Energy Management in Mobile Systems

Lab 4: Electrical Energy System

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Contents

1. Introduction

The main purpose of this chapter is to describe modifications of the initial Simulink model, which were necessary in order to perform system analysis and to implement the controller policy.

Using as reference the top-level Simulink model, the followings changes were applied:

- **Battery Model**: Since our policy also considers the possibility of recharging the battery (details in the following), we have added a control of the value `SOC` (State Of Charge). By running simulations with different load profiles we noticed that they would yield a value of SOC greater than one, which is unfeasible in reality. With the additional blocks, the value of `SOC` saturates at 1 and does not go above that level. For the same reason, a `Vbat` also saturates to a maximum value (namely the initial value) by adding a similar control. Another problem arisen during the very first simulations was due to the stop condition that signals the discharge of the battery. The default settings caused the simulation to run for too long (longer than it should have, leading to wrong system behaviour). We simply added the option "*zero detection*" to solve this issue. The last modification regards the equation for modelling the internal resistance of the battery. We decided to use a 5^{th} grade polynomial in order to achieve a higher precision, instead of the one suggested in the transparencies.

- **Controller, Converter and PV Panel**: Addition of an enable signal driven by the controller (in addition to further input and output ports on its interface, needed for implementing the policy) which serves the purpose of enabling the converter and the photo-voltaic panel (PV panel) under certain conditions. Two are the effects of this signal: setting the `Pin` (output of the converter) to zero, so that leakage current (included in the model) does not affect the PV module whenever the `Ipv` current is set equal to zero by the controller. It also disables the PV module itself, acting as a bypass for the control that eventually stop the simulation whenever it works out of the working conditions. The Simulink control box is fed with a constant value avoiding the condition to be true and thus stopping the simulation. The main reason behind this choice was the fact that leakage currents forced the output of the *look-up table* within the PV module to unexpected outputs that asserted the stop condition. The overall result of this signal is that it detaches the converter and the PV module from the rest of the system (and so making the battery work on its own). The reasons for which the controller needs to take these actions, as well as why other elements are present, are covered in chapter 3 (concerning how the policy works).

2. Battery characterization and analysis

In this chapter, a detailed description of how the battery behaves under certain conditions will be provided.

Before analysing the gathered results, few words are worth to be spent on the setup of the system. In order to perform battery analysis, we devised a suitable policy (Simulink block "`BatteryAnalysis`" within the Controller) that demands all the needed current to the battery. For the sake of simplicity, we do not exploit the enable signal although the `Ipv` current is set to zero. Hence, the block that eventually stops the simulation (within the PV module) was detached as well.

As first step, we performed simulations with different C-rates. The results of these tests have been also leveraged for testing the efficiency of the policy, since they gave us a broad idea of what kinds of currents are more suitable for emulating a real-case scenario.

According to the battery specifications (found on the datasheet), 1 C-rate is equal to 720mA. We generated a load current profile with such value and as expected, the simulation lasted for 3564 seconds (which correspond to more or less one hour) and stopped since the SOC was equal to 0.01 (simulation stop condition of the battery). The same approach was repeated for 2 C-rate (360mA) and simulation stopped at 7128 seconds (almost 2 hours) and ½ C-rate (1440mA) which was stopped after 30 minutes of simulation time. The results of this test are shown in figure 1. For the sake of completeness, `Vbat` is also shown. Its behaviour is fully compliant with that of the SOC.

