European Research Infrastructure supporting Smart Grid and Smart Energy Systems Research, Technology Development, Validation and Roll Out – Second Edition

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Project Number: **870620**

Technical Report Lab Access User Project

Open CAN-based communication architecture study for the association of modular open source power converters (OPEN-CANVERTER)

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User Group Leader:	[Name of Lab Access User Group Leader (institution name)]

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28/10/2021	v1.0	Luiz Villa (LAAS-CNRS)	Initial version ready for others
29/10/2021	v1.2	Martin Jäger	Added Libre Solar test descriptions and
03/11/2021	V1.3	Luiz Villa	Added all the images and descriptions
15/01/2022	V1.4	Luiz Villa, Martin Jäger, Alkistis Kontou (ICCS-NTUA)	Review and final version

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List of Abbreviations

CO	Project Coordinator
EC	European Commission
LA	Lab Access
UG	User Group
UP	User Project

Executive Summary

The OPEN-CANVERTER studied how a micro-grid can be expanded and be real time controlled (through distributed and centralized methods) by using software defined power converters and an open-source CAN-based communication system. Software defined power converters are re-programmable power hardware which can assume different power conversion functionalities, such as DC-DC and DC-AC. This generic power hardware can be used to create different types of micro-grids, from stand-alone solar home systems to more complex power converter based micro-grids. To expand a micro-grid from simple to complicated it can either have existing conversion function reinforced by parallel module connection (i.e. more power to a DC battery charger) or have the addition of new conversion functions (i.e. an inverter in a DC grid). A key to this expansion is a seamless communication system. A total of 5 tests conducted over the access period to assess the performance of such modular software defined power converters. The purpose, the exact scope, and the results of each one of the 5 tests are described in detail later in the document.

1 Lab-Access User Project Information

1.1 Overview

USER PROJECT PROPOSAL

User Project Acronym	OPEN-CANVERTER
User Project Title	Open CAN-based communication architecture study for the association of modular open source power converters
Main Scientific/Technical Field	Power electronics and control
Proposal resubmitted (Y/N)	Choose an item.
Keywords (5 max., free text)	Power Electronics, micro-grids, CAN-bus

PREFERRED HOST LABORATORY/RESEARCH INFRASTRUCTURE

Option 1	ICCS
Option 2	Choose an item.
Option 3	Choose an item.
Proposed starting date of the access	19/07/2021
Expected access duration (in weeks)	2

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1.2 Research Motivation, Objectives, and Scope

Fundamental Scientific and Technical value and interest

The main scientific value of these tests is the study of micro-grid seamless expansion both by reinforcing the existing power conversion functions or adding new ones. This reinforcement is coordinated by a single CAN based communication system, which will also be validated during this TA. The same communication link can be used to coordinate control between modules and acquire data from their operation, making for a single and simplified solution for seamlessly associating modular power converters and expanding micro-grids.

The technical value of this project is to validate a generic open-source communication protocol for micro-grid expansion. This will provide field practitioners with an important tool for implementing productive uses from renewable energies on the short to medium term. This work brings together the development of the OwnTech generic power converter with the communication protocol of Libre Solar. This cooperation will yield tools that can be used by the LCA to quickly assemble a micro-grid for future collaboration and testing.

Objectives of the project

The main objective of to study the real-time control of a micro-grid as it expands through the addition of generic open-source power modules either to reinforce conversion functions or add new ones.
To achieve its main objective, this project has a set of secondary objectives.

- Validate function reinforcement by adding module in parallel
- Validate adding new functions by adding a new set of modules
- Validate centralized the control approach based on CAN communication
- Validate decentralized the control approach based on CAN communication

1.3 Structure of the Document

This

document is organised as follows: Section 2 briefly outlines the state-of-the-art/state-of- technology that provides the basis of the realised Lab Access (LA) User Project (UP). Section 3 briefly outlines the performed experiments whereas Section 4 summarises the results and conclusions. Potential open issues and suggestions for improvements are discussed in Section 5.

2 State-of-the-Art/State-of-Technology

Power electronics is a key technology for the energy transition. It allows the control of electric power flows between sources, loads and storage elements. The ever-increasing electrification of society as an answer to decarbonizing the global economy shows that the role of power electronics will only grow in the coming years **[1]**.

Planned perennity in this context is the capacity for a power electronics hardware to withstand **multiple service lives** through a mix of repairs, refurbishing and reprogramming. It is the opposite of planned obsolescence but it goes **beyond the concept of sustainable design [2]**. This concept is novel and disruptive as it takes the industry into a different paradigm where hardware is an asset with a longer payback time whose behavior and aging is worth monitoring. This approach is spearheaded in batteries by Mob-Ion, a french company that builds electric scooters based on a planned perennity approach **[3]**.

Currently existing design techniques of power electronics converters focus on matching hardware to functional design through optimization **[4]**. This **function-defined design** means companies have a very long time to market, high development costs and high maintenance costs for having several different products to a same market. To help lower these costs, the scientific community has conducted research that focus on creating standardized power converters **[5]**. There are mainly two lines of research on this field: automation of converter design through software **[6]** and creation of generic and reprogrammable power hardware **[5]**. This project is built on and contributes to research that focuses on the latter .

Software defined power converters focuses on creating reprogrammable power hardware. This means that there is an abstraction between hardware and embedded software. This abstraction is key for a planned perennity approach as it provides the means of managing power hardware as an asset over time through repairing, refurbishing and reprogramming **[7]**. However, this approach sacrifices optimization (function-defined) for genericity of use (software-defined) and simplicity of maintenance.

Micro-grids based on software defined power converters have an **important scientific issue:** they require a a seamless method to associate and coordinate multiple elementary power converters as the micro-grid expands. These elementary conversion blocks can be added to the micro-grid either to reinforce an already existing functionality (more blocks in parallel to a DC-DC for more current) or to add a new functionnality (DC-AC inverter to a DC-DC solar home system).

As new blocks are added, the micro-grid will have to control all these new module and new functionalities either through a decentralized or a centalized approach [8]. Software defined power converters should provide the flexibility to implement both approaches. This implementation requires a communication system which can either centralized data and information into a single database or create mechanisms of coordination between power blocks.

