UNIVERSITAT POLITÈCNICA DE CATALUNYA
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INTEGRATION OF A PB-ACID BATTERY MANAGEMENT ALGORITHM WITHIN THE OPTIMIZATION OF PREDICTIVE CONTROL STRATEGIES FOR A CONNECTED MICRO GRID

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by

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Title of the thesis: Integration of a Pb-acid battery management algorithm within the optimization of predictive control strategies for a connected micro grid.

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Abstract

Within the framework of microgrid systems, ESS (energy storage systems) are becoming essential in developing relevant markets in the use of more renewable sources and for Smart Grids. ESS are projected to strengthen grid resilience by solving complications such as hourly variations in demand and price, excessive power fluctuation and lack of energy supply that are related with the instability of renewable energy sources.

Then, the preservation of the battery lifetime infers a starting point in the development of an ESS. It comprises everything related to the electrical system, where the critical inconvenient consist on dealing with the different charging process of the batteries, which consist on applying three stages: Bulk, absorption and float.

To address this problem, with the aim of providing a viable solution, this project introduces an ESS control algorithm within the optimization control strategies minimizing cost functions for a microgrid system. The proposed solution is established on a modification of the optimization strategy for adding absorption and float stages after each bulk charge to preserve the battery lifetime. Where, as a part of a tertiary control system, theses stages are estimated out of the optimization program to reduce computation complexity. Taken a look at the simulation results and at expenses of only a slight cost function increase, it has been confirmed the feasibility of this procedure. These growth of the cost function can be assumed to preserve the battery lifetime.

Keywords

Energy Storage System; Renewable energy; Batteries lifetime; Control Algorithm; Optimization Strategies.

Dedication: To my family and Anes…

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1. Introduction: application framework and objectives

1.1. System under study

The worldwide energy scenario is experiencing significant changes, energy requirements are increasing rapidly, reaching high new levels. The progressively emigration from large scale with traditional generation to systems that are more flexible represents a change in the paradigm of centralized electric power generation. In addition, technological evolution and the continuous less dependency on fossil resources are increasing the support on renewable technologies such as solar, mainly weather-dependent.

The continuous monitoring and balance between generation and consumption are motivating changes in the operation and configuration of the entire power grid. Consequently, large generation plants coexist with local generation technologies, storage devices and power electronics based controls.

The MED-Solar (Machrek Energy Development-Solar) initiative, a particular case where this work focus on, is aimed at reducing back-up diesel generators fuel consumption in the Machrek area (Lebanon, Palestine and Jordan) where the mains is severely affected by frequent black-outs. This reduction was carried out by building a microgrid, which integrates photovoltaic solar generation and an Energy Storage System (ESS) to the pre-existing electrical facilities composed by back-up gensets and the mains [1].

The configuration of the microgrid analyzed in this project is shown in Fig. 1 and includes two types of elements [2], referred as shows table 1, namely:

TABLE 1. MICROGRID CONFIGURATION

MICROGRID CONFIGURATION

Device	Controllable	Pre-Existing
Diesel generator and its control unit (Automatic Control Switch).	✔	✔
Photovoltaic (PV) generators and their inverters.	✔	-
Commercial Inverter/Battery charger (BC) to manage the stored energy (includes Pb-acid battery bank)	✔	-
Power Switch for main power supply selection.	✔	✔
Critical and non-critical AC loads connected to different AC buses to assure the critical loads demand.	-	✔
Grid energy supply	-	✔

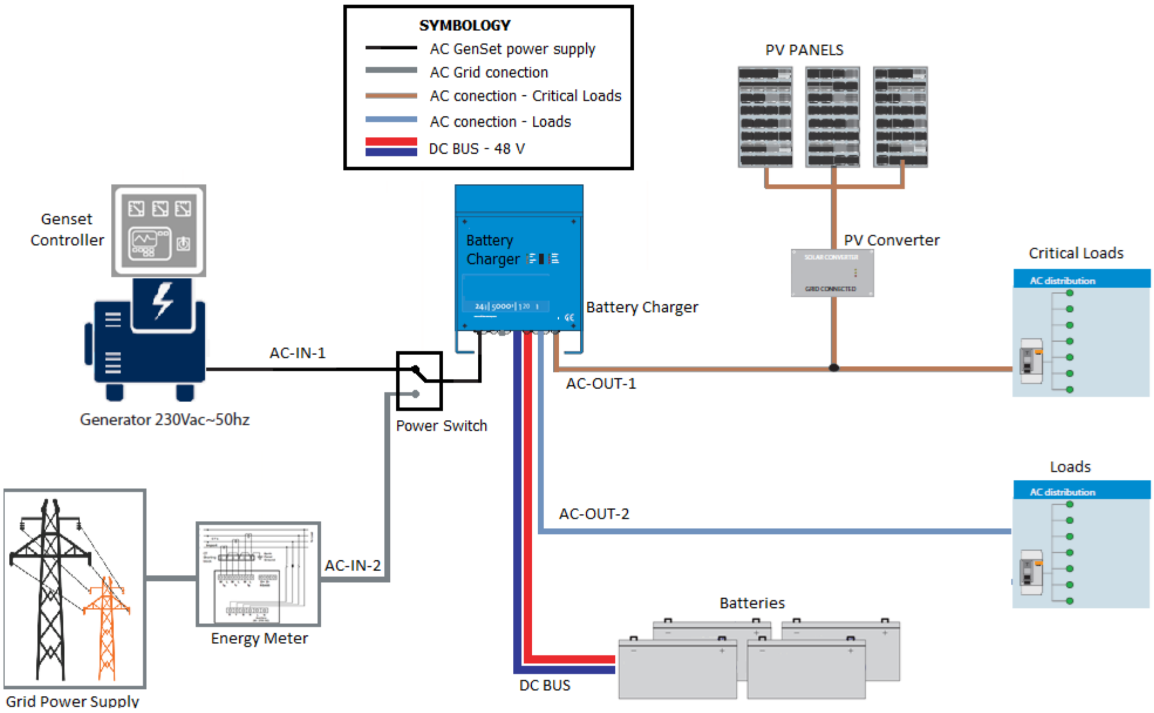


Fig. 1. Microgrid configuration

The voltage of the loads bus is set either by the mains, the genset or the BC whereas the PV inverter acts as a current source. This inverter is connected to the critical loads AC bus to contribute to satisfy their demand when neither the grid, nor the diesel generator are available.

A design of an Energy Management System (EMS) is required to properly schedule the power flow among the elements of the microgrid in order to satisfy the load demand at a minimum cost and to provide general solutions to the micro-grids management. The EMS design often incorporates energy optimization programs that minimize a certain cost function. These programs are formulated as constrained optimization problems, whose solution can be conveniently found through computational environments such as GAMS [3]-[4] or AIMMS [5].

1.2 EMS Description

One of the main technical problems that deal with the safe and economical operations of the microgrid is the control and energy management of all the devices. The EMS offers a solution for the energy administration. It gives the tools to increase the availability of the grid, to respond faster and more effectively to the energy balance of the network and react against malfunctions, to reduce the risk of system disturbances and outages [6].

The EMS considers several constraints as the physical operating limits of the energy system (technical characteristics of the microgrid elements, grid parameters and modes of operation), as well as the information from forecasting systems (e.g., load demand, solar radiation) in order to determine the optimal energy profiles of the resources to minimize a pre-defined cost function [7]. This allows to swiftly adapting the electric power system to new conditions. The technical and innovative concepts ensure that the network control system will continue to meet the requirements well into the future.

It also provides the instructions to the controllers for all the manageable devices, such as generation sources, energy storage systems and intelligent loads, supporting the two microgrid mode operations (connected or isolated to the grid) [8], see fig 2.

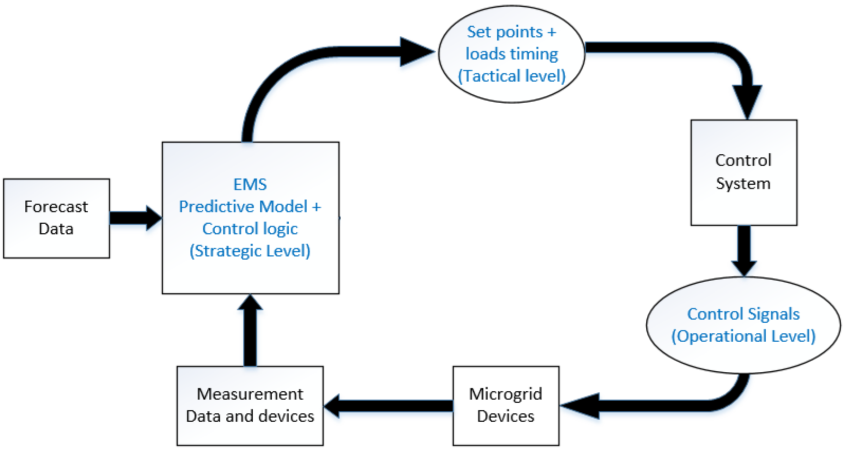


Fig. 2. EMS general scheme [7]

The configuration proposed in the MED-solar project corresponds to a connected microgrid. Where the implementation of an EMS plays an important role managing a cluster of several conditions and inputs that interacts according to a logical pre-set scheme that is processed in such a way the result is an optimal operation of the microgrid devices.

Then, a central controller that is at the head of the hierarchical control system is embedded into the grid to be on charge of the managing and controlling the microgrid, see fig 3.

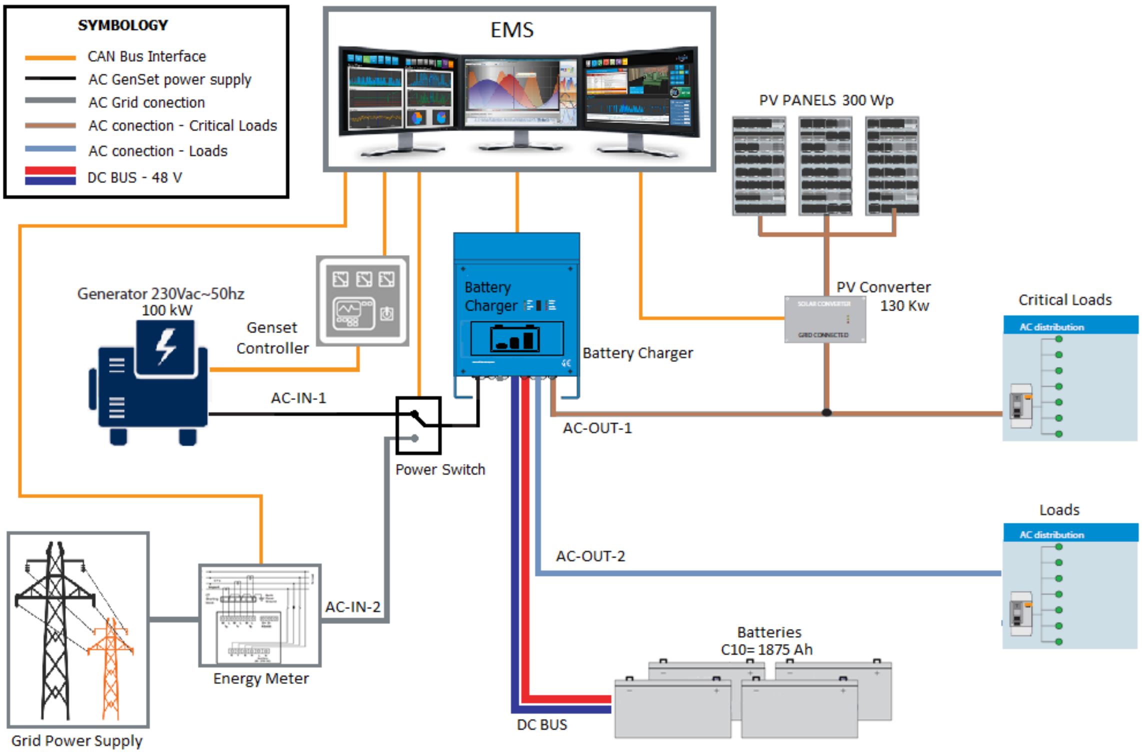


Fig. 3. Proposed Microgrid configuration of the MED-Solar Project

When the microgrid operates connected to the public distribution system, the network will provide the necessary voltage and frequency references so that all other generation elements of the microgrid work without any problems. Thus, when it operates connected there are no stability problems. If the microgrid is isolated, all the reference values will be given by the main power source, the diesel generators.

After solving the energy dispatch, the EMS sends to the suppliers and the loads controllers the active and reactive power commands as well as the signals to those loads that must be kept in service and those to be disconnected.

Moreover, the EMS must verify that none of the technical restrictions imposed on the microgrid are missed. This also, allows a much more efficient maintenance of all the components in the microgrid, which includes the implementation of remote management solutions. These characteristics can be helpful in sizing (of the microgrid) related problems.

As a result, the EMS gives the corresponding energy profiles to the controllable power elements of the microgrid to minimize the cost function.

These orders are placed at the highest hierarchical level of the microgrid control and are usually given in hourly / several minutes' time scales by setting the power / energy references of the controllable elements over the time. The predictive model makes evident the needs of forecasting and data collection systems that provide relevant information to perform the optimizations.

1.3 Operation of the EMS

Since the EMS maintains a constant communication with all the elements of the microgrid, the supervision can be done in real time in order to create a direct link to the implementation of a smart energy system.

In this project the time horizon is one day with hourly intervals and the output variables of the EMS are the PV energy prevision to be injected into the microgrid, the energy production of the diesel generator, the energy exchange with the mains, the energy exchange with battery bank, the prevision of the battery SOC and the hourly energy to supply the loads, a see in figure 4.

The EMS input information is (in green):

- The forecast of the renewable energy generators output for the given time horizon (usually one day) divided in N consecutive periods (usually 24 hours).
- The loads energy demand in the following consecutive n-periods.
- The State of Charge (SOC) of the ESS.
- The operational limits of non-renewable energy generators.
- The state of the loads.
- Operational limits of generators and ESS.
- Grid energy supply limitations.

The output information is (in blue):

- Set points for the control system for each manageable source.
- Control signals to connect or disconnect loads.
- Energy scheduling for generators.
- Battery charging and discharging profile

Restrictions (in red):

- Market prices (Mains energy cost prevision, diesel, etc.)
- Cost function included in a deterministic model of the microgrid energy management.
- **Battery management algorithm.**

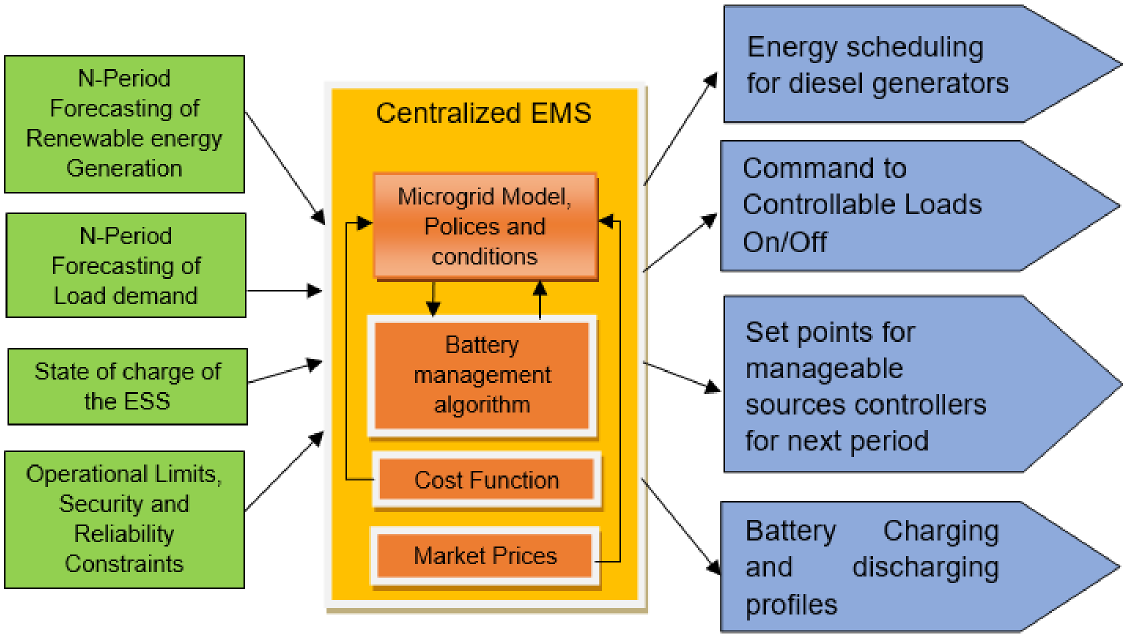


Fig. 4. EMS general scheme [2]

1.2. EMS Program optimization

The optimization program determines the ideal schedule of the elements minimizing a cost function, over a pre-specified period (horizon) with a pre-specified time granularity (usually, a day period with time slots of 15 minutes to one hour [9]).

In grid-connected systems, it is assumed that consumers are invoiced at the local market prices. The problem of the optimization is expressed according to the implicit market policy, which exploit the revenue from the consumed energy. Then, the microgrid can be analyzed as a bidirectional energy system, where positive flux of current is transmitted from the grid to the microgrid in order to supply the loads or to charge the batteries and negative flux of current is transmitted from the microgrid to the grid power supply. This means that the purchase or sale of energy to the main electricity grid must be considered. Because of the limited capacity of the transmission line between the grid and the microgrid, the input/output of this bidirectional system is restricted.

Once all these variables are introduced, the optimization is performed according several conditions and inherent limitations of the system. The EMS architecture is shown in Fig. 5

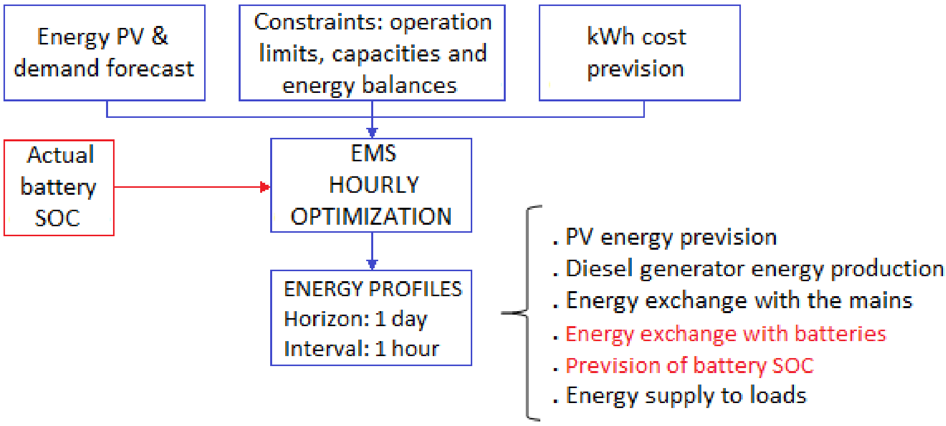


Fig. 5. EMS classical architecture

In this regard and specifically related to the energy storage system which is highlighted in red at the figure 5, a typical hourly EMS architecture must include the battery modelling and consider the basic battery restrictions (SOC-state of charge- within a range and hourly energy balance of the ESS [9], [10] and [11]).

A typical energy profile evolution given by the EMS, is shown at figure 6.

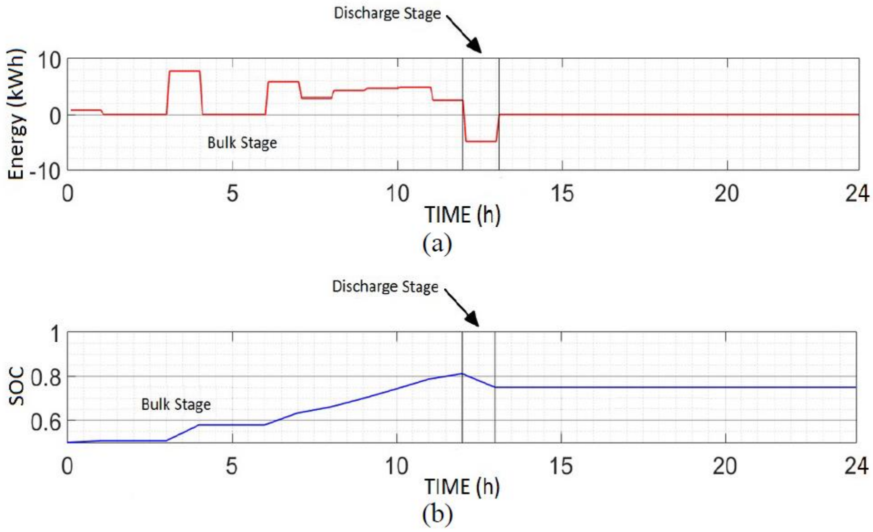


Fig. 6. EMS energy profile prososal (a) Hourly charge / discharge energy profile (b) SOC evolution

1.3. EMS limitations

Usually, these optimization programs do not take into account the limitations imposed by the processes of charge and discharge of the storage element (battery bank) for its lifetime preservation, which consist in group of phases defined as: Bulk, Absorption and Float, see fig. 7.

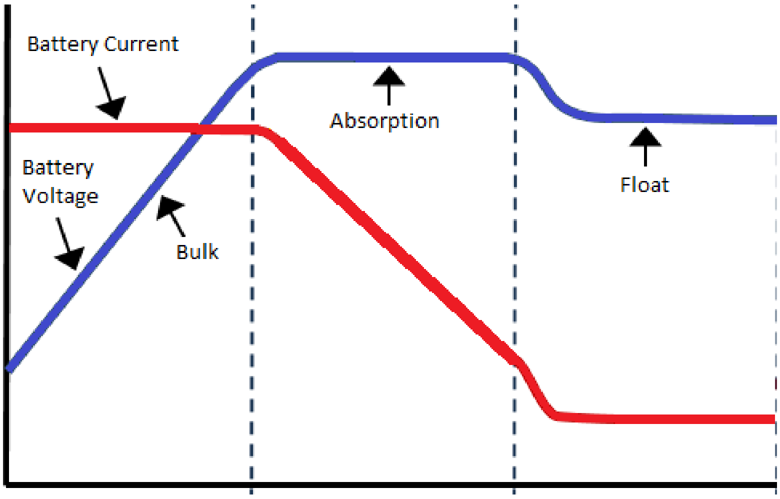


Fig. 7. Battery charging process [11]

The main reason why these processes are not integrated into the optimization programs is their high complexity characterized through highly nonlinear models. Similarly, the operation limitations (found in the manufacturer's datasheets) of commercial inverters/battery chargers of the microgrid are not taken into account by the optimization programs.

Based on the premise that, because of the highly computation complexity [12], [13], [14] and [15], the optimization softwares are not compliant with the modelling algorithms, this results in an hourly schedule that is not compatible with the BC operation modes, in particular, this equipment cannot process the power set points given by the optimization program, which in turn, has not taken into account the BC operation requirements to protect the battery bank.

These characteristics highlight the necessity to manage in a proper way the energy that is being stored, in order to reinforce power networks and maintain load levels.

Consequently, to implement a solution that takes into account the dynamics of the battery restrictions and charging process and to avoid convergence related problems, the decision-making sequence must be modified, then at the strategic level of the EMS hierarchy structure, the battery management algorithm must be managed as an external entity as seen in fig 8. It is supposed that energy storage system, adds external conditions and specific new data, in terms of energy requirements, to the core of the hierarchy structure with the purpose of adjusting the final optimization solution.

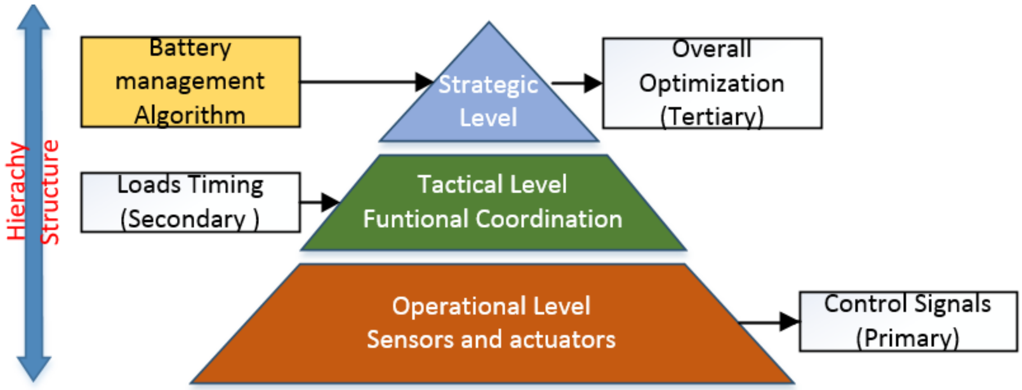


Fig. 8. EMS hierarchy structure

Therefore, the application of the optimization conditions should also be conducted by the objective of decreasing the excessive workload of the EMS, then the task related to the ESS can be calculated in a third party situation.

