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Project memo

Coordination of voltage regulators in the distribution grid – Laboratory results

Coordination of voltage regulation with OLTC, voltage booster and battery system

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ABSTRACT
This memo summarises the results from laboratory test performed as a collaboration between the projects SAMREG and IntegER. SAMREG aims to help DSOs make use of voltage regulation as an alternative to grid reinforcements to reduce the need for investments in the distribution grid. IntegER's objective is to contribute with new knowledge and practical guidelines that enables battery energy storage systems to be used and integrated into the Norwegian distribution grid. This memo presents the results from hardware-in-the-loop tests performed in the National Smart Grid Laboratory. The laboratory set-up includes an on-load tap changing (OLTC) transformer, a Magtech voltage booster and a battery system containing a converter and a battery. The OLTC transformer and battery are emulated, while the booster and converter are physical components in the lab. The interactions between the three regulators during events such as load changes and battery charging and discharging were explored to see how they regulate the voltage and if the resulting voltages are within the limits of the Norwegian regulation of power quality. One of the main conclusions that can be drawn from the results is that uncoordinated regulator settings, for example when the regulators have different voltage setpoints, can cause the regulators to work against each other, resulting in high losses.

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1 Introduction

This memo is a collaboration between the projects SAMREG[1] and IntegER[2]. SAMREG (Coordinated voltage regulation in the distribution grid) aims to help DSOs make use of voltage regulation as an alternative to grid reinforcements to reduce the need for investments in the distribution grid. A part of this goal is to identify both positive and negative interactions between different voltage regulators and voltage regulating actions, and test these interactions in simulations and lab tests. IntegER's (Integration of energy storage in the distribution grid) overall objective is to contribute with new knowledge and practical guidelines that enables battery energy storage systems to be used and integrated into the Norwegian distribution grid.

This memo presents the results from hardware-in-the-loop tests performed in the National Smart Grid Laboratory on November 6th 2019. The set-up included an on-load tap changing (OLTC) transformer, a Magtech voltage booster and a battery system containing a converter and a battery. The OLTC transformer and battery were emulated, while the voltage booster and converter were physical components in the lab. The OLTC transformer, voltage booster and converter regulate the voltage, and the performed tests explores the interaction between the three regulators during events such as load changes and battery charging and discharging.

The questions we aim to answer in this report are:

- How do the voltage booster and converter work together?
- Are the regulators capable of regulating the voltage within the regulatory limits?

The memo is organized in the following way: Chapter 2 presents the test method and laboratory setup and gives an overview of the performed tests. Chapter 3 presents the results and chapter 4 discusses and summarizes the findings.

[1] SAMREG – https://www.sintef.no/prosjekter/samreg-samordnet-spenningsregulering-i-distribusjonsnett/
[2] IntegER – https://www.sintef.no/prosjekter/integrasjon-av-energilager-i-distribusjonsnettet/

2 Method and laboratory setup

This chapter gives an overview of the method and laboratory setup for the tests performed. Figure 1 and Figure 2 show the laboratory setup in the National Smart Grid Laboratory. The variable resistive load in Figure 2 is only connected in some of the tests and is not shown in Figure 1. The setup is a hardware-in-the-loop simulation, where the booster and the converter are physical components in the lab, while the grid and battery are simulated with a real grid emulator. This is illustrated with black (physical) and blue (simulated) components in Figure 2. The grid and converter settings are specified in MATLAB Simulink and given as input to the emulator. The OPAL-RT performs the real-time simulations and controls the input to and output from the real grid emulator and the converter. The measurements analysed in this memo are taken at the input and output of the booster and will be referred to as "input" and "output" values (marked with green "Elspec measurements" in Figure 1).

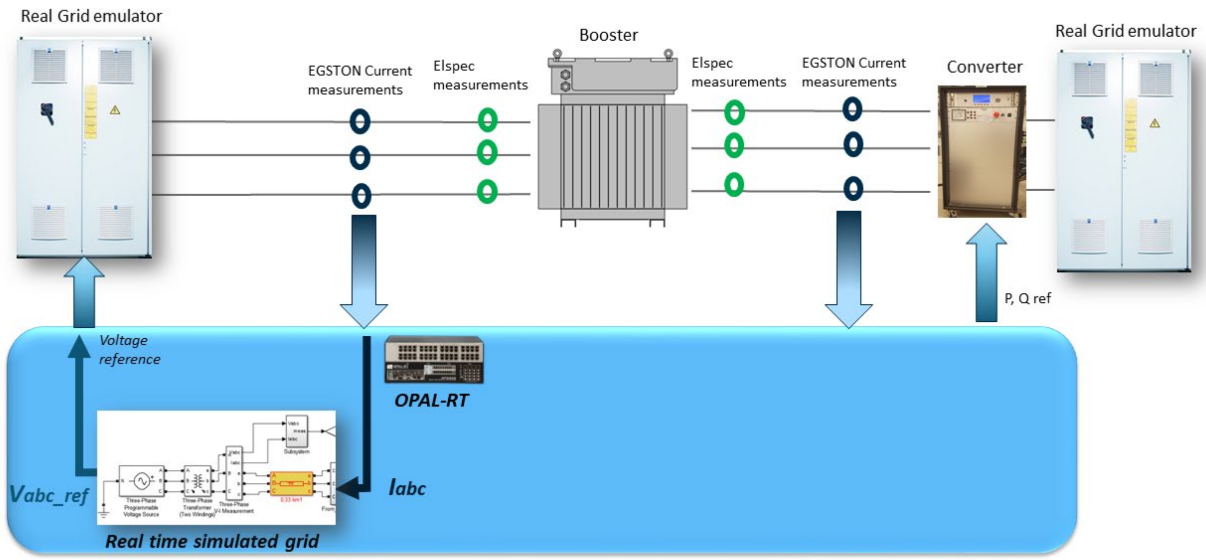

Figure 1: Laboratory setup with voltage booster and converter (battery).

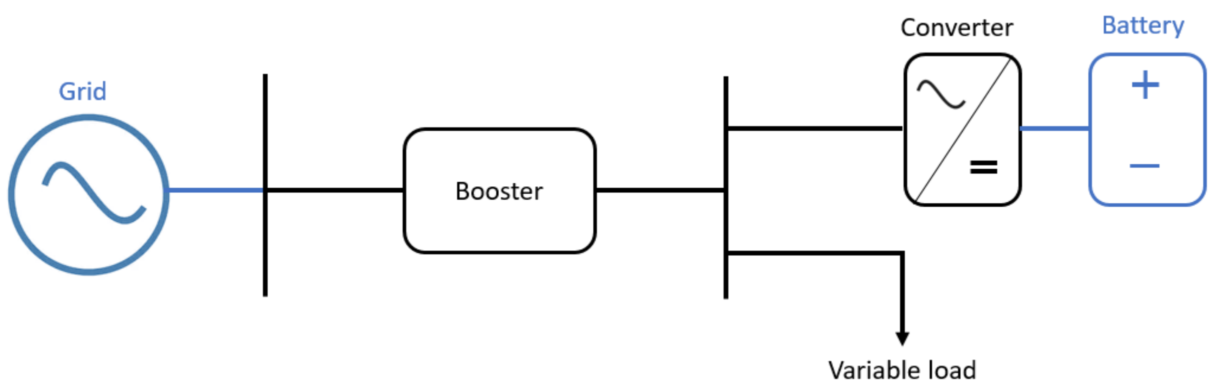

Figure 2: Simplified laboratory setup with voltage booster, converter, battery and variable load. The black symbols represent physical components, and the blue symbols represent emulated components.

The one-line diagram for the laboratory setup is given in Figure 3. The "Egston" component is the real grid emulator in Figure 1.

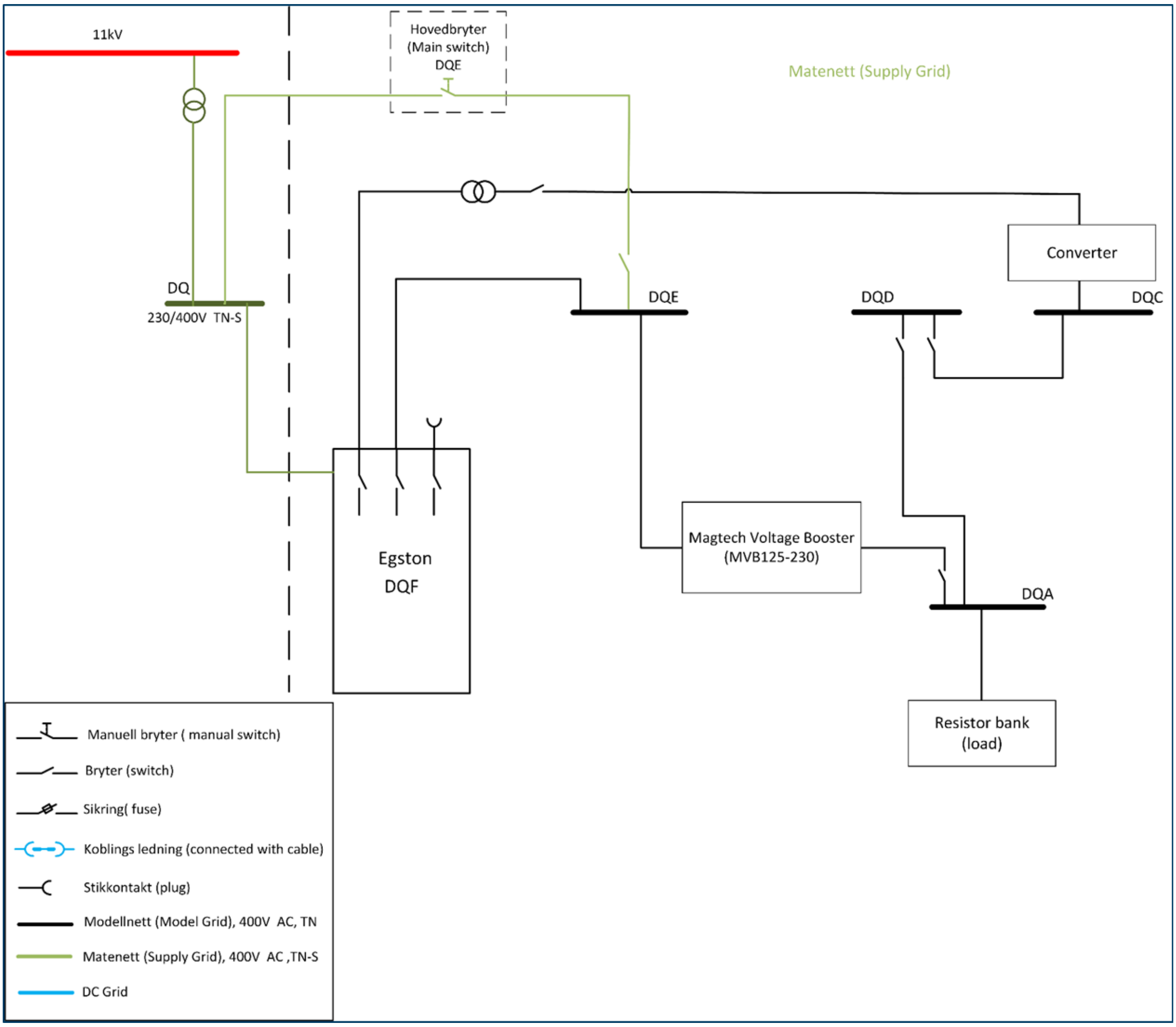

Figure 3: One-line diagram of laboratory setup.

The following applies for all tests:

- Varying input voltage for all experiments (two-minute intervals) as seen in Figure 4
- OLTC voltage setpoint: 1.04 pu (239 V)
- Voltage booster voltage setpoint: 235 V

2.1 Input voltage from MV grid

The varying input voltage from the medium-voltage (MV) grid is shown in Figure 4 (phase peak voltage) and was run in a loop during the tests. All tests were therefore performed for a minimum of 120 seconds (one loop duration).

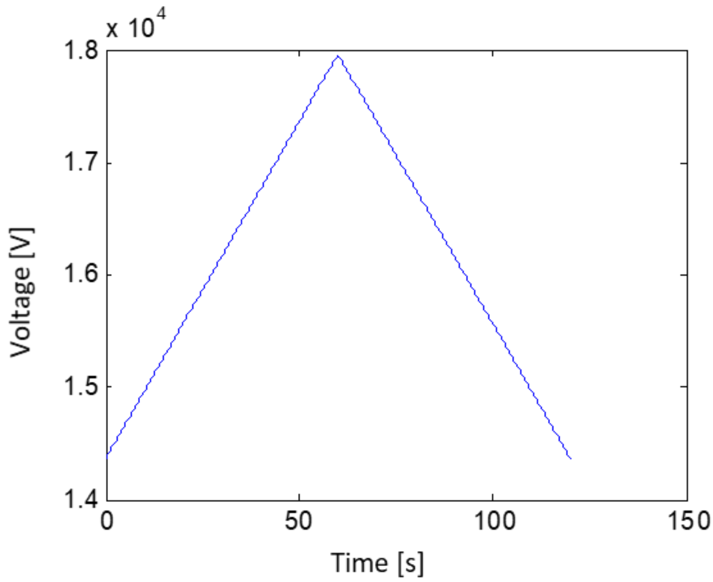

Figure 4: Input voltage (MV) used for all tests, loop duration was 120 seconds.

2.2 OLTC transformer

The specifications for the on-load tap changer (OLTC) transformer are shown in Table 1. The OLTC is simulated and included in the "grid"-component in Figure 2. The specifications for the OLTC are equal during all tests.

Table 1: OLTC specifications

Parameter	Value
Voltage step deltaU per tap (pu)	0.01875
Initial tap position	-4
Tap selection time (s)	3
Tap transition time (s)	0.04
Transfer resistances (ohms)	5
Voltage regulator reference (pu)	1.04
Voltage regulator deadband (pu)	0.0375
Voltage regulator delay (s)	1.0

2.3 Voltage booster

The booster used in these tests is a Magtech Voltage Booster MVB125-230, see Figure 5. It is a 32 kVA, 230 V booster for IT distribution systems. The technical data is given in Appendix A.4. The voltage booster uses a variable series inductance to regulate the voltage. This type of regulation requires reactive power in the form of magnetizing current to change the voltage in the series inductance. The reactive power is supplied by the grid. The response time from zero to maximum boost is 200 ms, but the booster can only boost the voltage if it is within a certain range (bandwidth). The upper limit is the booster voltage setpoint (235 V) and the lower limit is approximately 180-190 V. If the voltage is outside these limits the booster will go into bypass mode and stop boosting the voltage.

Figure 5: Magtech voltage booster in the smartgrid lab.

2.4 Converter

The converter is used as a voltage regulator in combination with an electrical battery. The battery is not a physical battery in the lab, but is emulated using the converter in combination with a real grid emulator. This way, a battery can be emulated, charging and discharging power based on the input from the control system.

Voltage droop control
Droop control is a form of regulation where the voltage is controlled by adjusting the active or reactive power flow. In these tests only reactive power regulation is used. The droop, which is the slope of the line in Figure 6, determines the rate of change of reactive power for a given change in voltage. A droop of 10 % means that if the voltage is reduced by 1 p.u., the reactive power increases by 10 % of nominal value. Equation (1), where *s* is the slope, describes the voltage-reactive power relationship in voltage droop control:

$$\Delta V = -s\Delta Q \tag{1}$$

The tests described in this memo were performed both with and without droop control, in order to observe the effects droop control has on voltage regulation. The droop characteristics of the converter is given below:

- 10 % slope
- Nominal voltage: 400 V
- Nominal current: 90 A

Given the characteristics above, a reduction in voltage of 0.01 p.u. is a reduction of 4 V. Solving for ΔQ this gives an increase in reactive power of 0.001 p.u. The nominal current is used to calculate the change in reactive power in VAr: $\Delta Q = 0.001 \cdot 90\ A \cdot 400\ V = 360\ VAr = 0.36\ kVAr$.

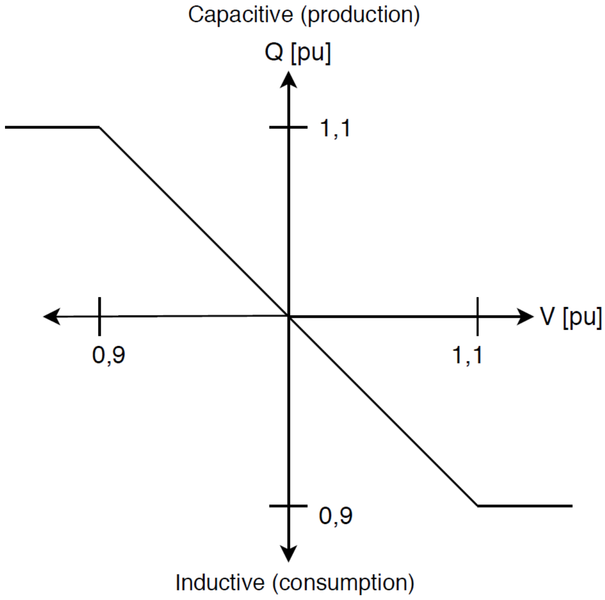

Figure 6: Illustration of voltage droop control with reactive power.

Droop control is used to both limit rapid changes in reactive power during rapid voltage changes, and to share reactive power contribution between parallel converters in the same grid. An example of the latter is using droop control to share the load between two or more generators in a power generating facility.

2.5 Regulation on quality of electricity supply (FoL)

The regulation on quality of electricity supply, hereafter referred to as FoL[3], defines the following relevant requirements for the power system:

- **Supply voltage variations**
  Definition: changes in RMS voltage, measured over a given time interval.

  DSOs shall ensure that supply voltage variations are within a range of ± 10 % of nominal voltage, measured on average over one minute, at the connection point in the low voltage grid.

  For a 230 V IT network: 110 % of nominal voltage is 253 V and 90 % of nominal voltage is 207 V.

[3] Forskrift om leveringskvalitet i kraftsystemet, https://lovdata.no/dokument/SF/forskrift/2004-11-30-1557.

- **Voltage swells, voltage dips and rapid voltage changes**
  Definitions:
  - Voltage dip: rapid change in RMS voltage to under 90 %, but larger than 5 % of nominal voltage level, lasting from 10 ms to 60 s.
  - Voltage swell: rapid change in RMS voltage to over 110 % of nominal voltage level, lasting from 10 ms to 60 s.
  - Rapid voltage change (RVC): a change in RMS voltage within $\pm$ 10 % nominal voltage, that occurs faster than 0.5 % of set voltage level per second.

  DSOs shall ensure that voltage swells, voltage dips and RVCs do not exceed the following limits:

Table 2: Limits for voltage swells, voltage dips and RVCs.

Voltage dips, voltage swells and rapid voltage changes	Maximum allowed number of voltage changes per 24-hour period	
	$0{,}23\ kV \leq U_N \leq 35\ kV$	$35\ kV \leq U_N$
$\boldsymbol{\Delta U_{steady} \geq 3}$ %	24	12
$\boldsymbol{\Delta U_{max} \geq 5}$ %	24	12

- **Voltage unbalance**
  Definition: condition where the RMS phase voltages or phase angles between consecutive line voltages are not identical.

  DSOs shall ensure that degree of asymmetry does not exceed 2 %, measured on average over 10 minutes.

In the tests performed, supply voltage variations and voltage swells and dips are the most relevant requirements.