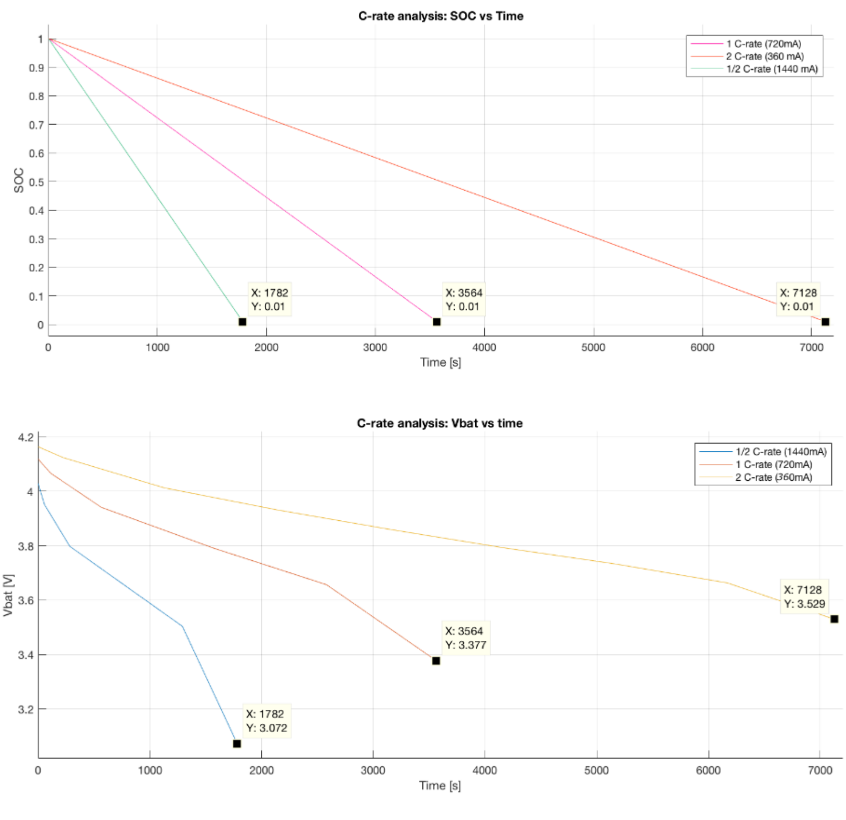

Figure 1 - SOC and Vbat behaviour with respect to different C-rates.

As final experiment, we tested the battery behaviour with non-constant load current profile (namely different current distributions). As reference, we used a constant current at 1 C-rate. The other two distributions were chosen to be somewhat related to the initial one, since they are a Gaussian distribution (mean 1 C-rate) and a uniform distribution (random values from 0 to 1 C-rate). The results confirm what we expected, that is random currents are the most stressful for the battery. However, even though oscillations are evident, the behaviour remains predictable and other side effects do not manifest themselves.

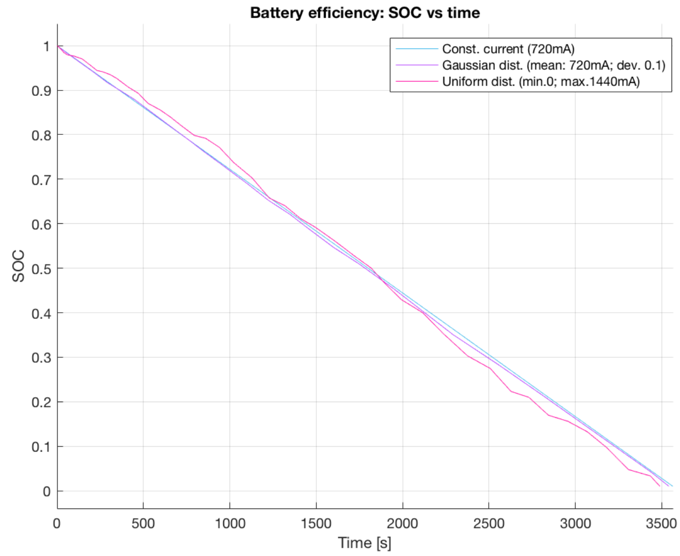

Figure 2 - SOC for different current distributions.

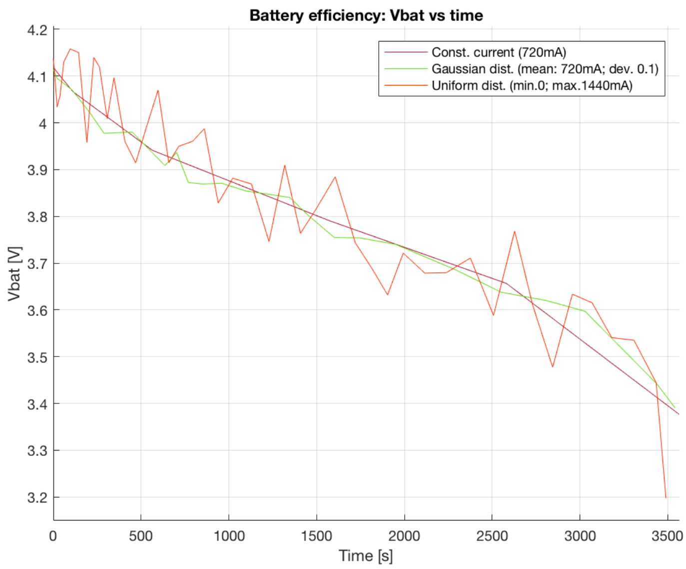

Figure 3 – Vbat for different current distributions.