Then, the management algorithm optimizes the relevant parameters defining the ESS so that the feed-in of electricity into the grid can be controlled to fulfil the conditions given by the EMS.

Objectives:

Therefore, this work proposes on one hand a modification of the EMS optimization algorithm to include time intervals in the battery-bank energy profile ensuring a proper charge/discharge process of the ESS. On the other hand, from the knowledge of these available time intervals the work proposes a control algorithm for a commercial battery-inverter set (ESS: Energy Storage System) based on charge/discharge analytical models. This control algorithm is computed out of the optimization program and delivers an energy profile compliant with the charge/discharge requirements of the battery bank, thus preserving its lifetime. Moreover, this ESS energy profile reasonably approximates the cost function minimization.

The organization of the work is as follows: chapter II describes the ESS modelling and the battery charging process. Chapter III defines the control problem, its influence on the EMS and the control algorithm, whereas Section IV presents the simulation results of a case of study and analyses the Battery charger selection. Chapter V defines the communication issues between the battery charger, the EMS and the algorithm solver. Chapter VI and Chapter VII introduces the budget and environmental impact of the project, respectively. Finally, Section VIII details the conclusions of this work and suggests further research in this field.

2. ESS – Modelling

2.1. Lead-acid Batteries

There are several alternatives to rechargeable batteries in the market, they are produced in many different shapes, magnitude and energy capacity. Among them, lead–acid are the most used in not-compact size applications. Their low manufacturing cost and their high surge current levels make them common where the capacity is more important than weight and handling issues.

The PB-acid technology consist of several flat lead plates immersed in an electrolyte (distilled water is normally used for this purpose), where the plates conform numerous two volt cells that are the basic element in the batteries configuration.

The main advantages consist on their high specific power and low self-discharge characteristic, on the other hand the principal disadvantages are their low specific energy, slow charge process and limited cycle life. However, regardless of these limitations Lead acid batteries are still being specified for microgrid applications because of the cost and the large developed technology behind them.

2.1.1. State of charge

The State of Charge (SOC), is the available battery capacity remaining and corresponds to the instant measure of the accessible energy of the battery expressed as a percentage of a reference, usually a full charged battery, which must be updated periodically, see fig 9. On the other hand, the depth of discharge (DOD) represents the emptiness of the battery respect to the energy.

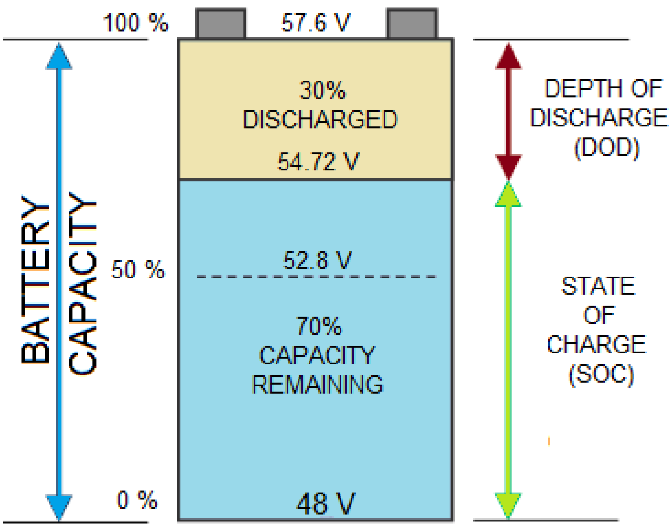


Fig. 9. SOC- Graphical description

The estimation of the state of charge is indispensable to achieve the optimum performance of a storage system. One of the most important aspects, which affects the estimation of the SOC of a battery, is the aging. Due to the charge and discharge cycles, the capacity of the battery's cells decreases with time. Then, the reference should be the rated capacity of a new cell rather than the current capacity of the cell. For instance, as the battery gets close to the end of its lifetime its nominal full capacity will be around 80% of its rated capacity.

Therefore, even if the cell were fully charged, its SOC may reach only the 80% of its original capacity.

If the current capacity is taken as reference instead of the rated capacity of the battery when is new, is comparable to gradually decreasing the size of the fuel tank over the lifetime of a vehicle without notifying the driver. Then, if the nominal value of battery capacity is taken as reference, the estimate may contain substantial errors.

In order to estimate the real remaining charge of the battery, environmental factors, as well the ageing must be taken in consideration.

2.1.2. State of Health

The State of Health (SOH) is an indicator of the general condition of a battery and its condition to provide the nominal performance compared with a new battery. This parameter takes into account the internal the resistance, voltage, charge acceptance and self-discharge. Then, this is not an absolute measure, but a reference value, which shows the available lifetime of the battery and how much has been consumed. For example, using an analogy, it can be compared to the odometer display function of a vehicle, which shows the how much the vehicle has been driven since it was new.

Due the SOH is a relative condition, there must be a measurement log since the initial operation of the battery or at least a base parameters to take as reference. Then, if the voltage is an aspect to be monitored, the system must keep a record of the initial voltage of a fresh cell, or if the number of charge and discharge sequences is used as a measure parameter, the estimated battery cycle life of a new cell may be used as the reference.

2.2. Lead acid battery charging process

Currently, most of energy storage systems involving photovoltaic systems use flooded lead-acid batteries [16], where two electrodes, positive and negative, interacts with chemical liquid compounds used for the electricity storage, in solution with some type of electrolyte [17].

The electrochemical reaction that allows the storage function is achieved through accumulators or cells. These systems allows the purpose of storage and release the flux of electrons by alternating the charge and discharge states. Transforming the chemical energy into electricity, and vice versa, is performed by the interaction of the electrochemical process. When the electrodes are connected to a closed circuit, generate an electric current, then the electrons flow from one electrode to another.

However it has a comparatively low robustness for great amplitude charging cycles. This limitation is produced by the electrochemical reaction by itself; creating solid compounds that are stored directly on the electrodes on which they form (sulfation). This produces limited-mass system, which obviously bounds the capacity of the batteries due to the damaging of the compounds. An appropriate method to preserve the Pb-acid batteries requires a charging profile that implies the controlled-current/controlled-voltage technique, proposing elementary charging capabilities necessary for exploiting performance and lifecycle of batteries.

The charging process is usually large, and takes several hours until finished depending on many factors such as voltage, current, state of charge and temperature. Primary, a controlled current is injected so that the differential voltage between the terminals of the battery increases its value until the maximum charge voltage where is kept constant, then, at this moment the current starts to fall down because of the saturation.

The challenge consists on maximize the charging rates and cell voltages without overcharging the cells. Increasing charger currents within manufacture limitations will result into the reduction of the charging time, nonetheless, the fully charge at constant current must be avoided in order to preserve the battery lifetime, then multi-stage methods should be applied as stated by the German Institute for Standardization at the normative DIN 41773, where the charging procedure for Pb-lead acid batteries is described.

Then, the charging process must be limited to prevent increasing the battery voltage above the recommended limits or applying charging currents that exceed manufacturer recommended levels. In either case, both conditions may damage the internal cells by breaking them down, resulting in failures and reducing the overall battery lifetime [17]. These characteristics are taken into account by commercial battery chargers and will be explained at chapter IV.

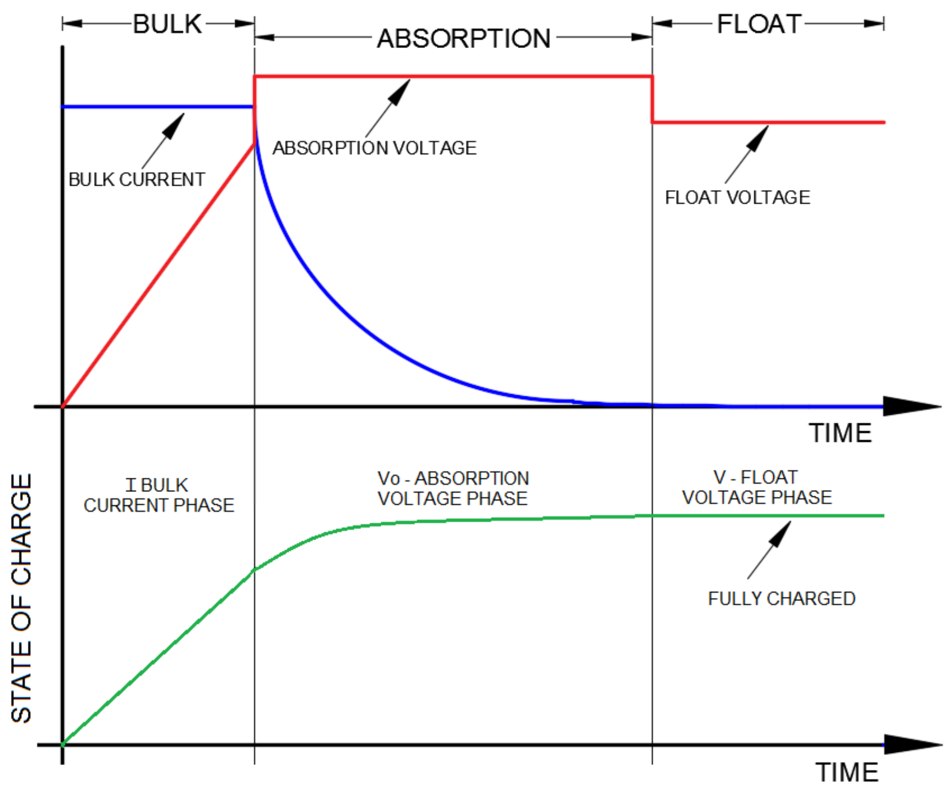


Fig. 10. Battery charge sequence through a bidirectional converter. [17]

According to [16], [17] and [18], Pb-acid batteries should be charged in a three successive stage sequence: constant current charging phase, constant voltage maintenance phase and constant voltage flotation phase. The first phase applies the main bulk part of the charge and last for the half time of the charge time, the second stage provides the saturation effect by reducing the current and avoiding the overcharge of the battery, finally, the third phase applies an even lower voltage and stands for keeping charged the battery.

To achieve this balance many commercial equipment use PWM chargers to drive the Pb-acid battery charge into the three consecutive stages: bulk, absorption and float [17] – [18] (Fig. 10).

Then, it becomes clear that the knowledge of the battery variables requires the modelling of the aforementioned stages, which can be characterized by the simplified model of J.B. Copetti et al. [18] used in [19] and [20] as a standard that not depends on the field analysis of the energy accumulators and only requires manufacturer's technical data.

Nonetheless, this model is a general solution that lacks in the analysis through all the charging phases required by the batteries. However, several models have been developed based on the work of Copetti in which the charging modalities are analyzed. The bulk and discharge stages are described by N. Achaibou et al. in [12], whereas absorption and float are studied using the model described by H. Fakham et al. in [13].

As a first approach, the batteries can be described by their voltage performance, where the main parameters are the open circuit voltage and the product of the internal resistance multiplied by the current, which is positive or negative depending on the charging an discharge stage respectively. Then, the resistance is variable and depends on other factors such as capacity, temperature and current among others. The main characteristics and the mathematical expressions defining each stage are the following:

Bulk stage – controlled Current: The transformation from the electrical to chemical energy takes place with higher intensity. This stage presents a high energy consumption at constant current until reaching a SOC value between 0.8 and 0.9; as a function of current and temperature [17] - [18], the battery voltage increases progressively as the SOC increases. A properly configured charger will supply the battery as much current as it safely accept (this value is recommended by the manufactures, which usually is the 20% of the capacity of the battery).

Mathematical model:

Eq.1 shows the cell voltage, as a function of the battery charging dynamics:

$$Vc(t) = \big(2 - 0.16 \cdot SOC(t-1)\big) + \frac{I(t)}{C10} \cdot (1 - 0.025 \cdot \Delta T) \cdot \left(\frac{6}{1+I(t)^{0.86}} + \frac{0.48}{\big(1-SOC(t)\big)^{0.86}} + 0.036\right) \quad (1)$$

Eq. 2 shows the quantity of useful accessible charge respect to the nominal capacity:

$$C = \frac{C10 \cdot 1.67 \cdot (1 + 0.005 \cdot \Delta T)}{1 + 0.67 \cdot \left(\frac{I(t)}{I10}\right)^{0.9}} \quad (2)$$

Finally, Eq. (3) represents the SOC of the battery at charging stage:

$$SOC(t) = SOC(t-1) + I(t) \cdot \frac{\Delta t}{C} \quad (3)$$

Discharge stage Mathematical Model:

In Eq. 4 the discharging voltage is modelled by the following equation, which depends on the load current, SOC and temperature variation:

$$Vc(t) = \left[2.085 - 0.12 \times \left(1 - SOC(t)\right)\right] - \frac{I(t)}{C10} \times \left(\frac{4}{1 + I(t)^{1.3}} + \frac{0.27}{SOC(t)^{1.5} + 0.02}\right) \times \left(1 - 0.007 \times \Delta T\right), \quad (4)$$

In Eq. (5) the SOC at time interval t is expressed recursively as:

$$SOC(t) = SOC(t-1) - I(t) \cdot \frac{\Delta t}{C} \quad (5)$$

Absorption stage – Constant Voltage: The event of reaching the gasification voltage (undesirable chemical reactions take place producing electrolyte loss) and the current decrease, marks the starting point of this stage, the electrolyte is recovered from being degraded by the previous process, this period is essential for the health of the battery. This stage has reduced energy consumption and the voltage level is set to a constant value from 2.30V to 2.45 V per cell, corresponding to the gasification voltage [22]. The load current progressively decreases its value until one of the following two conditions is met: the SOC reaches 0.95 or an elapsed time of 4 hours from the beginning of this stage; after that, the equipment automatically switches to the float stage. If this voltage is not applied, the battery cells will lose the ability to receive a full charge along the time, decreasing the performance due to sulfation [17].

Float stage - Constant Voltage: The battery is maintained at full charge, self-discharge is avoided and battery sulfation is prevented. This stage has an even lower energy consumption than the previous one since the applied voltage is reduced to 2.1 Volts per cell and the current is reduced to values close to 0A [17].

In this stage the BC apply a lower voltage than the other stages in order to prevent electrolyte gasification, but high enough to neutralize the self-discharge.

Absorption and Float Mathematical Model:

In order to analyze these stages and to avoid excessive complexity, a non-complex resistor-capacitor electrical model is used, Fig. 11.

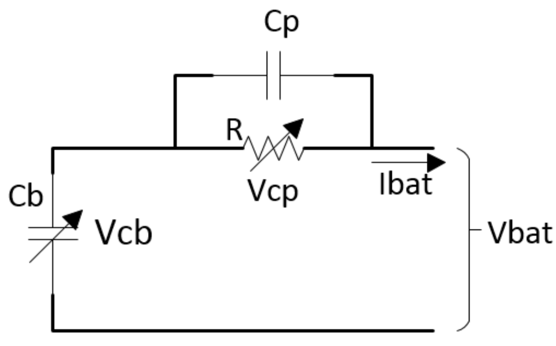


Fig. 11. Battery equivalent circuit [15]

In these stages, the voltages Vbat (Battery voltage, theoretical gassing voltage) and Vg (Manufacturer Gassing Voltage) are given.

Eq. 6 shows the internal current of the battery and the can be modelled as follow:

$$I(t) = I(t-1) - \frac{Vbat(t) - n \times Vg}{n \times R(t)}, \qquad (6)$$

In order to find the value of the resistance, it is necessary to determine the internal capacitance and its related electromotive force of the battery, can be computed at Eq. 7 and Eq. 8 respectively:

$$Cb(t) = \frac{C10}{1 + 0.67 \times \frac{I(t)}{I10}} \times \frac{1}{n \times 0.16}, \qquad (7)$$

$$Vcb(t) = Vcb(t-1) + \frac{I(t) \times dt}{Cb(t)}, \qquad (8)$$

Finally, the resistance is given by the Eq. 9:

$$R(t) = \frac{1}{C10} \times \left[\frac{6}{1 + I(t-1)^{0.6}} + \frac{0.48}{\left(1 - \frac{Vcb(t) - 2}{0.16}\right)^{1.2}} \right]. \qquad (9)$$

Where:

- *I(t)* is the battery current [A]
- Δ*t* is the duration of the time interval considered [h]
- *Vc(t)* is the cell voltage [V]
- *SOC (t)* is the battery state of charge [p.u.]
- *C10* is the charge/discharge capacity in 10 h at 25ºC [Ah]
- Δ*T* is the temperature variation referred to 25ºC [ºC]
- *C* is the battery capacity at the charge/discharge constant current [Ah]
- *n* is the number of battery cells
- *I10* is the charge/discharge current in 10 h at 25ºC [A]
- *Vcb(t)* is the internal electromotive force of the battery [V]
- *Cb(t)* is the battery capacitance [F]
- *R(t)* is the internal resistance of the battery [Ω]
- *Vg* is the gasification voltage given by the manufacturer [V]
- *Vbat(t)* is the battery bank voltage [V]
- Vcp: polarization voltage [V]

- Cp: polarization capacitor [F]

Following, in chapter III are analyzed the issues related on dealing with the life-span of the batteries as detailed by J. Salameh et al. in [21] and by K. Smith et al. in [22]. Then, later at chapter IV the analysis results and BC selection are analyzed.

The aim of this work focuses on the development of a specific energy management algorithm for a Pb-Acid battery bank driven by a commercial battery inverter/charger, which should be compliant with the recommended battery charging/discharging stages, namely: bulk, absorption and float.

Then, the project will adapt the proposed algorithm to be embedded in microgrid optimization software with a low increase of computational complexity. As a result, the global optimization programs will take into account the careful charge/discharge stages of the battery thus preserving its lifetime and reducing the operational cost of the microgrid.

3. ESS Control and EMS Modifications

3.1. EMS and EES interaction issues: proposed approach

Usually, the EMS's based on optimization cost functions does not take into account the battery charging phases [23] - [25]. The integration of the battery model given in (1-9) within the EMS optimization program leads to an excessive requirement of computational resources which would adversely affect the online operation of the EMS [26] - [31].

The execution of the strategy constraints must be established on the modelling of the battery behaviour, such that, the trade-off energy balance considers the State of Charge (SOC) of the accumulators, then, the scheduled profiles will contemplate the estimated power injected into the batteries bank.

In this project, in order to facilitate the integration of the charging stages modelling within the ESS for the battery requirements prediction, the proposed optimization alternative is based in a three steps solution, as summarized in Fig. 12 and explained as follows:

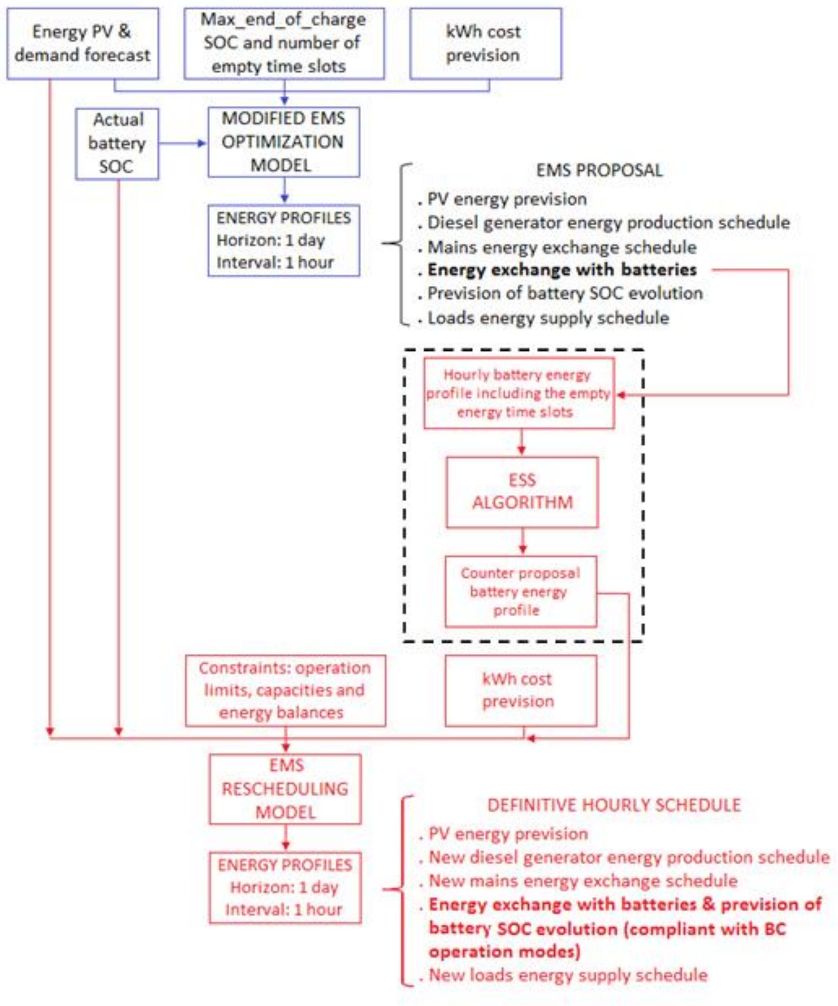


Fig. 12. Proposed EMS architecture

3.1.1. EMS optimization program modification

Initially the optimization program gives the peak value of the SOC evolution, namely the bulk-end-of-charge battery SOC so that the cost function is minimized. Accordingly, the end of the bulk charge process is detected when the SOC reaches this peak value. It is worth noting that the bulk-end-of-charge battery SOC value is bounded by the parameter “Max-end-of charge”, expressed in p.u. (per-unit) of the battery SOC, which is set to 0.8 or 0.9 to avoid the battery overcharge in the absorption phase.

Then, the EMS optimization program is modified to include energy empty time slots in the battery energy exchange profile just after each bulk charge process, so that absorption and floating stages could take place, as seen in figure 13.

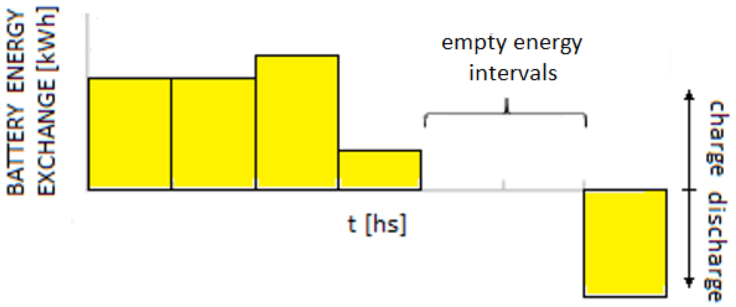


Fig. 13. EMS profile modification

The modification adds at least a time slot of pre-defined duration (usually from 1h to 4h) when the variable SOC(t) reaches the bulk-end-of-charge battery SOC. The Fig. 14 shows two possible examples of SOC evolutions where their peak values are lower than the parameter Max-end-of- charge and at least two time slots were inserted after the bulk phase. With these new restrictions, the modified optimization program redistributes along the time the available battery energy profile to both minimize the cost function and to assure the time slots for the charge process. This redistribution is shown in the example of Figs. 15 and 16.

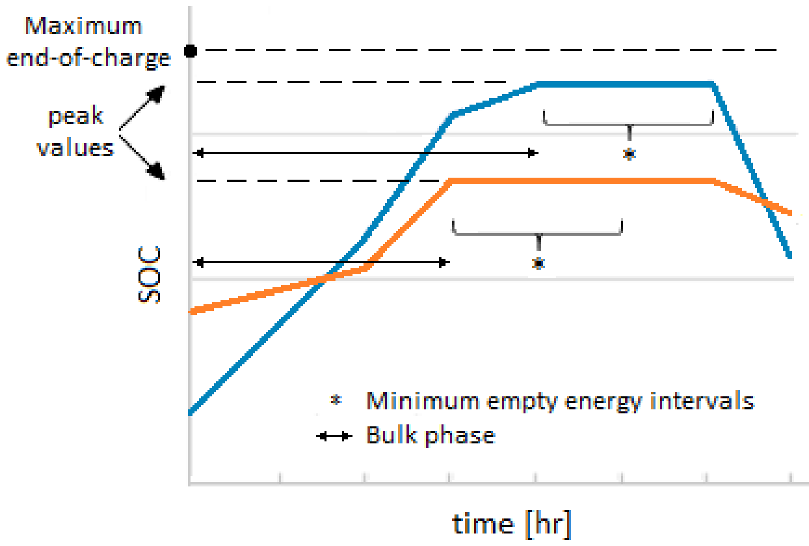
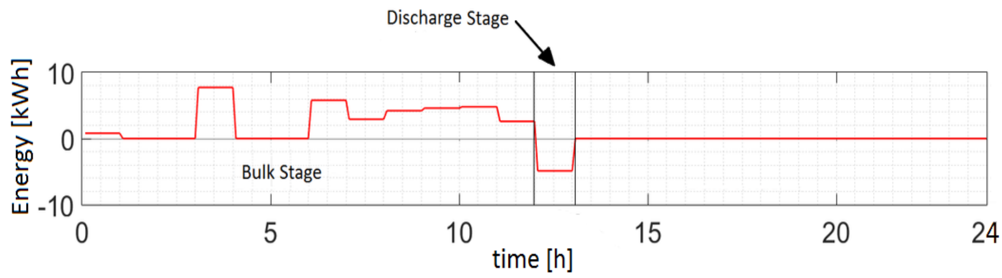
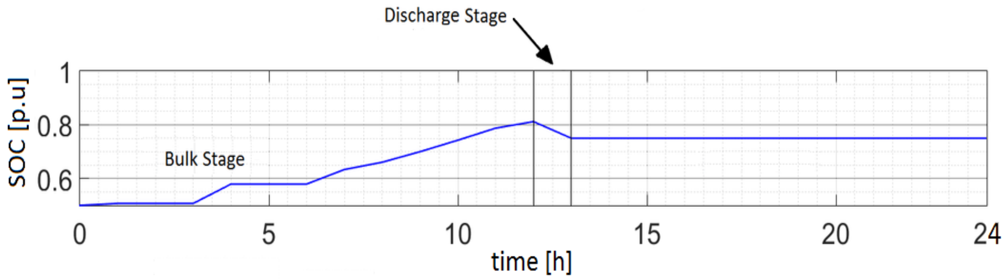


Fig. 14. Examples of battery SOC hourly evolutions within the modified optimization model.