2.6 Overview of cases and tests performed

We performed tests on five different lab setups, here named cases. Each case had several tests, to observe how variable load, battery charging/discharging and converter voltage regulation with and without droop control affect the quality of supply. It was also an aim to study how the three regulators (OLTC, booster and converter) worked together. The resistor bank is used as a varying load, representing sudden changes in load due to for example the charging of an electric car. The battery charging and discharging can also represent active power load and distributed generation, respectively. In some of the tests the converter used droop control, and in others it regulated the voltage without droop, in order to observe the effects droop control has on voltage regulation. The cases and tests are listed below. The test labels (A, B etc…) correspond with the labels on the figures in the results, and the voltage is the voltage setpoint of the converter during the test.

- Case 1: converter regulating voltage with droop control, resistor bank in parallel.
  - A: 232 V, no load
  - B: 232 V, 10 kW active load
  - C: 232 V, 20 kW active load

- Case 2: converter regulating voltage with droop control, and battery charging/discharging.
  - A: 234 V, discharging 5 kW

- B: 234 V, charging 5 kW
    - C: 225 V, charging 5 kW
    - D: 225 V, discharging 10 kW
    - C: 225 V, discharging 5 kW

- Case 3: converter regulating voltage without droop control, and battery charging/discharging.
    - A: 225 V, converter consuming reactive power
    - B: 234V, converter consuming reactive power
    - C: 234 V, discharging 5 kW
    - D: 234 V, charging 5 kW
    - E: 234 V, converter regulating voltage
    - F: 227 V, converter regulating voltage
    - G: 240 V, converter regulating voltage

- Case 4: converter regulating voltage with step response (no droop), resistor bank connected
    - A: 240 V, 10 kW active load
    - B: 240 V, 20 kW active load
    - C: step response

State of charge and time delay
The battery state of charge is not considered in any of the cases because of the short duration of the tests.

The three different regulators (OLTC, booster and converter) have different time delays. The time delay of the OLTC in the transformer is 1 s, which is faster than what is normal in a realistic grid. The general recommendation for time delay is minimum 15 s [1]. However, as the time delay of the OLTC is higher than the time response of the voltage booster and the converter, the results from the tests will still be close to what would be seen in real operation. This time delay setting of the OLTC is chosen due to the short duration of the tests.

Measurements
The voltage quality was measured both in the input and output side of the voltage booster using Elspec power quality analysers (PQA) of type *Elspec G4500*[4]. The Elspec devices have a sampling rate of 1024 S/cycle, which makes them able to measure voltage harmonics up to the 511th harmonic. The current flowing in each phase was measured using three flexible current clamps (probes) on each side of the booster (illustrated with green circles in Figure 1). The current sampling rate is 256 S/cycle.

In addition to the measurements with the Elspec measuring instruments, the power quality on both sides of the voltage booster was measured with Fluke measuring instruments of type *Fluke Power Quality Analyser 434 and 437*[5]. These devices have a user interface / display that was used during the tests to verify that the voltage and current levels were within the limits of the test setup.

The waveforms of the voltage and current signals on both sides of the voltage booster were captured using an oscilloscope. Some of the waveforms captured during the tests are presented in this memo.

[4] https://www.elspec-ltd.com/metering-protection/power-quality-analyzers/g4500-power-qaulity-analyzer-portable/
[5] https://no.rs-online.com/web/p/power-quality-analysers/7541268?cm_mmc=NO-PLA-DS3A-_-google-_-PLA_NO_NO_Test_And_Measurement-_-Power_Measurement%7CPower_Quality_Analysers-_-PRODUCT_GROUP&matchtype=&pla-393251457763&gclid=CjwKCAiA_f3uBRAmEiwAzPuaMwIa_oULcPw-L5-eBI4K9ebIfVvGcLvyhxjHhHntVnQ7gppi1qZyYhoCKU8QAvD_BwE&gclsrc=aw.ds

3 Results

This chapter shows the results for the different cases with OLTC, booster and converter. The measurements are gathered from Elspec Investigator (as shown in Figure 1) at 06.11.2019 between 13.30 and 16.00. Hence, the analyses are based on the measurements from the input and output of the voltage booster.

3.1 Case 1: converter regulating voltage with droop control, resistor bank in parallel

In case 1, the converter is regulating voltage with droop control, without charging/discharging the battery. A resistor bank is connected in parallel with the converter, representing a variable load. The setup is given in Figure 7. Three different tests were conducted, and an overview of the tests is given in Table 3.

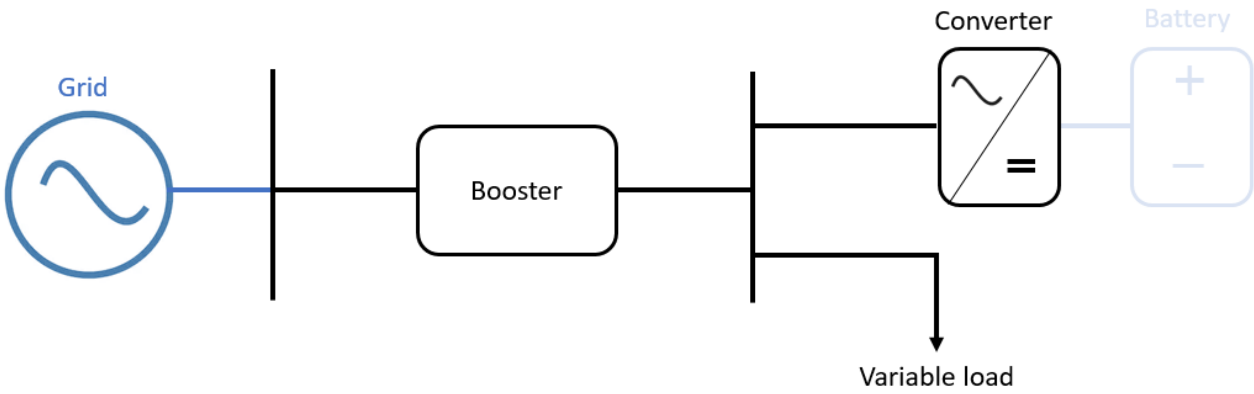

Figure 7: Laboratory setup for case 1: converter and variable load. The black symbols represent physical components, and the blue symbols represent emulated components.

Table 3: Log for converter regulating voltage with droop control, resistor bank in parallel.

Time	Test	Converter voltage setpoint	Label
14:21	No load	232 V Droop control	A
14:28	10 kW load (resistor bank) connected in parallel with converter	232 V Droop control	B
14:34	20 kW load (resistor bank) connected in parallel with converter	232 V Droop control	C

Figure 8 shows the average active power output from the booster for the duration of case 1. The tests with load (B and C) are shown in the figure. From 14:28 to 14:34 (B) the load is 10 kW (3.33 kW per phase), and from 14:34 to 14:37 (C) the load is 20 kW (6.67 kW per phase). In test A the active power output is close to zero, since no load is connected. The spikes that are occurring when there are no changes in load or converter setpoint are most likely due to measurement errors, since no such errors occur in the next cases. The graphs have therefore been cropped to get a better visualization of the events.

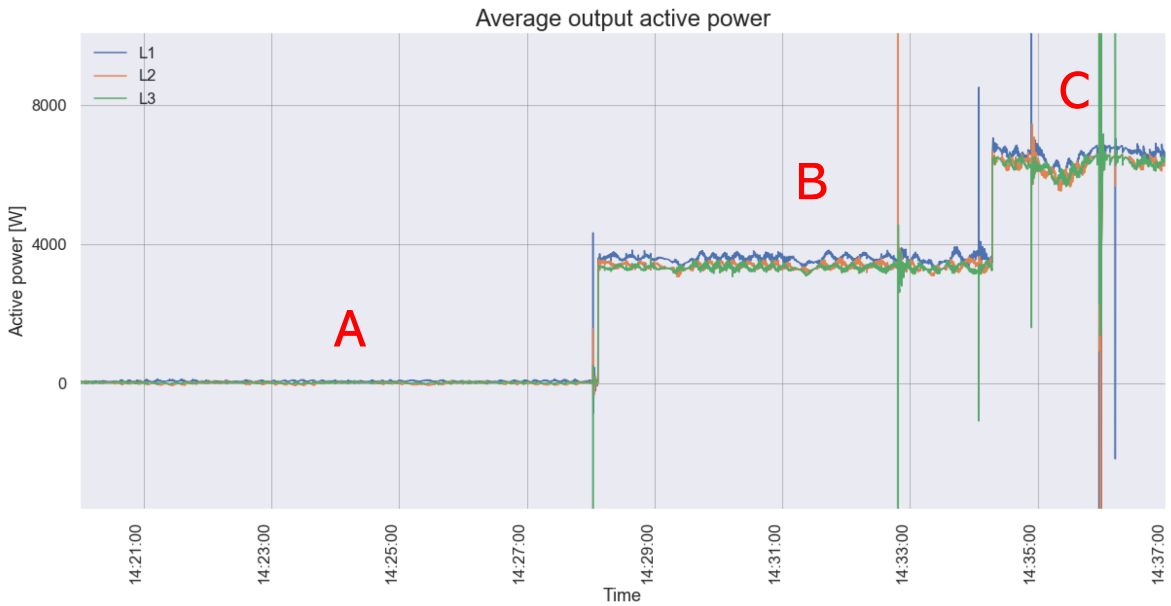

Figure 8: Case 1, average output active power from booster (14:40:00 to 14:44:00).

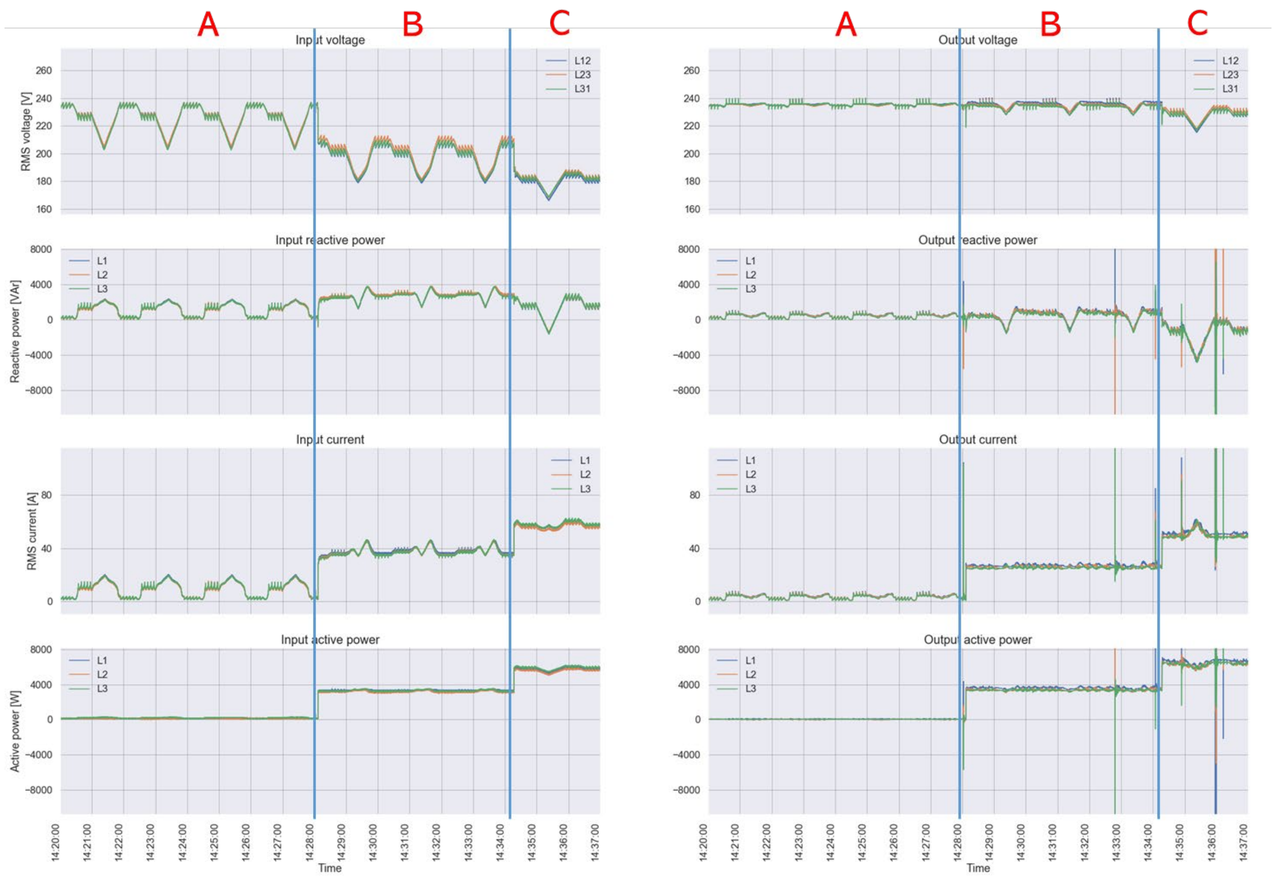

Figure 9: Case 1: converter regulating voltage with droop control, resistor bank in parallel. Input and output voltage, current, active and reactive power.

Figure 9 shows the input and output voltage, reactive power, current and active power for case 1 (14:20:00 to 15:37:00). The tests are labelled A through C as listed in Table 3.

Test A
Figure 10 and Figure 11 shows the input and output voltage, current, active- and reactive power for test A, where the converter setpoint is 232 V and no load is connected. When the input voltage is at its peak (18 kV from MV grid as shown in Figure 4) the OLTC changes tap positions and flattens the peak. The input voltage is below the booster setpoint (235 V) so the booster regulates the voltage. The reactive power drawn by the booster is dependent on the input voltage; when the voltage decreases the reactive power increases, and the resulting output voltage is approximately 235 V, remaining within the limits in FoL. Since the converter setpoint is lower than the booster setpoint, the converter is trying to lower the voltage by consuming reactive power. When the voltage is above 232 V (converter setpoint), the converter is working against the booster and consuming reactive power, which increases losses.

Figure 12 shows a screenshot from the oscilloscope during test 1.A. The graph shows the sinus signal for the input voltage (dark blue) and output voltage (light blue), and the input current (purple) and output current (green). The current signal is distorted by the booster and the converter, which causes distortion to the voltage signal on the output side of the booster.

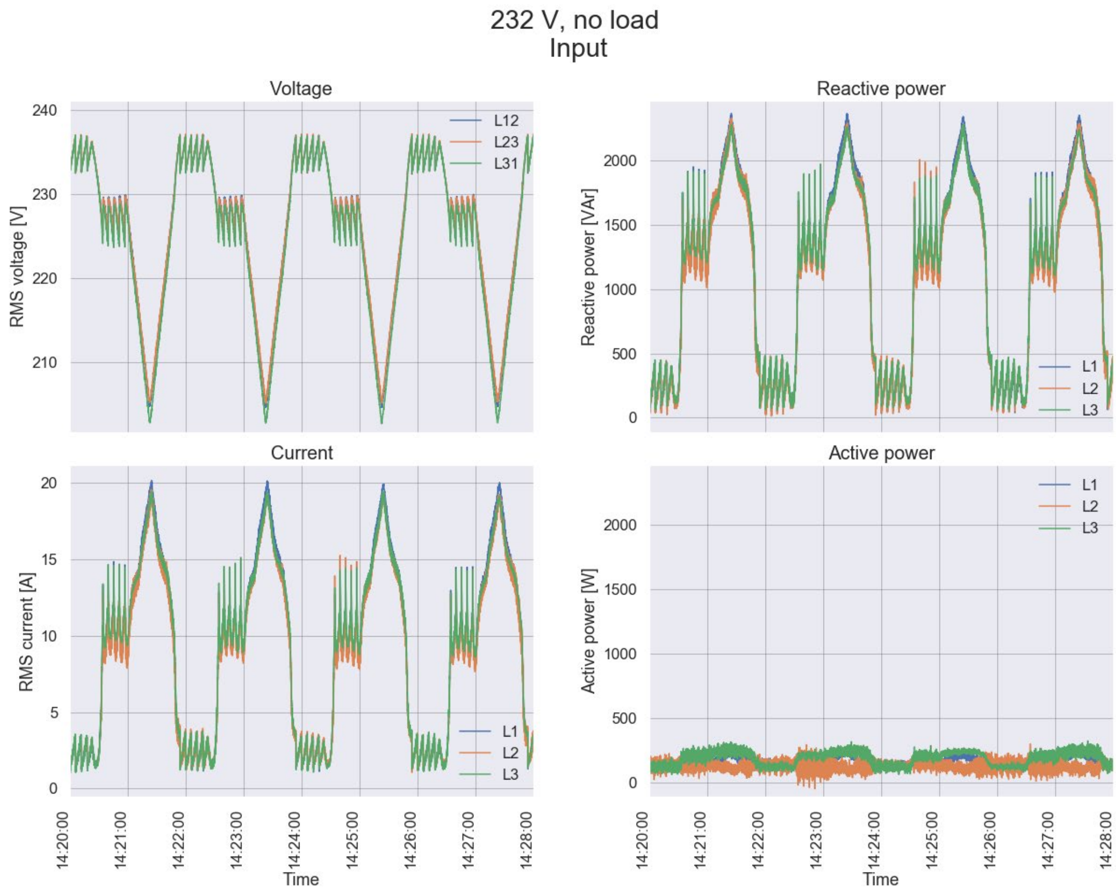

Figure 10: Test 1.A input.

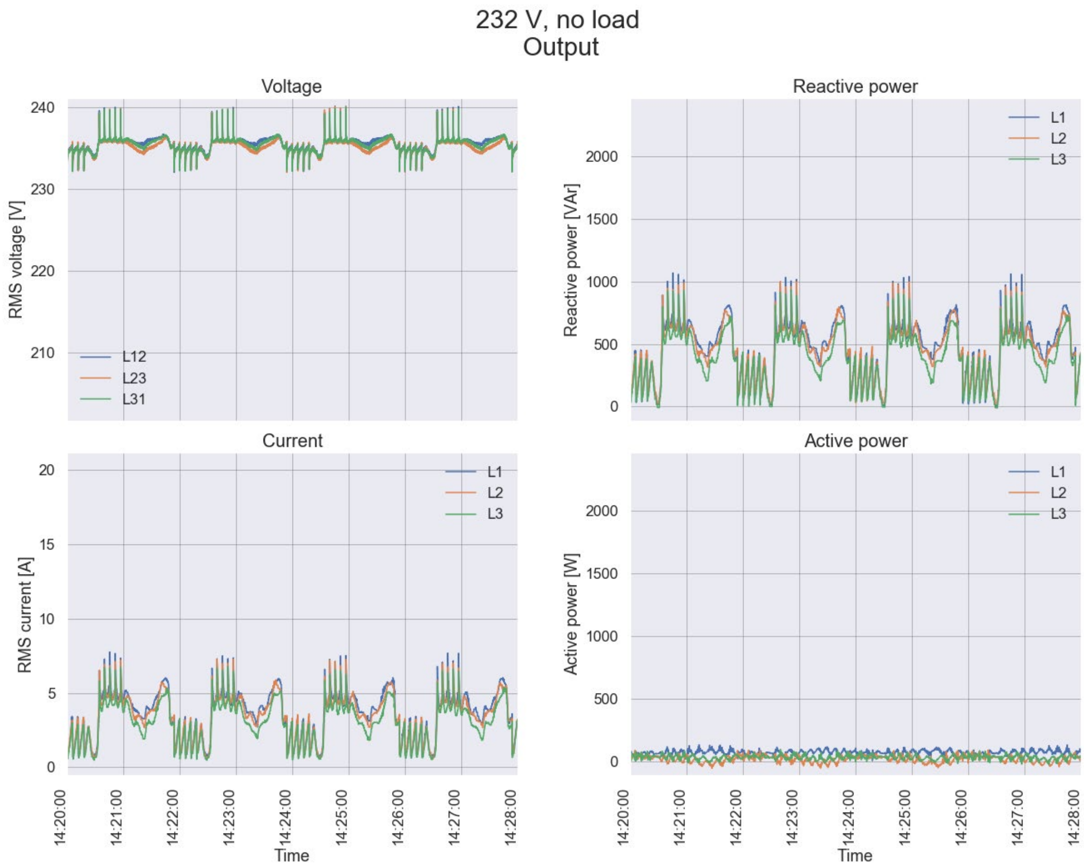

Figure 11: Test 1.A output.

