PEPS. A TOOL FOR POWER SYSTEM SIMULATION

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ABSTRACT

Missions are becoming more and more difficult and sometimes, figuring out what is the worst case orbit for energy balance in a satellite is becoming quite complex. Hence, simulation is paramount to perform a reliable analysis in order to understand if there is enough energy to power the satellite and recharge the battery. PEPS is a tool developed internally in ESA based on EcosimPro software. Experts from quite different fields have been involved in its development to end up having a flexible and powerful tool to perform energy balance simulations for conventional and non-conventional satellites.

1. INTRODUCTION

GEO telecom satellites is maybe the last simple power system scenario that remains more or less unchanged since quite a few years ago. The orbit is very well known and straightforward. The power architecture is quite homogeneous among the manufacturers and the loads are also well known. Hence, the analysis is relatively simple. However, Earth Observation (EO) satellites and Science satellites are becoming more and more challenging in terms of orbit, attitude and geometry complexity. This has an immediate effect on the energy balance simulation since the computation of the energy fluxes on the solar arrays is becoming nothing but trivial. Bepi Colombo, Swarm, Proba-3, Juice are just a few examples.

One of the main complexities with power system simulation is the fact that it is highly multi-disciplinary. It involves knowledge from many different fields and, as a consequence, the collaboration among different experts is essential.
First of all, an orbit simulator is needed in order to calculate the solar flux along an orbit. In fact, apart from the solar flux, the albedo and infrared fluxes are also needed. To complete this chapter, the dynamic computation of the view factors is necessary to calculate what are the energy inputs for the solar array.
And not only the orbit is needed: the satellite geometry and its attitude is also required for that purpose. Since this involves 3D modeling, the computation of coordinates and angles dynamically becomes tricky.

Immediately after, solar array modeling involves the interaction between solar cell experts and thermal engineers. As is known, temperature plays a major role in the calculation of the power generation in solar arrays. This interaction has to be dynamic, which means that the thermal model has to embedded with the electrical model in order to properly calculate the power available along the orbit.

Another key domain is the battery modeling. In fact, this is probably the most complex model in the whole space power system. The battery is an electrochemical component which performance depends on several aspects: temperature, aging, and electrical conditioning. It has to be noted that the battery is a multi-disciplinary model in itself since, apart from the internal electrochemical behaviour, the electrical performance is the key feature needed to interact with the rest of the system.

Finally, the power system electronics model are needed to process the solar energy, condition the battery and deliver power to the loads. These are the models that merge all the different components into a full power system.

Putting together such a wide team to develop models using the same platform is not always easy. Note that, in general, each domain is likely to use a different tool, the language used to describe things is different and hence, communication might not be so easy. Fig. 1 shows a conceptual diagram of a space power system. Note that a different expert is needed for almost every box represented in the picture.

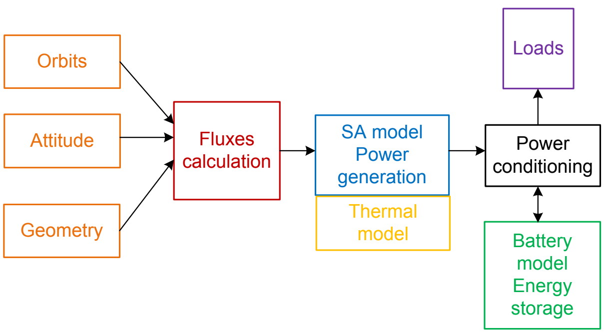

Fig. 1: Basic diagram showing the functions/models needed for a space power system

On top of that, keeping a tight control on the different evolving versions of all the models becomes quite complex when so many people interact.

ESA started an internal project to develop such system using EcosimPro as the underlying platform. The system is called Power Energy Platform Simulation (PEPS) and aims to achieve an independent simulation system that allows to virtually simulate any power system. All the models have been developed internally by ESA experts from different domains and using the same software. This paper presents the status of this activity and shows the main features of the development.

