%. The voltage on Phase 1, is in general lower than phases 2 and 3.

To remove some of the noise, the data was prepared using a moving average over 50 seconds and thereafter fitted with a linear model for each of the phases. The table below summarizes the coefficients from the bottom plot in Figure 4.

The R-squared value between 0,44 and 0,51 indicates some linear relation between the voltage and current, but at the same time indicates that there is very high variance in the dataset, and that the linear model is very uncertain.

Importantly the slopes are almost parallel, which indicates the impedance for the three phases are the same.

| Phase no. | Intercept | Slope | R2 |
|---|---|---|---|
| **1** | 231,5 | -0,47 | 0,44 |
| **2** | 234,4 | -0,42 | 0,50 |
| **3** | 234,8 | -0,41 | 0,51 |

Overview of the liniear regressions

Due to the variance in the data it would have been beneficial to run the test over a longer period, as well as, having a precision higher than ±500 mV.

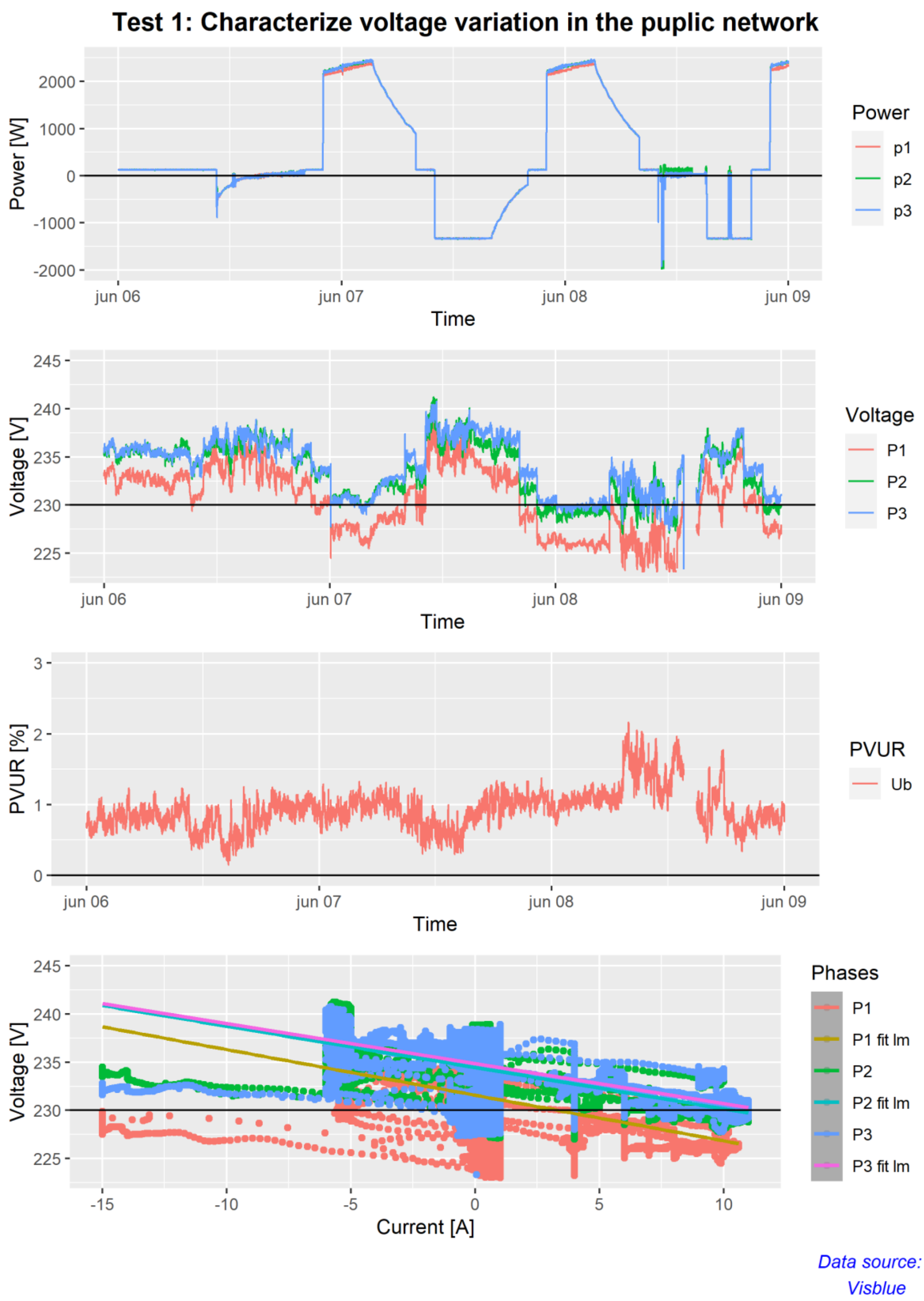



*Figure 4 a) Power of battery 2, charge and discharge circles. b) Phase voltages for battery 2. c) PVUR for the duration of test 1. Power of battery 2, charge and discharge circles. d) Voltage ~ Current plot for all three phases with fitted values.*