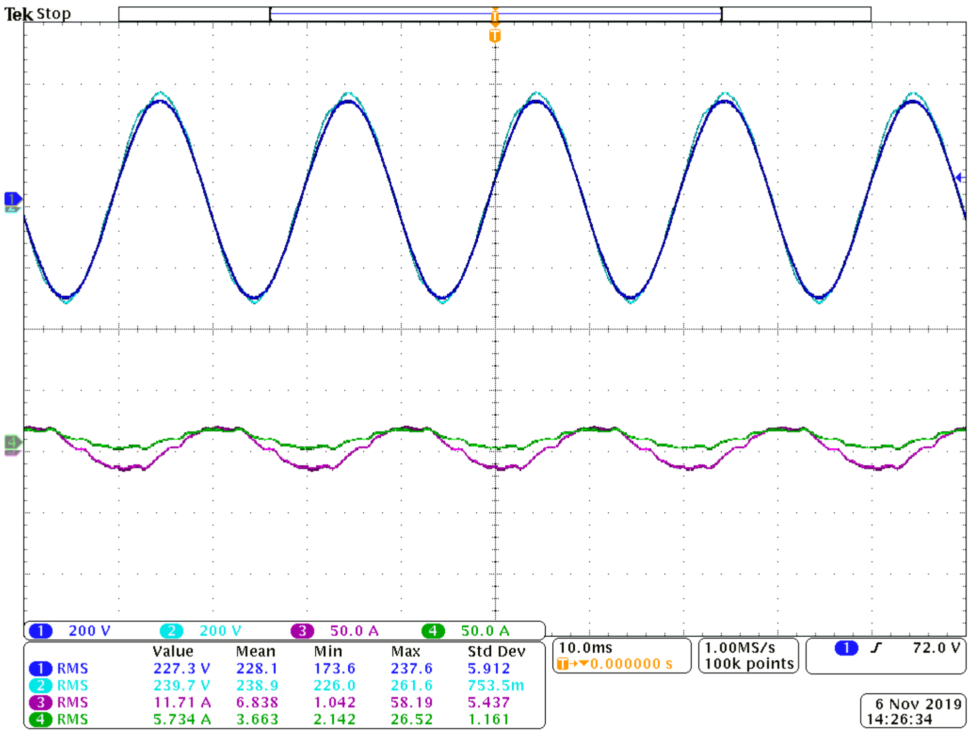

Figure 12: Oscilloscope screenshot tek009 taken at 14:26:34 during test 1.A.

Test B
The spikes that are occurring when there are no changes in load or converter setpoint are most likely due to measurement errors, and the graphs have therefore been cropped to get a better visualization of the curves.

Figure 13 and Figure 14 show the input and output voltage, current, active- and reactive power for test B, where the converter setpoint is 232 V and a 10 kW load (resistor bank) is connected. The input voltage drops considerably when the load is connected, well below both the booster and the converter setpoints. The booster tries to regulate the voltage, drawing up to 12 kVAr (4 kVAr per phase) of reactive power from the grid. However, when the voltage drops below approximately 190 V, the booster no longer manages to boost the voltage up to the setpoint at 235 V. This can be seen from the dips in reactive power in Figure 13 and consequently in the output voltage in Figure 14. At these points, when the booster fails, the converter supports the booster by delivering reactive power to the grid and increasing the voltage. The resulting output voltage remains well within FoL limits, varying from 229 V to 240 V.

Figure 13: Test 1.B input.

Figure 14: Test 1.B output.

Test C

Figure 15 and Figure 16 show the input and output voltage, current, active- and reactive power for test C, where the converter setpoint is 232 V and the load is increased to 20 kW. The graphs have been cropped due to measurement errors, as previously explained. The input voltage drops as low as 170 V when the input voltage is at its lowest, and the booster does not manage to boost the voltage up to the setpoint at 235 V. The converter increases its reactive power regulation, delivering over 12 kVAr at the most, increasing the output voltage to around 230 V.

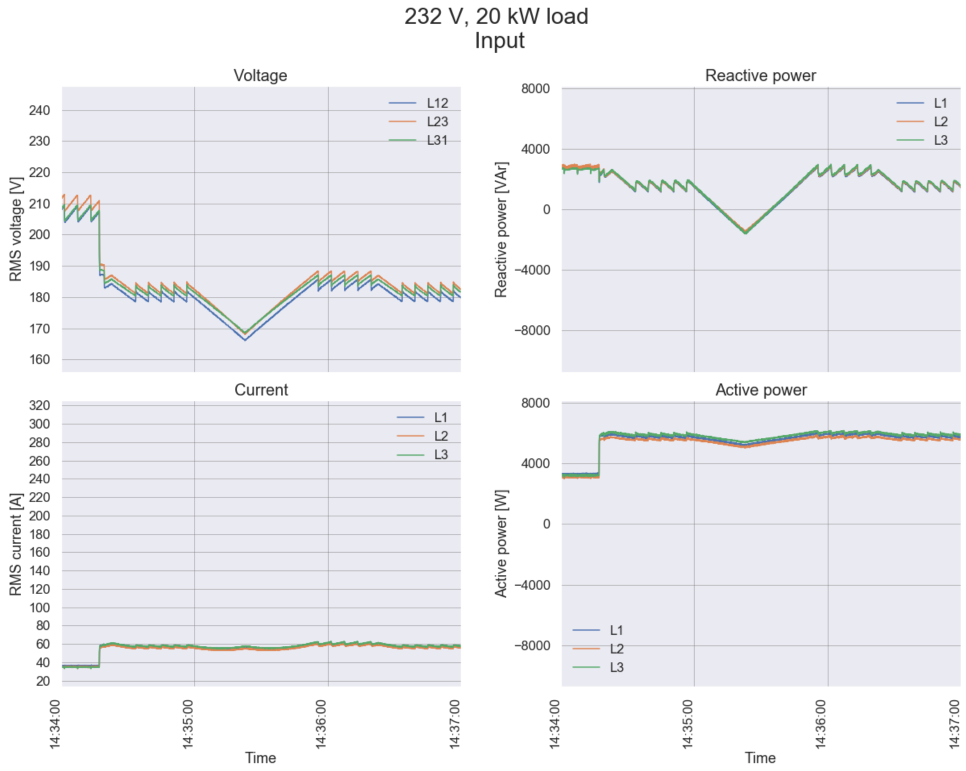

Figure 15: Test 1.C input.

Figure 16: Test 1.C output.

3.2 Case 2: converter regulating voltage with droop control and battery charging/ discharging

In this case, the grid emulator is acting as a battery charging and discharging active power. The converter is also regulating voltage with reactive power with droop control. The voltage setpoint for the converter is changed during the tests, the test log is given in Table 4. When the battery is charging it can represent a load, and when it is discharging it can represent distributed generation. The variable load is not connected in case 2. The setup is given in Figure 17.

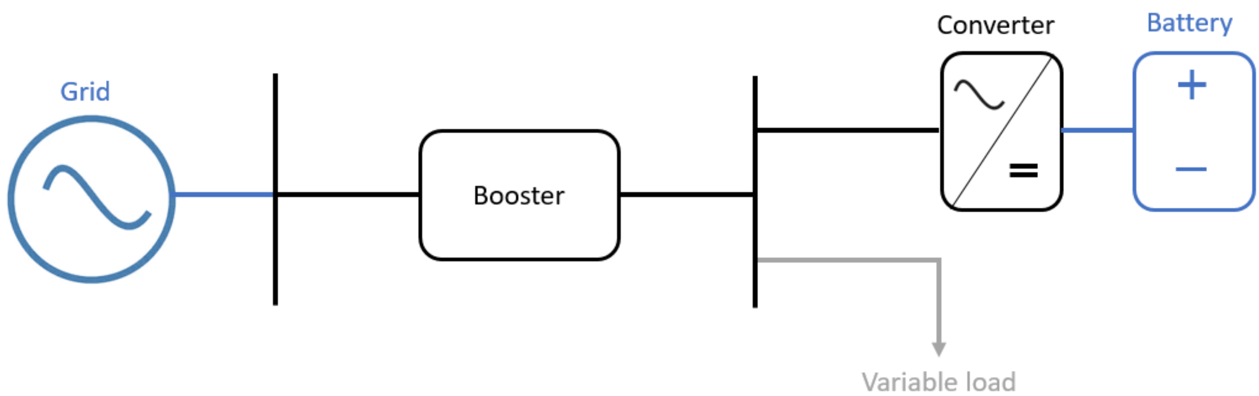

Figure 17: Laboratory setup for case 2: converter and battery. The black symbols represent physical components, and the blue symbols represent emulated components.

Table 4: Log for converter regulating voltage, with droop control, and battery charging/discharging.

Time	Test	Converter voltage setpoint	Label
14:59	Discharging 5 kW	234 V Droop control	A
15:05	Charging 5 kW	234 V Droop control	B
15:08	Charging 5 kW	225 V Droop control	C
15:12	Discharging 10 kW	225 V Droop control	D
15:13	Discharging 5 kW	225 V Droop control	E

Figure 18 shows the average active power output from the booster. The battery operations (charging and discharging) are clearly visible in the figure. From 14:59 to 15:05 (A) the battery is discharging 5 kW (1.67 kW per phase) which results in the negative active power output. From 15:05 to 15:12 (B to C) the battery is charging 5 kW resulting in the positive active power output. At approx. 15:08:40 the converter voltage setpoint is lowered to 225 V. Starting from approx. 15:12 (D) the battery is discharging 10 kW (3.33 kW per phase), and finally from 15:13 (E) the battery is discharging 5 kW.

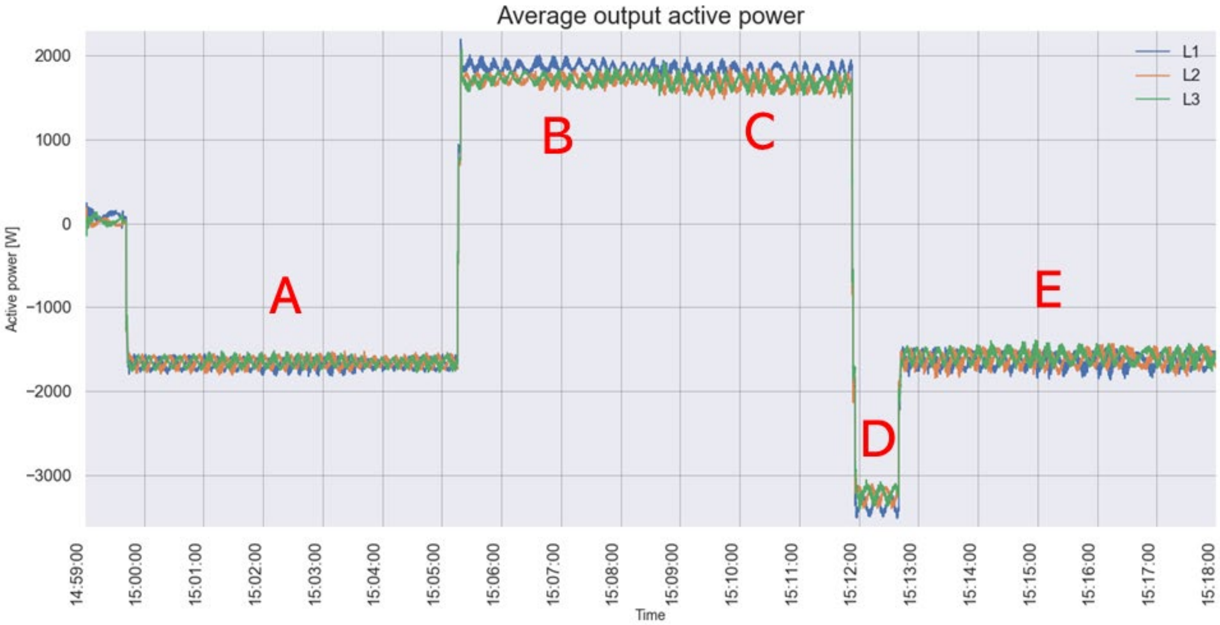

Figure 18: Case 2, average active power output from booster (14:59:00 to 15:18:00).

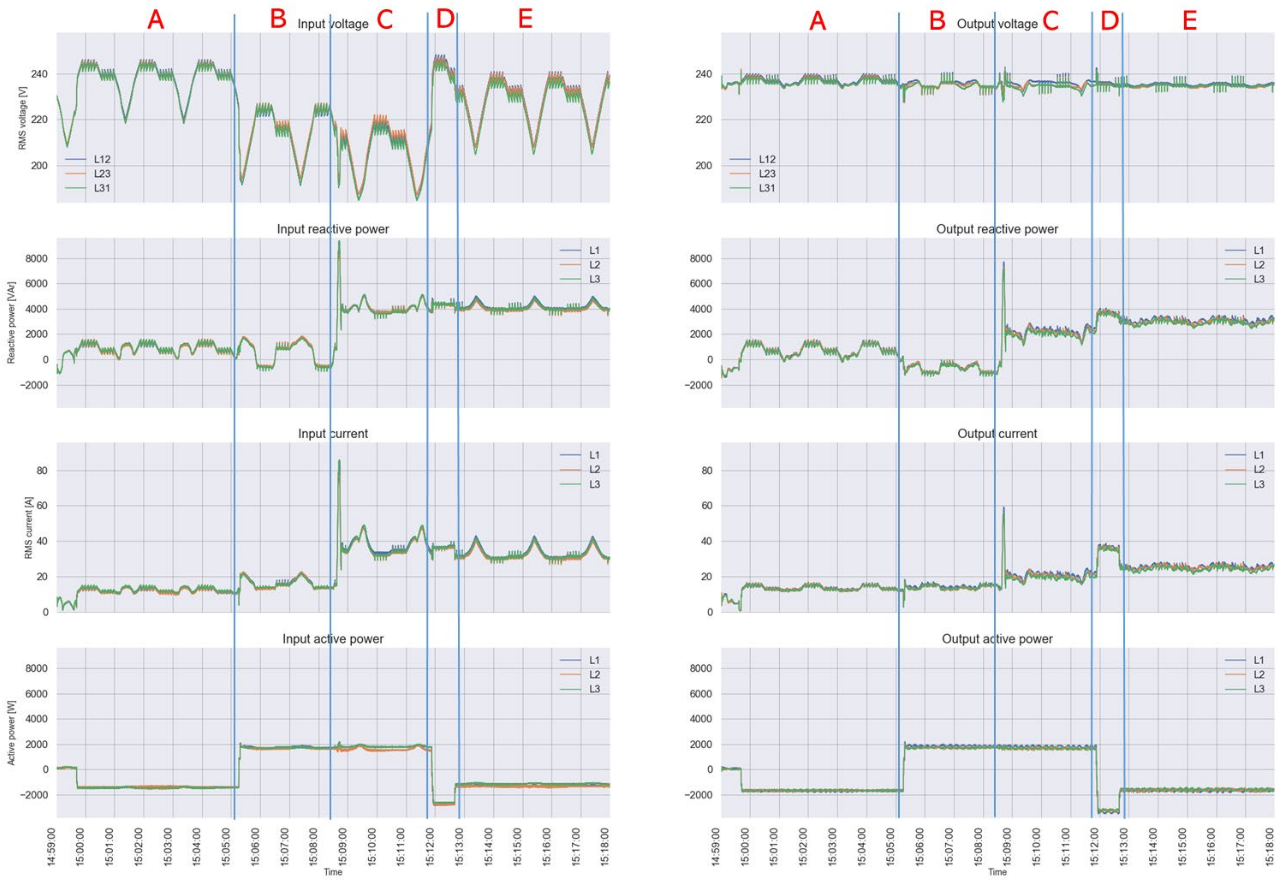

Figure 19: Case 2: converter regulating voltage with droop control and battery charging/discharging. Input and output voltage, current, active and reactive power.

Figure 19 shows the input and output voltage, reactive power, current and active power for the duration of the test (14:59:00 to 15:18:00). The tests are labelled A through E as listed in Table 4. More detailed figures for all tests in case 2 are found in Appendix A.1.

Test A

In test A the battery is discharging 5 kW and the input voltage is varying between 220 V and 245 V. When the input voltage is higher than the booster voltage setpoint, the booster goes into bypass mode and does not regulate the voltage. The output voltage is reduced by the converter, which is consuming reactive power in order to reduce the voltage to its setpoint at 234 V. In the two periods where the voltage drops below the booster setpoint (at approx. 15:01:30 and 15:03:30), the booster begins to regulate the voltage. The reactive power drawn by the booster is dependent on the input voltage. In these two periods, when the booster is regulating the voltage, the converter reduces its reactive power regulation. As a result, the output voltage is varying around approx. 235 V for the duration of the test. Figure 31 (input) and Figure 32 (output) are given in Appendix A.1.

Test B

In test B the battery is charging 5 kW (acting as a load). The setpoint is still 234 V. Due to the charging, the input voltage is reduced, and the voltage is now below the booster setpoint, so the booster is regulating the voltage. The converter voltage is below the setpoint, so the converter is delivering reactive power to the grid to increase the voltage. The output voltage is still around 235 V. Figure 33 (input) and Figure 34 (output) are given in Appendix A.1.

Test C

At 15:08:45 the converter voltage setpoint is changed to 225 V, resulting in a peak in current and power and a voltage dip. The battery is still charging 5 kW. The input voltage is lower than the booster setpoint, consequently the booster is regulating the voltage. The converter voltage is now significantly higher than the setpoint, and the converter is therefore consuming reactive power to reduce it. Both the booster and the converter are at this point regulating the voltage and the reactive power flow is high. This causes a high current flow and consequently high losses in the test system. For comparison: A 10 kW load will without reactive power flow draw a current of approximately 25 A. This means that in the period with high reactive power flow (when the battery is discharging 10 kW) the current increases with nearly 15 A. This can be observed in Figure 35 (input) and Figure 36 (output) that are given in Appendix A.1.

Figure 20 shows a screenshot of the oscilloscope during test C, and the signal distortions, mentioned in chapter 3.1, are clearly visible.