Fig. 15(a) shows the original energy profile given by the EMS when no battery charging restrictions are considered (see the immediate discharge from 12:00 to 13:00 after the last charge slot of bulk stage).



(a)

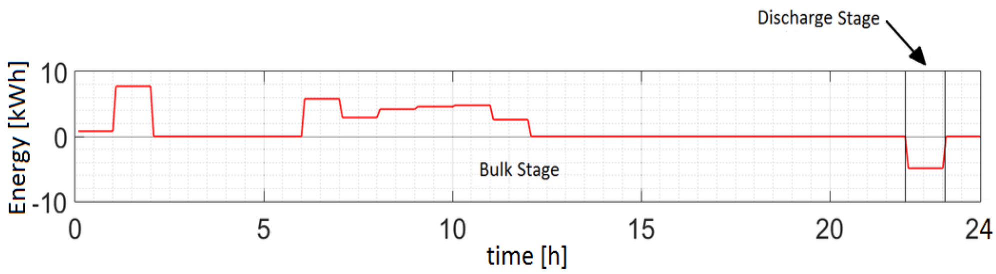


(b)

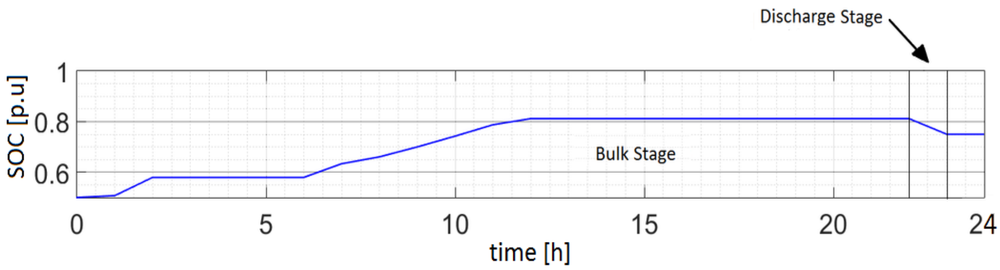
Fig. 15. Original EMS proposal without battery charging restrictions (a) Hourly charge / discharge energy profile (b) SOC evolution

On the other hand, Fig. 14(a) present the battery energy profile once the optimization program was modified to take into account the constraints of battery SOC Max-end-of-charge = 0.8 and an empty energy minimum time slot of 4 hours. It can be noted that the discharge stage takes place from 22:00 to 23:00 (10 hours after the last charge slot of bulk stage). Henceforth, this last profile will be referred as “modified EMS proposal”.

As it will be detailed in the simulation results section, in spite of these significant differences in the battery energy profile, the cost function value in both cases exhibits similar results.



(a)



(b)

Fig. 16. Modified EMS proposal with battery charging restrictions (a) Hourly charge / discharge energy profile (b) SOC evolution

3.1.2. An specific ESS algorithm control

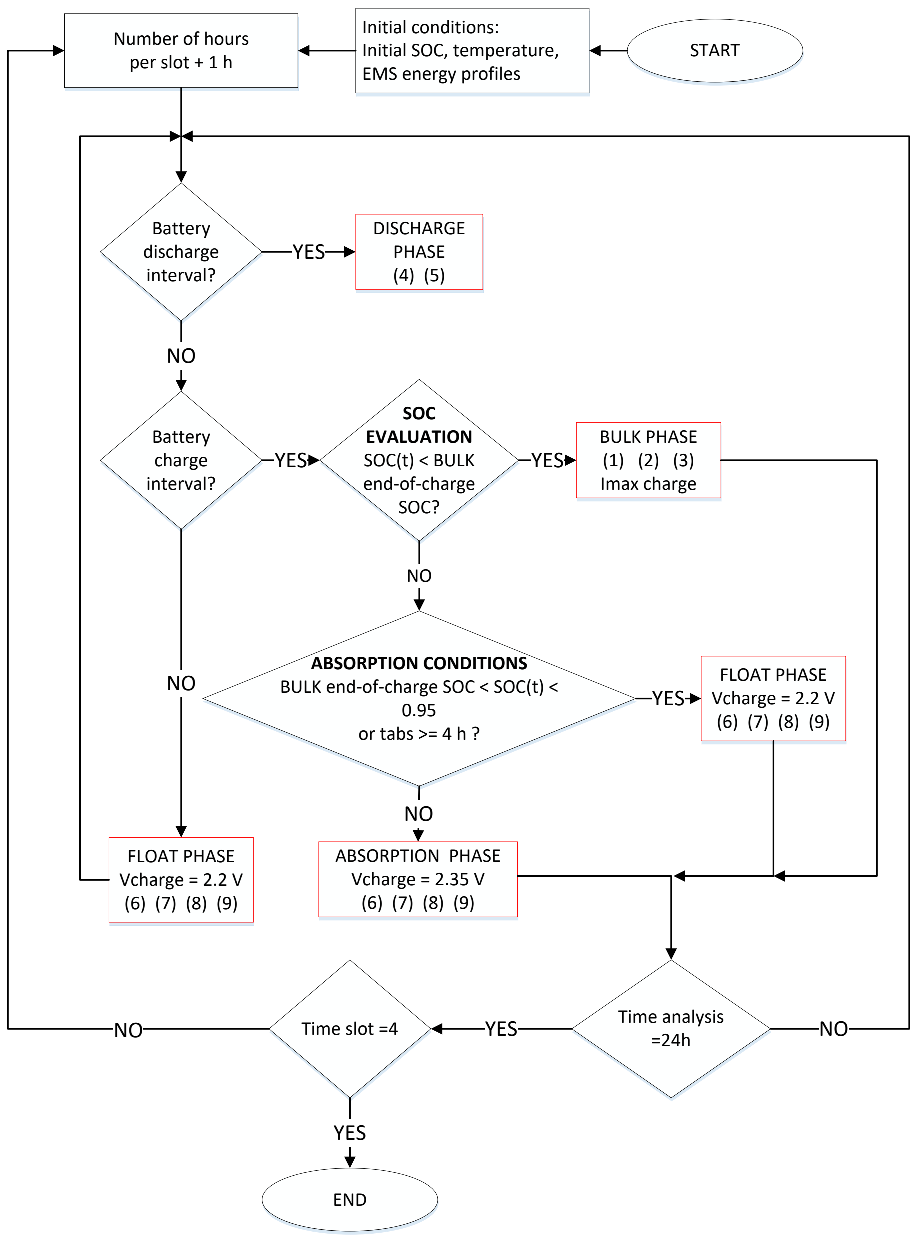


Fig. 17. Flow diagram of the ESS control algorithm

The algorithm is in charge to assure the proper battery operation and is computed out of the EMS optimization program to avoid heavy computations.

As summarized in Fig. 12, the algorithm is proposed to coordinate the dispatch of the three ESS levels. The control consists on several separate functionalities as described in a procedure explained below. The ESS algorithm starts from the hourly battery energy profile including the empty energy time slots given by the modified EMS optimization program.

Fig. 17 presents the flux-diagram of the ESS algorithm which inputs are the initial SOC and the energy profiles containing the empty times-lots given by the EMS modified optimization program. This algorithm is based on the following steps:

Step 1: Assign the number of hours per slot for the absorption stage.

Step 2: Determine, at the beginning of the process, the time intervals where each one of the stages is activated during the day.

Step 3: According to the stage where the battery operates and the corresponding restrictions, determine the voltage and the current of the battery, namely:

Bulk stage: The battery should be charged at a maximum current until the variable SOC(t) reaches the bulk-end-of-charge battery SOC value. From hourly available energy profile given by the EMS optimization program, the corresponding average power is computed each five minutes and the algorithm starts from a maximum current value given by the maximum current value given by 2 times the I10 charging current [14], then the battery voltage is computed through (1). If the resulting average power is lower than the available one, the bulk stage takes place and the battery is charged at this current value. Otherwise, the algorithm restarts the voltage computation reducing the charge current value in 1A (the current reduction step resolution is fixed by the commercial BC). This reduction is carried out until the resulting power is lower than the available one. In this case, the bulk stage takes place until the variable SOC(t) in (3) is equal to the bulk-end-of-charge battery SOC value given by the EMS optimization program.

Absorption: This stage takes place in the empty energy time slots given by the optimization program. In this case, there are no current limitations. After the bulk stage, the BC sets the battery voltage to the absorption one (2.352V); starting from an initial value, corresponding to the last current value of the bulk stage, the battery current evolution is computed through (6-9). The time ending of this stage is fixed by the user according to the available energy empty time slots.

Float: This phase takes place after the absorption one and the current computation follows the same steps but now with the float voltage value (2.1V).

In this regard, the EMS optimization program reschedules the microgrid devices in order to deliver the energy required by the absorption and float stages.

Discharge stage: from the last value of the battery voltage and the battery energy profile, the initial battery current is computed and subsequently the battery voltage and the battery SOC evolution are computed through (4) and (5).

Moreover, the EMS considers four time slots intervals (from 1h to 4h) to execute the absorption stage after the bulk one, as seen in fig. 18. These four counterproposal options are subsequently sent to the EMS which is in charge to make the definitive choice according to the optimization function value.

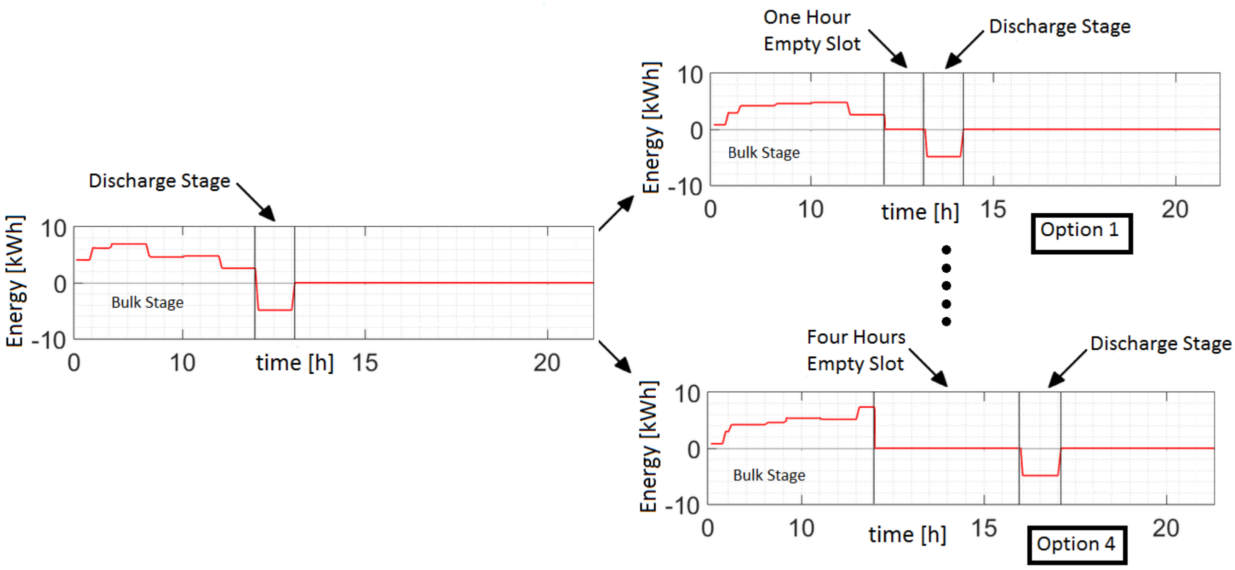
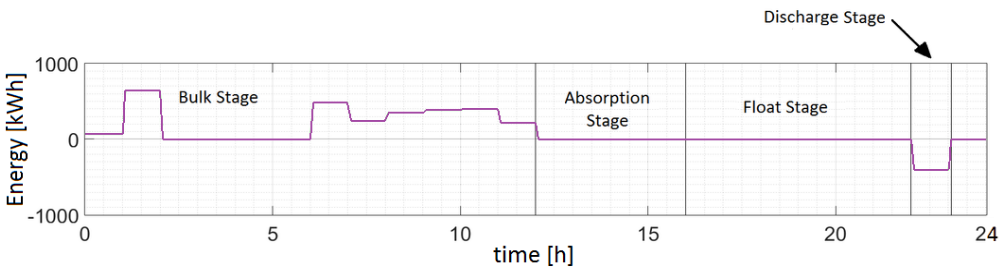


Fig. 18. EMS proposal options

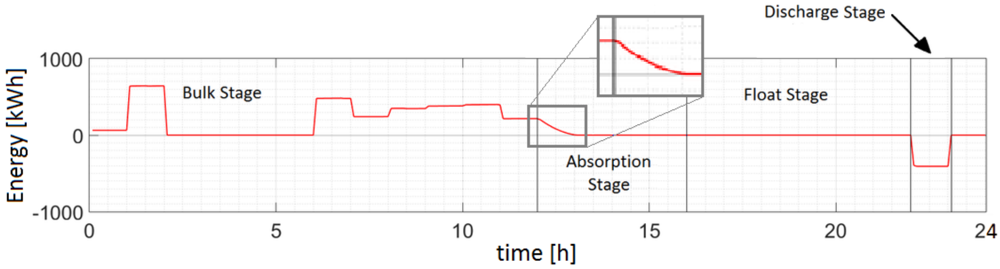
3.1.3. EMS proposal and ESS counterproposal management

As previously stated, starting from a modified energy profiles proposal including energy-empty time-slots given by the EMS (see Fig. 19(a)), the ESS algorithm delivers an energy profile counterproposal, shown in Fig. 19(b). As it can be seen, the ESS algorithm executes the absorption stage immediately after the end of the bulk stage and before the discharge one. Therefore, the profile guarantees at least a user-prefixed time interval of absorption/flotation phases for the transition from bulk to discharge.

Nevertheless, as seen in Fig. 19(b), absorption and float stages require a certain (low) amount of energy. As summarized in the lower red blocks of Fig. 12, this energy will be obtained from the knowledge of the ESS energy profile by means of the EMS optimization program, which reschedules the microgrid elements to both provide the absorption and float stage energy and minimize the cost function.



(a)



(b)

Fig. 19. EMS proposal vs. ESS counterproposal comparison (a) Modified EMS proposal with battery charging restrictions (b) ESS algorithm charge / discharge battery energy counterproposal.

4. Simulation results and implementation issues

In this Chapter, a real case is analyzed, it also presents a comparison between the results obtained by the EMS with and without the algorithm.

At the Appendices number 2, there is located the Matlab [32] code which develops the control algorithm.

4.1. Simulation and Results – Case 1

To verify the performance of the proposed system, a set of simulations of the control strategy are executed using the modified EMS proposal of Fig. 20(a). The following battery bank parameters are assumed: C10 = 1875 Ah, Vbat = 48 V, I10 = 187.5 A and I20 = 375 A and as initial conditions: ΔT=0ºC, SOC=0.5 and an initial current value provided to the battery bank of 50A. Irradiance and load demand data were measured on January 15th 2016 on a microgrid located at the municipality of Qobbet Bshamra, (Akkar province, Lebanon).

Table 2 states the energy proposals (expressed in kWh) sent by the EMS, in each one the energy balance is the same but the discharge state is distributed in a different manner in order to maintain the equilibrium in the energy trade-off. The squares in Cyan tone stand for the time slots available for the absorption charging stage.

TABLE 2. CASE 1 - EMS PROFILES PROPOSALS [KWH] – GIVEN PROFILES

TIME [h]	OPTION A [kWh]	OPTION B [kWh]	OPTION C [kWh]	OPTION D [kWh]		
00:00 to 01:00	0.789	0.789	0.789	0.789		
01:00 to 02:00	6.736	6.736	6.736	6.736		
02:00 to 03:00	0.0001	0.0001	0.0001	0.0001		
03:00 to 04:00	0.0001	0.0001	0.0001	0.0001		
04:00 to 05:00	0.0001	0.0001	0.0001	0.0001		
05:00 to 06:00	0.0001	0.0001	0.0001	0.0001		
06:00 to 07:00	4.798	4.798	4.798	4.798		
07:00 to 08:00	2.922	2.922	2.922	2.922		
08:00 to 09:00	2.203	2.203	2.203	2.203		
09:00 to 10:00	3.589	3.589	3.589	3.589		
10:00 to 11:00	4.809	4.809	4.809	4.809		
11:00 to 12:00	7.594	7.594	7.594	7.594		
12:00 to 13:00	0	0	0	0		
13:00 to 14:00	-4.896	0	0	0		
14:00 to 15:00	0	-4.896	0	0		
15:00 to 16:00	0	0	-4.896	0		
16:00 to 17:00	0	0	0	0		
17:00 to 18:00	0	0	0	0		
18:00 to 19:00	0	0	0	0		
19:00 to 20:00	0	0	0	0		
20:00 to 21:00	0	0	0	0		
21:00 to 22:00	0	0	0	0	Initial SoC	0,5
22:00 to 23:00	0	0	0	-4.896	Temp. Variation	0

23:00 to 24:00	0	0	0	0	Last Current [A]	50
	28.5444	28.5444	28.5444	28.5444		

Each one of the four proposals aims the execution of the Absorption stage after each Bulk stage and before each discharge stage, all seen from the point of view of the cost function of the EMS. Therefore, the option one guarantees one hour of absorption phase for the transition from Bulk to discharge and option four guarantees at least 4 hours.

The figures 20, 21, 22 and 23 summarize the EMS optimization program proposals and the ESS algorithm counterproposals in a five-minute scale.

Table 3, 4, 5 and 6 present the hourly values of the system response under the aforementioned modified EMS proposals and ESS algorithm counterproposals divided in charge/discharge energy, battery SOC and the different charge/discharge stages. At the lower part of the tables, the daily energy balances are also shown.

On each figure, the part (a) represents the battery energy profile proposal of the EMS, respectively. Part (b) and (c) show the battery voltage and current evolution. Part (d) displays the resulting required energy and finally part (e) plots the battery SOC evolution.

The four energy proposals have the same energy distribution from 00:00 until 12:00, where the bulk stage takes place, tending to use all the available energy delivered by the microgrid. Starting at this point, the slots are introduce in order to activate the absorption stage. In all cases at this phase, the current takes a softly decrease until reaching almost 0A at a charge voltage of 2.35V. Subsequently flotation stage takes place near 0A current value and a constant voltage value of 2.1 V, as reported in section III.

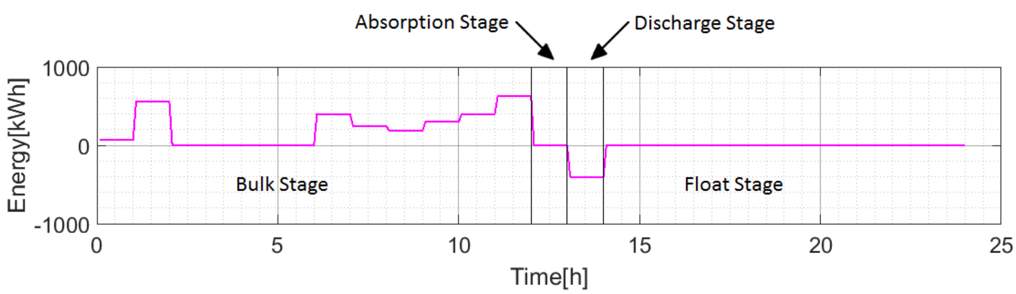
4.1.1. Algorithm response – One hour available Slot, Option A

At fig 20 and table 3, the absorption stage last for one hour and takes place from 12:00 to 13:00 reaching a SOC of 0.8116.

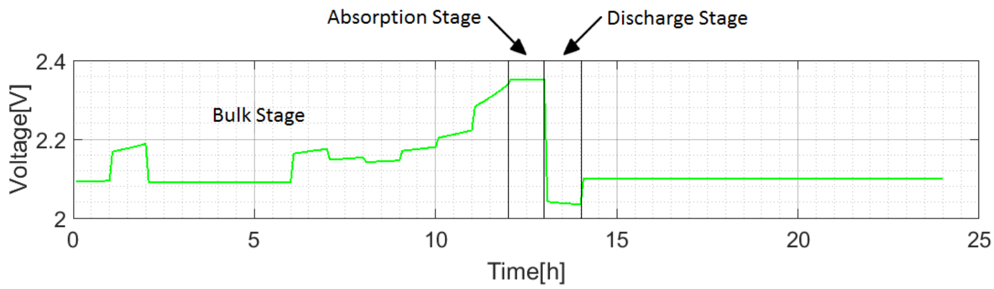
From 13:00 to 14:00 a discharge process is identified by the decrease of the battery voltage and the negative values of the battery current, the SOC value at this point is 0.7680.

Then, at 14:00 and then until the end of the day, the Float stage is active, consuming practically none energy.

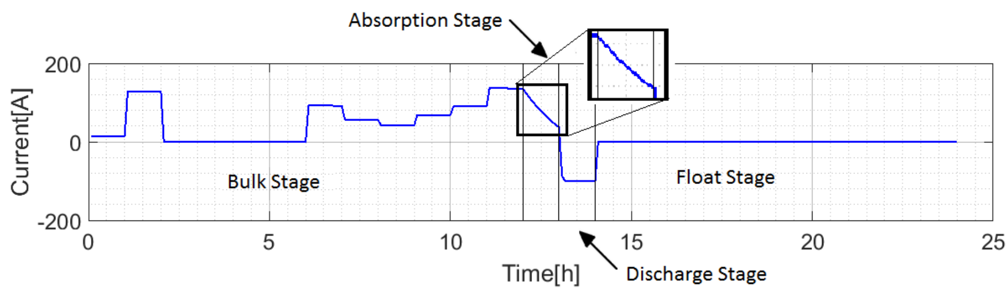
The result at this option, suggest an additional power consumption of 4.1484 kWh with a SOC at the end of the day of 0.7680.



(a)



(b)



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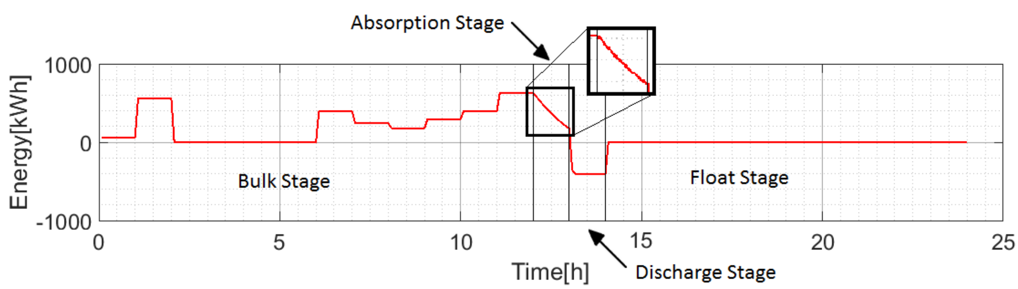
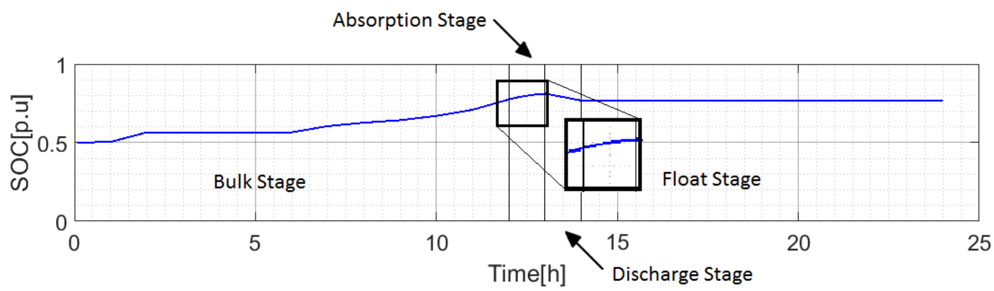


(d)



(e)

Fig. 20. Case 1 - Algorithm response in 5-minutes scale - One hour available Slot (a) EMS optimization program battery energy (b) Charge / discharge counterproposal battery energy (c) Voltage cell (d) Battery current (e) Counterproposal battery SOC evolution.

