Energy Management for IoT

Energy Storage, Generation and Conversion

LAB 3 report

Master degree in Embedded Systems

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1 Introduction

This lab focuses on the analysis of the energy management of an **IoT** system, under the points of view of energy generation, conversion and storage. The problem is addressed by using a SystemC model of the system, which is studied by means of **simulations**. In this way it is possible to study the whole system before building a prototype, by understanding the energy demand of all the various components (sensors, MCU etc...) and the behaviour of the energy sources. The main goal of this lab is to simulate an IoT system composed by 4 sensors (each one with different demands in terms of energy), a MCU, a battery with a DC-DC converter, a Photovoltaic (**PV**) module with a dedicated DC-DC converter and a radio-frequency(**RF**) module.

As first step, the simulator is going to be set up by inserting proper parameters and equations extracted from the datasheets of the various components. Then, a first simulation will be conducted based on the set-up provided by the instructors. Finally, the parameters for the simulation will be modified in order to run a custom simulation of the system.

2 Simulator setup

2.1 Photovoltaic panel

The PV panel is in charge of harvesting energy to supply the system. The irradiance is simulated by reading a dedicated *.txt* file, containing values for approximately 3 months. Data regarding voltage and current at the maximum power point (**MPP**) are extracted from the datasheet of the PV panel by using a *MATLAB*-based **digitizer**: by providing an image as input this tool is able to extract pairs *(x,y)* from it through a simple graphical user interface. By following the profiles of the V-I curves it is possible to obtain a digitized curve, used for the calculation of the MPP ad different irradiance values. In this case the most significant parameters are voltage and current at the MPP, which are inserted in a specific configuration file (`config_pv.h`) used by the simulator.

2.2 PV DC-DC Converter

The procedure for the configuration of the PV DC-DC converter is very similar to the one described for the PV panel. Starting from the datasheet of the converter, efficiency and input voltage are extracted by using the **digitizer**. Data are then inserted into the `config_converter_pv.h` configuration file, which is used by the related `.cpp` file

2.3 Battery DC-DC converter

The datasheet provides efficiency vs load current for this component as well. The latter is represented in logarithmic scale and it is expressed in mA so, in order to correctly report data in the `config_converter_battery.h` file, the efficiency was taken by using the **digitizer**, while the load current was reported by hand, following the logarithmic scale.

2.4 Battery model

Data regarding battery configuration and setting are extracted from the datasheet only, which provides different capacity-voltage curves depending on the discharge current (**C-rating**). The state of charge (**SOC**) is assumed to be 1 when the battery is fully charged and 0 when it reaches the voltage at which it is considered as discharged. In order to compute relevant parameters such as **resistance** and **open-circuit voltage (VOC)** we must consider two discharge curves. In particular, the 1C and the 0.5C curves have been selected and digitized for this analysis. Formulas regarding the above mentioned parameters are reported in the following:

$$V_{OC} = V_{1C} + R * I_{1C} \tag{1}$$

$$R = \frac{V_{0.5C} - V_{1C}}{I_{1C} - I_{0.5C}} \tag{2}$$

Digitized data are then interpolated through the *interp1* MATLAB function to have the same interval of SOC for both the curves. Equations related to R and V_{OC} are extracted by using the *Curve Fitting* tool provided by MATLAB as well: by giving the SOC interval and V_{OC} (or R) it is possible to choose the fitting equation for the two curves. For our purposes we have selected a 3^{rd} degree polynomial, whose equations are both reported in the battery source file (`battery_voc.cpp`), which was a good trade-off for points interpolation without incurring in the over-fitting issue.

3 Simulations

As mentioned in section 1, the system is composed of a series of loads: a PV panel, a DC bus, an MCU and a battery (with the related DC-DC converters). Loads are represented as simple two-state (active and sleep) PSMs, supplied with a fixed voltage. The activation mode and intervals of every load is defined in a dedicated `.json` file. This file must be provided to the simulator in order to start a simulation correctly, since it contains relevant informations about currents, activation times, activation windows etc. .

Moreover, the `.json` file includes critical parameters for the simulation such as total length of the simulation, simulation time step, reference voltage for bus and sensors, self-discharge factor of the battery. By acting on all these parameters it is possible to set up a considerable variety of configurations, in order to test the energy autonomy of our system.

3.1 Parallel simulation

A first simulation has been conducted based on the parameters defined in the `parallel.json` file provided by the instructors. As the name suggests, the file sets up a parallel simulation, activating all sensors at the same time instant. The simulation is periodic with period $T = 120s$ and all the loads have different *"ON"* periods. The same is valid for both the MCU and the RF module. At last, the self-discharge factor of the battery is set to 0 for our purposes. The PV panel provides a certain voltage and current to the PV DC-DC converter, which are based on the irradiance provided in the `gmonths.mat` file.

After running the simulation, considering these aspects, we focused on relevant quantities to be investigated, providing comparisons and evaluations related to voltages and current in the system. In particular, it is relevant to observe the behavior of the battery, analyzing the SOC and the V_{batt} voltage: with this configuration the system can be operative for about 14 days. Results are visible in fig. 1.

Currents flowing in the system are also crucial, so we must take into account that the simulator works with mA. It is worth noting the behavior of the computed PV panel current vs the real current generated by this element (fig. 2).

The parallel simulation has then been modified by adding a self-discharge factor of 0.0001 (equal to $100nA$ in the simulator) to see how it affects the battery voltage and to make results a bit more realistic. Fig. 3 shows the resulting voltage curves: the most remarkable difference is that the SOC shows an exponential decrease, differently from the linear reduction observed in fig. 1. As visible in fig. 4, the PV panel is not able to generate enough energy to supply the whole system, leading to a progressive depletion of the battery in approximately 12 hours. The behavior of the PV panel follows the pattern stated in the `gmonths.mat` file (fig. 5) but it is not able to provide enough current to rapidly compensate the effect of the self-discharge.

3.2 Serial simulation

By providing a different `json` file it is possible to execute other kinds of simulations. In particular, activation times of the various sensors in the design have been modified in order to execute a serial simulation: when the "ON" time of a sensor ends the following one is activated. During this simulation we have extended the duration of most of the "ON" times related to the components, while keeping a short idle interval at the end of the serial execution. To do so, the simulation period has been increased to $380s$. Simulation results can be observed in figures 6 and 7. For what concerns currents coming from the panel, no differences can be seen with respect to the results obtained in the parallel simulation, since the irradiance files used for the simulation are the same. Moving the attention on the battery voltage and the SOC the behaviour is very similar to the one observed in the first simulation, although in this second analysis there is a slightly wider gap between the SOC and the V_{batt} curves.

3.3 System lifetime improvements

Energy autonomy, intended as the time during which a system is able to accomplish its mission before some kind of maintenance is needed (e.g. battery swap), is one of the most important metrics to evaluate the effectiveness of an IoT device. In order to increase this parameter alternative solutions can be developed to power the device, acting on energy sources or energy storage devices or both. However, improvements are often limited by budget constraints, so only a subset of solutions can be applied in a real scenario.

For what concerns the design under analysis a maximum budget of 11$ is available to improve the lifetime of the device, which limits the choices to the following configurations (provided that the standard configuration is composed of 1 battery and one PV panel):

- 2 PV panels and one battery;
- 3 PV panels and one battery;
- 1 PV panel and 2 batteries;
- 1 PV panel and 3 batteries;
- 2 PV panels and 2 batteries.