As conclusion, we devised a test procedure for our policy starting from these figures. High currents obviously discharge the battery faster and the system does not survive until G (irradiance) approaches suitable values (enough to power the system with PV module instead of the battery). Thus, we decided that a reasonable load profile would be around 4-5 C rates, which is however reasonable for an embedded system.

3. Controller Policy

Ever since the first analyses, it emerged that in order to have the system up for all 14 hours of simulation time, we needed to include in the policy the possibility of recharging the battery. Of course, this strongly depends on the weather conditions, which influence the value of irradiance.

Assuming the irradiance profile that has been provided, the rationale behind our strategy is that if the current provided by the panel is enough for satisfying the load requests, then a fraction of such current can be used for recharging the battery. The idea is that the battery is needed only at the beginning and at the end of the simulation (characterized by a low value of irradiance).

The controller has to do an estimation of the past value of the `Ipv` current. This is implemented by adding two memory elements, storing last two past `Ipv` values (`IpvProvided` and `LastIpv`). `IpvProvided` represents the current provided by the PV module at time t - 1, whereas `LastIpv` is the current provided at time t - 2. Other inputs for the controller are `Iload` and `Vbat`. The output are the default ones, plus the enable signal (driven by a dedicated control logic). Such control logic simply sets the signal whenever the `Ipv` is zero.

At each time instant, the controller observes `IpvProvided` and `Iload`. Depending on the current demands, the policy splits into two branches. If current demands are below a certain threshold (50% of `IpvProvided`) then the PV panel is generating enough current for the load. Otherwise, the battery provides the entire current demand (`Ipv` is set to zero, causing the converter and the PV module to be detached from the system). The rationale behind that threshold is that two consecutive values of irradiance are highly correlated. It is very unlikely that the irradiance assumes values with a huge difference in two time instants close each other. Hence, for the sake of a safe estimation of the value of `Ipv`, we decided that 50% of the previous `Ipv` is a reasonable amount.

The curve representing the irradiance is bell-shaped. So, in the first part, it rises up to a maximum value and then it decreases. The policy is aware of this behaviour thanks to the memory elements. Indeed, once it has been assessed that the PV module generates enough current, the policy tries to understand whether simulation is currently evolving in the first part of the curve or in the second one. Since it is rising, the first part of the curve is characterized by the fact that the current at t -1 is greater than the current at t -2 (identified by the condition `IpvProvided > LastIpv`). If the system is in such situation, the controller asks the entire load demands to the PV module. With the remaining current (if any), the battery is recharged (up to a voltage equal to 4.0V).

As time goes by, the simulation advances to the second part of the irradiance curve. In this situation, the current provided by the PV panel progressively decreases. In order to maximize the duration of battery (and so of the entire system) the controller carefully divides the current demands to the two sources (70% to the PV module and the remaining to the battery). This will be clearer with the examples of chapter 5.

By doing so the battery last enough for the remaining part of the simulation, during which the PV module cannot be used anymore.

4. DC-DC Converter

The DC-DC converter adapts the PV panel's output voltage to the one required by the load.

It was completed with the addition of the provided expression of the `Ploss`. To obtain the coefficients of such formula we first used a digitizer to characterize the efficiency vs current curve from the datasheet for each step on the logarithmic scale (x-axis) giving us a total of 24 points. We then used the `polyfit` function to derive the coefficients.

To double-check whether the model reflected the behaviour expected from this plot, a load current vector with increasing values was applied, while a constant voltage of 4V forced in the converter. Figure 4 shows the results of the experiment. We see that, besides when the PV panel is not providing current (`Iout` is zero), the efficiency follows the behaviour of the requested current. In fact, as `Iout` increases in steps so does the efficiency; while around 27500 seconds a sudden decrease of the current entails the same behaviour for the efficiency (in this specific example the reason behind such immediate change in the `Iout` is related to our controller policy).

