



# **NAVAL POSTGRADUATE SCHOOL**

**MONTEREY, CALIFORNIA**

## **THESIS**

**DISTRIBUTED ENERGY STORAGE DESIGN  
AND MODELING TO IMPROVE THE ENERGY  
SECURITY OF NAVAL FACILITIES**

by

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June 2019

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**DISTRIBUTED ENERGY STORAGE DESIGN AND MODELING TO IMPROVE  
THE ENERGY SECURITY OF NAVAL FACILITIES**

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## **ABSTRACT**

Energy security for naval facilities is of strategic importance. Energy security is characterized by the ability to supply critical loads reliably, indefinitely, economically, and in an environmentally friendly manner (sustainably), which enables full-time mission support.

Combining renewable resources and, specifically, the emerging technology of photovoltaics (PV) with a battery storage system is considered a proven approach to providing energy security and serves as the basis of this research.

Most available design tools focus on the design of grid-tied or hybrid renewable power systems. The development of a user-friendly design tool for accurately sizing a stand-alone power system to meet the critical load demands of a naval, commercial/industrial, or even a residential facility is presented in this thesis. The tool complies with both IEEE Standards 1562 and 1013. In addition to these guidelines, the developed tool considers important factors that both standards should address in their future revisions.

Several case studies, which were simulated using a Simulink model based on the output of the design program, validate the design software. Finally, we successfully conducted 24-hour laboratory experiments, the results of which confirmed the simulations as well as the accuracy of the sizing methodology; this is a feature that many sizing programs lack.

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## LIST OF ACRONYMS AND ABBREVIATIONS

|                     |                                                   |
|---------------------|---------------------------------------------------|
| AC                  | Alternating Current                               |
| AGM                 | Absorbed Glass Mat                                |
| A:L                 | Array-to-Load ratio                               |
| EMS                 | Energy Management System                          |
| HESS                | Hybrid Energy Storage System                      |
| HOMER               | Hybrid Optimization Model for Electric Renewables |
| IEA                 | International Energy Agency                       |
| $I_{mp}$            | Maximum Power Point Current                       |
| I-V                 | Current-Voltage                                   |
| LiFePO <sub>4</sub> | Lithium-Ferro-Phosphate                           |
| Li-Ion              | Lithium-Ion                                       |
| LPF                 | Low-Pass Filter                                   |
| MDOD                | Maximum Depth of Discharge                        |
| MDT                 | Microgrid Design Toolkit                          |
| MPPT                | Maximum Power Point Tracker                       |
| MWh                 |                                                   |
| NOCT                | Normal Operating Cell Temperature                 |
| NREL                | National Renewable Energy Laboratory              |
| NSGA                | Non-dominated Sorting Genetic Algorithm           |
| PI                  | Proportional-Integral                             |
| PSH                 | Peak Sun Hours                                    |
| PV                  | Photovoltaic                                      |
| SAM                 | System Advisor Model                              |
| SC                  | Supercapacitor                                    |
| SNL                 | Sandia National Laboratories                      |
| SOC                 | State Of Charge                                   |
| STC                 | Standard Test Conditions                          |
| TCF                 | Temperature Correction Factor                     |

|          |                             |
|----------|-----------------------------|
| TFSC     | Thin-Film Solar Cells       |
| $V_{mp}$ | Maximum Power Point Voltage |
| $V_{oc}$ | Open-Circuit Voltage        |

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This thesis is dedicated to my family. Let it be an inspiration to my sister, Nancy.

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# I. INTRODUCTION

## A. BACKGROUND

Energy security constitutes one of the most important aspects of a nation's energy policy [1], [2]. According to the International Energy Agency (IEA), energy security is defined as “the uninterrupted availability of energy sources at an affordable price” [3]. Much research has been conducted on energy security, some of which is presented in [1]–[6], and many definitions have been given for this term. According to [1], “a succinct way to approach it [energy security] is through the four As: availability, affordability, accessibility (to all), and acceptability (from a sustainability standpoint).”

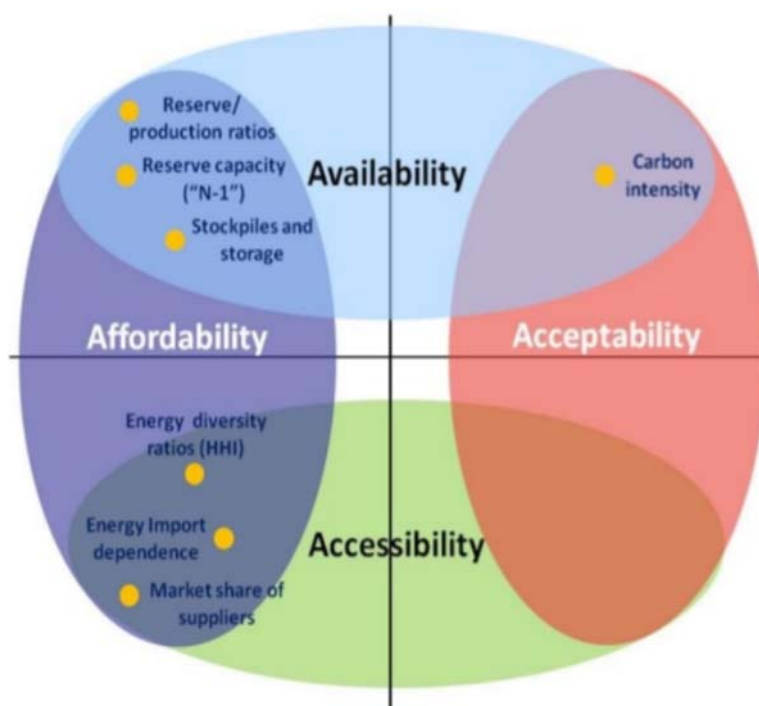


Figure 1. A-framework of energy security according to [1], [7]. Source: [8].

Energy security is of great strategic importance for naval facilities. Fuel shortage or disruptions, occasional unavailability, and unreliability of the commercial grid are just some of the major threats to a facility's critical loads, which, if impacted, will result in

mission disruption. The need to provide independence from petroleum or other fuel is essential when considering energy security. Nevertheless, energy security is not just about fuel diversification; it is about supplying critical loads reliably, continuously, economically, and in an environmentally friendly way (sustainably).

Renewable energy supports energy security because it is available at no cost in abundant amounts from natural resources which never diminish. Besides this, renewable sources of energy do not have a negative impact on the environment, as the fossil or nuclear fuels do. Having these characteristics, renewable sources provide availability, affordability, and accessibility, as well as acceptability. Consequently, renewable sources constitute the main component of energy security provision.

The most viable sources of renewable energy are solar and wind. Nevertheless, both are dependent on weather conditions; thus, the existence of an energy storage system is essential to energy security. The energy storage system stores the renewable energy and supplies the naval facility when needed, even when the production of renewable energy is reduced due to changing weather conditions. Moreover, the energy storage system is replenished when the renewable energy production increases. This constitutes the combination of renewable sources with an energy storage system, a validated approach of energy security provision.

Implementing this approach in a naval facility can support the critical loads with reliable and sustainable power indefinitely, allowing for full-time mission support.

## **B. RELATED WORK**

The emerging technology of photovoltaics (PV) has focused industry attention on the promotion of a variety of solutions implementing this renewable source of energy. Likewise, the continuous development of Lithium-Ion (Li-Ion) batteries over recent years has made them the first choice for energy storage [9], [10].

Many design programs are available to size, optimize, and run sensitivity and economic analysis of PV power systems. The most popular are the Hybrid Optimization Model for Electric Renewables (HOMER) [11], System Advisor Model (SAM) created by

the National Renewable Energy Laboratory (NREL) [12], and the Microgrid Design Toolkit (MDT) made by Sandia National Laboratories (SNL) [13].

These design tools are mainly focused on designing grid-tied and hybrid renewable power systems, but they can be used for designing stand-alone power systems as well. MDT is a design tool that has been used by a number of projects and agencies [13]. Although it considers many techno-economic characteristics, MDT does not account for battery capacity degradation due to temperature, according to the technical manual [13], which is very significant not only for lead acid batteries, but also for Li-Ion. It is noteworthy that HOMER, besides all the design considerations, provides sensitivity analysis, economic modeling, and even synthetic load profile generation [14]. On the other hand, SAM is considered the most complete design tool available, as it accounts for every single factor that affects the design of a renewable power system.

SAM provides models for selection by the user, including weather data and simulation models for every desired renewable source (wind, solar, geothermal, biomass). The battery model accounts for capacity degradation due to temperature. In addition, SAM accounts for temperature correction factors for the PV's operating voltage. Further, in SAM a shading simulation model is involved [12]. Finally, both SAM and HOMER provide most of the equations implemented.

Previously published literature, such as [15]–[18], focuses specifically on the design and analysis of off-grid power systems, but none of these fully capture the objectives of energy security. The research in [17] considers an arbitrary number of days of autonomy for the stand-alone power system. It also does not take into account the emerging technology of Li-Ion batteries. Moreover, it does not consider the temperature compensation for battery capacity. In [15], there are some points that should be reconsidered, such as the voltage-derating of the PVs in the case where maximum power point tracker (MPPT) are used. In addition, the Li-Ion batteries should be taken into consideration as well, with the appropriate temperature correction factors for their capacity. In [16] Li-Ion batteries are also not considered, but in the case of lead acid batteries, the temperature correction factors are not implemented, as [15] mentions. Furthermore, the voltage derating for PV modules operation voltage is not addressed. Finally, [18] is based

more on modeling, in Simulink, of stand-alone power systems, rather than on the design. It correctly considers the derating of power due to ambient temperature for the PVs, but it does not consider the temperature compensation for the battery capacity. In addition to the aforementioned documentation, user-friendly design software, the NSOL [19], is available for purchase online and is meant to design not only stand-alone power systems, but also hybrid and grid-tied systems, following the sizing guidelines of [20]. Nevertheless, this also does not address the emerging technology of Li-Ion batteries and, most importantly, does not take into account the temperature compensation for battery capacity, which is a very significant derating factor.

### **C. RESEARCH OBJECTIVES**

The provision of continuous power to critical loads on a naval facility is undisputable for desired energy security. This provision can be accomplished by proper design of a stand-alone (off-grid) power system.

This thesis presents a design tool for stand-alone PV power systems that will provide continuous power to critical loads. The design software developed will assist system designers and users in sizing stand-alone power systems, whether they aim to provide energy security in a naval facility, a commercial/industrial facility, or even a residential facility. The systematic approach used to size the PV array and batteries of the energy storage system to meet the critical load demand complies with both the IEEE Standards 1562 and 1013 [20], [21]. Besides these guidelines, the design tool takes it a step further and considers important factors that both standards should address in their future revisions. Among these are the voltage-derating factors for the PVs, according to the use (or not) of MPPTs, specific temperature derating factors for the battery capacity, and most importantly, the introduction of Li-Ion batteries.

The design tool presented in this thesis is based on a user-friendly windows-based environment, developed in Matlab, where the user can input and select his or her desired values. Any invalid inputs or combinations of inputs will warn appropriately and guide the user to enter valid ones. Help is always available through a manual. The users can either input the characteristics of the elements they have decided to use (PV, batteries) or select

from among a variety of the most efficient ones available on the market. The results of the calculations can be observed. Moreover, the tool provides simulation results for the desired autonomy period, based on a model created in Simulink. In the model, a scaled 24-hour load profile is used to simulate the system designed and demonstrate its performance. Finally, the method of designing the off-grid power system is validated by successfully conducting 24-hour laboratory experiments on an actual microgrid, without the use of emulators.

#### **D. ORGANIZATION**

A detailed description of the sizing methodology implemented in the software developed is presented in Chapter II.

In Chapter III, the simulation model that accepts the outputs of the design tool is described. Besides its basic concept/purpose, a hybrid energy storage system (HESS) with a novel control system for supercapacitors (SC) is implemented as presented in [22], [23].

In Chapter IV, results from simulations being performed for several design cases are presented and analyzed.

Chapter V contains a description of the laboratory experiments conducted to successfully validate the sizing methodology of the stand-alone power system, as well as the simulations.

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## II. SIZING METHODOLOGY OF THE PV ARRAY AND BATTERY FOR STAND-ALONE POWER SYSTEMS

Before examining the performance of a stand-alone power system, it is vital to introduce the method for determining the size of the PV array and the battery bank needed to supply the critical load demands indefinitely. It should be mentioned that a properly designed stand-alone power system will provide independence from both the commercial grid and fuel supply. Furthermore, it is noteworthy that, even in case the designed system is connected to the grid, in any circumstances when the grid is not reliable or available, the power system designed will ensure the support of the critical loads in order to provide mission support in the naval facility.

The method introduced and described in this chapter complies with both IEEE Standards 1013 and 1562 [20], [21], and is implemented in the program developed in Matlab. It is meant to assist designers and end-users in sizing stand-alone power systems, not only in naval facilities, but also in residential, commercial, and industrial facilities. It should be noted that the stand-alone power system chosen for this thesis includes only PV arrays as power sources and batteries as energy storage.

The main screen of the sizing program is shown in Figure 2. The windows with the inputs in both the “automatic mode” and the “manual mode” are shown in Figures 3 and 4.



Figure 2. Main screen of the sizing program developed in Matlab.

**Inputs**

**Input Parameters**

AC Load [MWh/day]

Peak-Sun Hours(PSH) [kWh/m²]

Required Usable Storage [days]

**Parameters of the Elements Used**

Inverter Efficiency

System Voltage [V]

Type Of Battery

Battery Model

Temperature [C]

PV module model

Use of MPP Tracker

Array-To-Load-Ratio

Figure 3. Window with inputs in the “automatic mode.”

**Inputs**

**Input Parameters**

AC Load [MWh/day]

Peak-Sun Hours(PSH) [kWh/m²]

Required Usable Storage [days]

**Parameters of the Elements Used**

Inverter Efficiency

System Voltage [V]

Battery Type

Battery Voltage [V]

Battery Capacity [Ah]

Temperature [C]

Maximum Power Point (MPP) Voltage

Maximum Power Point (MPP) Current

Use of MPP Tracker

Array-To-Load-Ratio

Figure 4. Window with inputs in the “manual mode.”

In this chapter, we introduce the components and the corresponding input parameters requested by the program in order to determine the size of the PV array and the battery bank of the stand-alone power system.

#### **A. INTRODUCTION TO BATTERIES FOR ENERGY STORAGE IN POWER SYSTEMS**

The key component of a stand-alone power system is the energy storage system. Among all the possible energy storage systems, the most commonly used is battery storage, especially for stand-alone power systems.

Despite the fact that lead acid batteries are considered a dated technology, they are worth mentioning. Lead acid batteries can be categorized according to three types: flooded, sealed gel electrolyte, and sealed Absorbed Glass Mat (AGM). The flooded lead acid batteries, due to their formulation (flooded), have safety issues and concerns, even though they are the least expensive. The sealed gel batteries are deep-cycle batteries, but their capacity is strongly affected by temperature. Finally, sealed AGM batteries are safer than the sealed gel and less expensive, too. Nevertheless, even if they are the only type of lead acid batteries recommended for solar energy storage, their capacity is also highly affected by temperature.

In recent decades, the use of Li-Ion batteries has been established for use in energy storage systems. Their advantages over the lead acid batteries are numerous. They are lighter, smaller, and relatively safer. They have a longer lifetime, higher roundtrip efficiency, higher maximum depth of discharge, higher capacity, and they need no maintenance. Figure 5 shows the superiority of the volumetric (y-axis) and gravimetric (x-axis) energy density of the Li-Ion batteries over other rechargeable batteries [24]. Finally, and most importantly, their capacity is not strongly affected by temperature. Even though they may be a bit more expensive, accounting for all the aforementioned advantages, they are considered cost-effective for long-term performance.

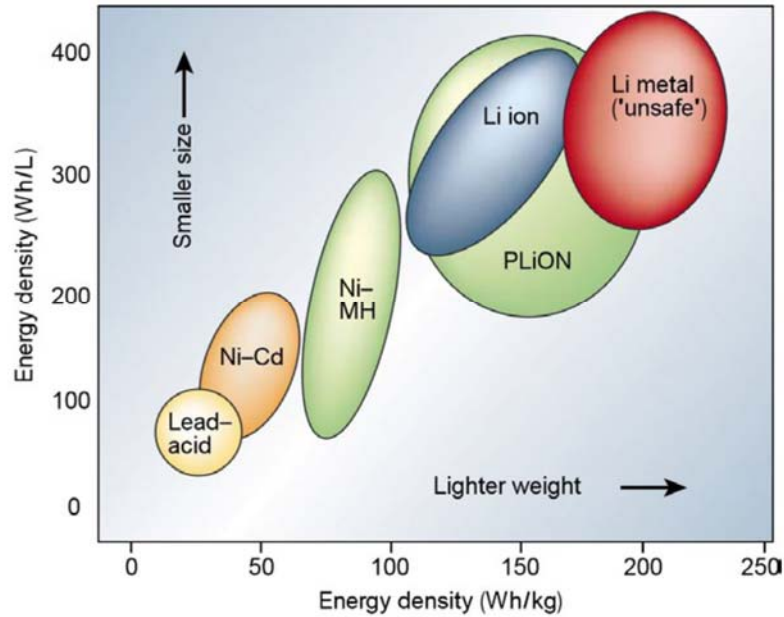


Figure 5. Comparison of energy densities and specific energy of different rechargeable batteries. Source: [24], [25].

## B. BATTERY SIZING

Before determining the size of the batteries used, it is necessary to calculate the appropriate battery capacity.

To begin with, one of the system design requirements is the load power demand in Megawatt hours (MWh). For this purpose, all loads anticipated throughout a day, along with their expected durations, should be recorded. For applications where the total load varies significantly each month, then the average daily load of the month should be considered; later, the maximum average daily load is chosen. The user should input the alternating current (AC) load in MWh per day.

Another vital design requirement is the autonomy period. This is the time period in days when the power system load is meant to be supported entirely by its fully charged battery bank; that means it will not receive power from the PV array. Several considerations should be made to determine the autonomy of the system, the most important of which are the criticality of the load application, the system availability, and solar irradiance variations throughout the day or season. For the estimation of the number of days of usable storage,

one can consider Figure 6 as a starting point. The figure is based on SNL and specifically on the guidebook *Stand-Alone Photovoltaic Systems Handbook of Recommended Design Practices* [26].

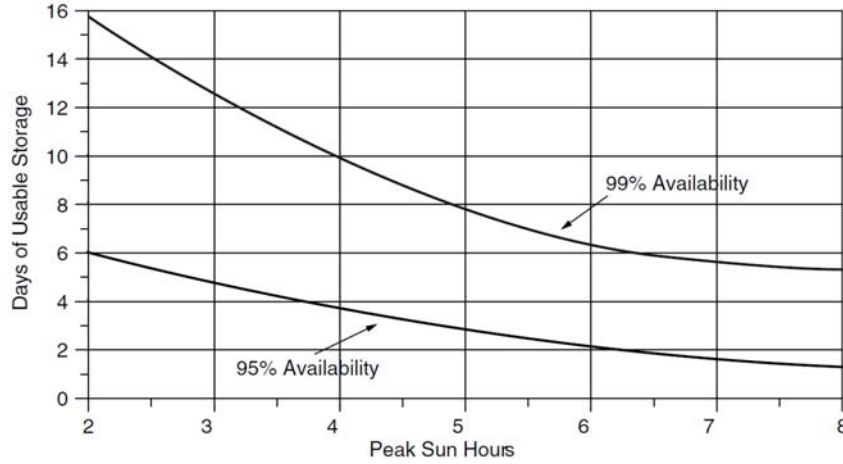


Figure 6. Days of battery storage needed for a stand-alone system with 95% and 99% system availability. Peak sun hours are on a month-by-month basis. Source: [26].

The equations that match the curves shown in Figure 6 are the following [15]:

$$\begin{aligned}
 \text{Autonomy}[\text{days}] &\approx 24.0 - 4.73 \cdot (\text{PSH}) + 0.3 \cdot (\text{PSH})^2, \text{ for } 99\% \text{ Availability} \\
 &\text{and} \\
 \text{Autonomy}[\text{days}] &\approx 9.43 - 1.9 \cdot (\text{PSH}) + 0.11 \cdot (\text{PSH})^2, \text{ for } 95\% \text{ Availability,}
 \end{aligned} \tag{1}$$

where Peak Sun Hours (PSH) is the “length of time in hours at a solar irradiance level of  $1\text{kW/m}^2$  needed to produce the daily solar radiation obtained from the integration of irradiance over all daylight hours,” according to [20].

Another consideration in determining how much power the batteries must supply is the loss in the direct current (DC)-to-AC inverter. Taking into account that the inverter efficiency depends on the load and that most inverters operate at approximately 90% efficiency; a fair assumption of about 85% of the total inverter efficiency is considered as a default input to the program. It should be mentioned that users are able to customize inverter efficiency to their desired value.

Furthermore, the bus voltage should be considered. The DC bus voltage is the inverter DC input voltage and, consequently, the battery bank and the PV array voltage. For a residential facility the system voltage can be 24V or 48V and certainly for larger facilities the voltage can be, for instance, 480V or higher.

Based on the previous considerations, the DC load can be expressed in MWh/day as:

$$DC Load [MWh/day] = \frac{AC Load}{Inverter's Efficiency} . \quad (2)$$

Knowing the system voltage ( $V_{bus}$ ), the battery bank needs to supply:

$$Load [Ah/day at DC Bus] = \frac{DC Load}{V_{bus}} . \quad (3)$$

Based on the two first design requirements, the unadjusted battery capacity is given by:

$$Unadjusted Battery Capacity[Ah] = Load \cdot Autonomy . \quad (4)$$

At this point, in order to proceed with the calculation of the adjusted battery capacity, and later with the sizing of the battery bank, a selection of a battery type should be made by the user. In this way, the capacity calculated in equation (4) is adjusted for the characteristics and operating conditions of the battery. The user can select the type of the battery—between deep cycle lead acid and Li-Ion, by selecting the manual mode, or one of the specific battery types and models suggested by the program, by selecting the auto mode. In case of the manual mode, except for the selection of the type of battery, two basic characteristics of the battery should be input into the program. These are its voltage ( $V_{bat}$ ) and its capacity (*Capacity*) in Ampere-hours [Ah] at the determined discharge rate. Depending on the type of the battery selected, additional characteristics are automatically considered. These are the Maximum Depth of Discharge (MDOD), the battery efficiency, and the multicell recharge voltage. These characteristics are defined in Table 1.

Table 1. Characteristics of different types of batteries.

|                         | Deep Cycle Lead Acid | Li-Ion  |
|-------------------------|----------------------|---------|
| MDOD                    | 80%                  | 100%    |
| Voltage/cell            | 2.35                 | 3.2-4.0 |
| Efficiency<br>(average) | 0.94                 | 0.98    |

It is important to mention that Lithium-Ion batteries, depending on the chemistry and architecture used, feature surface coating and electrolyte additives and consequently increase the nominal voltage per cell; this allows for higher charge voltages. Particularly, the voltage per cell for different Li-Ion chemistries is illustrated in Table 2, with the Lithium-Ferro-Phosphate (LiFePO<sub>4</sub>) being those most commonly used.

Table 2. Recharge voltage per cell for different chemistries of Li-Ion batteries.

|                                     | Voltage per cell |
|-------------------------------------|------------------|
| LiFePO <sub>4</sub>                 | 3.2              |
| LiCoO <sub>2</sub>                  | 3.7              |
| LiMn <sub>2</sub> O <sub>4</sub>    | 4.0              |
| LiNiO <sub>2</sub>                  | 3.5              |
| Li <sub>2</sub> FePO <sub>4</sub> F | 3.6              |

The program recommends specific models of batteries, either lead acid or Li-Ion, in the “automatic mode,” which are presented in Tables 3 and 4.

Table 3. Recommended models of lead acid batteries. Adapted from [27], [28].

| Model                   | Voltage<br>[V] | Capacity<br>[Ah] | Efficiency<br>[%] | MDOD<br>[%] | V/cell |
|-------------------------|----------------|------------------|-------------------|-------------|--------|
| Trojan SPRE 12 225 [27] | 12             | 204              | 0.94              | 80          | 2.35   |
| Trojan 8D-AGM [28]      | 12             | 230              | 0.94              | 80          | 2.35   |

Table 4. Recommended models of Li-Ion batteries. Adapted from [29]–[35].

| Model                   | Voltage<br>[V] | Capacity<br>[Ah] | Efficiency<br>[%] | MDOD<br>[%] | V/cell |
|-------------------------|----------------|------------------|-------------------|-------------|--------|
| SimpliPhi PHI 3.5 [29]  | 24             | 138              | 0.98              | 100         | 3.2    |
| Relion RB48V100 [30]    | 48             | 100              | 0.98              | 100         | 3.2    |
| Relion RB48V150 [31]    | 48             | 150              | 0.98              | 100         | 3.2    |
| Relion RB48V200 [32]    | 48             | 200              | 0.98              | 100         | 3.2    |
| Winston LFP400AHA [33]  | 48             | 400              | 0.98              | 80          | 3.2    |
| Winston LFP700AHA [34]  | 48             | 700              | 0.98              | 80          | 3.2    |
| Winston LFP1000AHC [35] | 48             | 1000             | 0.98              | 80          | 3.2    |

Besides the battery characteristics, one of the factors that should be considered is temperature, since it affects the available battery capacity. Specifically, the latter decreases for temperatures lower than 25° C and increases for temperatures greater than 25° C. The battery capacity should be adjusted by the temperature correction factor (TCF). For temperatures higher than 25° C, however, the TCF will be kept at 1. Figure 7 shows the effect of temperature on the battery capacity. The values for a moderate discharge

rate (C/20) can be also confirmed by experiments investigated by SNL for lead acid batteries, as well as by specifications from Trojan Battery Company and Hawker Power Source, one of the largest lead acid battery brands in the world.

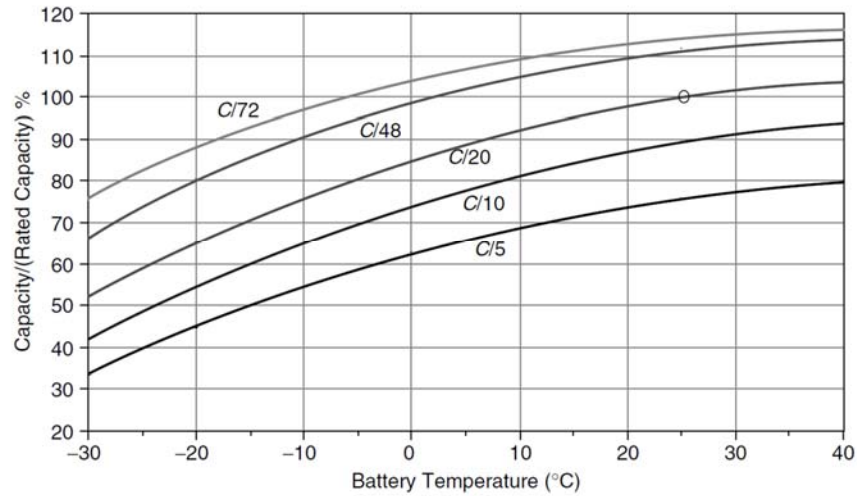


Figure 7. Lead acid battery capacity depends on discharge rate and temperature. Batteries are nominally rated at C/20 and 25° C. Source: [15].

Taking Figure 7 into consideration, it should be noted that the temperature the user inputs affects the capacity of the lead acid batteries by the following factors:

Table 5. TCF for lead acid batteries.

| Temp.<br>(° C) | >25 | 25 | 20   | 15   | 10   | 5   | 0    | -5  | -10  | -15 | -20  |
|----------------|-----|----|------|------|------|-----|------|-----|------|-----|------|
| TCF            | 1   | 1  | 0.98 | 0.95 | 0.93 | 0.9 | 0.85 | 0.8 | 0.75 | 0.7 | 0.65 |

On the other hand, Li-Ion batteries are not as significantly affected by temperature as the lead acid batteries are. Figure 8 depicts how the temperature affects the battery capacity percentage, as it was concluded by laboratory experiments conducted by [36].

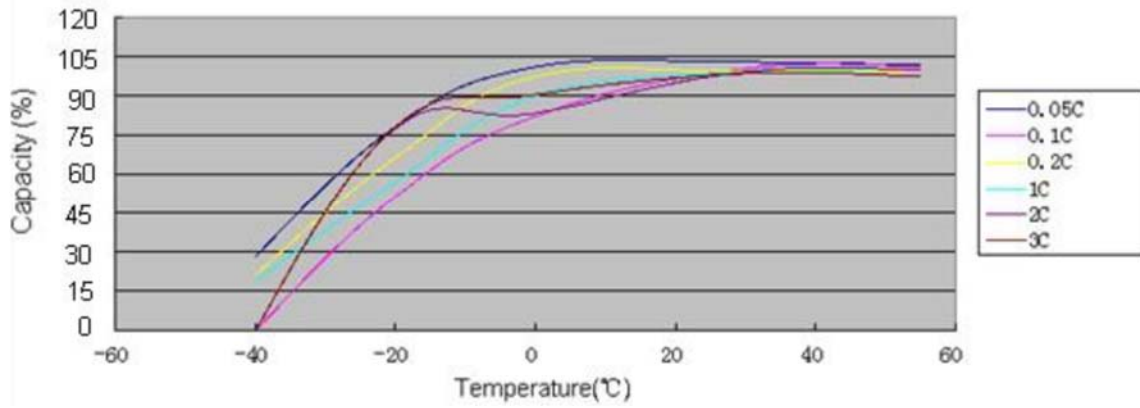


Figure 8. Li-Ion battery capacity depends on discharge rate and temperature. Batteries are nominally rated at C/20 and 25° C. Source: [36].

Similarly, taking Figure 8 into consideration, it should be noted that the temperature the user inputs affects the capacity of the Li-Ion batteries by the factors presented in Table 6. Here, too, the maximum value for the TCF will be 1.

Table 6. TCF for Li-Ion batteries.

| Temp.<br>(° C) | >25 | 25 | 20 | 15 | 10 | 5 | 0    | -5   | -10  | -15  | -20  |
|----------------|-----|----|----|----|----|---|------|------|------|------|------|
| TCF            | 1   | 1  | 1  | 1  | 1  | 1 | 0.98 | 0.95 | 0.92 | 0.85 | 0.77 |

Based on the previously mentioned considerations, the battery capacity can now be adjusted for MDOD and the temperature correction factor. A design margin is also be taken into consideration to maintain the system's availability, and for uncertainties in the load determination. For this reason, a design margin of 10% ( $Margin = 1.1$ ) is considered in the program's calculations:

$$Nominal\ Battery\ Capacity[Ah](rounded\ up) = Margin \cdot \frac{Unadjusted\ Battery\ Capacity}{MDOD \cdot TCF} \quad (5)$$

Knowing the nominal battery capacity, next we determine its size. For the sizing of the batteries, reference [21] refers to the system voltage window and also mentions that it

should be defined accordingly. Specifically, [21] defines  $V_{\max}$ , as the lowest maximum voltage and  $V_{\min}$ , as the highest minimum voltage, between which all loads operate properly. Then the number of series connected batteries is determined by:

$$Bat_{series}(\text{rounded down}) = \frac{V_{\max}}{V_{multicell}} , \quad (6)$$

where the multicell charging voltage ( $V_{multicell}$ ) is given by the product of the voltage of the individual cell and the number of cells in the battery:

$$V_{multicell} [V] = V_{cell} \cdot N_{cells} , \quad (7)$$

and the number of cells is defined as:

$$N_{cells} = \frac{V_{bat}}{2}, \text{ for Lead Acid Batteries}$$

and

$$N_{cells} = \frac{V_{bat}}{3}, \text{ for Li-Ion Batteries.} \quad (8)$$

Nevertheless, recording the maximum and minimum voltages for each DC load in order to determine the voltage window is almost impossible. Determining the number of series-connected batteries using the recharge voltage will, in some cases, result in a lower voltage during the periods when the batteries are not going to be charged. Furthermore, sizing upon the nominal battery voltage, even during battery charging when the voltage is going to be higher, is not a problem, since it is going to be in the input voltage range of the inverter. For these reasons, the proposed equation to determine the number of series connected batteries is simply:

$$Bat_{series}(\text{rounded up}) = \frac{V_{bus}}{V_{bat}} . \quad (9)$$

The number of batteries connected in parallel is readily given by dividing the adjusted nominal battery capacity by the battery capacity, and the results are rounded up to the next integer:

$$Bat_{parallel}(rounded\ up) = \frac{Nominal\ Battery\ Capacity}{Battery\ (unit)\ Capacity} . \quad (10)$$

Obviously, the total number of batteries used is given by:

$$Bat_{TOTAL} = Bat_{series} \cdot Bat_{parallel} . \quad (11)$$

And the final battery capacity  $Capacity_{TOTAL,final}$ :

$$Capacity_{TOTAL,final}[Ah] = Battery\ (Unit)\ Capacity \cdot Bat_{parallel} . \quad (12)$$

### C. INTRODUCTION TO PV PANELS

As for renewable energy, the first type of energy that comes to mind is unlimited, and it comes from the sun. This type of energy can be converted to electric energy using PV cells, which are the basic component of a PV module or panel. The cells, composed of semiconductor material, absorb the photons of the sunlight. The electrons in the material start flowing, producing current, which in turn flows out of the panel. The current output of the PV panel, being one of the two components of the power produced, depends mainly on the solar radiation. The voltage is kept mainly constant over the range of the current outputs, following the I-V characteristic curve of the PV panel. Of course, the voltage is affected by other parameters as well, as discussed later.

Types of cells commonly used are the thin-film solar cells (TFSC), polycrystalline silicon solar cells, and monocrystalline silicon solar cells, with the last being the most efficient, but the most expensive. Three factors should be mainly considered for the appropriate selection of a type of PV panel: initial cost, efficiency, and space available.

It should be mentioned that, in order to determine a higher efficiency of the PV array, MPPT charge controllers are often used. In these controllers, advanced algorithms are implemented in order to adjust the operating voltage of the PVs to the maximum power point, obtaining in this way the maximum power output of the PV. The use (or not) of MPPTs is also a choice for the user in the input window of the program, as mentioned later.

#### D. PV ARRAY SIZING

Before determining the size of the PV panels used, it is essential to collect the appropriate solar radiation data since the PV array size is going to be based on the worst-case scenario of solar radiation of the specific location for which the system is being designed, its load demand, and the system losses.

A typical daily solar radiation profile is represented by the parabolic curve in Figure 9. The same area under the parabola can be produced by a rectangle with a width of PSH at the Standard Test Conditions (STC) rated solar irradiance of  $1000 \text{ W/m}^2$ :

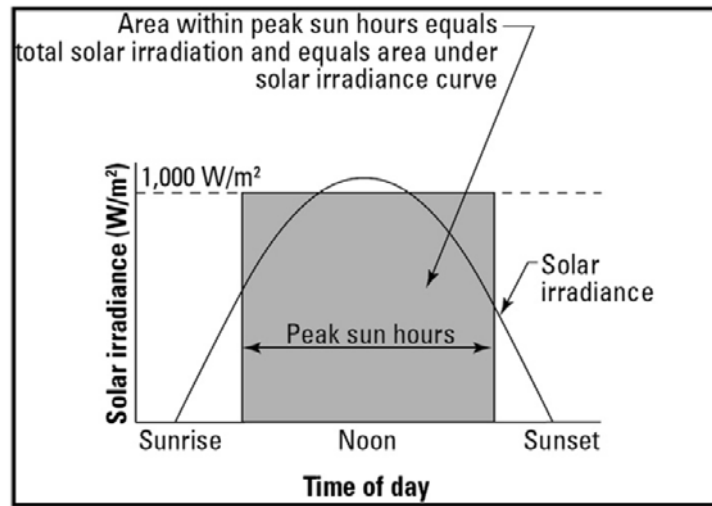


Figure 9. Hourly irradiation curve and PSH rectangle. Source: [37].