2. VERSION CONTROL

PEPS was conceived since the beginning to enable collaboration and concurrent development among different teams within ESA. In order to do so, next to defining common interfaces for all models allowing multidisciplinary simulations, a Subversion repository was put in place for the different disciplines to manage their libraries and for all users to access them using EcosimPro's built-in Source Code Control system based on TortoiseSVN. This system allows adding and retrieving libraries from the repository, keeping track of all configuration, source and documentation files, comparing file versions, etc.

Tortoise SVN was chosen because it can be natively integrated with EcosimPro and because it can handle all the needed functions. Once it has been installed, the corresponding features appear in the EcosimPro user interface (UI) and hence, make the process simpler.
The need for version control is obvious in an environment as dynamic as in ESA. Many people is interacting and taking care of different, domains, different missions, etc. Thus, we needed a way to make sure that the reference models were kept configured as they were conceived. Note that the validation effort for each model is quite heavy. Hence, the users need to be completely sure that they are using the right ones.

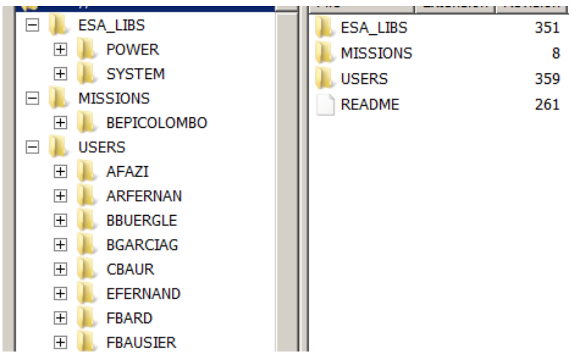

Fig. 2: folder structure of the SVN repository

Each domain has defined a library responsible who is in charge of uploading and maintaining a set of components. The other users can only download the configured models ensuring this way that the original ones remain as they should be. Obviously, modifications can be proposed to enhance the performance of the existing developments or to fix any bug.

On top of the configured models, the users can also develop specific models for their very own specific needs. Then, they can also upload those models to their own user library so that any other colleague can download them later on and benefit from them if needed. This system is very powerful because it enables a real collaborative environment and benefits from the work of many people at the same time.

Fig. 2 shows the structure of the repository at several levels. Under the ESA-LIBS folder, the different subsystems can store their controlled libraries. The power subsystem for example is organized in three libraries:

- POWERSAS for solar array models
- POWERBAT for batteries
- POWERSYS for the power system electronics

Each library has a responsible in charge of maintenance and uploading new verified models.
In principle, these libraries account for generic models for a very general use.

Mission specific models and schematics are stored under the MISSIONS folder. Hence, even if the supporting engineer changes or if the library is needed long time afterwards, the items will be kept under control. If the mission needs a very specific model that is not likely to be re-used in another mission, it will be stored here as well.

Finally, every individual user can upload models to its own folder. These are not official models but components that were developed by a user for a particular need. By putting them in this repository, this work is shared among the users and enhances significantly the development power of the tool.

Inside each folder, the structure is basically as shown in Fig. 3. There is a "trunk" folder which is the development folder. This means that it contains the copy of the working library used by the developer. It is a living folder. Only the developer can access it and modifiy it. On the other side, there are the tagged versions. Those are frozen versions that are completely configured and verified. The system keeps track of all older versions on top of the latest one. Hence, any user can retrieve any version from any moment in time to allow simulate a given system with the exact version that was used at any given moment. As can be seen, this system

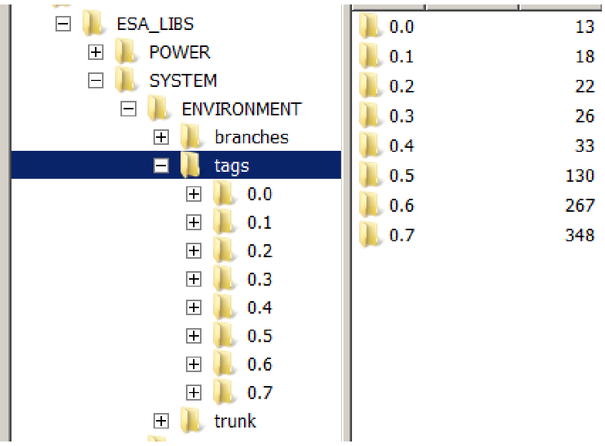

Fig. 3: internal folder structure of the SVN repository

is extremely powerful and allows a very accurate version control.