TABLE 3. CASE 1 - EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION A

TIME [h]	Energy EMS proposal [kWh]	ESS algorithm counterproposal- OP A		
		Hourly energy [kWh]	SOC	STAGE
00:00 to 01:00	0.7890	0.7538	0.5051	Bulk
01:00 to 02:00	6.7360	6.7124	0.5657	Bulk
02:00 to 03:00	0.0001	0.0000	0.5657	Bulk
03:00 to 04:00	0.0001	0.0000	0.5657	Bulk
04:00 to 05:00	0.0001	0.0000	0.5657	Bulk
05:00 to 06:00	0.0001	0.0000	0.5657	Bulk
06:00 to 07:00	4.7980	4.7774	0.6053	Bulk
07:00 to 08:00	2.9220	2.8905	0.6272	Bulk
08:00 to 09:00	2.2030	2.1610	0.6430	Bulk
09:00 to 10:00	3.5890	3.5501	0.6705	Bulk
10:00 to 11:00	4.8090	4.7799	0.7092	Bulk
11:00 to 12:00	7.5940	7.5648	0.7748	Bulk
12:00 to 13:00	0.0000	4.3436	0.8116	Absorption
13:00 to 14:00	-4.8960	-4.8406	0.7680	Discharge
14:00 to 15:00	0.0000	0.0000	0.7680	Float
15:00 to 16:00	0.0000	0.0000	0.7680	Float
16:00 to 17:00	0.0000	0.0000	0.7680	Float
17:00 to 18:00	0.0000	0.0000	0.7680	Float
18:00 to 19:00	0.0000	0.0000	0.7680	Float
19:00 to 20:00	0.0000	0.0000	0.7680	Float
20:00 to 21:00	0.0000	0.0000	0.7680	Float
21:00 to 22:00	0.0000	0.0000	0.7680	Float
22:00 to 23:00	0.0000	0.0000	0.7680	Float
23:00 to 24:00	0.0000	0.0000	0.7680	Float
Total	28.5444	32.6928	Difference	-4.1484

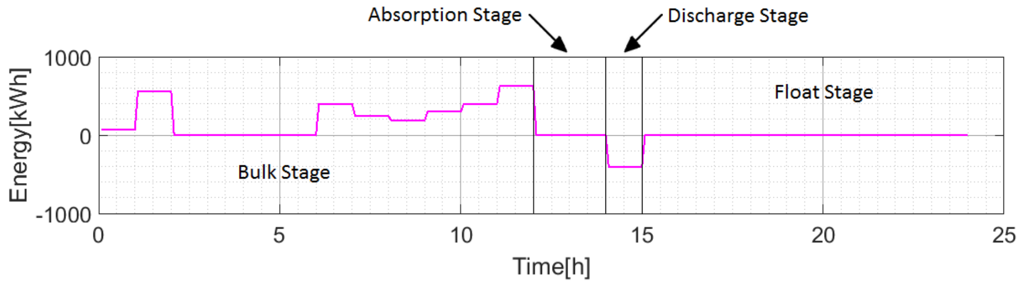
4.1.2. Algorithm response – Two hours available Slot, Option B

In the option B, fig 21 and table 4, the absorption stage takes place from 12:00 to 14:00, lasting for 2 hours and reaching a SOC of 0.8171, the additional 0.006 [p.u] SOC value correspond to the additional hour given for the absorption phase.

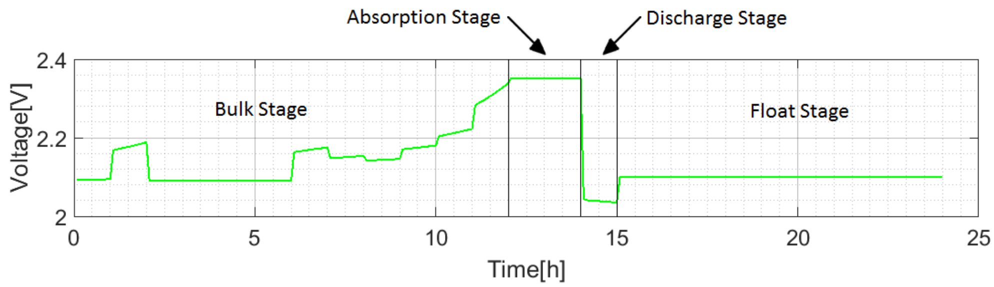
From 14:00 to 15:00 the discharge process is performed, taking from the battery 4.840 kWh and decreasing the SOC value until reach 0.7835.

Lately, at 15:00 starts the float stage, which last until the end of the day.

Finally, the energy balance in this option results with an increment of 4.793 kWh to reach a final SOC of 0.773



(a)



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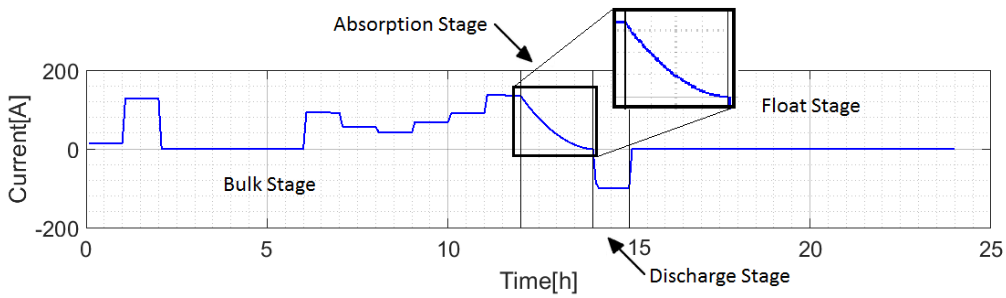

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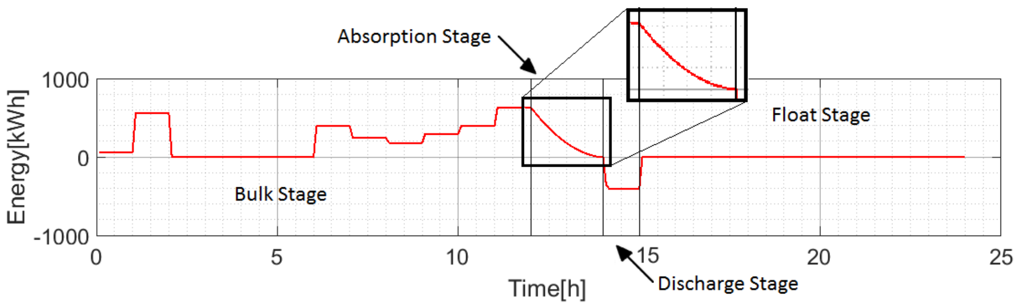

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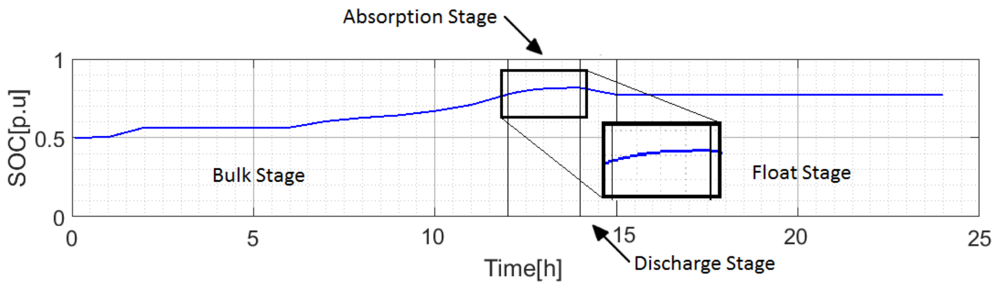


(e)

Fig. 21. Case 1 - Algorithm response in 5-minutes scale - Two hours available Slot (a) EMS optimization program battery energy (b) Charge / discharge counterproposal battery energy (c) Voltage cell (d) Battery current (e) Counterproposal battery SOC evolution.

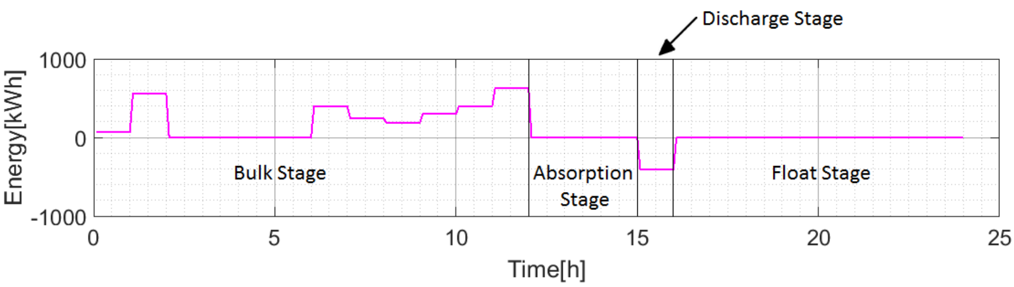
TABLE 4. CASE 1- EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION B

TIME [h]	Energy EMS proposal [kWh]	ESS algorithm counterproposal- OP B		
		Hourly energy [kWh]	SOC	STAGE
00:00 to 01:00	0.7890	0.7538	0.5051	Bulk
01:00 to 02:00	6.7360	6.7124	0.5657	Bulk
02:00 to 03:00	0.0001	0.0000	0.5657	Bulk
03:00 to 04:00	0.0001	0.0000	0.5657	Bulk
04:00 to 05:00	0.0001	0.0000	0.5657	Bulk
05:00 to 06:00	0.0001	0.0000	0.5657	Bulk
06:00 to 07:00	4.7980	4.7774	0.6053	Bulk
07:00 to 08:00	2.9220	2.8905	0.6272	Bulk
08:00 to 09:00	2.2030	2.1610	0.6430	Bulk
09:00 to 10:00	3.5890	3.5501	0.6705	Bulk
10:00 to 11:00	4.8090	4.7799	0.7092	Bulk
11:00 to 12:00	7.5940	7.5648	0.7748	Bulk
12:00 to 13:00	0.0000	4.3436	0.8116	Absorption
13:00 to 14:00	0.0000	0.6452	0.8171	Absorption
14:00 to 15:00	-4.8960	-4.8408	0.7735	Discharge
15:00 to 16:00	0.0000	0.0000	0.7735	Float
16:00 to 17:00	0.0000	0.0000	0.7735	Float
17:00 to 18:00	0.0000	0.0000	0.7735	Float
18:00 to 19:00	0.0000	0.0000	0.7735	Float

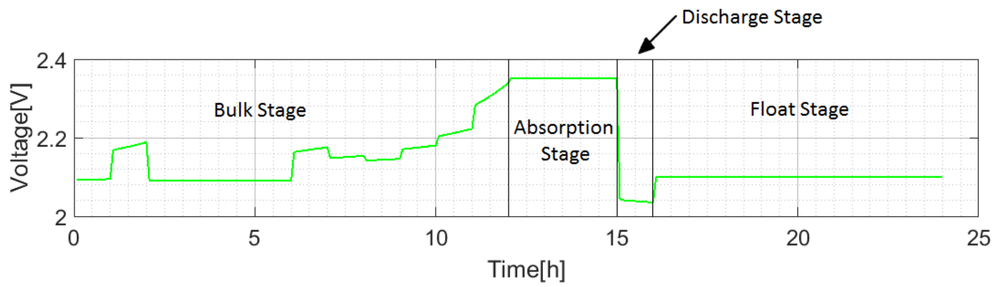
19:00 to 20:00	0.0000	0.0000	0.7735	Float
20:00 to 21:00	0.0000	0.0000	0.7735	Float
21:00 to 22:00	0.0000	0.0000	0.7735	Float
22:00 to 23:00	0.0000	0.0000	0.7735	Float
23:00 to 24:00	0.0000	0.0000	0.7735	Float
Total	28.5444	33.3378	Difference	-4.7934

4.1.3. Algorithm response – Three hours available Slot, Option C

Fig 22 and table 5 show the Option C response, where the absorption stage starts at 12:00 and finishes at 15:00, lasting for 3 hours and reaching a SOC of 0.8171. One can notice that in comparison with the previous case and besides the additional hour for the absorption stage, this response is practically the same in terms of SOC and trade-off of energy. On this situation the third hour of absorption stages produces a null effect in energy consumption and, therefore, none variation in the SOC evolution. However, because the additional hour at the absorption parameters, this option is better for the battery life-extension.



(a)



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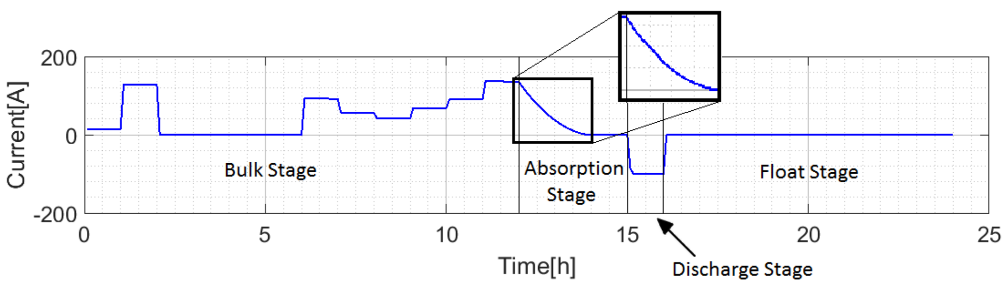

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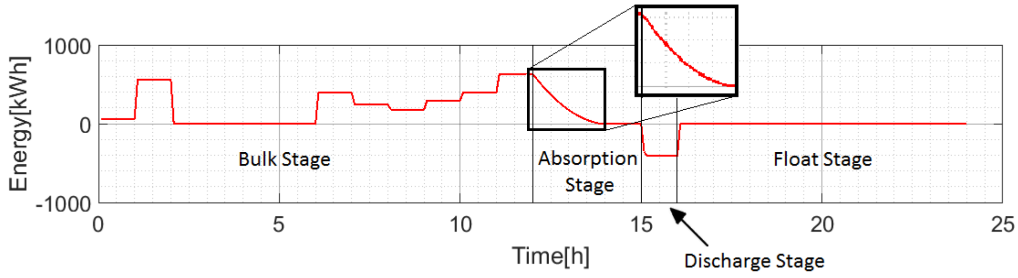

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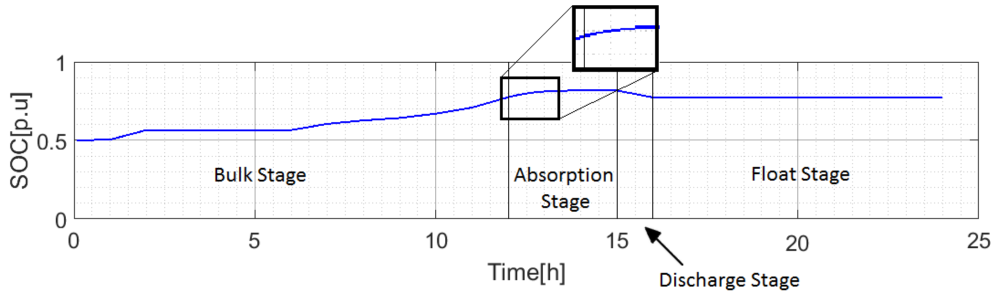


(e)

Fig. 22. Case 1 - Algorithm response in 5-minutes scale - Three hours available Slot (a) EMS optimization program battery energy (b) Charge / discharge counterproposal battery energy (c) Voltage cell (d) Battery current (e) Counterproposal battery SOC evolution.

TABLE 5. CASE1 - EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION C

TIME [h]	Energy EMS proposal [kWh]	ESS algorithm counterproposal- OP C		
		Hourly energy [kWh]	**SOC**	**STAGE**
00:00 to 01:00	0.7890	0.7538	0.5051	Bulk
01:00 to 02:00	6.7360	6.7124	0.5657	Bulk
02:00 to 03:00	0.0001	0.0000	0.5657	Bulk
03:00 to 04:00	0.0001	0.0000	0.5657	Bulk
04:00 to 05:00	0.0001	0.0000	0.5657	Bulk
05:00 to 06:00	0.0001	0.0000	0.5657	Bulk
06:00 to 07:00	4.7980	4.7774	0.6053	Bulk
07:00 to 08:00	2.9220	2.8905	0.6272	Bulk
08:00 to 09:00	2.2030	2.1610	0.6430	Bulk
09:00 to 10:00	3.5890	3.5501	0.6705	Bulk
10:00 to 11:00	4.8090	4.7799	0.7092	Bulk

11:00 to 12:00	7.5940	7.5648	0.7748	Bulk
12:00 to 13:00	0.0000	4.3436	0.8116	Absorption
13:00 to 14:00	0.0000	0.6452	0.8171	Absorption
14:00 to 15:00	0.0000	0.0000	0.8171	Absorption
15:00 to 16:00	-4.8960	-4.8408	0.7735	Discharge
16:00 to 17:00	0.0000	0.0000	0.7735	Float
17:00 to 18:00	0.0000	0.0000	0.7735	Float
18:00 to 19:00	0.0000	0.0000	0.7735	Float
19:00 to 20:00	0.0000	0.0000	0.7735	Float
20:00 to 21:00	0.0000	0.0000	0.7735	Float
21:00 to 22:00	0.0000	0.0000	0.7735	Float
22:00 to 23:00	0.0000	0.0000	0.7735	Float
23:00 to 24:00	0.0000	0.0000	0.7735	Float
Total	28.5444	33.3378	Difference	-4.7934

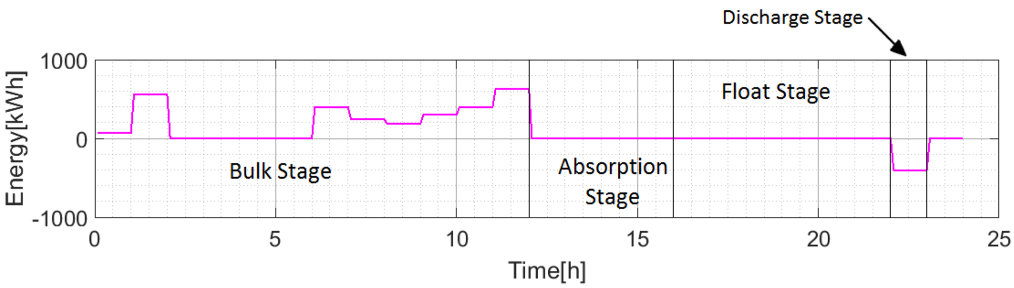
4.1.4. Algorithm response – Four hours available Slot, Option D

From table 6 and figure 23: At 00:00 the bulk stage is started during a time interval of 12 hours. It can be noted that from 02:00 to 06:00 the battery remains on bulk stage at zero current, since energy is neither provided nor required.

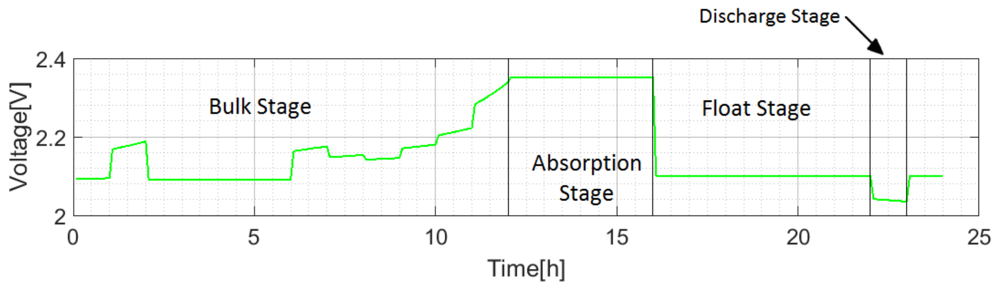
Then, at 12:00, the system is forced to use at least the following four hours (grey cells) to activate the absorption stage before the discharge. From 16:00 to 22:00 and then from 23:00 to 24:00, the algorithm proposes to activate the float stage, thus fulfilling the proposed conditions for the battery protection.

The result highlights that the microgrid must generate an additional energy of 4.7509 kWh distributed from 12:00 to 16:00 to reach the battery absorption phase.

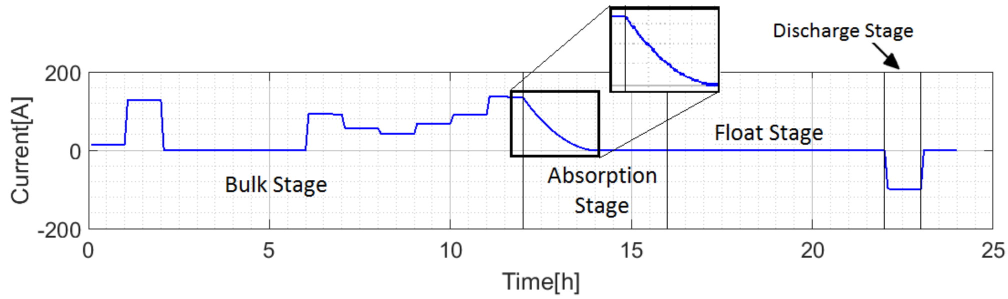
The final SOC in this option is equal to 0.7731 [p.u].



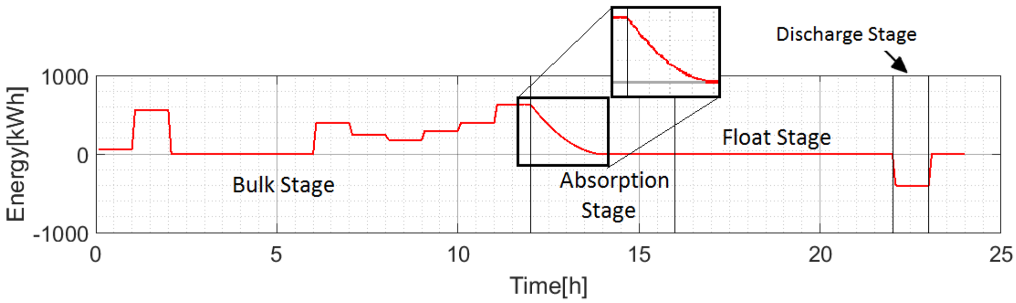
(a)



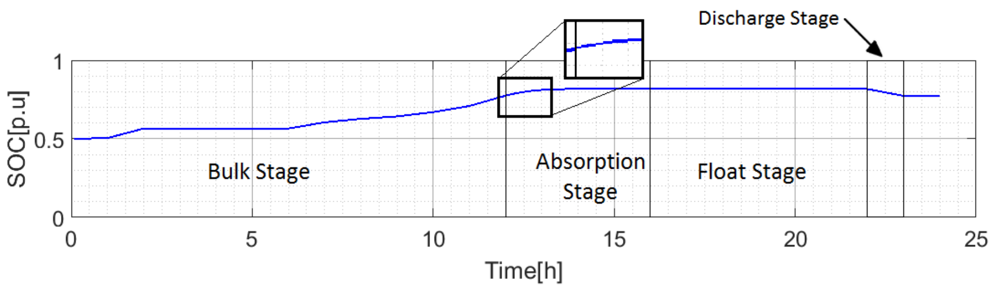
(b)



(c)



(d)



(e)

Fig. 23. Case 1 - Algorithm response in 5-minutes scale - Four hours available Slot (a) EMS optimization program battery energy (b) Charge / discharge counterproposal battery energy (c) Voltage cell (d) Battery current (e) Counterproposal battery SOC evolution.

TABLE 6. CASE 1 - EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION D

TIME [h]	Energy EMS proposal [kWh]	ESS algorithm counterproposal- OP D		
		Hourly energy [kWh]	SOC	STAGE
00:00 to 01:00	0.7890	0.7538	0.5051	Bulk
01:00 to 02:00	6.7360	6.7124	0.5657	Bulk
02:00 to 03:00	0.0001	0.0000	0.5657	Bulk
03:00 to 04:00	0.0001	0.0000	0.5657	Bulk
04:00 to 05:00	0.0001	0.0000	0.5657	Bulk
05:00 to 06:00	0.0001	0.0000	0.5657	Bulk
06:00 to 07:00	4.7980	4.7774	0.6053	Bulk
07:00 to 08:00	2.9220	2.8905	0.6272	Bulk
08:00 to 09:00	2.2030	2.1610	0.6430	Bulk
09:00 to 10:00	3.5890	3.5501	0.6705	Bulk
10:00 to 11:00	4.8090	4.7799	0.7092	Bulk
11:00 to 12:00	7.5940	7.5648	0.7748	Bulk
12:00 to 13:00	0.0000	4.3436	0.8116	Absorption
13:00 to 14:00	0.0000	0.6452	0.8171	Absorption
14:00 to 15:00	0.0000	0.0000	0.8171	Absorption
15:00 to 16:00	0.0000	0.0000	0.8171	Absorption
16:00 to 17:00	0.0000	0.0000	0.8171	Float
17:00 to 18:00	0.0000	0.0000	0.8171	Float
18:00 to 19:00	0.0000	0.0000	0.8171	Float
19:00 to 20:00	0.0000	0.0000	0.8171	Float
20:00 to 21:00	0.0000	0.0000	0.8171	Float
21:00 to 22:00	0.0000	0.0000	0.8171	Float
22:00 to 23:00	-4.8960	-4.8833	0.7731	Discharge
23:00 to 24:00	0.0000	0.0000	0.7731	Float
Total	28.5444	33.2953	Difference	-4.7509

4.2. Simulation and Results – Case 2

In this case, the performance of the system is tested considering a blackout in the main grid from 13:00 to 18:00, where the energy supply of the batteries is more requested in comparison a typical day. The following battery bank parameters are assumed: C10 = 1875 Ah, Vbat = 48 V, I10 = 187.5 A and I20 = 375 A and as initial conditions: ΔT=0ºC, SOC=0.50 and an initial current value provided to the battery bank of 50A. Irradiance and load demand data were measured on January 20th 2016 on a microgrid located at the same site as the previous case.