The main objective to the OPEN-CANVERTER project is to study the use of software defined power converters to create and expand a micro-grid and its real-time control through either decentralized and centralized methods. This in turn requires validating a communication system capable of integrating new modules and coordinating their power flow. This work proposes the use of an open CAN based communication protocol to create this communication link.

The generic power electronics converters used in this work are based on the OwnTech project [9, 10], whose main concept has been tested and validated in previous ERIGRID TAs [11, 12]. This open source generic power module can operate in bi-directional DC-DC and single phase DC-AC conversion functions. The association of blocks to create a micro-grid is the next step, which will be tested in the OPEN-CANVERTER project. The open CAN protocol to be tested is currently being developed by LibreSolar [13], one of the TA's members.

3 Executed Tests and Experiments

3.1 Test Plan, Standards, Procedures, and Methodology

There are two sets of hardware to be tested: the LibreSolar MPPT charge controller and the OwnTech O2 power converter. CAN-based communication from LibreSolar was used to inspire the OwnTech team to include the necessary hardware to provide communication between the two converters.

Figure 1 shows the two converters and their connectivity. The connectivity box-based representation will be used below to explain the test setups that were carried out during the TA.

Figure 1.a – The LibreSolar 2420HC MPPT Charge Controller

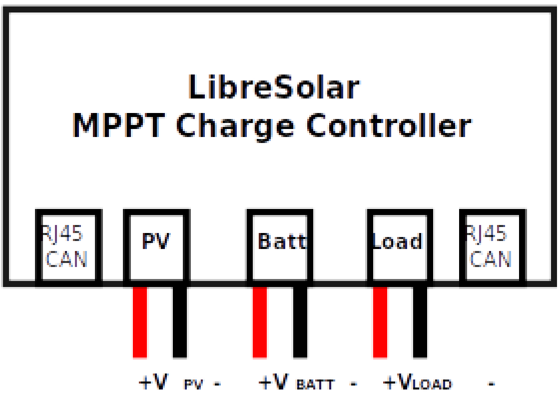


Figure 1.b – The schematic equivalent of the LibreSolar MPPT Charge Controller

Figure 1.c – The OwnTech O2 Power converter

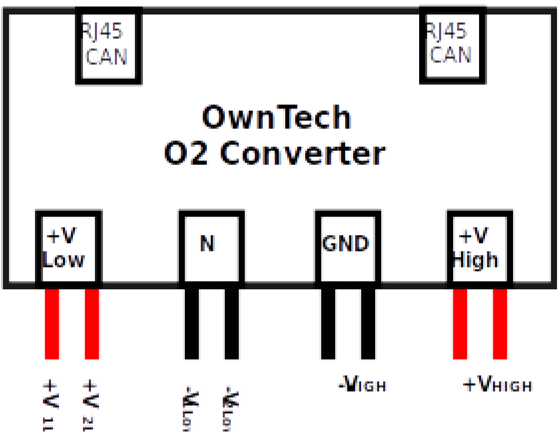


Figure 1.d – The schematic equivalent of the OwnTech O2 Power converter

Figure 1: The devices used in the OPEN-CANVERTER TA and their equivalent schematics

The tests were performed using an YokogawaWT3000 datalogger, whose image is shown below.

Figure 2: Photo of the Yokogawa datalogger

An incremental series of tests will be used to validate both devices and their capacity to communicate together in order to create a droop-control based micro-grid.

These tests are summarized in Table 1.

Table 1: Summary of all the tests performed during the OPEN-CANVERTER TA

Number	Test Name	Description	Equipment used
I	LibreSolar Device stand alone test	This test valiates the proper operation of the LibreSolar device	Controllable DC power supply, load and data acquisition
II	OwnTech Device stand alone test	This test valiates the proper operation of the OwnTech device	Controllable DC power supply, load and data acquisition
III	LibreSolar Device Droop Control (battery)	This test will validate the LibreSolar device operation in Droop control with CAN communication	Controllable DC power supply, load and data acquisition
IV	OwnTech Device Droop Control (load)	This test will validate the OwnTech device operation in Droop control with CAN communication	Controllable DC power supply, load and data acquisition
V	Full connection of both devices	Interconnection of both devices in Droop control function using the CAN-bus communication	Controllable DC power supply , loads and data acquisition, RTDS system and controllable loads and data acquisition

3.2 Test Set-up(s)

3.2.1 LibreSolar Device Stand alone Tests

Within this test, one Libre Solar MPPT 2420 HC device was tested in different setups. The objective was to get the measurement equipment, the lab power supplies and the CAN communication working together.

Two tests were conducted:

- MPPT algorithm efficiency

- Power converter efficiency

Equipment

- Yokogawa WT3000
- PV
  panel simulator

Test setup

The MPPT test schematics are shown in figure 3 and the efficiency test schematics are shown in figure 4.

