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AENEAS

innovAtive ENErgy storage systems onboArd vesselS

Deliverable D2.1: Components model of ESS, PMS/EMS, power consumers and mission profile

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Project Abstract

AENEAS aims to contribute towards climate-neutral and environmentally friendly water transport through three new next generation clean energy storage solutions. Eventual impact is an increase of the global competitiveness of the EU waterborne transport sector by European technology leadership for energy storage solutions for diverse waterborne applications.

AENEAS will develop three innovative electric Energy Storage Solutions (ESS) for waterborne transport, which are advanced beyond the traditional battery systems, including Solid-state batteries (SSB), Supercapacitors (SC) and a Hybrid system which combines SSB and SC.

The solutions enable (partial or full) electric shipping, taking into account conditions specific ships might encounter, including adverse conditions outside sheltered waters or going upstream on rivers. AENEAS will evaluate them for a range of applications and end uses in short-sea shipping and in-land waterways. At the same time AENEAS will define the pathway for the three ESSs for application in different ship types, achieving a comprehensive understanding of the ESSs and their applicability for diverse waterborne transport.

Table of Contents

Public Summary

This deliverable, “Components model of ESS, PMS/EMS, power consumers and mission profile” is a part of Task 2.1, Work Package 2 - Concept design and Optimization. The main objective of this task is pre-sizing of energy/power management strategies and architectures using advanced simulation tools. This also includes to draft the required simulation component requirements.

The final output of this task will be different Energy Storage Solutions (ESS) simulation components that will be used in the simulation models on system level to mimic the different Energy Storage Solutions (ESS) studied within AENEAS. The focus during the whole task, and this deliverable, will be on power/energy performances and efficiency using a DC grid.

A brief description of each of the tools used is also included in order to understand the backgrounds of different simulations.

1 Introduction

1.1 Rational of this deliverable

The main objective of this deliverable is to develop various simulation components for Energy Storage Solutions (ESS) simulation models. These simulation components shall be designed with a focus on power/energy performance and efficiency using new approaches.

This deliverable belongs to the WP2 whose lead beneficiary is SIEMENS.

The document consists of the following parts:

- Introduction
- Component model development
    - Descriptions of modelling tools used
    - SC, SSB, PMS/EMS models including required input data, applied modelling approaches, and modelling parametrisation and evaluation
- Mission profiles

SIE, I2M and ABEE provided the descriptions and overview of the tools that will be used for simulations in this task. Modelling approaches for SSBs and SCs were also described for all tools used.

EMS/PMS models and components were analysed and approaches were described by SIE and UVA.

The main result is a first version of all modelling approaches for each ESS type, as input for the definition of the use-cases of the following tasks.

<u>Attainment of the objectives and explanation of deviations</u>

The objectives of this deliverable are achieved without any deviations.

2 Component model development

2.1 Modelling tools

2.1.1 Simcenter Amesim

Simcenter Amesim is a commercial simulation software for the modelling and analysis of multi-domain systems. The software package is a suite of tools used to model, analyse and predict the performance of systems involving different physical domains (mechanical, electrical, magnetic, hydraulic, pneumatic, thermal, and thermodynamic) and control. Models are described using nonlinear time-dependent analytical equations that represent the system's behaviour. Compared to 3D CAD modelling this approach gives the capability to simulate the behaviour of systems before detailed CAD geometry is available, hence it is used earlier in the system design cycle or V-Model.

To create a simulation model for a system, a set of libraries is used. These contain pre-defined components for different physical domains. The icons in the system have to be connected through ports, which have several inputs and outputs. These external variables are either effort variables (intensive properties) or flux variables (extensive properties). This framework comes from the Bond Graph Theory [1]. In most of the physical domains (electrical, 1D translation mechanical, 1D rotation mechanical, hydraulic, magnetic), the product of the effort and flux variables gives the transmitted power and integration over time of this power gives the transmitted energy (Figure 1).