The above mentioned configurations have been simulated by using the `parallel.json` configuration file, but a serial simulation has been ran to make a comparison with respect to the original workload.

3.4 Additional PV Panel(s)

The key idea has been to modify the bus so that it could accept input current from more than one PV. In order to do so, we have modified the source code (in particular `main.cpp`, `bus.cpp` and `bus.h` files) to allow this configuration, since each panel has its own DC-DC converter. To support 1 or 2 additional PV Panels (since the theoretical budget cap allows it) pre-processor instructions to the C++ compiler have been added so that the bus gets the proper configuration, instances of the PV Panel object are added, and if necessary the new signals are added to the tracer. The bus behavior is now only slightly modified since it considers as total scavenged current the sum of the scavenged currents coming from each panel.

The additional panels have been considered in parallel configuration with respect to the original one to increase the scavenged current. Moreover, a serial configuration could not be supported with the provided PV DC-DC Converter because the resulting voltage would be out of its operating range.

For simplicity and for the purpose of this laboratory, we considered the same irradiance values (provided in the `gmonths.mat` file) for each panel, but in a more sophisticated version of the simulator one could also provide different versions of such file to emulate different light exposure for each panel whenever they have different position for whatever reason.

3.5 Additional Battery

In contrast with the solution adopted with the PV Panels, additional batteries have not been instantiated as new objects in the simulation. Instead they have simply been mocked by modifying the current drawn from the existing battery in the original design. The idea here is that for each battery added to the system, the current drawn from each battery linearly reduces on the number of batteries itself. In short, if N batteries are added, the current requested to each battery will be $\frac{1}{N}$ of the total. The scenario is repeated during the charging phase, but of course here the current is not requested but supplied to the batteries. Following the previous description, the expert reader can notice that batteries are added in a parallel configuration as well. Once again, a serial setup is not suitable given the provided DC-DC converter since the resulting voltage out of the battery pack would be too high for the converter's working range. This setup can be beneficial from the single battery point of view since requested and supplied currents are scaled. From this situation a lower strain is put on the battery itself which could lead to an overall operational life.

3.5.1 2 PV panels and one battery

The first alternative uses a system in which 2 PV panels are connected in parallel, this means one panel more than the original configuration. The main differences with respect to the standard configuration are related to the trends of the battery voltage and SOC, visible in fig. 8.

3.5.2 3 PV panels and one battery

In order to maximize the number of PV panels in the system, one more panel can be added, bringing the total amount to 3. By looking at fig.9 it is clear that this configuration can ensure an energy autonomy for the entire simulation. For what concerns the battery voltage V_{batt}, the fluctuations are limited to 0.2V in the worst case. This is supported by the trend shown in the SOC curve.

3.5.3 1 PV panel and two batteries

It is possible to add another battery to the design in order to improve the overall capacity.

Results of the simulation are visible in fig. 10. It is interesting to compare these results to the ones obtained after the first parallel simulation, with only one panel and a battery (fig. 1) the SOC of the battery progressively decreases over time in both cases, but with two batteries the lifetime of the system is longer than in the other case (about 26 days vs 13 days). A peculiar characteristic is that the V_{batt} voltage curve presents rounded peaks around $t = 1.5 * 10^6 s$. This is mainly due to the contribution given by the PV panel (fig.10b), whose voltage peaks are more frequent in the interval around the mentioned time instant.

3.5.4 1 PV panel and 3 batteries

Considering the cost for a single battery (4.99\$) it is possible to connect two additional modules of this kind to the standard configurations while respecting the budget constraints.

The simulation outcome is visible in fig. 11. Looking at fig. 11a the expected lifetime of the system (considering the parallel workload) is approximately equal to $3.25 * 10^6 s$, which is more than 37 days. Both the battery and the PV voltage show similar behaviours to the ones observed in the two previous cases: when the PV panel experiences more frequent peaks the battery voltage decreases in a smoother manner, avoiding steep peaks.

3.5.5 2 PV panels and 2 batteries

Another possible configuration foresees a system with 2 panels and 2 batteries connected in parallel. The budget constraint is still respected since the additional cost for the components is equal to $4.99\$ + 5.50\$ = 10.49\$$.

Since the irradiance defined in the `gmonths.mat` file is taken as reference for both the panels, the total contribution of the harvesting section is doubled if compared to the standard configuration.

The SOC and V_{batt} curves (fig. 12) show that the operational life of the system is guaranteed for the entire simulation period ($7736400s$). This is further confirmed by the behaviour of the SOC curve, which remains always above of the V_{batt} curve.

3.6 Global comparison

Fig. 13 shows the battery SOC trend for all the maximum cost configurations. Given the parallel workload and `gmonths.mat` irradiance file it is immediate to observe that additional batteries increase the operational time of the system but they are not suitable for long-term operations. PV panels, instead, ensure the energy autonomy of the system for a longer period. In case of 3 panels in parallel the SOC (apart from small fluctuations given by more energy demanding intervals, i.e. periods in which no irradiance is present) is comprised between 90% and 100%, and the system can fully sustain the simulated workload for any period of time (provided that light will be present at some point in the long run to harvest energy).

For what concerns the effects of different workloads on the overall system, fig.14a displays the SOC of the energy storage device with multiple PV panel configurations, taking into account a parallel and a serial simulation. At a first glance the difference between curves related to the same configuration is not noticeable, but focusing on a small time interval it is possible to see the single contributions due to sensor, RF module and MCU activity (fig.14b).

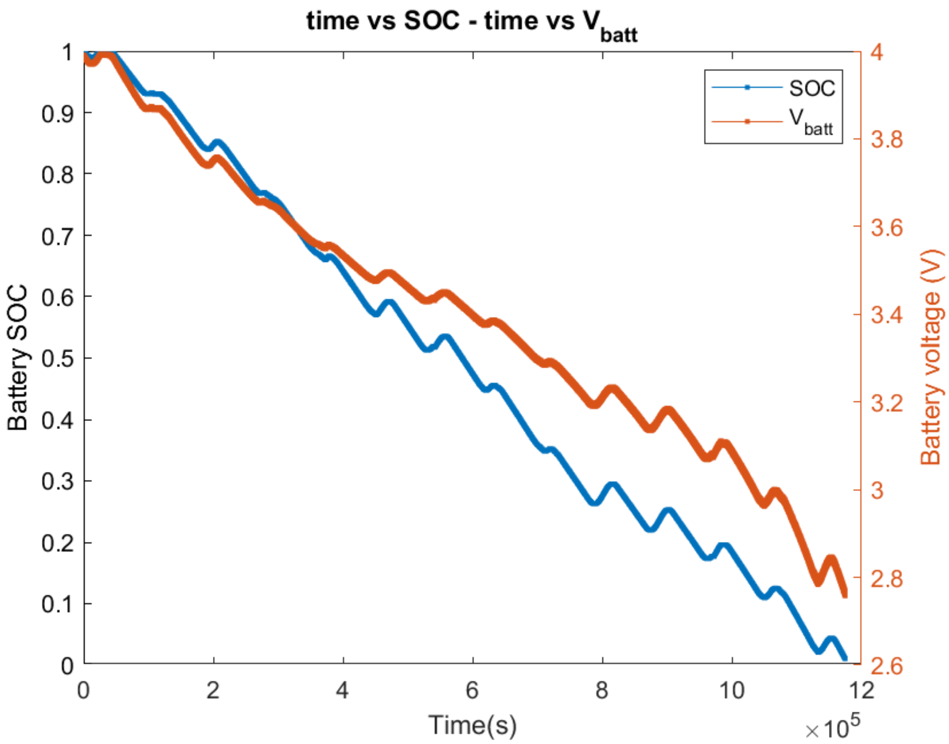
4 Conclusions

A detailed examination of the set of simulation outcomes shows that the proposed configurations present significant differences. In terms of lifetime, in particular, the analyzed alternatives can be divided in two main categories: multiple PV panel systems (i.e. more than one panel and one battery only) and multiple battery systems (i.e. one panel and multiple batteries). Both groups are characterized by a longer lifetime with respect to the original configuration. Some designs belonging to the first group, however, can ensure the energy autonomy of the system for the entire period of the adopted simulation, and the more panels are connected to the system the higher the SOC will remain over the simulation time.