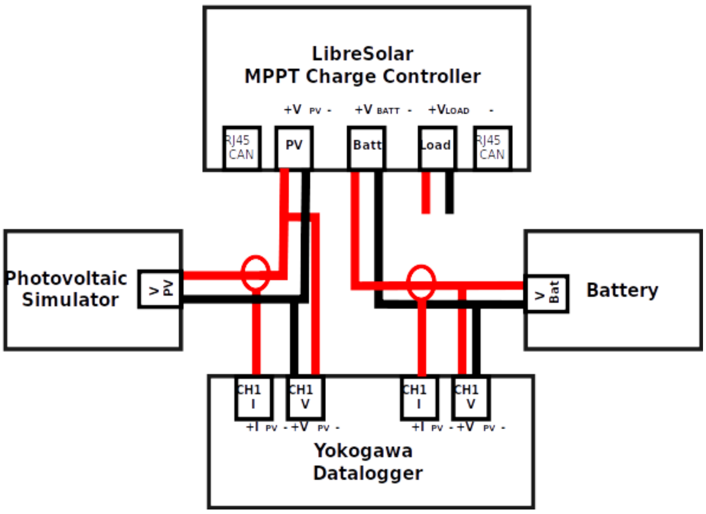


Figure 3: Schematics of LS MPPT experiment

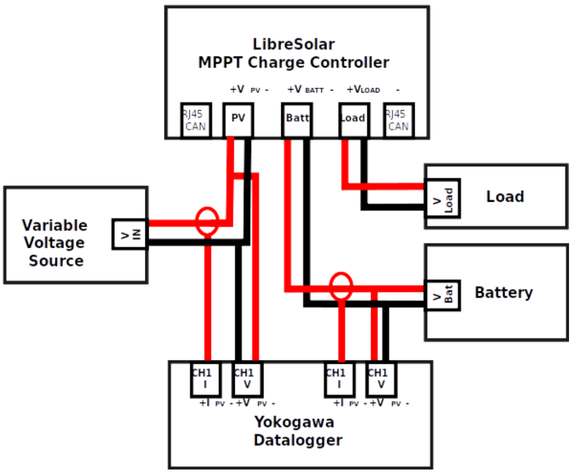


Figure 4: Schematics of LS Efficiency experiment

Table 2 shows the details of related to both experiments.

Table 2: Summary of the test setup connections to the LibreSolar MPPT Charge Controller

Experiment	**high side**	**battery**	**low side**

	type of device	voltage	protection	Type of device	voltage	protection	Type of device	voltage	current	protection	max.
Efficiency	power supply	40V	diode max voltage max current	Battery	12V	switch on the plus side	Passive Load	12V	10A	switch on the plus side	20A
MPPT	PV sim.	32 VOC	diode max voltage max current	Battery	12V	switch on the plus side	-	-	-	-	-

3.2.2 OwnTech Device Stand alone Tests

The OwnTech power converter was tested to validate its control stability and its control system. The schematics of the test are given in figure 5.

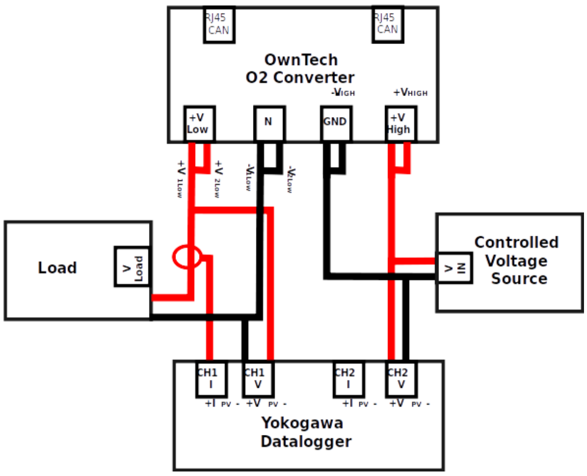


Figure 5: OwnTech Stand Alone Experiments schematics

The summary of the tests is given in Table 3.

Table 3: Summary of the OwnTech Device Stand Alone Tests

Experiment	**high side**			**low side**				
	type of device	*voltage*	*protection*	*Type of device*	*voltage*	*current*	*protection*	*max.*
Voltage mode control	power supply	40V	diode max voltage max current	Passive Load	12V	10A	switch on the plus side	16A

3.2.3 LibreSolar Power Sharing Tests

Background

In order to operate multiple power converters in parallel, only one converter can operate in constant voltage mode (master) and the other converters must operate in constant current mode with the current
setpoint shared via communication (slave).

For plug-and-play operation, the master device should be selected automatically so that the system can even continue to operate if the previous master device is removed or if it fails.

This structure was the theme of a discussion during the TA with the host team.

Figure 6: Discussion regarding architecture for system control and interconnection

After discussing multiple different options with the team in the lab, we decided to implement an automatic selection of the master based on its CAN identifier. The device with the lowest CAN ID (highest priority) automatically becomes the master device.

Equipment

- Extech 382270 DC power supply
- PCAN-USB FD
- ESP32 WiFi module

Test setup

Two Libre Solar MPPT 2420 HC were connected in parallel to a single battery. A lab power supply with two channels was used to provide the input power for each converter. The schematic of the test is given in figure 7.

The battery was almost fully charged so that the converters would quickly reach the maximum voltage

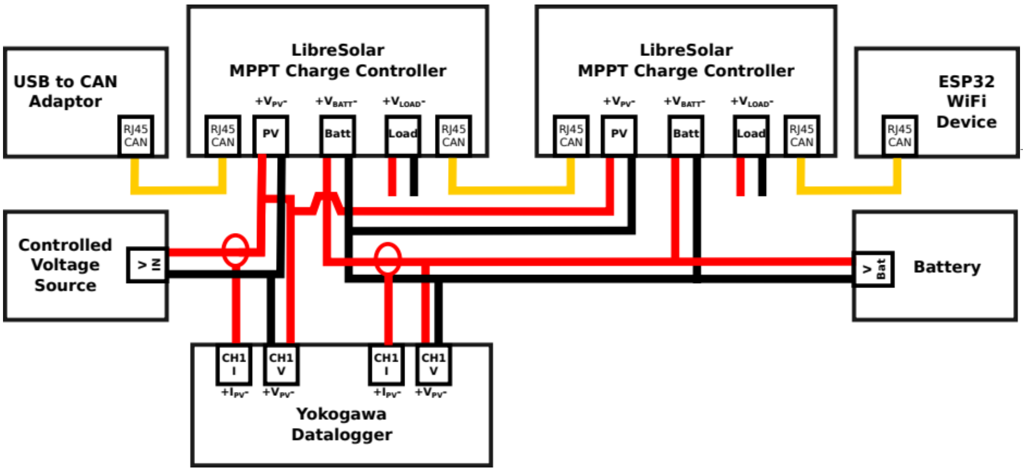


Figure 7: Schematics for the LibreSolar parallel charge controller test

setpoint and switch into float charging mode.

Both converters were connected via the CAN bus and the newly developed power sharing algorithm was enabled. The CAN messages are exchanged at a rate of 100 ms. The data was additionally recorded via WiFi and stored in a cloud database.