Table 7 states the energy proposal (in kWh) sent by the EMS. However, despite the previous case, the EMS is giving only one profile option, this is because the optimization program has determined it is only possible to assure one hour for the absorption stage, then the algorithm is considering one valid option for the charging process modelling.

The square in Cyan tone stand for the time slot available for the absorption charging stage.

TABLE 7. CASE 2 - EMS PROFILE PROPOSAL [KWH] – GIVEN PROFILE

TIME [h]	OPTION A
00:00 to 01:00	0.028
01:00 to 02:00	7.736
02:00 to 03:00	0.0001
03:00 to 04:00	0.0001
04:00 to 05:00	0.0001
05:00 to 06:00	0.0001
06:00 to 07:00	5.798
07:00 to 08:00	2.922
08:00 to 09:00	4.203
09:00 to 10:00	4.589
10:00 to 11:00	4.809
11:00 to 12:00	2.594
12:00 to 13:00	0
13:00 to 14:00	-7.565
14:00 to 15:00	0
15:00 to 16:00	0
16:00 to 17:00	0
17:00 to 18:00	0
18:00 to 19:00	0
19:00 to 20:00	0
20:00 to 21:00	0
21:00 to 22:00	0
22:00 to 23:00	0
23:00 to 24:00	0
	25.1144

Initial SoC	0.50
Temp. Variation	0
Last Current [A]	50

The fig. 24 summarizes the EMS optimization program proposal and the ESS algorithm counterproposal in a five-minute scale for the Case 2.

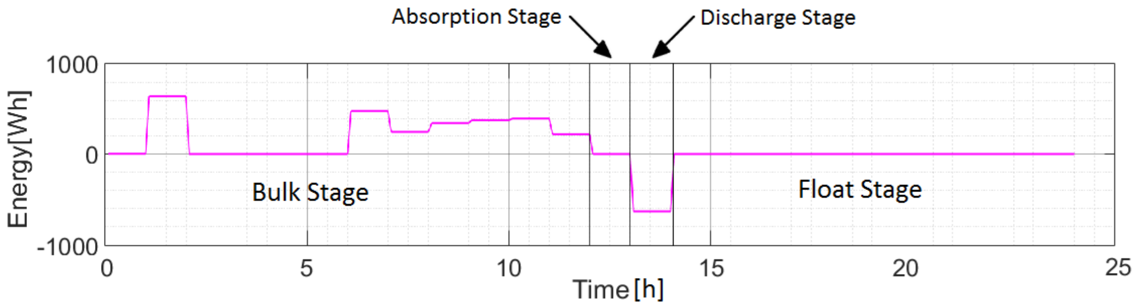
Table 8 present the hourly values of the system response under the modified EMS proposal and ESS algorithm counterproposal. The daily energy balance is also shown at the lower part of the table.

On the figure 24, the part (a) represents the battery energy profile proposal of the EMS, for the case 2. Part (b) and (c) show the battery voltage and current evolution. Part (d) displays the resulting required energy and finally part (e) plots the battery SOC evolution.

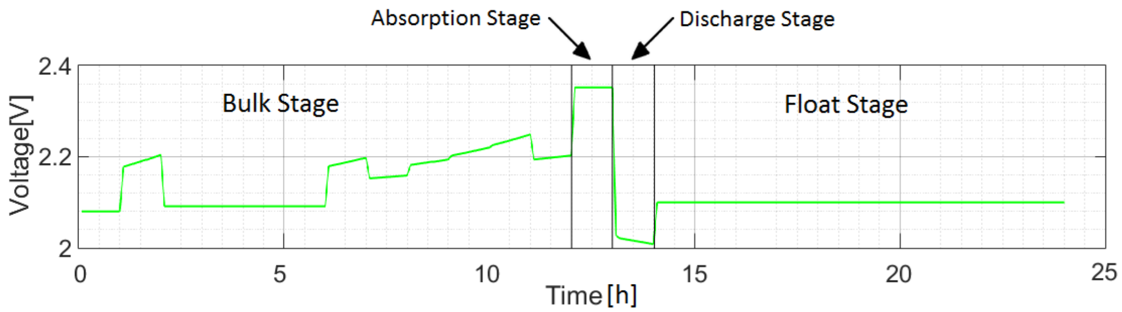
From 00:00 the bulk stage is started during a time interval of 12 hours. Then, at 12:00 the one hour slot is introduced in order to activate the absorption stage before the discharge. From 14:00 until the end of the day, the float stage is activated.

Finally, the microgrid must generate an additional energy of 0.997 kWh distributed from 12:00 to 13:00 to perform the battery absorption phase. Where the current reaches almost 0A at a charge voltage of 2.35V.

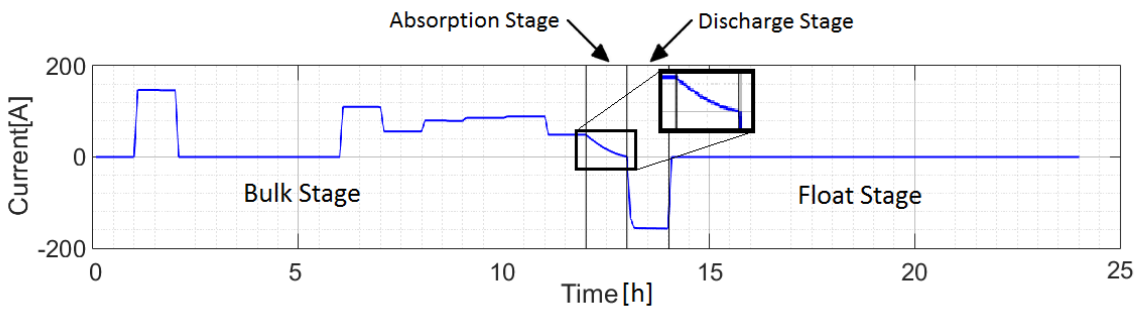
The final SOC in this case is equal to 0.66669 [p.u].



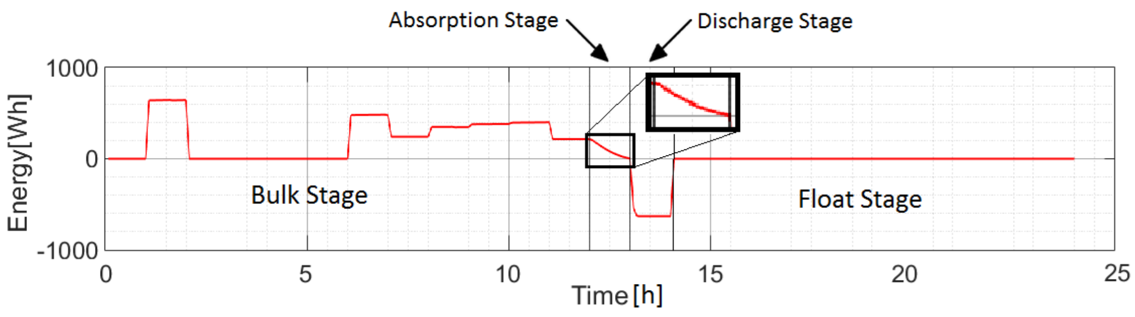
(a)



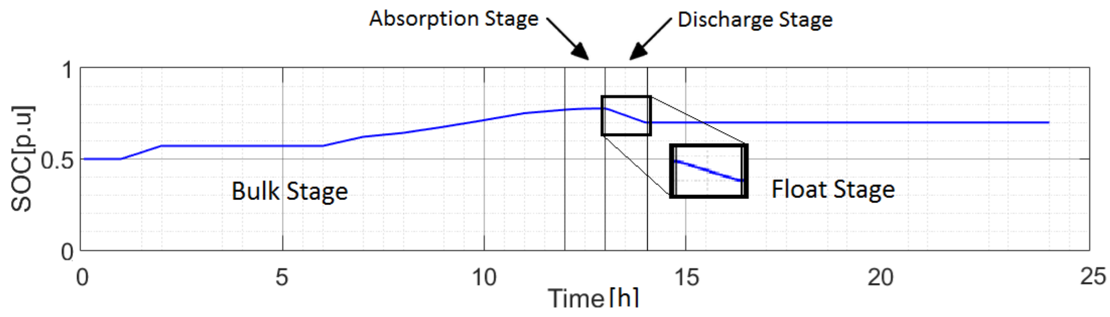
(b)



(c)



(d)



(d)

Fig. 24. Case 2 - Algorithm response in 5-minutes scale - One hour available Slot (a) EMS optimization program battery energy (b) Charge / discharge counterproposal battery energy (c) Voltage cell (d) Battery current (e) Counterproposal battery SOC evolution.

TABLE 8. CASE 2 - EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION A

TIME [h]	**Energy EMS proposal [kWh]**	**ESS algorithm counterproposal- OP A**		
		Hourly energy [kWh]	**SOC**	**STAGE**
00:00 to 01:00	0.028	0.000	0.5600	Bulk
01:00 to 02:00	7.736	7.707	0.5719	Bulk
02:00 to 03:00	0.0001	0.0001	0.5719	Bulk
03:00 to 04:00	0.0001	0.0001	0.5719	Bulk
04:00 to 05:00	0.0001	0.0001	0.5719	Bulk
05:00 to 06:00	0.0001	0.0001	0.5719	Bulk
06:00 to 07:00	5.798	5.773	0.6216	Bulk
07:00 to 08:00	2.922	2.897	0.6435	Bulk
08:00 to 09:00	4.203	4.179	0.6768	Bulk
09:00 to 10:00	4.589	4.564	0.7134	Bulk
10:00 to 11:00	4.809	4.778	0.7516	Bulk

11:00 to 12:00	2.594	2.585	0.7703	Bulk
12:00 to 13:00	0.000	0.997	0.7771	Absorption
13:00 to 14:00	-7.565	-7.472	0.69999	Discharge
14:00 to 15:00	0.000	0.000	0.69999	Float
15:00 to 16:00	0.000	0.000	0.69999	Float
16:00 to 17:00	0.000	0.000	0.69999	Float
17:00 to 18:00	0.000	0.000	0.69999	Float
18:00 to 19:00	0.000	0.000	0.69999	Float
19:00 to 20:00	0.000	0.000	0.69999	Float
20:00 to 21:00	0.000	0.000	0.69999	Float
21:00 to 22:00	0.000	0.000	0.69999	Float
22:00 to 23:00	0.000	0.000	0.69999	Float
23:00 to 24:00	0.000	0.000	0.69999	Float
Total	25.114	26.008	Difference	-0.8941

4.3. Summary Results

4.3.1. Case 1

The EMS determined the option D as the most suitable for the system. It should be taken into account that the EMS optimization program modification including additional "empty energy" time slots as well as the additional amount of energy consumed by the absorption phase modifies the cost function value. In order to quantify how the modifications, affect this value, the following simulations evaluating the total daily economic result in two different cases have been carried out:

1) Base situation: EMS optimization program with no ESS restrictions (no additional time slots)

2) Modified optimization program with ESS restrictions (Bulk-end-of-charge battery SOC = 0.8 and 4 time slots of 1h of empty energy after the bulk phase).

The function to minimize is the daily operation cost expressed in [€/day] defined as [33]:

$$\text{Operation cost} = \sum_{t=t1}^{t24} [\text{Diesel Cost}(t) + \text{Grid Cost}(t) + \text{Non-Critical Loads Penalty Cost}(t) - \text{Grid Income}(t)]$$

where t=t1, t2, …, t24 are the hourly intervals of a day, and:

- Diesel Cost(t) is the diesel generator operation cost, taking into account a unitary cost of 1.15 €/l.

- Grid Cost(t) is the hourly cost of purchasing the energy from the grid. The simulations have assumed an hourly tariff with time-dependent price levels: low (0.056 €/kWh) from 02:00 to 07:00, medium (0.153 €/kWh) from 00:00 to 01:00 and from 08:00 to 13:00 and high (0.219 €/kWh) from 14:00 to 23:00.

-Non-Critical Loads Penalty Cost(t) is the penalization cost for not supply energy to the non-critical loads. The penalty cost considered is 100 €/kWh.

-Grid Income(t) is the monetary income for selling the energy to the grid at 0.020 €/kWh.

This shows that the operation cost of the Microgrid with the BC algorithm in one particular day got an increase difference of 1.5% in comparison with the same case without the algorithm (operation cost for Situation-1 is 52.335 €/day while in Situation-2 is 53.141 €/day) This means that the cost of assuring an extension of the battery-bank lifetime reducing the early ageing factors is 0.252 €/day, in general terms, it may lead into an operational cost of 91.98 €/year. This slight cost increase can be assumed to assure an extension of the battery-bank lifetime.

4.3.1. Case 2

In this occasion, to quantify how the modifications affect the operational cost, the following simulations result in two events which were evaluated under the same cost function value as the Case 1, but considering the blackout of the main and the usefulness of the batteries supplies:

1) Base situation: EMS optimization program with no ESS restrictions (no additional time slots)

2) Modified optimization program with ESS restrictions (Bulk-end-of-charge battery SOC = 0.8 and 1 time slot of 1h of empty energy after the bulk phase).

Restrictions:

- Diesel Cost(t) is the diesel generator operation cost, taking into account a unitary cost of 1.15 €/l.

- Grid Cost(t). The simulations have assumed an hourly tariff with time-dependent price levels: low (0.056 €/kWh) from 02:00 to 07:00, medium (0.153 €/kWh) from 00:00 to 01:00 and from 08:00 to 13:00 and high (0.219 €/kWh) from 14:00 to 23:00.

-Non-Critical Loads Penalty Cost(t) is the penalization cost for not supply energy to the non-critical loads. The penalty cost considered is 100 €/kWh.

-Grid Income(t) is the monetary income for selling the energy to the grid at 0.020 €/kWh.

Finally, the operational cost of the Microgrid with the algorithm in this specific day and considering the blackout event, got an increase difference of 2.1% in comparison with the same situation without the algorithm (operation cost for Situation-1 is 55.897 €/day while in Situation-2 is 54.784 €/day)

Then, the cost of guaranteeing an extension of the battery-bank lifetime respect to the early ageing factors is 1.113 €/day, in general terms, if this was the tendency during all the year, it may lead into an operational cost of 406.245 €/year. This cost increase, much higher than the previous case, can be assumed to assure an extension of the battery-bank lifetime.

4.4. <u>Battery Charger Selection</u>

Once the EMS has optimized the solution within its cost function evaluation, the execution orders must be sent to the BC to implement the selected charging procedure. The premise of the project is to develop a solution based on a commercial battery charger (BC) capable to implement the predictions of the modified EMS optimization program.

Table 9 shows the dynamical values generated by the algorithm at the option D from the case 1, which will be sent to the BC in order to perform the charging process. This table correspond to the plot of the fig. 24.

TABLE 9. CASE 1 - EMS PROPOSAL AND ESS ALGORITHM COUNTERPROPOSAL – OPTION D

Hours	00:00 to 01:00				12:00 to 13:00				22:00 to 23:00			23:00 to 24:00		
TIME [h]	0.083		1.000		12.083		13.00		22.083		23.00	23.083		24.00
Available Energy [kWh]	0.789		0.789		0.0		0.0		-4.896		-4.896	0.0		0.0
Battery Cell Voltage [V]	2.093		2.094		2.352		2.352		2.042		2.035	2.10		2.10
Battery Current [V]	15.00	…	15.00	…	124.51	…	37.006	…	-97.143	…	-100.22	0.0	…	0.0
Required Energy [Kwh]	62.803		62.829		585.69		174.07		-396.72		-407.88	0.0		0.0
SOC [p.u]	0.50		0.505		0.78		0.812		0.814		0.773	0.773		0.773

Note: The time variation is equal to 5 minutes, but in an hourly scale 5 minutes is equivalent to 0.0833 hours.

As seen in table 9 the control references to be sent from the EMS to the ESS are the charging current for the bulk stage, the SOC end of bulk charge value and the battery voltages for the float and absorption stage. Driving a commercial Battery Charger to be compliant with the ESS reference values depends on the programmability of the BC. In this concern SMA and Victron commercial BC programmable characteristics (which are resumed in Appendices 3 and 4) have been analyzed. This analysis has revealed that SMA BC performs by itself a very careful management of the battery health but leaves less degrees of freedom to the user as the SOC values which are not easily accessible. For this reason Victron BC has been finally chosen as a platform able to implement the ESS control references.

5. Communication characteristics

The main issue at this point is to assure the data transfer process from the algorithm solver to the EMS and from the EMS to the BC.

5.1.1. From the Algorithm solver to EMS

Being Matlab a Numerical computing software who needs a user to execute commands, and taking into account the EMS must obtain the results from the algorithm constantly and sequentially, an application was developed in order to give the EMS the control over the solver.

Knowing that the EMS uses the spreadsheet Excel (developed by Microsoft-Office), a code in VBA (visual basic for applications) was developed to perform the Matlab program, creating an automatic process, which is on charge of the algorithm execution. Fig. 25 shows an example of the app, where each time the button A "Battery Modelling" is clicked, Matlab process the information.

The codification sentences used to develop the app can be found in the appendices.

The purpose consists in establishing a connection between two independent softwares, later, and considering the developing of the EMS, the codification of the app can by modified to fit the global requirements.

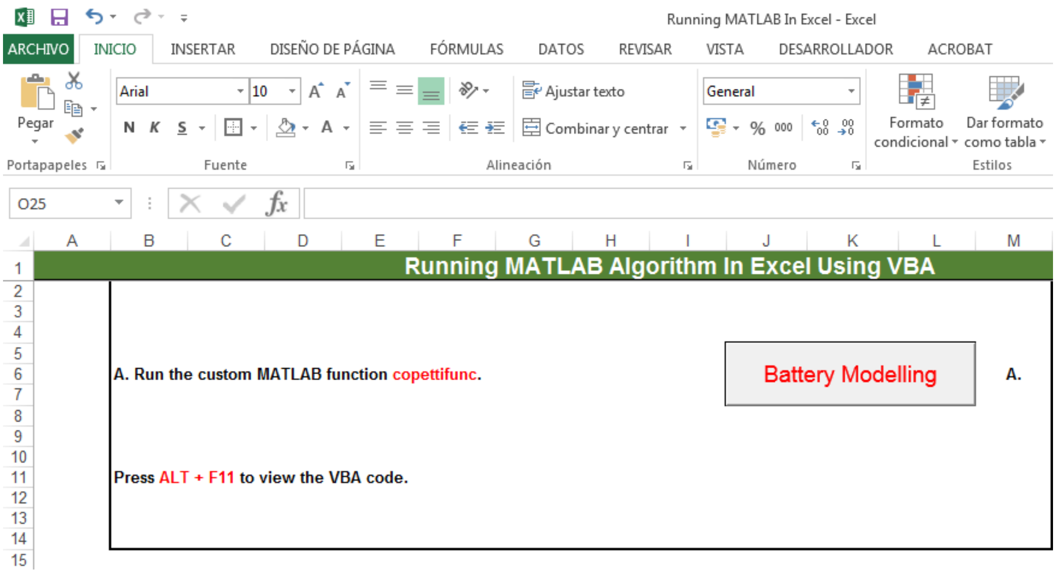


Fig. 25. Application - Microsoft Excel

5.1.2. From EMS to BC (Victron-Quattro)

Once the EMS has finished all the data managing process, execution orders are sent to all the actuators of the microgrid. Being the battery charger one of them, there must be a secure path for command the requests.

All settings in the Victron-Quattro can be modified using the communication protocols CAN-bus or Mod-bus. However, the last protocol has some communication limitations proper of the Victron [37], for this reason, the CAN-bus protocol is selected in this project.

5.1.2.1. Victron – CAN bus protocol

The CAN-bus is a message-based protocol designed for microcontrollers and other artefacts to intercommunicate among each other in applications avoiding a host computer.

All the functionalities in the Victron-Quattro are grouped in clusters of registers (VREGs), depending on the functionality of each one; this characteristic allows a large amount of manageable settings.

Vregs may involve single or multiple associated topics. However, should not be initialized if there is no necessity.

In a general description, Vregs are divided in two groups: static and dynamic. Static Vregs, which defines internal settings of the device, these ones are not meant not be sent intermittently, on the other hand, dynamic VREGs values (parameters) can be sent periodically.

As seen in the Table 10, the Vregs are organized in pages using the higher byte of each register in hexadecimal notation [38].

TABLE 10 VREG CLASSIFICATION

Vreg Page	Description
0x00	Vreg commands
0x01	Product information / Update
0x02 to 0x7F	Device Control
0x80 to 0xEE	Product specific, message depends on the device sending them
0xF0 to 0xFF	Reserved

Because of particular purposes, pages from 0x02 to 0x7F and from 0x80 to 0xEE are registers that can be used by the user to manage the Quattro; these pages are specific for the control of the device. All the other pages are out of the interest of this project.

The following tables indicate the most important parameters in order to control and supervise the BC:

Table 11 states for the general aspects to control the device, changing the operational mode or request the state of the device are common actions in this section.

TABLE 11. GENERAL SETTINGS

VREG	Function	Type	# of bits	Characteristic	Observations
General aspects					
0x0200	Device Mode	read / write	un8	mode	1: Charger Only (rw) 2: Inverter Only (rw) 3: On (rw) 4: Off (rw)

0x0201	Device State	read only	un8	state	0x00: Off 0x01: Low Power Mode, 0x02: Fault, 0x03: Bulk, 0x04: Absorption, 0x05: Float, 0x06: Storage, 0x07: Equalize, 0x08: Pass thru, 0x09: Inverting, 0x0A: Assisting, 0x0B: Power Supply Mode, 0x0C-0xFA: Reserved, 0xFB: Test, 0xFC: Hub-1, 0xFD-0xFE: Reserved, 0xFF: Not Available

The Vregs shown in Table 12 allow the user to control or request the limit current on any of both inputs. One can notice the precision on this registers is in the order of 100 mA.

TABLE 12. AC INPUTS

VREG	Function	Type	# of bits	Characteristic	Observations
AC INPUTS					
0x0204	AC active input	read only	un8	Active input	The AC input being used (or the last used one).
0x0210 0x0220	AC IN1/IN2 Current Limit	read only	un16	limit	The ac current limit in units of 100mA.
0x0211 0x0221	AC IN1/IN2 Current Limit Min	read only	un16	limit	The minimum acceptable current limit in 100mA
0x0212 0x0222	AC IN1/IN2 Current Limit Max	read only	un16	limit	The current limit in steps of 100mA.
0x0213 0x0223	AC IN1/IN2 Current Limit Internal	read only	un16	limit	The current limit in 100mA.
0x0214 0x0224	AC IN1/IN2 Current Limit Remote	read / write	un16	limit	Set the current limit to the passed value in 100mA

Moreover, Table 13 identifies the registers that allow the user to control the battery settings, like the different limits of times or boundary voltages and currents.

TABLE 13. BATTERY SETTINGS

VREG	Function	Type	# of bits	Characteristic	Observations
BATTERY SETTINGS					
0xEDFD	Battery automatic equalization mode	read write	un8	auto equalization mode	0=off (default), 1=on
0xEDFC	Battery bulk time limit	read write	un16	bulk time limit	0=off, time in 0.01 hours*
0xEDFB	Battery absorption time limit	read write	un16	absorption time limit	0=off, time in 0.01 hours*
0xEDFA	Battery float time limit	read write	un16	float time limit	0=off, time in 0.01 hours*
0xEDF9	Battery repeated absorption time duration	read write	un16	rep. abs. time duration	time in 0.01 hours (default 1 hour)
0xEDF8	Battery repeated absorption time interval	read write	un16	rep. abs. time interval	time in 0.01 days (default 7 days)
0xEDF7	Battery absorption voltage level	read write	un16	absorption voltage	voltage in 0.01V
0xEDF6	Battery float voltage level	read write	un16	float voltage	voltage in 0.01V
0xEDF5	Battery storage voltage level	read write	un16	storage voltage	voltage in 0.01V
0xEDF4	Battery equalization voltage level	read write	un16	equalization voltage	voltage in 0.01V
0xEDF3	Battery discharge voltage level (lower alarm boundary)	read write	un16	discharge voltage	voltage in 0.01V
0xEDF2	Battery temperature compensation setting	read write	un16	temperature comp.	voltage in 0.01 mV / degree centigrade
0xEDF0	Battery maximum current	read write	un16	charge current limit	current in 0.1A
0xEDEF	Battery voltage selection	read write	un8	battery voltage	0=automatic, 12/24/36/48. multiple voltages
0xEDEB	Battery overcharge	read write	un16	overcharge voltage	voltage in 0.01V

	voltage level (upper alarm boundary)				
0xEDE9	Battery power supply voltage	read write	un16	voltage	Voltage in 0.01V. Voltage set point used when the charger operates in power-supply mode.