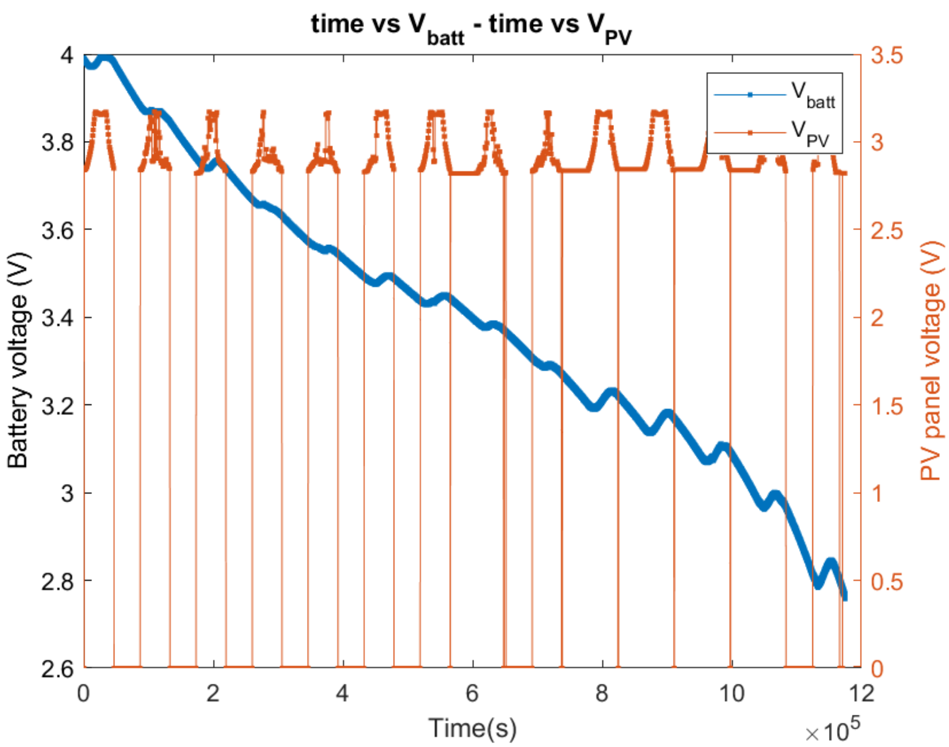
Going into detail, a configuration with 2 PV panels in parallel and 1 battery is able to stay active 5 times more the "ON" time associated to the original configuration. With 3 panels in parallel the system can be classified as "energy autonomous" (fig. 9): energy produced by the harvesting system far exceeds the consumption due to the system activity, and the SOC of charge of the battery never drops below 80%.

Hybrid designs (multiple batteries and PV panels) have intermediate performances between the two above mentioned categories: they can ensure a longer lifetime than multiple battery system but they are inferior to multiple panel systems.

One last point is worth of attention which is the response of the system to different simulations: if we perform a serial activation of the sensors the differences for what concerns SOC and battery voltage V_{batt} are almost indistinguishable with respect to the parallel one. This is mainly due to the way in which most of the components embedded in the system are modeled. Specifically, the most current consuming sensor (air quality) has an "ON" current of $48.2mA$, followed by the methane sensor with $18.0mA$, while the other elements only consume a fraction of mA and they do not affect the drawn current in a substantial way. In fig.14b it can be appreciated, especially in the curves which refer to a system with 1 PV panel only (blue and red lines), how the SOC curve changes its behavior when different sensors are active. The steeper discharge always happens when the air quality sensor is active, then the curve smooths. This behavior is mitigated in the serial execution of the sensor samplings, even if it only slightly affect the battery life due to the very low differences in the SOC of barely 0.005%.



(a) *SOC vs battery voltage*



(b) *Battery voltage vs PV panel voltage*

Figure 1: Variation of battery and PV panel voltages over simulation time

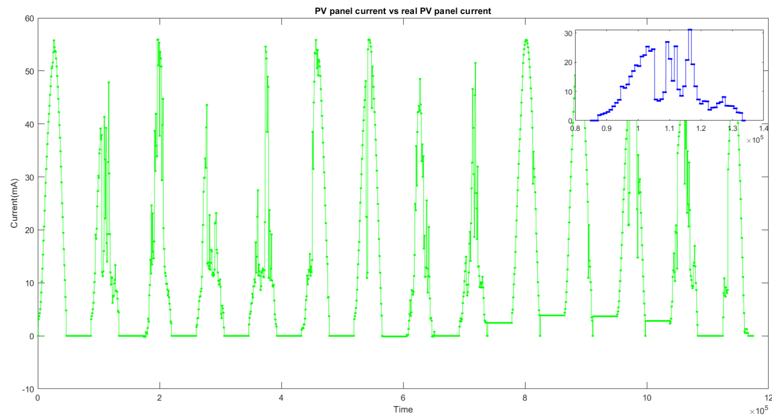


Figure 2: PV panel current (in green) vs real current (in blue)