The target was to observe if both converters reduce their output power simultaneously based on the master controller's state. A photo of the setup is shown in figure 8.

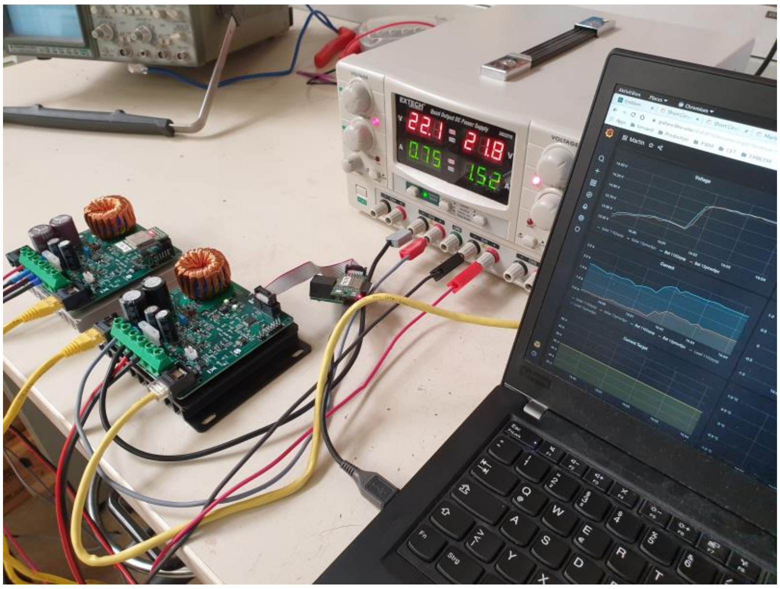


Figure 8: Photo of the LibreSolar parallel converter test setup

The details of the setup are given in Table 4.

Table 4: Summary of the test setup connections to the LibreSolar parallel converter connection

Experiment	PV side			battery			low side				
	type of device	*voltage*	*protection*	*Type of device*	*voltage*	*protection*	*Type of device*	*voltage*	*current*	*protection*	*max.*
Efficiency	power supply	40V	diode max voltage max current	Battery	12V	switch on the plus side	-	-	-	-	-

3.2.4 OwnTech Device Droop control Tests (Load)

In order to operate together with the LibreSolar device to create a droop controlled micro-grid, the OwnTech device needed to be both capable of derating its current and apply this derating as a function of its input voltage.

This application is a smart load that lower its power consumption to preserve the battery.

Sawtooth and Current derating

The control algorithm from the OwnTech O2 converter was updated and tested to generate a sawtooth wave. Once this sawtoothwave was operational, a current derating routine was coded onto the power controller.

The schematic used in this test is the same as shown in figure 5.

Smart Load Droop Control

Once the current derating was validated, the system was then programmed to behave as a smart load. The setup is summarized in table 5.

Table 5: Summary of the OwnTech Device Stand Alone Tests

Experiment	high side			low side				
	type of device	*voltage*	*protection*	*Type of device*	*voltage*	*current*	*protection*	*max.*
Current derating with sawtooth	power supply	48V	diode max voltage max current	Variable Load	-	10A	switch on the plus side	16A
Smart Load Droop control	power supply	48V	diode max voltage max current	Variable Load	-	10A	switch on the plus side	16A

3.2.5 Full connection of both devices

If the DC grid voltage is decoupled from all power sources and sinks, the locally measured voltage of each grid participant can be used to control the power flows within the grid. This droop control method was implemented using both LibreSolar and OwnTech devices together.

The schematic of the final experiment is given in figure 9.

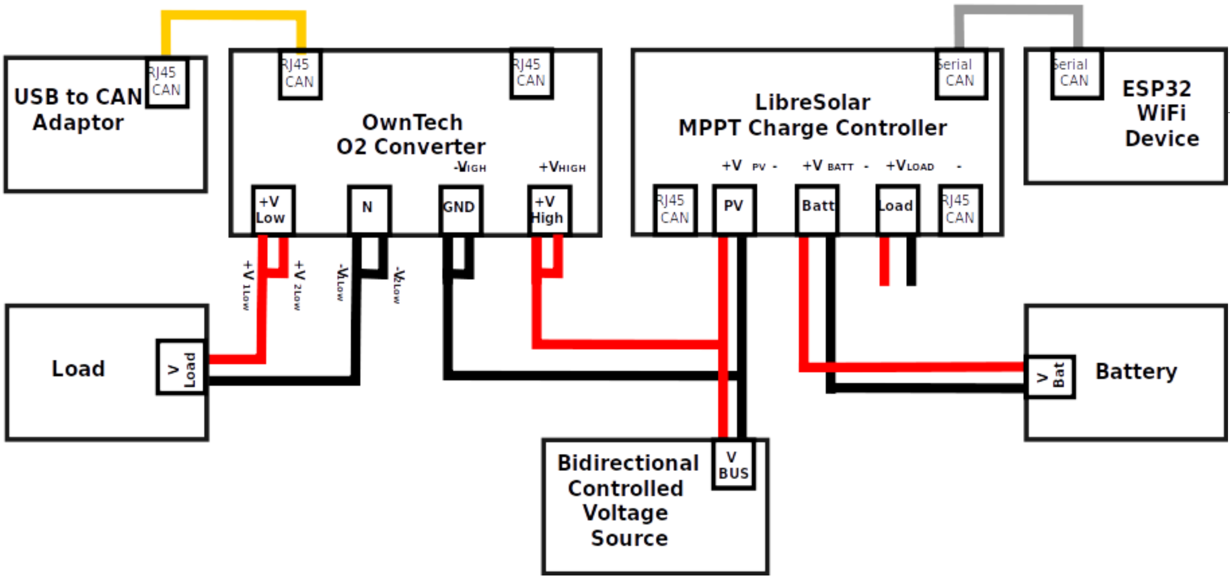


Figure 9: Droop contorl micro-grid experiment schematics

A bi-directional power supply will behave as a floating DC bus. This bus will be controlled upwards and downwards while the data form both devices are logged using their own CAN connections.