Table 14 indicates the monitor battery settings.

TABLE 14. BATTERY MONITORING SETTINGS

VREG	Function	Type	# of bits	Characteristic	Observations
BATTERY MONITOR SETTINGS					
0x0FFE	Time-to-go	read only	un16	TTG	Time-to-go in minutes
0x0FFF	State of Charge	read write	un16	SoC	State of Charge in 0.01% Range: 0.00 - 100.00%
0x1000	Battery Capacity	read write	un16	Capacity	Battery capacity in Ah
0x1001	Charged Voltage	read write	un16	Voltage	Charged voltage of the battery in 0.1V
0x1002	Charged Current	read write	un16	Tail current	Charged current as percentage of the battery capacity (0x1000) in 0.1%
0x1004	Charge Efficiency	read write	un16	Efficiency	The charge efficiency of the battery in % Range: 0 - 100%
0x1006	Current Threshold	read write	un16	Current	Current threshold in 0.01A. Everything below this threshold is considered 0A.
0x1008	Low State-of-Charge	read write	un16	Low SoC set/clear	Percentage in 0.1%.

Finally, Table 15 allows setting the parameters related to the charger itself.

TABLE 15. CHARGER SETTINGS

VREG	Function	Type	# of bits	Characteristic	Observations
Charger settings					
0xEDDF	Charger maximum current	read only	un16	charger current	current in 0.1A

0xEDDB	Charger internal temperature	read only	sn16	internal temperature	Temperature in 0.01 degrees centigrade
0xEDD7	Charger current	read only	un16	actual current	current in 0.1A
0xEDD6	Charger power	read only	un16	actual power	power in 0.01W
0xEDD5	Charger voltage	read only	un16	actual voltage	voltage in 0.01V

Because the inverter settings can be managed directly from the Victron's software HMI, the Vregs associated to this function are nor necessary, this settings are set only once at the operational beginning of the system.

The following examples show how to manage the protocol in order to send, receive and perform a modification at the registers.

A single PDU in CAN protocol is defined as follow:

Initializer	Addresses	Identifier		reg.L	reg.H	Data	Data	Data	Data
7.0.0.EF	FF.30	0x66	0x99	0x01	0x02	0x03	0x00	0x00	0x00

The first two bytes are used to identify the manufacturer. Proprietary messages are sent with priority level 7. Then, the header for a single frame is 7.0.0.EF.tg.src, where src (source) is the sending CAN device and tg (target) the element. When tg is 0xFF the message will become in sent in broadcast. Next, 0x66 and 0x99 bytes correspond to the Victron' manufacturer code. Then, the total header for all the messages is 7.0.0.EF. tg.src 0x66 0x99. The codes in purple correspond to the Vreg identifier and the ones in blue to data.

5.2. <u>Bus can based data transfer</u>

Based on the state diagram at fig 26, which sums up the explains behavior of the ESS respect to the EMS, a description of how the Bus Can protocol must be used to follows the Victron sequence mode control is as follows:

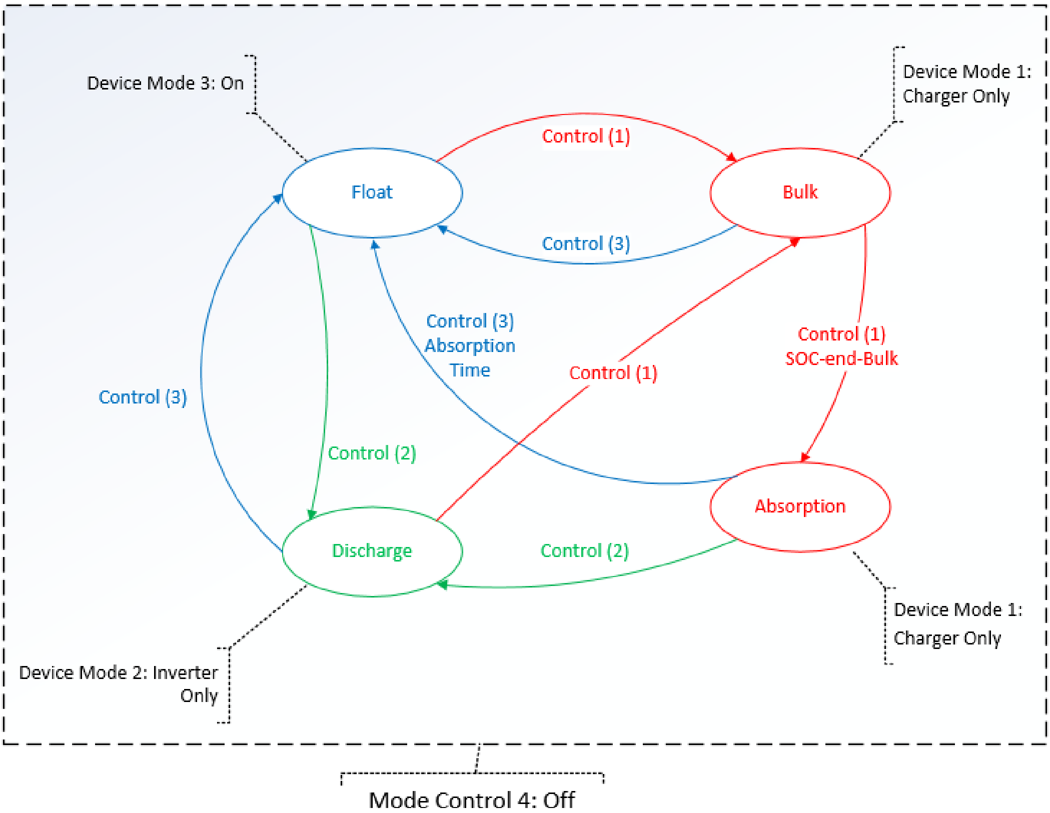


Fig. 26. ESS State diagram

Within the Victron-Quattro operational system, the Vreg 0x0201 (read) indicates the state operation:

- 0x00: Off
- 0x03: Bulk
- 0x04: Absorption
- 0x05: Float
- 0x09: Inverting
- 0x0A: Assisting

Meanwhile the Vreg 0x0200 (read / write) indicates the device mode operation:

- 0x01 - Control (1): Charger Only
- 0x02 - Control (2): Inverter Only
- 0x02 - Control (3): On
- 0x02 - Control (4): Off

For the example purposes, in this case, 0x30 is the device target (Victron - Quattro) and 0x50 is the EMS address.

Data Requirement steps:

To request the BC state (VREG 0x0201) the EMS should send:

7.0.0.EF.30.50 0x66 0x99 0x01 0x00 0x01 0x02 0xFF 0xFF

Then, some of the possible answers from the BC for this case can be:

7.0.0.EF.FF.30 0x66 0x99 0x01 0x02 0x03 0x00 0x00 0x00 - Bulk stage mode on

7.0.0.EF.FF.30 0x66 0x99 0x01 0x02 0x04 0x00 0x00 0x00 - Absorption stage mode on

7.0.0.EF.FF.30 0x66 0x99 0x01 0x02 0x05 0x00 0x00 0x00 - Float stage mode on

7.0.0.EF.FF.30 0x66 0x99 0x01 0x02 0x09 0x00 0x00 0x00 - Inverting operation

If the request for the BC is the charger voltage (VREG 0xEDD5), then the EMS should send:

7.0.0.EF.30.50 0x66 0x99 0x01 0x00 0xD5 0xED 0xFF 0xFF

Answer, the BC charger voltage is 50 Volts:

7.0.0.EF.FF.30 0x66 0x99 0xD5 0xED 0x88 0x13 0x00 0x00

Request for the battery maximum current (VREG 0xEDF0):

7.0.0.EF.30.50 0x66 0x99 0x01 0x00 0xF0 0xED 0xFF 0xFF

Answer, the battery maximum current 10 Ampere:

7.0.0.EF.FF.30 0x66 0x99 0x10 0x02 0x64 0x00 0x00 0x00

Because this register has a resolution of 0.1, to get 10 A the sent value must be 100 in hexadecimal nomenclature, which is 64-Hex.

Data Modification steps:

Whenever a change in any of the registers is performed, the target device sends an ACK to notify the modification was succeeded. In this cases the examples are focused on changing the following settings: state of the BC, maximum battery current and the maximum SOC for the bulk stage.

First, request the BC state (VREG 0x0200), sent from the EMS:

7.0.0.EF.30.50 0x66 0x99 0x01 0x00 0x00 0x02 0xFF 0xFF

Then, the answer from the BC is:

7.0.0.EF.FF.30 0x66 0x99 0x00 0x02 0x01 0x00 0x00 0x00 - Chager Only

Then, in order to modify the device mode operation (VREG 0x0200), the PDU from the EMS must be:

7.0.0.EF.30.50 | 0x66 0x99 0xF0 0xED 0x02 0x00 0x00 0x00

Answer, confirming the modification in VREG 0x0200:

7.0.0.EF.FF.30 | 0x66 0x99 0x00 0x02 0x02 0x00 0x00 0x00

In this case, the mode operation has changes from “charger only” to “inverter only”; this means the EMS has planned a discharge stage either from the float or the absorption stage.

In this case, in order to modify the battery maximum current to 15 Ampere (VREG 0xEDF0), the PDU must be:

7.0.0.EF.30.50 | 0x66 0x99 0xF0 0xED 0x96 0x00 0x00 0x00

Answer, confirming the modification in VREG 0xEDF0:

7.0.0.EF.FF.30 | 0x66 0x99 0xF0 0xED 0x96 0x00 0x00 0x00

Because this register has a resolution of 0.1, to get 10 A the sent value must be 150, in hexadecimal nomenclature is equal to 96-Hex.

Finally, to adjust the maximum SOC value in bulk stage (VREG 0x0FFF) to 75%, the flowing data must be sent:

7.0.0.EF.30.50 | 0x66 0x99 0xF0 0xED 0x4C 0x1D 0x00 0x00

Answer, confirming the modification in VREG 0x0FFF:

7.0.0.EF.FF.30 | 0x66 0x99 0xFF 0x0F 0x4C 0x1D 0x00 0x00

This register has a resolution of 0.01%; if the required value for this setting is 75%, the sent value must be 7500, which in hexadecimal nomenclature is 1D4C-Hex.

6. Budget

The purpose of this project is to develop a control algorithm considering the technical specifications of the commercial inverter Victron-Quattro related to the Machrek program, because of this reason no prototype was constructed. Therefore, the component list correspond to designing, planning, programming and simulating tasks.

Then, basic commitments of a feasibility study are to demonstrate the viability of the business to Investors, owners and financial institutions and to estimate the potential Economical return of a business initiative

6.1. Workload development

The analysis formalizes and revalidates the idea of a business based in the developed project, reducing the risk associated with an investment decision.

The approximate amount of time inverted in this projects was about 650 hours; this quantity includes all the tasks which were involved, since the organization of activities until obtain results and manageable data. In addition, there must be taken into account weekly meetings with the advisors, one hour/week with a senior engineer and two hour/week with a semi-senior engineer for 14 weeks.

Table 16 summarizes the given information including prices:

TABLE 16. WORKLOAD DEVELOPMENT

Activity	Time [h]
Research Activities	50
Objectives Planning	30
Documentation	40
Matlab™ Training	30
Microsoft VBA™ Training	10
Development and codification	160
Tests	70
Results analysis	40
Prototype validation	20
Final report	130
Revision and correction	60
Software final presentation	10
TOTAL	**650**

In addition, Figure 27 shows the time distribution of the involved activities:

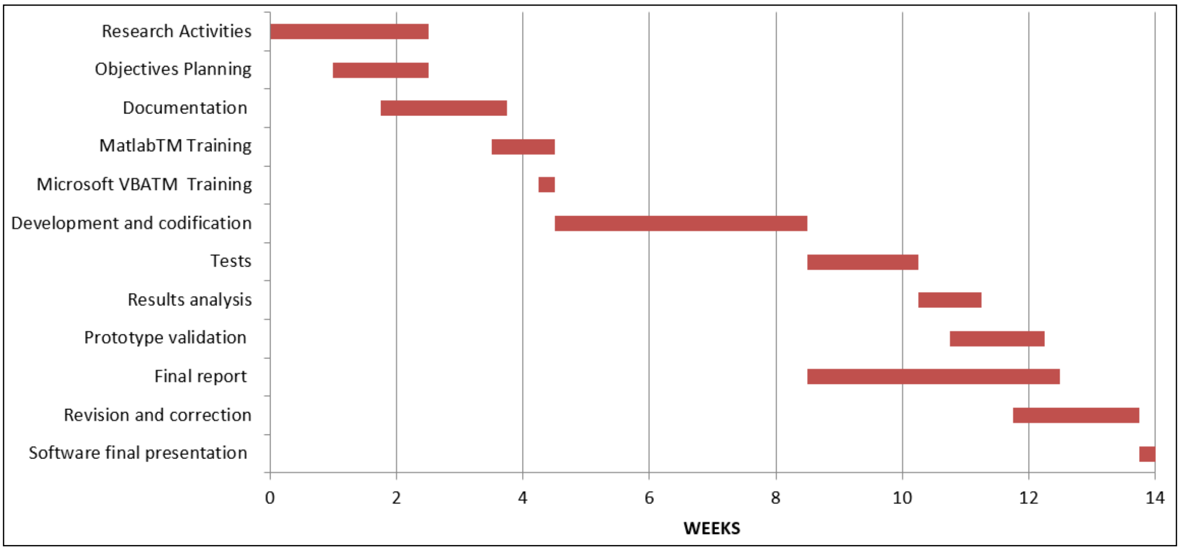


Fig. 27. Workload Distribution

6.2. Economic analysis

Table 17 shows the total cost involved in the project development; to carry out this, there must be taken into account the expenditures derived from the tasks, which were carried out (elaboration and validation of the prototype):

TABLE 17. PROJECT DEVELOPMENT BUDGET

Budget				
Item	**Details**	**Price**	**Quantity**	**Cost [€]**
Office	Computer depreciation 20%	200 [€]	1 u	200
	Office supplies	80 [€]	GLB	80
	Office services bill	350 [€]	4 u	1400
	Printer depreciation 10%	15 [€]	1 u	15
Software Licenses		2170	GLB	2170
Human resources	Junior Engineer	10 [€/h]	650 h	6500
	Semi-senior Engineer	45 [€/h]	28 h	1260
	Senior Engineer	80 [€/h]	14 h	1120
Documents / Patents		2000	1 u	2000
Sub Total				14745
+ Incidents (5%)				737.25
TOTAL				**15482.25**

6.3. Financial viability

The Financial viability consists of the preparation of forecasts in a medium term, within a horizon of 5 years. Being forecasts for more than a year, it has a high degree of uncertainty; nevertheless, it is advisable to do it in order to have more information, which will support the decisions of the course to take, analyzing and correcting trends. This financial analysis consists of evaluating the current economic-financial situation of the project and its eventual future. With the financial plan, one can try to find out the future liquidity of the investment, which can make in the most opportune way to highlight its components.

It is assumed that a business plan will be implemented, based on the growing needs of this type of product and the sales forecasts. Thus, Table 18 summarizes the information of the expected income and capital expenditures for this software lifetime estimated at 5 years and a sale price of € 2500 per software unit.

TABLE 18. INCOME/EXPENSES QUANTIFICATION

YEAR	0	1	2	3	4	5
Sales Forecast [€]	-	3.00	6.00	8.00	12.00	9.00
Unitary price [€]	-	2500.00	2512.50	2525.06	2537.69	2550.38
Total Income revenues [€]	**0**	**7500.00**	**15075.00**	**20200.50**	**30452.25**	**22953.39**
Software budget development [€]	-29234.00	-	-	-	-	-
Advertising and marketing Expenses [€]	-	-800.00	-1400.00	-2000.00	-2500.00	-1800.00
Technical Support and Maintenance [€]	-	-2000.00	-3000.00	-4500.00	-6000.00	-5000.00
Total Expenses [€]	**-29234.00**	**-2800.00**	**-4400.00**	**-6500.00**	**-8500.00**	**-6800.00**
Result [€]	-29234.00	4700.00	10675.00	13700.50	21952.25	16153.39
Final result [€]	**-29234.00**	**-24534.00**	**-13859.00**	**-158.50**	**21793.75**	**37947.14**

Assuming an annual inflation of 0.5%, the results obtained are:

NPV (5%)	**26710€**
IRR	**27.43%**
Payback	**4 years**

Taking as a reference the NPV (net present value) and IRR (internal rate of return), which are positive, one can assume that the development of this technology is profitable under the supposed conditions, although the joint evaluation of all the indicators in each particular circumstance will decide its Economic viability.

7. Environment Impact

7.1. Project development

All the activities related on designing and execution of the project were fully realized with a computer in an office, then, there is no significant direct impact on the environment. Therefore, the main environmental impact is generated by the consumption of the electricity, which supplies this device.

The rational use of computer equipment and the correct environmental management of the office appliances (paper, printer cartridges, etc.) are considered as good environmental practices.

7.2. Project Execution

Since one of the main objectives of the project consist on the preservation of the lifetime of the batteries, the correct performance of the algorithm an all the related tasks will result on the diminution in the acquisition of the number of batteries and the correct managing of the non-used energy. Therefore, these effects could lead into the following positive results:

First, there is a high environmental cost related to the production and fabrication of batteries, then the longer we keep the batteries; the less of them will be by acquired.

Secondly, giving the microgrid the ability to storage the surplus energy in order to use it whenever is required by the EMS, allows the battery to work as an active element in the microgrid by taking care of the effects of its continuous use. Then, whenever is determined by the EMS, the batteries can be used to supply energy to the loads instead of the diesel generators. This behavior may generate a positive side effect, the possibility of non-diesel energy production, where the reduction on the emissions of global warming gases from the combustion of fossil fuels are involved.

Then, the reduction of these emissions, contributes to the improvement of the quality of the area.

8. Conclusions and future development

This project has suggested a procedure to integrate a Pb-acid ESS management algorithm into a global optimization program devoted to minimize a cost function of microgrid systems. This approach is based on a modification of the optimization program to support the proper charge/discharge stages of a battery bank handled by commercial BC. These stages are computed out of the optimization program to reduce both computation complexity and convergence problems. Simulation results have confirmed the feasibility of this procedure and have highlighted a slight cost function increase. This cost can be easily assumed to preserve the battery lifetime and thus to extend the microgrid proper operation time.

However, the two major drawbacks consist in the lack of information related on how to calculate the proper time for the absorption stage and how measure of the SOH. Until now, after following the recommendations of the fabricants, one can only assume that the implemented method assures the extension on the life-time of the battery, but there is no feasible technique to prove how much or until when the batteries will work in a proper way.

To partly mitigate these drawbacks, finding accurate methods on how to calculate both the SOH and the proper time for the absorption stage as well as an experimental verification of the suggested approach are mandatory.

It is worth noting that the method can be extended to other storage technologies and other energy scenarios.

Part of the developed project and the results presented in this TFM have been submitted in paper format in ISEE'17 (International Symposium on Industrial Electronics) organized by the IEEE, which will be held in Edinburgh from the 19th - 21th of June of the present year. The acceptance result is pending.

Bibliography

A thorough reference list such as that shown in the following:

[1] Universitat Politècnica de Catalunya - Barcelona Tech (UPC), "Energy Campus. MED-Solar project," UPC, [Online]. Available: https://campusenergia.upc.edu/en/news/med-solar-more-than-one-year-of-project. [Accessed 22 December 2016].

[2] D. E. Olivares, C. A. Cañizares and M. Kazerani, "A Centralized Optimal Energy Management System for Microgrids," in 2011 IEEE Power and Energy Society General Meeting, San Diego, 2011.

[3] G. Velasco and F. Guinjoan, "WP5.3 - Benchmarking of R&D Needs version 1.0," 2014. Internal report.

[4] GAMS Development Corporation, [On line]. Available: http://www.gams.com/. [Last access: 14 May 2016].

[5] R. Palma-Behnke, C. Benavides, F. Lanas, B. Severino, L. Reyes, J. Llanos and D. Sáez, "A Microgrid Energy Management System Based on the Rolling Horizon Strategy," IEEE Transactions on Smart Grid, vol. 4, no. 2, pp. 996-1006, 22 January 2013.

[6] EUROBAT Association of European Automotive and Industrial Battery Manufacturers, "Battery Energy Storage in the EU - Barriers, Opportunities, Services and Benefits," 2016.

[7] A. Parisio and L. Glielmo, "Energy Efficient Microgrid Management using MPC," in 2011 50th IEEE Conference on Decision and Control and European Control Conference (CDC-ECC), Orlando, 2011.

[8] National Renewable Energy Centre (CENER) - CENER - CIEMAT Foundation [Online]. Available: http://www.cener.com/es/areas-de-investigacion/departamento-de-integracion-en-red-de-energias-renovables/infraestructuras-y-recursos-tecnicos/atenea-microgrid-cener/introduccion-a-las-microrredes/

[9] M. P. Marietta, M. Graells and J. M. Guerrero, "A Rolling Horizon Rescheduling Strategy for Flexible Energy in a Microgrid," in 2014 IEEE International Energy Conference (ENERGYCON), Cavtat, 2014.

[10] R. Dufo-López, J. M. Lujano-Rojas and J. L. Bernal-Agustín, "Comparison of different lead–acid battery lifetime prediction models for use in simulation of stand-alone photovoltaic systems," Applied Energy, vol. 115, pp. 242-253, 2014.

[11] "Victron Energy B.V.," July 2016. [Online]. Available: https://www. victronenergy.com/upload/documents/Manual-Quattro-5k-8k-10k-100-100A-230V-(firmware-xxxx4xx)a-EN-NL-FR-DE-ES-SE.pdf

[12]N. Achaibou, M. Haddadi and A. Malek, "Modeling of lead acid batteries in PV systems," Energy Procedia 18, pp. 538-544, 2012.

[13] H. Fakham, D. Lu and B. Francois, "Power Control Design of a battery charger in a Hybrid Active PV generator for load following applications," IEEE Transaction on Industrial Electronics, vol. 58, no. 1, pp. 85-94, 2011.

[14] P. Manimekalai, R. Harikumar and S. Raghavan, "An Overview of Batteries for Photovoltaic Systems," International Journal of Computer Applications, vol. 82, no. 12, 2013.

[15] H. Ibrahima, A. Ilincaa , J. Perron. "Energy storage systems—Characteristics and comparisons", Science Direct, Renewable and Sustainable Energy Reviews, 12 (2008) 1221–1250, January 2007

[16] I. Buchmann, Cadex Electronics Inc, Fraserwood Way, Richmond, Canada [Online]. Available: http://batteryuniversity.com/learn/article/charging_the_lead_acid_battery

[17] R. Vader, "Victron Energy B.V.," June 2011. [Online]. Available: https://www.victronenergy. com.es/upload/documents/Book-Energy-Unlimited-EN.pdf. [Accessed 03 November 2016].

[18] SMA Solar Technology AG, Sonnenallee, Germany. Battery Management of the Sunny Island [Online]. Available: http://files.sma.de/dl/7910/SI_Batteriemanagement-TI-en-21.pdf

[18] J. B. Copetti and F. Chenlo, "A general battery model for PV system simulation," Progress in fotovoltaics, vol. 4, no. 1, pp. 283-92, 1993.

[19] J. B. Coppeti and F. Chenlo, "Lead/acid batteries for photovoltaic applications. Test results and modeling," Journal Power Sources, Vols. (1-2), no. 47, pp. 109-18, 1994.

[20] J. M. Lujano-Rojas, R. Dufo-Lopez and J. L. Bernal-Agustin, "Optimal sizing of small wind/battery systems considering the DC bus voltage stability effect on energy capture, wind speed variability, and load uncertainty," Applied Energy, vol. 93, pp. 404-12, 2012.