3. ENVIRONMENT, ORBIT AND ATTITUDE SIMULATION

As foundations for any space system simulation, a series of libraries were developed to provide the different sub-system models with their required inputs from the external environment.

For what is relevant for power sub-system simulations, environment models are provided to compute the solar flux, the central body (any solar system planet) albedo and infrared fluxes, and the eclipses at the spacecraft position.

The position of the spacecraft and solar system bodies are either based on different types of Keplerian orbits or ephemeris interpolation, although it is also possible to simulate spacecraft orbiting any Sun-Planet Lagrange point or freely moving on the surface of any planet.

Additionally, in order to assess the impact on power generation, it is possible to choose several attitude orientations including inertial or tracking pointing with different alignment conditions such as velocity align or power optimisation with fixed offsets based on the degrees of freedom of the solar arrays. Furthermore, extra rotations can be applied on top of the basic attitude to define fixed pitch, roll and yaw offsets or fixed along/cross track distances.

4. SPACECRAFT GEOMETRY DEFINITION

The calculation of the actual aspect angles for all fluxes and relevant view factors applicable to each solar panel are computed using surface models from the geometry library. These surfaces are defined in the spacecraft body fixed frame and linked to the actual attitude. Different models are provided to represent fixed body mounted solar panels or solar arrays with degrees of freedom. For those with the degrees of freedom, they can be left as inputs for the simulation, so providing the solar array drive mechanism angle, or computed internally using additional conditions such as fixed solar aspect angle.

5. SOLAR ARRAY MODELING

Among the several models proposed in literature to build the solar cell I-V curve [1], from an engineering point of view, the most useful are the ones based only on those main three points of the I-V curve (I_{sc}, V_{oc}, P_{max}) that are immediately available in a commercial solar cell datasheet, or measurable in laboratory. PEPS adopted the so-called "TRW" model [2] in which the solar cell is modeled with an exponential curve. The choice of this type of model was driven by the system perspective. The power conditioning system needs to know in advance where is the P_{max} or the V_{oc} point. Otherwise, a system calculating those points without SA insight would be needed and it would slow down the simulation very heavily. Note that system level simulations are interested in analysing the performance along several orbits, which means a simulation time of many hours or even days.

The complete model of the solar array includes the matrix of in-series cells strings, each one protected by blocking diodes, and the transfer harness computation. Both the diode and the harness performance are temperature dependent.

The user can choose among a number of predefined solar cell models, diodes, coverglass, harness, adhesives, etc. However, to improve the flexibility of the system, the user can also define a completely new set of data to cover newly developed hardware. In total , the model needs in the order of 50 inputs to be completely parameterised. Fig. 4 shows the symbol and the parameter window that pops out when the user double clicks on it. As can be seen, the parameters are distributed among meaningful tabs that simplifies the task of parameterising the component for a given simulation exercise.

The thermal model is completely embedded with the electrical model so that the solar cell temperature is always in the loop to calculate the electrical parameters. There are four options available:

- 1 thermal node
- 2 thermal nodes
- 4 thermal nodes
- No thermal nodes

The last one is meant to be able to force the temperature by the user to study particular issues at a very specific

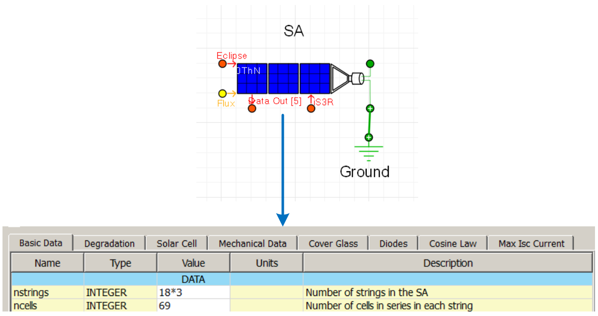

Fig. 4: Solar array symbol and the parameter window that pops out when clicking on it.

temperature point. Otherwise, the temperature is completely dependent on the operating conditions and it would be very difficult to configure to give a specific temperature output.