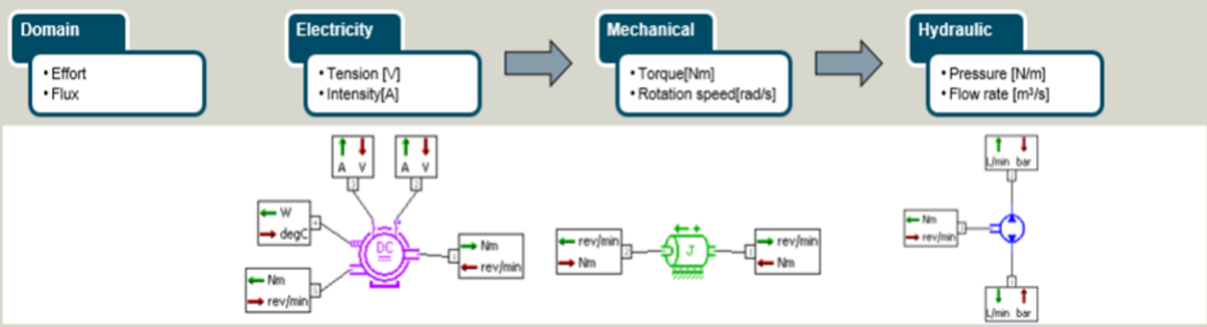


Figure 1: Component connections

Simcenter Amesim is therefore naturally made for multi-domains simulations as components can connect different physical domains using different ports ensuring the conservation of energy.

At each time step in each component several variables are computed, from received inputs and the parameters, including the output external variables and the derivative value of the state variables. Between the time steps, the Simcenter Amesim solver integrates over time all the states variables to calculate the next point. Both the time steps and the integration algorithm are dynamically chosen by the solver to ensure a very good accuracy of the integration.

Simcenter Amesim is an open simulation platform that can be coupled with other simulation software in multiple ways. It complies with the Functional Mock-up Interface (FMI), which is a set of standards that specify how to couple simulation models built with various simulation software tools or how to couple the simulation software themselves in the aim of performing transient simulations of the coupled system. A simulation software tool which complies with these standards may act:

• either as an exporting tool that can create components called Functional Mock-up Units (FMU) containing models or simulators to be used by other simulation software

• or as an importing tool that can use FMU generated by other simulation software

The FMI standards define two kinds of interface:

• FMI for Model Exchange which describes a standardized way for interfacing a model with a simulation environment that provides at least a numerical solver.

• FMI for Co-simulation [2] [3], which deals with the coupling of simulators (each simulator having its own numerical solver embedded in the FMU) through a master co-simulation environment.

Similarly, Simcenter Amesim has dedicated coupling capabilities with Simulink. The Simcenter Amesim-Simulink and Simulink-Simcenter Amesim interfaces make it possible to perform simulations with a combination of Simcenter Amesim and Simulink models. Since there are two software packages involved, the interfaces provide two main options: importing the Simcenter Amesim model into Simulink, or importing the Simulink model into Simcenter Amesim. With the Simcenter Amesim-Simulink interface the user has the choice of these two methods.

In addition to these two methods, it is also possible to export the Simcenter Amesim solver (with the Simcenter Amesim model) to Simulink. This is sometimes called co-simulation since we use the solvers from the two software packages, and they perform the simulation together.

2.1.2 ConfigTool

ConfigTool simulation tool is based on an ultra-lean novel power-driven energy distribution system simulation method. The fundamental idea of this simulation method is to simplify the simulation approach to such an extent that a faster simulation and subsequently numerical optimization becomes feasible, which is to be used in particular in the early concept phase for the design of “energy distribution systems” like the design of a battery thermal management system of vehicles of all kinds. This simplification is achieved through a smart new modelling approach by reducing the equations to exclusively those physical quantities that are either relevant to the energy exchange between the individual components or of interest to the results.