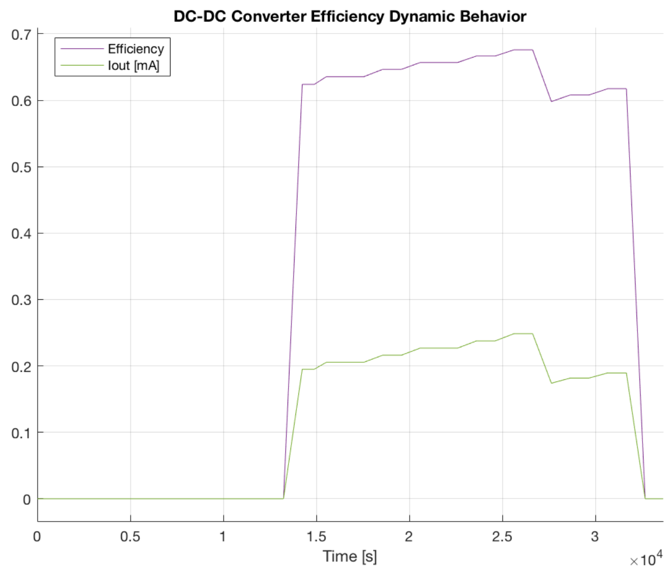

Figure 4 – Converter efficiency example.

Additionally, the Simulink block was extended with the aforementioned *"Enable"* signal as part of our controller policy.

5. Test runs and complete system analysis

In order to test the complete system, we performed several test runs with simulation time set to the default of 14 hours (50400 seconds). As a starting point, a base run with a constant load current of 144mA was done. This value corresponds to 5 C-rate so in absence of the PV panel and the controller the simulation would last 5 hours. Instead, in the complete system, it lasts for the total 14 hours of simulation. Figures 5 and 6 show the behaviour of some significant system parameters over time.

In the bottom plots of Figure 5 we see how that panel works for a certain time interval (that is when the `Enable` signal is asserted) while in the beginning and towards the end of the simulation it's off. Moreover, the power slightly increases as irradiation rises (and so does the current in response) while the voltage decreases as to keep power more or less constant. In correspondence of the irradiation peak things start to change as the provided current starts decreasing (see the abrupt steps for power and voltage around time 26000). This is due to the controller policy we implemented.

Also, in order to provide the requested power level, `Vpv` changes (and in this case rises) up to the point when the policy shuts down the panel and delegates all work to the battery.