Generally, it is recommended to use the PSH in  $\text{kWh/m}^2$  of the month with the lower solar radiation for the desired location. These data are available in several different resources, such as SNL or the NREL [38]. This data resulted from the collection of solar radiation data over many years, together with other influencing factors like wind and temperature, in order to determine the number of hours per day a solar panel can produce usable energy in the location of interest.

|              | Los Angeles, CA  |      |      |      |      |      |      |      |      |      |      |      |      |
|--------------|------------------|------|------|------|------|------|------|------|------|------|------|------|------|
|              | Latitude 33.93°N |      |      |      |      |      |      |      |      |      |      |      |      |
| Tilt         | Jan              | Feb  | Mar  | Apr  | May  | Jun  | July | Aug  | Sept | Oct  | Nov  | Dec  | Year |
| Lat − 15     | 3.8              | 4.5  | 5.5  | 6.4  | 6.4  | 6.4  | 7.1  | 6.8  | 5.9  | 5.0  | 4.2  | 3.6  | 5.5  |
| Lat          | 4.4              | 5.0  | 5.7  | 6.3  | 6.1  | 6.0  | 6.6  | 6.6  | 6.0  | 5.4  | 4.7  | 4.2  | 5.6  |
| Lat + 15     | 4.7              | 5.1  | 5.6  | 5.9  | 5.4  | 5.2  | 5.8  | 6.0  | 5.7  | 5.5  | 5.0  | 4.5  | 5.4  |
| 90           | 4.1              | 4.1  | 3.8  | 3.3  | 2.5  | 2.2  | 2.4  | 3.0  | 3.6  | 4.2  | 4.3  | 4.1  | 3.5  |
| 1-Axis (Lat) | 5.1              | 6.0  | 7.1  | 8.2  | 7.8  | 7.7  | 8.7  | 8.4  | 7.4  | 6.6  | 5.6  | 4.9  | 7.0  |
| Temp. (°C)   | 18.7             | 18.8 | 18.6 | 19.7 | 20.6 | 22.2 | 24.1 | 24.8 | 24.8 | 23.6 | 21.3 | 18.8 | 21.3 |

Figure 10. Insolation table for Los Angeles, CA. Source: [15].

To properly design a sufficient stand-alone power system, the user should consider the month with the lowest radiation. The array tilt angle should be adjusted in order to maximize solar irradiance depending on the location. Typically, the array needs to be oriented to face north for locations in the southern hemisphere and south for those in the northern hemisphere. Generally, for fixed-tilt arrays, in order to optimize performance in the winter, the array tilt angle should be the latitude plus 15 degrees [39].

To begin with, the PV array is addressed to recharge the batteries that are supplying the power to the load, overcoming the system losses. The system losses that should be considered include battery efficiency, wire losses, dust, and aging of the PV array, and other parasitic losses. A fair assumption of about 15% total system losses is considered as a default value in the program, and this is updated by adding the battery roundtrip losses (complement of the roundtrip battery efficiency):

$$SL = 0.15 + (1 - Bat_{eff}) . \quad (13)$$

Furthermore, the number of PV modules that should be connected in series is determined by:

$$PV_{series} (rounded\ up) = \frac{V_{system}}{V_{mod}} . \quad (14)$$

Nevertheless, it should be noted that the PV module's nominal voltage is not specified by the manufacturers, since it depends on factors like losses, but mostly on the use (or not) of a MPPT module, which provides controllers that track the PV panel

operating point toward the maximum power point of the current-voltage (I-V) characteristic curve. For this reason, and taking into account that the output voltage of the PV array should be greater than the battery bank recharge voltage, we can take the equation that is proposed by IEEE Standard 1562–2007 a step further by determining the number of PV modules that should be connected in series by:

$$PV_{series}(\text{rounded up}) = \frac{V_{multicell} \cdot Bat_{series}}{V_{mp} \cdot (\text{Derating Voltage Factor})} \quad (15)$$

The  $V_{mp}$  is the voltage at the maximum power point (according to STC<sup>1</sup>) of the PV's I-V curve, as seen in Figure 11. The derating voltage factor accounts for voltage drops through the power system, and an average assumption of about 80% is considered as the default value in the program that is going to assure that the knee of the maximum power point is well above the battery recharge voltage.

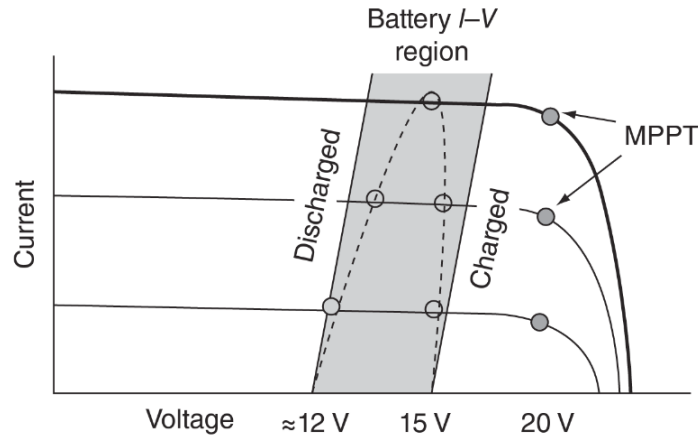


Figure 11. With PVs directly connected to batteries, the operating point will move around within the shaded area as voltage rises during charging and as insolation changes throughout the day. Source: [15].

At this point, it should be mentioned that the operating voltage of the PV panel is affected by the ambient temperature, since the cells operate at a temperature higher than

<sup>1</sup> “The accepted conditions under which PV devices are commonly rated: 1000W/m<sup>2</sup> irradiance at a spectral distribution of air mass (AM) 1.5 and a 25°C PV cell temperature” [20].

the STC reference, which is 25° C. At higher temperatures, the operating voltage drops and the maximum power point moves toward the characteristic I-V curve of the battery. Nevertheless, when no MPPT is used, the operating point is already far away from the knee, and thus, any variations of high temperatures are considered minimal [15]. In case MPPT is used for the connection of the PV array with the battery bank, then variations of high temperatures should be considered for the derating of the PV operating voltage. The ambient temperature, however, is variable, and if requested, the input by the user or designer may be higher or lower in some cases. Besides that, manufacturers provide the temperature coefficient for voltage,  $T_{CV}$ , in many different units, such as V/°C or %/°C or even ppm/°C. Considering the aforementioned, according to the author, it is preferable to use a voltage-derating factor of 0.95 to account for any variations of high temperatures when MPPT is used. Also, in this factor, the power conversion losses of the MPPT is considered. The latter is very important to mention since the factor of 1, according to [15], is considered as misleading in real applications. When MPPT is used, it is important to note that it is based upon the PV array wattage. Thus, the configuration of the PV array can be adjusted depending on particular MPPT specifications, such as maximum wattage input at the rated voltage and maximum current output. An example, to make this clearer, is provided in Chapter V, where the PV array configuration for the conduction of the laboratory experiment is determined.

A parameter considered for the determination of the number of PV modules that should be connected in parallel is the PV array-to-load ratio (A:L). This is the average daily PV ampere-hours [Ah] output to average daily load demand in ampere-hours [Ah] ratio [20]. According to [20], “typical values for A:L are as follows:

- For non-critical loads and areas with high and consistent solar radiation, an A:L of 1.1 to 1.2 is typical.
- For critical loads or areas with low solar irradiance, an A:L of 1.3 to 1.4 or higher is typical.”

The program provides users the choice to select their desired A:L according to their location and criticalness of the loads. Moreover, in this way, the user can observe through

the simulations how the different values of A:L affect the time required to recharge the battery bank, since the higher the A:L is, the less the time required to recharge the batteries. At the same time, though, the number of PV panels obviously increases.

As for the value for A:L, the number of modules that should be connected in parallel is determined by:

$$PV_{parallel}(rounded\ up) = \frac{Load[Ah/day] \cdot (A:L)}{(1-SL) \cdot I_{mp} \cdot PSH} . \quad (16)$$

The total number of PV panels used is given by:

$$PV_{TOTAL} = PV_{series} \cdot PV_{parallel} . \quad (17)$$

Including the system losses (SL), the PV output at the derated  $V_{mp}$  is given by:

$$PV_{out}[Ah] = PV_{parallel} \cdot I_{mp} \cdot PSH \cdot (1-SL) . \quad (18)$$

The models of PV panels that the program recommends are presented in Table 7.

Table 7. Recommended models of PV panels. Adapted from [40]–[42].

| Model                         | $V_{mp}$ [V] | $I_{mp}$ [A] | Efficiency [%] |
|-------------------------------|--------------|--------------|----------------|
| LG365Q1C-A5 [40]              | 36.7         | 9.95         | 21.1           |
| SunPower SPR-X22-360 [41]     | 60.6         | 5.94         | 22.2           |
| SunPower SPR-X22-360-COM [42] | 60.6         | 5.94         | 22.2           |

After all inputs have been provided by the user, the output results are presented in the next window. A typical window with outputs is shown in Figure 12.

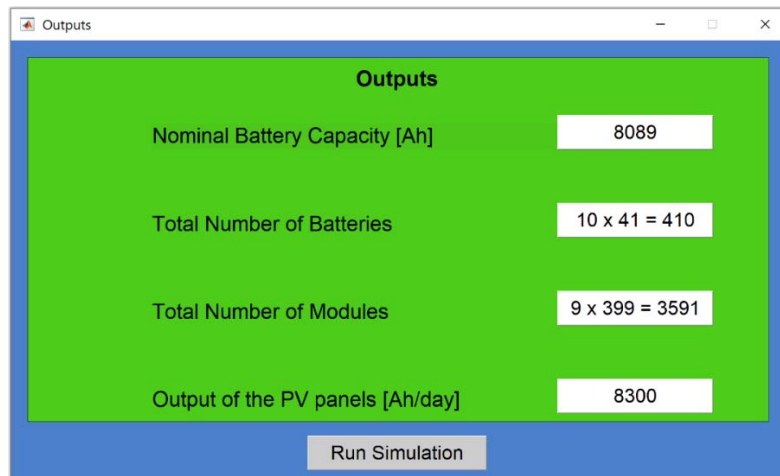


Figure 12. Window with outputs.

### III. STAND-ALONE POWER SYSTEM MODELING

In order to examine the performance of the stand-alone power system, which is sized by the program as described in Chapter II, we used Matlab and Simulink to create a model of a microgrid consisting of the PVs and a HESS. The model is described in this chapter.

#### A. ARCHITECTURE AND SIMULINK MODEL OF THE STAND-ALONE POWER SYSTEM

The microgrid that was modeled consists of the PV array, a HESS, which is formed by the battery bank and the SCs and also the DC load, simulated by a load profile after the conversion from the AC load demand. The architecture of the system is shown in Figure 13. It should be mentioned that the SCs, an additional feature adopted from [22], can be turned off. The feature is used only to show how the SCs can improve the battery lifetime, since they have higher capacitances, and also thanks to their high power densities, they can supply a high fast charge when short-term power is needed.

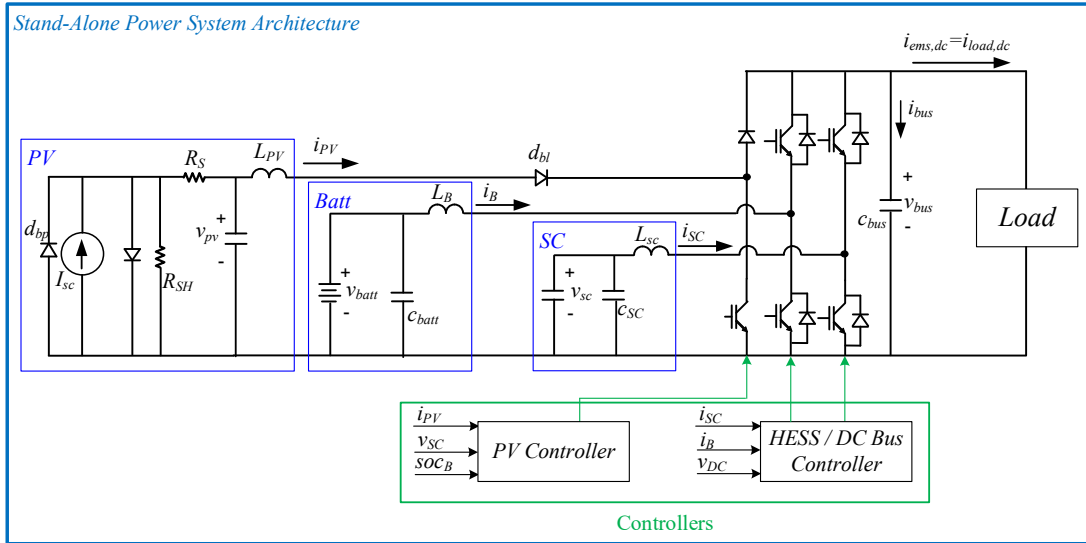


Figure 13. Architecture of the stand-alone power system.

The DC equivalent circuit of the PV array is shown on the left side of the system architecture. It consists of a five-parameter input model according to [43]–[45]. Specifically, the current source depends mostly on the solar radiation and on the cell temperature. The diode determines the maximum voltage output of the PV panel and also protects the PV array by preventing reverse voltage from being applied to specific PV panels by any others panels of the array, such as in the shading phenomenon. The diode current is determined by Shockley’s equation, according to circuit analysis done in [43], [44]. According to [44] the parallel shunt resistance  $R_{sh}$  is considerably high, and thus the current flowing through this branch can be considered zero. So, finally, the PV equivalent circuit can be simplified by a current source that is dependent on the solar radiation and a series resistance  $R_s$  representing the system losses.

The power module consists of three legs [23]. The first leg of the power module is operating as a boost converter of the PVs. Before this a blocking diode,  $d_{pl}$ , is depicted. The purpose of this diode is to block the current leaking from the batteries back to the PV panels during the night, when the voltage across the PV array is going to be lower than the battery bank voltage. Furthermore, the PV controller designed in the Simulink model controls the switch of the boost converter. The PV controller lets the current output of the PV flow in order to charge the HESS or bypass the PV array through the by-pass diode  $d_{bp}$  when the batteries and SCs, which form the HESS, are fully charged. The second leg is operating as a bi-directional buck-boost converter, allowing the charging or discharging of the battery bank. Similarly, the third leg is operating as a bi-directional buck-boost converter, allowing the charging or discharging of the SCs [23].

Since the PV array has been already sized, accounting also for losses, the PV output in Ah is implemented by a step profile forming a parabola to approach the hourly solar irradiance [46]. This profile is scaled according to the PV output that is being calculated from the program. The typical PV profile is shown in Figure 14. In this way, the purpose of the blocking diode is also accomplished. Here, it should be mentioned that the model does not account for any PV shading effects.

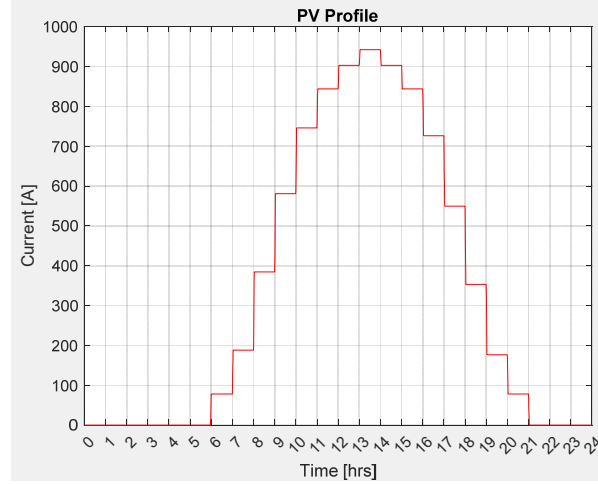


Figure 14. PV profile.

This model is designed to supply a variable daily load. Since it simulates in DC, the AC load demand is converted to DC and applied on a “typical load current profile of a remote microgrid” [22], [23], [47]. The area of the load profile over the 24-hour period is the DC load in Ah/day. The profile is scaled each time, depending on the load demand input by the user. The current load profile used for the simulations is shown in Figure 15. It should be mentioned that an interesting thought for future work could be to generate synthetic load profiles according to specific parameters requested from the users, similar to the approaches discussed in [48]–[50].

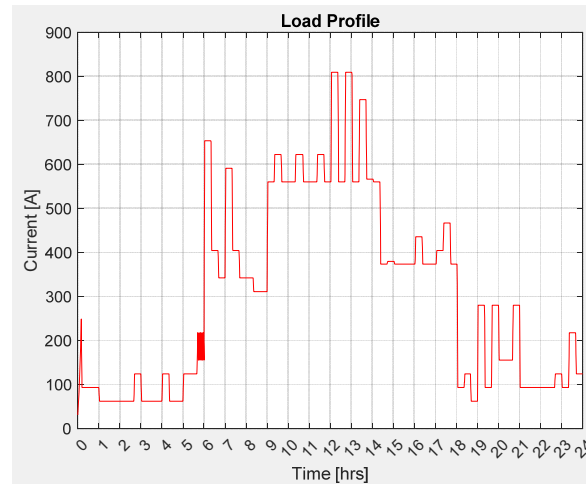


Figure 15. Load profile. Adapted from [22], [23], [47], [51].

The equivalent circuit of the model is shown in Figure 16 where, in order to achieve faster simulations, the switching power converters are replaced by current sources. Specifically, the PV current  $i_{PV}$ , the battery current  $i_B$ , and the SC current  $i_{SC}$  are flowing to the Energy Management System (EMS) DC bus and the load current  $i_{load}$  is flowing away from the EMS DC bus [51].

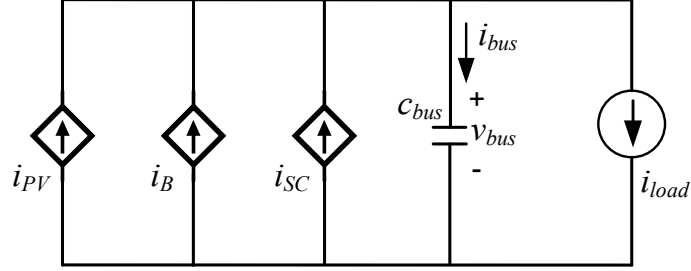


Figure 16. Equivalent circuit for analysis.

Using basic circuit analysis, we obtain:

$$\begin{aligned}
 i_{bus} + i_{load} &= i_{PV} + i_B + i_{SC} \Leftrightarrow \\
 \Leftrightarrow i_{bus} &= i_{PV} + i_B + i_{SC} - i_{load} \Leftrightarrow \\
 \Leftrightarrow V_{DC} &= \frac{1}{s \cdot C_{bus}} \cdot (i_{PV} + i_B + i_{SC} - i_{load}).
 \end{aligned} \tag{19}$$

The current of the HESS is the sum of the battery current and SC current:

$$i_{HESS} = i_B + i_{SC} . \tag{20}$$

Based on the aforementioned analysis the Simulink implementation of the microgrid model is presented in Figure 17:

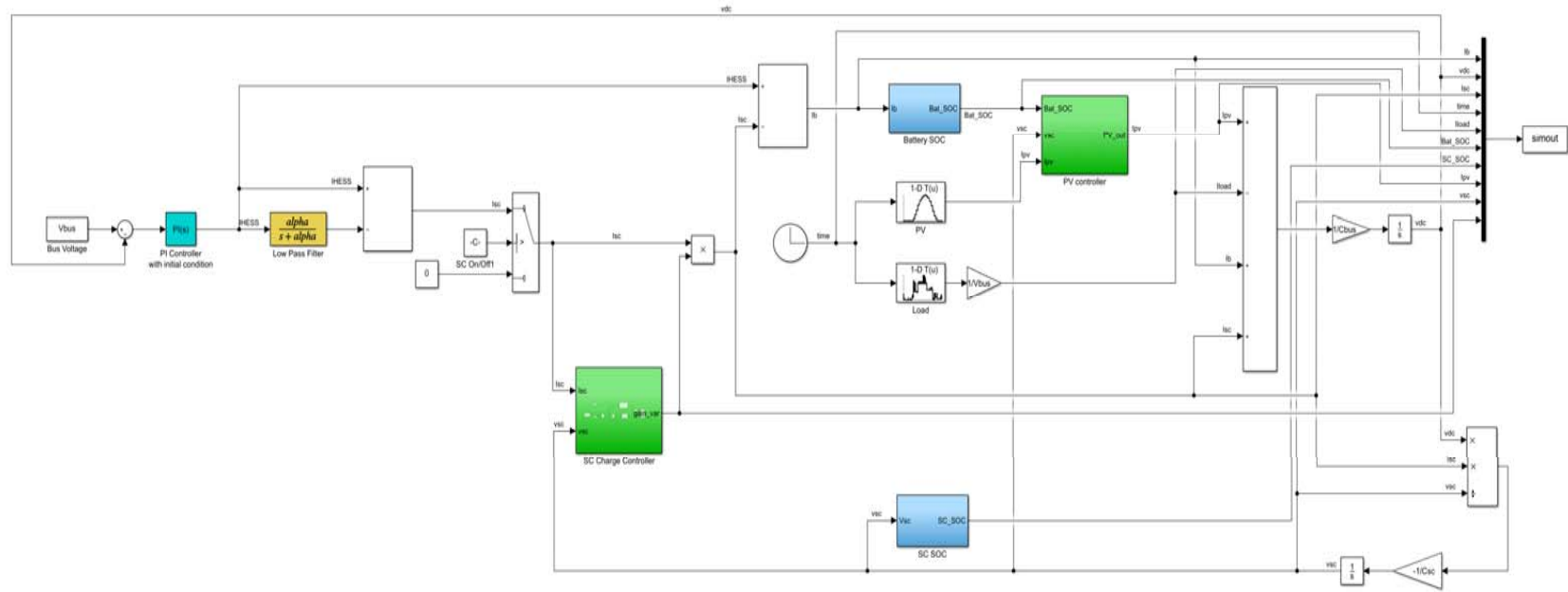


Figure 17. Simulink model.

## B. CONTROLLERS

The Simulink model incorporates a novel HESS control system presented in [22]. The control system demonstrated in Figure 18 is first comprised of a proportional-integral (PI) controller to regulate the DC bus voltage. The output of the PI controller is the current of the HESS. A low-pass filter (LPF) is implemented for the identification of the battery current [22], [51], [52]. Consequently, the output of the LPF is the battery current  $i_B$ . Hence, the remaining current from the HESS is the SC current,  $i_{SC}$ . When the SC controller is in the off state, the battery current is the output of the PI controller [22].

Following the concept presented in [51], the goal of the control system is to avoid over or undercharging the SCs. Specifically, as can be concluded by Figures 18 to 21, the SC current will be limited by the lookup table, if the commanded current is about to over/undercharge the SCs [22]. Moreover, as seen from the logic, if the SCs are fully charged, yet the SC current is meant to reduce their voltage ( $i_{SC}^* > 0$ ), then the SC current gain is not limited [22].

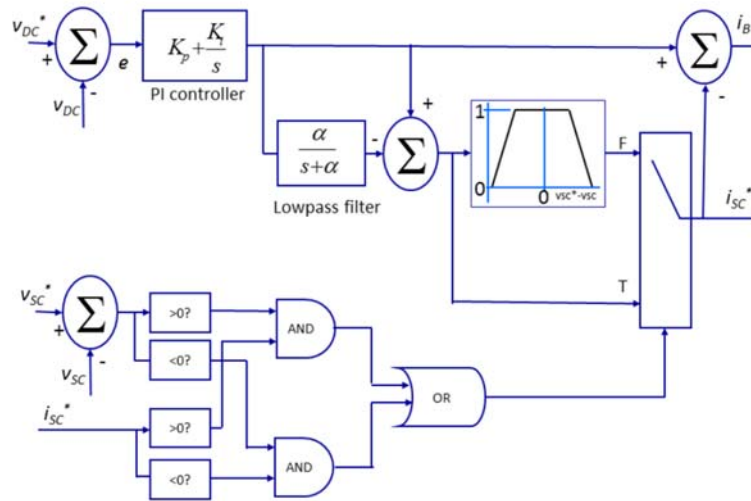


Figure 18. Novel HESS control system. Source: [22].

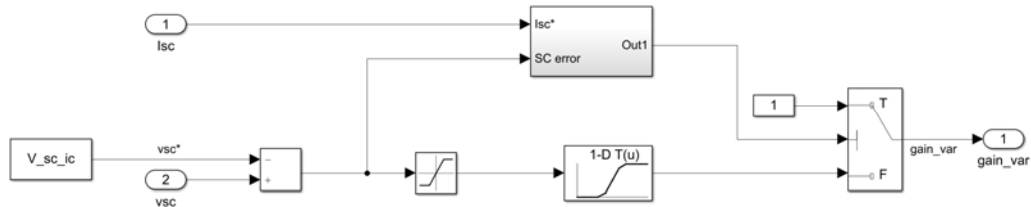


Figure 19. SC charge controller. Adapted from [22].

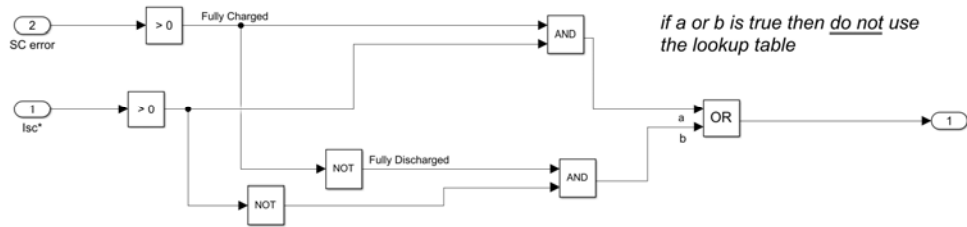


Figure 20. Logic for the switch of the SC charge controller. Adapted from [22].

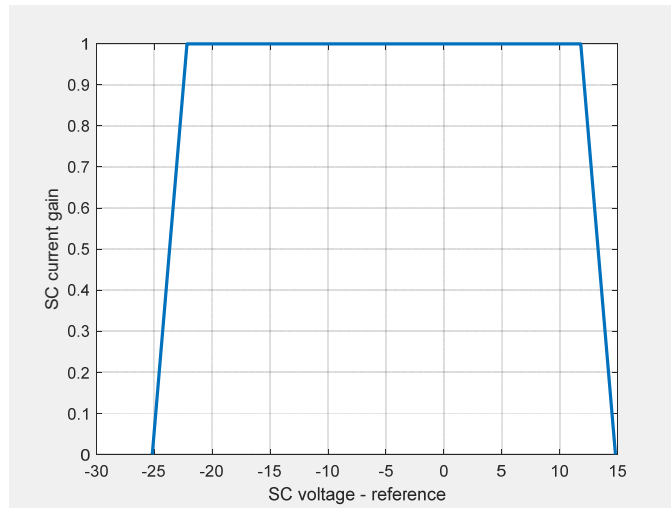


Figure 21. SC current gain. Adapted from [22].

It should be mentioned again that this feature of a HESS consisting of both batteries and SCs is not the main purpose of this thesis, but it is meant to highlight that such a novel control system can significantly relieve the batteries of the stand-alone power system from high frequency currents, increasing the battery life expectancy.

When MPPT modules are used, a higher voltage-derating factor is accounted for in the design tool, as mentioned in Chapter II. Then, the only thing that remains is to ensure the batteries and SCs are not overcharged by bypassing the PV array. For this purpose, a simplified overcharge controller was designed [53]. The controller allows the current output when the HESS is not fully charged. By this, when the battery state of charge (SOC) is less than the maximum battery SOC, which is 100%, or when the voltage of the SC is less than the maximum voltage of the SC, which is 56V, the PV output current is allowed to flow through the controller. In the case where both storage elements are fully charged, then the controller bypasses the PV array to avoid overcharging them. This concept is presented in Figure 22.

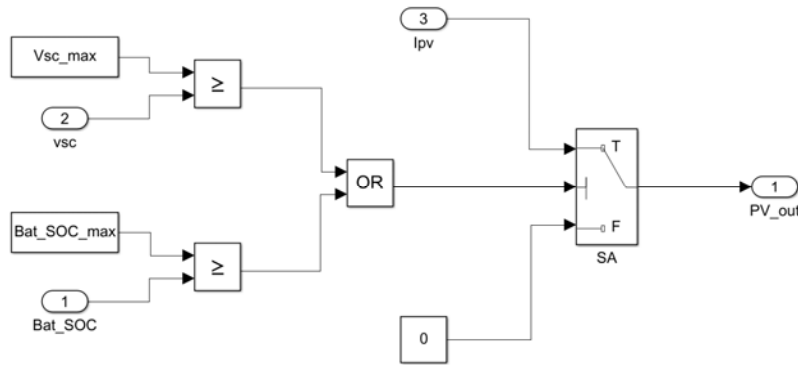


Figure 22. HESS overcharge controller.

### C. BATTERY AND SC SOC

The SOC of both batteries and SCs is computed as in Figures 23 and 24, respectively.

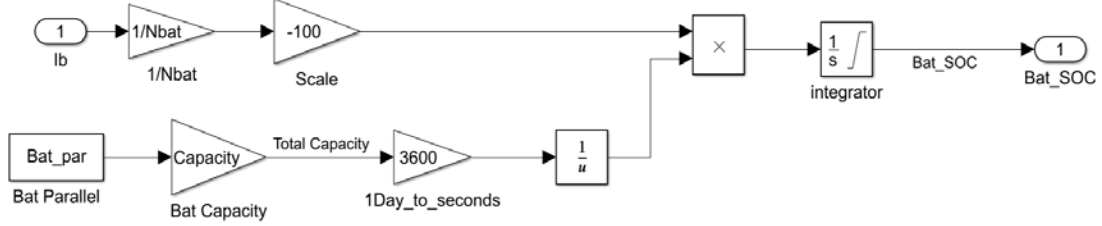


Figure 23. Battery SOC.

Specifically, the battery bank SOC is given by:

$$SOC(t) = SOC(t-1) - \int \left( \frac{i_B(t)}{n_{bat} \cdot C_{total} \cdot 3600} \cdot 100 \right) dt , \quad (21)$$

where the total capacity is the product of the number of batteries in parallel and the nominal battery capacity:

$$C_{total} = Bat_{parallel} \cdot Capacity , \quad (22)$$

and  $n_{bat}$  is the battery Coulomb efficiency.

As far as the SOC of the SCs is concerned, the energy stored in an SC is a function of voltage and capacitance, and specifically [54, 55],

$$E = \frac{1}{2} \cdot C \cdot V_{SC}^2 , \quad (23)$$

where the capacitance is constant. As a result, the output voltage determines the SOC of the SCs. As can be seen in Figure 24, the SOC is determined by:

$$SOC_{SC} = \frac{V_{SC}^2}{V_{SC,max}^2} . \quad (24)$$

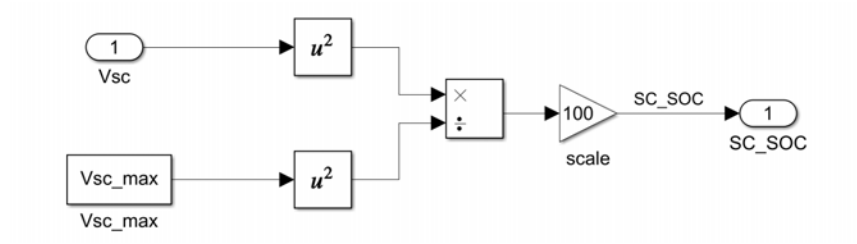


Figure 24. SC SOC.

The simulation parameters are listed in Table 8.

Table 8. Simulation parameters. SC parameters adapted from [56].

| Parameter             | Value |
|-----------------------|-------|
| PI controller, $K_p$  | 0.022 |
| PI controller, $K_i$  | 0.38  |
| LPF, alpha $\alpha$   | 0.01  |
| $C_{bus}$ [ $\mu F$ ] | 500   |
| SC [F]                | 130   |
| SC, $V_{max}$ [V]     | 56    |
| SC, $V_{min}$ [V]     | 16    |

## IV. STAND-ALONE POWER SYSTEM SIMULATIONS

Various cases of stand-alone power systems were simulated using the Simulink model described in the previous chapter. In this chapter, simulation results are presented for each case, confirming the basic concept of the design of an off-grid power system, as well as how the system is affected by specific design parameters.

### A. INITIAL OBSERVATIONS

To begin with, even before simulating a stand-alone power system, we can offer some important observations regarding the influence of specific parameters on the design of the system. For instance, a system with the characteristics shown in Table 9 can be designed using either deep cycle lead acid batteries or Li-Ion batteries for energy storage.

Table 9. Design characteristics of a stand-alone power system.

|                                          |      |
|------------------------------------------|------|
| AC Load [MWh/day]                        | 3    |
| Peak Sun Hours PSH [kWh/m <sup>2</sup> ] | 4.12 |
| Required Usable Storage [Days]           | 4    |
| Inverter Efficiency                      | 0.85 |
| System Voltage [V]                       | 480  |
| Temperature [C]                          | 25   |
| Array-to-Load Ratio (A:L)                | 1.3  |
| Number of SCs                            | 60   |

For the design of the energy storage system, the following batteries are considered:

- Trojan 8D-AGM, 12V, 230Ah (Deep cycle lead acid) [28]
- Winston LFP1000AH, 48V, 48kWh, 1000Ah (Li-Ion) [35]

For each case, the total number of batteries is computed using the design program. A summary of the results, for the design of a system with characteristics shown in Table 9, is shown in Table 10, where the cost is also mentioned in order to highlight the savings that can be obtained using Li-Ion batteries.

Table 10. Lead acid vs. Li-Ion batteries for the energy storage of a stand-alone power system. Costs adapted from [57], [58].

|                             | Deep Cycle Lead Acid | Li-Ion    |
|-----------------------------|----------------------|-----------|
| <b>Nominal Voltage [V]</b>  | 12                   | 48        |
| <b>Capacity [Ah]</b>        | 230                  | 1000      |
| <b>Number of Batteries</b>  | 40x176=7040          | 10x41=410 |
| <b>Cost of each battery</b> | \$561.97             | \$1,210   |
| <b>Total Cost</b>           | \$3,956,268.80       | \$496,100 |
| <b>Savings</b>              | -                    | 87.4%     |

The large percentage of savings (87.4%) when using Li-Ion batteries is an additional advantage beyond the many others that Li-Ion batteries offer over the lead acid batteries, as mentioned in Chapter II.

Besides the previous considerations, it is very important to use the MPPT modules to connect the PV panels with the batteries, not only to avoid losing large amounts of power when the voltage drops, but also to achieve a smaller number of PV panels required to design the power source of the off-grid system. For this purpose, the same system characteristics and the same model of PV panel (SunPower X22-360-COM [42]) were used. A summary of the results is shown in the Table 11:

Table 11. Use of MPPT vs no-MPPT for the energy source of a stand-alone power system. Cost adapted from [59].

| PV Model Used                                |             |             |
|----------------------------------------------|-------------|-------------|
| Maximum Power Point Voltage ( $V_{mp}$ ) [V] | 60.6        |             |
| Maximum Power Point Current ( $I_{mp}$ ) [A] | 5.94        |             |
| Power Output [W]                             | 360         |             |
| Efficiency [%]                               | 22.2        |             |
| Use of MPPT                                  | NO          | YES         |
| Number of PV Panels                          | 10x495=4950 | 9x471=4239  |
| Cost of each PV Panel                        | \$625       |             |
| Total Cost                                   | \$3,093,750 | \$2,649,375 |
| Savings                                      | -           | 14.4%       |

Observing the results obtained, it was expected that the number of PV panels connected in series would change due to the use of MPPT. Remarkably, the number of parallel-connected panels is reduced, because when the system losses are accounted for, the Coulomb efficiency is higher, since Li-Ion batteries are used for the energy storage.

## B. SIMULATION FOR ONE DAY WITHOUT SUN

As stated in Chapter II, the basic concept of the design of the energy storage component of the stand-alone power system is to be able to support the system load, without receiving power from the PV array. This simulation is meant to confirm this design concept. The design characteristics of the system are provided in Table 12:

Table 12. Design characteristics of a stand-alone power system.

|                                            |      |
|--------------------------------------------|------|
| AC Load [MWh/day]                          | 3    |
| Peak-Sun Hours (PSH) [kWh/m <sup>2</sup> ] | 4.12 |
| Required Usable Storage [Days]             | 1    |
| Inverter Efficiency                        | 0.85 |
| System Voltage [V]                         | 480  |
| Temperature [C]                            | 25   |
| Array-to-Load Ratio (A:L)                  | 1.1  |

For the design of the energy storage component, Li-Ion batteries were used and, specifically, the Relion RB48V200, the specifications of which are shown in Table 13.

Table 13. Specification data of the Li-Ion batteries (Relion RB48V200). Adapted from [32].

|                     |       |
|---------------------|-------|
| Nominal Voltage [V] | 48    |
| Capacity [Ah]       | 200   |
| Volts/cell          | 3.2   |
| Energy [kWh]        | 10.24 |
| Efficiency [%]      | 98    |

For the design of the PV array, the SunPower X22-360-COM PV panels were used, the specification data of which are mentioned previously in this chapter. Besides that, the PV array is not connected directly to the batteries; rather, an MPPT is used.

Considering the aforementioned factors, let us examine the windows showing inputs in Figures 25 and 26 for the case of “auto mode” and “manual mode,” respectively. The window with the outputs (Figure 27) follows the windows of the inputs.