### 1.5.8.2 Test 2: characterize the network impedance

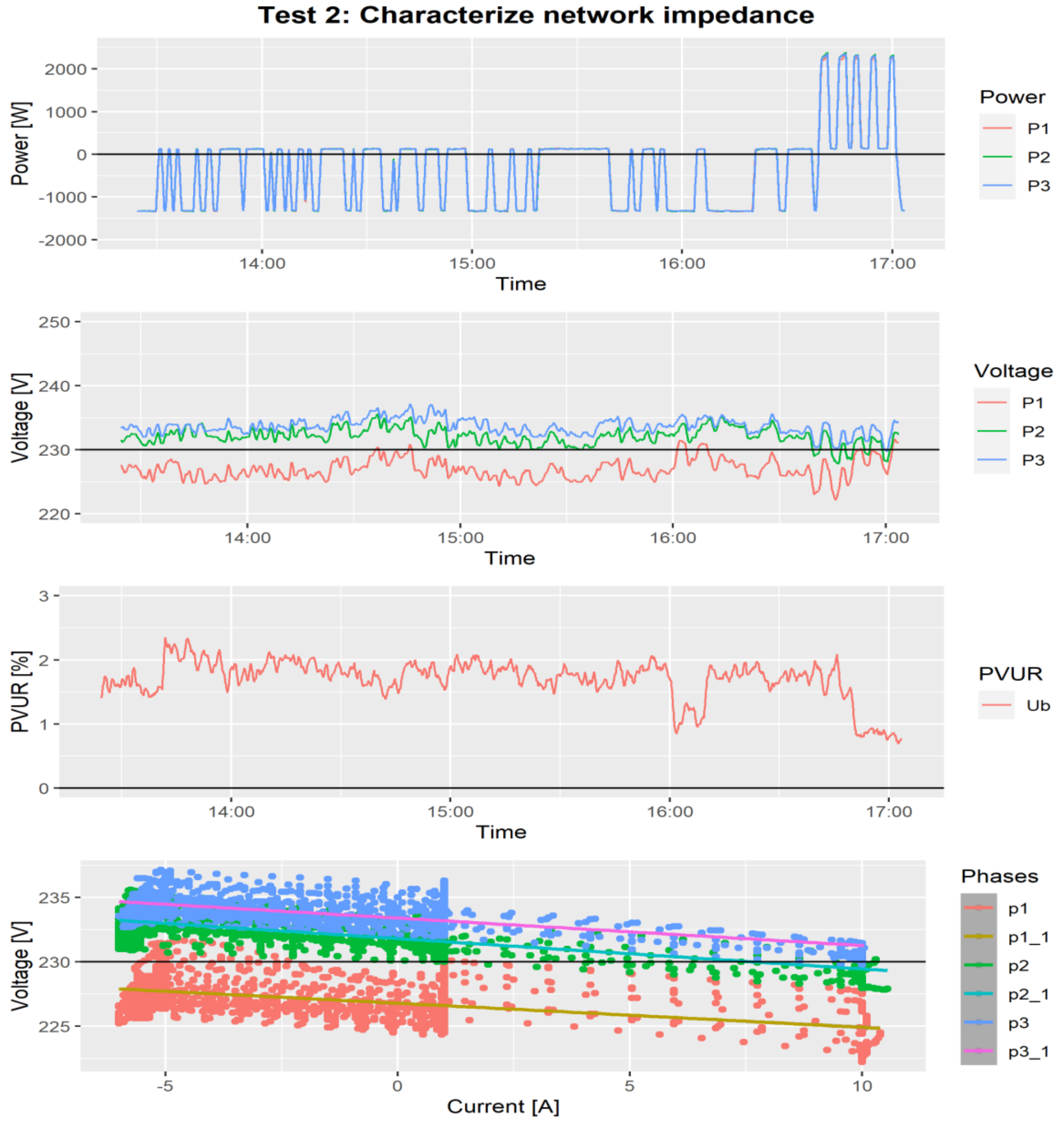
The main objective of test 2 is to characterize the network impedance. This is done by making step changes, from 0 to full consumption and from 0 to full production. Each of the step changes was repeated 30 and 6 times respectively.
During test 2 the voltage, in general, is lower than in test 1, which applies especially for phase 1. The unbalance of the three phases are plotted in Figure 5 c. The mean PVUR is 1,71% and a maximum of 2,35%. It is worth noting, that the test period for test 1 was during the weekend, and that test 2 was performed during the afternoon on a Tuesday.

The data was prepared with a 50 second moving average. The voltage vs. current plot, including a fitted linear model can be seen in the Figure 5. The coefficients from the linear model is summarized in the table below.
In this experiment, the linear relation between voltage and current as about the same as for test 1, except for phase 1 where R-squared is just 0,20. The lower R-squared for phase 1 is apparent from the plot, as there seams to be a higher variance in the data. Also, from the graph, the datapoints for part 2 of the test is few compared to the first part. Based on the found slope, the Thevenin impedance is approximately 0,2 Ω, however the R-squared values are low, and therefore there are many uncertainties to this result.

| Phase no. | Intercept | Slope | R2 |
|---|---|---|---|
| **1** | 226,8 | -0,19 | 0,20 |
| **2** | 231,8 | -0,24 | 0,47 |
| **3** | 233,4 | -0,21 | 0,43 |

Overview of the linear regressions

For a more certain result, it would have been preferred, that the measurements would have had a better resolution (0,1V rather than 1V) and that the tests had more repetitions to get more datapoints for the regression.