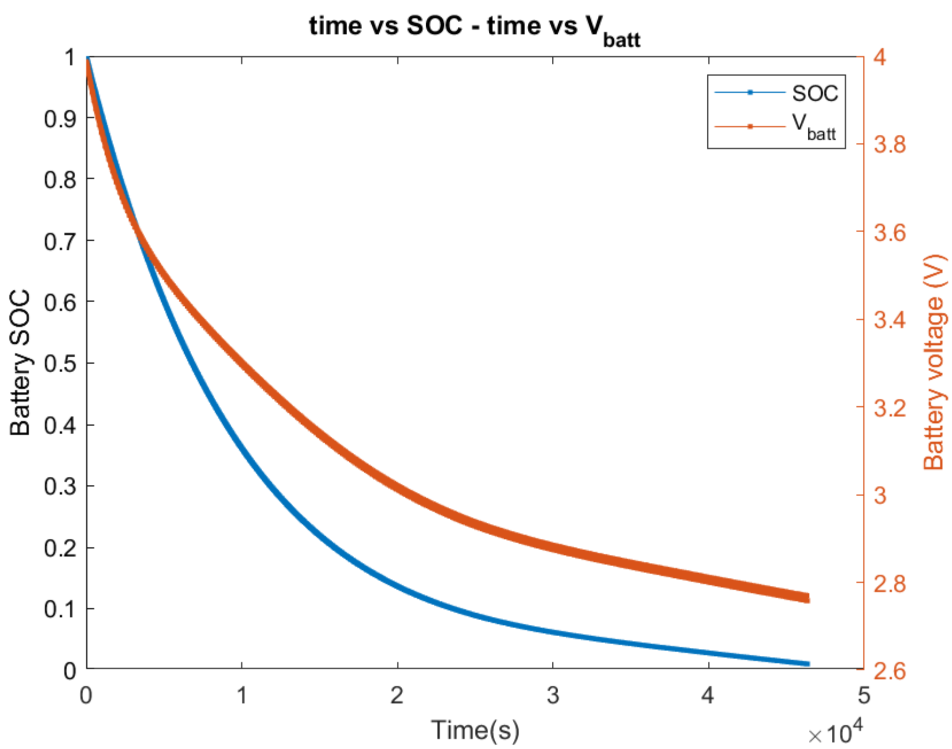


Figure 3: Battery voltage and SOC variations considering battery self-discharge

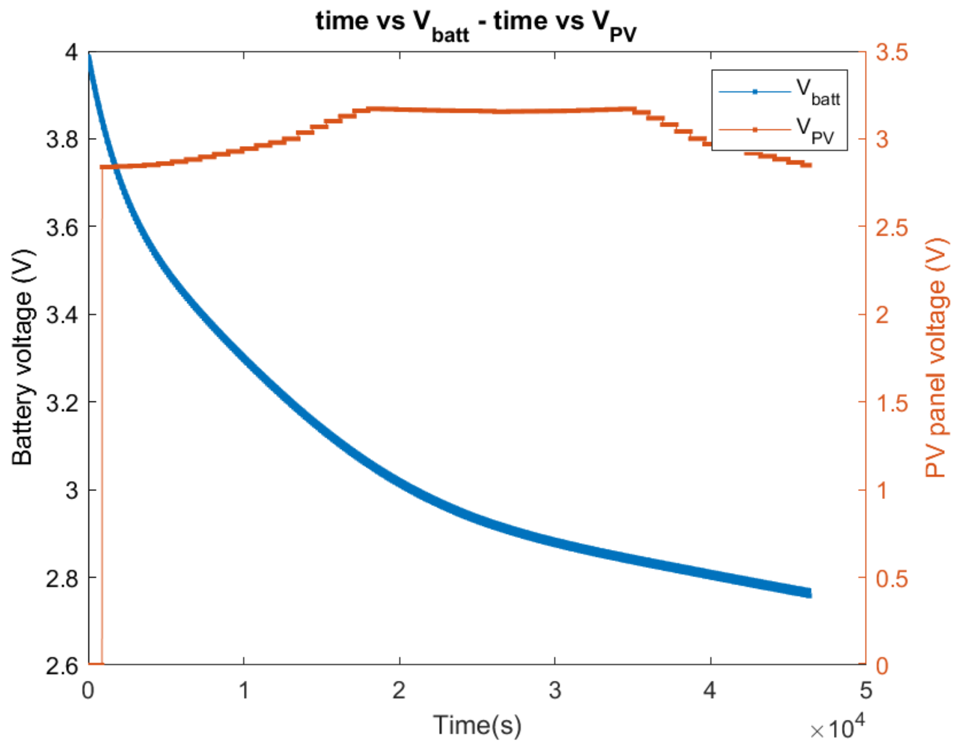


Figure 4: Battery voltage and PV voltage variations considering battery self-discharge

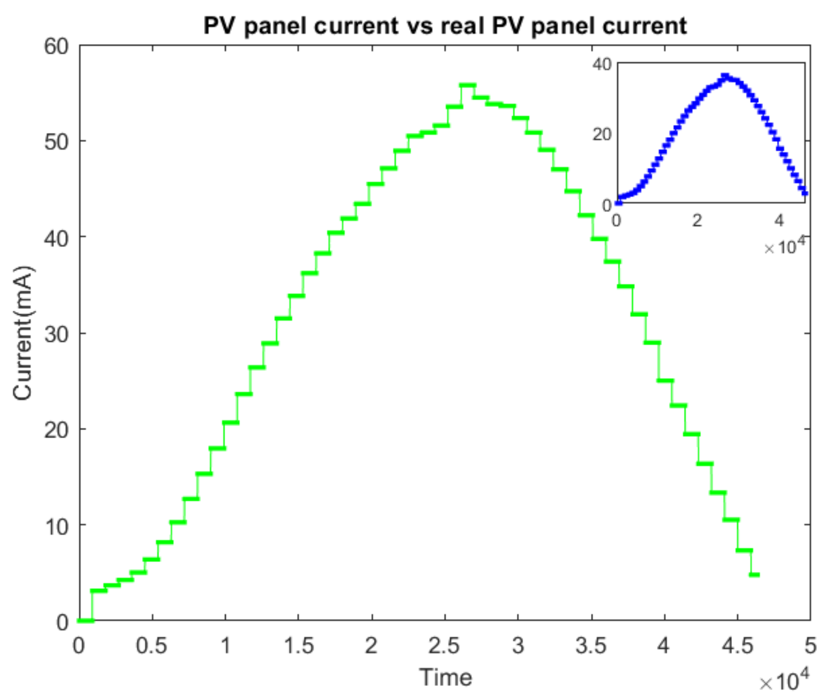
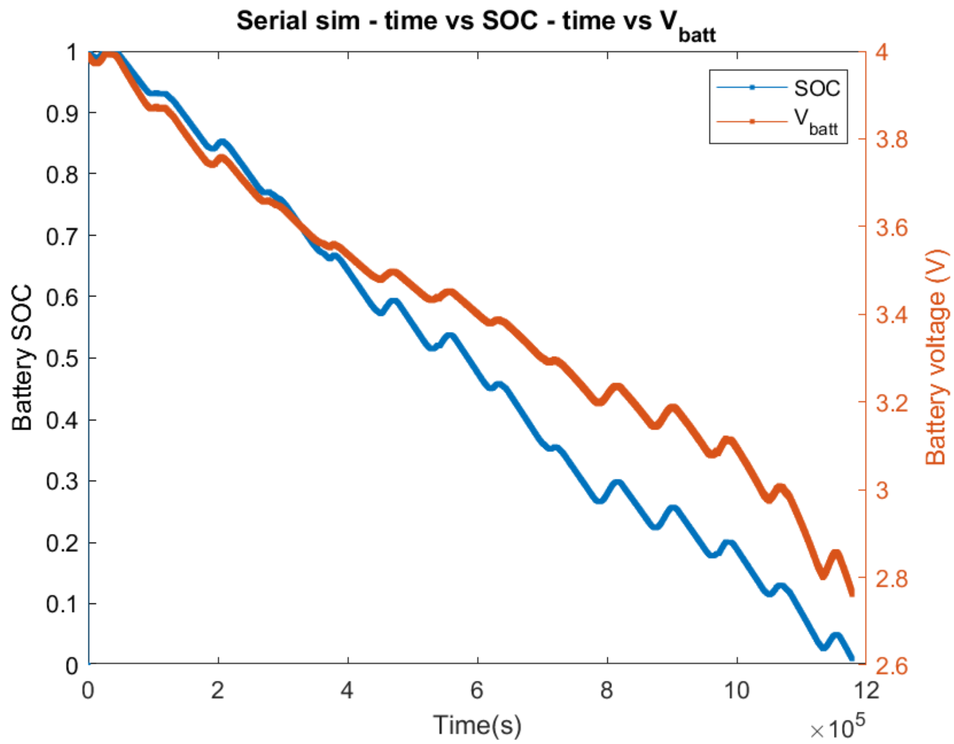
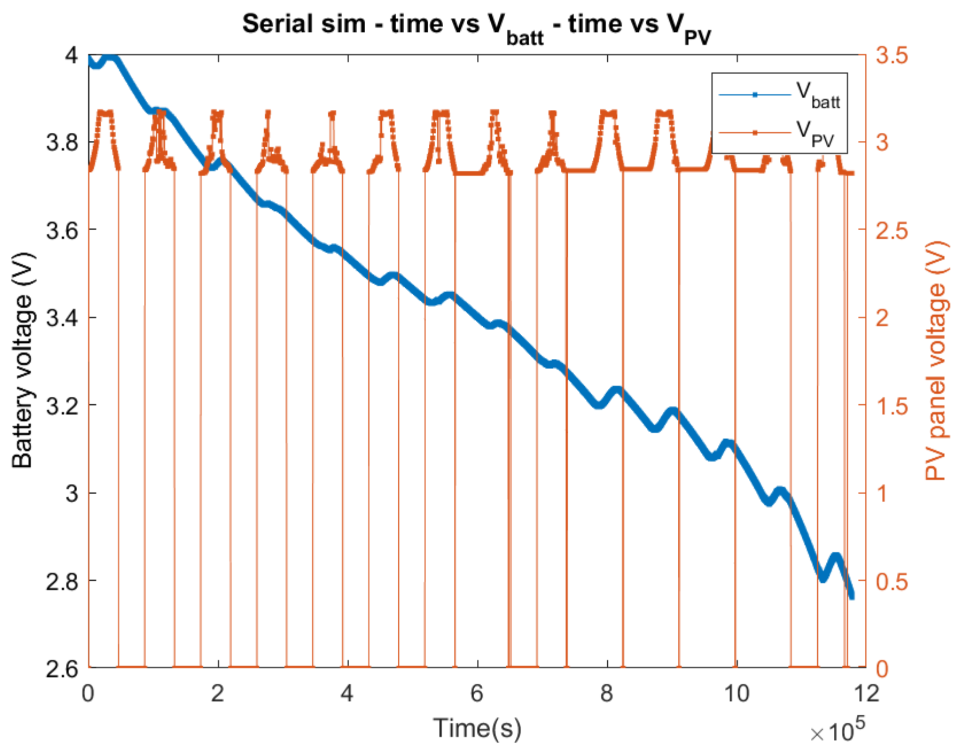