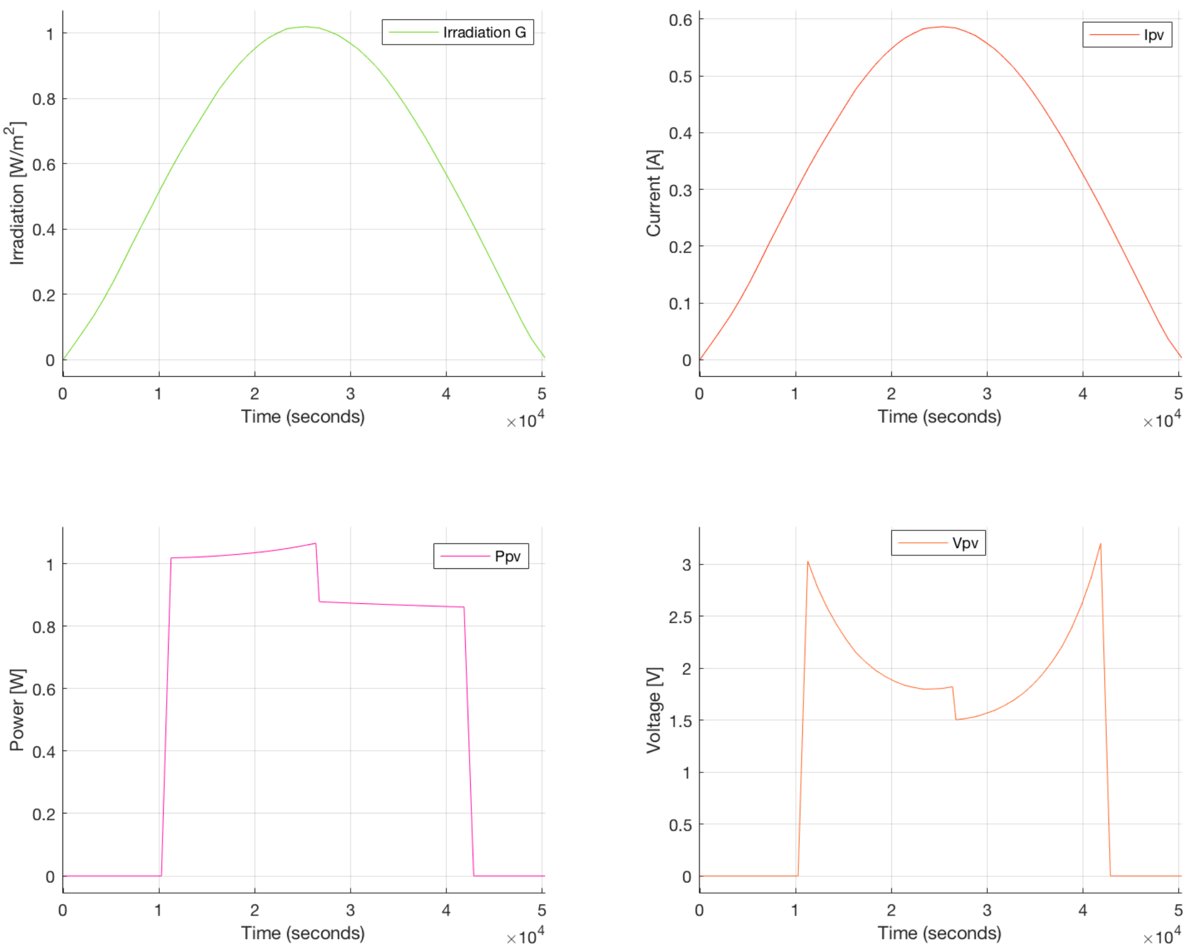

Figure 5 – PV panel parameters: 144mA constant load current

In Figure 6, instead, we get some interesting insights about the battery behaviour. Initially, as the panel is off, the state of charge and voltage decrease linearly and `Ibat` is constant and equal to the load current. As irradiation rises the policy forces the panel to work, in part delivering power to the load and in part providing a recharge current to the battery (notice how `Ibat` is negative between 11000 and 26000 seconds) and so the SOC and voltage rise significantly.

Once the irradiation peak is reached and the panel current starts decreasing some work is delegated to the battery as well and so we see the SOC and voltage decrease linearly again, until `Ipv` is so low that the load is powered solely by the battery (notice the steeper slopes for SOC and `Vbat` around time 43000 s, and the change of `Ibat` back to 144mA for the last part).
The system would've been able to run longer as the SOC is still above the threshold of 0.01 but was stopped as the maximum time of 14 hours was reached. For such reason we consider our policy to be successful in its purpose.

For what concerns the converter we see the aforementioned behaviour, strongly dependant on the panel current.