At the moment, the TRW model is being submitted under a process of verification and validation w.r.t temperature, sun intensity and irradiation conditions: it fits the experimental data and predict the EOL performance with an error on P_{max} within ±3% in the following conditions: 0.1-3 Solar Constant; -170 -:- 200 °C and up to 3E15 e^{-}/cm^2 1 MeV equivalent. Also the effect of the order in the use of degradation factors was estimated and typical cases in LEO and GEO missions was simulated with very good results.

PEPS is also able to calculate the solar array mass budget very efficiently, taking into account both PVA and mechanical parts of the solar array. Hence, the same model is able to perform a mass breakdown prediction of a solar array, which is a very interesting feature for the early stages of a project, like phase 0 or phase A. Of course, if a particular design needs very specific technologies or design solutions, the model might not be able to predict the mass with the same accuracy as in a more conventional case. Fig, 5 shows some graphical outputs of the model like the IV curve or the power curve and also some harness and mass data.

6. BATTERY MODELING

The aim of battery modelling within the Power Energy Platform Simulation (PEPS) is manifold. On the one hand it is needed for correctly sizing batteries and for predicting the power capability at different conditions (e.g. State of Charge and/or temperature). Therefore, an electric model for describing the cell electric performance beginning of life (BoL) is needed. On the other hand, it is also required to predict the end of life (EoL) performance of a battery that is still required to meet certain performance demands imposed by the power requirements of a spacecraft. Thus, an ageing model of the envisaged battery cells is also needed.

The electric model for describing the behaviour of Li-ion cells has been developed at ESTEC and is described in [3, 4]. Conceptually, the model is implemented as an electrical circuit that mocks the physical properties of the battery. The basic idea is to slice the electrodes in pieces in order to account for the dynamic behavior as shown in Fig. 6. Then, each one of those slices is modeled as an RC network as shown in the same figure. As a consequence, the dynamics of the battery behavior in transient conditions can be simulated accurately. Other physical characteristics as voltage hysteresis or temperature dependence are also modeled.

The model is giving good agreement between the observed and modeled voltage response of Li-ion cells, when subjected to different electric current profiles. This cell model is currently implemented in EcosimPro software in PEPS [5].

For every new cell type a test campaign has to be carried out for determining the cell specific model parameters. A standard test specification for determining these parameters has been developed at ESTEC. Currently, tests on the basis of the new SAFT VES16 cells are being done in order to implement this cell model in PEPS.

The aging model that was also developed at ESTEC [6] is capable of describing an aged cell with the same basic model