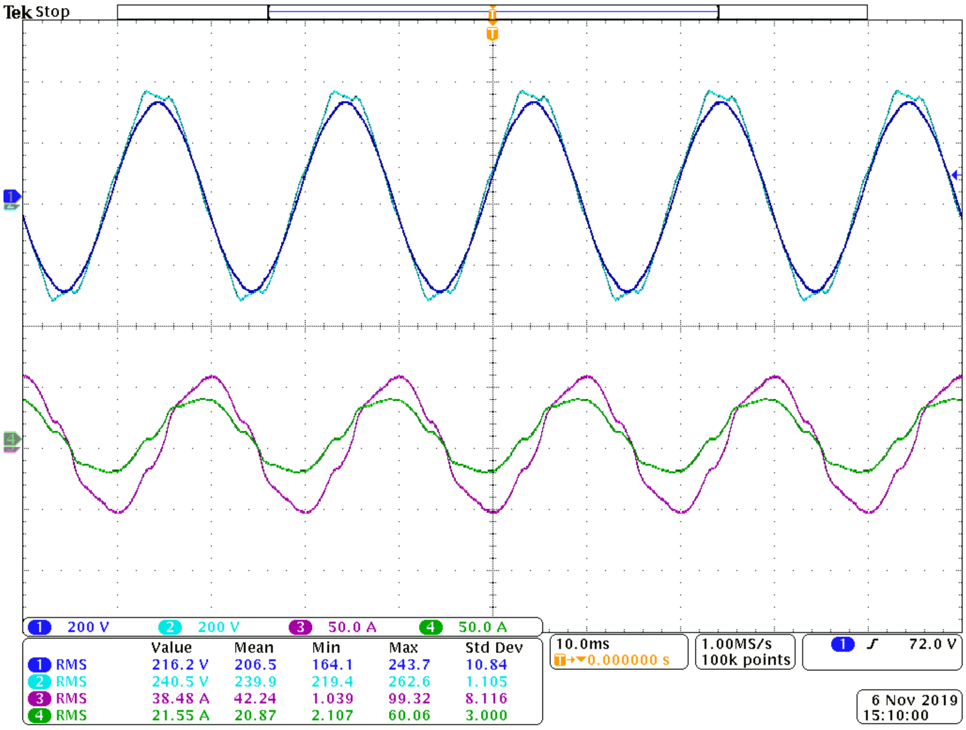

Figure 20: Oscilloscope screenshot tek0011 taken at 15:10:00 during test 2.C.

Test D

At 15:11:53 the battery is discharging 10 kW. This causes the input voltage to increase above the booster setpoint and the booster stops regulating. The converter is consuming reactive power and decreases the voltage from over 240 V to around 235 V.

Test E

The active power discharge from the battery is now reduced from 10 kW to 5 kW. The booster regulates when the input voltage is below its setpoint. The converter is still consuming reactive power to lower the voltage and the resulting reactive power flow is high. See Figure 37 (input) and Figure 38 (output) in Appendix A.1.

When the converter voltage setpoint is lower than the booster setpoint and both the converter and the booster are regulating the voltage, the reactive power flow is high. This is a sign of poor regulator settings and it results in high losses. The voltage remains within FoL limits during all tests in case 2.

3.3 Case 3: converter regulating voltage without droop control and battery charging/ discharging

In case 3, the converter does not have droop control when regulating the voltage and the voltage setpoint is changed in each test. Some tests are performed with the battery charging/discharging. The different tests are listed in Table 5 and the laboratory setup is given in Figure 21. This setup is equal to the setup in case 2.

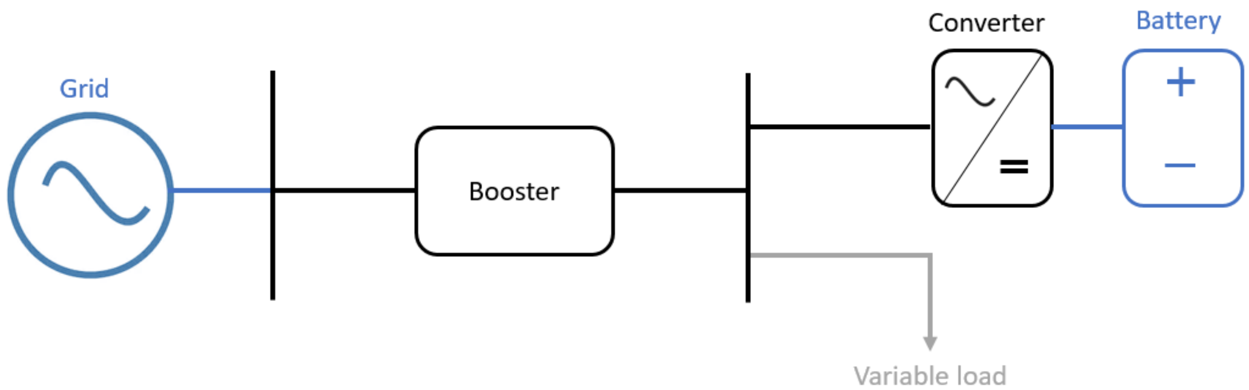

Figure 21: Laboratory setup for case 3: converter and battery. The black symbols represent physical components, and the blue symbols represent emulated components.

Table 5: Log for converter regulating voltage, without droop control, and battery charging or discharging.

Time	Test	Converter voltage setpoint	Label
15:18	Converter consuming reactive power	225 V	A
15:28	Converter consuming reactive power	234 V No droop	B
15:30	Battery discharging 5 kW	234 V No droop	C
15:32	Battery charging 5 kW	234 V No droop	D
15:35	Converter only regulating voltage	234 V No droop	E
15:37	Converter only regulating voltage	227 V No droop	F
15:42	Converter only regulating voltage	240 V No droop	G

From the active power in Figure 22 the periods where the battery is charging/discharging (C and D) are clearly visible. Figure 23 shows the input and output voltage, reactive power, current and active power for the duration of the tests (15:18:00 to 15:47:00). The tests are labelled A through G as listed in Table 5. More detailed figures for all tests in case 3 are found in Appendix A.2.

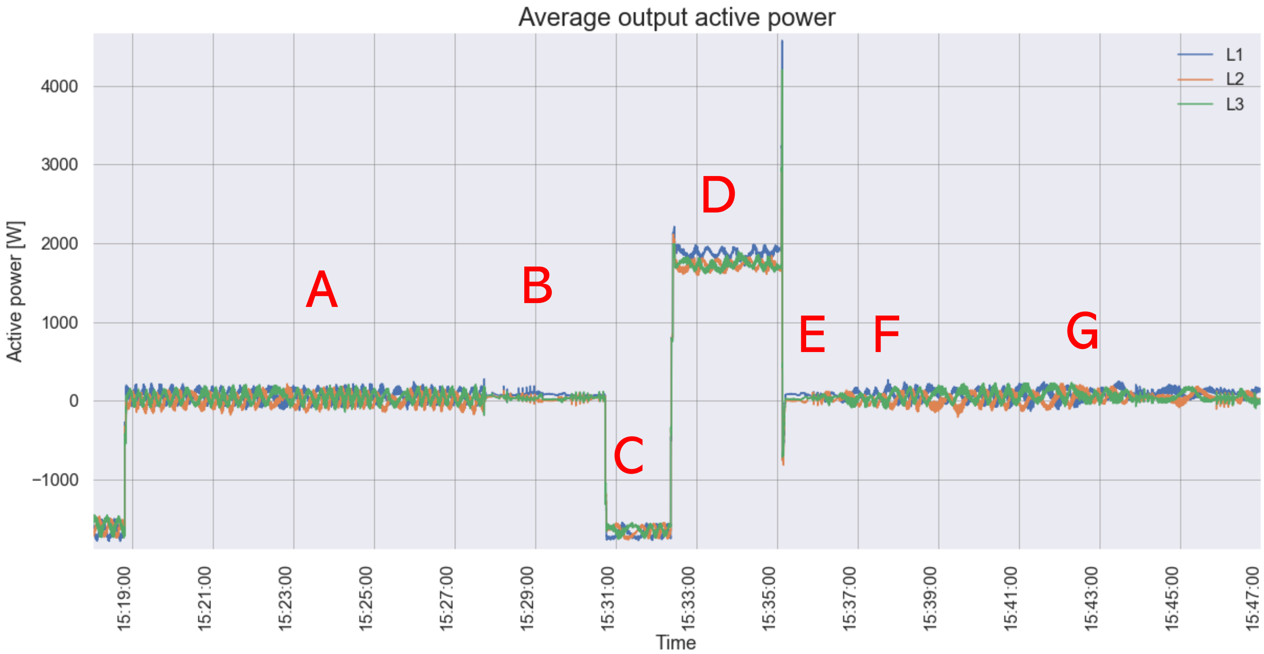

Figure 22: Case 3: average active power output from booster (15:18:00 to 15:47:00).

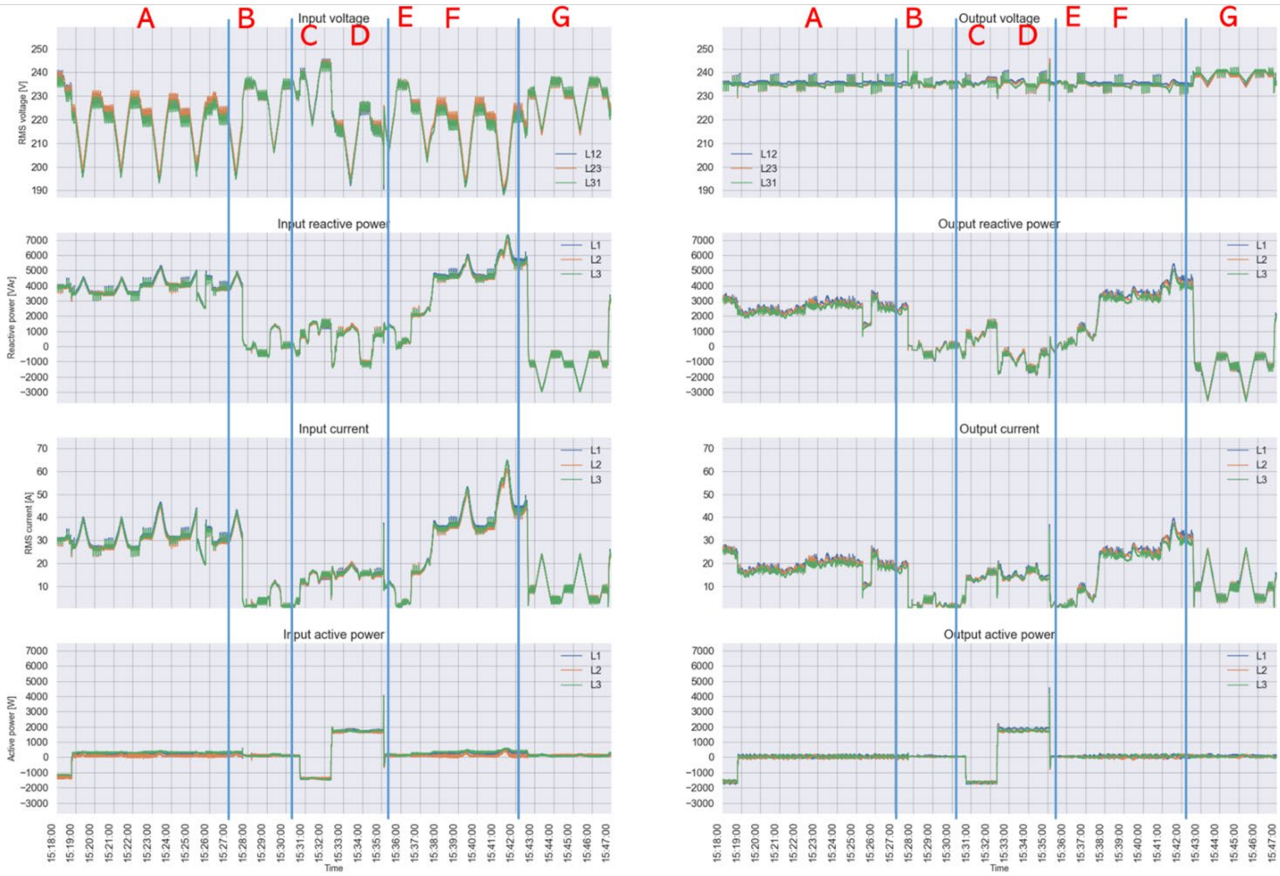

Figure 23: Case 3: converter regulating voltage without droop control and battery charging/discharging. Input and output voltage, current, active and reactive power.

Test A and B

In test A the converter setpoint is 225 V, which is lower than the booster setpoint (235 V), so the converter is consuming a lot of reactive power to decrease the voltage. Simultaneously the booster is boosting the voltage, also consuming a lot of reactive power, which means that the resulting losses are high. The output voltage remains at 235 V. In test B the converter setpoint is increased to 234 V, which decreases the overall flow of reactive power since the two regulators are not working against each other.

Test C and D

The situation in test C (Figure 43 and Figure 44) is the same as test 2.A (Figure 31 and Figure 32), but without droop control, and no distinct difference can be seen in the regulation. The output voltage in both tests is around 235 V. Test D (Figure 45 and Figure 46) is the same as test 2.B (Figure 33 and Figure 34), but without droop control. The reactive power flow is slightly higher with no droop compared to tests with droop, and although the output voltage in both tests is 235 V with no violation of FoL, the losses will be slightly higher without droop control. However, since the input voltage is different for the two tests, it is hard to compare them exact.

Test E, F and G

In tests E, F and G the converter is only used for regulating voltage, and the setpoint is changed from 232 V to 227 V in F and 240 V in G. From Figure 23 it can be seen that during these tests, from 15:35 to 15:47, the output voltage is never below 230 V and only slightly above 240 V in G. In other words the voltage is relatively constant. When the converter setpoint is reduced to 227 V this does not appear to affect the output voltage much, but the reactive power flow increases up to 16 kVAr when both the booster and converter are consuming reactive power. The converter consumes reactive power to decrease the voltage and the booster consumes reactive power from the grid to increase the voltage. In test G the converter setpoint is set to 240 V, which is higher than the booster setpoint. In the periods when the voltage is over the booster setpoint at 235 V, the booster is in bypass mode and only the converter is regulating the voltage. The converter manages to stabilize the voltage at around 240 V, except in the periods when the input voltage is below 235 V. The figures for the individual tests are given in Figure 47 to Figure 52 in Appendix A.2. Figure 24 shows a screenshot from the oscilloscope taken during test F.

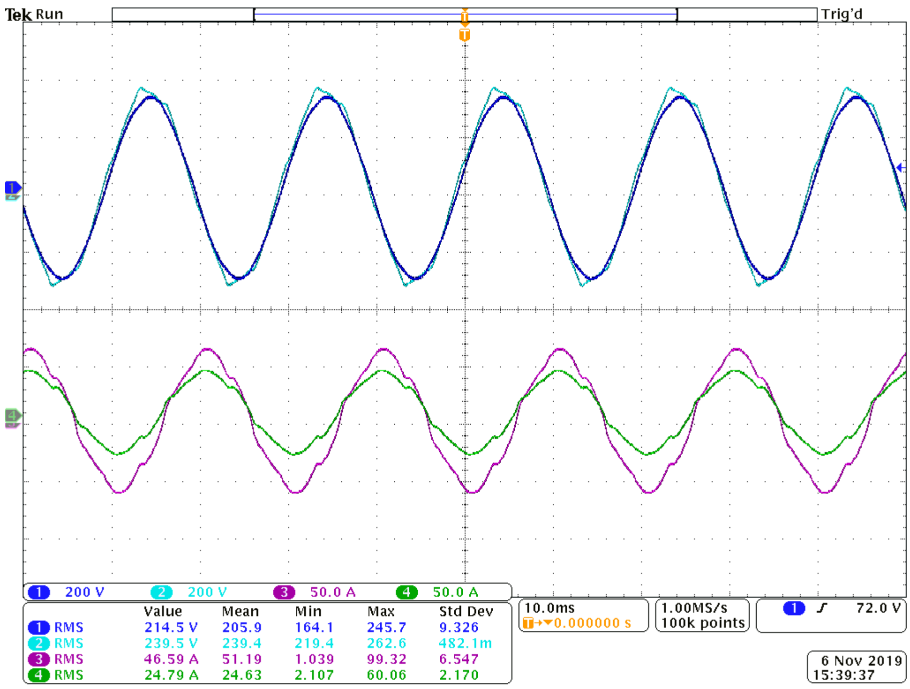

Figure 24: Oscilloscope screenshot tek0012 taken at 15:39:37 during test 3.F.

3.4 Case 4: converter regulating voltage with step response

In this case, the converter is regulating voltage with step response (no droop control) and a resistor bank is connected as load, see Figure 25. There is no emulated battery (no charging/discharging).

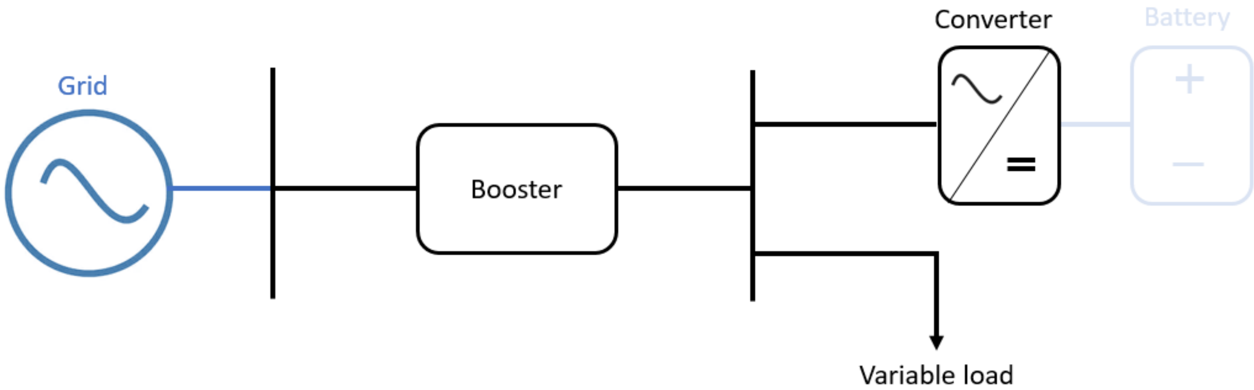

Figure 25: Laboratory setup for case 4: converter and variable load. The black symbols represent physical components, and the blue symbols represent emulated components.

Table 6: Log for converter regulating voltage, with resistor bank as load, testing step response.

Time	Test	Converter voltage setpoint (V)	Label
15:48	Converter only regulating voltage, connecting resistor bank 10 kW	240 V No droop	A
15:50	Converter only regulating voltage, connecting resistor bank 20 kW	240 V No droop	B
15:51	Step response (0-20 kW)	240 V	C

The average active power output is given in Figure 26. From 15:48 to 15:50 (A) the load is 10 kW, from 15:50:30 (B) the load is 20 kW, and from 15:51:45 (C) there are step changes in the load, between 0 kW and 20 kW. The input and output voltage, current, active and reactive power for the case is shown in Figure 27. More detailed figures for all tests are found in Appendix A.3.