Figure 5: PV panel current (in green) vs real current (in blue) considering battery self-discharge



(a) *SOC vs battery voltage*



(b) *Battery voltage vs PV panel voltage*

Figure 6: Serial simulation - Variation of battery and PV panel voltages over simulation time

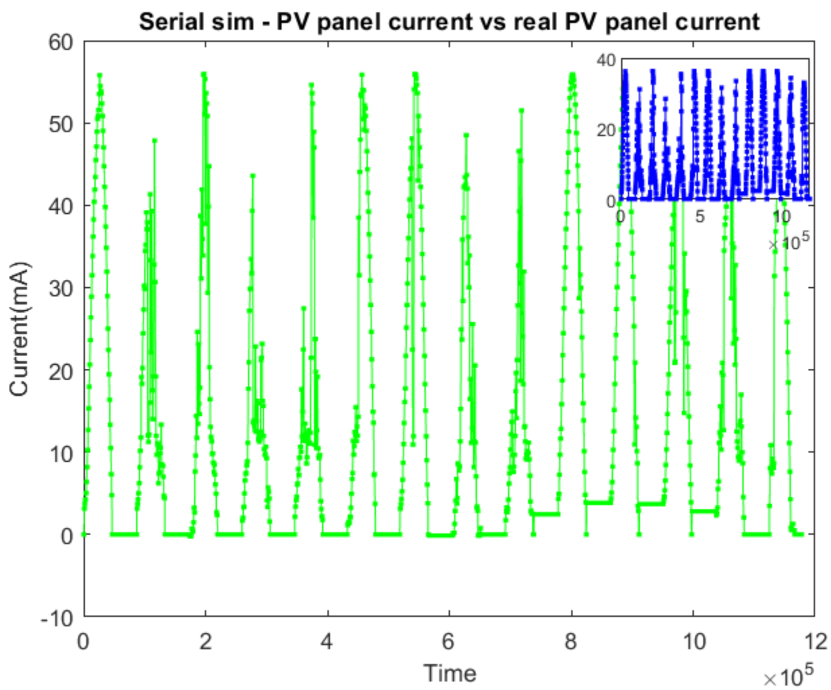
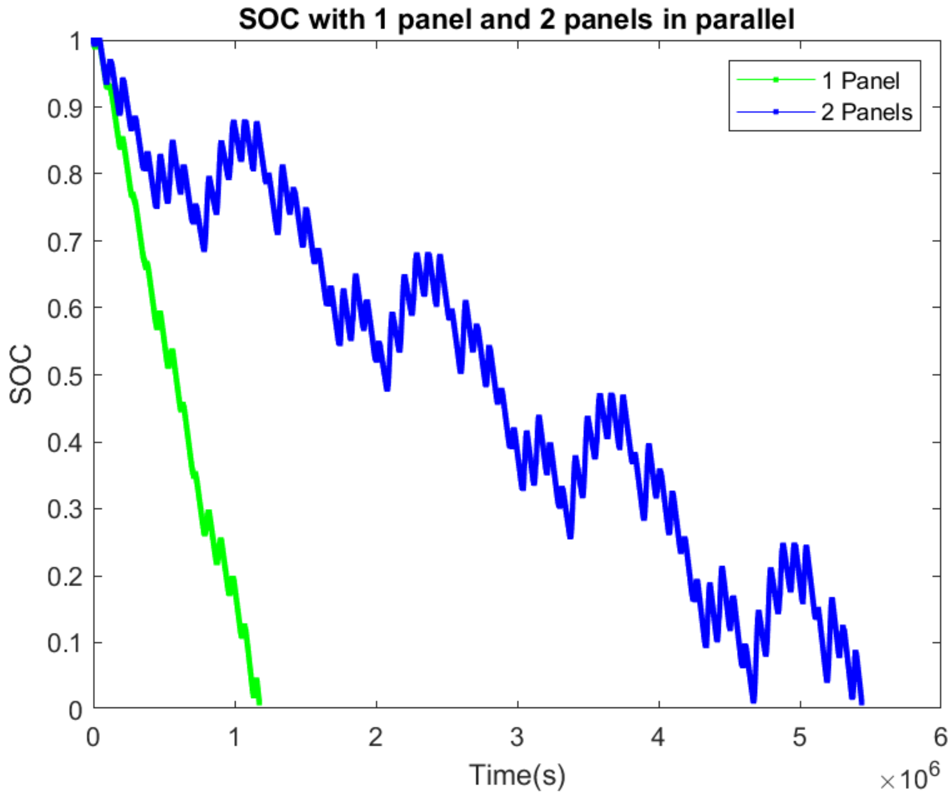
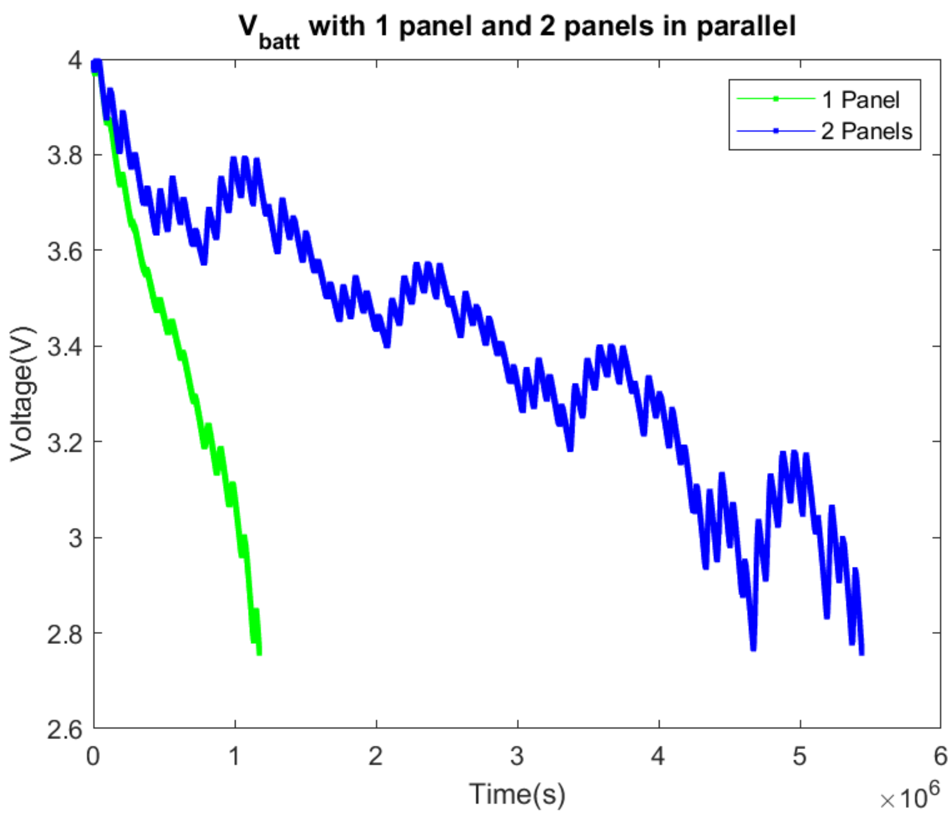