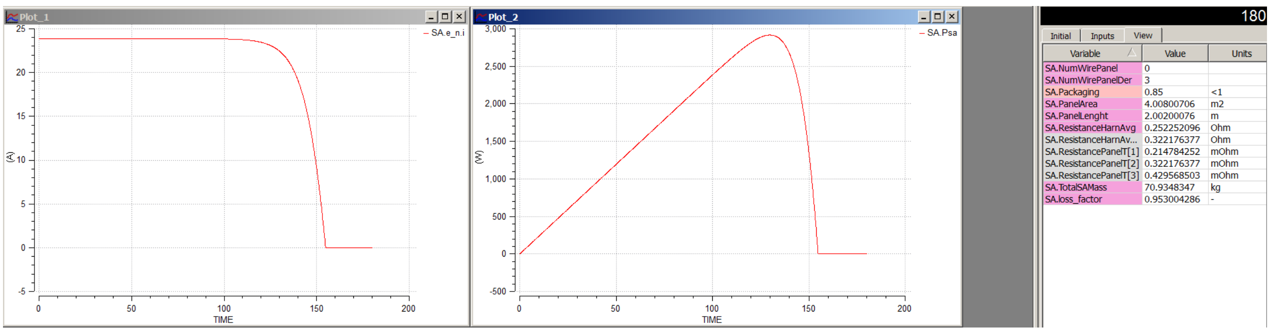

Fig. 5: Some outputs of the solar array model. Both graphs and mass and harness data outputs

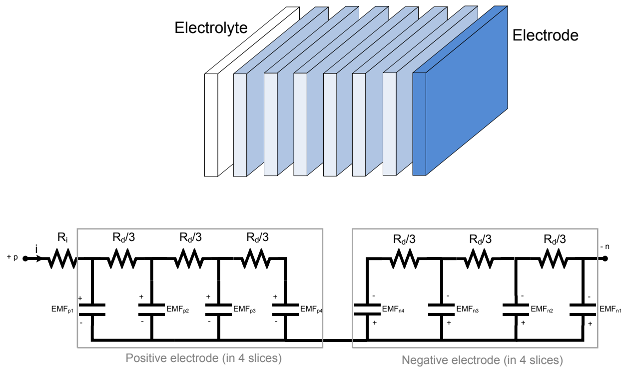

Fig. 6: electrode slicing concept and its implementation as RC networks.

as for the new cell. The parameters of the new cells need to be modified with five individual ageing parameters. In order to adapt the model to an aged condition. The model allows two options for aging:

- Ad-hoc parameter modification
- Pre-loaded parameters based on previous tests

The validation has been shown in [6] and shows an excellent agreement between the simulated and the experimental results. Fig, 7 shows a comparison of the battery voltage and temperature under a load step test.

The exact characterisation of cells, which have been aged in a defined way is the basis of any experimentally validated ageing model. The controlled ageing of cells, however, is a very time consuming and costly thing to do. In consequence, the availability of independent and representative ageing test data is very scarce. Furthermore, the missions for which an evaluation of the battery ageing is desired, often use a differing profile as compared to the cycling profile used during the experimental tests. It would be highly desirable to elaborate a means to correlate the scaling factors from experimental data to real usage in terms of ageing.

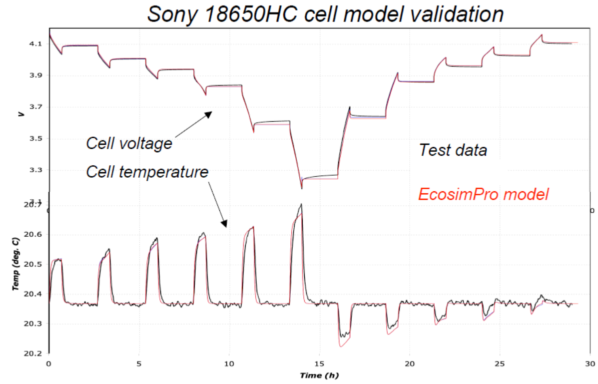

Fig. 7: comparison of simulated and experimental results in the Sony HC18650 cell.

7. POWER SYSTEM MODELING

Regarding the power systems models, all the main power conditioning units have been modelled as well with the tool: S3R regulator for battery bus systems and also for fully regulated buses, DC/DC converters with MPPT both for unregulated and fully regulated buses, generic DC/DC converters, distribution units, different kinds of loads, etc. Generally speaking, it would be possible to simulate all the basic power systems around. Fig. 8 shows an example of one schematic with a basic power system connected to the orbital components giving the fluxes to the solar array. There are also several components that allow reading data files in real time. This implies that the data can be used for any purpose in the simulation, either as an input for any given component or just to compare results in real time with experimental data or other simulated data.