The voltage setpoints can be set arbitrarily. Below graphs show the setpoints of the 48V droop-controlled grid as it was tested within this project.

As a convention, current/power flow towards the grid (export) has a positive sign and current consumed from the grid (import) has a negative sign.

Energy storage device (Libre Solar converter)

An energy storage device like a battery can import and export power, as shown in Figure 10.

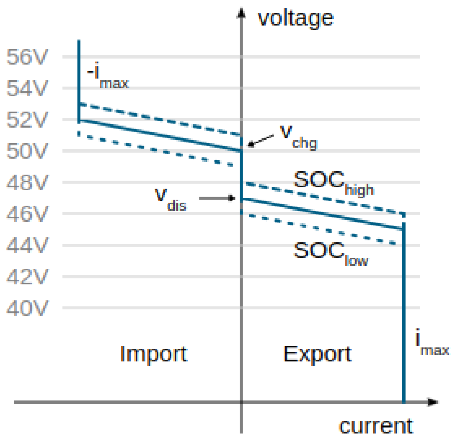


Figure 10: Voltage versus current graph of a droop control smart battery

Figure 10 shows the battery will import once grid voltage reaches a high threshold voltage (Vchg) and will export at a lower threshold (Vdis) voltage to support the grid.

Between importing and exporting mode, the battery needs a voltage hysteresis to prevent circulating currents flowing between parallel connected batteries.

In contrast to the solar panel, the operating curve of an energy storage device has a slope, which is called the droop curve. This droop makes the system react like a voltage source with a series resistor. If the power increases, the voltage drops, indicating that the load in the system is high.

If the state of charge (SOC) of the battery is high, the operating curve can be slightly moved upwards, which causes full batteries to start exporting their energy before batteries with low state of charge.

Within this test, the battery was used in exporting mode, i.e. it provided power to the grid. The idle voltage is set to 47V with a droop resistance of 0.1 Ohm, which leads to a voltage reduction of 1V per 10A.

Smart load (OwnTech converter)

Loads can be connected directly to the grid and don't have to be smart, i.e. measure the grid voltage and change their operation depending on it.

However, in order to prioritize different loads depending on the available power or energy, it makes sense to implement at least a threshold below which a load would shut off itself.

If possible, a load should also implement a droop curve behavior, as shown figure 11.

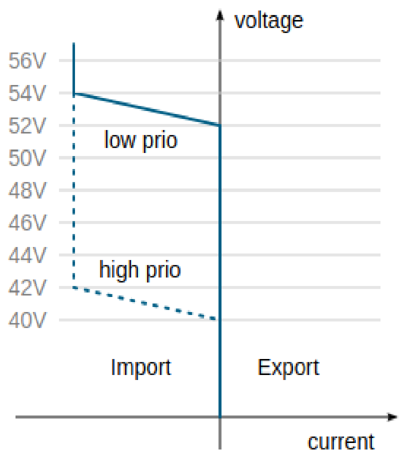


Figure 11: Smart Load voltage versus current setup

Loads with low priority operate only at high grid voltages.

The line indicated with "low prio" would switch the load on only after all batteries have been fully charged (i.e. don't pull the grid voltage down anymore). So it would only use abundant renewable energy. This method could be used for heating producing loads.

The high priority load with dashed lines would only get switched off when there is no energy left in the grid at all.

Remote load (OwnTech converter)

One last implementation of this final test was the possibility of turning off the power converter using the CAN-based communication. This possibility was implemented prior to and tested during the experiment.

The summary of the setup for the OwnTech converter and the LibreSolar charge controller are given in tables 6 and 7 respectively.

Table 6: Summary of the OwnTech Device Stand Alone Tests

Experiment	high side			low side				
	type of device	*voltage*	*protection*	*Type of device*	*voltage*	*current*	*protection*	*max.*
Final Droop grid test	Bi-directional power supply	Variable (48V to 56V)	diode max voltage max current	Variable Load	-	Variable	switch on the plus side	16A

Table 7: Summary of the test setup connections to the LibreSolar MPPT Charge Controller

Experiment	high side			battery			low side				
	type of device	*voltage*	*protection*	*Type of device*	*voltage*	*protection*	*Type of device*	*voltage*	*current*	*protection*	*max.*
Final Droop grid test	Bi-directional power supply	Variable (48V to 56V)	diode max voltage max current	Battery	12V	switch on the plus side	-	-	-	-	-

3.3 Data Management and Processing

Data was acquired directly from Yokogawa devices and online monitoring using the CAN-based system. Data was stored on a shared folder online hosted at LAAS-CNRS. It was treated directly through spreadsheets to generate the graphs on the next section.

All participants have access to all the data.

There was some data loss due to server malfunction from the LibreSolar side, which meant all the data relative to the final test was lost.

4 Results and Conclusions

4.1 Discussion of Results

4.1.1 LibreSolar Device Stand alone results

MPPT algorithm efficiency

The target of the MPPT algorithm test is to evaluate whether the maximum power point of the solar panel is found at all and if the reaction speed is fast enough.

Figure 12 shows the result of one such test.

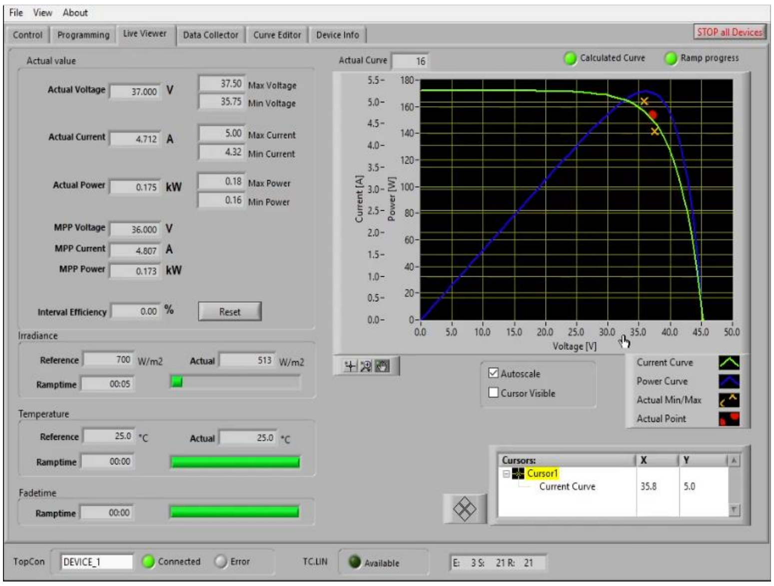


Figure 12: Screen caption of the PV simulator from NTUA

The green curve is the current vs. voltage of the solar panel, the blue one the power vs. voltage. The maximum power point is shown with the red marker. The yellow markers show the range in which the perturb & observe algorithm was operating.