*Data source: Visblue*

*Figure 5 a) Power of battery 2, charge and discharge circles. b) Phase voltages for battery 2. c) PVUR for the duration of test 1. Power of battery 2, charge and discharge circles. d) Voltage vs. Current plot for all three phases with fitted values*

#### 1.5.8.3 Test 3.1: Test unbalance compensation – fixed setpoints

Test 3.1 is the first test where the compensation algorithm is tested. The experimental set-up is as follows: the unbalance is created by batteries 1 and 3, and battery 2 runs in compensation mode. The objective is to counter the unbalance.

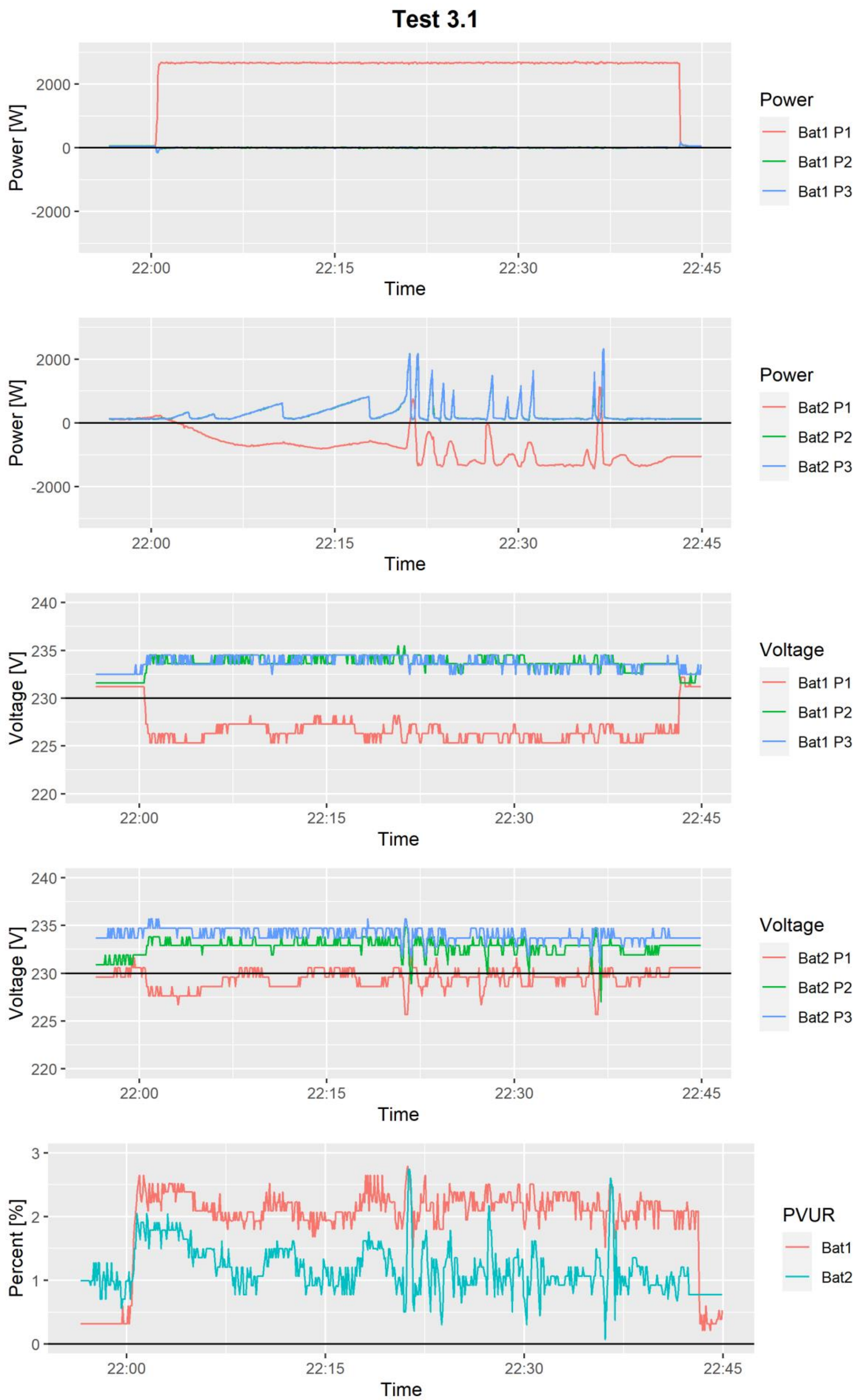
Figure 4 show the results of this test. The test runs from 22:00 to 22:17. Figure 6 a) the power of battery 1 is plotted, just after 22:00 the power rises to 2,6 kW. There is then a voltage drop on phase 1 of the busses of both batteries 1 and 2 (Figure 6 plots c) and d)).

This results immediately in a rise in PVUR from 0 to ~2,5% on bus of battery 1 Figure 6 e). Hereafter battery 2 starts to compensate the rise in PVUR. As the power from battery 2 rises the PVUR drops on both phases.

It is noted that during this test there is also a compensation on phase 3, even though the voltage on phase 3 is stable. The compensation power of 3 phase starts out small, and gets larger and larger, which indicates an oscillation of the regulator. The oscillations on phase 3 get larger as the test continues. The reason for this behavior needs further research.