Figure 7: Serial simulation - PV panel current (in green) vs real current (in blue)



(a) *SOC behaviour with 1 PV panel and 2 PV panels*



(b) *Battery voltage behaviour with 1 PV panel and 2 PV panels*

Figure 8: SOC and battery voltage in 1 PV and 2 PV panel configurations (1 battery)

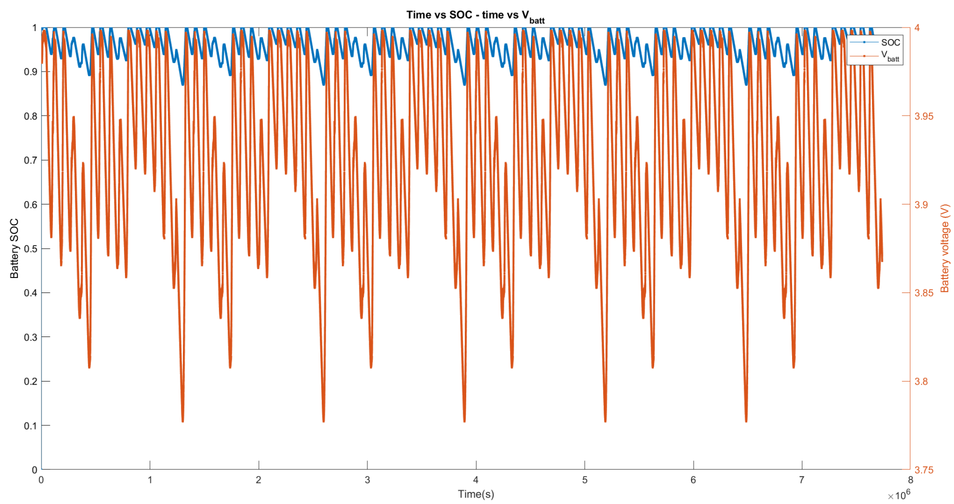
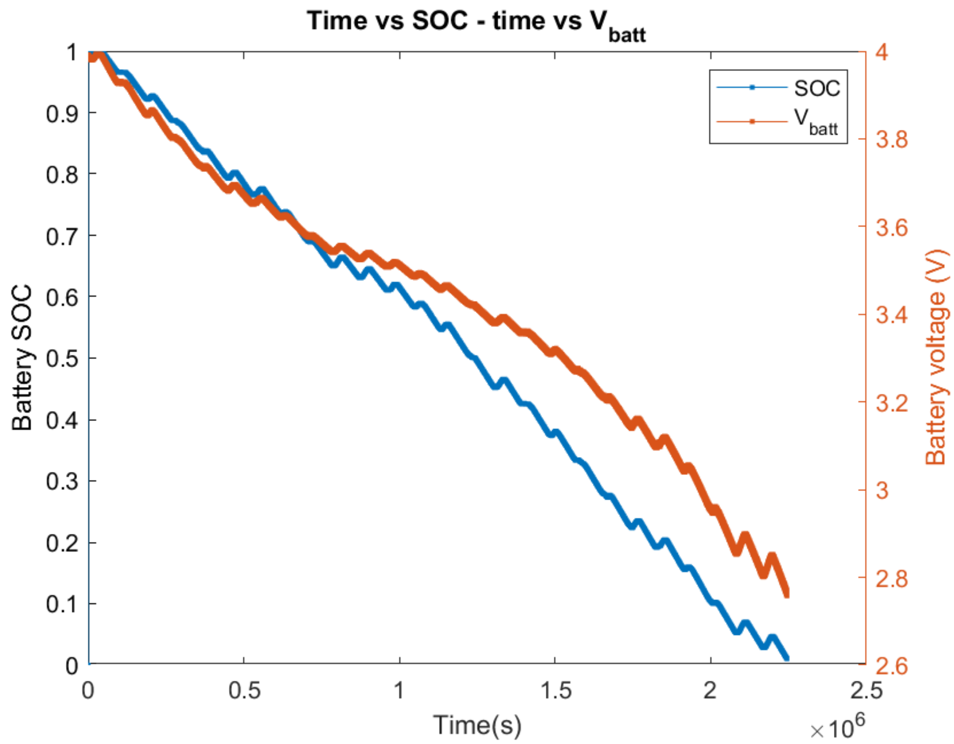
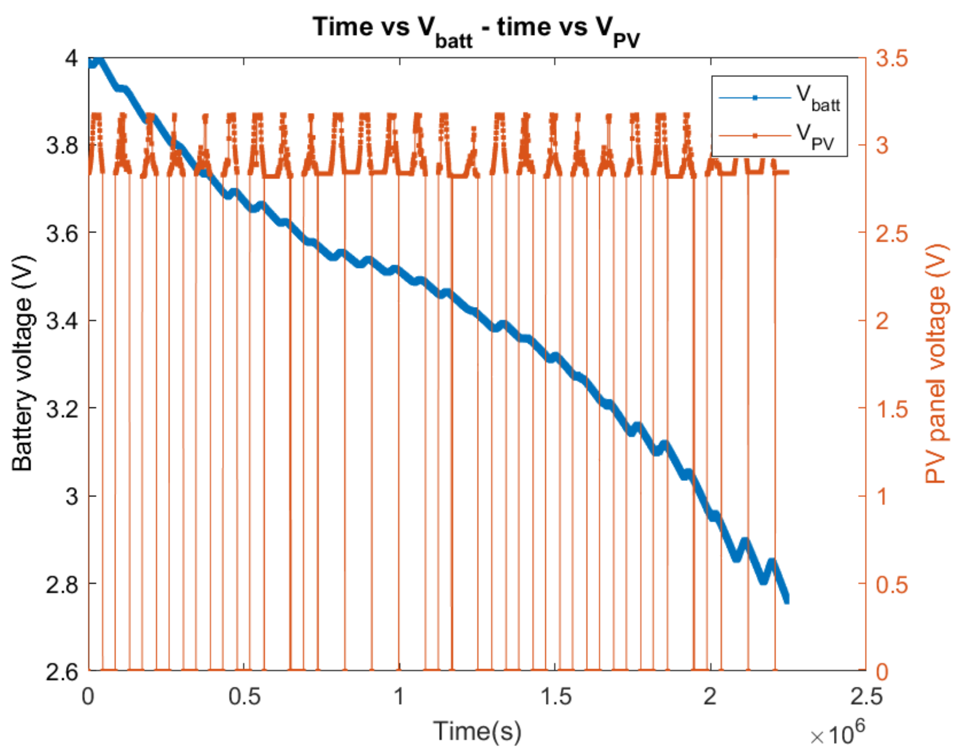