[21] J. Salameh, N. Ghossein, M. Hassan, N. Karami, M Najjar. Department of Electrical Engineering, University of Balamand, El Koura, Lebanon. [Online]. Available: http://www.ozenergyfuture.com/wp-content/uploads/2016/06/3-Battery-Modelling-and-lifetime-prediction_Nagham.pdf

[22] K. Smith, E. Wood, S. Santhanagopalan, G. Kim, A. Pesaran. NREL - National laboratory of the U.S. Department of Energy, [Online]. Available: http://www.nrel.gov/docs/fy14osti/61037.pdf

[23] A. Chaouachi, R. Kamel, R. Andoulsi, K. Nagasaka, "Multiobjective Intelligent Energy Management for a Microgrid". IEEE Transactions on Industrial Electronics, Vol: 60, Issue: 4, April 2013

[24] A. Luna, N. Diaz, Student, M. Graells, J. Vasquez and J. Guerrero, "Mixed-Integer-Linear-Programming Based Energy Management System for Hybrid PV-wind-battery Microgrids: Modelling, Design and Experimental Verification", IEEE Transactions on Power Electronics, Vol. 32, no. 4, April 2017

[25] M. Cirrincione, M. Cossentino, S. Gaglio, V. Hilaire, A. Koukam, M. Pucci, L. Sabatucci, G. Vitale. "Intelligent Energy Management System". IEEE International Conference on Industrial Informatics (INDIN 2009), 2009

[26] I. S. C. C. 21, "Guide for optimizing the performance and life of lead-acid batteries in remote hybrid power systems," IEEE Std 1561-2007, pp. C1–25, 2008.

[27] F. Nejabatkhah and Y. W. Li, "Overview of power management strategies of hybrid ac/dc microgrid," IEEE Transactions on Power Electronics, vol. 30, no. 12, pp. 7072–7089, Dec 2015.

[28] W. Shi, X. Xie, C.-C. Chu, and R. Gadh, “Distributed optimal energy management in microgrids,” IEEE Transactions on Smart Grid, vol. 6,no. 3, pp. 1137–1146, May 2015.

[29] F. Marra and G. Yang, “Decentralized energy storage in residential feeders with photovoltaic,” in Energy Storage for Smart Grids, P. D. Lu, Ed. Boston: Academic Press, 2015, pp. 277 – 294.

[30] P. Malysz, S. Sirouspour, and A. Emadi, “An optimal energy storage control strategy for grid-connected microgrids,” IEEE Transactions on Smart Grid, vol. 5, no. 4, pp. 1785–1796, July 2014.

[31] A. Luna, N. Diaz, Student, M. Graells, J. Vasquez and J. Guerrero, “Mixed-Integer-Linear-Programming Based Energy Management System for Hybrid PV-wind-battery Microgrids: Modelling, Design and Experimental Verification”, IEEE Transactions on Power Electronics, Vol. 32, no. 4, April 2017

[32] The MathWorks, Inc., «MATLAB,» [On line]. Available: https://es.mathworks.com /products/matlab/. [last acces: 10 January 2017].

[36] M. Marietta, F. Guinjoan, G. Velasco, R. Pique and D. Arcos-Aviles, “Analysis of a strategy of predictive control based on time scales for the management of a connected microgrid,” in 23th Annual Seminar on Automation, Industrial Electronics and Instrumentation (SAAEI 2016), Elche - Spain, 2016.

[37] Matthijs Vader, “Victron Energy B.V.,” [Online]. Available: https://www.victronenergy.com/upload/documents/Whitepaper-Data-communication - with-Victron-Energy-products_EN.pdf

[38] “Victron Energy B.V”, VE.Can registers in NMEA 2000 – version 20. [On line]. Available: https://www.victronenergy.com.es/download-document / 4636/ve.can-registers-public.pdf

[37] SMA Solar Technology AG, Sonnenallee, Germany. SUNNY ISLAND 6.0H / 8.0H [Online]. Available: http://www.sma.de/en/products/battery-inverters/sunny-island-60h-80h.html#Downloads-229866

[38] SMA Solar Technology AG, Sonnenallee, Germany. SUNNY ISLAND 6.0H / 8.0H for Off-Grid and On-Grid Application [Online].
Available: http://files.sma.de/dl/17632/SI_OFF_ON_6H_8H-DEN1642-V21web.pdf

[39] SMA Solar Technology AG, Sonnenallee, Germany. Solar Solutions for Off-grid Power Supply [Online]. Available: http://files.sma.de/dl/2485/SHS_HYBRID-AEN121410W.pdf

APPENDIX 1

Matlab code program

```
%Copetti`s Model
clc
close all
clear all
aux=('The SOC at the end of the BULK stage is 0.8');
disp(aux)
SOC_MAX_B=0.8;
SOC_O=input('Introduce the initial SOC of the Batteries SOC_O=  ');
if SOC_O>=0.8
   SOC_O=.79;
   aux=['Then, initial SOC of the Batteries SOC_O:  ',num2str(SOC_O)];
   disp(aux)
end
Ta=input('Introduce the ambient temperature Ta=  ');
Last_Day_Current=input('Introduce the last velue of the current=  ');
C10=1875;
I10=C10/10;
t=5/60;
VarTa=Ta-25;
Ct=1.67*C10*(1+0.005*VarTa);
   aux=('Due to the known value of C10=1875 Ah,');
   disp(aux)
   aux=('The maximum charge current at the bulk stage is 187.5x2=375 Amps');
   disp(aux)
%-------------------------------------------------
         lineM=zeros(10,120);
         veluesM=zeros(10,1152);
         stagesM=zeros(10,576);
         numberoftimesM=zeros(10,3);
         %SOCM=zeros(10,6);
         %positionM=zeros(10,6);
         mat=0;
```

```
%-----------------------------------------------
filename = 'PlanillasV4.xlsx';
for option=1:1:4
    switch option
        case 1
            AV_E=xlsread(filename,'Option1','E7:KF7');%available energy
        case 2
            AV_E=xlsread(filename,'Option2','E7:KF7');%available energy
        case 3
            AV_E=xlsread(filename,'Option3','E7:KF7');%available energy
        otherwise
            AV_E=xlsread(filename,'Option4','E7:KF7');%available energy
    end
        AV_E=AV_E*1000/12;
    final=length(AV_E);
    if AV_E(1)<0
        %Vc_O=2.085;
        Vc_O=2.1;
    end
    %-----------------------------------------------
    AV_E_table=zeros(1,24);
    aux_e=0;
    time=t:t:24;
    for i=12:12:288
        aux_e=aux_e+1;
        if aux_e==1
            AV_E_table(aux_e)=sum(AV_E(1:i));
        else
            AV_E_table(aux_e)=sum(AV_E(i-11:i));
        end
    end
    for caso=option:1:4
             vector_abs_on=zeros(1,288);
            %--------------- CASE 1 HOUR -------------
```

```
if caso==1 || caso==2 || caso==3 || caso==4
   for i=2:1:24
     if AV_E_table(i)==0 && AV_E_table(i-1)>0
        %asb(i)=1;
        for j=(i-1)*12+1:1:(i*12)
        vector_abs_on(j)=1;
        end
     end
   end
end
%---------------- CASE 2 HOURS ------------
 if caso==2 || caso==3 || caso==4
   for i=2:1:23
     if AV_E_table(i)==0 && AV_E_table(i-1)>0 && AV_E_table(i+1)==0
        %asb(i)=1;
        for j=(i)*12+1:1:((i+1)*12)
        vector_abs_on(j)=1;
        end
     end
   end
 end
%--------------- CASE 3 HOURS ------------
 if caso==3 || caso==4
   for i=2:1:22
     if AV_E_table(i)==0 && AV_E_table(i-1)>0 && AV_E_table(i+1)==0 &&
AV_E_table(i+2)==0
        %asb(i)=1;
        for j=(i+1)*12+1:1:((i+2)*12)
        vector_abs_on(j)=1;
        end
     end
   end
 end
%-------------CASE 4 HOURS-----------
if caso==4
```

```
      for i=2:1:20
         if AV_E_table(i)==0 && AV_E_table(i-1)>0 && AV_E_table(i+1)==0 &&
AV_E_table(i+2)==0 && AV_E_table(i+3)==0

            for j=(i+2)*12+1:1:((i+3)*12)
            vector_abs_on(j)=1;
            end
         end
      end
end
%---------------------------------------------
bulk=zeros(1,24);
vector_bulk_on=zeros(1,288);
for i=1:1:24
  if AV_E_table(i)>=0
      %bulk(i)=1;
      for j=(i-1)*12+1:1:(i*12)
          if vector_abs_on(j)==0
            vector_bulk_on(j)=1;
          else
            vector_bulk_on(j)=0;
          end
      end
  end
end
%-----------------------------------------------
SOC=zeros(1,final);
Q=zeros(1,final);
Vc=zeros(1,final);
nc=zeros(1,final);
RQ_E=zeros(1,final);
e=2.7172;
I_b=375;
if I_b>375
    I_b=375;
```

```
    aux=['Then, the charge current is:  ',num2str(I_b),'Amps'];
    disp(aux)
end

C=Ct/(1+0.67*(I_b/I10)^0.9);
I_b=I_b*ones(1,final);
%------------------------------
%------------------------------
flag=0;
inx=0;
aux=0;
minBulk_V=0;
lastBulk_I=0;
I_zero_a=0;
%----------------------------------------
temporal=0;
time_abs=0;
time_float=0;
time_bulk=0;
time_negative=0;
abs_temp=0;
float_temp=0;
negativ_temp=0;%to calculate the current, i need to take into account only the number of times im executing the absorption stage
bulk_temp=0;%to calculate the current, i need to take into account only the number of times im executing the absorption stage
%----------------------------------------
n=24;%Number of cells
Cb=zeros(1,final);
Vcb=zeros(1,final);
%----------------------------------------
while flag==0
     inx=inx+1;
       if inx==final
           flag=1;
```

```
        end
    %---------------------------------------------
    %THIS PART IS PERFORMED IF THE AV_E IS NEGATIVE
    %---------------------------------------------
        if AV_E(inx)<0
            negativ_temp=negativ_temp+1;%to calculate the current, i need to take into account only the number of times im executing the absorption stage
            time_negative=negativ_temp*t;
            if inx==1
                I_b(1)=AV_E(1)/(t*24*Vc_O);
                SOC(1)=SOC_O-(-1)*I_b(1)*t/C;
                Vc(1)=(2.085-0.12*(1-SOC(1)))-(-1*I_b(1)/C10)*((4/(1+(I_b(1)*-1)^1.3))+(0.27/(SOC(1))^1.5)+0.02)*(1-0.007*VarTa);
                RQ_E(1)=24*Vc(1)*I_b(1)*t;
                Cb(inx)=abs((1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16));
                Vcb(inx)=abs(I_b(inx)*t/Cb(inx));

            else
                I_b(inx)=AV_E(inx)/(t*24*Vc(inx-1));
                %.........................................
                C=(C10*1.67*(1+0.005*VarTa)/(1+0.67*(-I_b(inx)/I10)^0.9));
                %.........................................
                SOC(inx)=SOC(inx-1)-(-1)*I_b(inx)*t/C;
                Vc(inx)=(2.085-0.12*(1-SOC(inx)))-(-1*I_b(inx)/C10)*((4/(1+(I_b(inx)*-1)^1.3))+(0.27/(SOC(inx))^1.5)+0.02)*(1-0.007*VarTa);
                RQ_E(inx)=24*Vc(inx)*I_b(inx)*t;
                abs_temp=0;%Each time the negative stage isactivated, the reset for time_abs is executed
                Cb(inx)=abs((1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16));
                Vcb(inx)=Vcb(inx-1)+I_b(inx)*t/Cb(inx);
            end
    %---------------------------------------------
    %THIS PART IS PERFORMED IF THE AV_E IS POSITIVE
    %---------------------------------------------
            else
```

```
            if inx==1
               SOC_AUX=SOC_O;
            else
               SOC_AUX=SOC(inx-1);
            end
%-----------------BULK STAGE---------------------------
            if SOC_AUX<0.8  %BULK STAGE-----------------------------------
                 if vector_bulk_on(inx)==1
                       bulk_temp=bulk_temp+1;
                       time_bulk=bulk_temp*t;

                   if AV_E(inx)==0
                        Vc(inx)=2.1;%FLOAT STAGE-------
                        Vbat=2.1*n;%FLOAT STAGE-------
                     if inx==1
                        %if  Last_Day_Current<0
                          R(inx)=(2.35-2.16)/Last_Day_Current;
                        %else
                          %R(inx)=((1/C10)*(6/(1+   Last_Day_Current^0.6)+0.48/(1-
(Vcb(1)-2)/0.16)^1.2));
                        %end
                        I_b(inx)=(Last_Day_Current)-((Vbat-(n*2.098))/(n*R(inx)));
                         if I_b(inx)<0.00001
                          I_b(inx)=0;
                         end
                        Cb(inx)=(1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16);
                        SOC(inx)=SOC_O+I_b(inx)*t/C;
                        %Vcb(inx)=I_b(inx)*t/Cb(inx);
                        Vcb(inx)=SOC(inx)*0.16+2/24;
                        RQ_E(inx)=24*Vc(inx)*I_b(inx)*t;
                     else
                        if I_b(inx-1)<0
                          R(inx)=(2.35-2.16)/375;
                        else
```

```
              R(inx)=((1/C10)*(6/(1+I_b(inx-1)^0.6)+0.48/(1-(Vcb(inx-1)-
2)/0.16)^1.2));
             end
            %R(inx)=((1/C10)*(6/(1+I_b(inx-1)^0.6)+0.48/(1-(Vcb(inx-1)-
2)/0.16)^1.2));
             I_b(inx)=((I_b(inx-1))-((Vbat-(n*2.098))/(n*R(inx))));
               if I_b(inx)<0.00001
                I_b(inx)=0;
               end
             Cb(inx)=(1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16);
             Vcb(inx)=Vcb(inx-1)+I_b(inx)*t/Cb(inx);
             SOC(inx)=SOC(inx-1)+I_b(inx)*t/C;
             %Vcb(inx)=SOC(inx)*0.16+2;
             RQ_E(inx)=24*Vc(inx)*I_b(inx)*t;
         end
     else
           aux=0;
           if vector_bulk_on(inx)~=1
              I_b(inx)=0;
           end
           while aux==0
               if inx==1
           %...........................................
                   if I_b(1)==0
                   C=1;
                   else
                   C=C10*1.67*(1+0.005*VarTa)/(1+0.67*(I_b(1)/I10)^0.9);
                   end
           %...........................................
                   SOC(inx)=(SOC_O+I_b(inx)*t/C);
                   Vcb(inx)=SOC(inx)*0.16+2/24;
                   Cb(inx)=(1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16);
               else
           %...........................................
                   if I_b(inx)==0
```

```
                    C=1;
                    else
C=C10*1.67*(1+0.005*VarTa)/(1+0.67*(I_b(inx)/I10)^0.9);
                    end
                 %..........................................
                    SOC(inx)=(SOC(inx-1)+I_b(inx)*t/C);
                    Cb(inx)=(1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16);
                    Vcb(inx)=Vcb(inx-1)+I_b(inx)*t/Cb(inx);
                  end
Vc(inx)=(2+0.16*SOC(inx))+(I_b(inx)/C10)*((6/(1+I_b(inx)^0.86))+(0.48/(1-SOC(inx))^1.2)+0.036)*(1-0.025*VarTa);
               minBulk_V=Vc(inx);%Storing the last Bulk voltage, this value will be the referencie for the absorption stage
               RQ_E(inx)=24*Vc(inx)*I_b(inx)*t;
               %--------------------------------------------
                    if AV_E(inx)>=RQ_E(inx)
                        aux=1;
                    else
                        I_b(inx)=I_b(inx)-1;
                    end
                    if AV_E(inx)==0
                      Vc(inx)=2.1;
                    end
                  if inx>1
                    if I_b(inx)>0 && vector_bulk_on(inx)==1
                      lastBulk_I=I_b(inx);
                    end


                  end
                end
              end
            abs_temp=0;%Each time the bulk is activated, the reset for time_abs is executed
            end
```

```
            end
        %-----------------------------------------------------
        %----------------BULK STAGE END----------------------
        %-----------------------------------------------------
            if SOC_AUX>=0.8 && vector_bulk_on(inx)==1
              temporal=1;
            end
            if (vector_abs_on(inx)==1 || temporal==1)%ABSORPTION STAGE/FLOAT STAGE---------------------------------------
                temporal=0;
                %aux=0;
                if I_b(inx-1)<0
                  R(inx)=(2.35-2.16)/375;
                else
                  R(inx)=((1/C10)*(6/(1+I_b(inx-1)^0.6)+0.48/(1-(Vcb(inx-1)-2)/0.16)^1.2));
                end
        %-------------------------
        %--------FLOAT STAGE-------
        %-------------------------
                time_abs=abs_temp*t;%This step will allow us to know the total time of the absorption stage
                if (SOC_AUX>=0.95)  ||  (time_abs>=4) %FLOAT STAGE-------
                        Vc(inx)=2.1;%FLOAT STAGE-------
                        Vbat=2.1*n;%FLOAT STAGE-------
                        I_b(inx)=((I_b(inx-1))-((Vbat-(n*2.098))/(n*R(inx))));
                        float_temp=float_temp+1;
                        time_float=float_temp*t;
        %-------------------------
        %-----END FLOAT STAGE------
        %-----ABSORPTION STAGE-----
        %-------------------------
                else %ABSORPTION STAGE
                   Vc(inx)=2.352;%ABSORPTION STAGE
```

```
            Vbat=2.352*n;
            I_b(inx)=(I_b(inx-1))-((Vbat-(n*2.35))/(n*R(inx)));
            I_last_abs=I_b(inx);
            abs_temp=abs_temp+1;

         end   %ABSORPTION STAGE/FLOAT STAGE
  %--------------------------
  %---END ABSORPTION STAGE---
  %--------------------------
         if I_b(inx)<0.00001
            I_b(inx)=0;
         end
         Cb(inx)=(1.67*C10)/((1+0.67*(I_b(inx)/I10)^0.9)*n*0.16);
         SOC(inx)=SOC(inx-1)+I_b(inx)*t/C;
         %Vcb(inx)=Vcb(inx-1)+I_b(inx)*t/Cb(inx);
         %Vcb(inx)=SOC(inx)*0.16+2;
         Vcb(inx)=Vcb(inx-1)+I_b(inx)*t/Cb(inx);
         RQ_E(inx)=24*Vc(inx)*I_b(inx)*t;
         if SOC_AUX>=1
            SOC(inx)=1;
            RQ_E(inx)=0;
            I_b(inx)=0;
            Vc(inx)=Vc(inx-1);
         end
      end
      if vector_abs_on(inx)==0 && vector_bulk_on(inx)==0 && SOC_AUX>=0.8
         SOC(inx)=SOC(inx-1);
         I_b(inx)=0;
         Vc(inx)=Vc(inx-1);
         RQ_E(inx)=0;
      end
   end
end
%---------------------TIMES---------------------
```

```
    hour_b=floor(time_bulk);
    min_b=(time_bulk-hour_b)*60;
    hour_a=floor(time_abs);
    min_a=(time_abs-hour_a)*60;
    hour_f=floor(time_float);
    min_f=(time_float-hour_f)*60;
    hour_n=floor(time_negative);
    min_n=(time_negative-hour_n)*60;
%-----------------DATA MANAGING---------------------
bloquear_bulk=0;
bloquear_abs=0;
bloquear_neg=0;
posicion_bulk=zeros(1,2);
posicion_abs=zeros(1,2);
posicion_neg=zeros(1,2);
cuantos_bulk=0;
cuantos_abs=0;
cuantos_neg=0;
posicion_maxsoc_bulk=zeros(1,2);
j=0;
k=0;
l=0;
for i=2:1:288
  if (0<I_b(i-1)<I_b(i))&&(Vc(i)<2.352)&& bloquear_bulk==0
      bloquear_bulk=1;
      bloquear_abs=0;
      bloquear_neg=0;
      cuantos_bulk=cuantos_bulk+1;
      j=j+1;
      posicion_bulk(j)=i;
  end
  if (0<I_b(i)<I_b(i-1))&&(Vc(i)==2.352)&& bloquear_abs==0
      bloquear_bulk=0;
      bloquear_abs=1;
```

```
      bloquear_neg=0;
      cuantos_abs=cuantos_abs+1;
      k=k+1;
      posicion_abs(k)=i;
      posicion_maxsoc_bulk(k)=i-1;
    end
    if  0>I_b(i)&& bloquear_neg==0
      bloquear_bulk=0;
      bloquear_abs=0;
      bloquear_neg=1;
      cuantos_neg=cuantos_neg+1;
      l=l+1;
      posicion_neg(l)=i;
    end
  end
  SOC_Max_hour=0;
  SOC_Max_min=0;
    %disp('---------------------------------------------')
     aux=['Number of times the bank of batteries will enter in BULK MODE: ',num2str(cuantos_bulk)];
    disp(aux)
     aux=['Maximum reachable SOCs at BULK will be:  '];
     disp(aux)
    for i=1:1:length(posicion_maxsoc_bulk)
        SOC_Max_hour=floor(posicion_maxsoc_bulk(i)*t);
        SOC_Max_min=(posicion_maxsoc_bulk(i)*t-SOC_Max_hour)*60;
         aux=['SOC(',num2str(i),')=    ',num2str(SOC(posicion_maxsoc_bulk(i))),'    at ',num2str(SOC_Max_hour),'h:',num2str(SOC_Max_min),'m'];
         disp(aux)
    end
     aux=['Number of times the bank of batteries will enter in ABSORPTION MODE: ',num2str(cuantos_abs)];
     disp(aux)
     aux=['Number of times the bank of batteries will enter in DISCHARGING MODE:',num2str(cuantos_neg)];
```

```
     disp(aux)
     disp('-------------------------------------------')
%*************************PLOTS*******************
abs_cont=zeros(1,288);
ok=0;
inc=0;
vector=zeros(1,2);
for i=2:1:288
    if Vc(i)==2.352
        abs_cont(i)=1;
    end
    if abs_cont(i)~=abs_cont(i-1)
        inc=inc+1;
        vector(inc)=(i-1)*t;
    end
end
x_plot=zeros(length(vector),2);
for i=1:1:length(vector)
x_plot(i,:) = [vector(i) vector(i)];
end
y_V=[2 2.4];
y_I=[-200 200];
y_R=[-1000 1000];
y_A=[-1000 1000];
y_S=[.4 1];
i=0;
Time_plot=t:t:24;
%------------------------------------------
 figure
subplot(5,1,1)
plot(Time_plot,Vc,'g','LineWidth',1.4);
hold on
  grid on
  grid minor
```

```
 for i=1:1:length(vector)
    plot(x_plot(i,:),y_V,'Color','k')
 end
 set(gca,'xtick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24])
 set(gca,'FontSize',24);
legend('VOLTAGE','Location','northoutside','Orientation','horizontal')
 ax = gca; % Get handle to current axes.
 ax.GridAlpha = .3;  % Make grid lines less transparent.

subplot(5,1,2)
plot(Time_plot,I_b,'b','LineWidth',1.4);
hold on
  grid on
  grid minor
 for i=1:1:length(vector)
    plot(x_plot(i,:),y_I,'Color','k')
 end
set(gca,'xtick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24])
 set(gca,'FontSize',24);
legend('CURRENT','Location','northoutside','Orientation','horizontal')
 ax = gca; % Get handle to current axes.
 ax.GridAlpha = .3;  % Make grid lines less transparent.

subplot(5,1,3)
 plot(Time_plot,RQ_E,'r','LineWidth',1.4);
hold on
grid on
 grid minor
  for i=1:1:length(vector)
 plot(x_plot(i,:),y_R,'Color','k')
  end
set(gca,'xtick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24])
  set(gca,'FontSize',24);
  legend('REQUIRED ENERGY','Location','northoutside','Orientation','horizontal')
```

```
 ax = gca; % Get handle to current axes.
 ax.GridAlpha = .4;  % Make grid lines less transparent.

subplot(5,1,4)
plot(Time_plot,AV_E,'g','LineWidth',1.4);
hold on
grid on
grid minor
 for i=1:1:length(vector)
 plot(x_plot(i,:),y_A,'Color','k')
 end
set(gca,'xtick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24])
 set(gca,'FontSize',24);
 legend('AVAILABLE ENERGY','Location','northoutside','Orientation','horizontal')
 ax = gca; % Get handle to current axes.
 ax.GridAlpha = .4;  % Make grid lines less transparent.

subplot(5,1,5)
plot(Time_plot,SOC,'b','LineWidth',1.4);
hold on
grid on
grid minor
 for i=1:1:length(vector)
 plot(x_plot(i,:),y_S,'Color','k')
 end
set(gca,'xtick',[0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24])
 set(gca,'FontSize',24);
 legend('SOC','Location','northoutside','Orientation','horizontal')
 ax = gca; % Get handle to current axes.
 ax.GridAlpha = .4;  % Make grid lines less transparent.
%----------EXPORT------------
Time_table=zeros(1,24);
RQ_E_table=zeros(1,24);
AV_E_table=zeros(1,24);
```

```
        SOC_table=zeros(1,24);
        NU_E_table=zeros(1,24);
        aux=0;
        NU_E=AV_E-RQ_E;
        for i=12:12:288
          aux=aux+1;
          Time_table(aux)=Time_plot(i);
          SOC_table(aux)=SOC(i);
          if aux==1
            NU_E_table(aux)=sum(NU_E(1:i));
            RQ_E_table(aux)=sum(RQ_E(1:i));
            AV_E_table(aux)=sum(AV_E(1:i));
          else
            NU_E_table(aux)=sum(NU_E(i-11:i));
            RQ_E_table(aux)=sum(RQ_E(i-11:i));
            AV_E_table(aux)=sum(AV_E(i-11:i));
          end
        end
        %---------EXPORT V2----------
        %SOCM=zeros(10,6);
        %positionM=zeros(10,6);
          mat=mat+1;
 lineM(mat,:)=[Time_table       RQ_E_table/1000       AV_E_table/1000       SOC_table
NU_E_table/1000];
          valuesM(mat,:)=[Vc I_b RQ_E SOC];
          stagesM(mat,:)=[vector_bulk_on vector_abs_on];
          numberoftimesM(mat,:)=[cuantos_neg cuantos_abs cuantos_bulk];
          %SOCM=SOC(posicion_maxsoc_bulk);
          %positionM=posicion_maxsoc_bulk*t;
  end
end

xlswrite(filename,lineM','mlab','A1');
xlswrite(filename,valuesM,'mlab','A121');
xlswrite(filename,stagesM,'mlab','A131');
```

```
xlswrite(filename,numberoftimesM,'mlab','A141');
```

APPENDIX 2.