The screenshot shows a software window titled "Inputs" with a green background. It contains two sections of input parameters. The first section, "Input Parameters", includes AC Load [MWh/day] (3), Peak-Sun Hours(PSH) [kWh/m²] (4.12), and Required Usable Storage [days] (1). The second section, "Parameters of the Elements Used", includes Inverter Efficiency (0.85), System Voltage [V] (480), Type Of Battery (Lithium ...), Battery Model (Relion ...), Temperature [C] (25), PV module model (SunPo...), Use of MPP Tracker (Yes), and Array-To-Load-Ratio (1.1). At the bottom are "Calculate" and "Help" buttons.

| Input Parameters               |      |
|--------------------------------|------|
| AC Load [MWh/day]              | 3    |
| Peak-Sun Hours(PSH) [kWh/m²]   | 4.12 |
| Required Usable Storage [days] | 1    |

| Parameters of the Elements Used |             |
|---------------------------------|-------------|
| Inverter Efficiency             | 0.85        |
| System Voltage [V]              | 480         |
| Type Of Battery                 | Lithium ... |
| Battery Model                   | Relion ...  |
| Temperature [C]                 | 25          |
| PV module model                 | SunPo...    |
| Use of MPP Tracker              | Yes         |
| Array-To-Load-Ratio             | 1.1         |

Figure 25. Window with inputs in program’s “auto mode.”

The screenshot shows a software window titled "Inputs" with a green background. It contains two sections of input parameters. The first section, "Input Parameters", includes AC Load [MWh/day] (3), Peak-Sun Hours(PSH) [kWh/m²] (4.12), and Required Usable Storage [days] (1). The second section, "Parameters of the Elements Used", includes Inverter Efficiency (0.85), System Voltage [V] (480), Battery Type (Li-Ion(Li...)), Battery Voltage [V] (48), Battery Capacity [Ah] (200), Temperature [C] (25), Maximum Power Point (MPP) Voltage (60.6), Maximum Power Point (MPP) Current (5.94), Use of MPP Tracker (Yes), and Array-To-Load-Ratio (1.1). At the bottom are "Calculate" and "Help" buttons.

| Input Parameters               |      |
|--------------------------------|------|
| AC Load [MWh/day]              | 3    |
| Peak-Sun Hours(PSH) [kWh/m²]   | 4.12 |
| Required Usable Storage [days] | 1    |

| Parameters of the Elements Used   |              |
|-----------------------------------|--------------|
| Inverter Efficiency               | 0.85         |
| System Voltage [V]                | 480          |
| Battery Type                      | Li-Ion(Li... |
| Battery Voltage [V]               | 48           |
| Battery Capacity [Ah]             | 200          |
| Temperature [C]                   | 25           |
| Maximum Power Point (MPP) Voltage | 60.6         |
| Maximum Power Point (MPP) Current | 5.94         |
| Use of MPP Tracker                | Yes          |
| Array-To-Load-Ratio               | 1.1          |

Figure 26. Window with inputs in program’s “manual mode.”

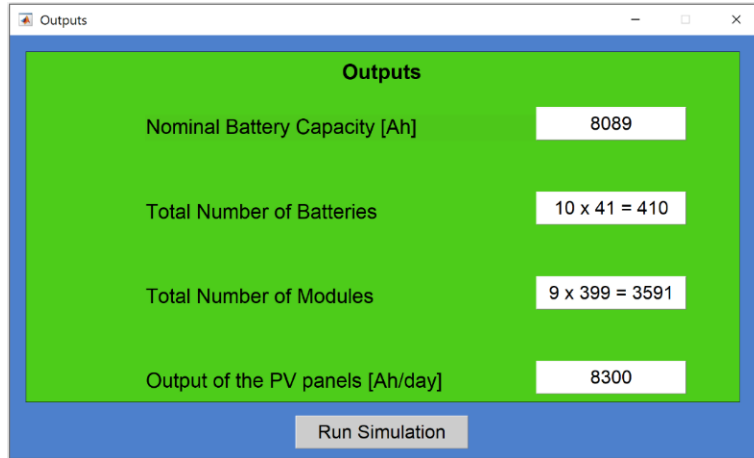


Figure 27. Window with outputs.

After running the simulation for the autonomy period of one day and setting the power output of the PV array equal to zero, in order to simulate for a cloudy day, we obtain the plots shown in Figures 28 through 36.

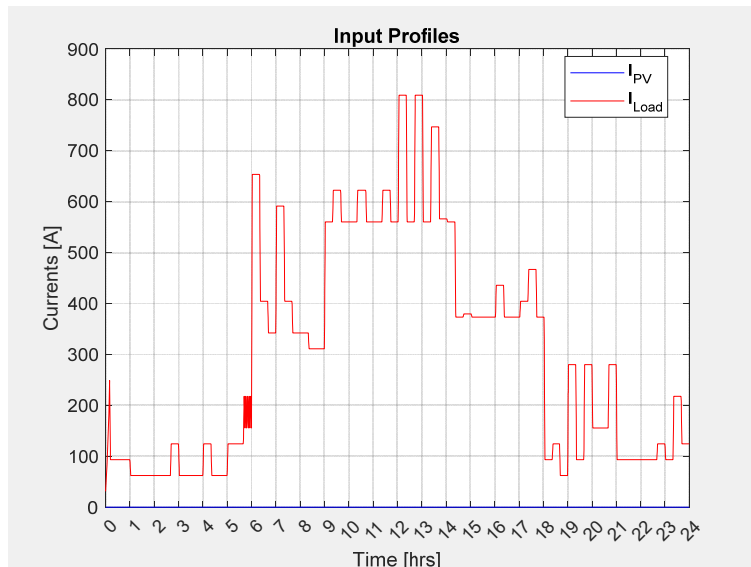


Figure 28. Profiles of the load and PV output.

Obviously, since the simulation is for a cloudy day and the output of the PV array is zero, the total load current demand is supplied by the batteries. This is the reason that the battery current matches the load current, as Figure 29 indicates.

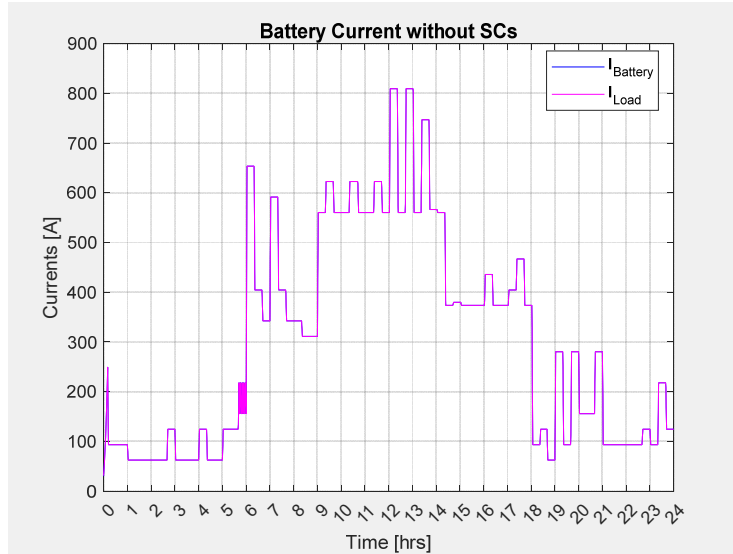


Figure 29. Battery current without the use of SCs.

It is remarkable, as shown in Figure 30, that the batteries are not depleted even in the case in which there is no sun. This result confirms the basic design concept of the energy storage of the off-grid power system. The energy storage system is able to support the system load, without receiving power from the PV array for the time period of the desired autonomy. It should also be noted that the SOC will never drop lower than the complement of the MDOD of the batteries. This means that in case of deep cycle lead acid batteries, at the end of the day, in the same scenario, the final SOC will be higher than 20%.

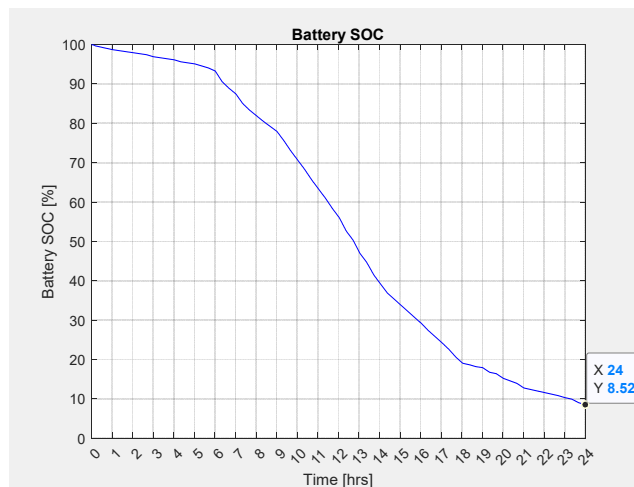


Figure 30. Battery SOC.

When the SC is used, the compensation of the SC current is noticeable, as shown in Figures 31 and 32. For the DC load of 3.529 MWh, 60 SCs were used, which consists less than 0.1%. The novel hybrid energy storage control [22], redirects the higher frequency load currents to the SCs. For this reason, an appropriate LPF with an alpha of 0.01 rad/sec, which corresponds to a time constant  $\tau_{LPF} = 100\text{sec}$ , that is close to the time resolution of the load profile, is used. In this way, the life expectancy of the batteries is improved, since the stress on the batteries is significantly reduced.

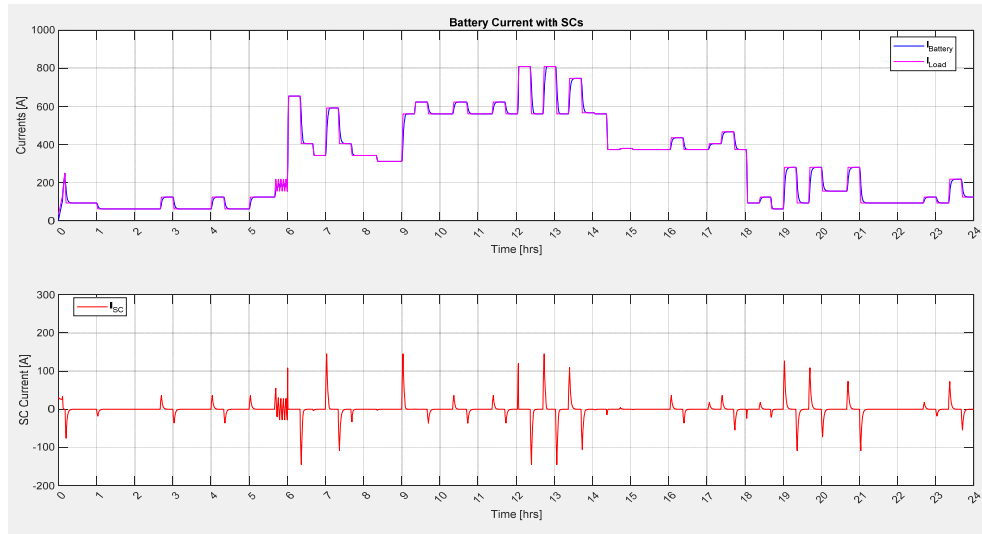


Figure 31. Compensation of the SCs on the battery current.

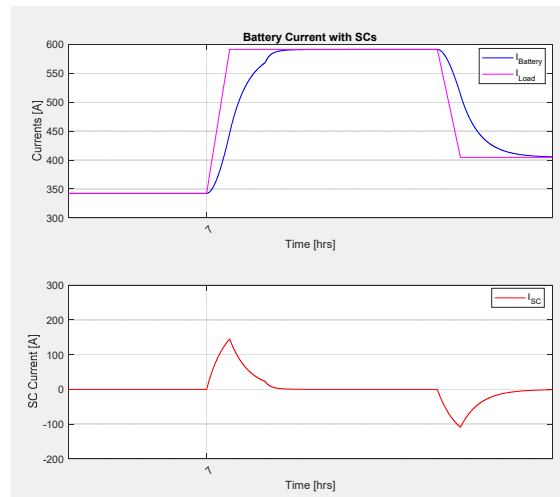


Figure 32. Compensation of the SCs on the battery current (zoomed-in at 7 a.m.).

In Figure 33, the effectiveness of the new control system for the SC current can be observed. For instance, at 06:00, the SCs are fully discharged, since the voltage error is negative reaching the design lower limit. Consequently, the controller “reduces the current, which is being drawn from the SCs” [22]. Moreover, after 06:30, the SCs are fully charged, since the voltage error is positive reaching the design upper limit. For this reason, the controller “reduces the current injected into the SCs” [22].

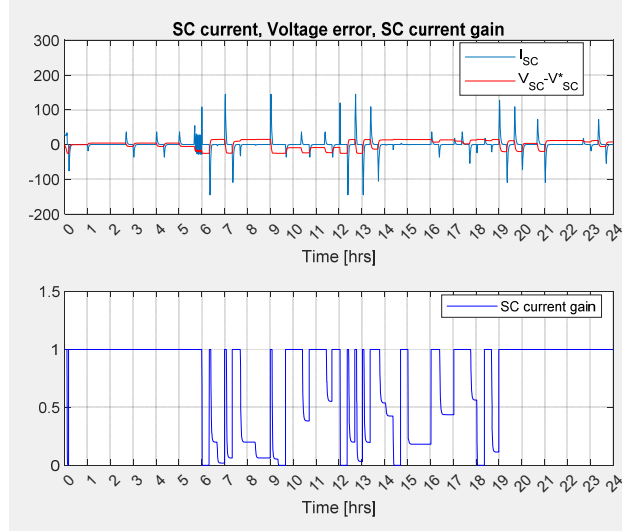


Figure 33. SC current, voltage error, and SC current gain.

The SOC of the SCs shows also the functionality of the controller, since the SCs never get overcharged or undercharged, as Figure 34 indicates.

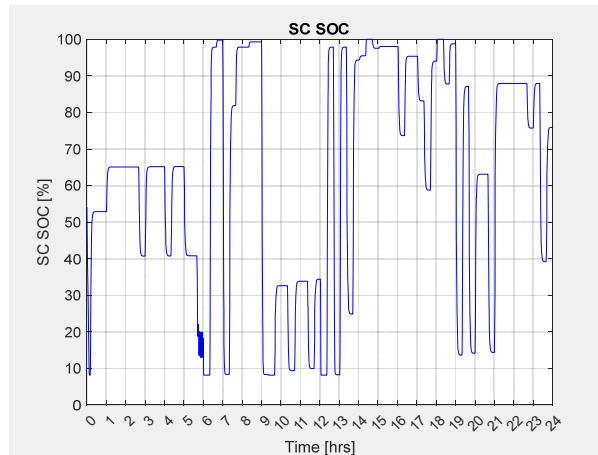


Figure 34. SC SOC.

In Figure 35 it is observed that the battery SOC does not change much when SCs are used. Obviously, this is not the aim of the use of SCs. The SCs are not featured to supply a percentage of the power load demand, as stated in many publications such as [60], [61], since in this case the cost of the HESS would be extremely large. They are just meant to supply the higher frequency currents in order to relieve the batteries. So, finally, they depend mostly on the shape of the load profile. For this reason, a possible future work would be the optimization for sizing the SCs, based on algorithms, neural network, fuzzy logic, etc. Some of these concepts are presented in [62]–[64] but are beyond the purpose of this thesis.

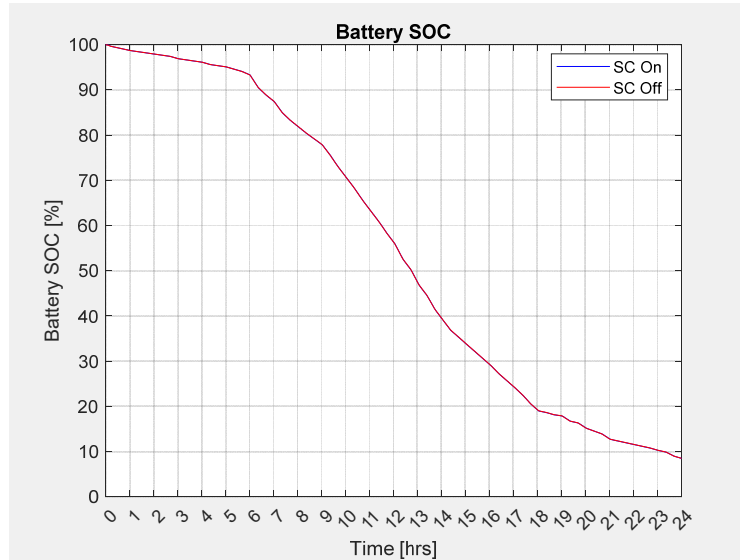


Figure 35. Battery SOC with and without SC.

Besides all the aforementioned, the effectiveness of the PI controller used can be observed in Figure 36, showing a maximum voltage ripple of 2.2%:

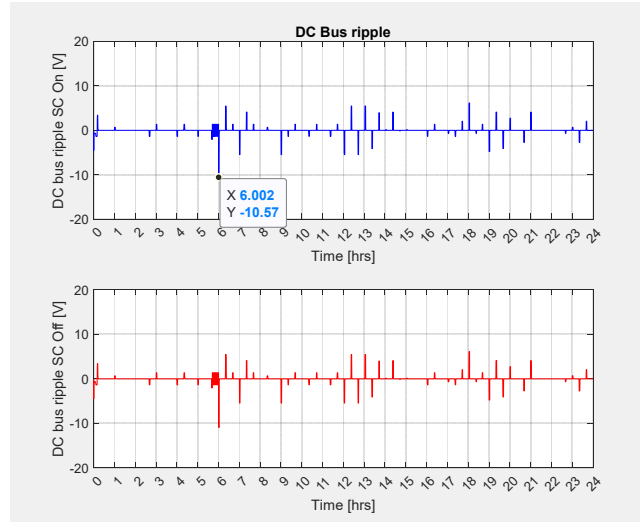


Figure 36. DC bus voltage ripple.

### C. SIMULATION FOR ONE DAY WITH SUN

In this section, simulation results for the same stand-alone power system are presented, with the exception that there is a full PV output profile for the PSH of the location, which is 4.12, in order to account for a sunny day. The plots obtained can be observed in Figures 37 to 44.

In this simulation, the PV array output current from 06:00 until 21:00 hours compensates for the battery current, as shown in Figure 38.

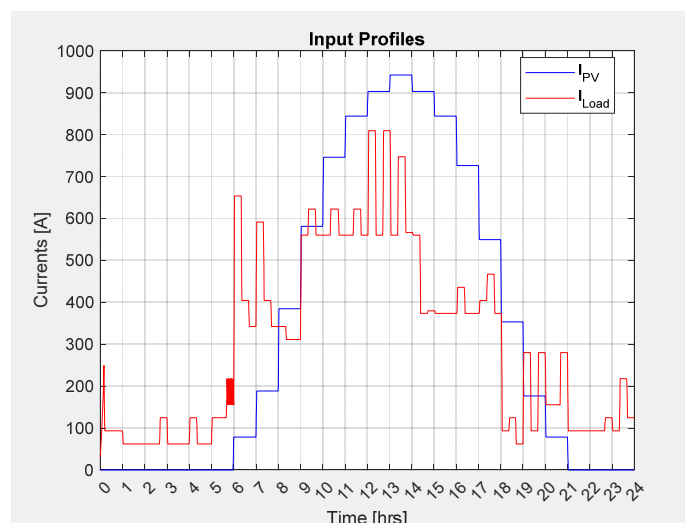


Figure 37. Profiles of the load and PV output.

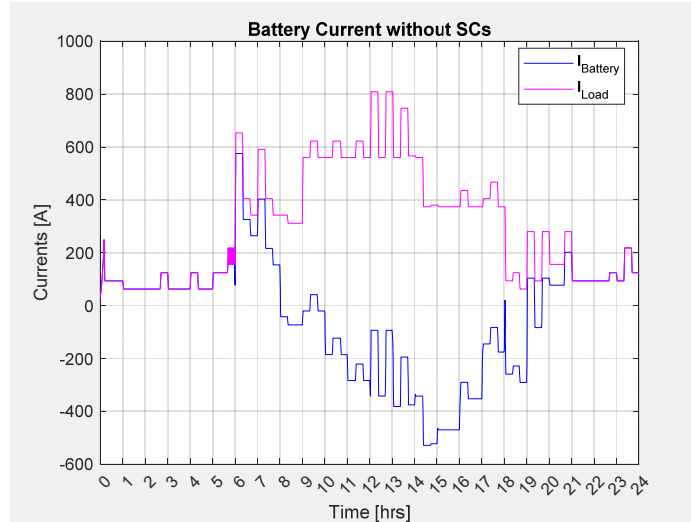


Figure 38. Battery current without the use of SCs.

Up to 08:00 hours, the load demand is higher than the output of the PV array and thus the battery current is still positive, delivering most of the power to the load. As expected, the SOC of the batteries decreases to the value of 85.33%, as Figure 39 indicates. The reason for the steeper slope from 06:00 to 08:00 hours is that the load demand for this time significantly increases.

Beginning at 08:00 hours, when the PV array output gets higher than the load demand, it charges the batteries. The battery current is negative, showing that they are being charged until about 14:30, when they are fully charged.

Finally, at 19:00 hours the solar insolation has been reduced significantly, but the load demand remains at a moderate level. The battery current is positive, showing that the batteries are supplying the load, and at the same time, they are being discharged until the end of the day, at which point they reach an SOC of 93.79%.

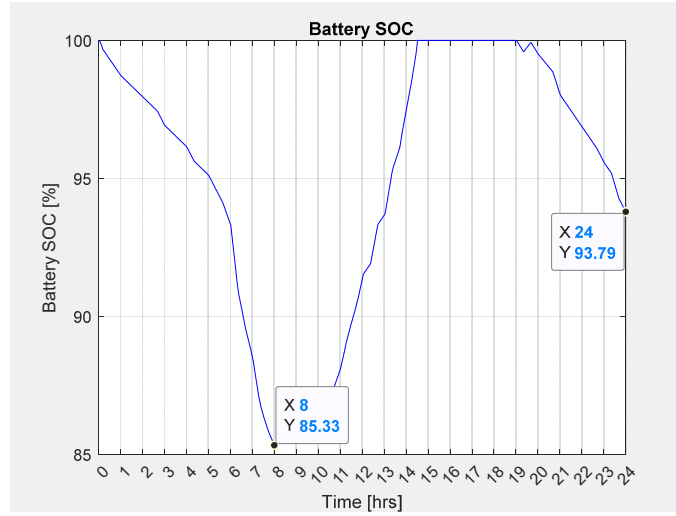


Figure 39. Battery SOC.

Similarly, the compensation of the SCs and the SC controller for the battery current is shown in Figure 40.

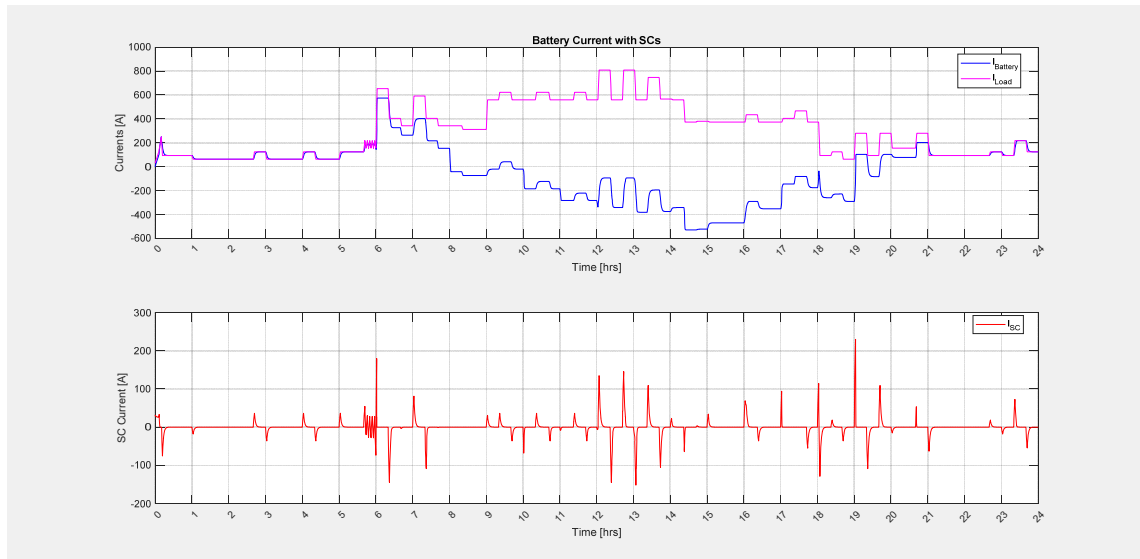


Figure 40. Compensation of the SCs on the battery current.

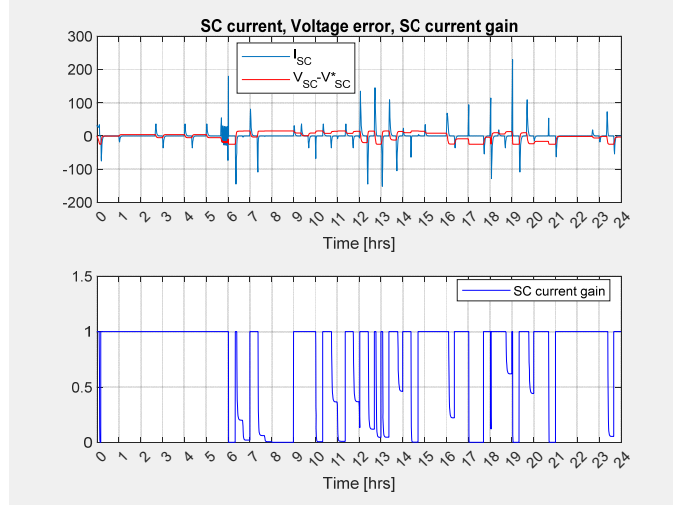


Figure 41. SC current, voltage error, and SC current gain.

As expected, the SOC of the SC is affected by the PV array output. In Figure 42 it is shown that from 07:00 hours, when the batteries begin discharging, the point of SOC they reach is 45%, rather than the full discharge reached in the last simulation. From this time and until 21:00 hours, the SOC is being improved significantly by the charging of the PV array. It should be mentioned though that at 16:00 and 19:00 hours, the PV array output significantly decreases, and at the same time, the load current demand increases rapidly. These high frequency load currents are redirected to the SCs, and consequently the SCs are fully discharged, as can be observed from Figure 42.

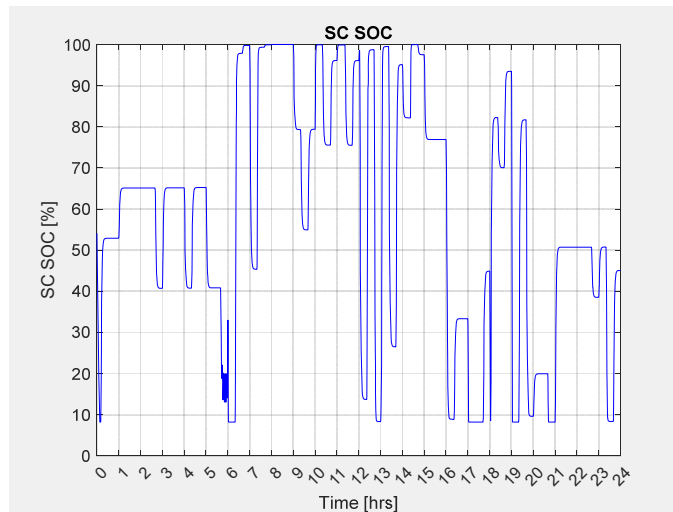


Figure 42. SC SOC.

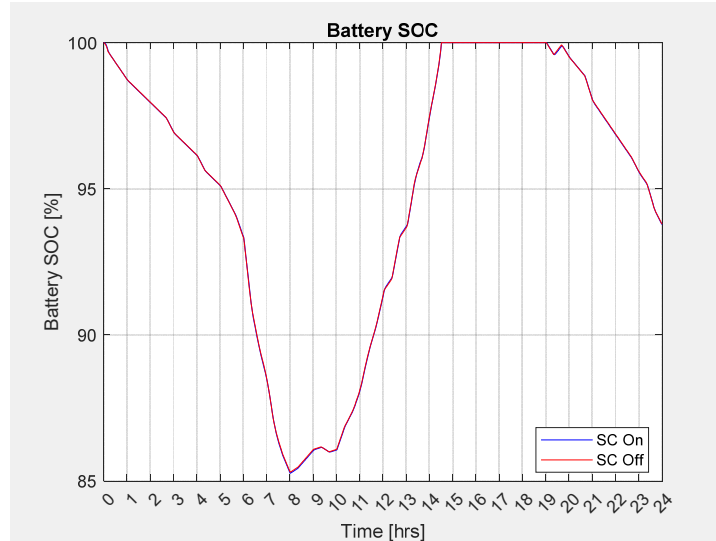


Figure 43. Battery SOC with and without SC.

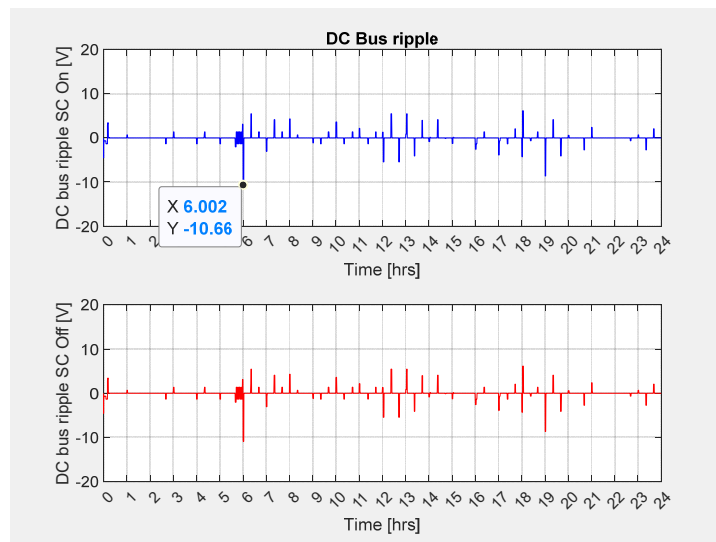


Figure 44. DC bus voltage ripple.

#### D. INFLUENCE OF THE ARRAY-TO-LOAD RATIO

In this simulation, the influence of the A:L on how fast the batteries are going to be charged, is observed and discussed. The same system characteristics are used to simulate one day. The only change is that the A:L is increased from 1.1 to 1.3. The input and output windows can be seen in the Figures 45 and 46:

**Inputs**

**Input Parameters**

AC Load [MWh/day] 3

Peak-Sun Hours(PSH) [kWh/m²] 4.12

Required Usable Storage [days] 1

**Parameters of the Elements Used**

Inverter Efficiency 0.85

System Voltage [V] 480

Type Of Battery Lithium ...

Battery Model Relion ...

Temperature [C] 25

PV module model SunPo...

Use of MPP Tracker Yes

Array-To-Load-Ratio 1.3

Calculate Help

Figure 45. Window with inputs in program's "auto mode."

**Outputs**

Nominal Battery Capacity [Ah] 8089

Total Number of Batteries 10 x 41 = 410

Total Number of Modules 9 x 471 = 4239

Output of the PV panels [Ah/day] 9798

Run Simulation

Figure 46. Window with outputs.

The plots obtained can be observed in Figures 47 to 55.

The most important observation of these simulation results is the change of the battery SOC during the sunny hours, where now the PV array output is higher and, specifically, 20% higher as Figure 47 indicates, due to the increase of the A:L ratio from 1.1 to 1.3.

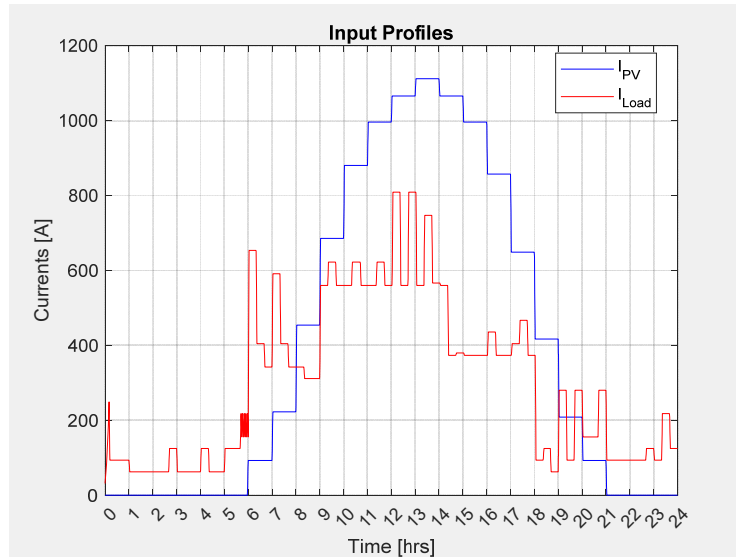


Figure 47. Profiles of the load and PV output.

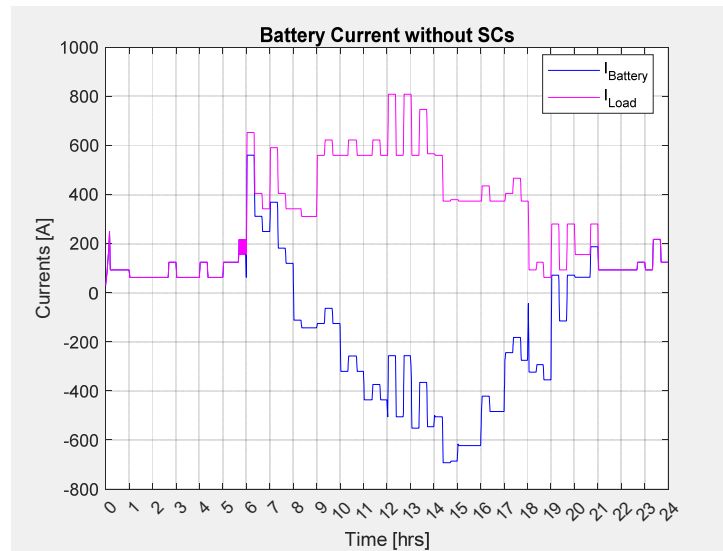


Figure 48. Battery current without the use of SCs.

Furthermore, Figure 49 indicates that the lowest state of charge that the batteries reach is now 85.93% instead of 85.33%, and the final SOC is 94.18% instead of 93.79%. The differences in these lowest points are minimal, since at these times the increase of the PV array output is not that high. Nevertheless, the most remarkable point is that the batteries are being fully charged faster, and this is shown more clearly in the comparison done in Figure 50. In the last simulation, they got from the lowest SOC at 08:00 hours to fully charged at 14:30, which is 6.5 hours. However, in this simulation, they reach their 100% SOC at 12:30 hours, which is 4.5 hours in total. Thus, the increase of the A:L on the battery SOC resulted in approximately 30% faster battery charging. This suggests an interesting topic for future work to optimize the stand-alone power system: the research project would size the PV array in such a way that it would correspond to the location's solar radiation and, at the same time, achieve the resilience and reliability at the lowest initial cost.

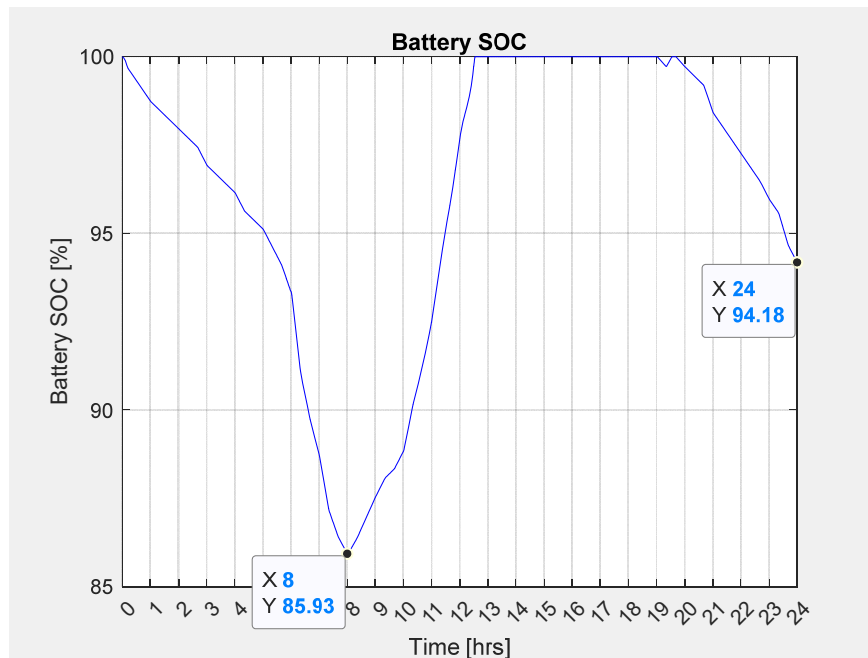


Figure 49. Battery SOC.