Figure 9: SOC vs Battery voltage in the 1 battery - 3 PV panels configuration

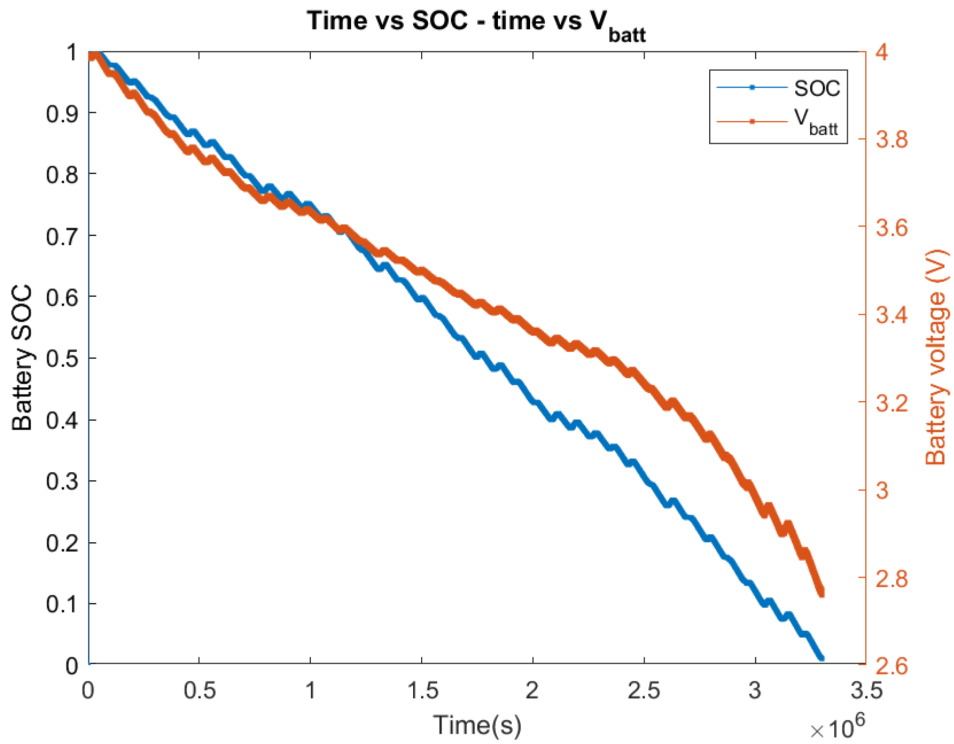


(a) *SOC vs battery voltage*

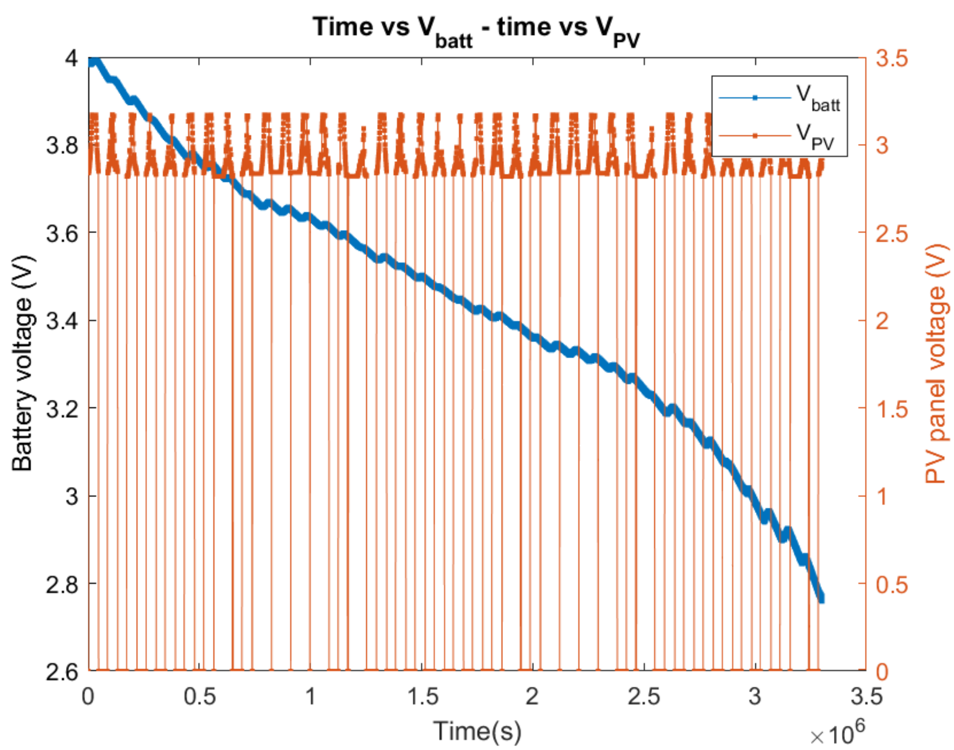


(b) *Battery voltage vs PV panel voltage*

Figure 10: SOC and battery voltage in the 2 batteries - 1 PV panel configuration



(a) *SOC vs battery voltage*



(b) *Battery voltage vs PV panel voltage*

Figure 11: SOC and battery voltage in the 3 batteries - 1 PV panel configuration