Because of the schematic entry of PEPS, the user can build a power system flexibly by means of the different building blocks and connect them as needed. However, it is also likely that very specific features of some projects cannot be implemented out of the box. A way to solve

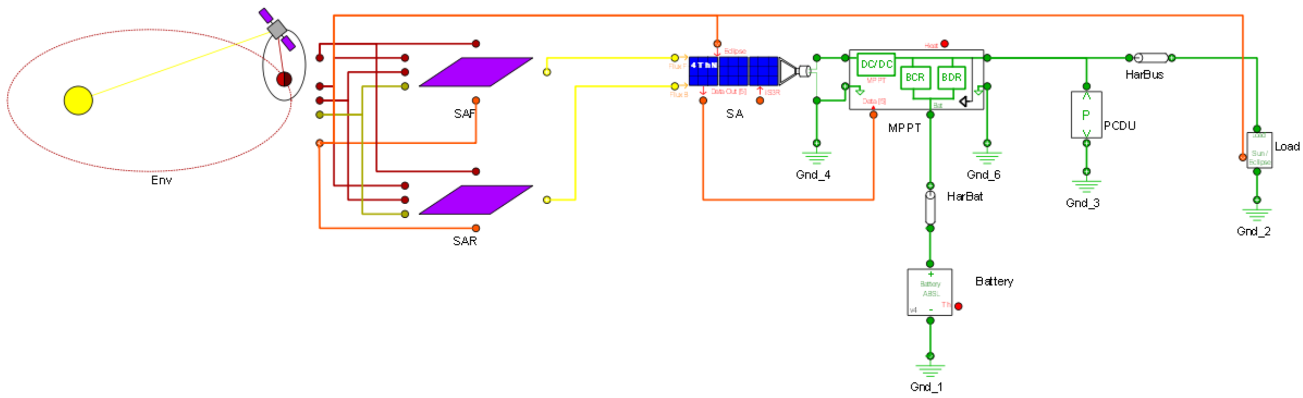

Fig. 8: Schematic view of a power system example and some orbit and geometry models in PEPS.