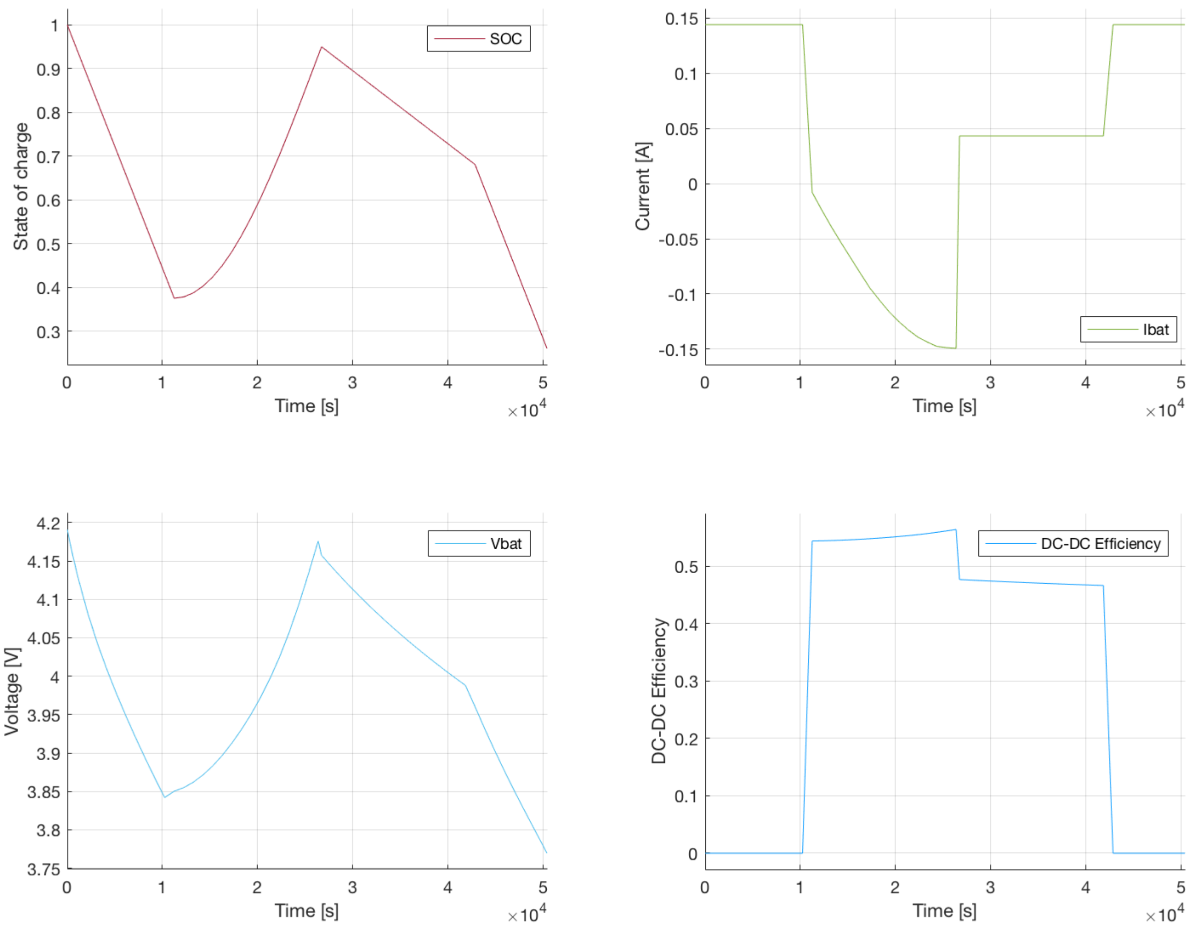

Figure 6 – Battery and converter parameters: 144mA constant load current

The following simulation was done with a Gaussian distribution (mean 144mA and 20mA standard deviation). Figure 7 reports some significant parameters in these cases but overall the system behaved in a similar fashion to the above. We here report only two plots as all are pretty much the same of the previous test. Of course, some slight variations were introduced due to the dynamic behaviour of the load current. Notice how `Ibat` and `Ppv` have several changes in magnitude over time but are generally shaped like before.