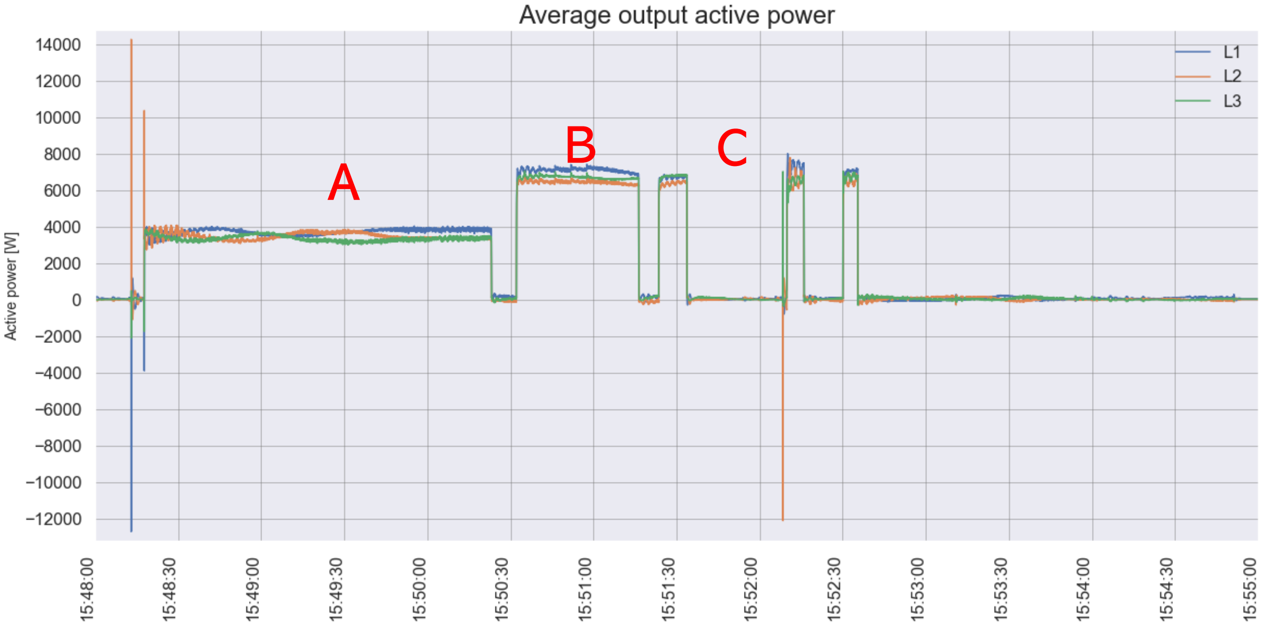

Figure 26: Case 4, average active power output from booster (15:48:00 to 15:55:00).

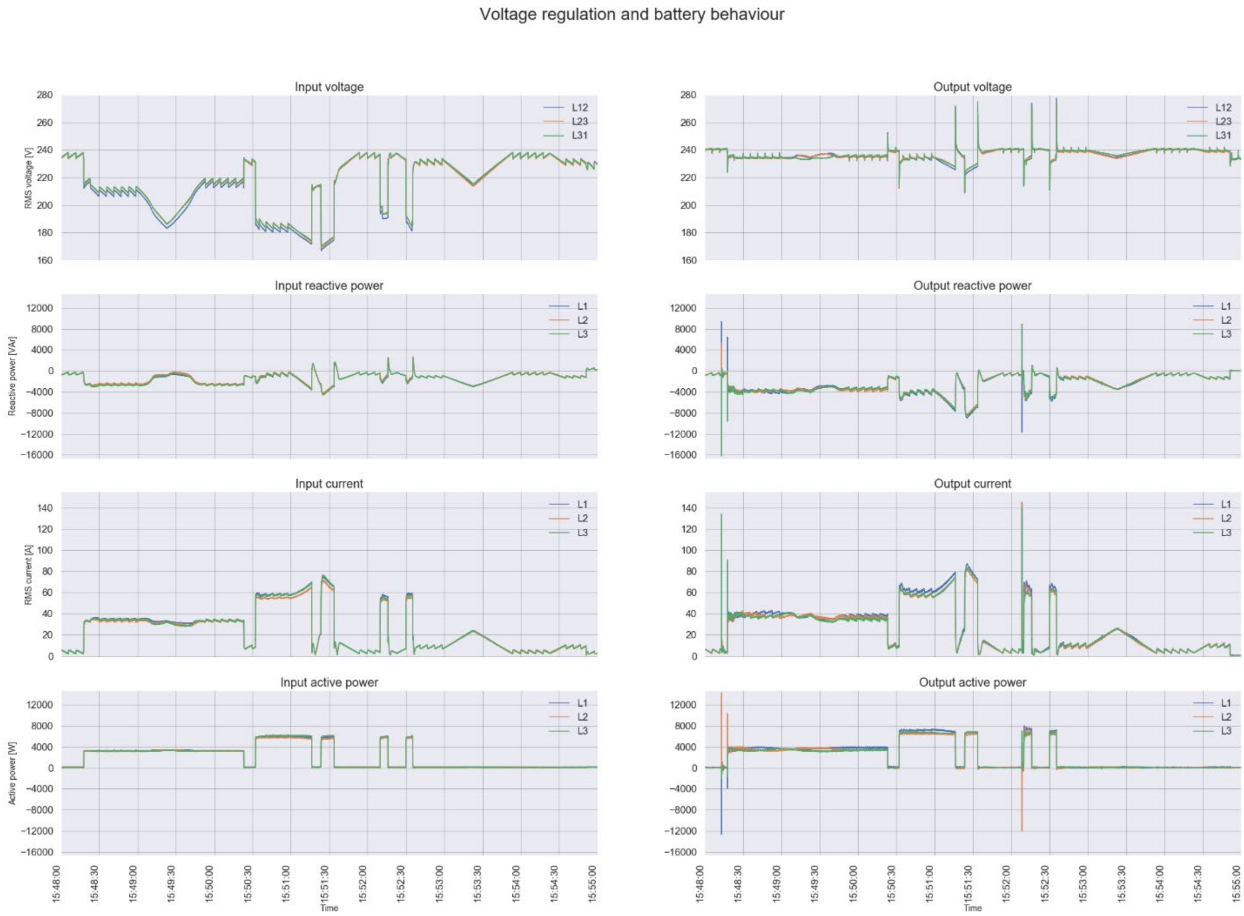

Figure 27: Case 4: converter regulating voltage with step response. Input and output voltage, current, active and reactive power.

Figure 53 and Figure 54 in Appendix A.3 show the input and output measurements for the step response (B and C). The changes in load are reflected in the sudden voltage drops in the input voltage and the surges in reactive power. The load changes cause peaks in the output voltage that are above the FoL limit by 20-30 V.

Figure 28 and Figure 29 show the step change in load at around 15:51:30. The input voltage drops from 215 to 170 V during the load change, when the booster goes into bypass mode. The converter produces a lot of reactive power and increases the output voltage to 230 V at the time when the load is disconnected again. This causes the input voltage to increase, and the booster begins to boost the voltage. This results in a voltage swell to almost 280 V, and it takes approx. 4 seconds for the voltage to stabilize at 240 V. A maximum of 24 voltage swells are allowed in a 24-hour period according to FoL, so this type of voltage regulation will not be sufficient in areas of the network with frequent load changes.

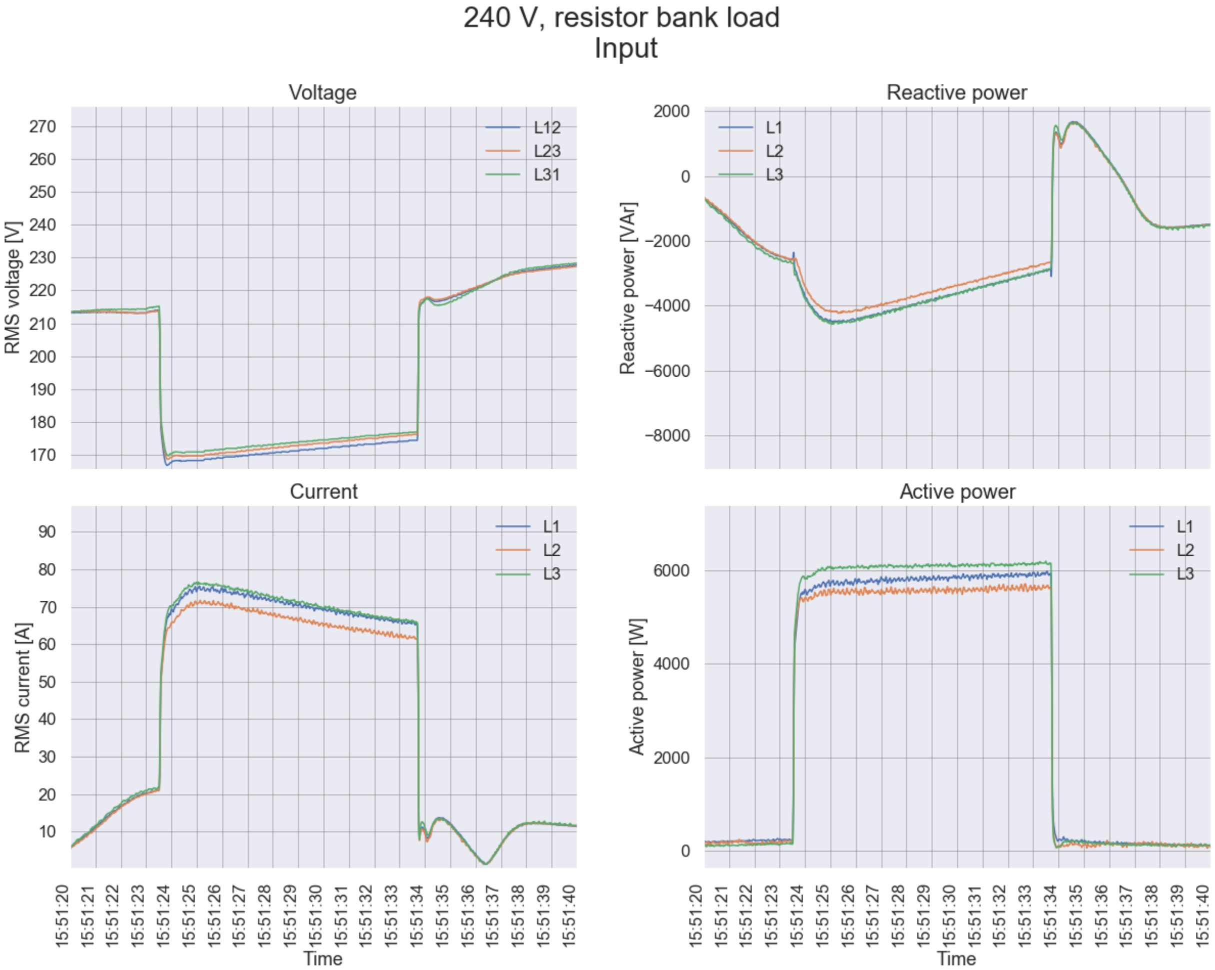

Figure 28: Test 4 step change in load, input.

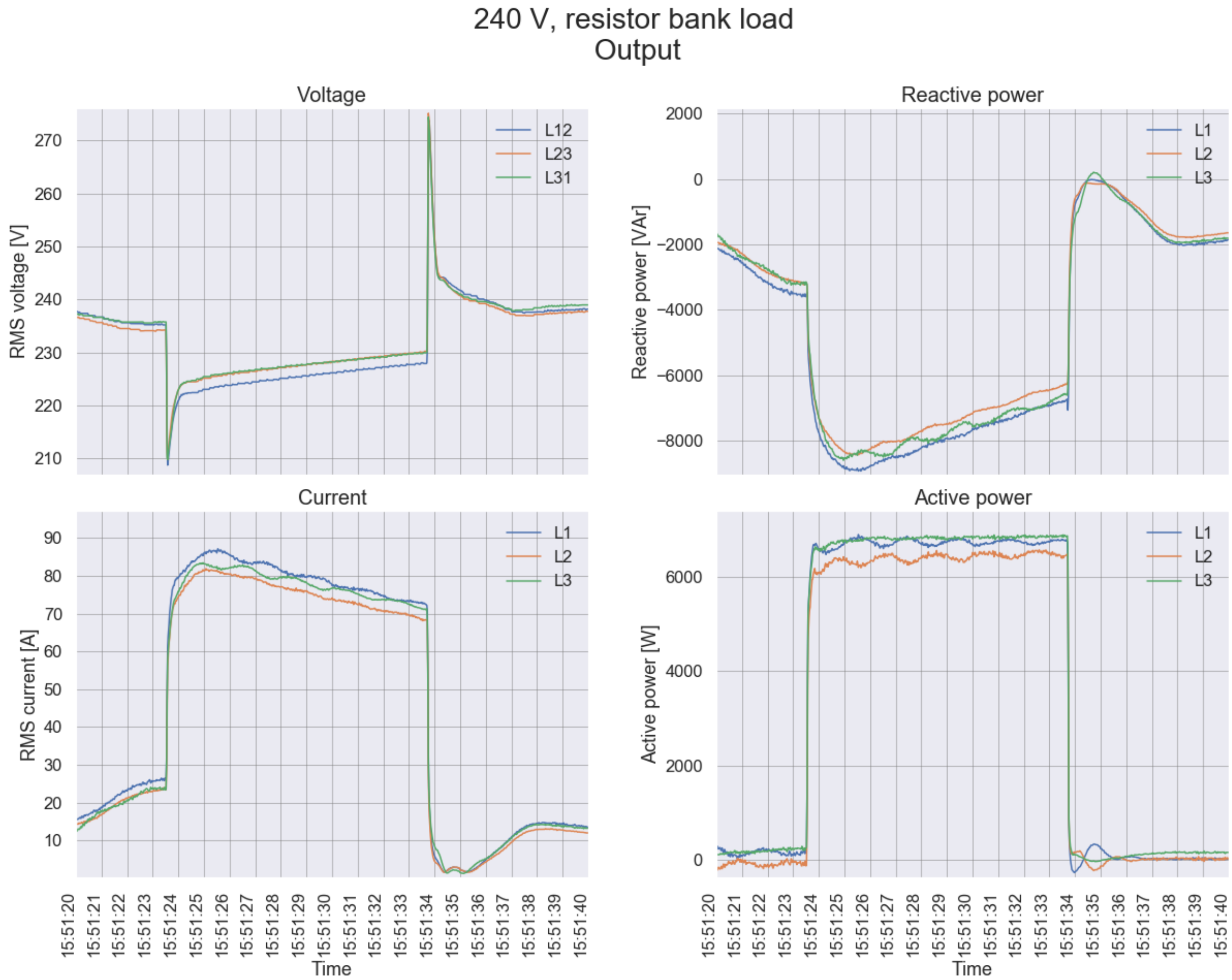

Figure 29: Test 4 step change in load, output.

Figure 30 shows the oscilloscope screenshot taken at 15:49:03, during test A.

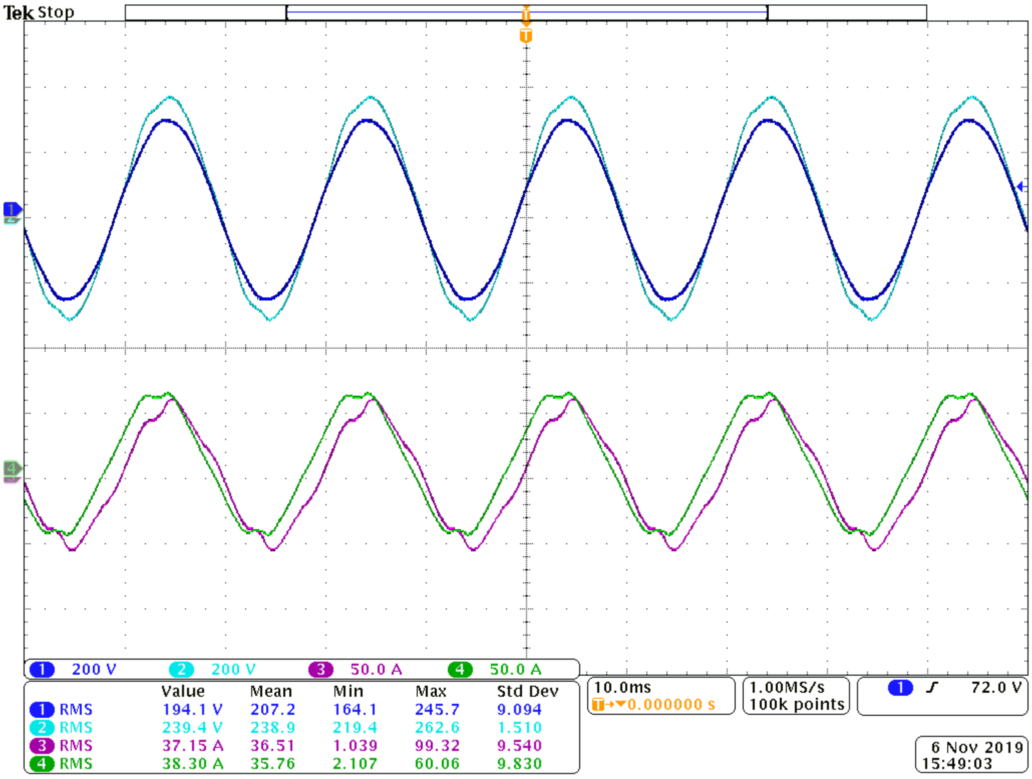

Figure 30: Oscilloscope screenshot tek0013 taken at 15:49:03 during test 4.A.

3.5 Elvia demo with booster and battery

Elvia has conducted a demo with a voltage booster and battery in a weak low-voltage distribution grid, demo Mysen. The problems at Mysen were low short circuit capacity, supply voltage variations, asymmetry and voltage dips below 200 V during start-up of high-power equipment. A voltage booster was installed to remedy these problems, but it was too slow to handle the rapid voltage changes. The customer is a private household at the end of a long radial. The idea in Mysen was to combine the voltage booster (to handle asymmetry and slow voltage variations) with a small battery (to handle the rapid voltage changes), and develop a standardised solution that can be used in other areas of the grid with similar issues.

The system was first tested in a lab prior to installation in the grid in July 2019. The results from the lab test showed that the booster kept the (long term) voltage around 230 V, but it did not handle rapid voltage dips below 200 V. When the battery was connected, the voltage was kept between 225-235 V. In November 2019, the battery system was installed at the customer. The battery control is set to limit the current from the grid to 14 A, and the rest of the load is covered by the battery. This limit of 14 A (maximum current from the grid) is I_{max}. The voltage quality was improved immediately, but with some occurrence of voltage swells. This issue can also be seen in the results from the tests in the smartgrid lab when large voltage changes occur while the booster is still "attending to" a previous voltage change.

The current conclusion from the case is that the booster and battery combination works better than just booster alone. However, the setpoint for I_{max} should be continuously updated based on the power demand at the given time. For I_{max} to be continuously updated, an automatic control is required. Further, as derived from the results in this memo, for the battery and booster to collaborate rather than work against each other, the regulator settings should be chosen accordingly.

4 Summary and discussion

This memo has summarised the results of the tests performed in the Smart Grid laboratory with an on-load tap changing (OLTC) transformer, a voltage booster and a converter/battery system. Several tests have been performed to analyse the behaviour of the regulators in different cases. The first case used the converter as a voltage regulator with a resistor bank in parallel. In case 2 and 3 the grid emulator was emulating a battery charging and discharging active power while the converter regulated the voltage both with and without droop control. Finally, in case 4 the converter step response was tested with a resistor bank as a variable load.

The settings for the OLTC were unchanged during all tests, and its behaviour during all tests was consistent. The weight of the discussion is therefore on the interactions between the booster and the converter.