The data from the Yokogawa is shown in figure 13.

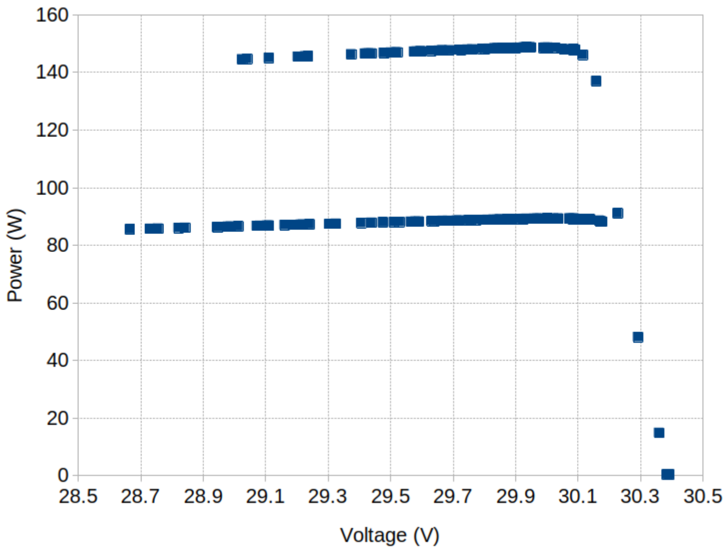


Figure 13: Power versus Voltage curve of LibreSolar's MPPT algorithm

Power was tested at two different irradiance levels. For each case, the LibreSolar MPPT charge controller was capable of finding and staying within the vicinity of the MPP. The power variation, is shown in figure X to be of a few watts, while the voltage variation was around 1.5V.

According to the lab personnel, the accuracy and speed was high compared to other devices in the market.

This test has proven that the MPPT algorithm works well.

Power converter efficiency

In contrast to previous test, which showed how good the maximum power point is found, this test shows how efficient the solar panel power can be converted into the lower voltage of the battery.

Below graphs show the results of the efficiency measurement performed using the Yokogawa power analyzer.

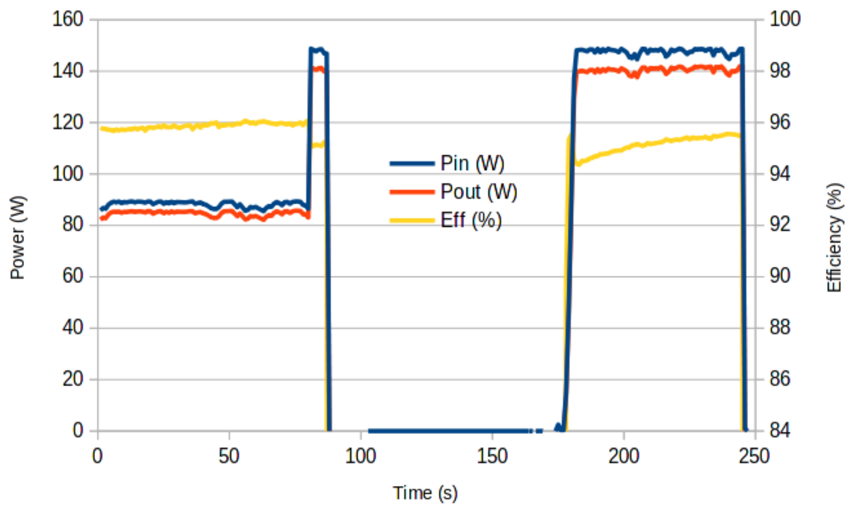


Figure 14: Libre Solar power efficiency tests results

At a power level of 90W, the efficiency is around 96%. At increased power, the efficiency gets slightly lower to around 94.5%. The increase of the efficiency towards the end of the test is caused by an increasing battery voltage as it gets more full.

4.1.2 OwnTech Device Stand alone results

The OwnTech converter was tested under varying power conditions using a variable load to sweep the power. The results are shown in figure 15.

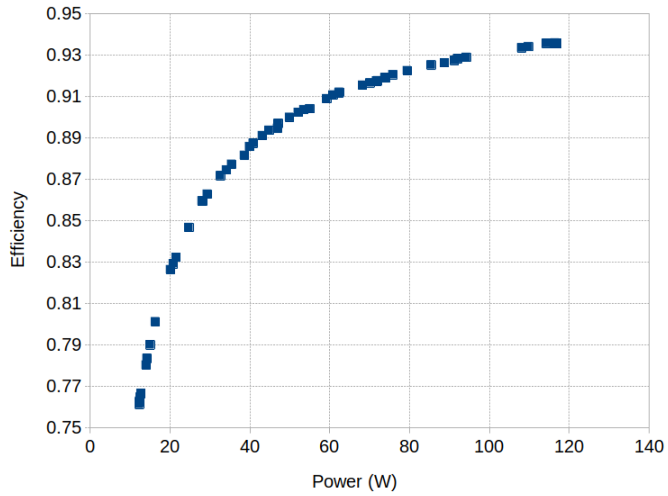


Figure 15: Efficiency versus power curve for the OwnTech power converter

At low power the efficiency lower dramatically because of unbalanced current distribution in the two power legs of the interleaved topology.

4.1.3 LibreSolar Power Sharing results

Both converters shared power as expected, whereas the controller with the highest priority CAN ID automatically became the master device.