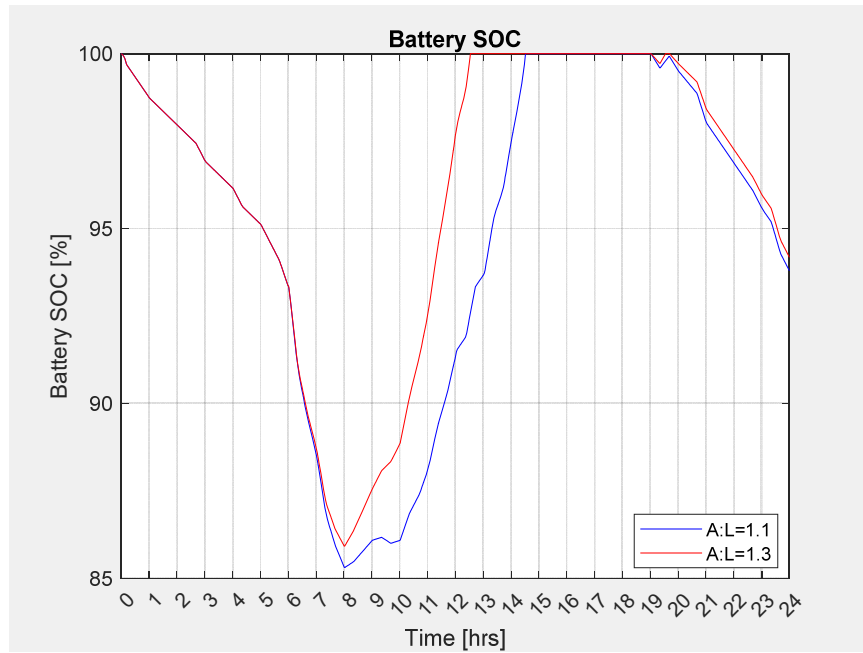


Figure 50. Battery SOC (A:L=1.1 vs. A:L=1.3).

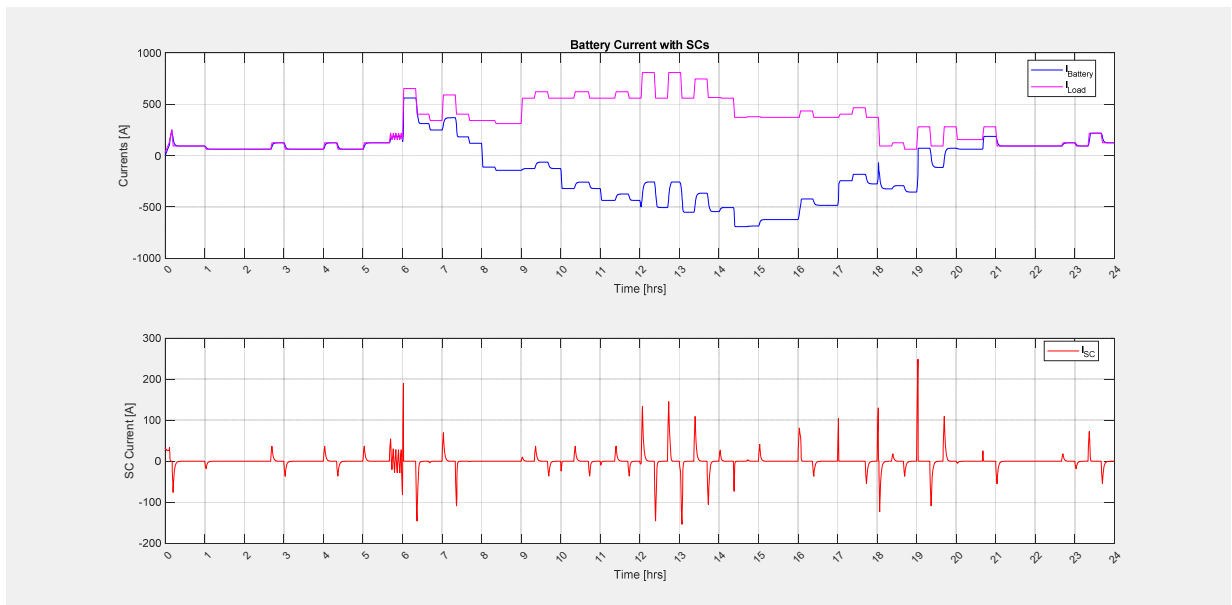


Figure 51. Compensation of the SCs on the battery current.

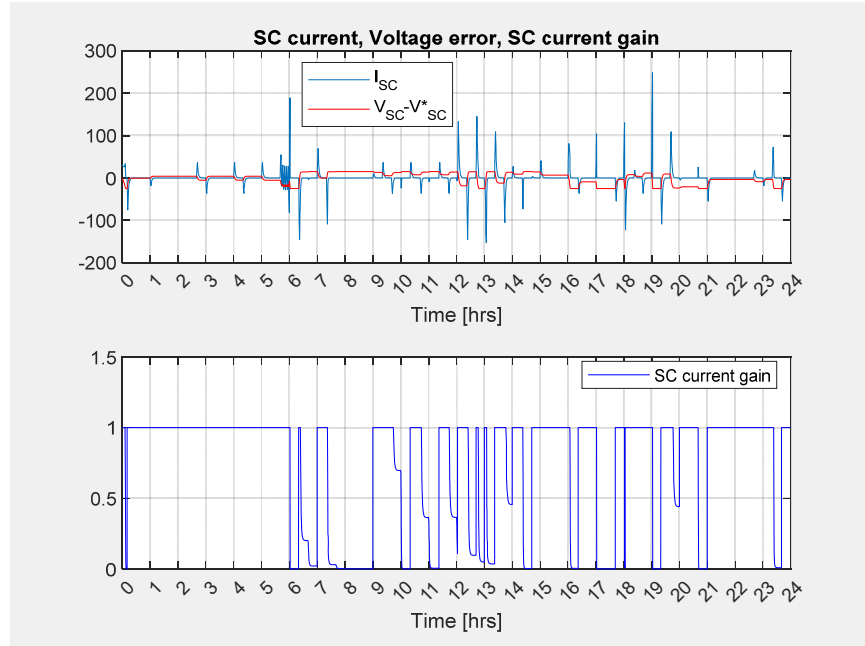


Figure 52. SC current, voltage error, and SC current gain.

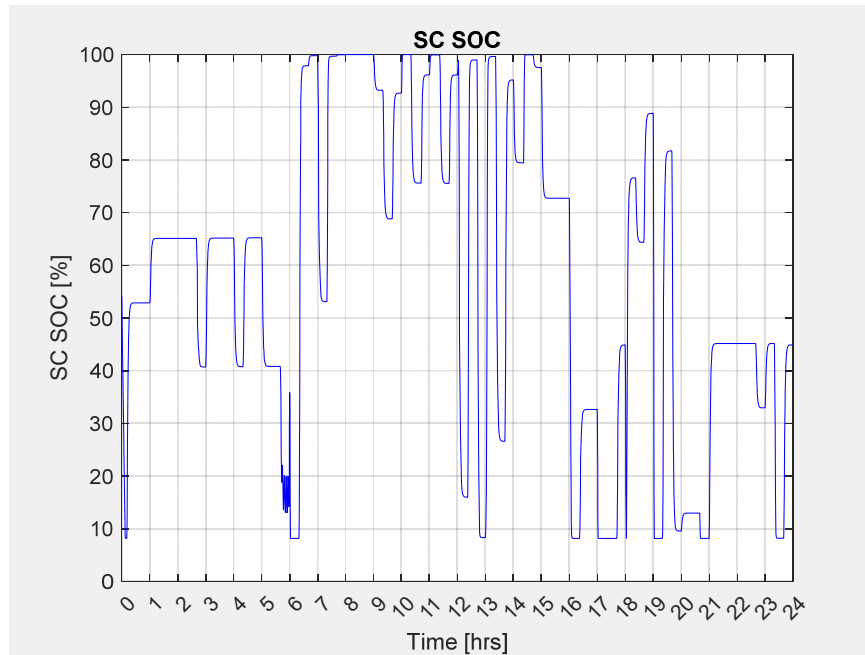


Figure 53. SC SOC.

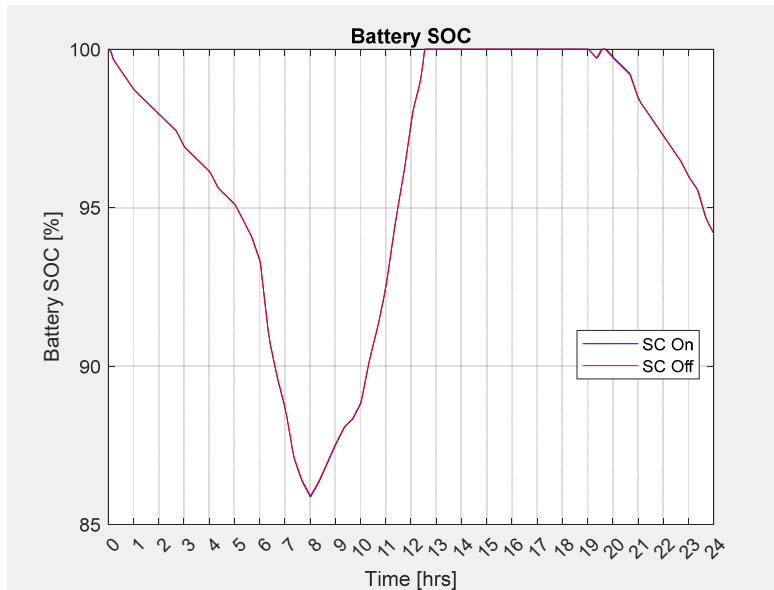


Figure 54. Battery SOC with and without SC.

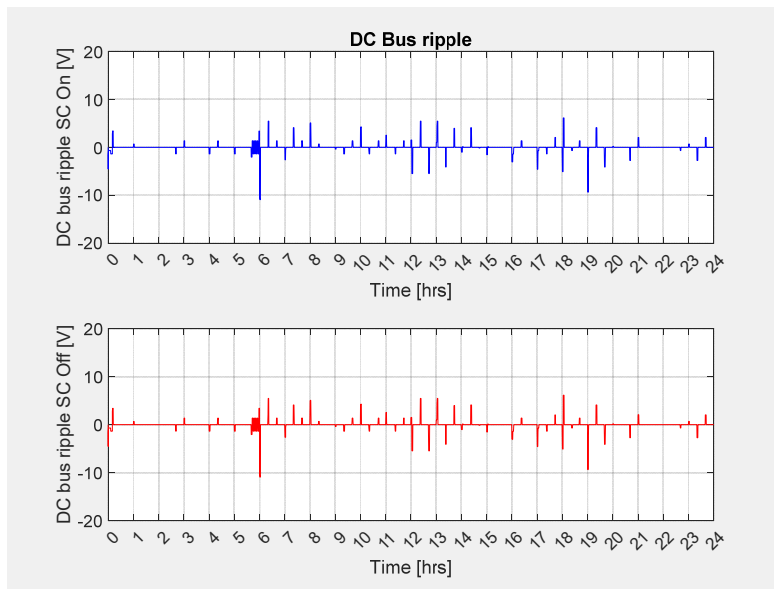


Figure 55. DC bus voltage ripple.

#### **E. SIMULATION FOR FOUR DAYS WITHOUT SUN**

In this simulation, the design characteristics of the system are the same (Table 14), except for the fact that the period of autonomy is four days. The A:L is kept at 1.3, as in the last simulation.

Table 14. Design characteristics of a stand-alone power system.

|                                                 |      |
|-------------------------------------------------|------|
| <b>AC Load [MWh/day]</b>                        | 3    |
| <b>Peak-Sun Hours (PSH) [kWh/m<sup>2</sup>]</b> | 4.12 |
| <b>Required Usable Storage [Days]</b>           | 4    |
| <b>Inverter Efficiency</b>                      | 0.85 |
| <b>System Voltage [V]</b>                       | 480  |
| <b>Temperature [C]</b>                          | 25   |
| <b>Array-to-Load Ratio (A:L)</b>                | 1.3  |

The input and output windows can be seen in Figures 56 and 57.

| Input Parameters               |      |
|--------------------------------|------|
| AC Load [MWh/day]              | 3    |
| Peak-Sun Hours(PSH) [kWh/m²]   | 4.12 |
| Required Usable Storage [days] | 4    |

| Parameters of the Elements Used |             |
|---------------------------------|-------------|
| Inverter Efficiency             | 0.85        |
| System Voltage [V]              | 480         |
| Type Of Battery                 | Lithium ... |
| Battery Model                   | Relion ...  |
| Temperature [C]                 | 25          |
| PV module model                 | SunPo...    |
| Use of MPP Tracker              | Yes         |
| Array-To-Load-Ratio             | 1.3         |

Calculate Help

Figure 56. Window with inputs in program's "auto mode."

From Figure 57, as expected, the number of PV panels did not change, since they are affected by the energy drawn from the batteries per day. Nonetheless, the number of batteries increased significantly, as expected, since the autonomy of the off-grid system is now four days instead of one.

| Outputs                          |                 |
|----------------------------------|-----------------|
| Nominal Battery Capacity [Ah]    | 32353           |
| Total Number of Batteries        | 10 x 162 = 1620 |
| Total Number of Modules          | 9 x 471 = 4239  |
| Output of the PV panels [Ah/day] | 9798            |

Run Simulation

Figure 57. Window with outputs.

After running the simulation for four days and setting the power output of the PV array equal to zero, in order to simulate for all cloudy days, the plots obtained are shown in Figures 58 to 65. Similar results are observed in this simulation, where the autonomy of the stand-alone power system is four days. Each day is defined with vertical dashed lines in all plots.

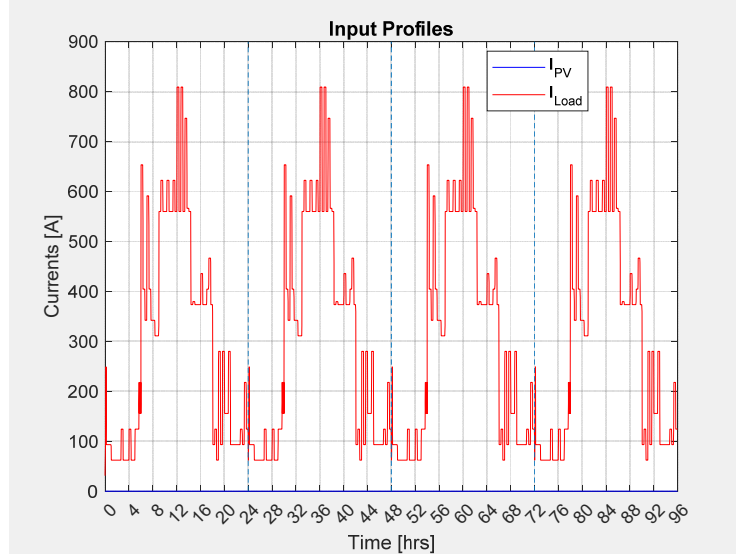


Figure 58. Profiles of the load and PV output.

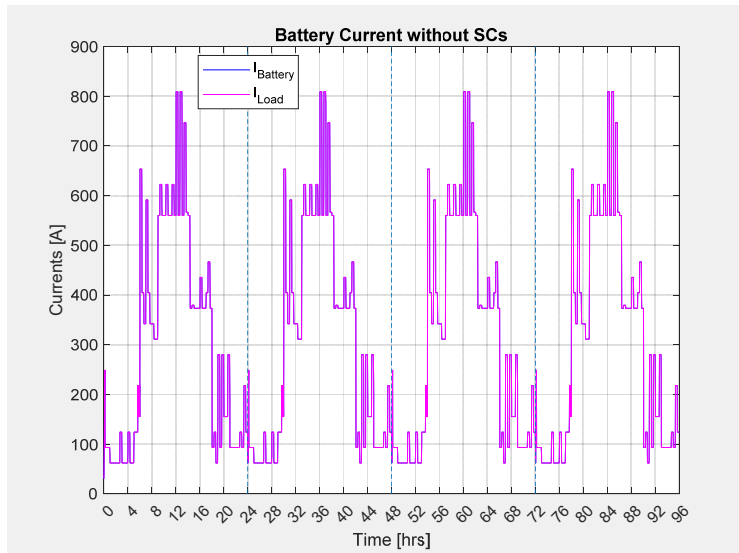


Figure 59. Battery current without the use of SCs.

Figure 60 shows that the battery SOC reaches 76.85% at the end of the first day, 53.69% at the end of the second day, 30.53% at the end of the third day, and the final SOC is 7.375%, which again confirms that the batteries are not depleted.

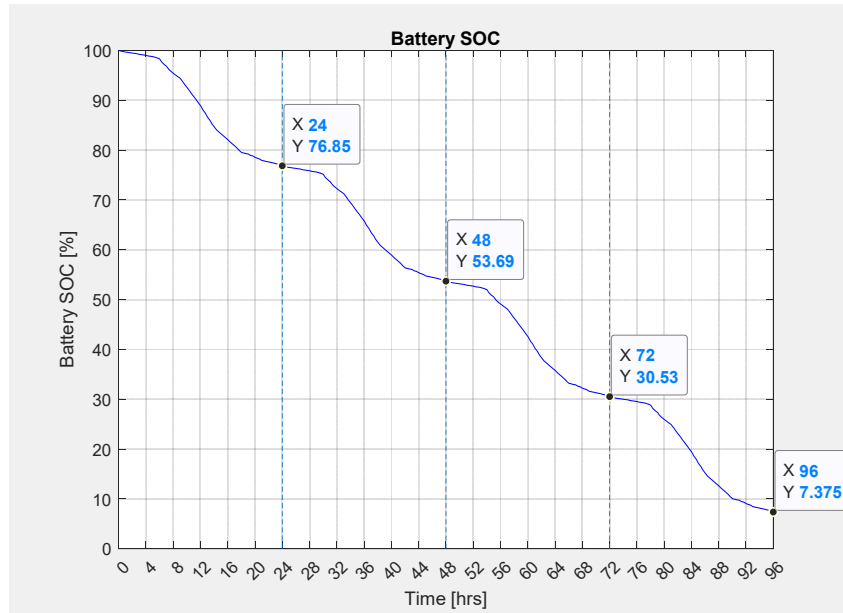


Figure 60. Battery SOC.

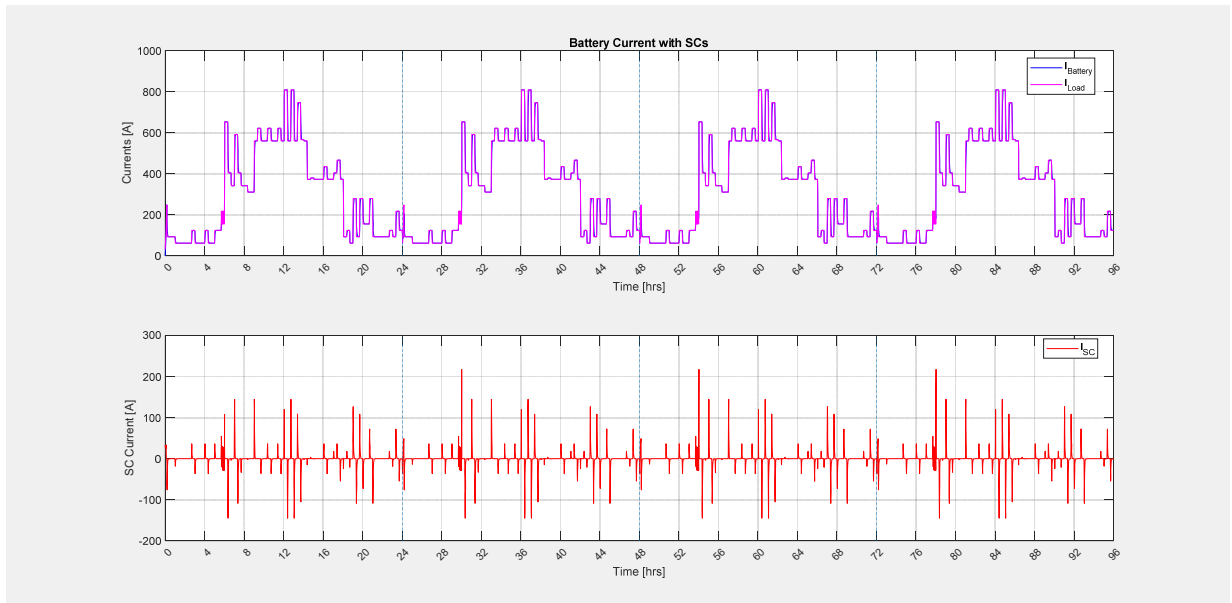


Figure 61. Compensation of the SCs on the battery current.

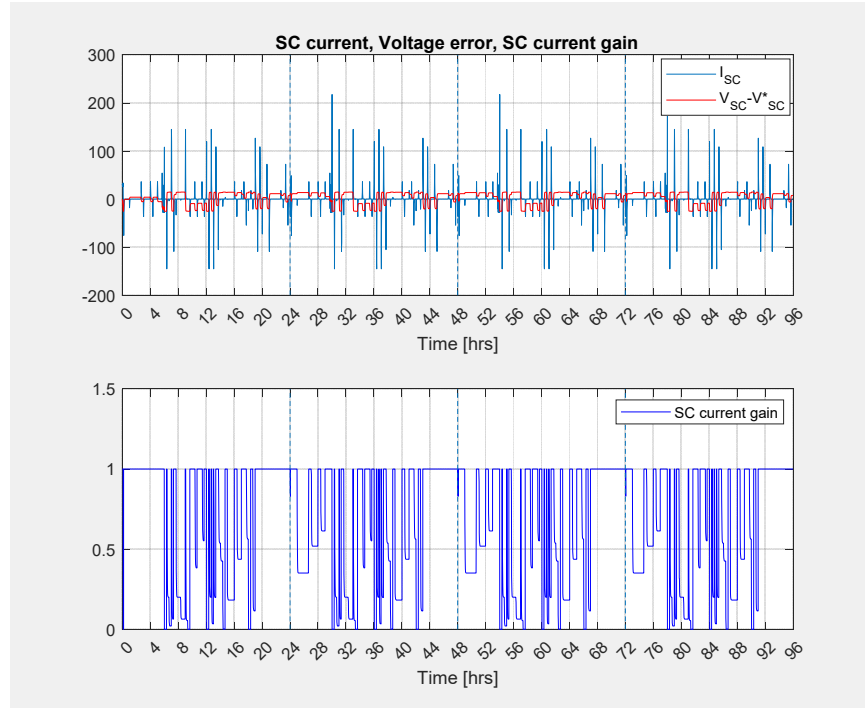


Figure 62. SC current, voltage error, and SC current gain.

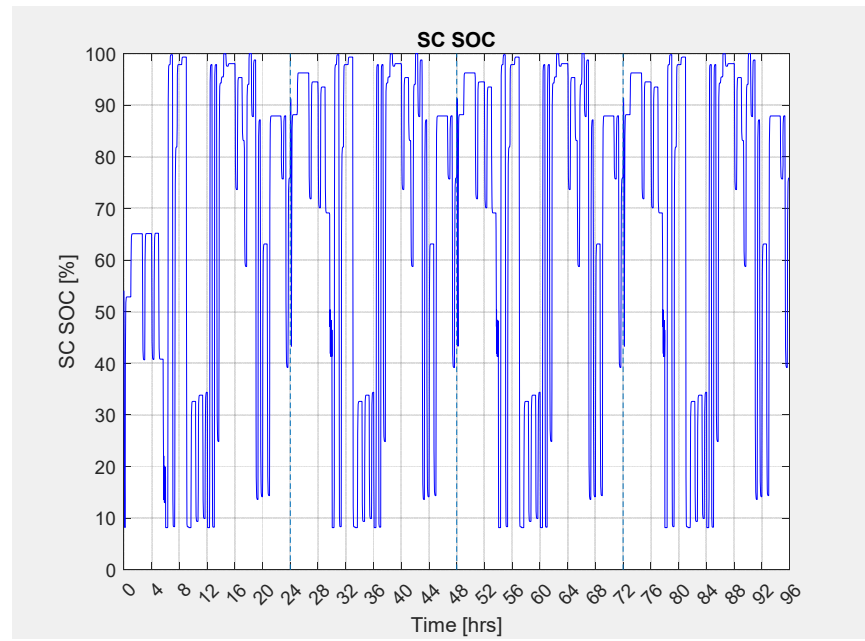


Figure 63. SC SOC.

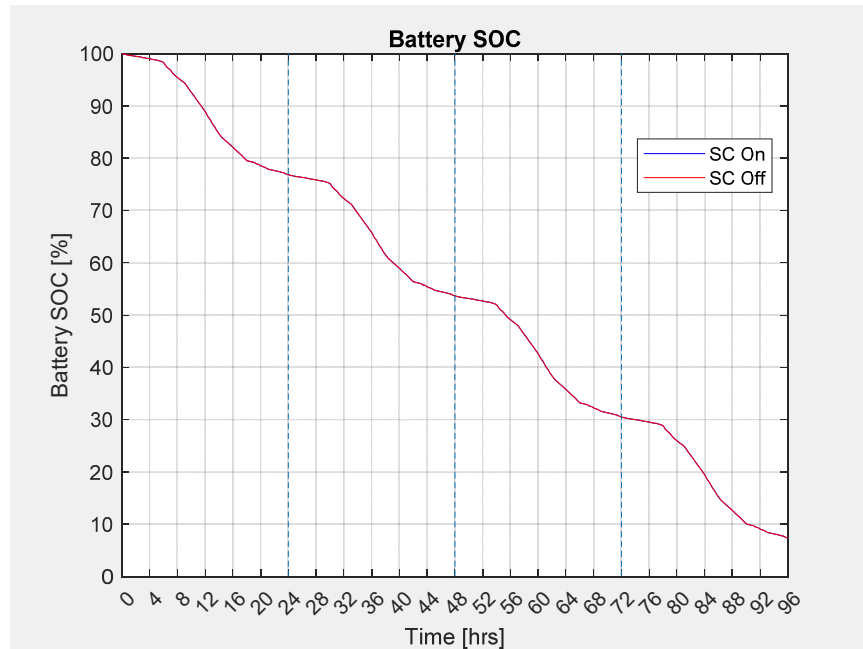


Figure 64. Battery SOC with and without SC.

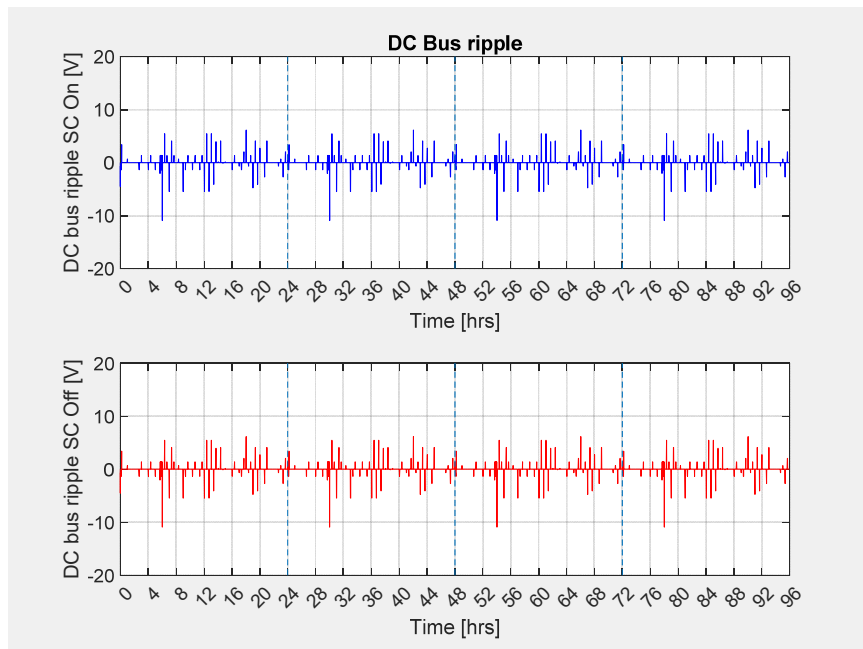


Figure 65. DC bus voltage ripple.

## F. SIMULATION FOR FOUR DAYS WITH SUN ON THE LAST DAY ONLY

In this section, simulation results for the same stand-alone power system are presented, with the exception that there is a full PV output profile for the PSH of the location on the last day, in order to observe how much the battery SOC is affected. The plots obtained are observed in Figures 66 to 73.

In this simulation, the first three days are cloudy, while the last one corresponds to a sunny day, showing the performance explained in the second and the fourth sections of this chapter, respectively.

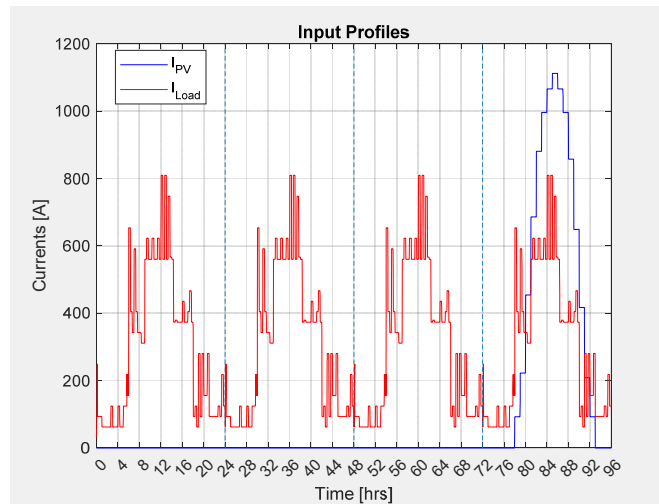


Figure 66. Profiles of the load and PV output.

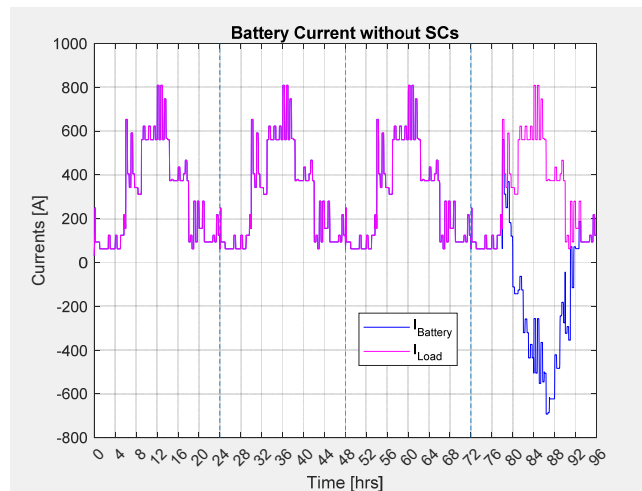


Figure 67. Battery current without the use of SCs.

The most important observation of these simulation results is the change of the battery SOC on the fourth day, as Figure 68 indicates. Specifically, the 30.53% SOC at the end of the third day is increased to 38.23% at the end of the simulation, which is a 25.22% increase, due to the full solar insolation that takes place that day.

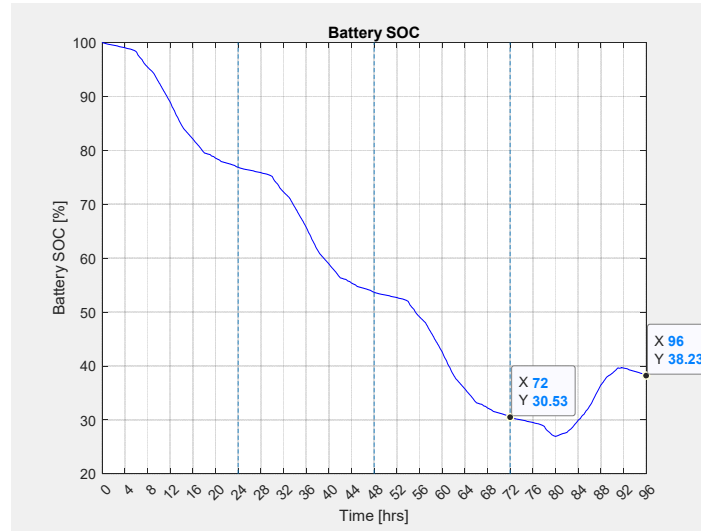


Figure 68. Battery SOC.

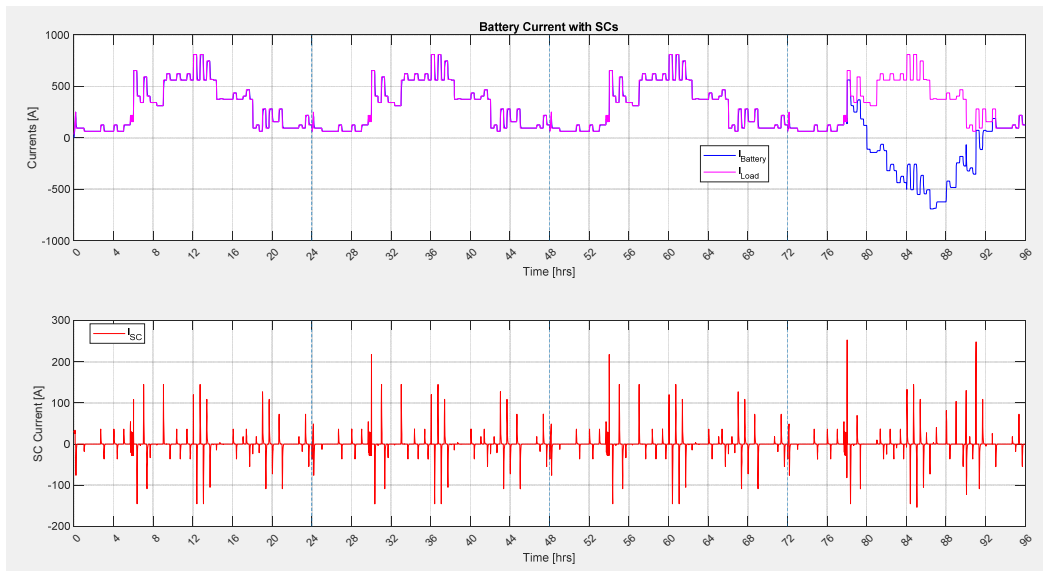


Figure 69. Compensation of the SCs on the battery current.

The discharging of the SCs at 16:00 and 19:00 hours, when the PV array output decreases significantly and at the same time the current load demand increases rapidly, is observed in Figures 70 and 71. This redirection of the high frequency current to the SCs is similar to what is observed in the simulation of one day with sun (Figure 41).

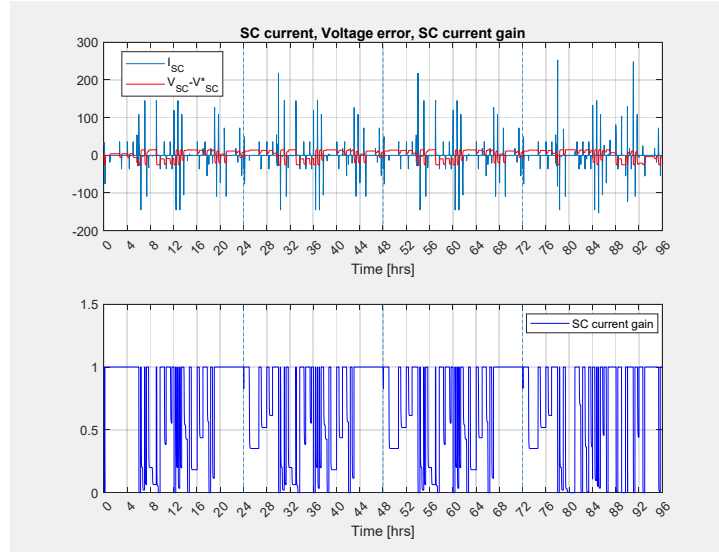


Figure 70. SC current, voltage error, and SC current gain.

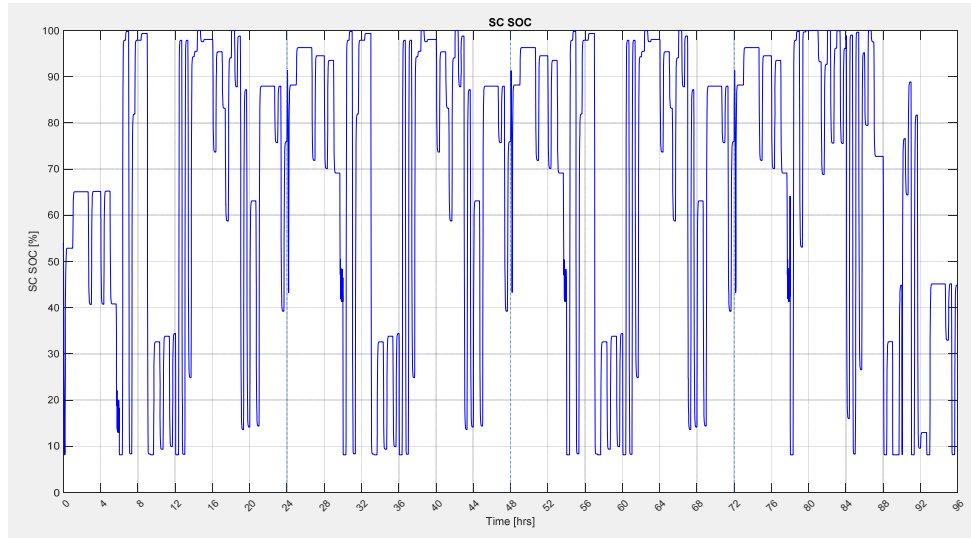


Figure 71. SC SOC.