A summary of the most important observations from the four cases are listed below:

- The booster fails to boost the voltage up to the setpoint at 235 V when the input voltage drops too low and it goes into bypass mode. At these points the converter delivers reactive power to the grid to increase the voltage, see for example test 1.B in Figure 13 and Figure 14.
- When the converter voltage setpoint is lower than the booster setpoint and both the converter and the booster are regulating the voltage, the reactive power flow is high. The converter draws reactive power to decrease the voltage and the booster draws reactive power from the grid to increase the voltage. This is a sign of poor regulator settings and it results in high losses. This happens in case 2 test C, D and E when the converter setpoint is 225 V, see Figure 35 to Figure 38 in Appendix A.1.
- When the converter voltage setpoint is close to the voltage setpoint of the booster, the reactive power flow is lower since the two regulators are not working against each other.
- The reactive power flow is slightly higher when the converter regulates *without* droop control, and although the output voltage in both tests is 235 V with no violation of FoL, the losses will be slightly higher in the tests without droop control.
- The step regulation in case 4 causes voltage swells, see Figure 28 and Figure 29. A maximum of 24 rapid voltage changes are allowed in a 24-hour period, so this type of regulation will not be sufficient to regulate frequent load changes.

The booster can only boost the voltage if it is within its bandwidth, meaning that if the voltage is higher than the booster setpoint, or lower than 180-190 V, the booster goes into bypass mode and does not boost the voltage. At these points, the converter is the only regulator (apart from the OLTC) that is regulating the voltage, and it manages to keep the voltage within the FoL-limits in almost every test. In these situations, and when the booster and converter have the same voltage setpoint, they work together to keep the voltage at the setpoint and manage to do so without drawing too much reactive power. When they do not have the same setpoint they work against each other, causing a high reactive power flow and consequently high losses. Although the losses are high, the output voltage remains within FoL limits in all tests except for the step response in case 4. To summarize, the regulators manage to keep the voltage within acceptable limits, ensuring quality of supply.

The three regulators are in these tests working to keep the voltage at a setpoint that is quite high (235-240 V) and they are therefore producing and consuming a significant amount of reactive power to sustain this setpoint. This is not strictly necessary since the FoL limits allow for a wider voltage range (207-253 V). It is therefore important to set the regulators to the correct voltage setpoints depending on where in the grid they are located and what is the normal operating voltage in that area.

5 References

[1] J. H. Harlow, *Electric Power Transformer Engineering*. CRC Press, 2007.

A Appendix

A.1 Case 2

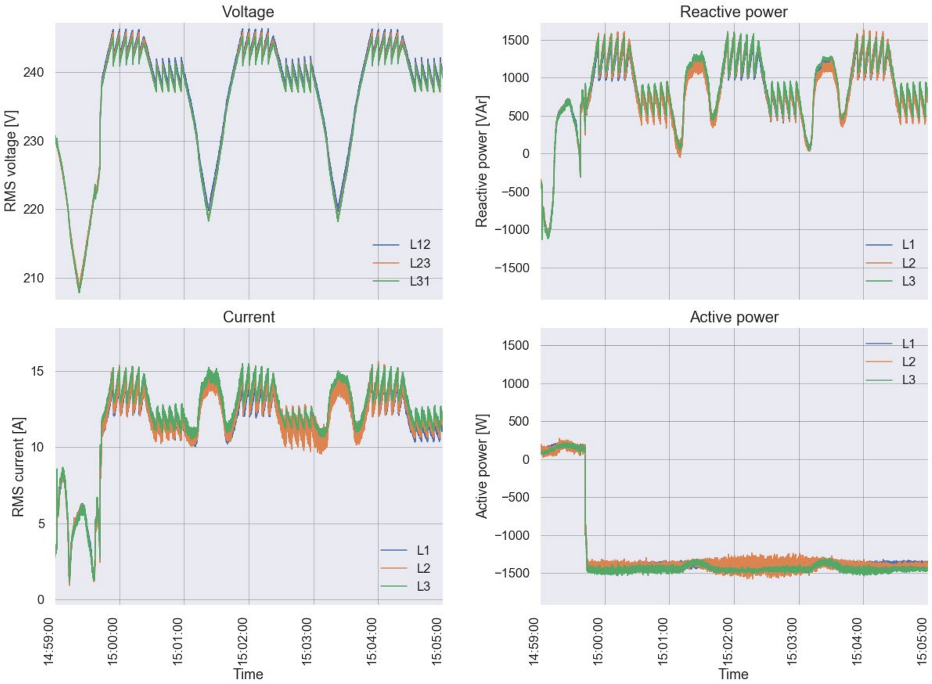

Figure 31: Test 2.A input. 234 V, discharging 5 kW.

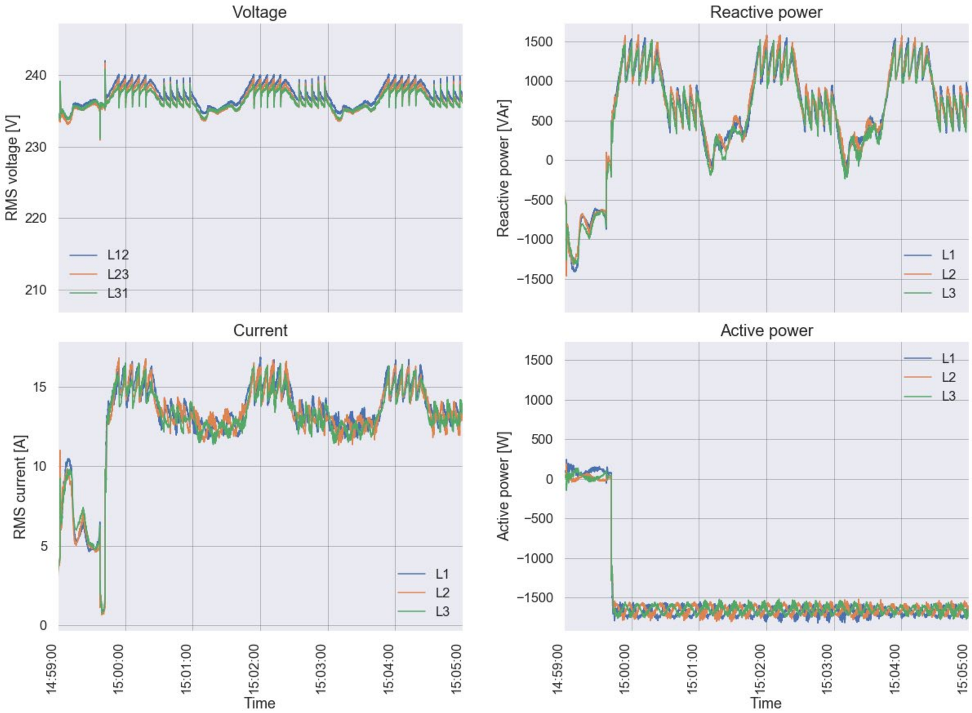

Figure 32: Test 2.A output. 234 V, discharging 5 kW.

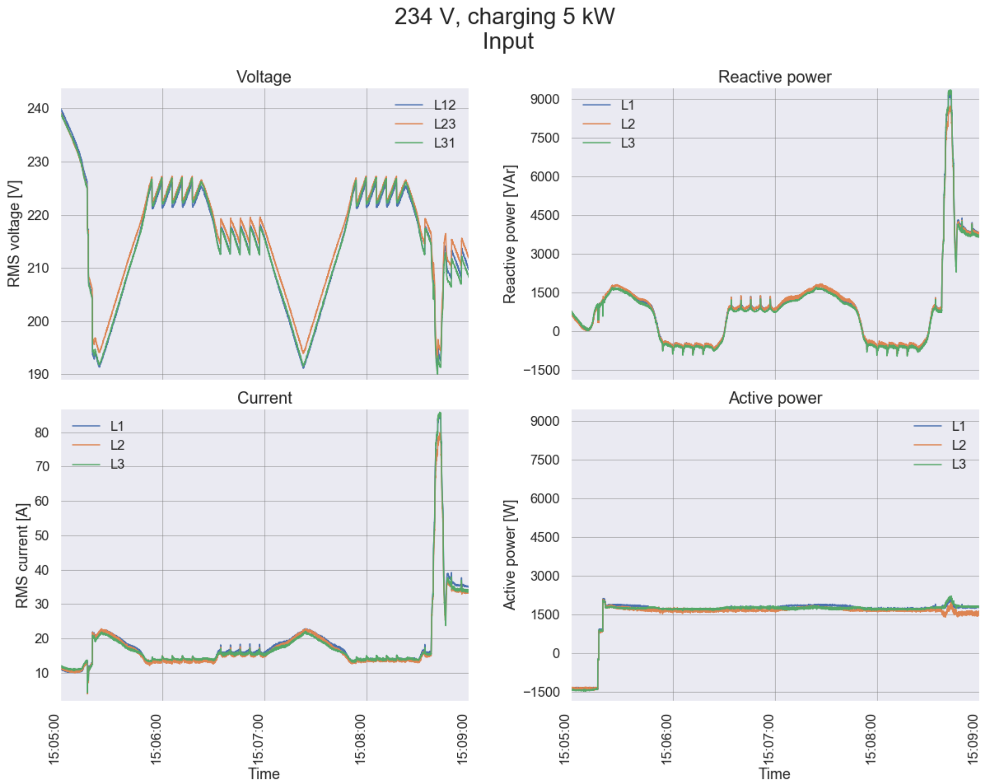

Figure 33: Test 2.B input.

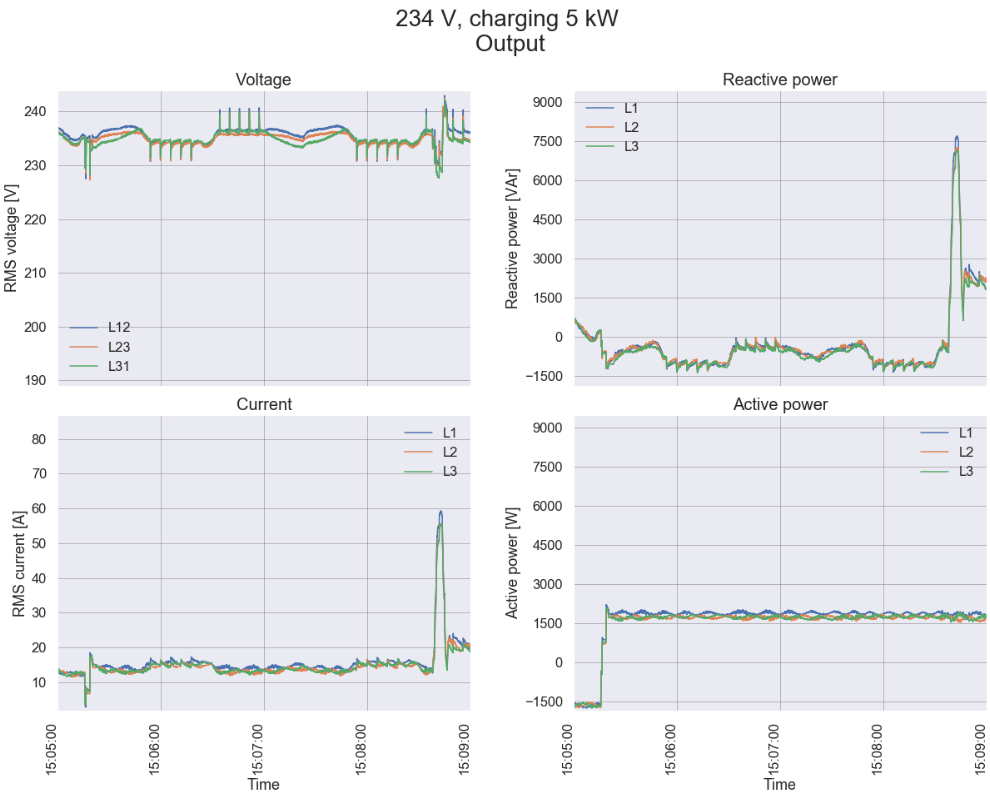

Figure 34: Test 2.B output.

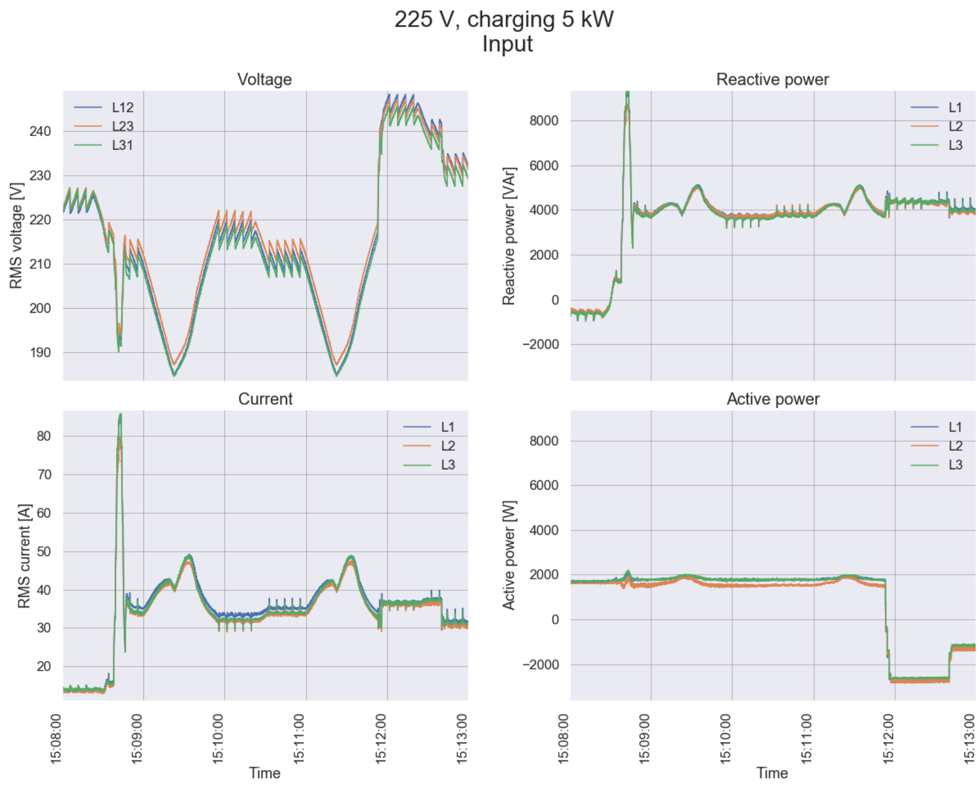

Figure 35: Test 2.C input.

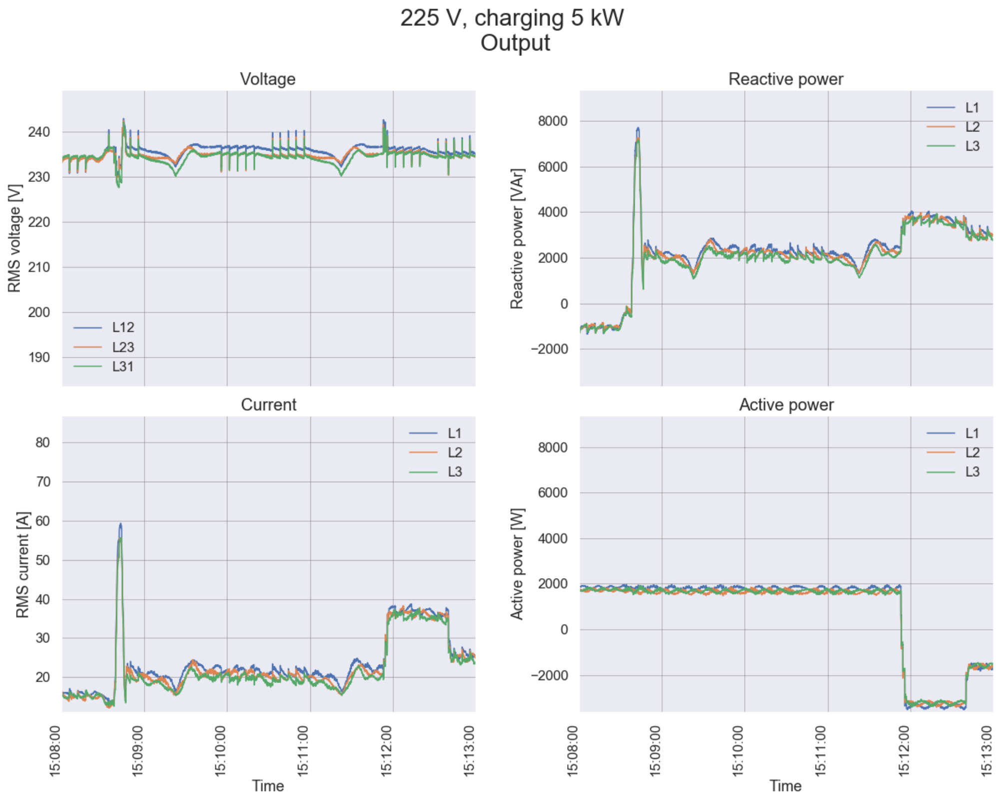

Figure 36: Test 2.C output.

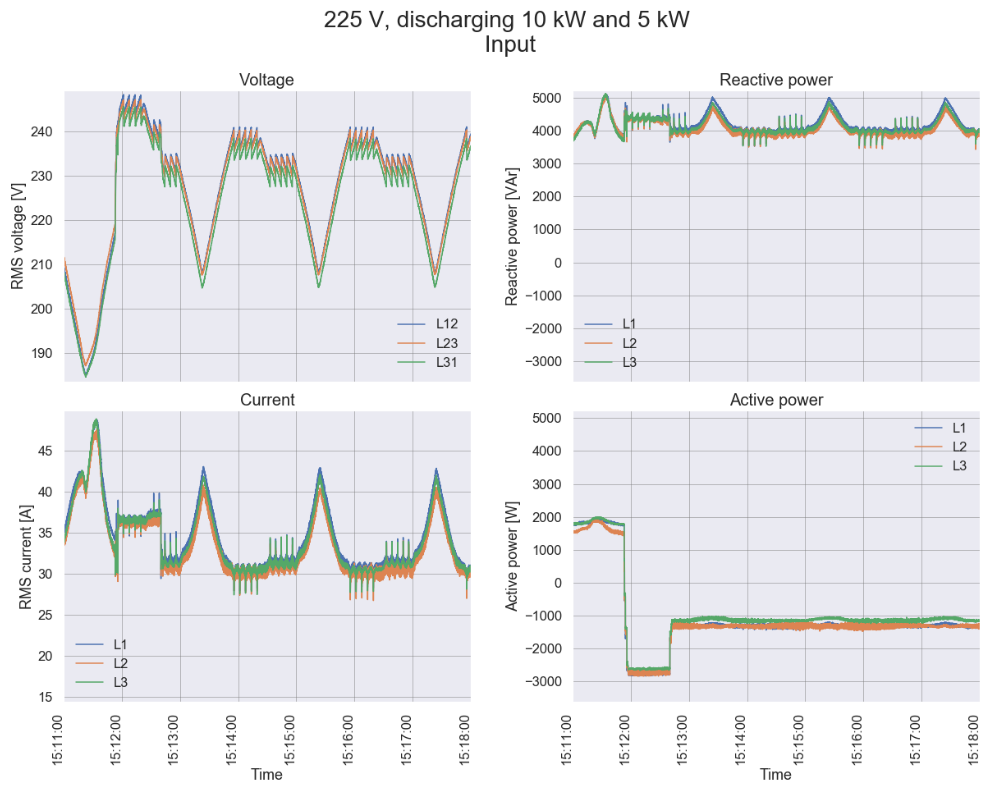

Figure 37: Test 2.D and 2.E input.

Figure 38: Test 2.D and 2.E output.