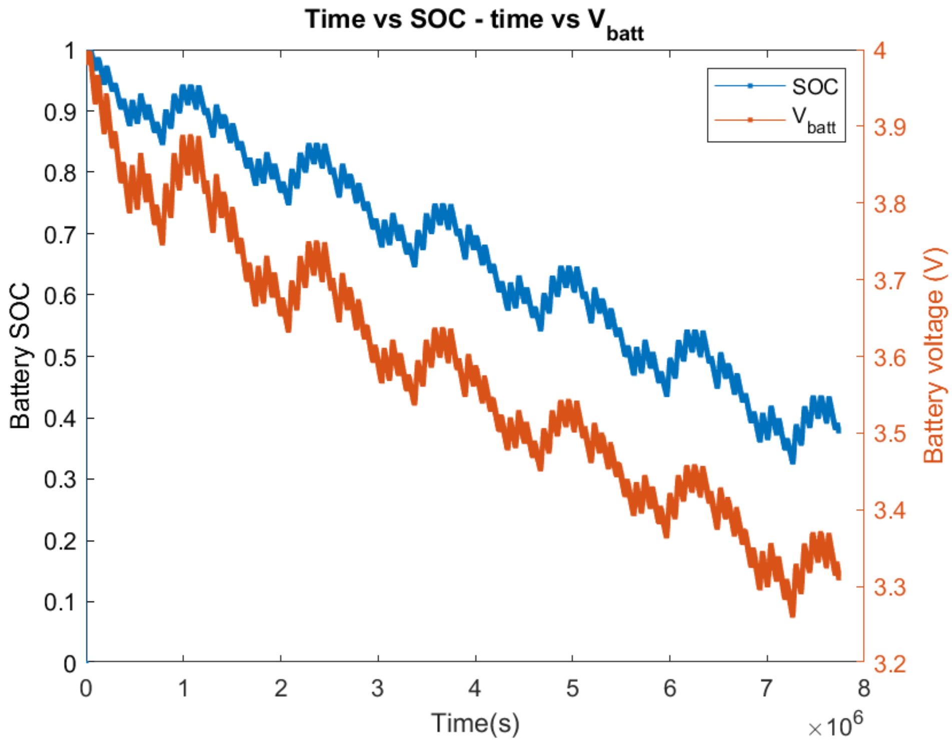


Figure 12: SOC vs Battery voltage in the 2 batteries - 2 PV panels configuration

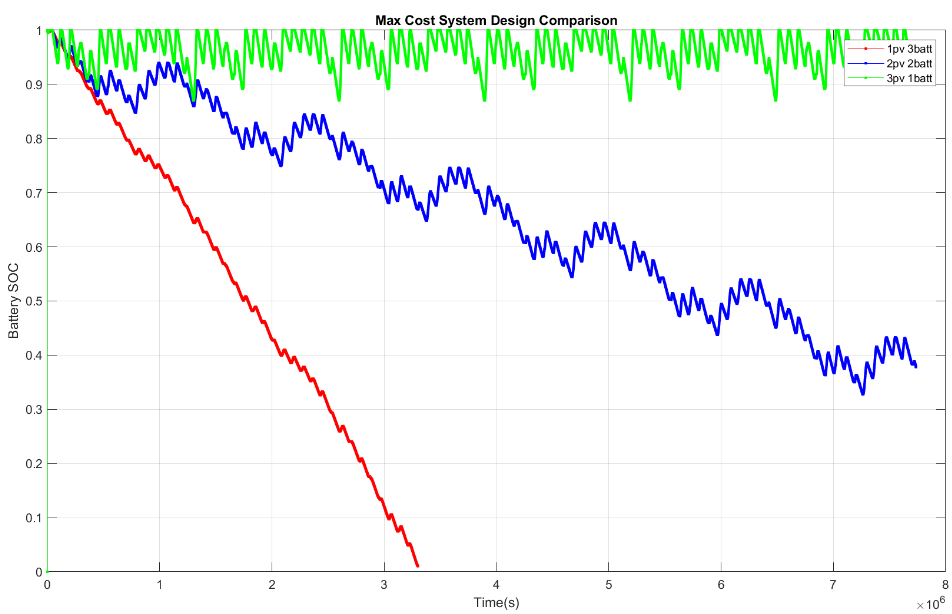
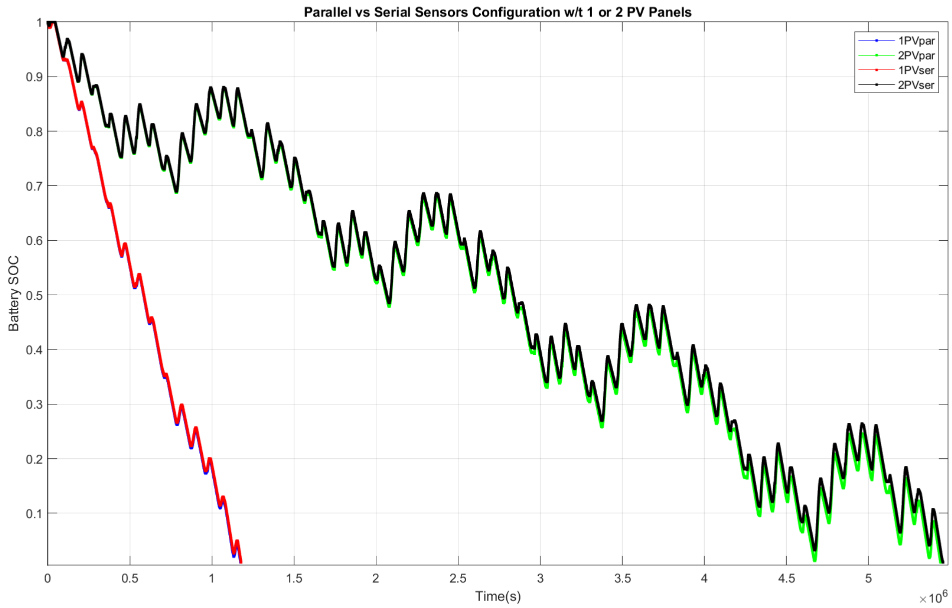
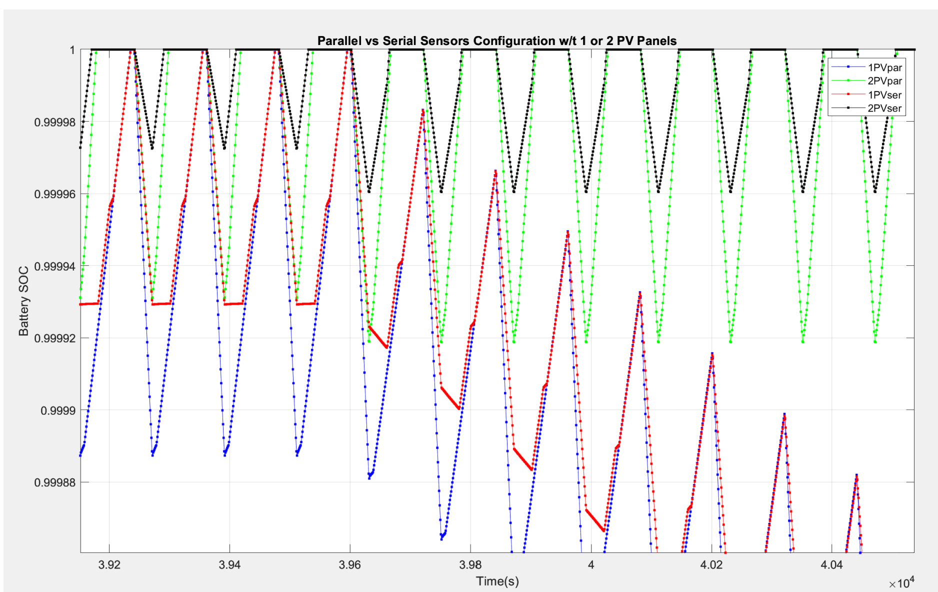


Figure 13: SOC for maximum cost configurations



(a) *Battery SOC - Serial vs parallel comparison*



(b) *Battery SOC - Serial vs parallel comparison detail*

Figure 14: Battery SOC analysis - Serial vs parallel