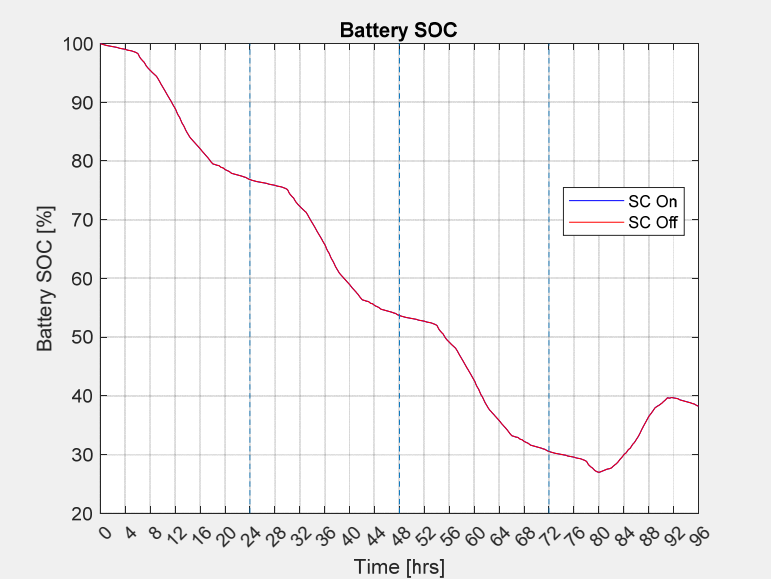


Figure 72. Battery SOC with and without SC.

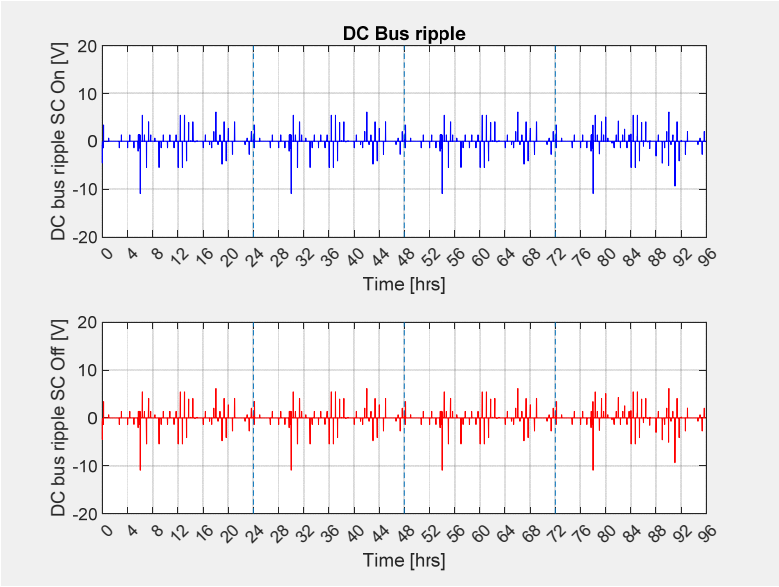


Figure 73. DC bus voltage ripple.

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## V. LABORATORY EXPERIMENTS

In this chapter, results from the laboratory experiments conducted are presented and compared with the simulation results in order to validate the design tool.

First, the elements used are introduced, along with their specification data. Then, the measuring devices used in the laboratory experiments are presented with their settings.

Two laboratory experiments were conducted. The first represents one day without sun, while the second one represents one day with sun. Both experiments are described and compared with the simulation results.

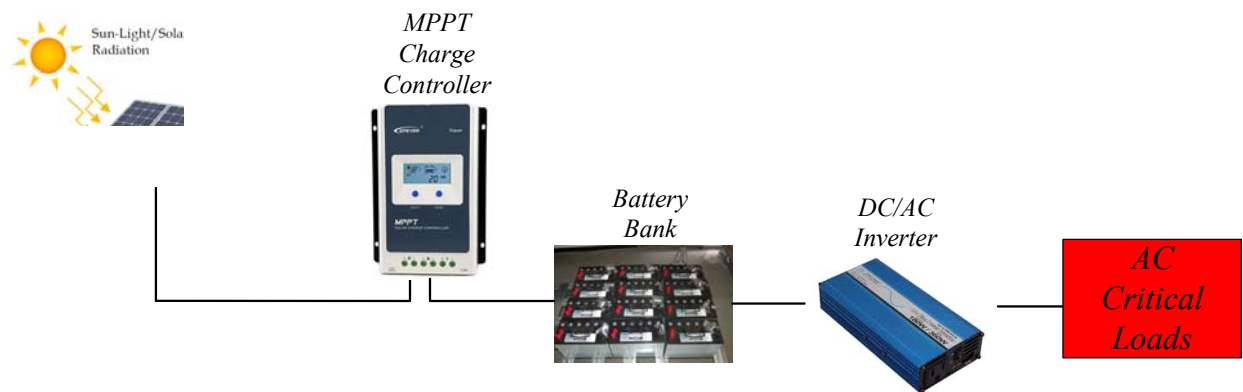


Figure 74. Block diagram of a stand-alone power system.

### A. ELEMENTS USED

To begin, the basic elements used for the laboratory experiments are presented.

The batteries used were sealed deep cycle AGM batteries, manufactured by Werker (Figure 75), with the specifications shown in Table 15:

Table 15. Specification data of the batteries used for the laboratory experiments. Adapted from [65].

|                                       |                             |
|---------------------------------------|-----------------------------|
| Type of Battery                       | Sealed deep cycle lead acid |
| Manufacturer                          | Werker                      |
| Model                                 | WKDC12-100PUS               |
| Nominal voltage [V]                   | 12                          |
| Capacity [Ah] at 20-hr discharge rate | 100                         |
| MDOD[%]                               | 80                          |



Figure 75. 12V-100Ah sealed deep cycle lead acid batteries.

The PV panels used had a maximum rated power of 100W, consisting of 33 monocrystalline cells (Figure 76). The specification data are presented in Table 16:

Table 16. Specification data of the PV panels used for the laboratory experiments. Adapted from [66].

|                                |                               |
|--------------------------------|-------------------------------|
| <b>Manufacturer</b>            | High Quality Solar Technology |
| <b>Model</b>                   | HQST-100D-S                   |
| <b>Number of Cells</b>         | 33 (3S x 11P)                 |
| <b><math>V_{mp}</math> [V]</b> | 16                            |
| <b><math>I_{mp}</math> [A]</b> | 6.25                          |
| <b>Power Output [W]</b>        | 100                           |



Figure 76. 100W HQST-100D-S PV panel. Source: [66].

The MPPT modules used have the specifications presented in Table 17:

Table 17. Specification data of the MPPT module used for the laboratory experiments. Adapted from [67].

|                                        |                                 |
|----------------------------------------|---------------------------------|
| <b>Manufacturer</b>                    | Epever                          |
| <b>Model</b>                           | Tracer 4210AN                   |
| <b>Type of batteries compatibility</b> | Sealed AGM or flooded lead acid |
| <b>Maximum PV input power [W]</b>      | 520W/ 12V<br>1040W/ 24V         |
| <b>Maximum PV input voltage [V]</b>    | 100                             |
| <b>Maximum current output [A]</b>      | 40                              |
| <b>Peak conversion efficiency [%]</b>  | 98                              |

The MPPT modules (Figure 77) involve advanced algorithms in order to track with accuracy the maximum power point of the PV array. They support lead acid battery charging. The users can customize the charge options for their batteries, such as charging voltage and float voltage. In the experiments conducted, the settings for the MPPT modules that were customized from the defaults are presented in Table 18, according to the battery manufacturer's specifications:

Table 18. MPPT module charge settings.

|                                   |        |
|-----------------------------------|--------|
| <b>Type of battery</b>            | Sealed |
| <b>Charging limit Voltage [V]</b> | 14.6   |
| <b>Charging Voltage [V]</b>       | 14.6   |
| <b>Float Voltage [V]</b>          | 13.6   |



Figure 77. MPPT module Epever Tracer 4210 AN.

Finally, the inverter used is manufactured by AIMS Power (Figure 78) and has the specifications shown in Table 19. It is a DC-to-AC power converter, converting the input DC voltage to AC voltage.

Table 19. Specification data of the inverter used for the laboratory experiments. Adapted from [68].

| Manufacturer                    | AIMS Power     |
|---------------------------------|----------------|
| Model                           | PWRI150012120S |
| DC voltage input [V]            | 12             |
| AC voltage output [V]           | 120            |
| Maximum continuous power [W]    | 1500           |
| Efficiency at maximum power [%] | 90             |
| Input Voltage range [V]         | 9.5–16         |



Figure 78. Inverter PWRI150012120S [68].

## B. MEASURING DEVICES

First, the DC and AC currents (output of the battery bank and output of the inverter, respectively) were measured with two AC/DC current probe amplifiers (Tektronix TCPA300), the settings of which are shown in Table 20:

Table 20. Settings of the current probe amplifiers.

|             | Current probe<br>amplifier 1 | Current probe<br>amplifier 2 |
|-------------|------------------------------|------------------------------|
| Range [A/V] | 10                           | 10                           |
| Coupling    | DC                           | AC                           |

Moreover, two oscilloscopes (Tektronix TDS 3012B) displayed the waveforms of the voltages and currents, respectively. The first one displayed the DC voltage in Channel 1 and the AC voltage in Channel 2. The second displayed the DC current in Channel 1 and the AC current in Channel 2, which were the outputs of the corresponding current probe amplifier.

A Fluke (434 Power Quality Analyzer) was monitoring DC voltage and current in Channel A, and in Channel B, the AC voltage and current, as shown in Figure 79:

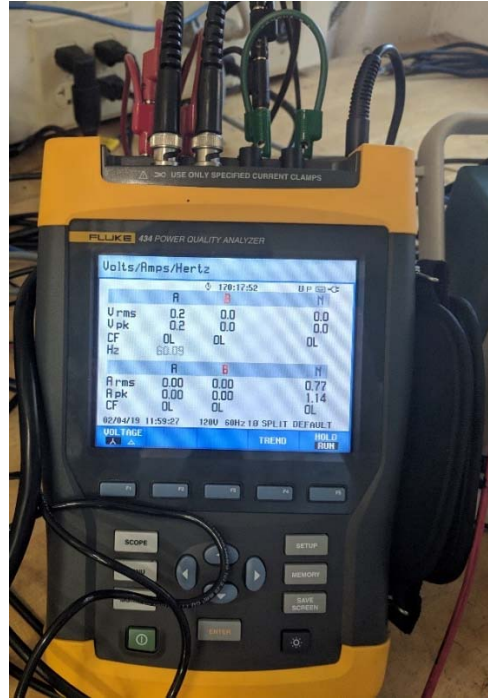


Figure 79. Fluke 434.

The settings of the Fluke are presented in Table 21. It can be observed that the range of the currents is the same as the one in the current probe amplifiers, since the current that is measured by the Fluke is the output current of those.

Table 21. Settings of the Fluke 434.

| Configuration       | 1 $\Phi$ Split |
|---------------------|----------------|
| Frequency [Hz]      | 60             |
| Nominal Voltage [V] | 120            |
| Voltage ratio       | 1:1            |
| Ampere ratio        | 10:1           |

Furthermore, the Fluke 434 was sending the data to the corresponding software, the FlukeView Three-Phase power quality analyzer [69], which was plotting and logging the data measured in real time.

All the data from the MPPT modules, which include the voltage, current, and power output of the PV array, as well as the voltage and current input to the batteries, were being displayed not only on their screens, but also on the screens of remote meters connected to them, as shown in the Figure 80. Specifically, in Figure 80, it can be observed that the operating voltage of each PV parallel string is about 68 V and the current is 2.7 A. The voltage of the battery is measured 13.6 V, which corresponds to the floating voltage set in the MPPT module, and the current input to the batteries is about 13.2 A.



Figure 80. Remote meters monitoring in real time.

Finally, three devices, called elog01, from Epever [70], were connected to each MPPT module and were logging all the data from the MPPT modules.

### C. LABORATORY EXPERIMENT FOR ONE DAY WITHOUT SUN

For this laboratory experiment, there are four lead acid batteries, with the specifications described previously, available to execute it.

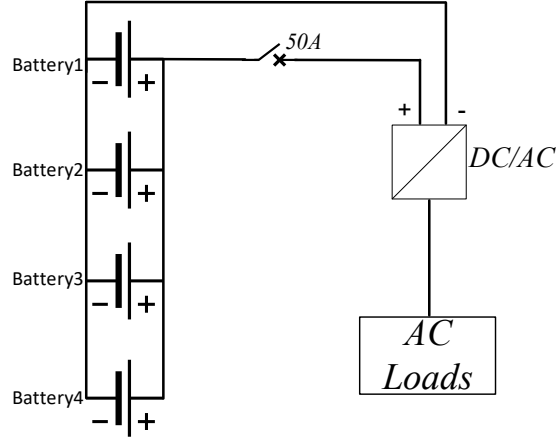


Figure 81. Equivalent circuit of the laboratory experiment.

To begin, the TCF should be determined, depending on the room temperature. The room temperature was measured to be 65° F, which corresponds to 18° C. So, based on Table 5, the TCF is 0.98.

The capacity provided by the manufacturer is 100 Ah at a 20-hour discharge rate. So, for four batteries, the nominal battery capacity comes to:

$$\text{Nominal Battery Capacity}[Ah] = 4 \cdot 100 = 400Ah \quad (25)$$

From Table 15, the MDOD is:

$$MDOD = 0.8 \quad (26)$$

Finally, the unadjusted battery capacity is computed as:

$$\begin{aligned} \text{Nominal Battery Capacity}[Ah] &= \text{Margin} \cdot \frac{\text{Unadjusted Battery Capacity}}{MDOD \cdot TCF} \Leftrightarrow \\ \Leftrightarrow \text{Unadjusted Battery Capacity} &= \frac{\text{Nominal Battery Capacity}[Ah] \cdot MDOD \cdot TCF}{\text{Margin}} \Leftrightarrow , \quad (27) \\ \Leftrightarrow \text{Unadjusted Battery Capacity} &= \frac{400 \cdot 0.8 \cdot 0.98}{1.1} = 285.09Ah \end{aligned}$$

with the design margin introduced in Chapter II.

For an autonomy of one day, we have:

$$\begin{aligned}
Unadjusted\ Battery\ Capacity[Ah] &= Load \cdot Autonomy \Leftrightarrow \\
\Leftrightarrow Load &= \frac{Unadjusted\ Battery\ Capacity}{Autonomy} \Leftrightarrow \\
&= \frac{285.09}{1} \Leftrightarrow \\
\Leftrightarrow Load &= 285.09\ Ah / day.
\end{aligned} \tag{28}$$

The DC load in Wh is computed as:

$$\begin{aligned}
Load\ [Ah/day\ at\ DC\ Bus] &= \frac{DC\ Load}{Bus\ Voltage} \Leftrightarrow \\
\Leftrightarrow DC\ Load &= Load\ [Ah/day\ at\ DC\ Bus] \cdot Bus\ Voltage \Leftrightarrow, \\
&= 285.09 \cdot 12 \Leftrightarrow \\
\Leftrightarrow DC\ Load &= 3421.09\ Wh/day.
\end{aligned} \tag{29}$$

We apply an inverter efficiency of 85% as a fair assumption, since the continuous power will be significantly less than the rated power for which the efficiency is given at 90%. The AC load in Ah for one day is computed as:

$$\begin{aligned}
DC\ Load\ [MWh/day] &= \frac{AC\ Load}{Inverter's\ Efficiency} \Leftrightarrow \\
\Leftrightarrow AC\ Load &= Inverter's\ Efficiency \cdot DC\ Load \Leftrightarrow \\
&= 0.85 \cdot 3421.09 \Leftrightarrow \\
\Leftrightarrow AC\ Load &= 2907.93\ Wh/day.
\end{aligned} \tag{30}$$

Finally, the average load in Watts that these batteries can supply for one day without being depleted is:

$$\begin{aligned}
AC\ Load &= 2907.93\ Wh/day \\
AverageLoad &= \frac{AC\ Load}{24h} = \frac{2907.93}{24h} = 121.2\ Watts.
\end{aligned} \tag{31}$$

For the implementation of 121.2 Watts, we used the following loads presented in Table 22:

Table 22. Loads used in the laboratory experiment.

|              | Consumption [W] | Time [h]  | Total load [Wh] |
|--------------|-----------------|-----------|-----------------|
| Halogen lamp | 100             | 24        | 2400            |
| LED lamp     | 10              | 24        | 240             |
| Fan          | 9.5             | 24        | 228             |
| <b>Total</b> | <b>119.5</b>    | <b>24</b> | <b>2868</b>     |

Finally, the setup of the laboratory experiment can be observed in Figure 82.

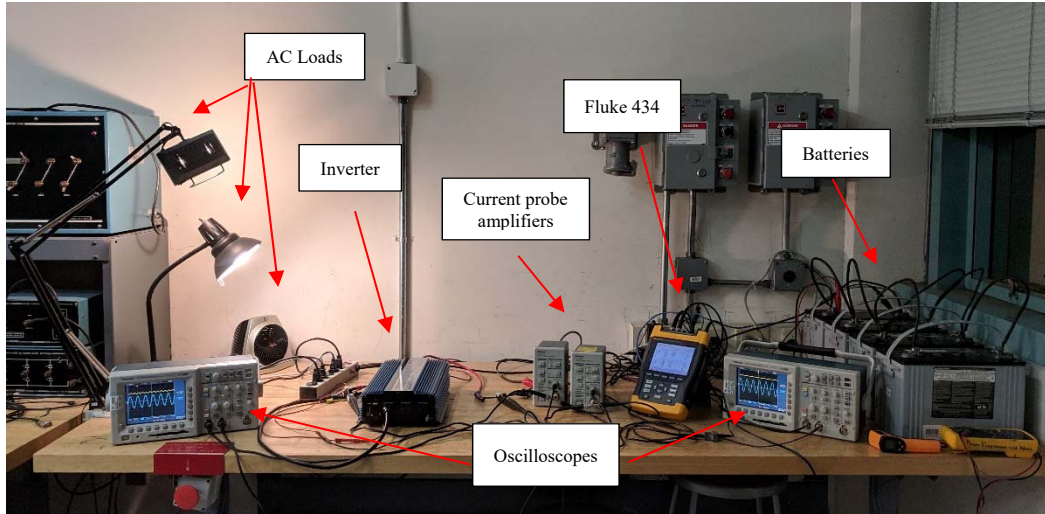


Figure 82. Laboratory experiment setup.

For safety reasons, a circuit breaker of 50A is inserted between the inverter and the battery bank.

In this experiment, the DC voltage and current as well as the AC voltage and current were measured, using a Fluke 434 in collaboration with the corresponding software FlukeView Three-Phase power quality analyzer [69], as mentioned before. An overall view of the measurements taken over the 24-hour experiment can be observed in Figure 83.

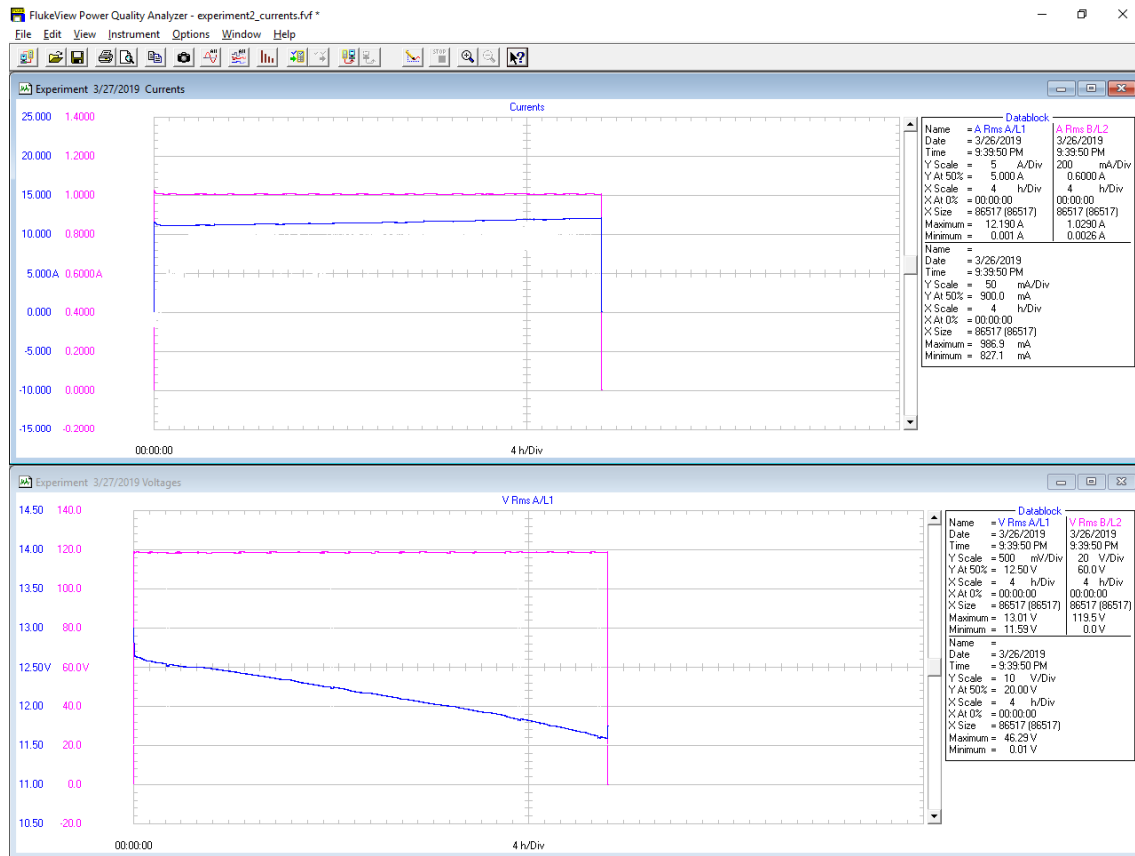


Figure 83. FlukeView measurements of the laboratory experiment (upper window: DC current (blue), AC current (red), lower window: DC voltage (blue), AC voltage (red)).

Plotting the values in Matlab, we obtain a more detailed view, shown in Figures 84 to 87.

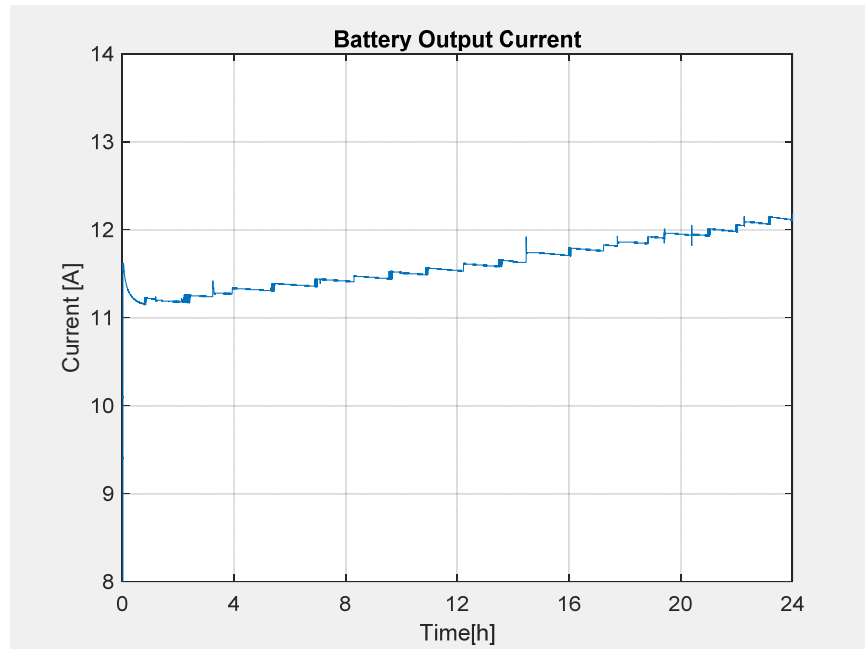


Figure 84. Battery output current.

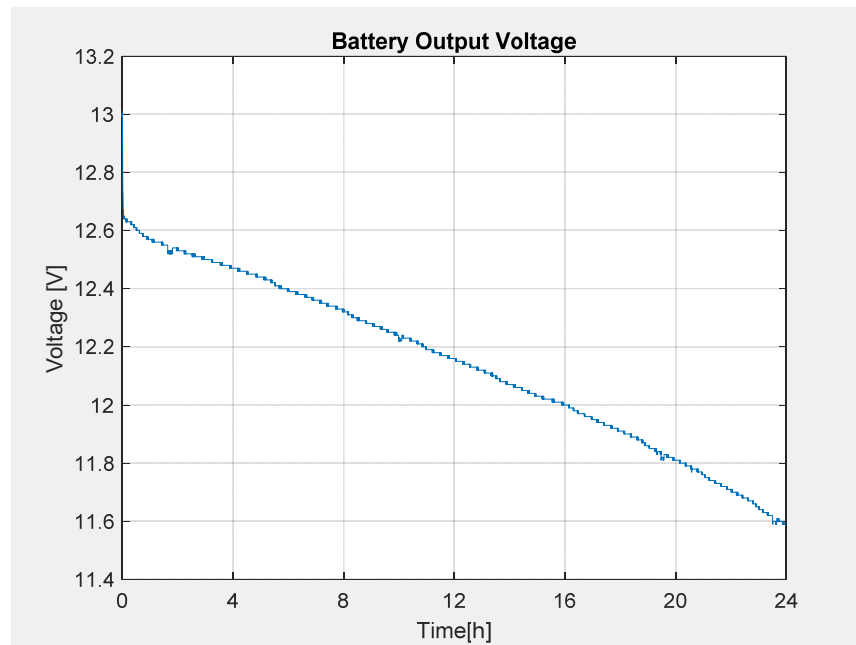


Figure 85. Battery output voltage.

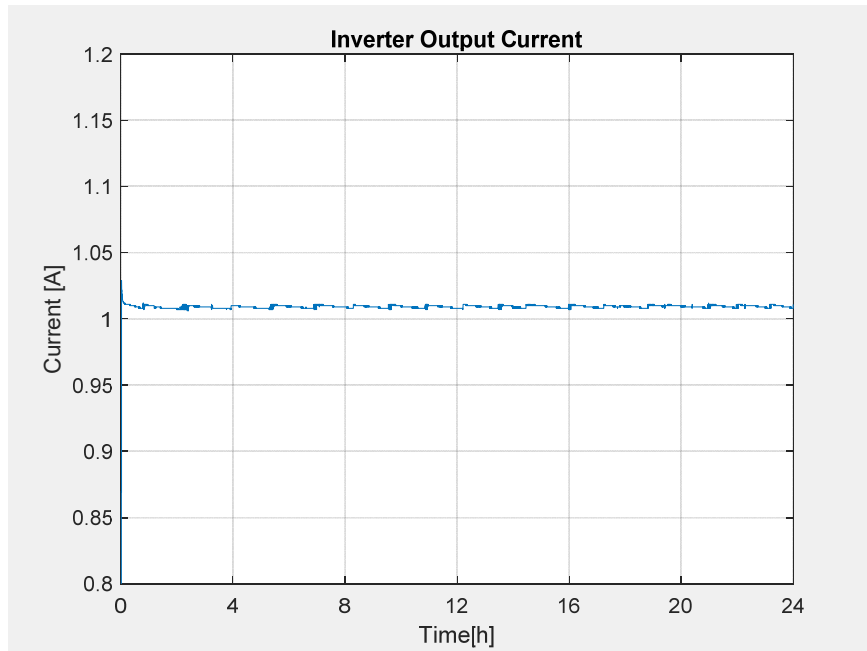


Figure 86. Inverter output current.

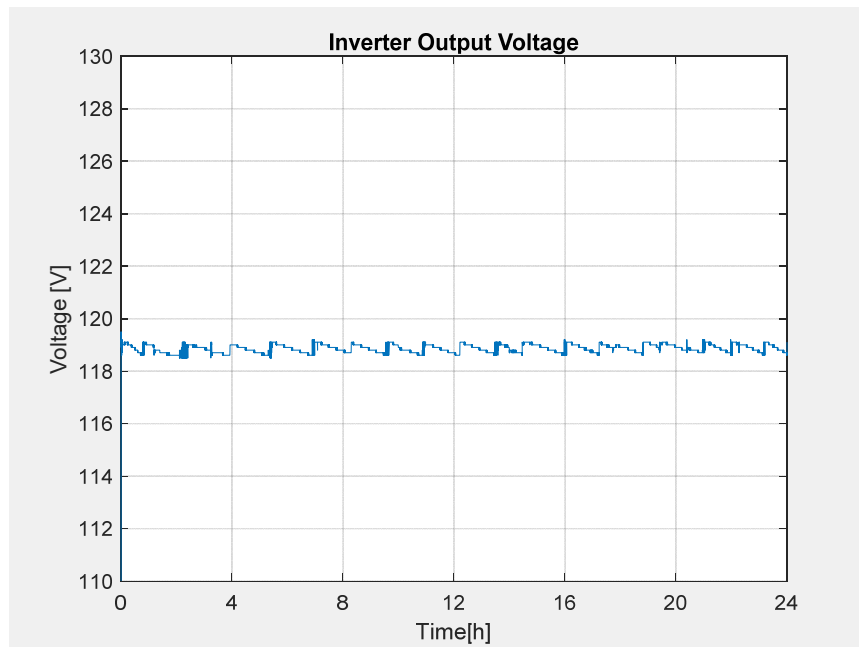


Figure 87. Inverter output voltage.

Since the AC load is constant throughout the experiment, the DC power supplied by the batteries is also constant, since their relation is linear according to the inverter efficiency. The plots of the battery output current and voltage confirm this. As the battery output voltage is being reduced, the current drawn from the batteries increases to keep the power constant before the inverter.

The inverter efficiency can be calculated by:

$$\eta_{INV} = \frac{AC \text{ Power out}}{DC \text{ Power in}} = \frac{V_{AC} \cdot I_{AC}}{V_{DC} \cdot I_{DC}} = \frac{118.7 \cdot 1.008}{12.55 \cdot 11.19} = 85.2\% \quad (32)$$

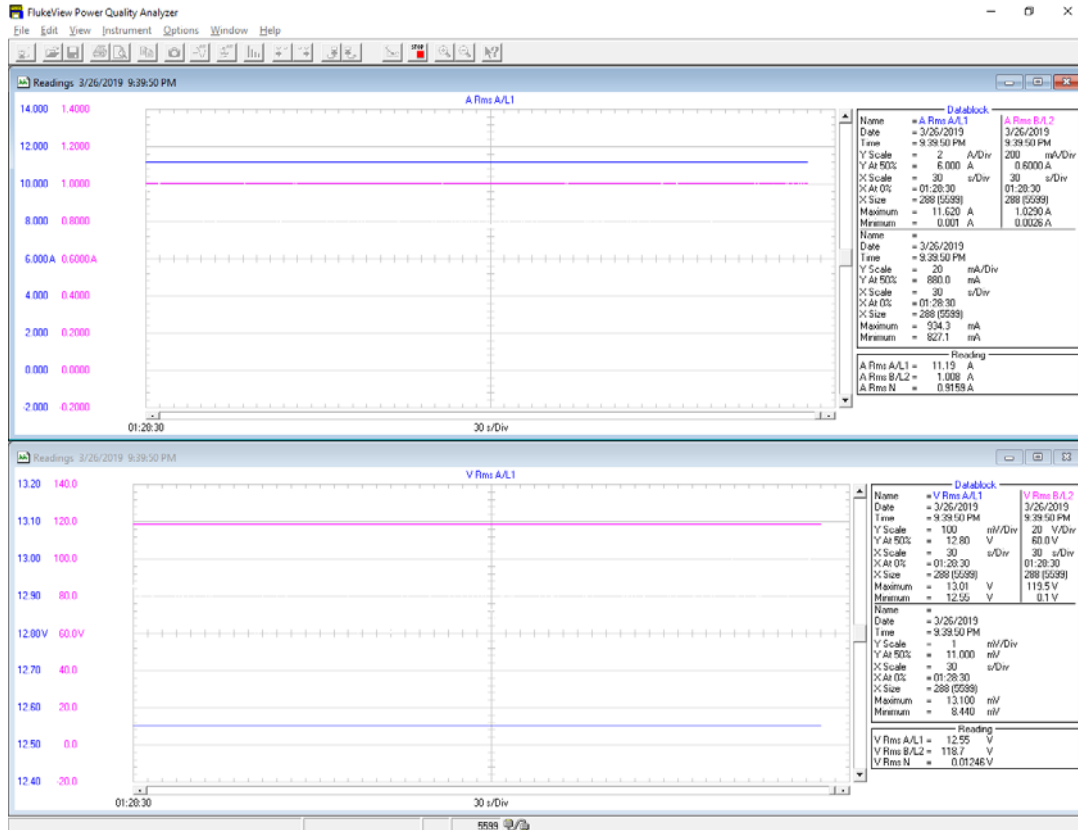


Figure 88. Screenshot of FlukeView after 1 hour and 20 minutes have elapsed (upper window: DC current (blue), AC current (red), lower window: DC voltage (blue), AC voltage (red)).

Plots from the oscilloscopes at different timings of the experiment are presented in Figures 89 to 96. A summary of the values monitored is presented in Table 23. The

aforementioned observation is confirmed again. The AC load, voltage, and current are constant, as is the DC power supplied by the batteries. This is shown in Table 23; as the batteries are being discharged, and consequently their voltage is reduced, the current output increases in order to keep the DC power input to the inverter constant.

Table 23. Summary of measurements obtained by the oscilloscopes.

|                | Time<br>elapsed<br>[hr:min] | DC<br>Current [A]<br>Ch.1 | AC<br>Current (rms)<br>[A]<br>Ch.2 | DC<br>Voltage [V]<br>Ch.1 | AC<br>Voltage (rms)<br>[V]<br>Ch.2 |
|----------------|-----------------------------|---------------------------|------------------------------------|---------------------------|------------------------------------|
| Figures 89, 90 | 1:20                        | 11.23                     | 0.999                              | 12.54                     | 119.8                              |
| Figures 91, 92 | 9:30                        | 11.56                     | 0.999                              | 12.29                     | 119.8                              |
| Figures 93, 94 | 19:00                       | 12.04                     | 0.999                              | 11.88                     | 119.6                              |
| Figures 95, 96 | 23:00                       | 12.24                     | 1.002                              | 11.70                     | 119.9                              |

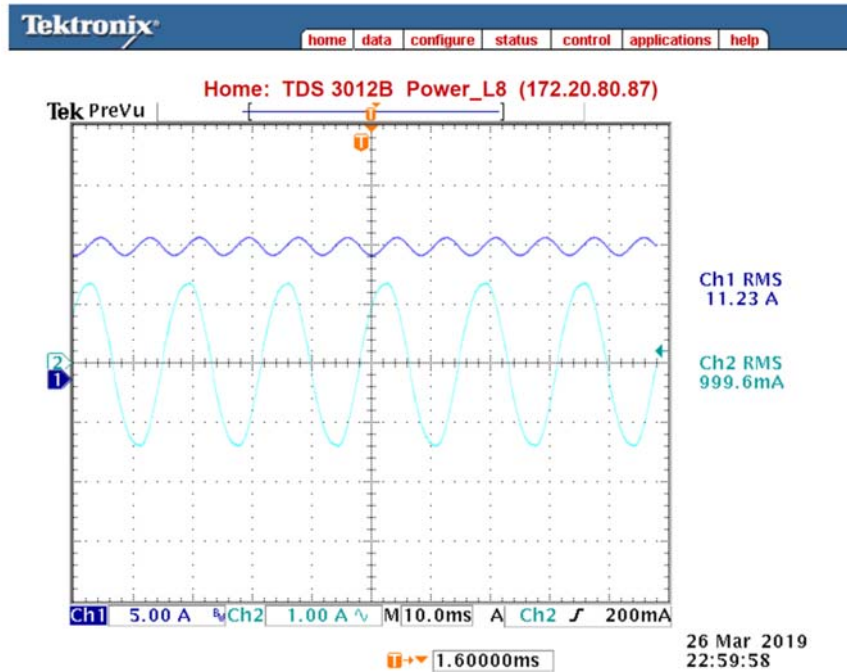


Figure 89. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) after 1 hour and 20 minutes have elapsed.