In conclusion the result of this test is promising. There is an effect of the compensation battery on the bus of battery 1, which indicates that the public network is positively affected by the compensation.

However, more tests should be conducted to verify the results. Also, the oscillations should be addressed, as this indicates that the compensation algorithm should be further developed. Further, the lack of measurements from the shared AC bus could be addressed, to see the actual effect in the public network.




Data source:
Visblue

*Figure 6 a) Power of battery 1. b) Power of battery 2. c) Voltage of battery 1. d) Voltage of battery 2. e) PVUR in percent for battery 1 and 2.*

#### 1.5.8.4 Test 3.2: Test unbalance compensation – fixed setpoints

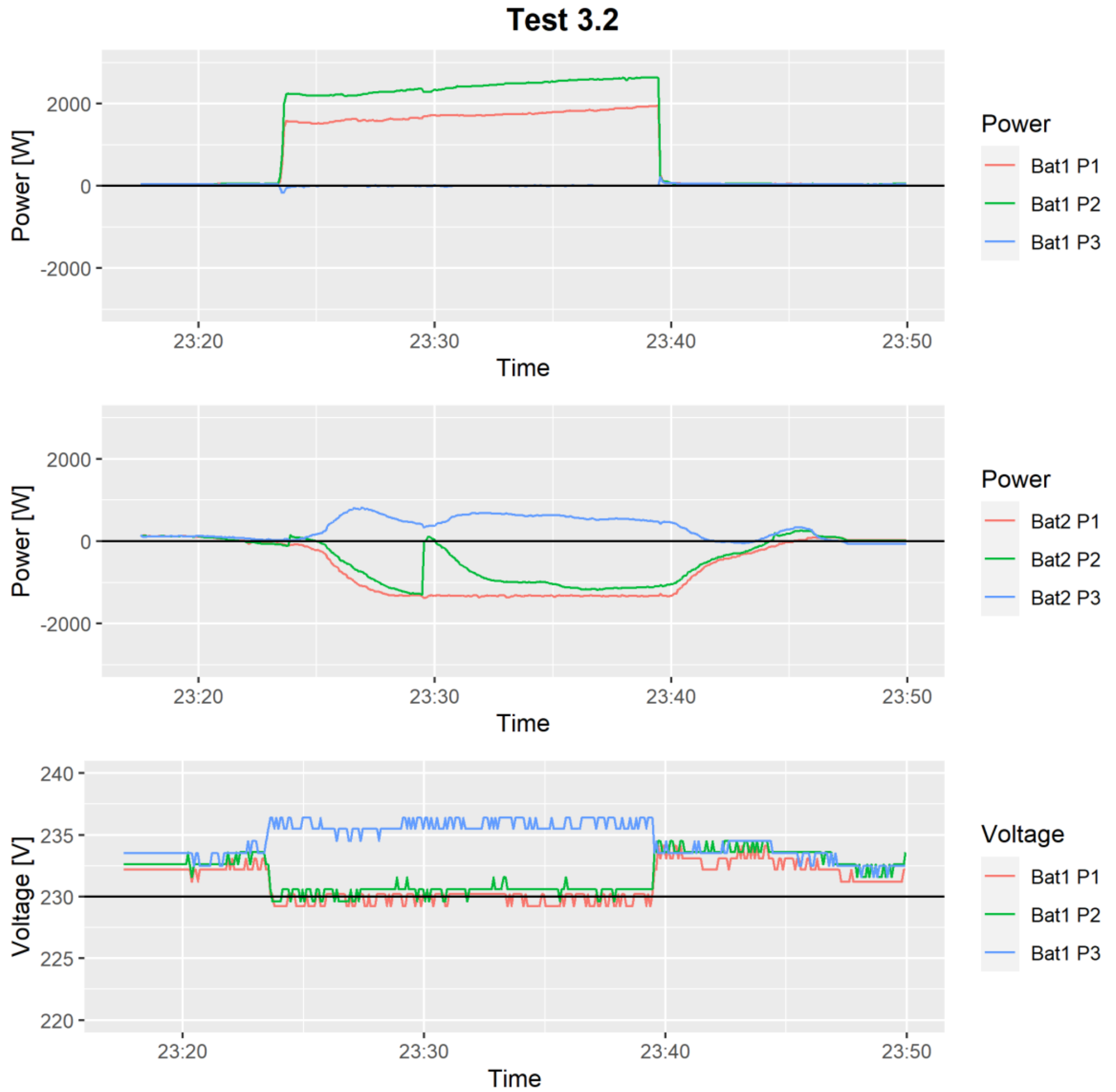
This is the second unbalance compensation test. In this test two of the phases are creating the unbalance. The test is conducted between 22:23 and 22:45.