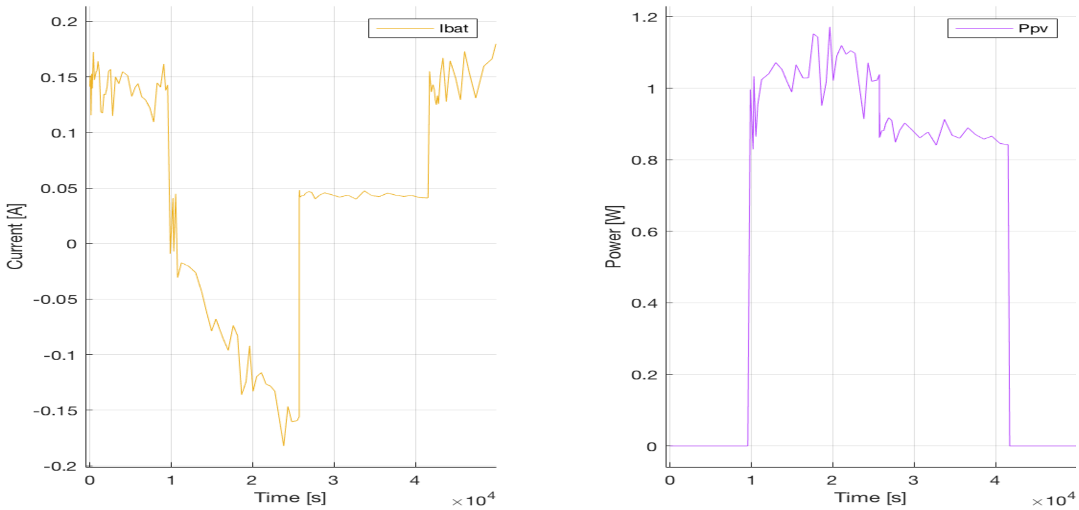

Figure 7 – Battery current and panel power: Gaussian distribution of load current (144mA mean, 20mA standard deviation.)

The final simulation was done using a uniform distribution of 2000 samples with values between 120mA and 360mA (6 and 2 C-rate respectively). We here see that this set of load currents is significantly larger than the previous runs as the simulation runs for only 3.1 hours because the battery is depleted. This triggers the end of the simulation and no work is ever commissioned to the PV panel (`Ppv` and `Vpv` constant at value zero).

This is a good example as to show how, when designing an electrical energy system like the one in consideration, many are the actors in play. In this case, perhaps a different policy or a higher level of initial irradiation would've been able to make the simulation last longer.

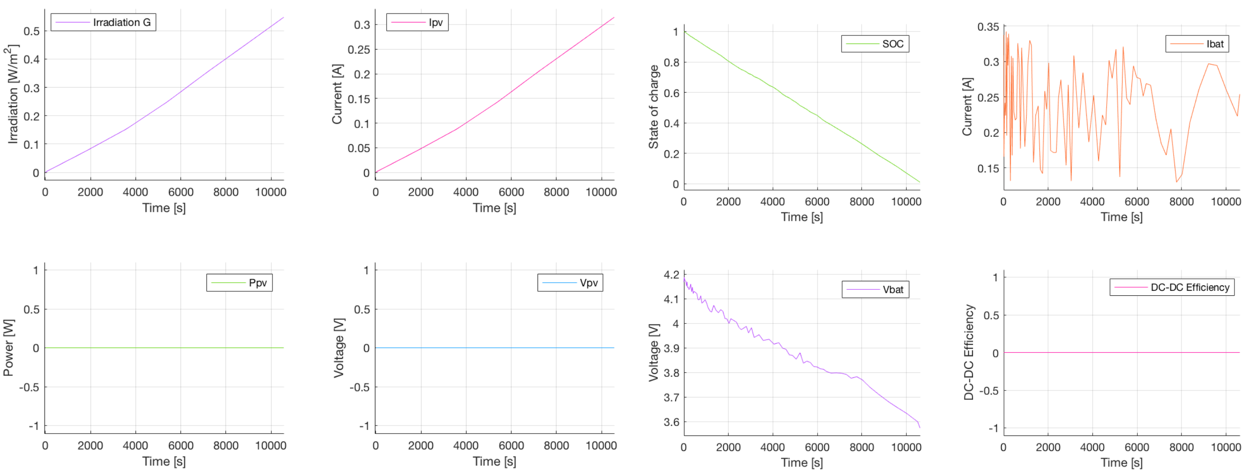

Figure 8 – System parameters: uniform distribution between 120mA (6 C-rate) and 360mA (2 C-rate).

6. Conclusions

The system behaves correctly for the whole simulation time and unexpected behaviour never manifested. With the developed policy, the system was able to survive for the whole simulation (14 hours) when the load current profile was around 144mA.

Although an MPP tracking algorithm has not been considered, the policy guarantees the availability of the system and as the simulation suggested the battery could probably last slightly more than 14 hours (again with the above workload profile).

In our controller, its simplicity along with the possibility of tuning the main parameters (i.e. the ability to easily split the current demands on the two power sources, and the threshold current in the policy) enable quick and easy adaptation to different scenarios (for example a new PV panel and/or battery) and workload profiles.