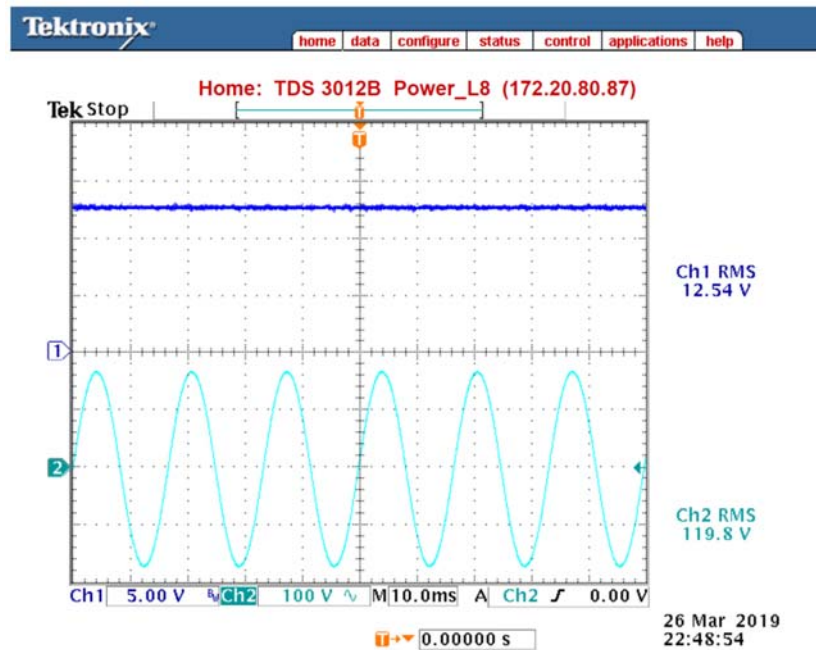


Figure 90. DC voltage (Ch1 [5V/div]) and AC voltage (Ch2 [100V/div]) after 1 hour and 20 minutes have elapsed.

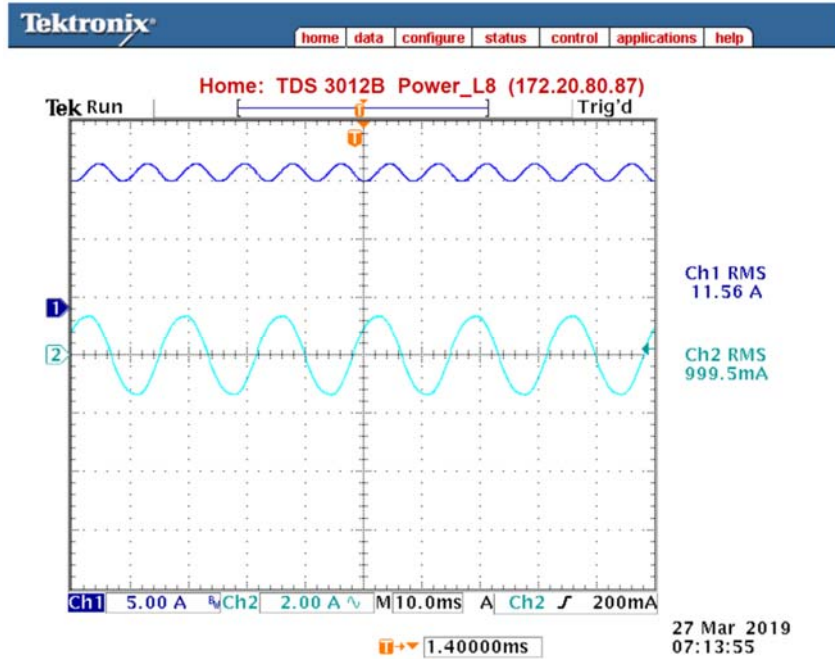


Figure 91. DC current (Ch1 [5A/div]) and AC current (Ch2 [2A/div]) after 9 hours and 30 minutes have elapsed.

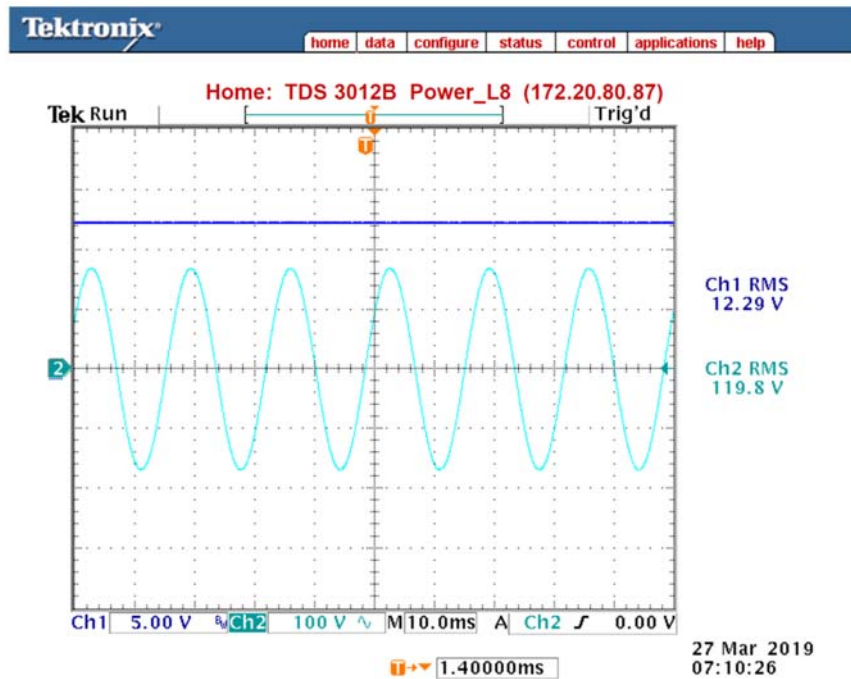


Figure 92. DC voltage (Ch1 [5V/div]) and AC voltage (Ch2 [100V/div]) after 9 hours and 30 minutes have elapsed.

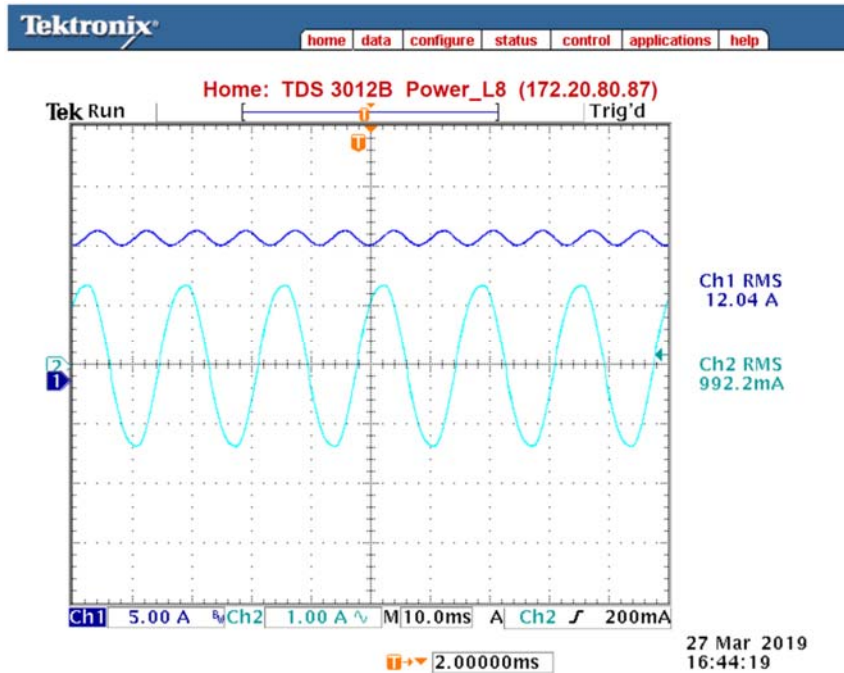


Figure 93. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) after 19 hours have elapsed.

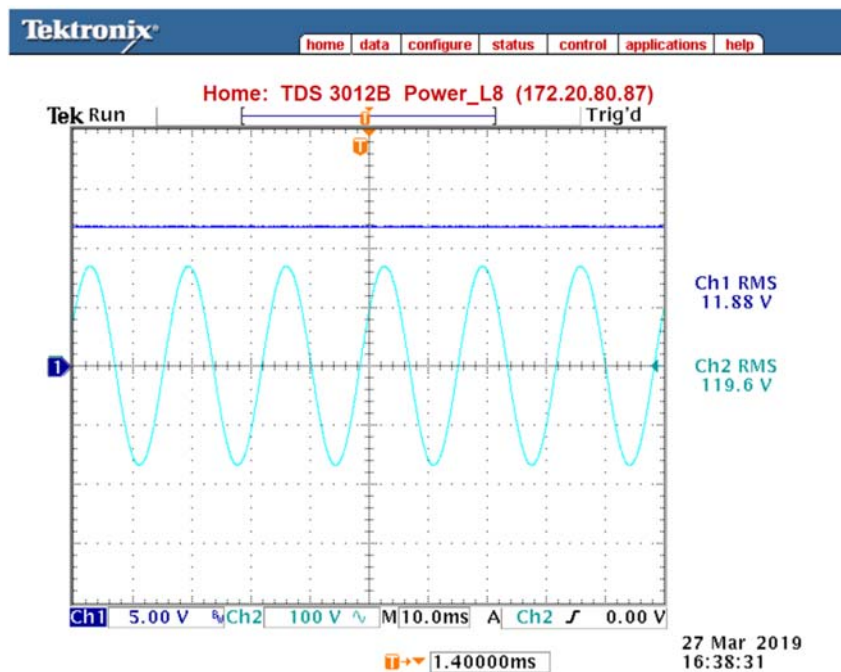


Figure 94. DC voltage (Ch1 [5V/div]) and AC voltage (Ch2 [100V/div]) after 19 hours have elapsed.

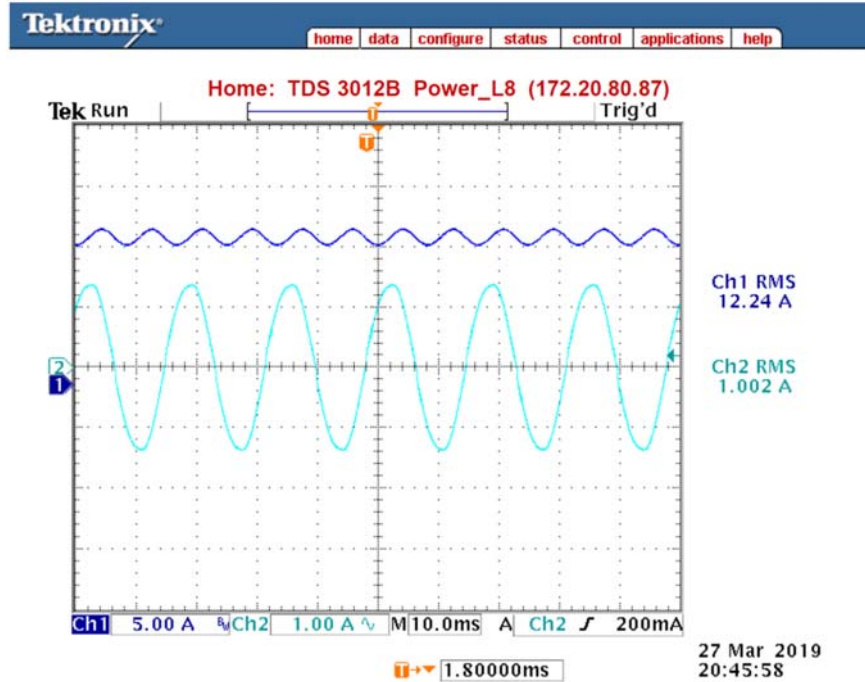


Figure 95. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) after 23 hours have elapsed.

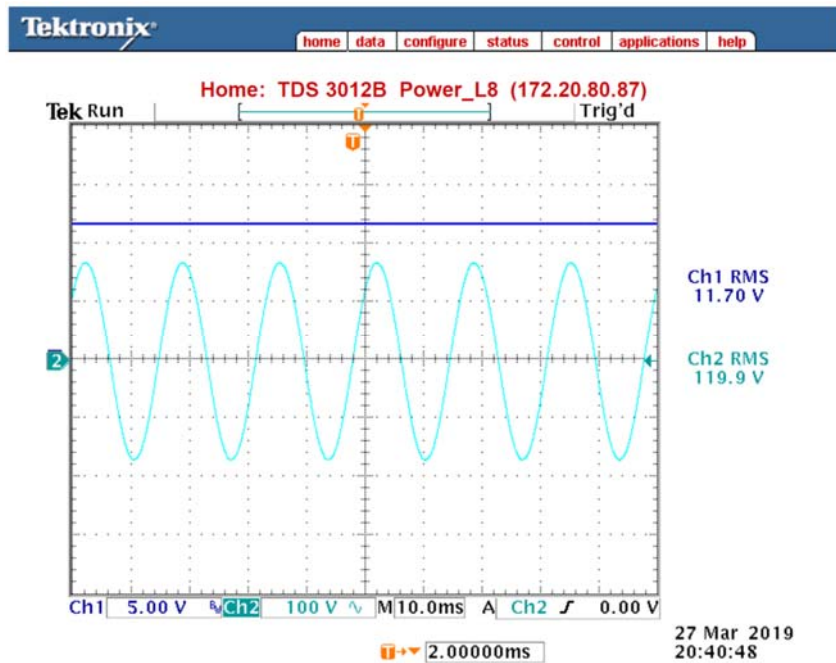


Figure 96. DC voltage (Ch1 [5V/div]) and AC voltage (Ch2 [100V/div]) after 23 hours have elapsed.

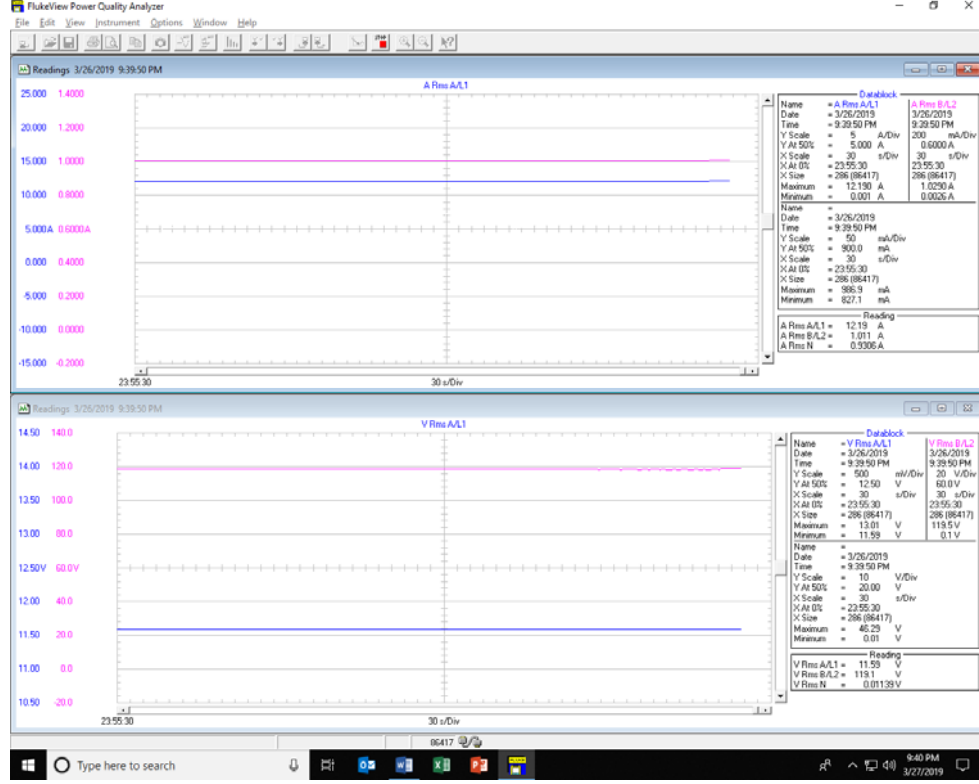


Figure 97. Screenshot of FlukeView just before the end of the experiment (upper window: DC current (blue), AC current (red), lower window: DC voltage (blue), AC voltage (red)).

One method commonly used to estimate the battery SOC is the Coulomb counting method [71]. Measuring the current that is discharged from the battery and integrating it over time gives an estimation of the SOC. This value is repeatedly subtracted from the initial SOC or, later, the previous SOC value. This is shown in equation (33), used to determine the SOC of the batteries in this experiment:

$$\begin{aligned}
 SOC(t) &= \frac{1}{n_{bat}} \cdot \frac{q - q_{discharge}}{q_{max}} \cdot 100 = SOC_0(t-1) - \frac{1}{n_{bat}} \cdot \frac{q_{discharge}}{q_{max}} \cdot 100 \Leftrightarrow \\
 &\Leftrightarrow SOC_0(t-1) - \frac{1}{n_{bat}} \cdot \frac{\int i_B dt}{q_{max}} \cdot 100
 \end{aligned} \quad (33)$$

where  $q_{max} = 400 Ah$ .

From Figure 98, we observe that the batteries' SOC, as expected, is gradually decreasing, reaching the lowest value of 25.92% at the end of the experiment, which confirms the basic concept of the design of the stand-alone power system: that is, the energy storage can supply the load, without the need of receiving power from the PV array.

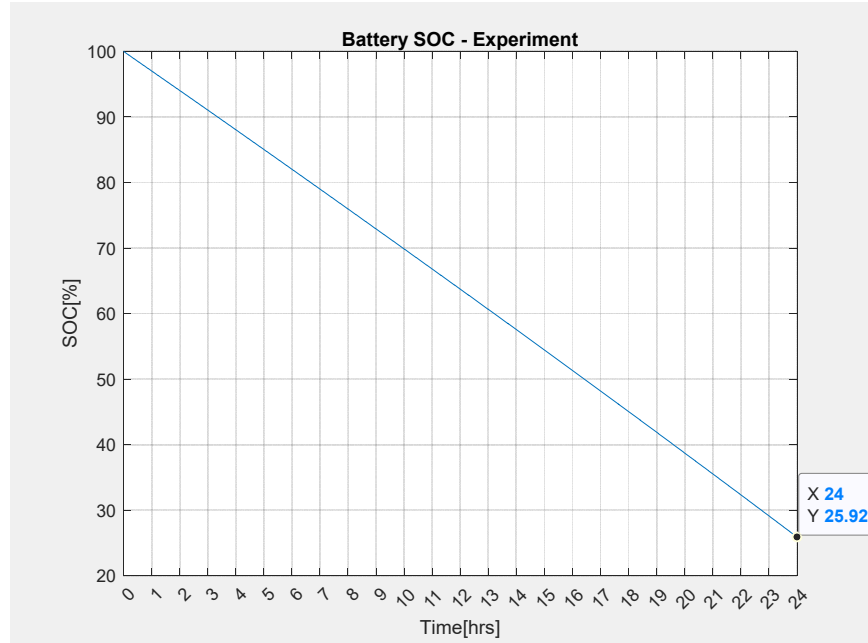


Figure 98. Battery SOC (laboratory experiment).

Another way to measure the battery's SOC is by measuring the specific gravity of the electrolyte with a hydrometer. Nevertheless, the batteries are sealed. Thus, we will also determine the SOC using the open circuit voltage ( $V_{oc}$ ) method. The results of this method depend on several factors, the most important of which is the chemistry of the battery. There are several tables available online that relate different chemistries of lead acid batteries through the specific gravity to SOC values, but we are not to rely on them. Yet, according to [71] and [72], the linear plot of the  $V_{oc}$  of the battery and its SOC can be determined, by knowing the value of  $V_{oc}$ , at a SOC of 100%, when the batteries are fully charged, and the value at SOC 0%, when the batteries are fully discharged. For this purpose, the batteries were depleted to obtain the value of  $V_{oc}$  at SOC of 0%, after we confirmed that they can reach this state and be recharged again. The values of  $V_{oc}$  at SOC

of 100% and 0% measured 12.87 V and 11.49 V, respectively. The following plot presents the relationship between the SOC and the  $V_{oc}$  of our batteries:

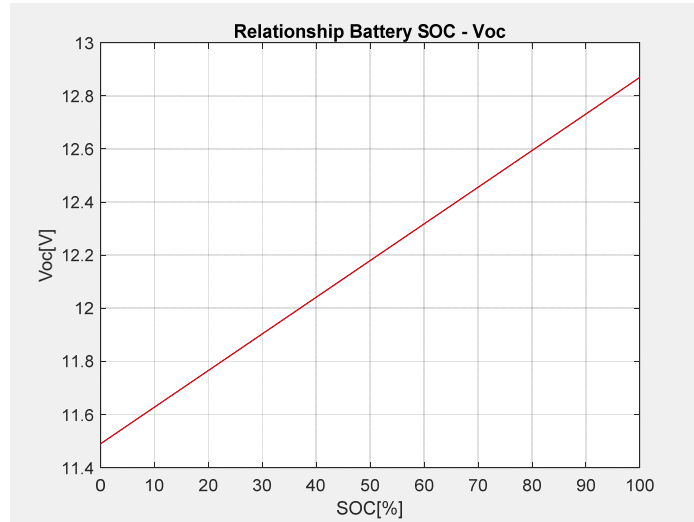


Figure 99. Relationship between Battery SOC and  $V_{oc}$ .

After the batteries were at rest in open circuit for at least 12 hours, the  $V_{oc}$  measured 11.85 V, which from the plot in Figure 100 corresponds to a SOC of 25.77%, which matches the value obtained from the Coulomb counting method in Figure 98.

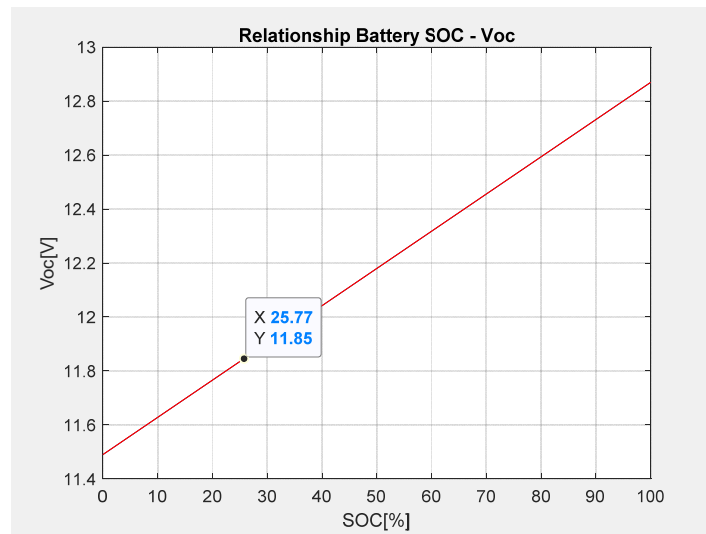


Figure 100. Battery SOC (laboratory experiment).

Implementing the element's parameters used in the laboratory experiment, in the program, as in Figure 101, we obtain the same configuration of batteries. That is four parallel-connected lead acid batteries to supply the AC load of 2868 Wh/day, which is the total AC load determined by the loads used in the experiment. The outputs are shown in Figure 102.

| Input Parameters               |      |
|--------------------------------|------|
| AC Load [MWh/day]              | 0028 |
| Peak-Sun Hours(PSH) [kWh/m²]   | 4.12 |
| Required Usable Storage [days] | 1    |

| Parameters of the Elements Used   |            |
|-----------------------------------|------------|
| Inverter Efficiency               | 0.85       |
| System Voltage [V]                | 12         |
| Battery Type                      | Lead Ac... |
| Battery Voltage [V]               | 12         |
| Battery Capacity [Ah]             | 100        |
| Temperature [C]                   | 20         |
| Maximum Power Point (MPP) Voltage | 16         |
| Maximum Power Point (MPP) Current | 6.25       |
| Use of MPP Tracker                | Yes        |
| Array-To-Load-Ratio               | 1.1        |

Calculate Help

Figure 101. Window with inputs.

| Outputs                          |             |
|----------------------------------|-------------|
| Nominal Battery Capacity [Ah]    | 395         |
| Total Number of Batteries        | 1 x 4 = 4   |
| Total Number of Modules          | 1 x 16 = 16 |
| Output of the PV panels [Ah/day] | 351         |

Run Simulation

Figure 102. Window with outputs.

It should be mentioned that since the AC load of the experiments conducted is constant, in order to validate the design tool with the simulations, a constant load profile input is used in the Simulink model. The load profile is scaled according to the AC load demand by the user and is totally irrelevant with the results obtained by the experiment.

Running the simulation for one day without sun for the inputs shown in Figure 101, we obtain the results shown in Figures 103, 104, 105:

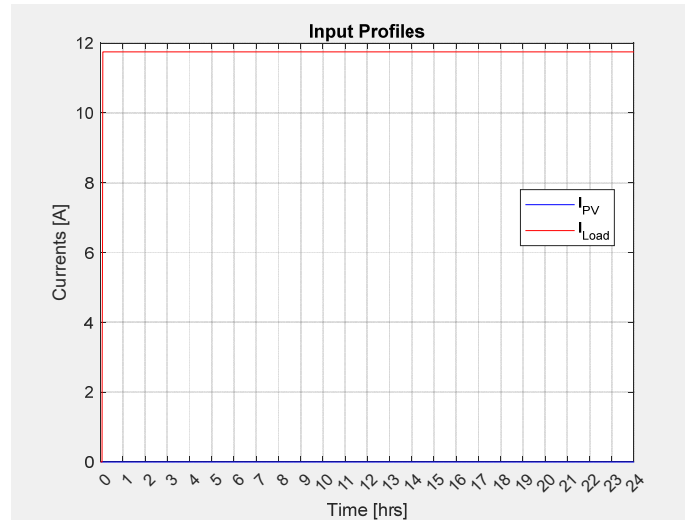


Figure 103. Input profiles.

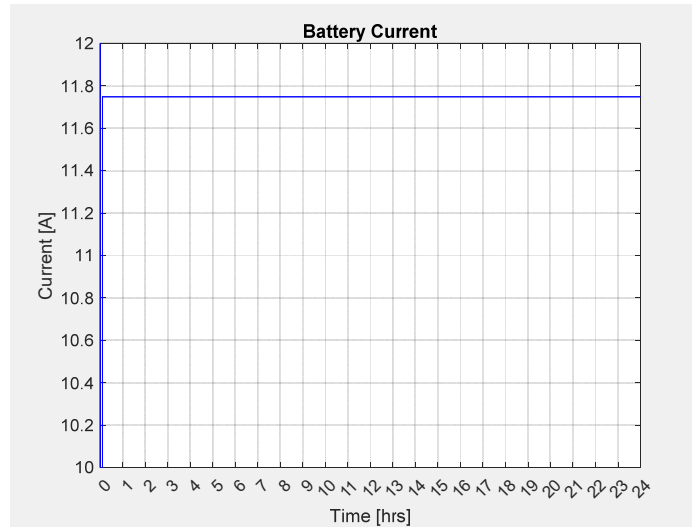


Figure 104. Battery current.

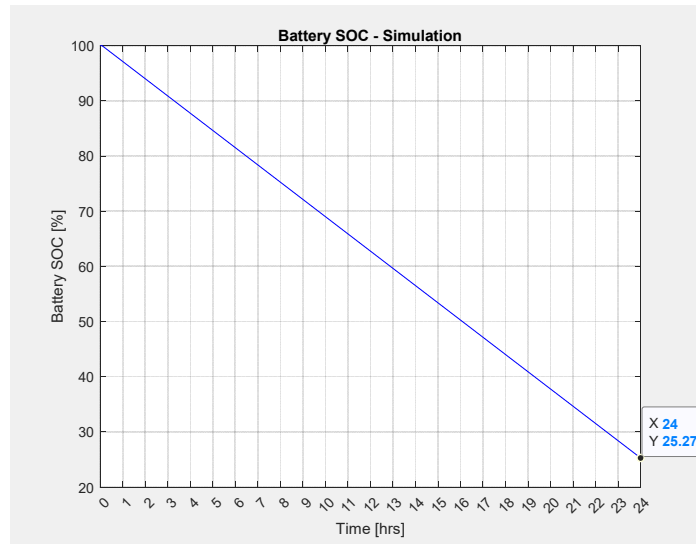


Figure 105. Battery SOC (simulation).

Plotting together the battery SOC of the laboratory experiment and the simulation, we obtain Figure 106:

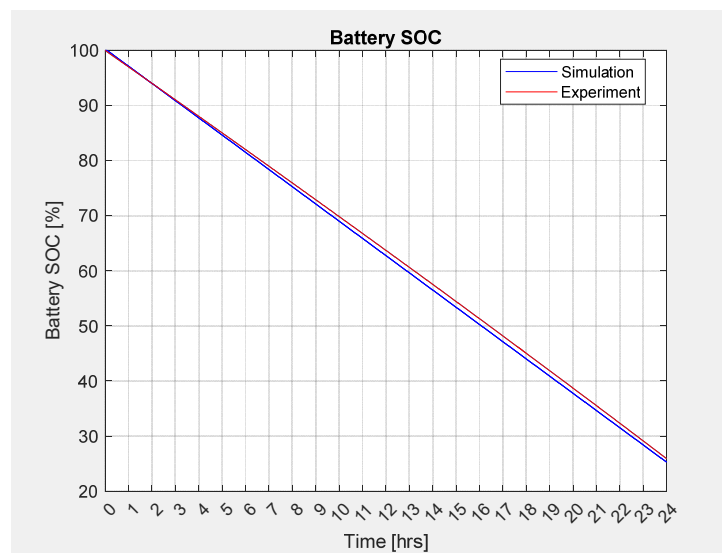


Figure 106. Battery SOC (simulation vs. experiment).

The matching of the plots of the battery SOC in the experiment and the simulation validates the design tool.

#### D. LABORATORY EXPERIMENT FOR ONE DAY WITH SUN

For this laboratory experiment, there are 12 PV panels and four batteries available to execute it. Three MPPTs will be used, which gives the opportunity to adjust the configuration depending on their input power. The configuration is done as follows, considering the fact that the MPPTs can deliver a maximum output of 40 A; four PV panels are connected in series and there are three parallel strings of them. Each parallel string is connected to one MPPT, as shown in Figure 107.

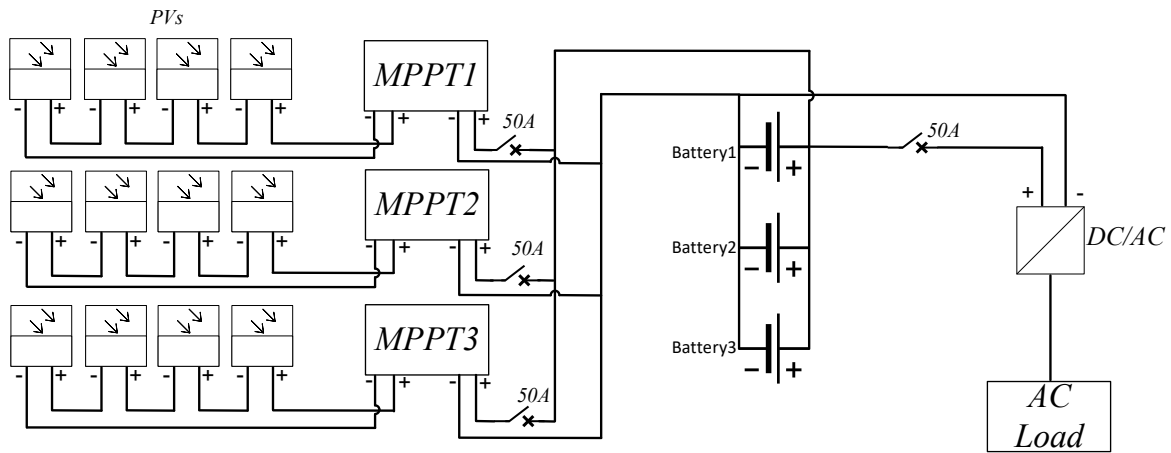


Figure 107. Equivalent circuit of the laboratory experiment with PV panels.

Here, the ambient temperature is considered to show any differences with the program calculations, where in case of MPPTs used, a voltage-derating factor of 0.95 is accounted for. Considering the temperature compensation for the maximum power output of each PV, which according to the specification sheet is  $-0.44\%/^{\circ}\text{C}$ , the derating power for each PV is calculated:

$$P_{\max} \cdot (-0.44\%/^{\circ}\text{C}) = 100 \cdot (-0.44\%/^{\circ}\text{C}) = -0.44\text{W}/^{\circ}\text{C} . \quad (34)$$

The ambient temperature is considered to be  $13^{\circ}\text{C}$ . Given the Normal Operating Cell Temperature (NOCT) of  $45^{\circ}\text{C}$  from the specification sheet and knowing that the insolation level in normal operating conditions is:

$$S = 80mW / cm^2 . \quad (35)$$

The cell temperature is computed [73]:

$$T_{cell} = T_{air} + \frac{NOCT - 20}{80} \cdot S = 13 + \frac{45 - 20}{80} \cdot 80 = 38^\circ C . \quad (36)$$

The loss of power for one PV due to the ambient temperature is given by:

$$P_{loss} = (T_{cell} - 25^\circ C_{STC}) \cdot (-0.44W / ^\circ C) = -5.72W . \quad (37)$$

For the whole PV array, consisting of four panels in series, the total maximum power is:

$$P_{array} = 4 \cdot (P_{max} - P_{loss}) = 4 \cdot (100 - 5.72) = 377.12W . \quad (38)$$

This is the input power to each MPPT module. According to the power conversion curves given in the specification sheet of the MPPT module (Figure 108), a power conversion of 95.5% is considered.

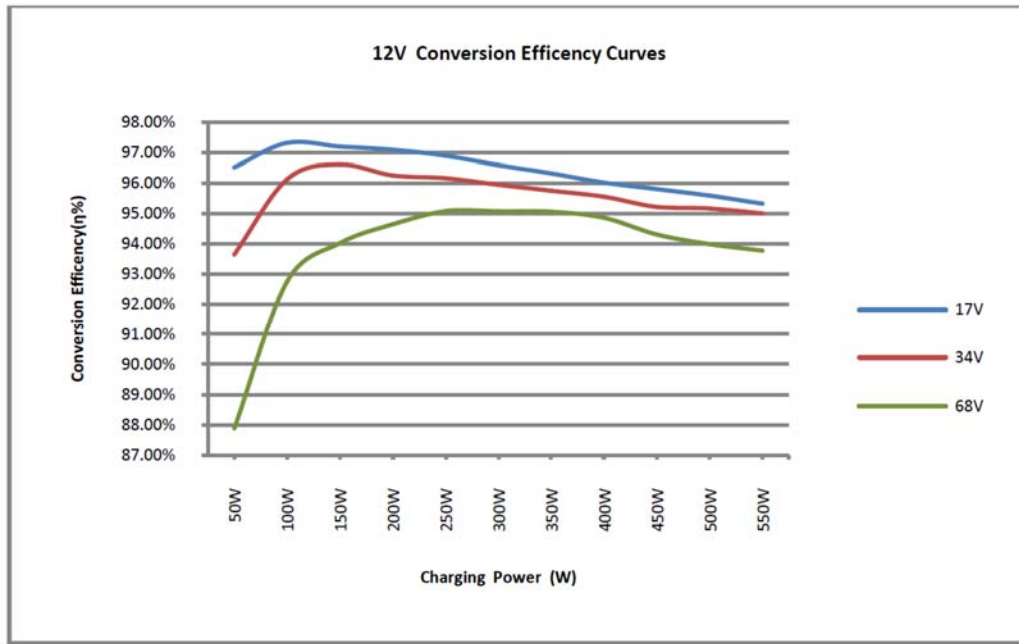


Figure 108. Power conversion curves of the MPPT [67].

As a result, the maximum power output of the MPPT is given:

$$P_{out} = 0.955 \cdot P_{in} = 0.955 \cdot 377.12 = 360.15W . \quad (39)$$

The MPPT module is going to charge the batteries with the recharge multicell voltage, as explained in Chapter II, which is for the case of 12V batteries, 14.6V.

As a result, the maximum current that will charge the batteries is:

$$I_{mp} = \frac{P_{out}}{V_{recharge}} = \frac{360.15W}{14.6V} = 24.67A . \quad (40)$$

Using this current as an  $I_{mp}$  and applying the calculation procedure of the design tool, the number of parallel-connected PVs can be determined. An assumption of using three batteries instead of four is made. Also, a moderate A:L of 1.1 is used for the calculation.