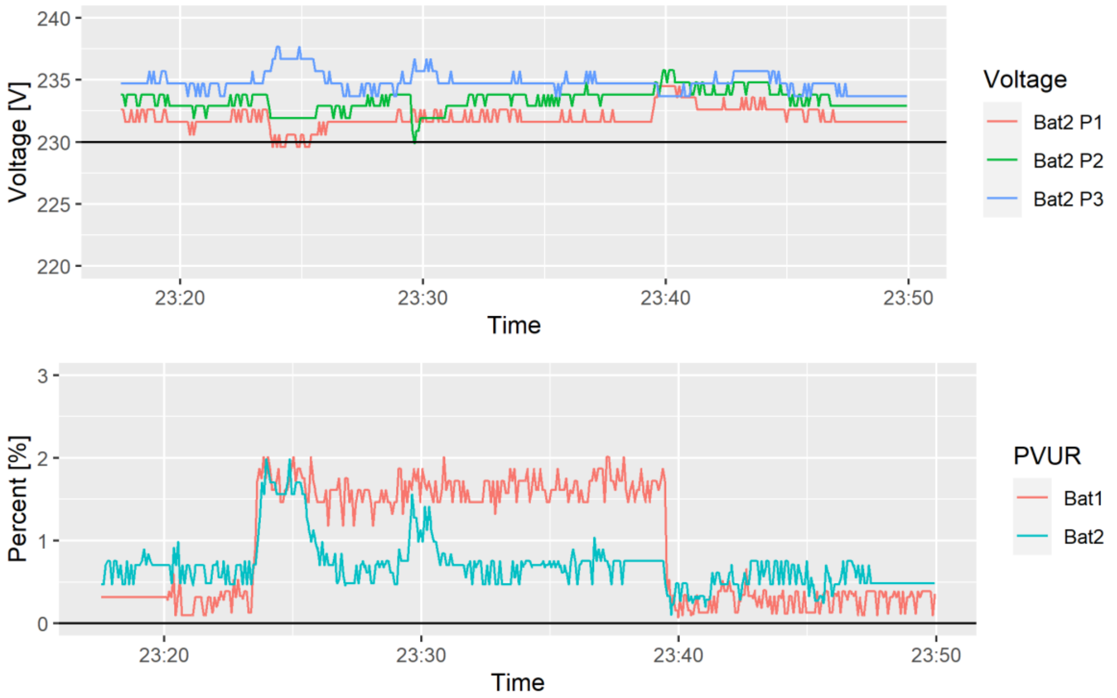
In Figure 7 a) it is seen that phases 1 and 2 of battery 1 are starting the unbalance, which results in a voltage drop on both phases of about 2,5 V and at the same time there is an voltage rise on phase 3 of 1,5 V. The voltage fluctuation is seen on the bus of battery 2 (Figure 7 d).

This results in a PVUR on the two busses between 1,5 and 2%. Battery 2 starts to compensate the unbalance. The PVUR on the bus of battery 2 drops as the compensation starts and falls to the level before the compensation started. However, the drop in PVUR is not seen on the bus of battery 1. The lack of change in PVUR on the bus of battery 1, could be due to the fact the total unbalance from batteries 1 and 3 is 5,3 kW/phase and the compensation is only 1,3 kW/phase.

For reasons unknown, phase 2 of battery 2 stops the compensation for a short moment just before 22:30, which results in a rise in PVUR, which drop as soon as the compensation starts again. This could be due a reset of the integrator, however, this need further investigation.

In conclusion, the results of test 3.2 are promising. The compensation works on the local bus. However, it is unknown the effect on the public network. This leads to the conclusion that more testing should be done, and that the lack of measurements from the shared AC bus makes the effect on the public network uncertain. Lastly, the stability of the compensation controller should be further developed.