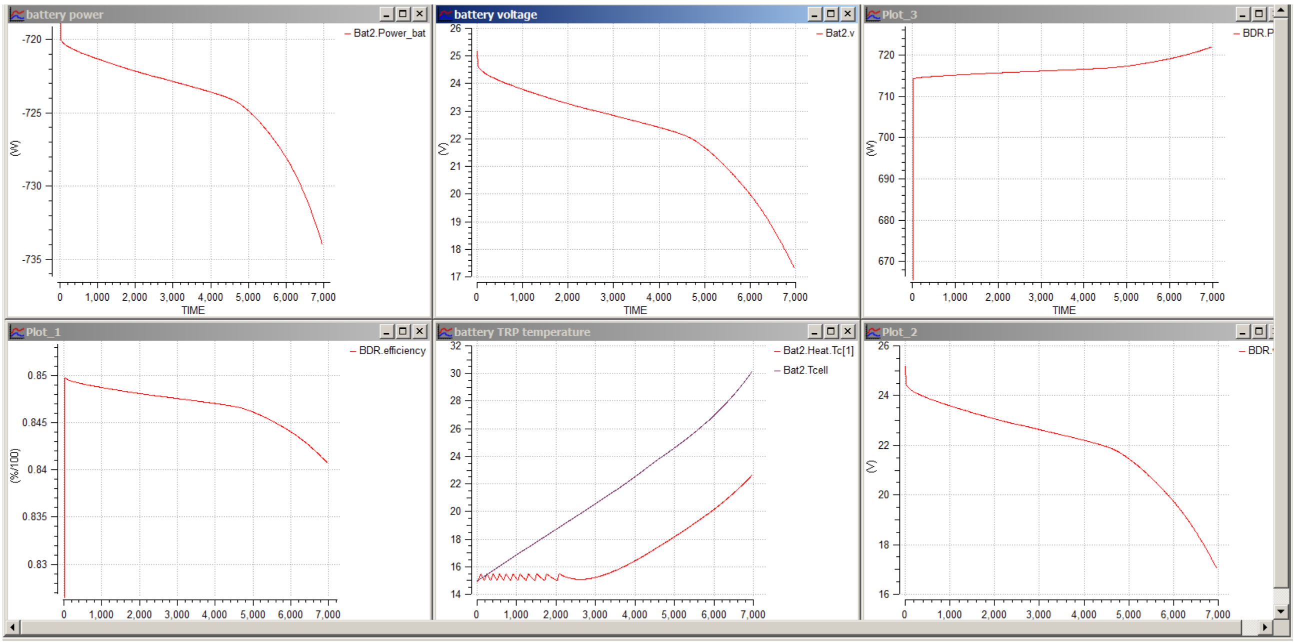

Fig. 9: several variables from a battery discharge phase displayed together.

this is to be able to modify the components in a simple way. In fact, this is a very interesting feature that can be achieved with EcosimPro since the modeling language is very simple. The equations are written as they would be in paper and hence, it is easy to read and understand the model. In general, by doing minor changes to the existing models, any specific demand from a project can be easily accommodated. As was explained before, the changes can be traced with the SVN system.

In all the cases, the most important parameter to model is the efficiency. If breadboards or engineering models are already developed, the efficiency data experimentally measured can be implemented in the simulation model so that the losses are exactly the same under the same conditions. The data input is bi-dimensional so that the efficiency changes according to the input voltage and the output power. Several curves can be used for different operating conditions and the model will interpolate to calculate the value needed for each particular case. The power units also have a thermal input so that the information about the baseplate temperature is known by the model. Hence, temperature dependent parameters can be changed accordingly.

From the system perspective, the biggest challenge to model the electronic units is to ensure the compatibility with the rest of the components of the power system, mainly the solar array and the battery. This is one of the strongest points of EcosimPro since the software takes care of putting together the equations of the full schematic and finds a way to solve it. This means that the user does not have to take care of defining the sequence in which the equations have to be solved. Note that this is a major challenge when using components provided by different engineers.

Once the system schematic has been built and the simulation has been defined, the user will have access to every variable inside each component. The graphical representation of all those variables can be displayed as needed by the user. Note that in a basic power system, the number of variables is typically in the order of 400 to 500. Fig. 9 shows some results from a battery voltage evolution during the eclipse phase, including the thermal performance, and some other parameters.

The simulation runtime is also quite fast. A typical LEO power subsystem simulation of 10 orbits runs in around 1 minute in a conventional laptop. This means that it is possible to perform iterations in real time in order to perform trade-offs or to verify the impact of any design parameter in the system performance. I also allows to have a working meeting in which the simulation results are displayed live and discussed by the attendees.

8. FUTURE WORK

PEPS is a living project and the development is continuously evolving to incorporate new models or improve the existing ones. Apart from that “normal work” process, the long term development includes a geometrical 3D input plug-in for the satellite geometry and a 3D viewer for the orbit visualization.
In terms of the power units, there are developments on going to simulate systems at a deeper detail level. For example, to simulate solar arrays at cell level in order to evaluate the effects of shadowing and failure modes with cells oper-

ating in reverse characteristic. This will also imply to introduce a thermal model able to calculate operative and non-operative temperatures at cell level. Hence, the extension of the validity of the model to different environments like Mars and High Intensity High Temperature missions will be needed as well.

Some developments are also exploring the simulation of the power system at solar array section level with a lower level of integration of the electronics models.

9. CONCLUSIONS

Power system simulations have been proven as a valuable tool for system and mission analysis but, the constantly increasing complexity of ESA missions is challenging the feasibility of those simulations. PEPS is a power system simulation tool that has been internally developed in ESA integrating the knowledge of many different fields using EcosimPro as software platform. The overall development is quite complex and time consuming but the results achieved in a short period of time demonstrate that the project is feasible, the software package chosen is the right one and that the data obtained from simulations are worth the investment.

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