Using three batteries, we obtain the unadjusted battery capacity as:

$$\begin{aligned} \text{Nominal Battery Capacity}[Ah] &= \text{Margin} \cdot \frac{\text{Unadjusted Battery Capacity}}{\text{MDOD} \cdot \text{TCF}} \Leftrightarrow \\ \Leftrightarrow \text{Unadjusted Battery Capacity} &= \frac{\text{Nominal Battery Capacity}[Ah] \cdot \text{MDOD} \cdot \text{TCF}}{\text{Margin}} \Leftrightarrow . \quad (41) \\ \Leftrightarrow \text{Unadjusted Battery Capacity} &= \frac{300 \cdot 0.8 \cdot 0.98}{1.1} = 213.82Ah \end{aligned}$$

For an autonomy of one day, we have:

$$\begin{aligned} \text{Unadjusted Battery Capacity}[Ah] &= \text{Load} \cdot \text{Autonomy} \Leftrightarrow \\ \Leftrightarrow \text{Load} &= \frac{\text{Unadjusted Battery Capacity}}{\text{Autonomy}} \Leftrightarrow \\ \Leftrightarrow \text{Load} &= \frac{213.82}{1} \Leftrightarrow \\ \Leftrightarrow \text{Load} &= 213.82Ah / \text{day} \end{aligned} \quad (42)$$

The DC load in Wh is computed as:

$$\begin{aligned}
Load [Ah/day \text{ at DC Bus}] &= \frac{DC Load}{Bus Voltage} \Leftrightarrow \\
\Leftrightarrow DC Load &= Load [Ah/day \text{ at DC Bus}] \cdot Bus Voltage \Leftrightarrow . \\
&\Leftrightarrow DC Load = 213.82 \cdot 12 \Leftrightarrow \\
&\Leftrightarrow DC Load = 2565.84 Wh/day
\end{aligned} \tag{43}$$

Applying an inverter efficiency of 85%, as before, the AC load in Ah for one day is computed as:

$$\begin{aligned}
DC Load [MWh/day] &= \frac{AC Load}{Inverter's Efficiency} \Leftrightarrow \\
\Leftrightarrow AC Load &= Inverter's Efficiency \cdot DC Load \Leftrightarrow . \\
&\Leftrightarrow AC Load = 0.85 \cdot 2565.84 \Leftrightarrow \\
&\Leftrightarrow AC Load = 2180.96 Wh/day
\end{aligned} \tag{44}$$

Finally, the average load in Watts that these batteries can supply for one day without being depleted is:

$$\begin{aligned}
AC Load &= 2180.96 Wh/day \\
Average Load &= \frac{AC Load}{24h} = \frac{2180.96}{24h} = 90.87 Watts .
\end{aligned} \tag{45}$$

For the implementation of this load, a halogen lamp of 90 Watts was used for the whole 24-hour time period.

At this point, the number of parallel-connected PV panels is confirmed for the 213.82 Ah/day drawn from the three batteries.

The system losses are given by:

$$SL = 0.15 + (1 - Bat_{eff}) = 0.15 + (1 - 0.94) = 0.21 . \tag{46}$$

For PSH of 4.12 and an A:L of 1.1, we have:

$$\begin{aligned}
PV_{parallel}(rounded\ up) &= \frac{Load[Ah/day] \cdot (A:L)}{(1-SL) \cdot I_{mp} \cdot PSH} \Leftrightarrow \\
\Leftrightarrow PV_{parallel}(rounded\ up) &= \frac{213.82 \cdot 1.1}{(1-0.21) \cdot 24.67 \cdot 4.12} = 2.929 \Leftrightarrow . \\
\Leftrightarrow PV_{parallel}(rounded\ up) &= 3
\end{aligned} \tag{47}$$

Including the system losses ( $SL$ ), the maximum PV output at the derated  $V_{mp}$  is given by:

$$\begin{aligned}
PV_{out}[Ah] &= PV_{parallel} \cdot I_{mp} \cdot PSH \cdot (1-SL) \Leftrightarrow \\
\Leftrightarrow PV_{out}[Ah] &= 3 \cdot 24.67 \cdot 4.12 \cdot (1-0.21) \Leftrightarrow . \\
\Leftrightarrow PV_{out}[Ah] &= 240.89 Ah
\end{aligned} \tag{48}$$

Finally, the setup of the laboratory experiment can be observed in Figures 109 to 111:

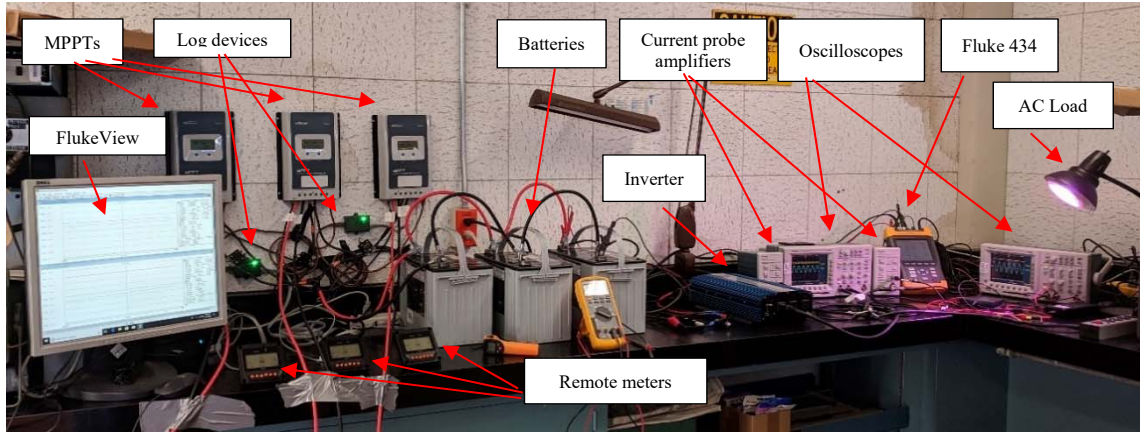


Figure 109. Laboratory experiment setup.



Figure 110. Setup of the PV panels.

It should be mentioned that since the experiment is held in the northern hemisphere, the PV panels should face south. Besides that, the tilt angle is very important as well. According to [39] the tilt angle was arranged at the latitude of the location (Monterey, CA) plus 15 degrees to optimize for the winter performance; that is,  $36+15=51$  degrees.

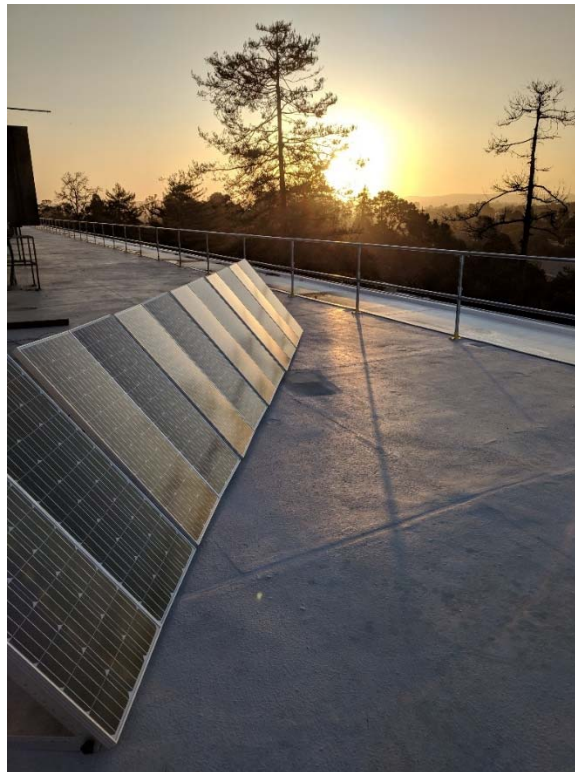


Figure 111. Setup of the PV panels (facing exactly south at a tilt angle of 51 degrees).

For safety reasons, a circuit breaker of 50 A is used before the inverter, as well as one at every MPPT module output. It should be mentioned that the wiring was also considered for the maximum currents flowing at each branch according to [74].

The laboratory experiment purposely started at 21:00 hours, when there is no sun, in order to show the lowest state of charge that the battery bank can reach before the sun comes up. This also shows how fast from this state of charge the batteries can be fully charged during the day.

The measurements of the experiment were the DC voltage and current, as well as the AC voltage and current. All measurements were monitored and logged by the Fluke 434 in collaboration with the corresponding software FlukeView Three-Phase power quality analyzer [69]. An overall view of the measurements taken over the 24-hour experiment can be observed in Figure 112:

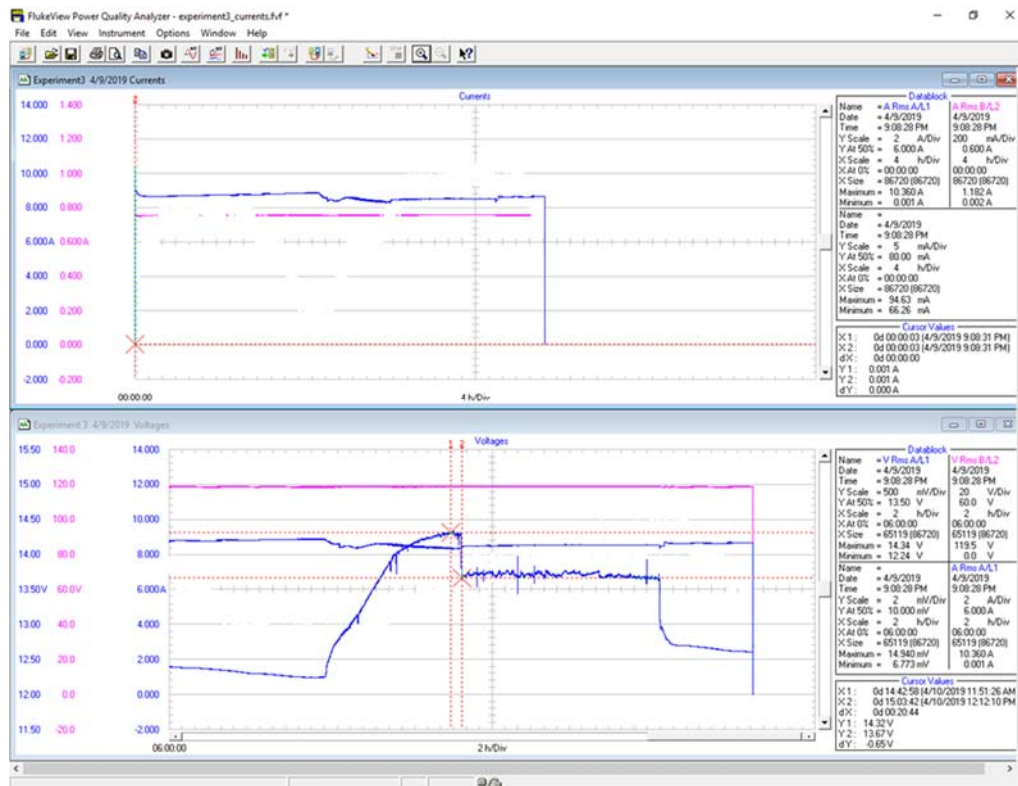


Figure 112. FlukeView measurements of the laboratory experiment (upper window: DC current (blue), AC current (red), lower window: DC voltage (blue), AC voltage (red)).

Plotting the values in Matlab, we can obtain a more detailed view, as shown in Figures 113 to 116.

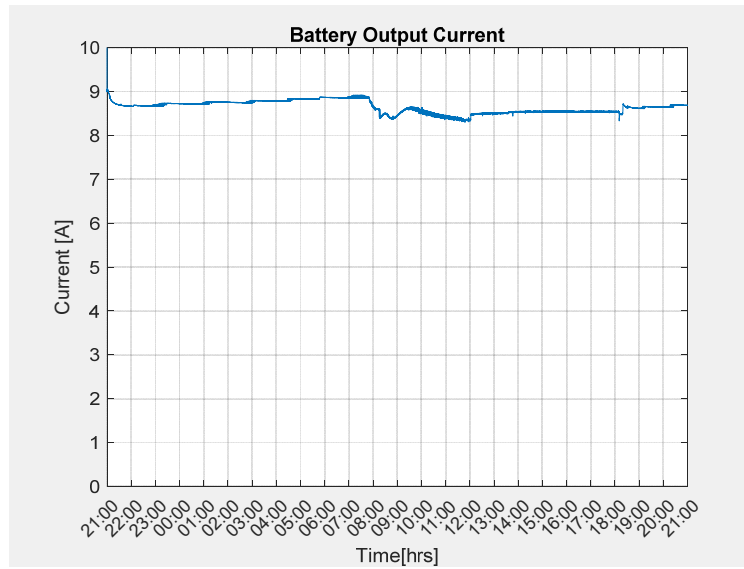


Figure 113. Battery output current.

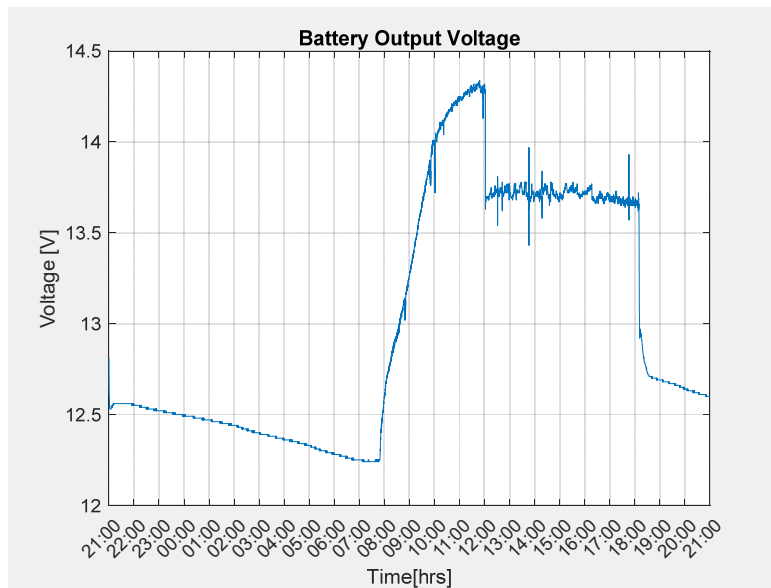


Figure 114. Battery output voltage.

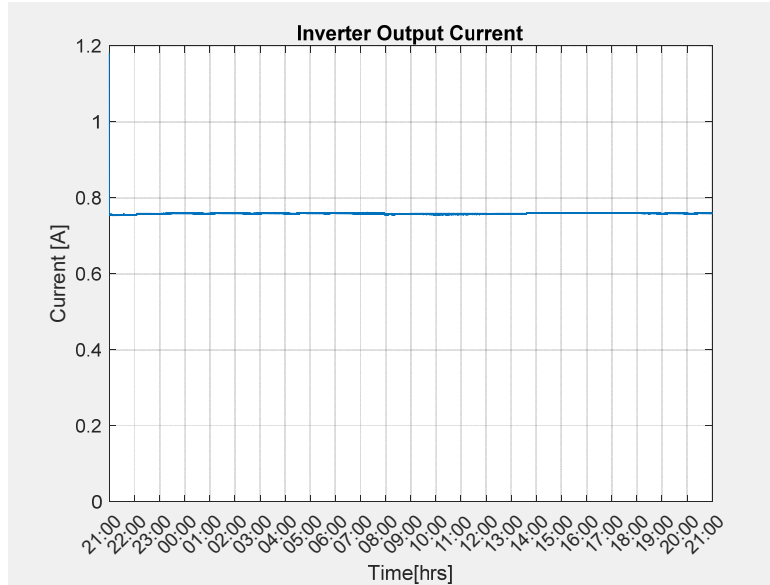


Figure 115. Inverter output current.

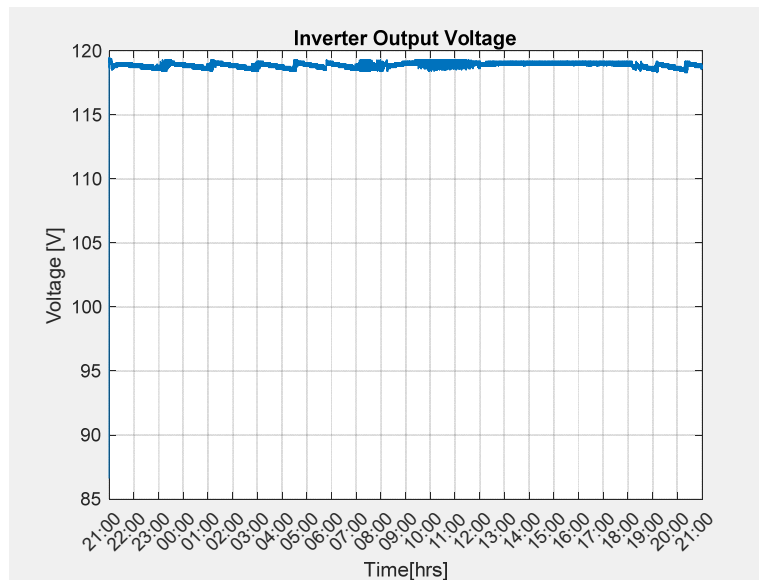


Figure 116. Inverter output voltage.

It is noteworthy how the battery output voltage changes depending on its state. The batteries are discharged until 08:00 hours. Then, their voltage is continuously increasing, which means that they are being charged until about 12:00, when they reach the charging voltage, which was set in the MPPT controller at 14.4 V. At this time, the batteries are fully charged. From 12:00 hours on, their voltage drops to the floating voltage, which was set at

13.8V, until 18:00, when the PV output current is not adequate to keep them fully charged. From 18:00 hours until the end of the experiment, they are being discharged.

Plots at different times of the experiment are presented in Figures 117 to 128. A summary of the values monitored is presented in Table 24.

The AC load, voltage, and current are constant, as is the DC power supplied by the batteries. As shown in Table 24, the battery voltage is changing, and the current changes in an indirectly proportional way such that the DC power input to the inverter remains constant. Moreover, the oscilloscopes confirm the aforementioned observations. The battery voltage in the beginning of the experiment (21:23) is 12.68 V. Then, until the sunrise, which was about 06:45 hours, the batteries are being discharged. This is shown by the lower voltage, 12.45 V, at 06:56 in Table 24. Until noon, it was observed that the batteries are being charged. This is also confirmed by the voltage of 14.44 V, which corresponds to the charging voltage, shown at 11:19. Later on, at 16:05, the batteries are already charged and their voltage is 13.88 V, which corresponds to the floating voltage. After 18:00, the batteries are getting discharged and this is confirmed by the lower voltage of 12.91 V at 18:38. At the end of the experiment, at 21:07, the batteries reach the lowest voltage, which is 12.76 V, as shown in Table 24:

Table 24. Summary of measurements obtained by the oscilloscopes.

|                  | Time  | DC<br>Current [A]<br>Ch.1 | AC<br>Current (rms)<br>[A]<br>Ch.2 | DC<br>Voltage<br>[V]<br>Ch.1 | AC<br>Voltage (rms)<br>[V]<br>Ch.2 |
|------------------|-------|---------------------------|------------------------------------|------------------------------|------------------------------------|
| Figures 117, 118 | 21:23 | 8.90                      | 0.752                              | 12.68                        | 119.8                              |
| Figures 119, 120 | 06:56 | 8.96                      | 0.760                              | 12.45                        | 119.7                              |
| Figures 121, 122 | 11:19 | 8.60                      | 0.753                              | 14.44                        | 120.0                              |
| Figures 123, 124 | 16:05 | 8.73                      | 0.756                              | 13.88                        | 119.9                              |
| Figures 125, 126 | 18:38 | 8.82                      | 0.753                              | 12.91                        | 119.5                              |
| Figures 127, 128 | 21:07 | 8.90                      | 0.755                              | 12.76                        | 119.7                              |

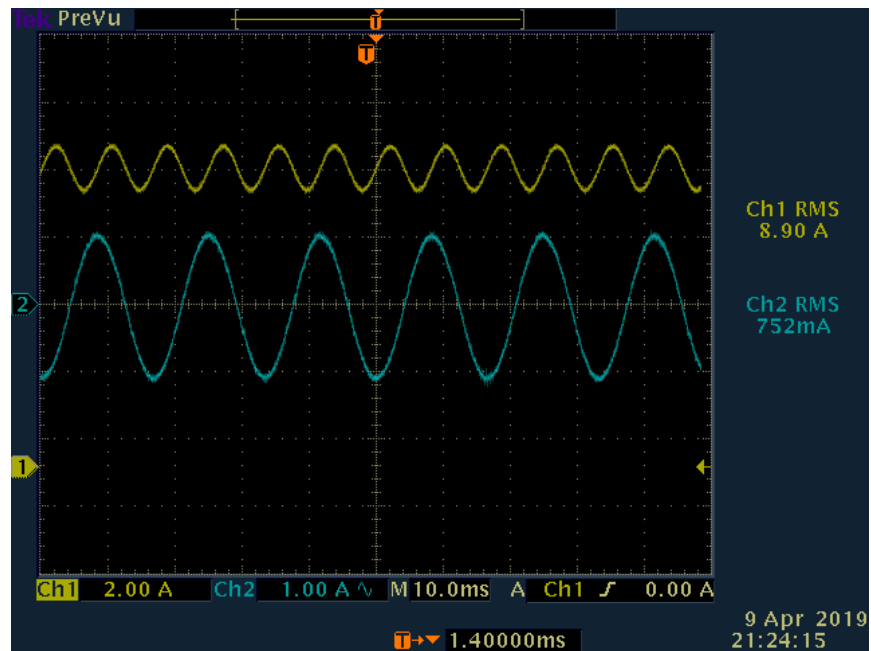


Figure 117. DC current (Ch1 [2A/div]) and AC current (Ch2 [1A/div]) at 21:24 hours (beginning of the experiment).

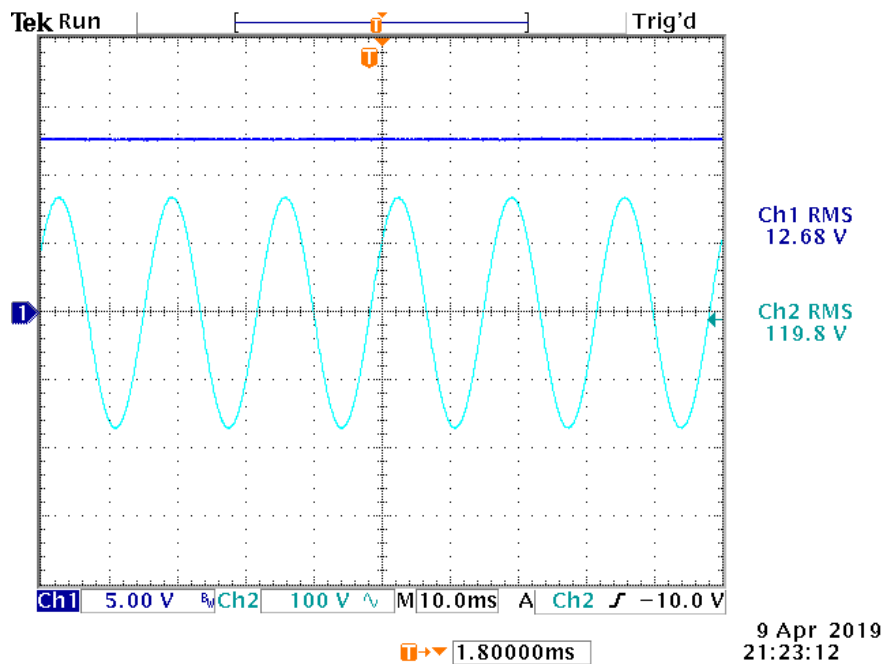


Figure 118. DC voltage (dark blue) and AC voltage (light blue) at 21:23 hours (beginning of the experiment).

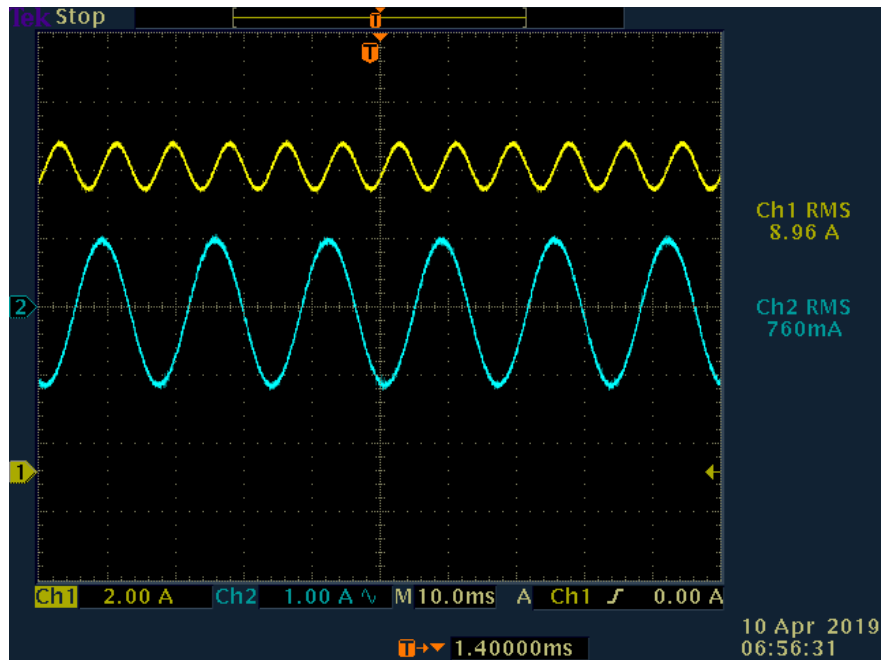


Figure 119. DC current (Ch1 [2A/div]) and AC current (Ch2 [1A/div]) at 06:56 hours (just at sunrise).

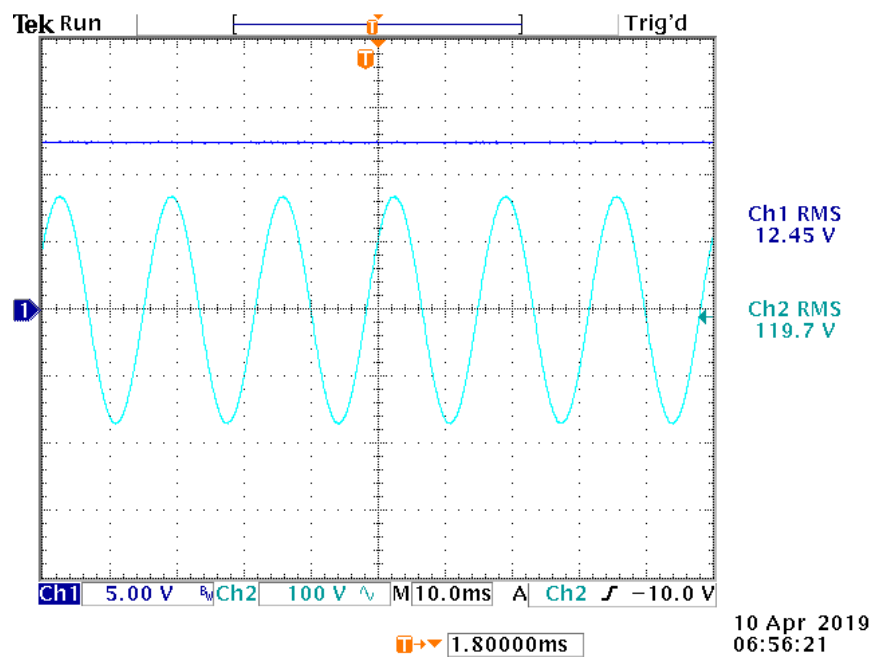


Figure 120. DC voltage (dark blue) and AC voltage (light blue) at 06:56 hours (just at sunrise).

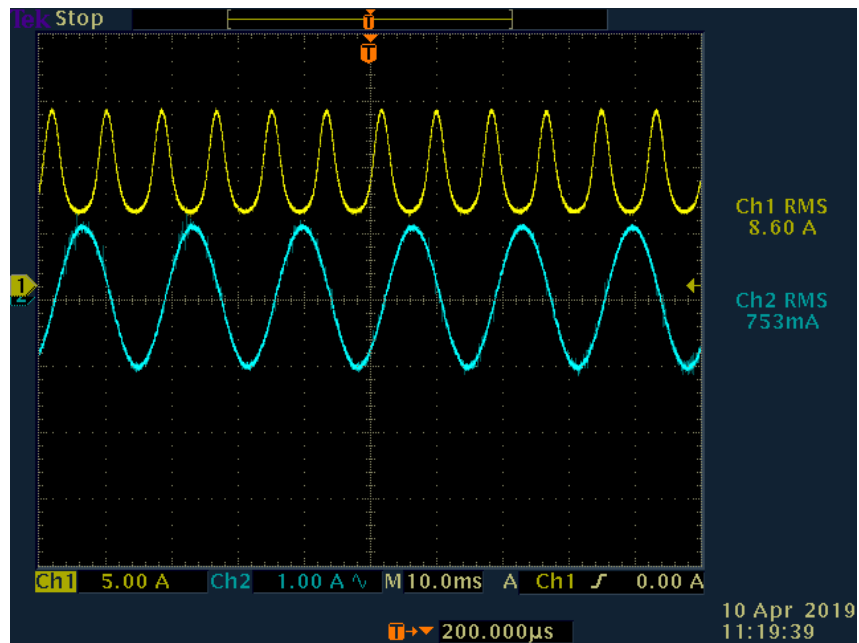


Figure 121. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) at 11:19 hours (almost fully charged).

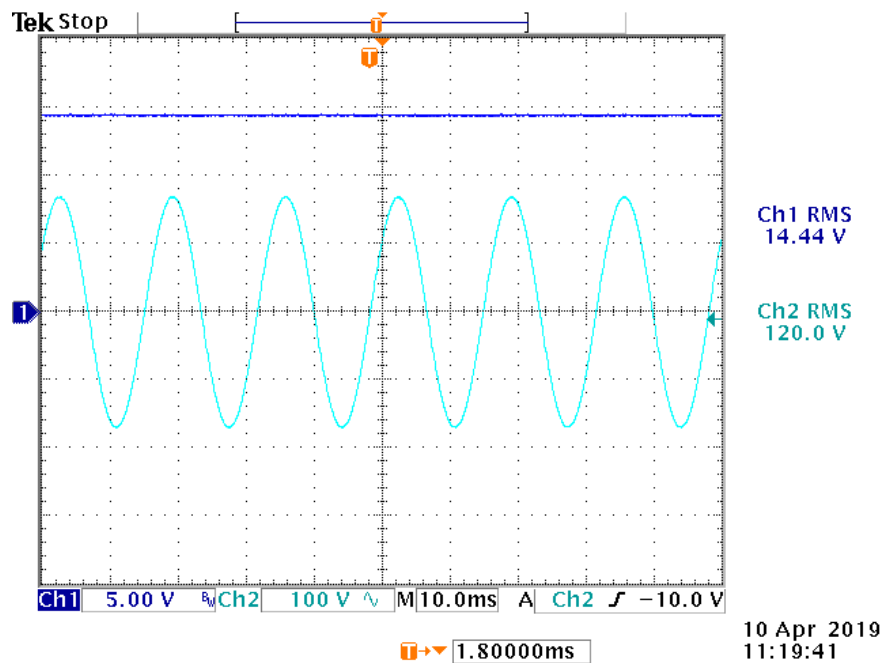


Figure 122. DC voltage – charging voltage (dark blue) and AC voltage (light blue) at 11:19 hours (almost fully charged).

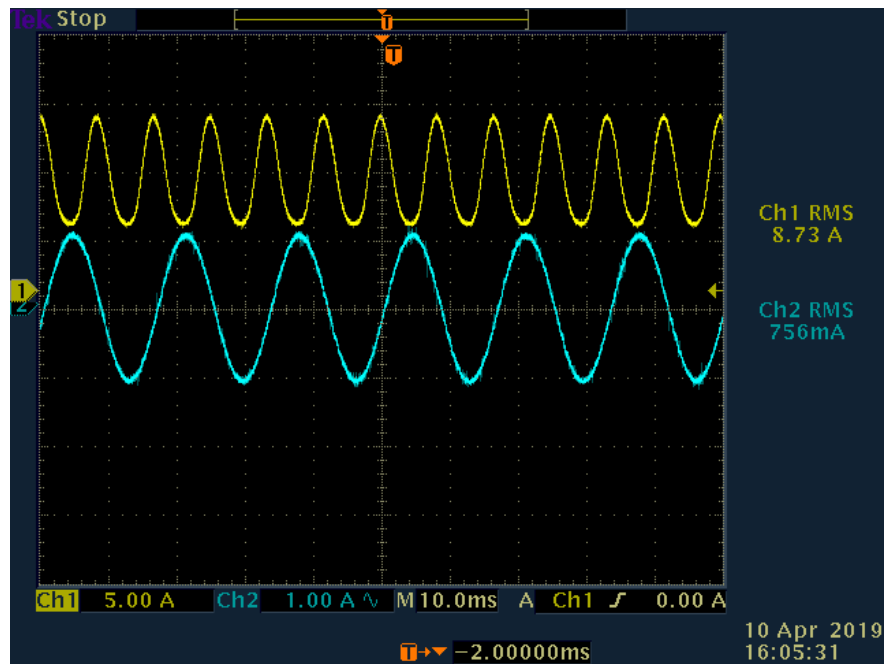


Figure 123. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) at 16:05 hours.

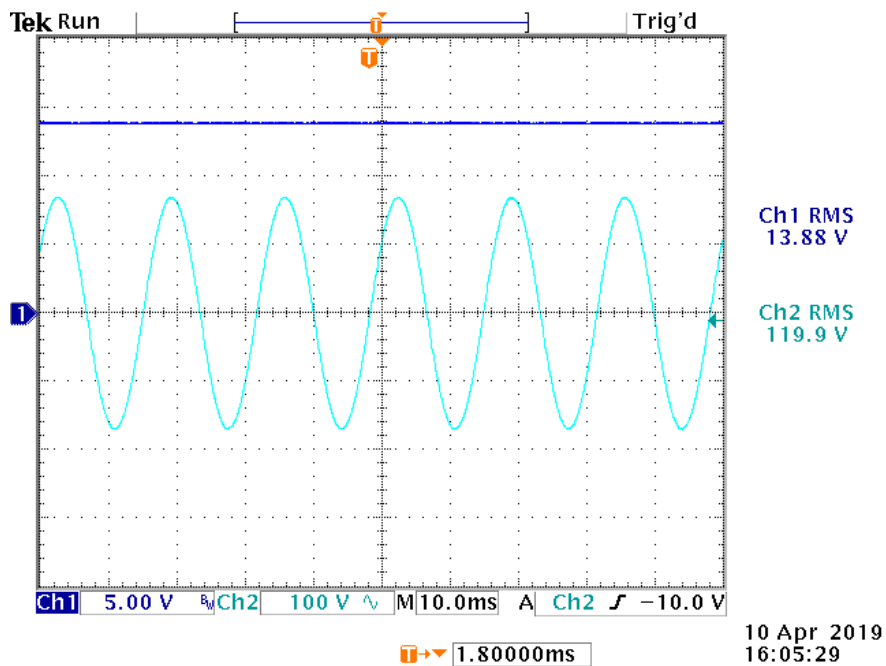


Figure 124. DC voltage – floating voltage (dark blue) and AC voltage (light blue) at 16:05 hours.

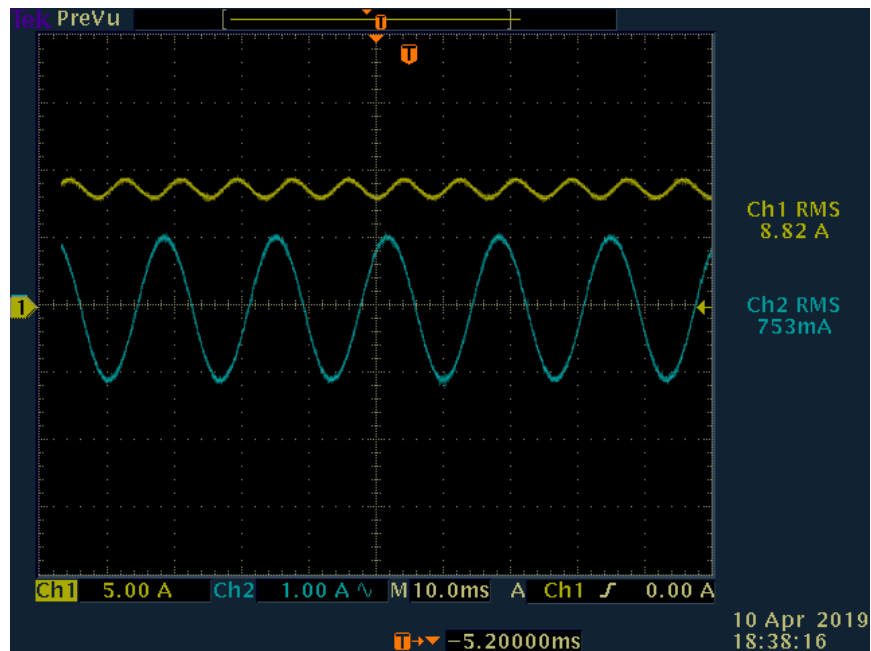


Figure 125. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) at 18:38 hours (just after sunset).