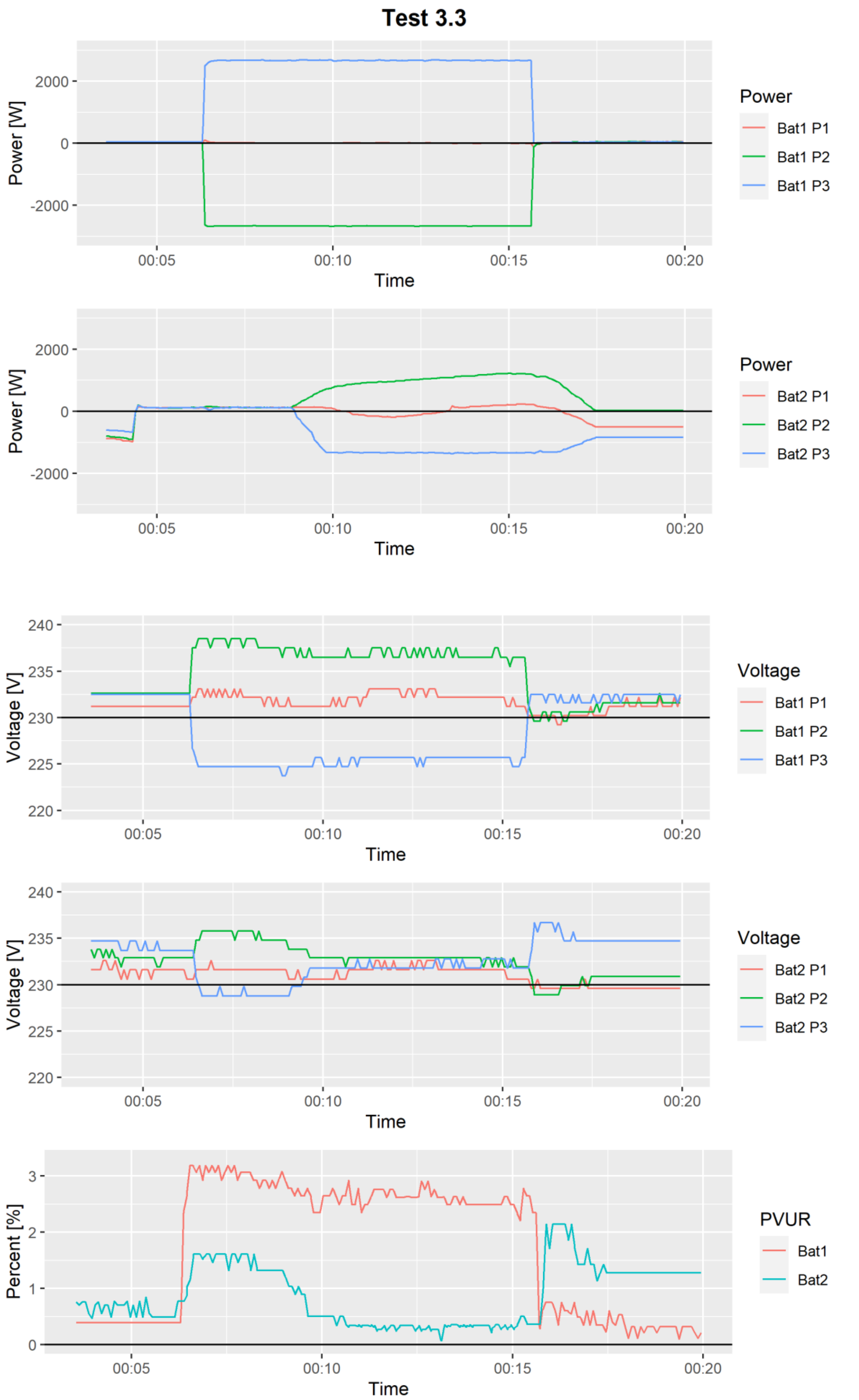



*Data source: Visblue*

*Figure 7 a) Power of battery 1. b) Power of battery 2. c) Voltage of battery 1. d) Voltage of battery 2. e) PVUR in percent for battery 1 and 2*

#### 1.5.8.5 Test 3.3: Test unbalance compensation – fixed setpoints

Test 3.3 is the third unbalance test. In this test the unbalance is crated by battery 1 and 3, where phases 2 and 3 are making the unbalance by charging on one phase, while the other discharges. The test ran from 00:06 to 00:17.
The same pattern as the previous tests is seen in Figure 8. As the power rises/drops on phases 2 and 3, the voltage drops/rises as well. The PVUR increases to approx. 3%. At the same time the voltage on battery 2 is exhibiting the same behavior as battery 1 albeit less pronounced. The PVUR on battery 2 increases to about 1,5%.
When the compensation starts, the PVUR drops to pre-testing levels, which is a promising result. It is noted the PVUR of battery 1 drops from approximately 3% before the compensation starts to approximately 2,5% during the compensation phase, which is also a promising result. However, there are no measurements on the shared AC bus, which would have been interesting, to confirm a drop in unbalance at the connection point to the public grid.
In this test the time it takes for the compensation algorithm to start compensating is longer. The unbalance of battery 1 starts at 00:06:22. The compensation of battery 2 starts at 00:08:58, this means there is approximately 2,5 min delay from the time when the unbalance starts to the time when compensation starts. Why this happened, is not apparent; from the provided dataset it is noted that the "No Load Voltage" changed just as the test started. The question is if there is a connection between the change in No Load Voltage and the delayed operation of the regulator.
Another point is that when the unbalance created by battery 1 stops, there is a long period before battery 2 reacts to the change in power, which leads to a rise in PVUR on the bus of battery 2, which falls when the Power from battery 2 starts to drop.
In conclusion, this test shows some promising results, although the reaction time from the compensation battery was slow, there are some indications that compensation influenced the PVUR of bus at battery 1. Again, more testing is needed to confirm this conclusion, also measurements at the shared AC bus would help to get a better conclusion.