A.2 Case 3

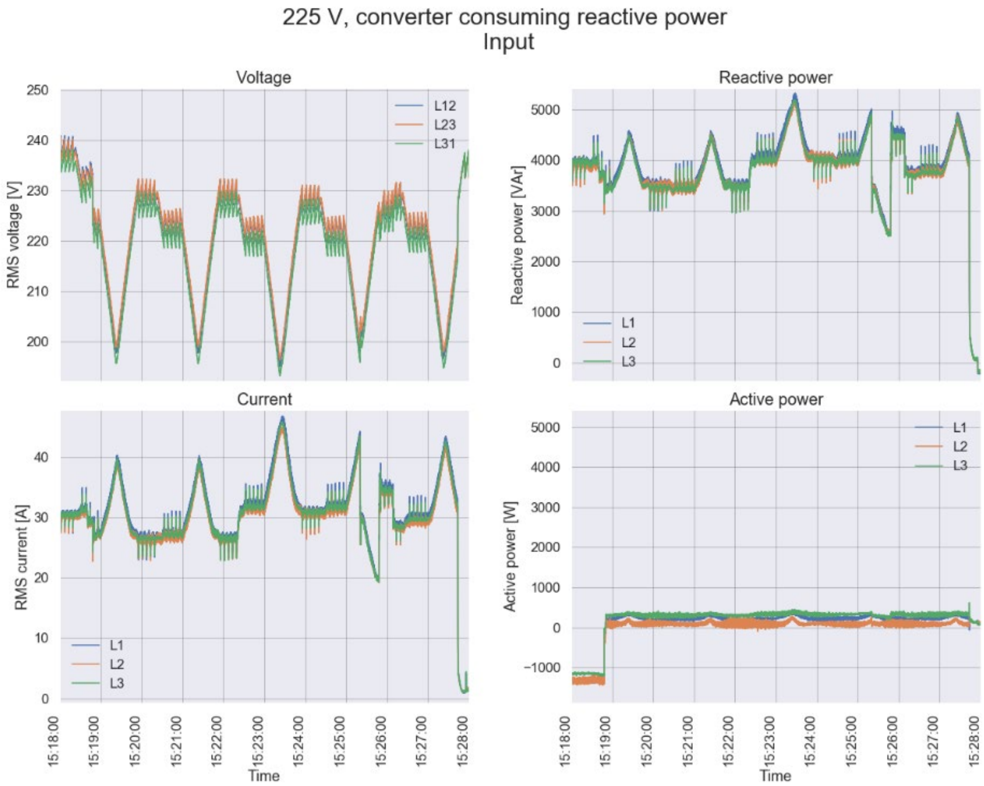

Figure 39: Test 3.A input.

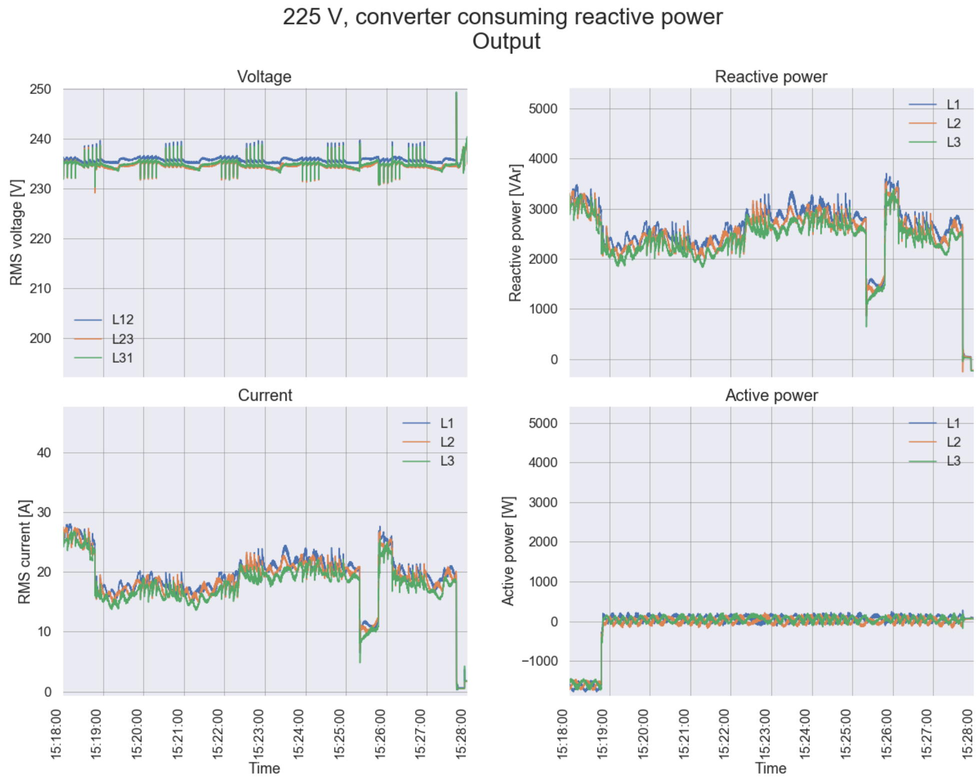

Figure 40: Test 3.A output.

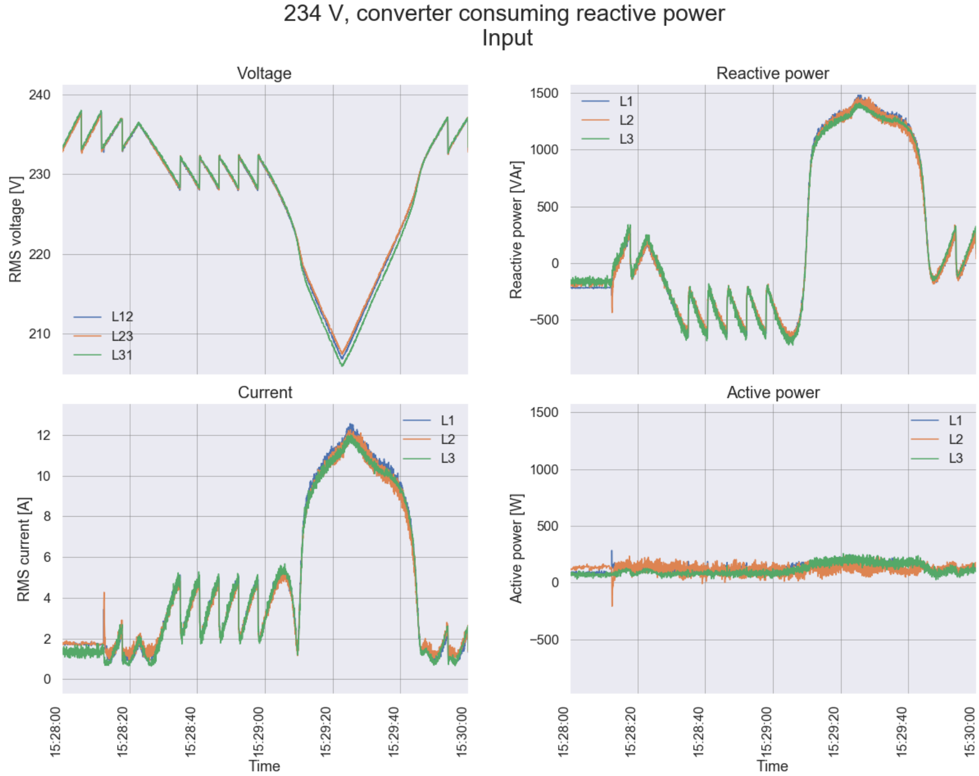

Figure 41: Test 3.B input.

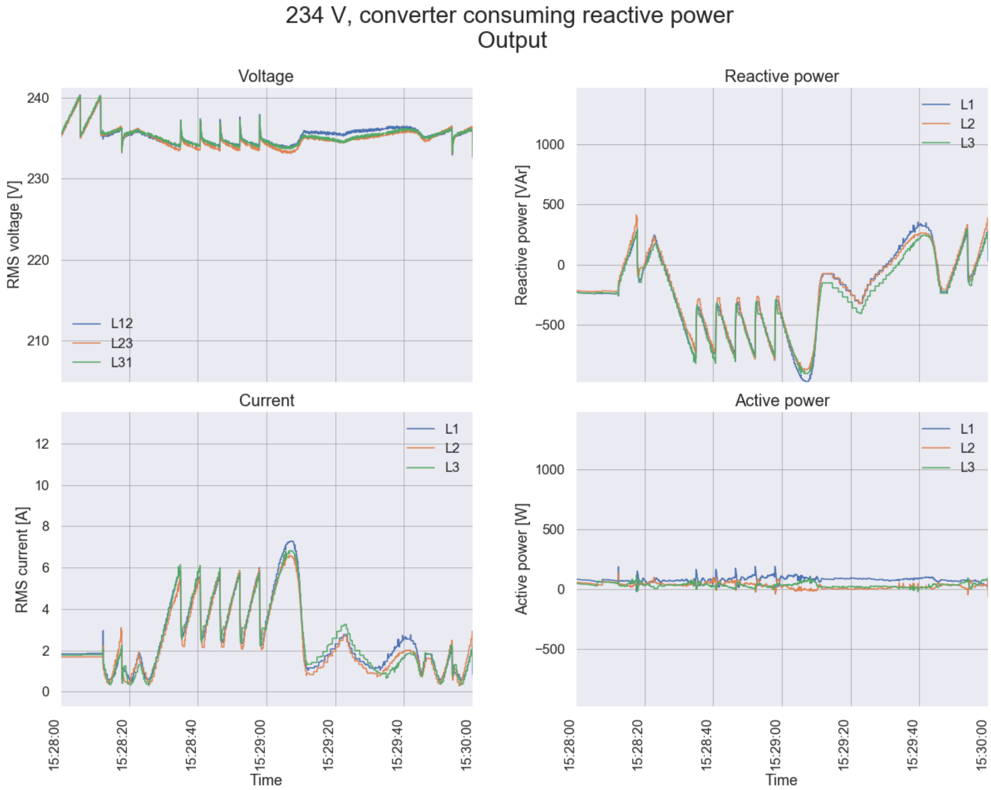

Figure 42: Test 3.B output.

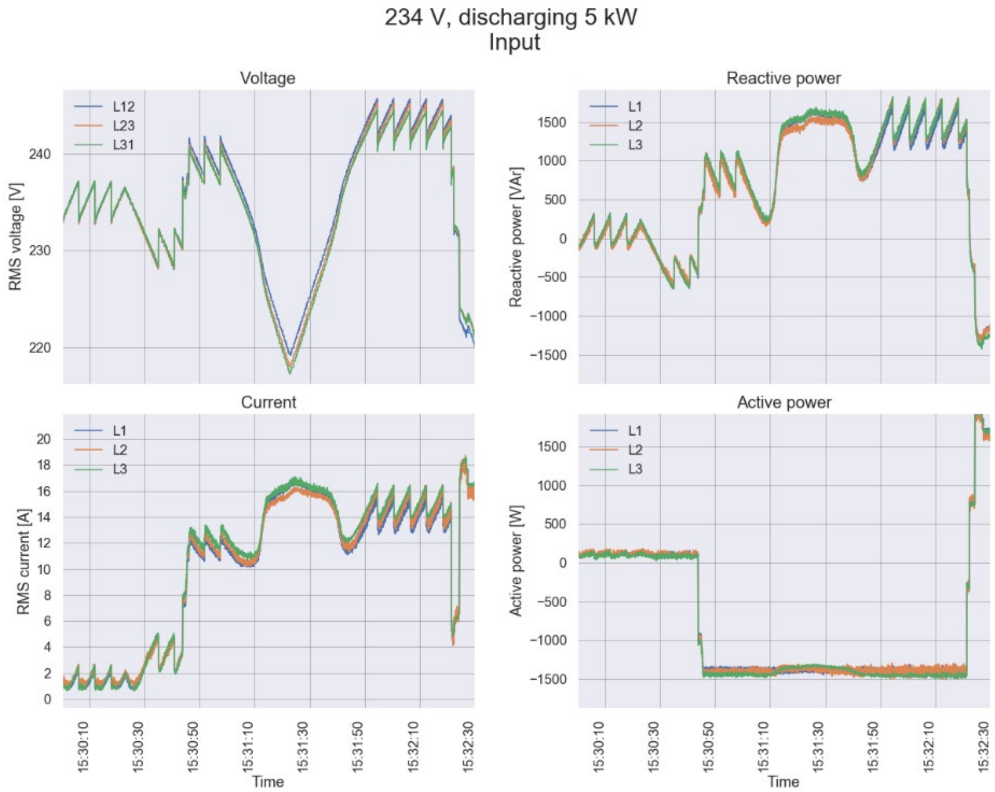

Figure 43: Test 3.C input.

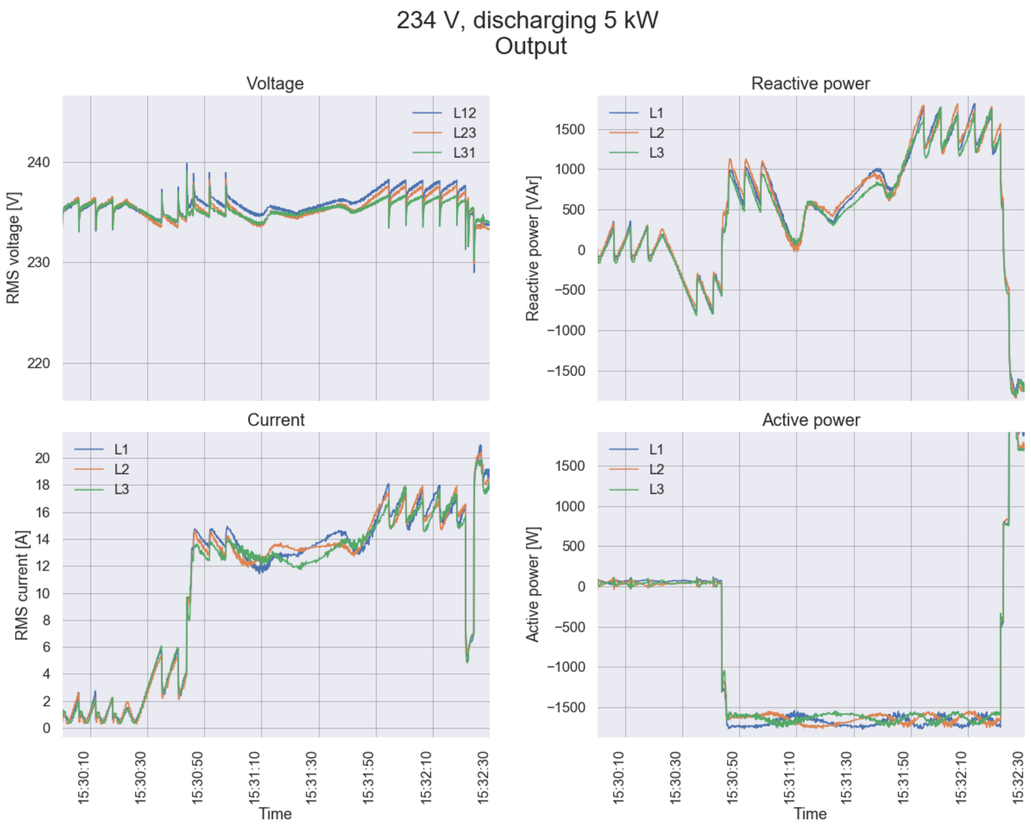

Figure 44: Test 3.C output.

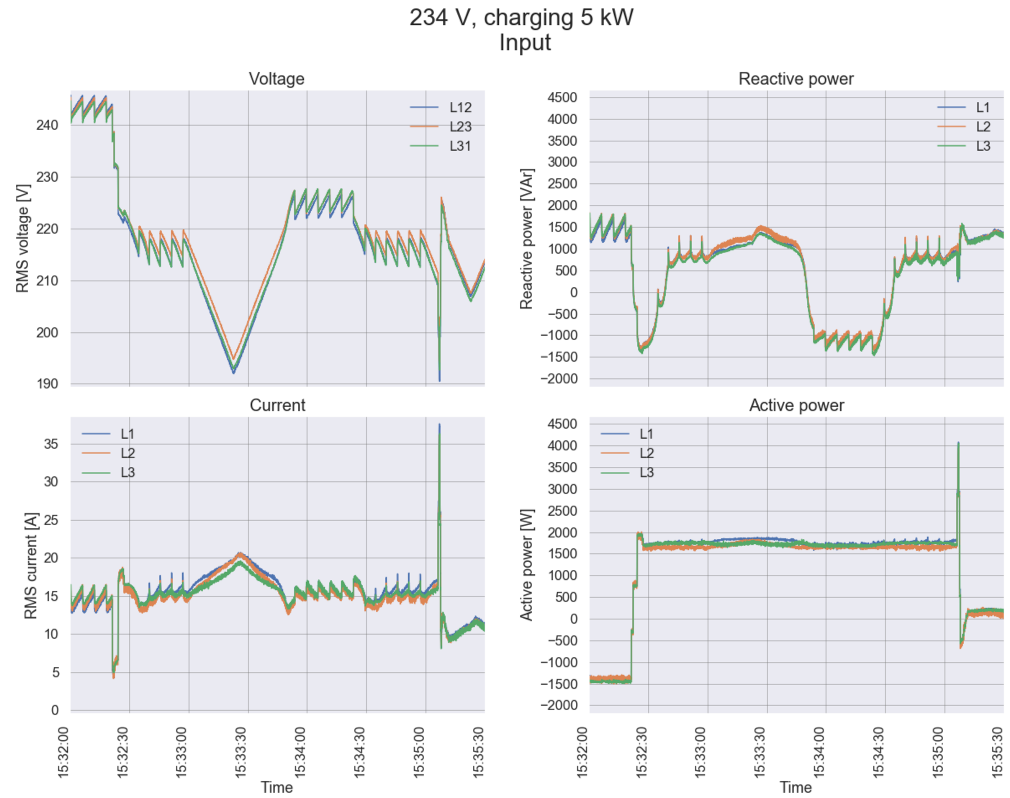

Figure 45: Test 3.D input.

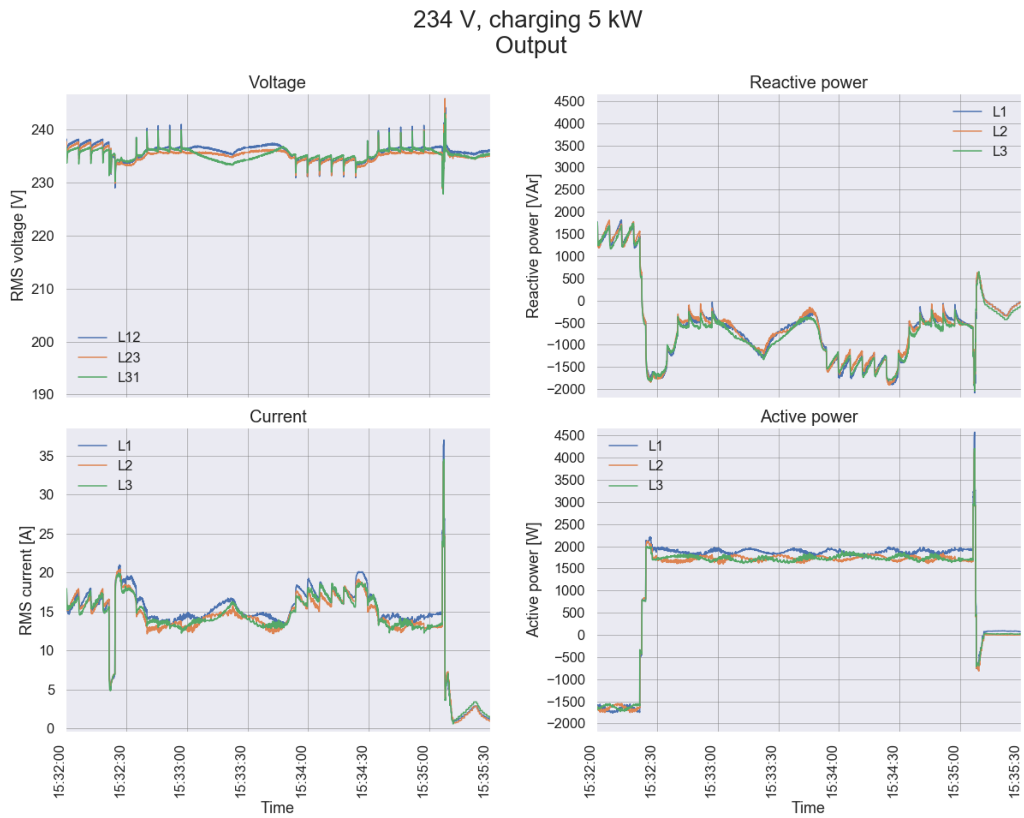

Figure 46: Test 3.D output.