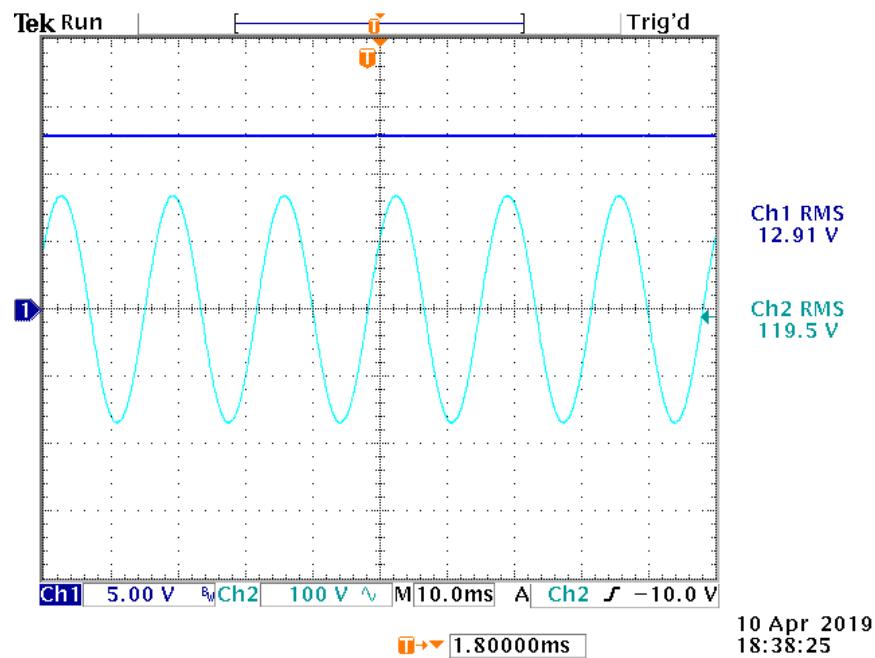


Figure 126. DC voltage (dark blue) and AC voltage (light blue) at 18:38 hours (just after sunset).

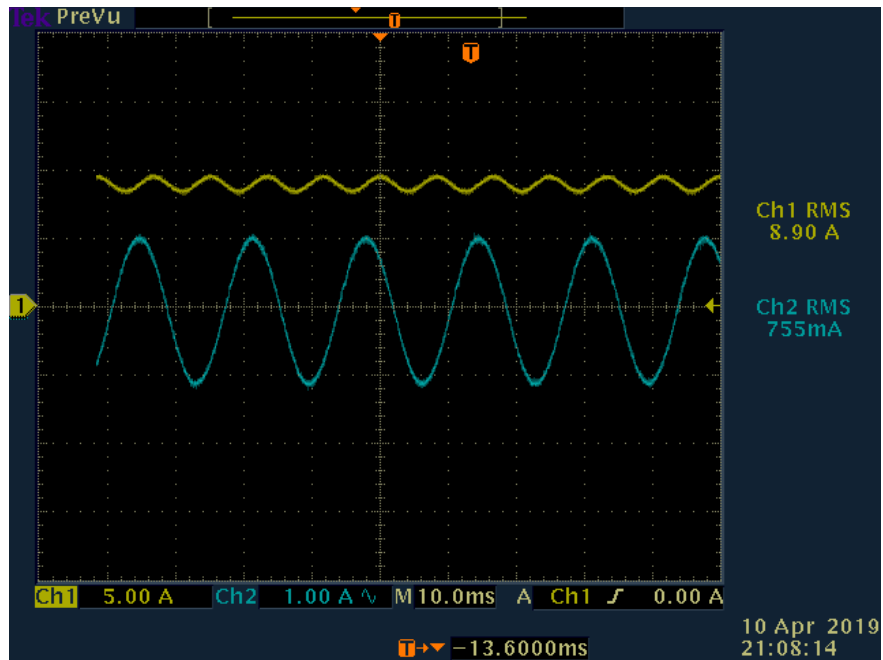


Figure 127. DC current (Ch1 [5A/div]) and AC current (Ch2 [1A/div]) at 21:07 hours (end of the experiment).

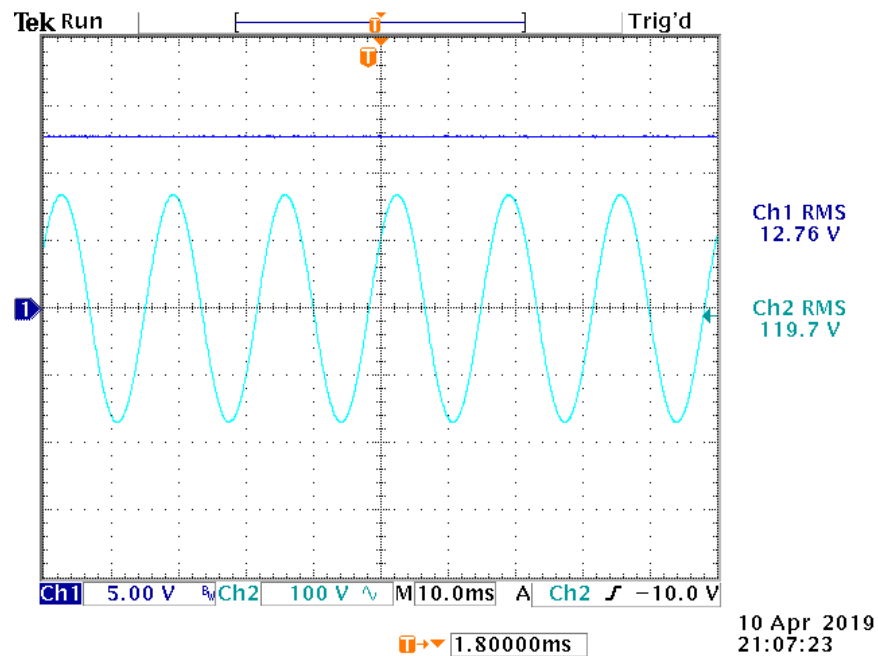


Figure 128. DC voltage (dark blue) and AC voltage (light blue) at 21:07 hours (end of the experiment).

Besides the measurements with the Fluke 434 and the oscilloscopes, three elog01 devices by Epever [70] were logging the data from the PV array, as mentioned before. The PV array output current is shown in Figure 129:

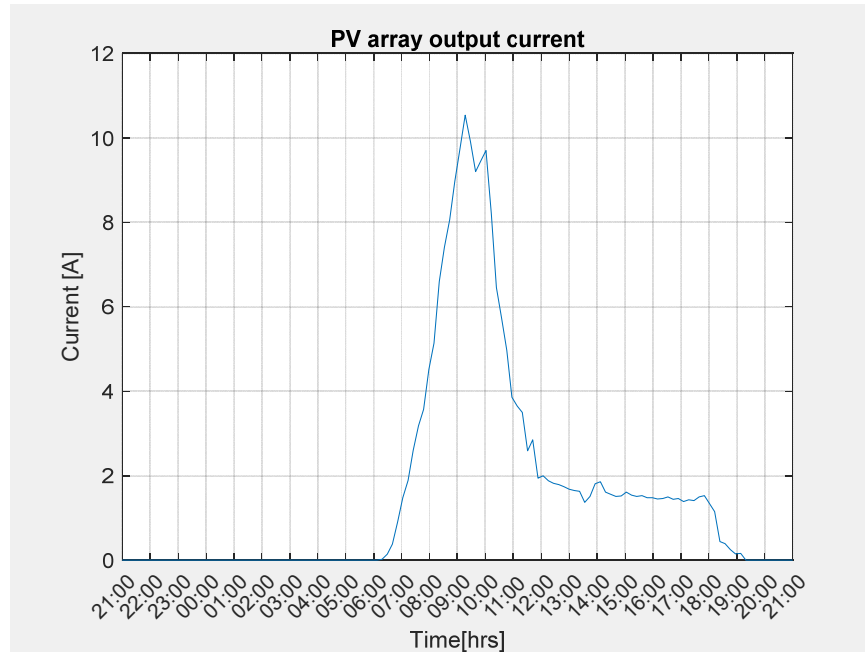


Figure 129. PV array output current (total).

The times of sunrise as well as the sunset, which were about 06:30 and 19:30 hours that day, respectively, are confirmed by the values of the current output. In addition, the peak of PV current output is observed at about 09:30, which is significantly reduced just after two hours to a value that holds until the sunset time (18:40 hours). It should be mentioned that this is the PV current output at the operating voltage of the array. Moreover, the PV array output power, as well as the mean operating voltage of the three parallel PV strings, is observed in Figures 130 and 131:

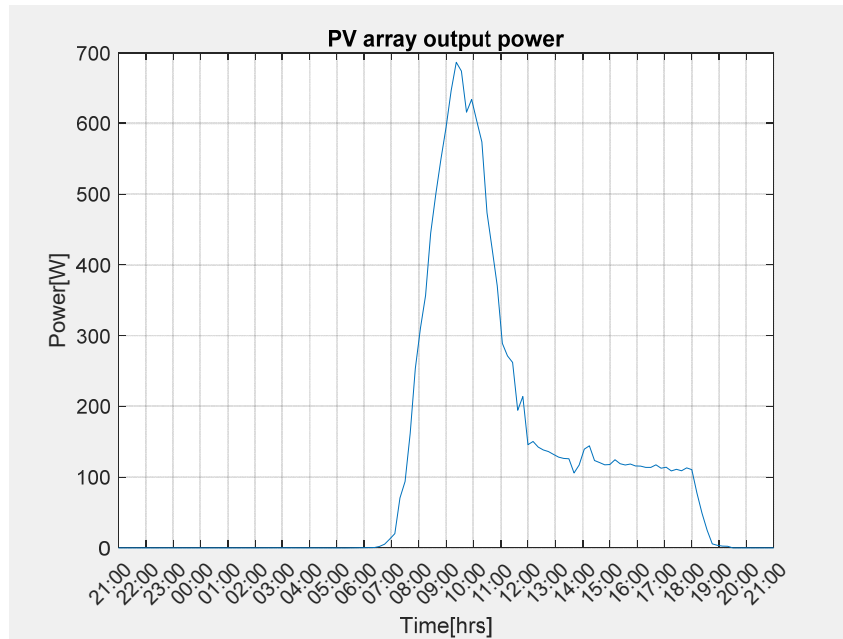


Figure 130. PV array output power.

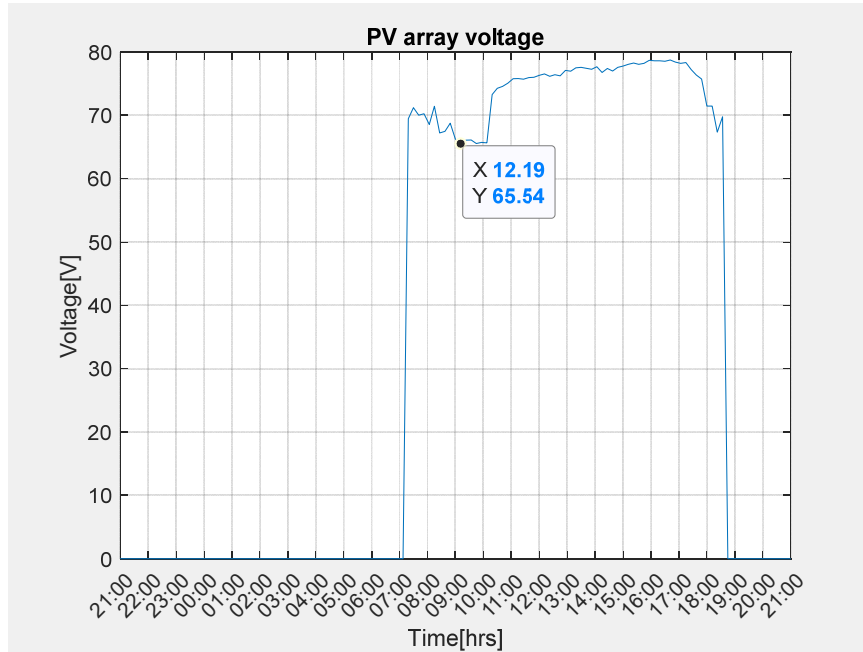


Figure 131. PV array operating voltage.

Observing the results obtained, we confirm that the shape of the power output is similar to, if not the same as, that of the current output, since the operating voltage is kept fairly constant, as mentioned in Chapter II. Besides that, it can be observed that the mean operating voltage of the three PV strings is more than the sum of the four maximum power point voltages (four PVs connected in series). This was expected, since the current produced by each parallel string was significantly less than the  $I_{mp}$ , and as it was also highlighted in Chapter II, the operating point should follow the I-V characteristic curve of the PV panel. Thus, the operating voltage of each PV string moves toward the open circuit voltage.

It should be noted that if sun-tracking PV mounts were used, additional power would be generated by the PV array. Nevertheless, these tracking mounts are expensive and the cost of them probably does not pay for itself for the additional energy generated. This suggests an interesting topic for future work: to implement sun-tracking PV array mounts in both simulations and experiments in order to estimate how much additional power would be obtained as well as the trade-off of this implementation.

The MPPT module is converting the power input, which is the product of the operating PV voltage and the PV output current, to a power output, which will be divided by the battery recharge voltage that was set in the MPPT controller and finally charge the batteries. The battery input current is shown in Figure 132:

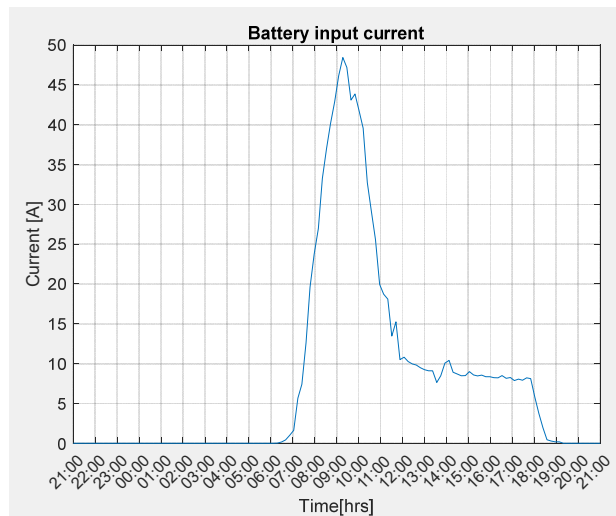


Figure 132. Battery input current.

Finally, knowing the battery input current as well as the battery output current, we can determine and plot the SOC of the batteries, as shown in Figure 133.

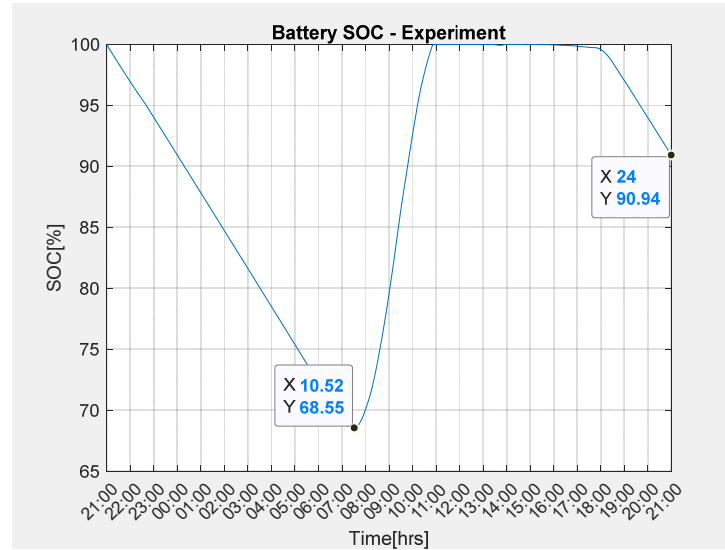


Figure 133. Battery SOC (experiment).

All experimental observations can be confirmed once again in the plot of the battery SOC. A little bit after sunrise, when the PV current produces more than the battery output current, at about 07:30 hours, the batteries reach their lowest SOC, which is 68.55%. From this time on, they start being charged until 11:00 hours, when they reach the maximum SOC, 100%. They remain fully charged and at the same time are able to supply the load until 18:00 hours, just before sunset, until they finally reach a SOC of 90.94% at the end of the experiment. Furthermore, it is noteworthy how fast, in just 3.5 hours, the PV array with a moderate A:L (1.1) achieves an increase of SOC of 31.45%.

Implementing the element parameters used in the laboratory experiment, in the program, as in Figures 134 and 135, we obtain the same configuration as the setup. Here, it should be reminded that since the use of MPPT modules is based upon the PV array wattage, the configuration can be adjusted depending on the MPPT modules specifications. This means that the configuration of one series of 12 parallel PV panels, as the program suggests, can be adjusted to four series consisting of three parallel PV panels each, as in the laboratory experiment.

**Inputs**

**Input Parameters**

AC Load [MWh/day] 0.218

Peak-Sun Hours(PSH) [kWh/m²] 4.12

Required Usable Storage [days] 1

**Parameters of the Elements Used**

Inverter Efficiency 0.85

System Voltage [V] 12

Battery Type Lead Ac...

Battery Voltage [V] 12

Battery Capacity [Ah] 100

Temperature [C] 20

Maximum Power Point (MPP) Voltage 16

Maximum Power Point (MPP) Current 6.25

Use of MPP Tracker Yes

Array-To-Load-Ratio 1.1

Calculate Help

Figure 134. Window with inputs.

**Outputs**

Nominal Battery Capacity [Ah] 300

Total Number of Batteries 1 x 3 = 3

Total Number of Modules 1 x 12 = 12

Output of the PV panels [Ah/day] 263

Run Simulation

Figure 135. Window with outputs.

Since the laboratory experiment was purposely started at 21:00 hours, the simulation results also start from 21:00 hours. Here, it should be mentioned that the PV

output is the maximum possible, if the PSH of the day is going to be 4.12. The outputs of the simulation are observed in Figures 136 to 138:

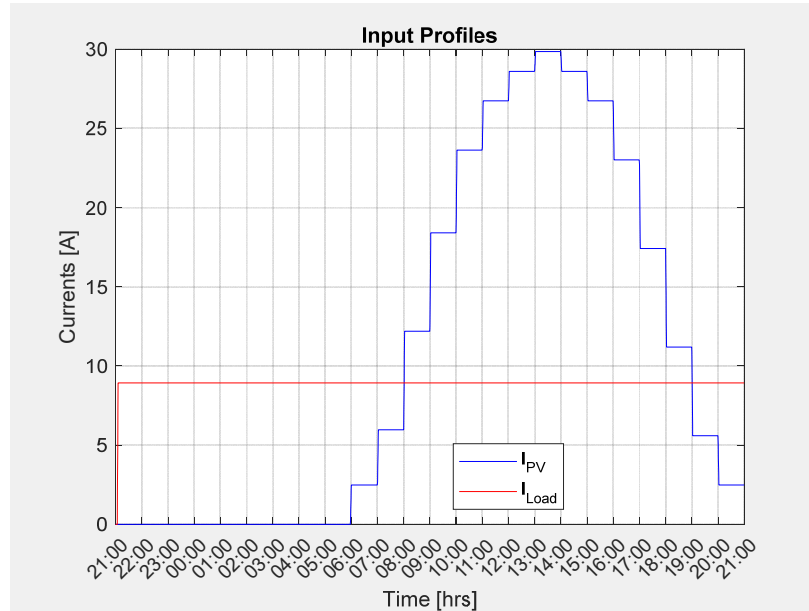


Figure 136. Input profiles.

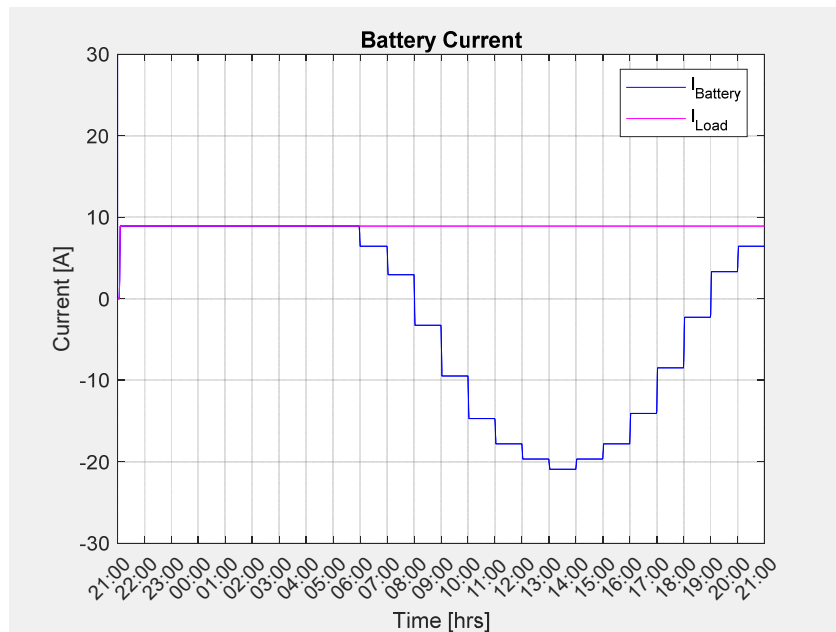


Figure 137. Battery current.

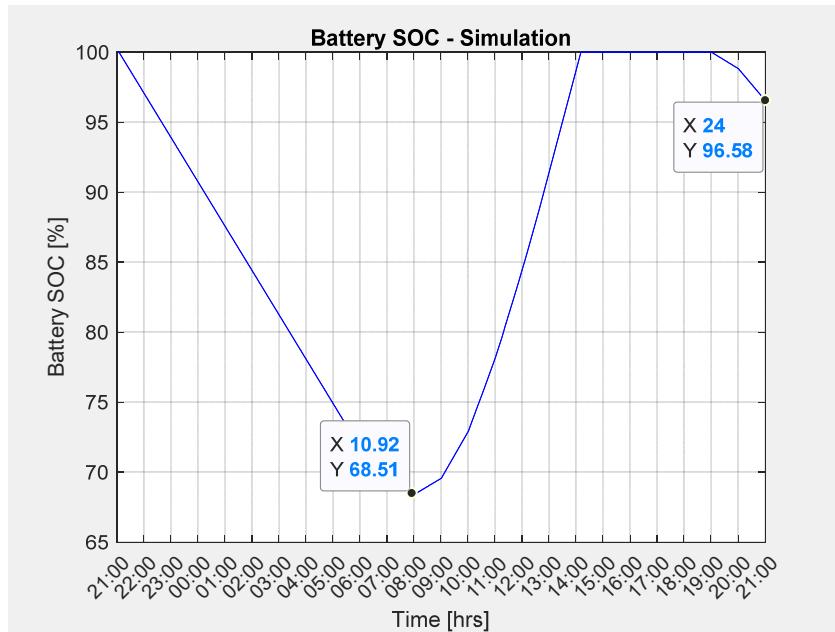


Figure 138. Battery SOC (simulation).

Plotting the curves in Figures 133 and 138 on the same plot, we obtain Figure 139:

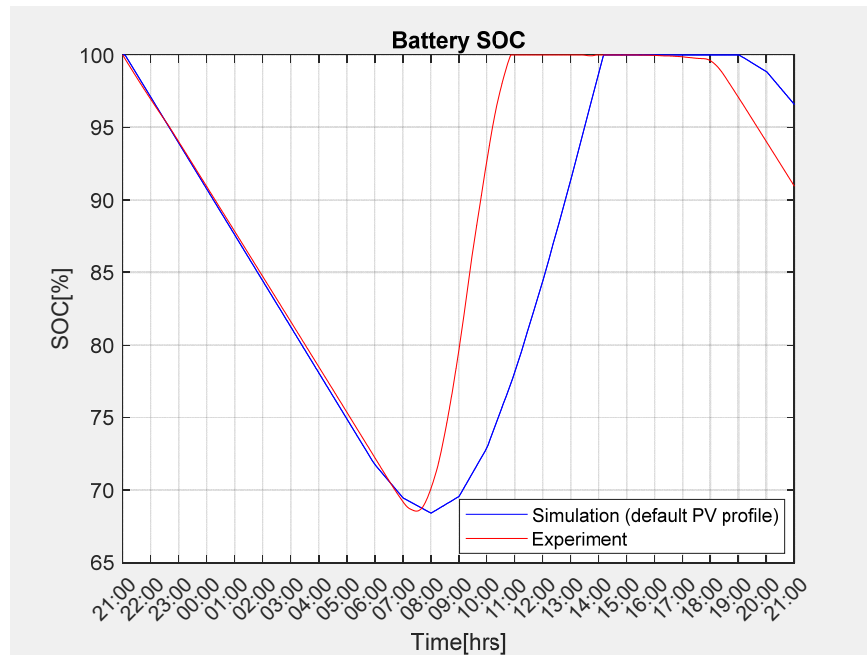


Figure 139. Battery SOC (simulation with default PV profile vs. experiment).

Observing the obtained results, we conclude that the battery SOC is similar to the one in the experiment, as far as the shape is concerned. The basic difference can be addressed in the time needed to fully charge the batteries, which is about six hours; that is, from 08:00 to 14:00. This is because the PV current implemented in the model, being closer to the reality, is gradually increasing until noon, while in the experiment the solar radiation was high until about 09:30 that day and then it dropped to one fifth already at noon! Another difference is that the PV current in the simulation profile ends at 21:00 hours to account also for sunset time during the summer. And this is actually the reason that, even if the PV current is considerably low at these times, it can keep the batteries' SOC at the value of 96.58% at the end of the simulation (21:00).

Implementing in the simulation model the actual PV current of the day of the experiment, as the three log devices measured, we can obtain the following results shown in Figures 140 to 142.

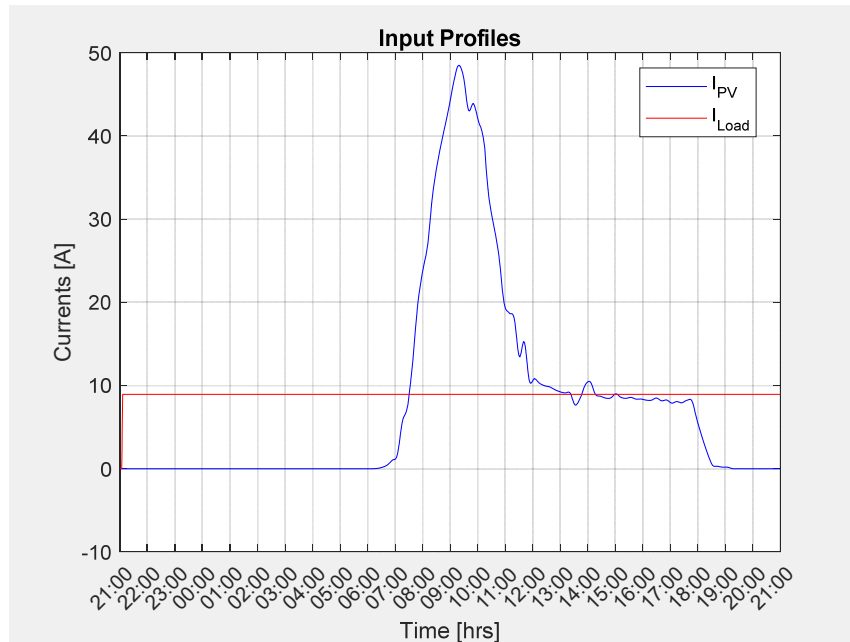


Figure 140. Input profiles.

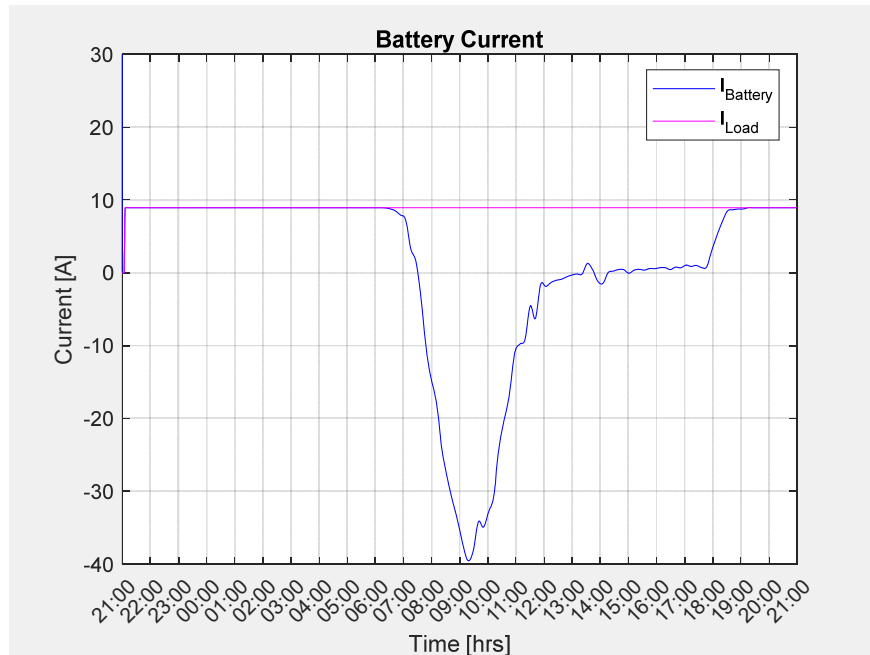


Figure 141. Battery current.

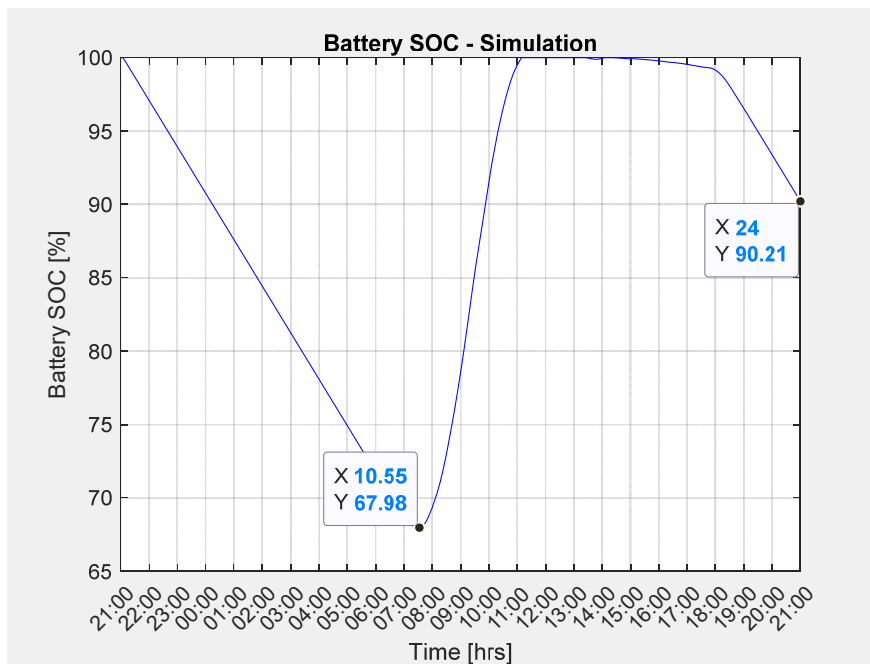


Figure 142. Battery SOC (simulation).

The matching of the plots of the battery SOC in the experiment and the simulation validates the model.

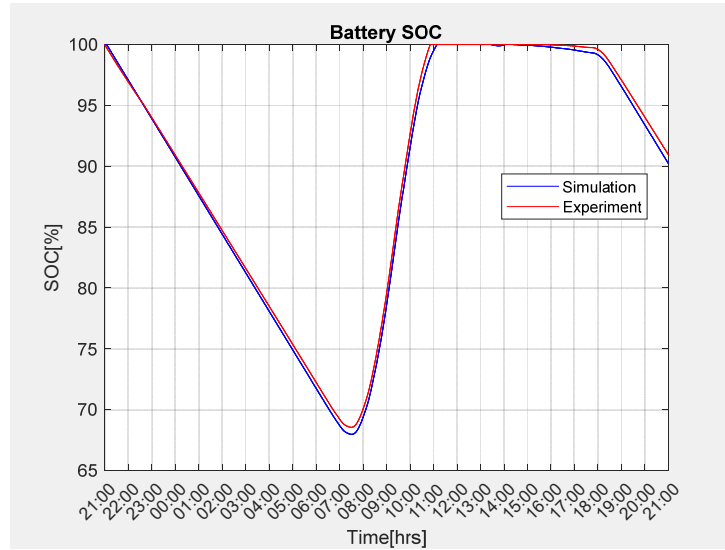


Figure 143. Battery SOC (simulation vs. experiment).

The same final SOC can be also confirmed by the curve relating the  $V_{oc}$  with the SOC of these batteries. After letting the batteries rest in open circuit for 12 hours, the  $V_{oc}$  measured 12.75 V, as shown in Figure 144.

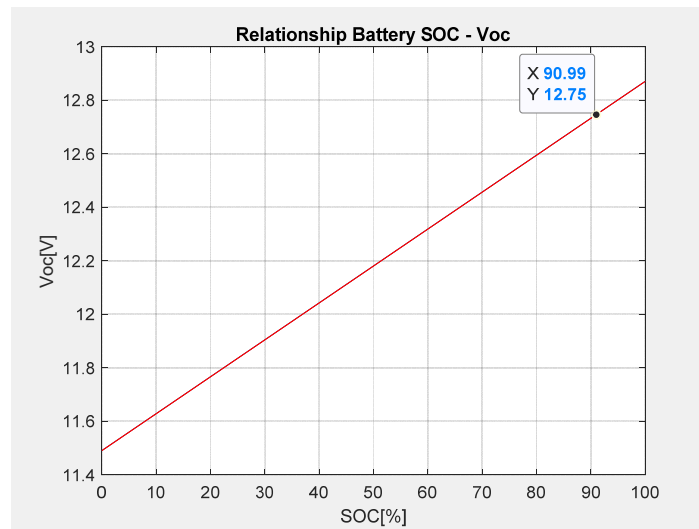


Figure 144. Battery SOC (open circuit voltage method).

## **VI. CONCLUSION AND RECOMMENDED FUTURE WORK**

In this chapter, we present a summary of the validation of the design program created for this thesis using simulations based on the output calculations, as well as the experimental results. In addition, several thoughts for future work are recommended.

### **A. CONCLUSION**

Energy security for naval facilities is of great strategic importance. The main concept of energy security in a naval facility is the ability to supply critical loads reliably, indefinitely, economically, and in an environmentally friendly manner (sustainably).

Renewable sources provide availability, affordability, and accessibility, as well as acceptability—the four A’s of the energy security concept [1], [7]. Consequently, renewable sources constitute the main component of energy security. Combining renewable sources with an energy storage system is considered a valid approach to provide energy security. Implementing this approach in a naval facility can support the critical loads with reliable and sustainable power indefinitely, successfully providing full-time mission support.

The objective of this thesis research was to create a user-friendly design tool that enables users to size a stand-alone power system properly and accurately in order to meet the critical load demands of a naval facility. Even in cases where the power system is connected to the grid, the developed tool eliminates the threat of an unreliable and occasionally unavailable commercial grid, which allows for continuous mission support.

The design software developed in this research can assist system designers and users in sizing stand-alone power systems, whether such systems are aimed to provide energy security in a naval facility, a commercial/industrial facility, or even a residential facility. The developed tool complies with both IEEE Standards 1562 and 1013 [20], [21]. In addition to these guidelines, the design tool considers important factors that both standards should address in their future revisions.

Secondary objectives are included in the evaluation of the sizing methodology using both simulations and laboratory experiments. Several case studies were simulated using a Simulink model based on the outputs of the design program. Finally, the method of designing the off-grid power system was validated by successfully conducting 24-hour laboratory experiments, the results of which confirm the simulations as well as the accuracy of the sizing methodology; this is a significant feature that many sizing programs lack.

## **B. FUTURE WORK**

The design tool presented, unlike others, is fully editable and available to research groups for optimization. All other design tool codes are not available, and most of them do not even mention the computations that are implemented. A team of research engineers is already working on optimization of different aspects of this design in order to provide resilience in naval facilities. Having a tool that is completely editable is of great advantage for the achievement of such a goal.

Besides this work that is already in progress, there are several recommendations for future work to be accomplished as a follow-up to this thesis research.

First, the simulation model should be able to support the importing of different 24-hour load profiles through specific parameters requested in the design program. Several approaches to achieve this capability have been documented, such as [48]–[50] with a view to generating synthetic load profiles. Once this is implemented, the load profile will be more randomly created, but at the same time customized according to user or designer's needs, at least as far as the profile general shape is concerned.

Moreover, advanced algorithms or fuzzy logic systems [62]–[64] can be developed in order to achieve a cost-effective HESS, where SCs are basically sized according to the form of the contextually load profile.

Furthermore, a multi-objective optimization can be conducted using a non-dominated sorting genetic algorithm (NSGA-II) for the optimal configuration of the PV array and battery such that it will reflect the solar radiation of the location, based on solar

radiation utilization [75], [76], and at the same time achieve the resilience and reliability at the lowest possible initial acquisition cost.

Finally, sun-tracking PV array mounts can be implemented in both simulations and experiments in order to estimate how much additional power would be obtained, compared to the use of fixed PV array mounts, as well as the trade-off of this implementation.

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