Figure 16 shows a graph of the voltage and current measurement of both controllers (recorded from internal measurements). Initially, both controllers are operated in their maximum power point and charge the battery with maximum available power (in this case resulting in around 1.5 A per converter).

As soon as the full charge voltage of 14.4V is reached, both controllers reduce their output current simultaneously.

As it can be seen, the current is less stable as in the previous operating point at full power. This is a possibility for future improvements, e.g. by changing digital filters inside the controllers or by increasing the speed of control messages exchange (currently 10 Hz).

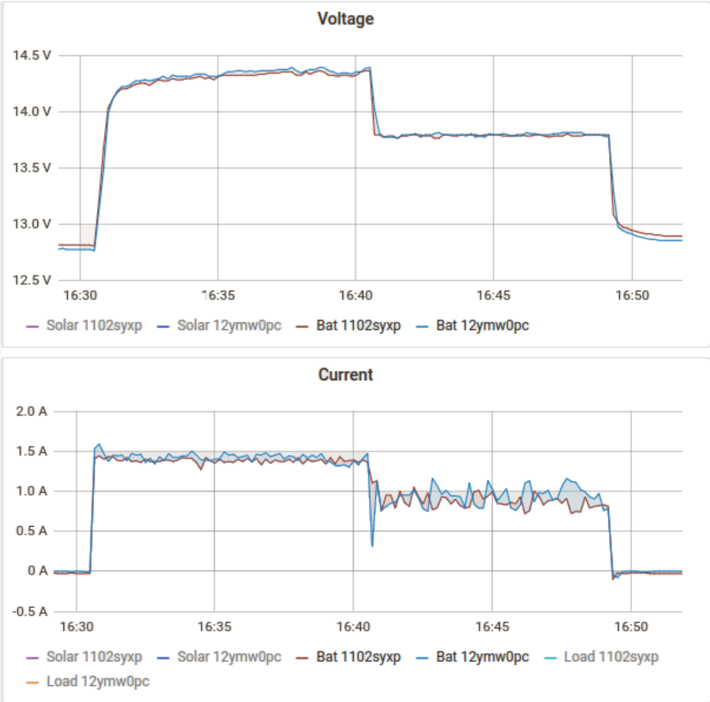


Figure 16: Results for the parallel connection of two LibreSolar MPPT charge controllers

4.1.4 OwnTech Device Droop control results

The OwnTech smart load control tests depended on the correct implementation of a current limitation for the OwnTech converter. This limitation was tested with a sawtooth generator and validated.

Once this current limitation test was finished, another test was performed where the high-side votage was connected to a variable voltage source. The voltage limit to implement the droop was 50V. Results are shown in figure 17.

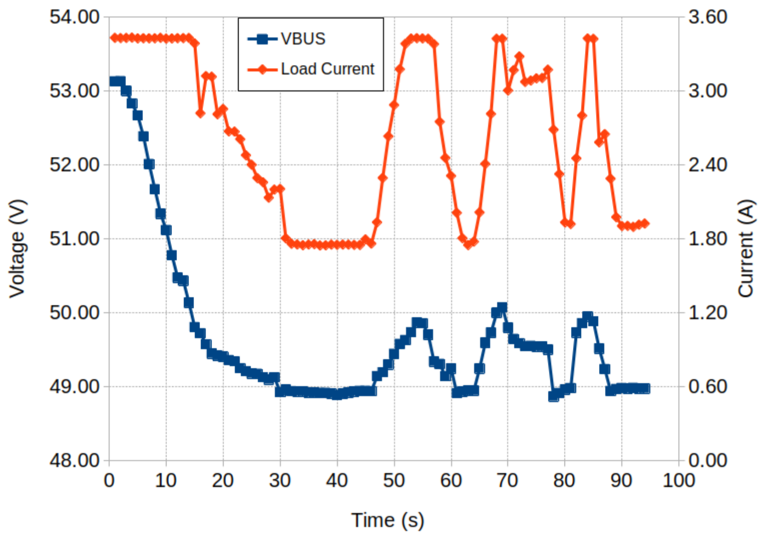


Figure 17: Results from the OwnTech smart load droop control tests

Once the O2 converter high-side voltage reaches 50V (shown in blue), the output current to the load is reduced from its nomical 3.5A down to 0.6A for Vhigh of 49V.

4.1.5 Full connection of both devices results

During the full connection of both devices, data was logged separetely between the LibreSolar and the OwnTech devices.

Due to server issues, all the data for the LibreSolar device was lost.

The data for the OwnTech device was retrieved and it is shown below.

Results for the droop

The droop control performed well as shown in Figure 18. The droop level was set at 47V and it shows that as the vhigh drops, so does the output current for leg 1. An important conclusion from this experiment is that it validates the issues of both legs being unevenly used. Current in leg 2 was below 700mA while current in leg 1 was about 4.2.

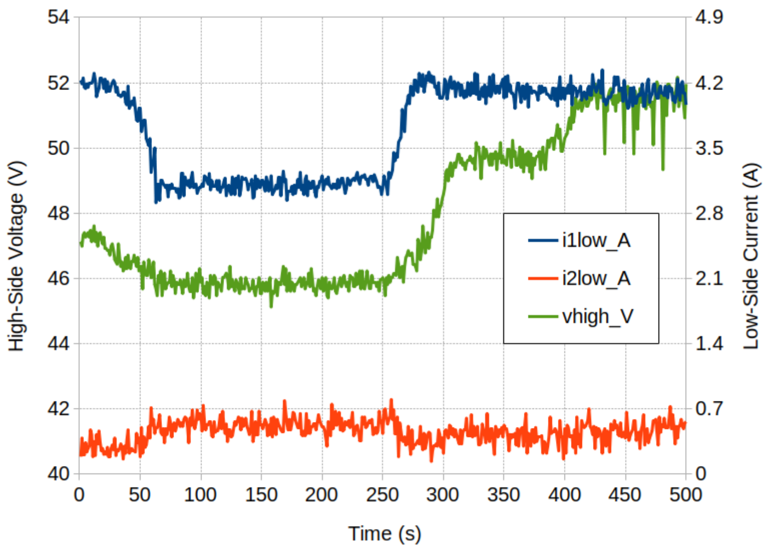


Figure 18: OwnTech converter final experiment showing its droop control

Results for the remote control

The remote control experiment showed a less than second reaction time. As the O2 converter received the order to lower its output voltage, it is possible to see it stepping down from 30V to 24V and then

18V and back again.
This experiment also corroborated the observation that current in leg 2 is way below the current in leg 1.