VBA code program

```
Sub CustomFunctionOneOutput()
'----------------------------------------------
'This app executes the MATLAB function "copettifunc" using the MATLAB COM Automation Server.
'---------------------------------------------
   'Declaring variables.
    Dim Base    As Double
    Dim Matlab       As Object
    Dim mFilePath   As String
    Dim Result       As String
    'Input value.
    Base = Sheet1.Range("O17").Value
    ' MATLAB object (the COM server).
    On Error Resume Next
    Set Matlab = CreateObject("matlab.application")
    'In the case of error inform the user and exit the macro.
    If Err.Number <> 0 Then
        MsgBox "Could not open Matlab!", vbCritical, "Matlab Error"
        Exit Sub
    End If
    On Error GoTo 0
    'Specify the location of the m file
    mFilePath = ThisWorkbook.Path
    'Load the m file in MATLAB.
    Matlab.Execute ("cd('" & mFilePath & "\')")
    'Execute the function.
    Result = Matlab.Execute("copettifunc(" & Base & ")")
End Sub
```

APPENDIX 3

SMA SUNNY ISLAND – BATTERY CHARGER

The SMA [37] device is supposed to be a fundamental element within the Microgrid, storing the generated solar power and working intelligently with the EMS in the energy consumption process. In addition, it has an energy management that keeps the system running in case of critical situations.

Fig. SMA – Sunny Island [37]

It is a robust but simple device for microgrid systems and can be personalized for specific uses. The Sunny Island comes with the capability to administrate the charging and discharging phases fully automatically, increasing the electrical resilience of the batteries.

Consequently, catastrophically events such as overcharging or energy deployment of the batteries are carefully avoided. It comes with a proprietary management system that assures the performance stated by the battery manufacturers in both architecture connections, isolated or connected to the grid [38].

The battery charger

This device adapts itself to the current operating conditions of the battery by the employment of a self-learning SOC algorithm. Then, the charging and discharging procedures are fully delimited and monitored by the BC controller in real time. This makes easier measuring the state of charge and the real capacity of the batteries, allowing the determination of the SOC based on the real-effective capacity rather than the value rated by the battery manufacturer. The described characteristic is more effective as the battery gets old, as well as under harassed environments or in low temperature conditions. The result is a substantial upgrading in the precision of the measures [38].

Moreover, the advanced management of the Sunny Island automatically decides the most favorable charging strategy for the battery depending on its situation and type. This aspect supports to the improvement of the charge regulation by evading the inaccuracies on determining the SOC over long periods of time and preventing overcharging circumstances when the battery is fully charged [39]. This is exceptionally remarkable to assure a longer battery durability.

In addition, in case of available power, it is used optimally to charge the batteries by identifying the exceeding energy from the difference between the source and the loads.

These characteristics reduce the necessity of replacing the battery bank in short operational periods, increasing the independence from the grid.

Battery Charging Aspects [18]

The Sunny Island complies the battery charging with the recommended three phases:

- Bulk (Constant current phase)
- Absorption (Constant Higher - voltage phase)
- Float (Constant Lower - voltage phase)

Which work as follow:

Bulk - Constant Current Phase: The main role of battery management is to limit the current to the maximum permissible value; this can be set by the user, in this case by the EMS.

However, the bulk charging current can also be limited by two other parameters:

- Nominal currents of the external energy sources.
- Maximum AC charging current of the Sunny Island.

Whenever one of those values is reached, the battery current will be limited by the constraint that triggered the limit condition. The constant current phase ends when the cell SOC of the battery reaches the SOC-end-of-charge value for the relevant battery type.

Absorption – Higher Constant Voltage Phase

At the higher constant voltage phase, the battery voltage is limited at a constant value. For this voltage phase, the battery management chooses one of the following three charging processes: Boost charge, Full charge and Equalization charge. The unique difference among them is the voltage magnitude which is near the gassing voltage, the Sunny Island and its self-learning characteristic, determine the adequate value according the circumstances related to operating time and temperature.

Through different communications protocols, the EMS can adjust the voltage level and the charging time of the absorption phase.

Float Charge – Lower Constant Voltage Phase

The battery management reduces the voltage from the absorption to the float voltage charge. The stage remains activates until the float charge one of the following conditions:

- The electric discharges has reached 30% of the nominal capacity.
- The SOC is lower than 70% of the charging capacity.

Then battery management switches to the bulk phase.

Technical characteristics

Technical data	Sunny Island
AC output (loads / stand-alone grid)	
Rated grid voltage / AC voltage range	230 V / 202 V ... 253 V
Rated frequency / frequency range (adjustable)	50 Hz / 45 Hz ... 65 Hz
Rated power (for Unom / fnom / 25 °C / cos φ = 1)	6 000 W
AC power at 25 °C for 30 min / 5 min / 3 sec	8 000 W / 9 100 W / 11 000 W
Rated current / maximum output current (peak)	26 A / 120 A
Total harmonic factor output voltage / power factor with rated power	< 4 % / -1 ... +1
AC input (PV array, grid or MC box)	
Rated input voltage / AC input voltage range	230 V / 172.5 V ... 264.5 V
Rated input frequency / allowable input frequency range	50 Hz / 40 Hz ... 70 Hz
Maximum AC input current	50 A
Maximum AC input power	11 500 W
Battery DC input	
Rated input voltage / DC voltage range	48 V / 41 V ... 63 V
Maximum battery charging current	140 A
Rated DC charging current / DC discharging current	115 A / 136 A
Battery type / battery capacity (range)	FLA, VRLA / 100 Ah ... 10 000 Ah
Charge control	IUoU charge procedure
Efficiency / self-consumption	
Maximum efficiency	95%
Self-consumption without load / standby	< 26 W / < 4 W
Protective devices (equipment)	
AC short-circuit / AC overload	● / ●
DC reverse polarity protection / DC fuse	– / –
Overtemperature / battery deep discharge	● / ●
Overvoltage category as per IEC 60664-1	III
General data	
Dimensions (width x height x depth)	467 mm x 612 mm x 242 mm
Priority	63 kg
Operating temperature range	-25 °C ... +60 °C
Protection class (according to IEC 62103)	I
Climatic category according to IEC 60721	3K6
Degree of protection according to IEC 60529	IP54
Features / function	
Operation and display / multifunction relay	External via SRC-20 / 2
Three-phase systems / parallel connection	● / ●
Integrated bypass / multicluster operation	– / ●
State of charge calculation / full charge / equalization charge	● / ● / ●

Integrated soft start / generator support	● / ●
Battery temperature sensor / data cables	● / ●

Limitations

As a first approach, the SMA integrates a complex and precise battery management algorithm that results in a proper solution for not supervised microgrids. This means that the Sunny Island and its proprietary algorithm set its own operating instructions for the energy management [18].

Although the SMA gives the EMS great programmability characteristics, these are focused only to the configuration settings and not to the entire control of the equipment; therefore, the system cannot be considered as flexible as it should. As pointed before, the uncertainty of the system lies in the determination of SOC, this values must be fully manageable, however, with the SMA this parameter is not accessible to the user. The BC disposes a locked software environment, which complicates the task of controlling the equipment externally. This is mainly because the Sunny Island was conceived as a primary element in the microgrid administration, taking the decisions of the energy management related to the batteries [18].

Then, the proper operation of the Sunny Island creates a disparity with the EMS, where the BC is not an actuator anymore, but operating in parallel with the main processing system. This functionality may be avoided by turning off much of the devices settings; the Sunny Island disposes a Modbus interface [18] in order to allow the data transfer with another device, eluding the SMA proprietary software. Consequently, after analyzing all the possible communication's features, the result is that the charging process would be still locked from external manipulations.

On the other hand, the SMA algorithm procedure lacks on the forecast analysis of the supply/consumption energy, this means that the concept of microgrid energy balance is not fully developed. For instance, at the beginning of the operation day the ESS charging process takes place whenever there is an exceeding amount of energy from the suppliers, this means the battery will be charged by the main grid instead of the energy surplus from the renewable energy, then the unique criteria for the charging is the presence of the available energy.

While the Sunny Island is intended exclusively for the specific supervision of battery lifespan [38] – [39], the EMS generates a global analysis where battery operation and preservation features are part of a complex system. The cost optimization criteria is the principal characteristic, resulting in a much more complete solution.

It must be noted, that the purpose of this project is to develop an algorithm to manage the battery energy balance process, which is mainly the correct control of the voltage, current and time of each of the three charging phases, as well as the SOC (state of charge). Then, even when the voltages and currents of the phases can be regulated externally by the Modbus interface, it is not possible to control the time operation of each one, to decide when each phase will be activated or turned off nor the SOC end of charge.

The EMS is able to fix the events based on the minimization of the cost function that is established on the production and consumption forecasting. A hierarchical decision-making process gives the feasibility of the system, where all the elements of the microgrid, including the BC, are subordinated. It is precisely the estimation of the future events that allows the performance of the network.

To solve the incompatibility inconvenient, the project was reevaluated with the intention of changing the BC and finding a device that engages the needed requirements of the system.

The new element must offer the same technical characteristics as the SMA, but have to integrate an improved and much flexible controllability feature by releasing the settings parameters. Selecting the correct charger for this specific situation is relevant to guarantee not only all requirements are accomplished but also to avoid the choosing of an over specified element, this may result in a more expensive solution.

However, after evaluated a range of commercial devices the Victron Quattro, a 10kVA bi-directional and fully administrable inverter is introduced in order to manage the bank battery, offering an alternative in this energy exchange situation.

APPENDIX 4

Victron Quattro – Bidirectional Converter

The Victron Quattro is a combination of an inverter, battery charger and transfer switch in one device. Whenever AC power is available, the inverter-charger uses this energy to recharges the battery bank, as seen in the following image:

Fig. Victron - Quattro [11]

In case the AC power supply is disconnected, the unit inverts DC battery power to provide the required energy to the AC output.

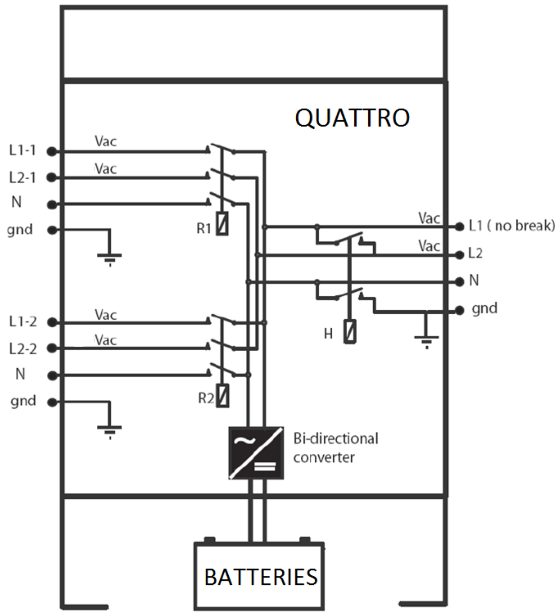


Fig. Internal configuration – Victron Quattro [11]

The Quattro comes with two AC inputs, which incorporates an internal transfer switch, as seen in the previous figure. Then, there is the possibility to connect two independent AC power supply sources to the BC, this means, the grid and a generator, or two other options. The Quattro will automatically connect to the active one.

A brief description of the Victron-Quattro and its main characteristics are specified as follow.

Three phase capability

A unique element cannot offer the possibility to manage 3 phases loads, then, three units can be connected and organized to provide the three-phase system, as is shown in the following figure. Nonetheless, each unit is able to manage up 10 kVA at the output; consequently, a maximum of six sets of three units can be arranged in parallel to deliver 180kVA power, which means a charging capacity of 2500 A.

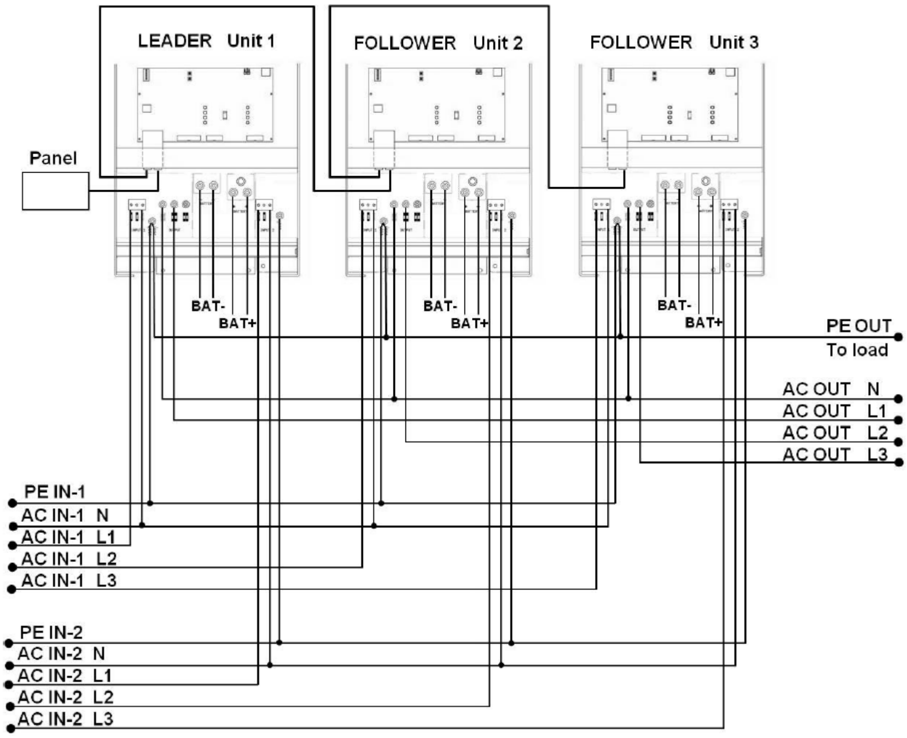


Fig. 23. Three phase structure – Victron Quattro [11]

Power Control

If any of the power sources presents a limited energy production, a current limit can be configured on each input. Then, the battery charger will consider the loads in order to take any unused energy to charging purposes, avoiding the overload of the supply inputs.

The UPS functionality (Uninterruptible Power Supply) is also available, in case of a supply failure or there is no presence of energy at any of the inputs, the Quattro changes the functionality from charging to inverter operation, taking over the supply of the loads.

Power Assist

This characteristic allows the Quattro to work in parallel with the energy source in case of any current shortfall (co-supply feature), delivering extra energy from the batteries, avoiding an energy misbalance at the loads. Therefore, by discharging the batteries, the peak demands can be assimilated by the BC, as well the peak demands can go forward to the charging process.

Two AC Outputs

The BC has two outputs, being the AC-OUT-1 the most significant one; it presents the no-break (UPS) characteristic, taking over the energy requirements of the devices connected in case of an input failure. This event takes less than 20 milliseconds; hence, no electronic device will suffer any interference.

In contrast, AC-OUT-2 delivers energy only when the inputs are active. Therefore, no critical loads are connected in this output.

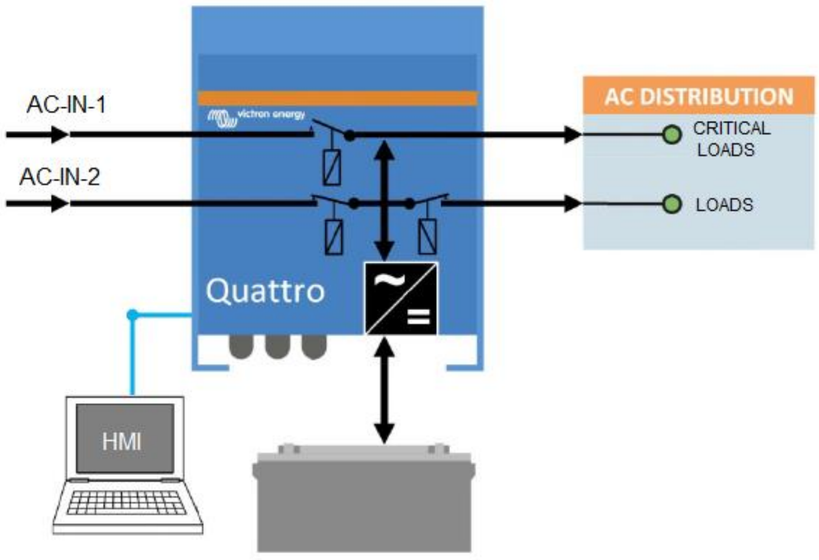


Fig. Victron Quattro - scheme [11]

Battery Charger

The batteries are charged in case of excess power or whenever the EMS establish it using the energy delivered by the inputs, and discharged when consumption exceeds production.

Victron´s technology is based on a smart system to implement the charging process using four regulated stages: Bulk, Absorption, Float, and Storage. The three firsts steps were explained in the chapter 2 (Charge stages of the Battery charger). Nonetheless, the purpose of the Storage mode consists in keeping the battery charged without any energy consumption. This stage is activated if the time of the float stage is extended by more than 24 hours, applying a voltage even lower than in the previous stage [12]. **Due to the no energy consumption characteristic and the lack of dynamics, this stage is not taken into account in this work.**

Additionally, if the batteries are not discharged in a long period in the order of days, once a week the BC activates the absorption stage to refresh the batteries voltage. This step must be done in order to prevent the stratification of the electrolyte, the main cause of early battery failure

Technical parameters

Within all the range of Quattro's chargers options, the model used in this project is 48/10000/140-100/100. This code stands for: 48 is the nominal voltage of the batteries, 10000 is the maximum power in kVA that is able to manage, 140-100 is the range of current in case an auxiliary battery is connected and the last number 100 is the maximum current at each output.

TABLE 2. VICTRON QUATRO – TECH. SPECIFICATIONS

Quattro	**Model: 48/10000/140-100/100**
AC inputs (2x)	Input voltage range: 187-265 VAC Input frequency: 45 – 65 Hz Power factor: 1

Maximum feed through current (A)	AC-IN-1: 100 A	AC-IN-2: 100 A
INVERTER		
Input voltage range (V DC)	38 – 66V	
Output (1)	Output voltage: 230 VAC ± 2% Frequency: 50 Hz ± 0.1%	
Output power at 25°C (VA) Non-linear load, crest factor 3:1	10000	
Output power at 25°C (W)	8000	
Output power at 40°C (W)	6500	
Output power at 65°C (W)	4500	
Peak power (W)	20000	
Zero load power (W)	20	
CHARGER		
Max. Charge voltage 'absorption' (V DC)	57.6	
Max. Charge voltage 'float' (V DC)	55.2	
Max. Storage mode (V DC)	52.8	
GENERAL		
Protection	a) output short circuit b) overload c) battery voltage too high	d) battery voltage too low e) temperature too high f) 230 VAC on inverter output g) input voltage ripple too high
VE.Bus communication port	For parallel and three phase operation, remote monitoring and system integration	
General purpose com. Port	2X	
Common Characteristics	Operating temp.: -40 to +65˚C Humidity (non-condensing): max. 95%	
ENCLOSURE		
Common Characteristics	Protection category: IP 21	
Weight (kg)	45	
Dimensions (hxwxd in mm)	470 x 350 x 280	

Equalization

Because of production tolerances, irregular temperature distribution and variations in the ageing characteristics of particular cells, it is possible that individual cells in a chain could become overstressed leading to premature failure of the cell. With every charge - discharge cycle the weaker cells will get weaker until the battery fails.

During discharging, the weakest cell will have the greatest depth of discharge and will tend to fail before the others. It is even possible for the voltage on the weaker cells to be reversed as they become fully discharged before the rest of the cells also resulting in early failure of the cell. There is a danger that once it has reached its full charge it will be subject to overcharging until the rest of the cells in the chain reach their full charge. Once a cell has failed, the entire battery must be replaced and the consequences are extremely costly.

At each charging and discharging cycle, a small amount of sulphate is adhered to the plates. When using three-state chargers, this small amount decreases significantly, but not in its entirety. Then, the sulphate adhered will increase. If the lead sulphate remains in the plates for long periods of time, it will harden and crystallize and consequently will reduce the capacity of the battery, increasing its internal resistance and making it impossible to deliver an adequate amount of energy in its terminals. When this happens, the battery becomes unusable; it is not possible to remove the crystallized sulphate.

Equalization is a charging method whose purpose is to return the batteries to their storage capacity, increase efficiency and extend life. This is achieved by a voltage overload applied in a controlled manner on the batteries. The process of equalization must be carried out periodically, under inspection.

This high voltage causes a vigorous charge within each cell and brings all cells to similar levels, incorporating a cell balancing scheme to prevent individual cells from becoming overstressed.

In the equalization mode, the Quattro will charge with increased voltage for one hour.

State of Charge determination

The calculation of the SOC, is performed by internal measures of the charge and discharge currents, for this reason, no DC loads are supported in this system.

The charge and discharge rates affect the effective capacity of a cell because the electrochemical activities in the cell take precise time to be completed, then, they are not able to track the instantaneous electrical stimulus on the cell.

Glossary

Battery bank: It is a set of batteries connected together in parallel or in series.

Definition Distributed Energy Systems (DES): is a term, which encompasses a diverse array of generation, storage and energy monitoring, and control solutions.

Distributed energy resources (DER): are smaller power sources that can be aggregated to provide power necessary to meet regular demand.

Prediction model: it is a dynamic model of the future behavior of a micro-grid. Future behavior is related to a standard to be optimized.

Protocol data unit (PDU): Information that is delivered as a unit among peer entities of a network and that may contain control information, such as address information, or user data, also known as a service data unit.

Operating cost curve: is the function that relates the hourly cost of fuel consumption [€ / h of operation] to the generated power expressed in [kW] of a non-renewable energy source.

MATLAB (matrix laboratory): is a multi-paradigm numerical computing environment and fourth-generation programming language. It is a proprietary programming language developed by MathWorks.

Renewable energy: Is energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat.

Renewable resource: Is a natural resource, which replenishes to overcome resource depletion caused by usage and consumption, either through a biological process or through other naturally recurring processes in a finite amount of time in a human time scale.

Spread Sheet: Is an interactive computer application for organization, analysis and storage of data in tabular form.

Visual Basic for Applications (VBA): Is an implementation of Microsoft's event-driven programming language Visual Basic 6 and it’s an associated integrated development environment.

Time horizon: is the absolute time of completion for the forecast horizon in seconds

List of Terms and Abbreviations

AC	Alternating current
AIMMS	Advanced Interactive Multidimensional Modeling System
BC	Battery Charger
C	Battery capacity at the charge/discharge constant current [Ah]
Cb	Battery capacitance [F]
Cp	Polarization capacitor [F]
C10	Charge/discharge capacity in 10 h at 25ºC [Ah]
dt	Duration of the time interval considered in hours
DOD	Depth of discharge
DC	Direct current
ESS	Energy Storage System
EMS	Energy Management System
GAMS	General Algebraic Modeling System
I10	Charge/discharge current in 10 h at 25ºC [A]
n	Number of battery cells
Pb-Acid	Lead–acid battery
PDU	Protocol data unit
pu	Per-unit system
PVS	Photovoltaic system
R	Internal resistance of the battery [Ω]
SOH	State of Health
SOC	State of Charge
UPS	Uninterruptible power supply
VBA	Visual Basic for Applications
Vbat	Battery bank voltage [V]
Vc	Cell voltage [V]
Vcb	Internal electromotive force of the battery [V]
Vcp	Polarization voltage [V]
Vg	Gasification voltage given by the manufacturer [V]
VREG	Clusters of registers
ΔT	Temperature variation referred to 25ºC [ºC]