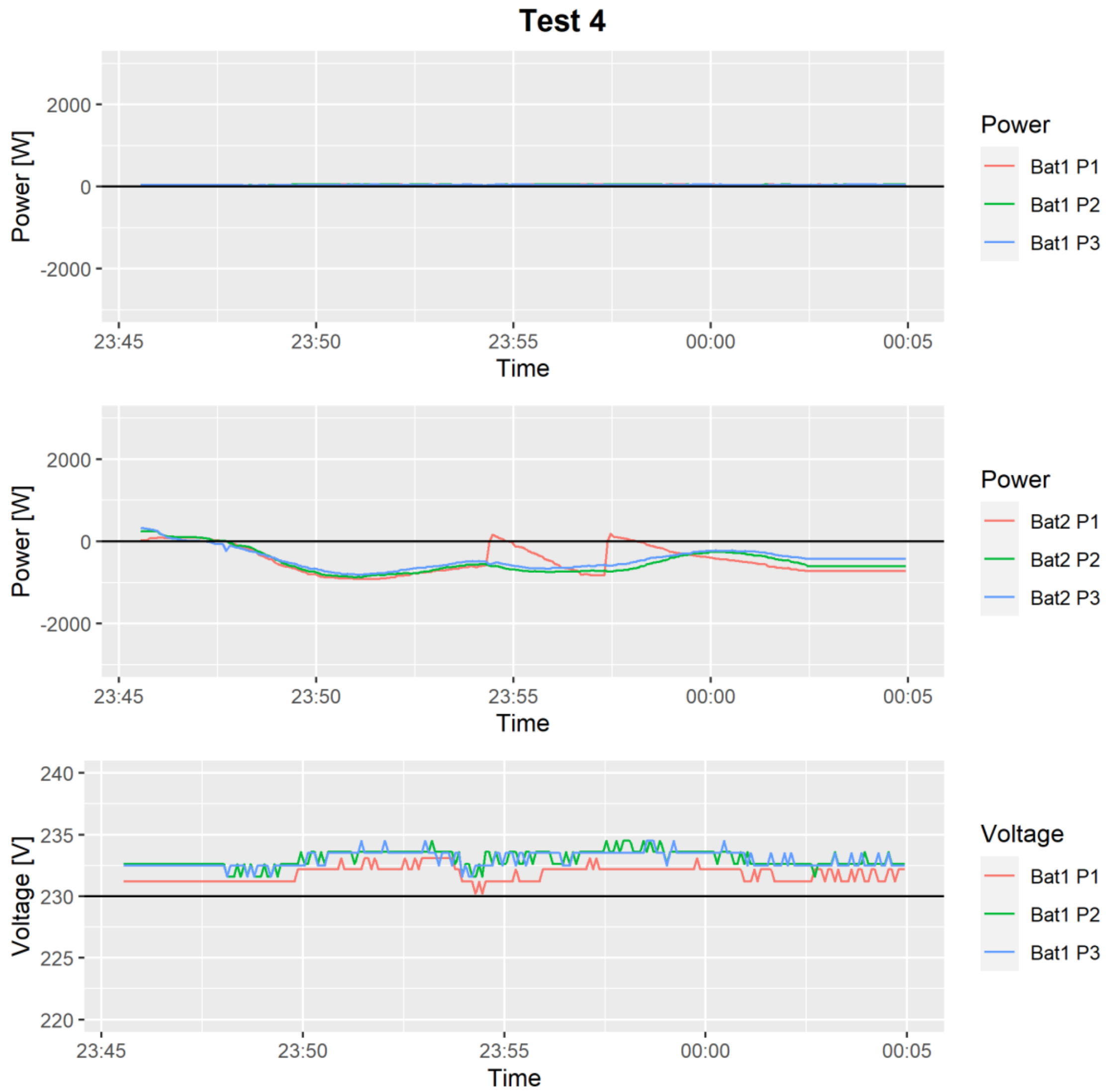


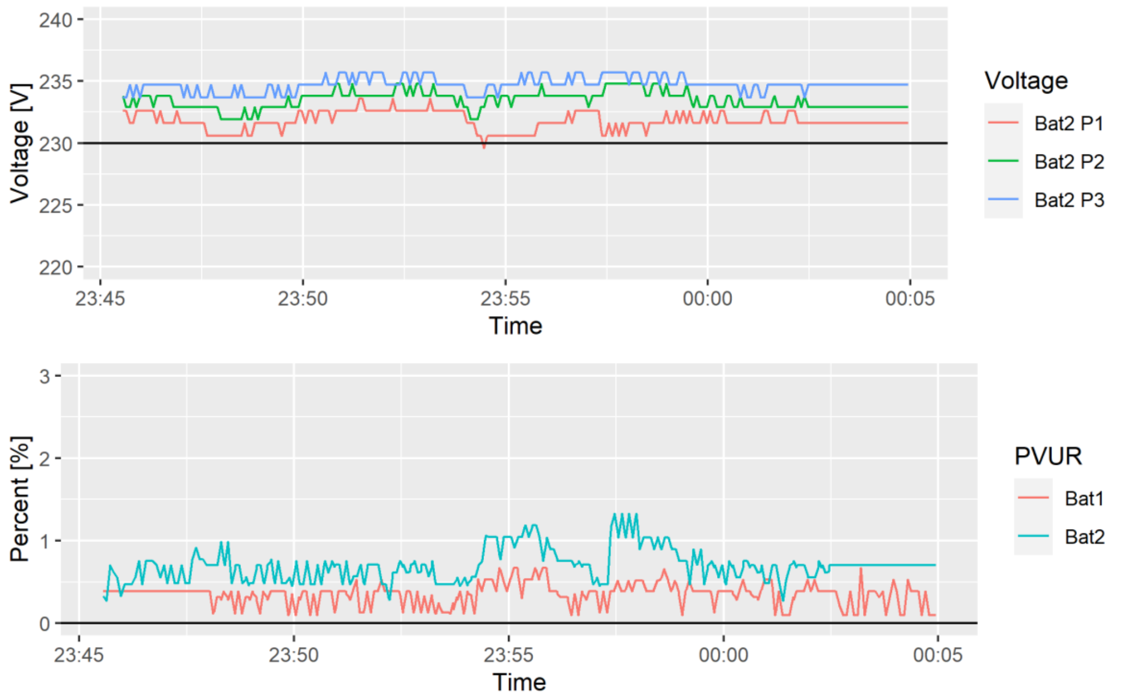

*Data source: Visblue*

*Figure 8 a) Power of battery 1. b) Power of battery 2. c) Voltage of battery 1. d) Voltage of battery 2. e) PVUR in percent for battery 1 and 2*