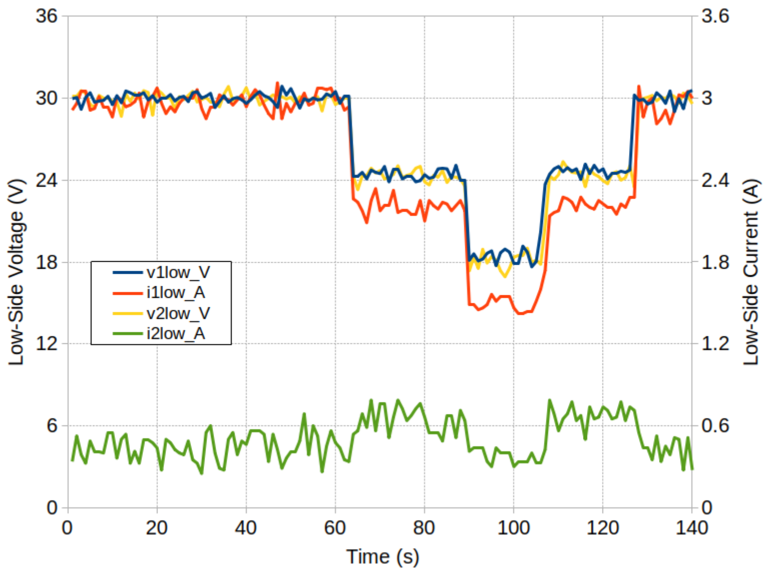


Figure 19: Remote control tests using the CAN-based communication protocol

4.2 Conclusions

The OPEN-CANVERTER project has helped both teams to debug and develop new features to their software. It allowed the OwnTech team to understand ThingSet, the CAN-based protocol developed by Martin Jager in LibreSolar. And it demonstrated that two different systems can now be used as building blocks of a more complex micro-grid.
The list of open issues for OwnTech and LibreSolar is given on the next section.

5 Open Issues and Suggestions for Improvements

Improvement for OwnTech converters

During our stay at NTUA some shortcomings have been discovered in the converter prototypes. Both in term of hardware and software. Finding and identifying these flaws is invaluable as it permits to improve the overall quality of the prototype by fixing them.

Hardware

- Serial communication was not working - RX and TX pins were reversed.
- Measurements were noisy and required a lot of calibration
- 2 out of 4 converters were not flashed correctly by the STLINK programmer when using the C implementation but were flashed correctly by using Matlab generated code.
- Testing the converters efficiency lead us to 93% overall efficiency which is below the calculated efficiency. We were not sure if it was an hardware issue or a control issue.
- More solder bridges are required to isolated the digital to analog converters (DAC) in order to be able to test out the sawtooth generation in current mode.
- More test points are needed to check out the DAC generation
- JP1 jumper must be a through hole jumper and not a solder bridge.

Software

- Requesting the temperature measurement was crashing the data acquisition system

Control

- The error calculation of the feedback loop was reversed
- The gain of the PID controller of the C implementation were not corresponding to the optimal gains calculated in Matlab. This was due as a difference in the PID implementation in Matlab / C library.
- The controller was not able to recover when the converter was placed out of its zone of controllability. When a fault occurred, the only way to restart the controller was to reset the microcontroller.
- No anti-windup was implemented in the PID controller.

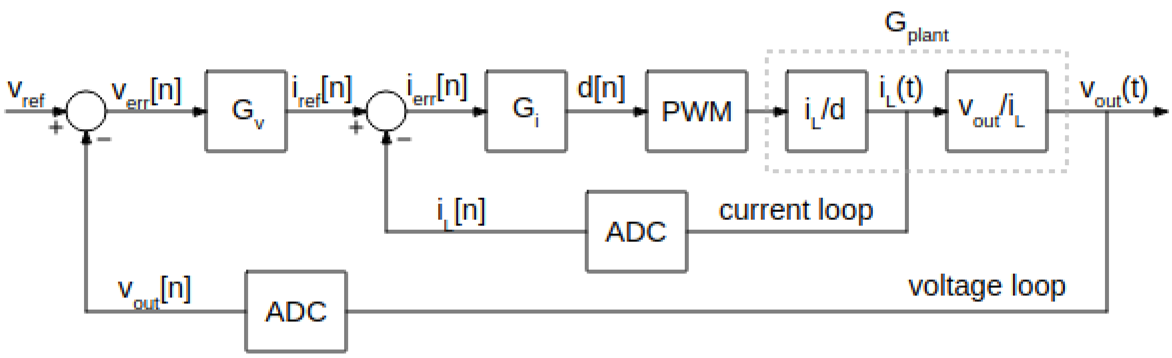
CAN

- Request/respond mode is not fully stable when having a control thread
- Python code works but would greatly benefit from a data-visualization add-on
- We have to define a list of data-objects and get inspiration from existing PMBus standard.

To follow up with these issues after the Erigrid access, with have derived “issues” in the corresponding Gitlab repository, this hence permit to breakdown the work load to different contributors.

Improvements for Libre Solar converters

The main issues identified during the lab access are related to the control algorithms.
Currently, the digital DC/DC control is based on a step-wise increase or decrease of the PWM duty cycle in each switching cycle (70 kHz) without any PID controller, as the PID tuning results did not lead to a stable control behaviour. This step-wise control is stable, but very slow.
The tests and discussions with experts during the lab access have shown that a cascaded controller with an inner PI current-control loop and an outer PI voltage-control loop are the right way to achieve fast response time.
The following image shows the planned control for the DC/DC converter, which will be implemented as a follow-up of the lab access experience.



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