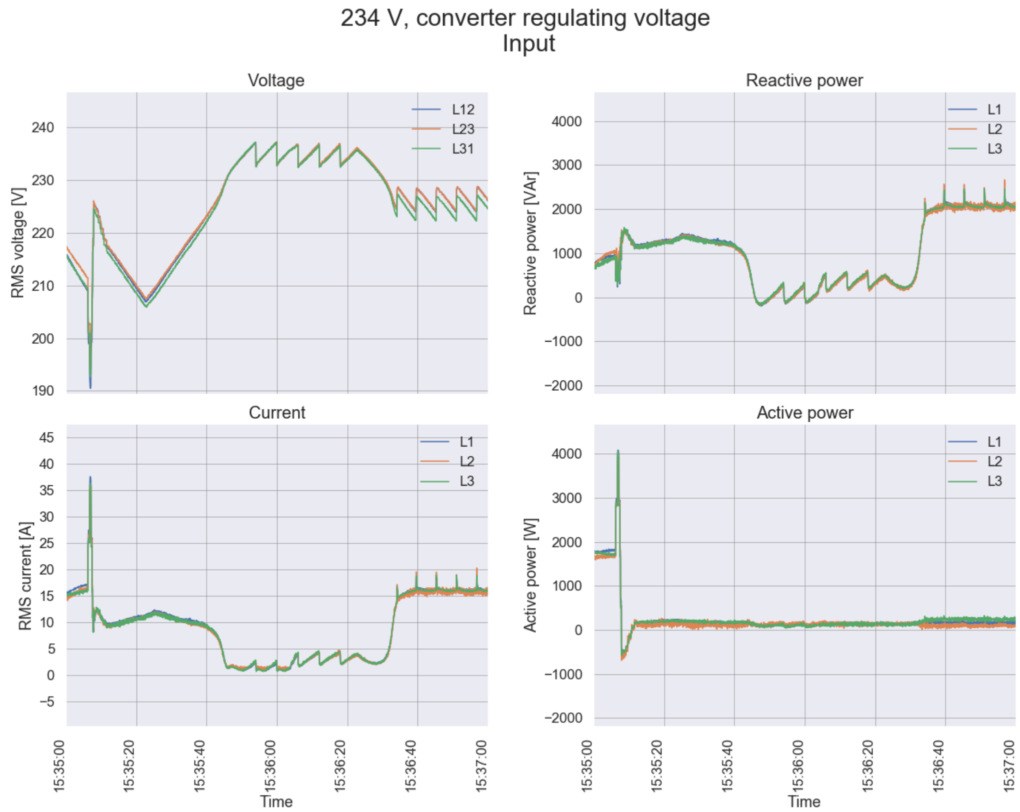

Figure 47: Test 3.E input.

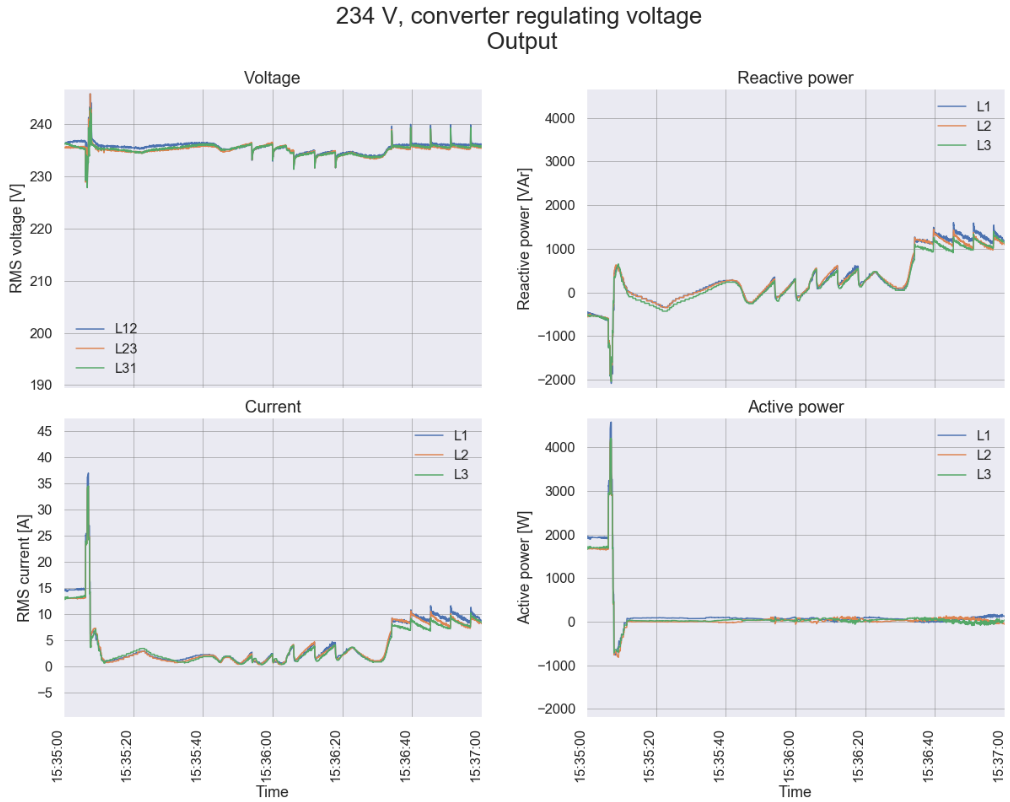

Figure 48: Test 3.E output.

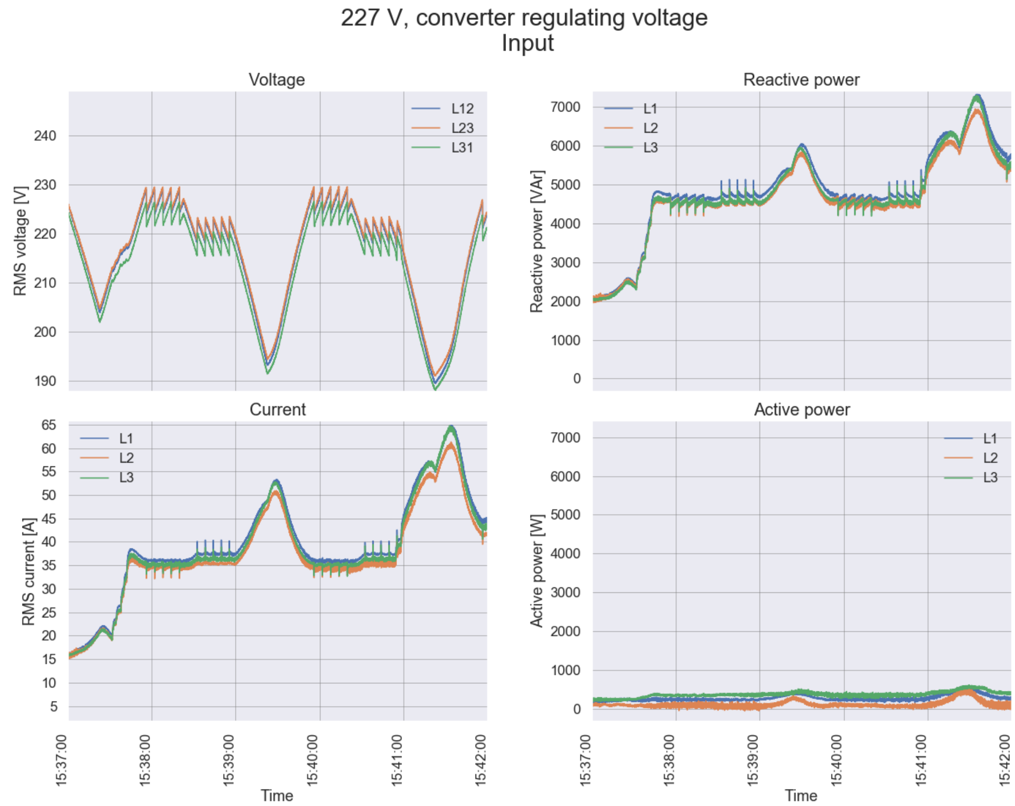

Figure 49: Test 3.F input.

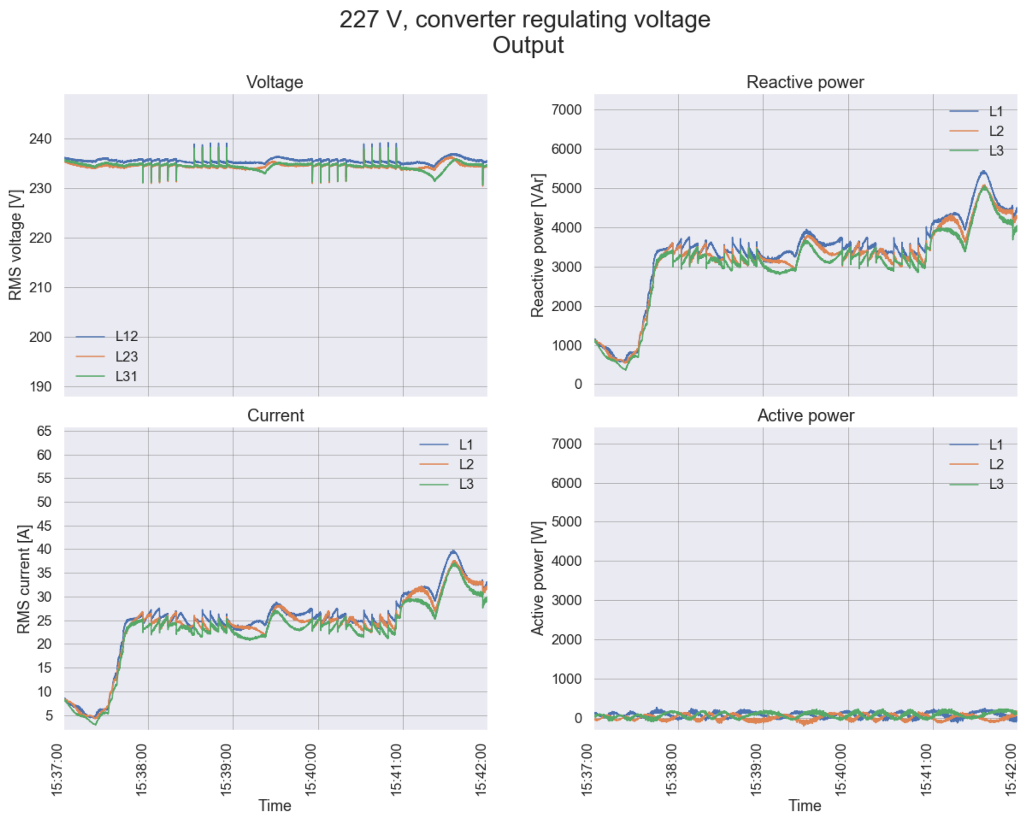

Figure 50: Test 3.F output.

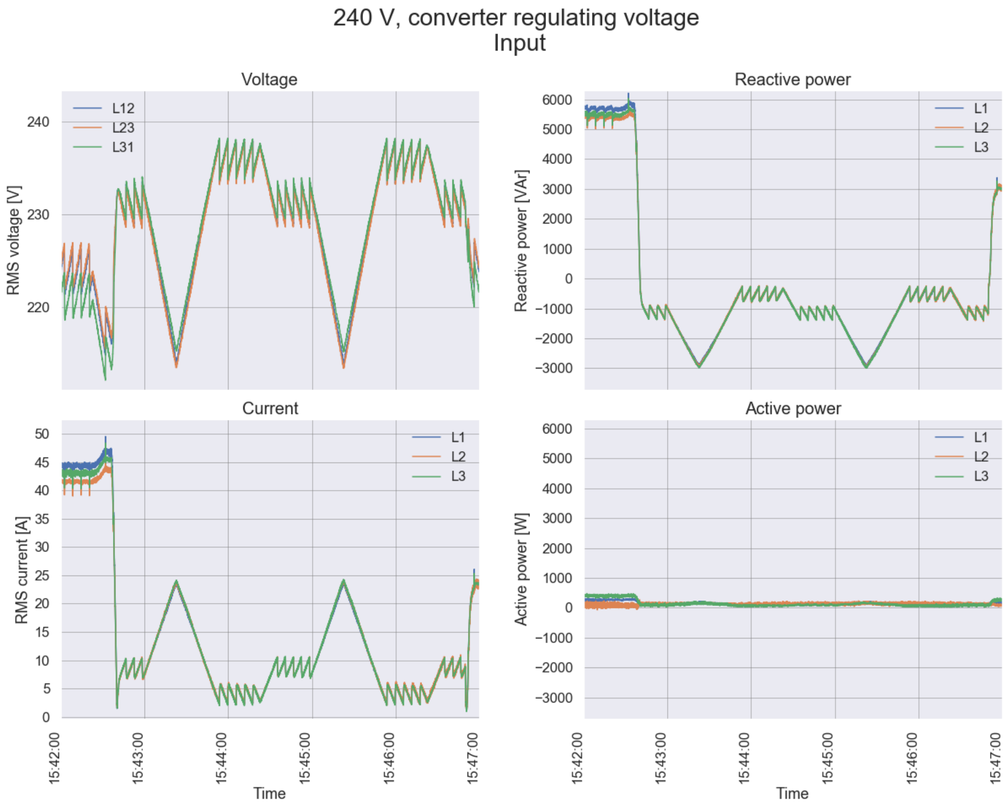

Figure 51: Test 3.G input.

Figure 52: Test 3.G output.

A.3 Case 4

Figure 53: Test 4.B and 4.C input.

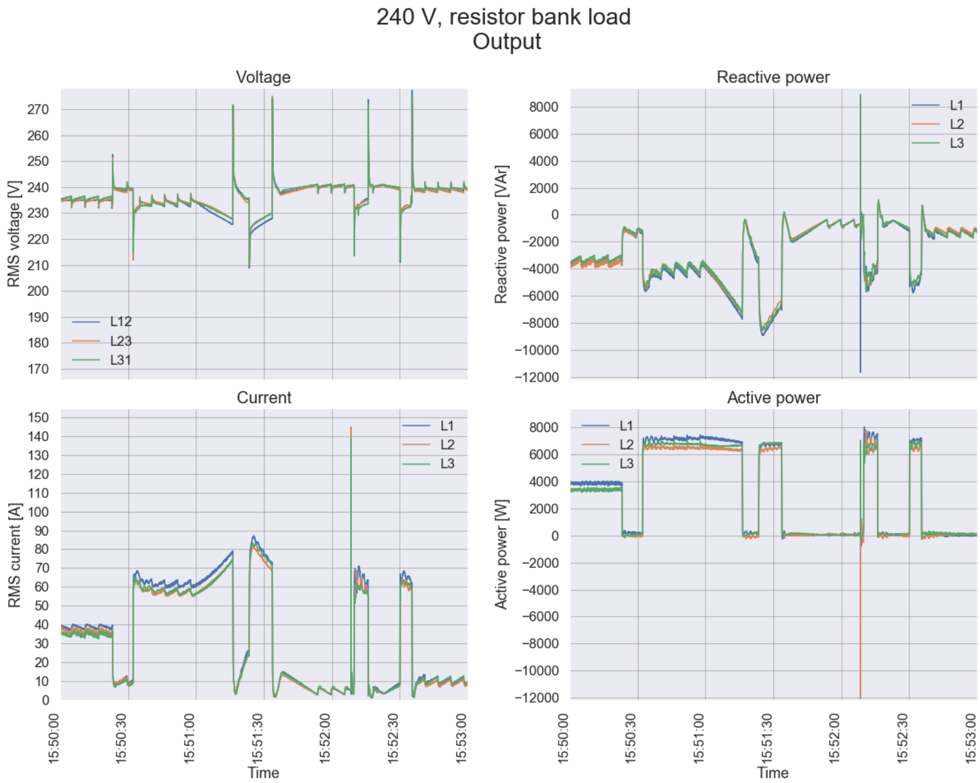

Figure 54: Test 4.B and 4.C output.

A.4 Technical data for Magtech Voltage Booster MVB125-230

Tekniske data

Modell	MVB40-230	MVB125-230
Distribusjonssystem	IT	IT
Frekvens [Hz]	50	50
Spenning [volt] (3 – fase)	230	230
Nominell last [kVA]	10	32
Last, 6 timer, @20°C, inngangsspenning 195 V [kVA]	16	50
Nominell strøm [A]	25	80
Strøm, 6 timer, @20°C, Inngangsspenning 195 V [A]	40	125
Setpunkt utgangsspenning [V]	235	235
Spenningsløft [%] (symmetrisk last)	0...+17	0...+20
Spenningsløft, -reduksjon [%] (ubalansert last)	0...+17	0...+20
Dynamisk respons [ms] [1]	150	200
Tomgangsstap [W] [2]	180	220
Virkningsgrad [%] [3]	95-97	95-97
Power factor [cos φ] [3]	0,96-0,97	0,96-0,97
Harmonisk forvrengning [%] [3]	1-4	1-4
Mekaniske dimensjoner		
Bredde x Høyde x Dybde [mm]	754 x 928 x 539	1003 x 1190 x 648
Vekt [kg]	390	750
Kabel tilkobling [Copper mm²]	≤ 16	≤ 50
Olje [liter]	75	158
Kapsling	Galvanisert	Galvanisert
Features		
Bypass @ U_out ±15% eller høy temp - Ingen spenningsbortfall - Automatisk restart	√	√
Klarer 100% ubalansert last og opprettholder alle fasespenninger	50%	50%
Enpolt korslutningsstrøm øker med typisk 60% eller mer i svake nett	Uforandret	Uforandret
Ingen bevegelige deler i kraftkrets	√	√
Vedlikeholdsfri	√	√
Levetid kraftkrets som vanlige distribusjonstransformatorer	√	√
Rask installasjon < en dag	√	√

Opsjon: SSP = Short-Circuit Safety Protection, 3-polt effektbryter installert på utgang, FR3 = miljøvennlig organisk olje.
[1] – fra null spenningsløft til maks boost [2] – null spenningsløft [3] - nominell last, varierende spenningsløft

http://www.magtech.no/ Patent nr.: NO 317045 U

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