### 1.5.8.6 Test 4: Test unbalance compensation – compensate public network

In this test, the performance of the compensation algorithm was exiamined to test the behaviour of the compensating battery when operating on its own.
In test 4 batteries 1 and 3 were turned off while battery 2 ran the compensation algorithm (Figure 9). The test ran for about 20 minutes, from 23:45 to 00:05.
As seen in Figure 9 b), battery 2 injects about 1 kW active power to the grid on all three phases. The voltage is relatively stable during the test, as shown in Figure 9 c) and d).
The only significant voltage deviations are the two times the power of battery 2 drops on phase 1 and consequently increasing the PVUR on the bus of battery 2, shown in Figure 9 e). During the first power drop, there is also a voltage drop in the buses of batteries 1 and 2.
The cause of this behaviour is not known. However similar power drops and rises were observed in tests 3.1 and 3.2, therefore the implementation compensation algorithm should be checked, to see if for some reason the integrator is reset.
Based on this test, because of the power drops, the compensation battery caused more unbalance than, if it was not connected.






*Data source: Visblue*

*Figure 9 a) Power of battery 1. b) Power of battery 2. c) Voltage of battery 1. d) Voltage of battery 2. e) PVUR in percent for battery 1 and 2.*

### *1.5.9 Summary of results*

The section 1.5.8. analyzed the results from the performed tests, this section summarizes the results.

#### 1.5.9.1 Noise in the Network Environment

The first two test showed that there was a high variance in voltage, and consequently, the calculated Thevenin impedance. However, the impedance in the public network is high enough to create measurable changes to RMS voltage when charging and discharging the battery.

#### 1.5.9.2 Unbalance Compensation

The table below, summarizes the change in PVUR in the respective tests on both battery busses. As can be seen from the table in all tests, there is change in PVUR on the bus compensation battery form between 1,5% and 1,75% to between 0,4% and 1,1%. This result must be considered positive. Also, in the bus of the unbalance battery, there is a small change in PVUR in some cases, which indicated, that the decrease in PVUR also affected the shared AC bus.

Test 4 is special, as the unbalance seams to be unchanged on the compensation bus but falls a bit on the unbalance bus. This could be due to a general decrease in PVUR in the public network.

| Test no. | PVUR Bat2 Before [%] | PVUR Bat2 After [%] | PVUR Bat1 Delta [%] | PVUR Bat1 Before [%] | PVUR Bat1 After [%] | PVUR Bat2 Delta [%] |
|---|---|---|---|---|---|---|
| **3.1** | 1,75 | 1,0 | 0,75 | 2,4 | 2,0 | 0,4 |
| **3.2** | 1,75 | 0,75 | 0,75 | 2,75 | 2,75 | 0 |
| **3.3** | 1,5 | 0,4 | 1,1 | 3,0 | 2,75 | 0,25 |
| **4** | 0,6 | 0,6 | 0 | 0,45 | 0,3 | 0,15 |

#### 1.5.9.3 Stability of the control algorithm

In all tests, there appears to be some unstable behavior of the compensation algorithm. It seems that the controller resets, during some of the tests. Further, there are some oscillations in test 3.1. Debugging the implementation, and fine tuning of the parameters in the controller could improve its performance.

#### 1.5.9.4 Further testing

The tests in this experiment lasted only a short period of time, therefore it is recommended to do further testing, to verify the results, as the results in general are promising.

## 1.6 Utilisation of project results

Based on the promising results of the project, the project partners can see the perspective and have already discussed how to roll out a real test site and test the battery. During the project, DE has gained a better understanding of the flow battery, where the organisation will use this in their work and counselling of Distribution System Operators (DSO's) and other stakeholders.

VisBlue expects to utilise the results of the project as a battery configuration in the company's product portfolio.

## 1.7 Project conclusion and perspective

The project results will be used as a "proof of concept" of VisBlue's flow battery solution and to prove that it can compete with other solutions and an upgrade of the electrical distribution network on site.

Simulations, done by DE, of the low voltage grid show that the installation of batteries has a significantly positive influence on the grid voltage and grid components. On the one hand, if the battery is placed close to the transformer station, only the transformer station and the middle voltage grid will be relieved. In this case, the grid voltage and degradation of other components in the low voltage grid will not be changed.
On the other hand, if the battery is installed in different places in the low voltage grid, the battery will be able to change the power flow in such way that the grid voltage will be more stable and the degradation of the grid components is reduced.

VisBlue has attained a large amount of knowledge about this type of grid issues and exactly how to solve this with the company's battery solution. Using the battery configuration with independent control of each phase, VisBlue expects to be able to adapt to other real life applications of the battery solution.

The project partners expect to be able to use the knowledge and battery design in their future businesses. The project missed results from the field test site, but based on the project results, there is a good basis to go out and perform a real life test. A real life test is also needed to convince the DSO's and the energy/grid industry that a flow battery can be a genuine and sometimes better alternative to transmission upgrading and other battery systems.

## 1.8 References


[1] Visblue, "Sw. Control design description", Technical Report, October 2018.
[2] Visblue "Test report: Flow battery system, Grid Connected Flow Battery", Technical Report June 2020.
[3] Phillip J. Douglass, Ionut Trintis, "Balancing distribution systems with threephase
active front end rectifiers: field experiment results", IET Generation, Transmission & Distribution, May 2017. doi: 10.1049/iet-gtd.2016.1901.