The emphasis of this simulation method is to simulate energy exchange between the individual components, but not the exchange of those substances (e.g., coolants, hydraulic liquids) that are responsible for this energy transfer. In contrast to conventional modelling approaches, the connections of the components in the system are not physically modelled, however, all physical limits and boundary conditions such as available power, possible power consumption, as well as technical feasibility and constraints such as minimum/maximum power of the individual components will be respected in the simulation. This permits to substantially reduce a large number of equations. For example, the very computationally intensive flow equations are completely omitted for characterizing an energy management system.

In addition, each component will be modelled only in a way that is less physically complicated, but in accordance with all the physical laws and technical constraints of the component. This results in a reduction of the elaborated equations that characterize each component physically in detail to the essentials equations that adequately describe the overall physical behaviour as such.

Each physical component is characterized by its power (P). Moreover, there is a controlled process that manages the exchange of energy packages (1) between the components at specific time steps.

$$\Delta E = P \cdot \Delta t \qquad (1)$$

Dynamic connection and disconnection of components based on user-defined strategies is possible. Due to this the approach is considered as a discrete-event simulation.

Main application areas of the Config-Tool are for example:

- configuration of “energy distribution systems” (e.g., electric vehicle powertrains)
- right-sizing of components
- optimization of concept variants
- peak shaving of energy distribution
- operation & control strategies concepts

To sum up: ConfigTool focuses on system simulation for energy distribution systems for concept development in very early design stage. The tool unique selling point is its robust and fast simulation that enables numerical optimization of concept variants.

2.1.3 Simulink

Simulink is a complete software tool that offers a block diagram environment for conducting multidomain simulations and implementing model-based designs. It facilitates the development of complex systems by supporting system-level design, simulation, automatic code generation, and continuous testing and verification of embedded systems.

With Simulink, users can create and manipulate block diagrams using a user-friendly graphical editor. It provides a wide range of customizable block libraries, which contain pre-built components representing various system elements. These blocks can be interconnected to represent the desired system architecture and behaviour.

Simulink also includes solvers that enable the modelling and simulation of dynamic systems. These solvers accurately compute the system’s response to inputs and help analyse its behaviour over time. The software integrates seamlessly with MATLAB, allowing users to incorporate MATLAB algorithms directly into their models. Furthermore, simulation results can be exported to MATLAB for further analysis and post-processing.

Simulink supports the modelling of both linear and nonlinear systems, incorporating real-world phenomena like battery, gear slippage, and hard stops. It allows users to design hierarchical models by organizing blocks into subsystems, enabling the representation of discrete components that mirror real-life systems. Through simulation, these components can interact and their behaviour can be analysed. This approach proves valuable in testing conditions that are challenging to replicate solely with hardware prototypes, particularly in the early stages of the design process when physical hardware may not be accessible.

Model-Based Design places a system model as the central element in the development workflow. This approach enables the rapid and cost-effective development of dynamic systems, including control systems, signal processing systems, and communications systems.

Model-Based Design offers several advantages, including:

- Utilizing a unified design environment across project teams
- Establishing direct links between designs and requirements

- Continuously identifying and rectifying errors by integrating testing with the design process
- Enhancing algorithms through multidomain simulation
- Automating the generation of embedded software code and documentation
- Facilitating the development and reuse of test suites

The key tasks involved in Model-Based Design include:

- Identifying modelling goals, determining components, and designing the system layout
- Modelling and testing individual components, integrating them, and testing the overall system
- Designing and testing new components

By following these tasks, Model-Based Design allows for efficient and effective system development, ultimately leading to improved outcomes in various domains. Figure 2 depicts the workflow of tasks for model-based design.

Simscape

Simscape enables a rapid creation of models of physical systems with the Simulink environment. With Simscape physical components models can be built based on physical connections that directly integrate with block diagrams and other modelling paradigms, Simscape add-on products more complex components and analysis capabilities.

Simscape helps to develop control systems and test system level performance. It helps to create custom components models using the MATLAB based Simscape language, which enables test-based authoring of physical modelling components, domains and libraries. Models can be parametrized using MATLAB variables and expressions, and design control systems for your physical system in Simulink. Models can deploy to other simulations environments, including hardware-in-the-loop (HIL) systems, Simscape supports C-code generation.

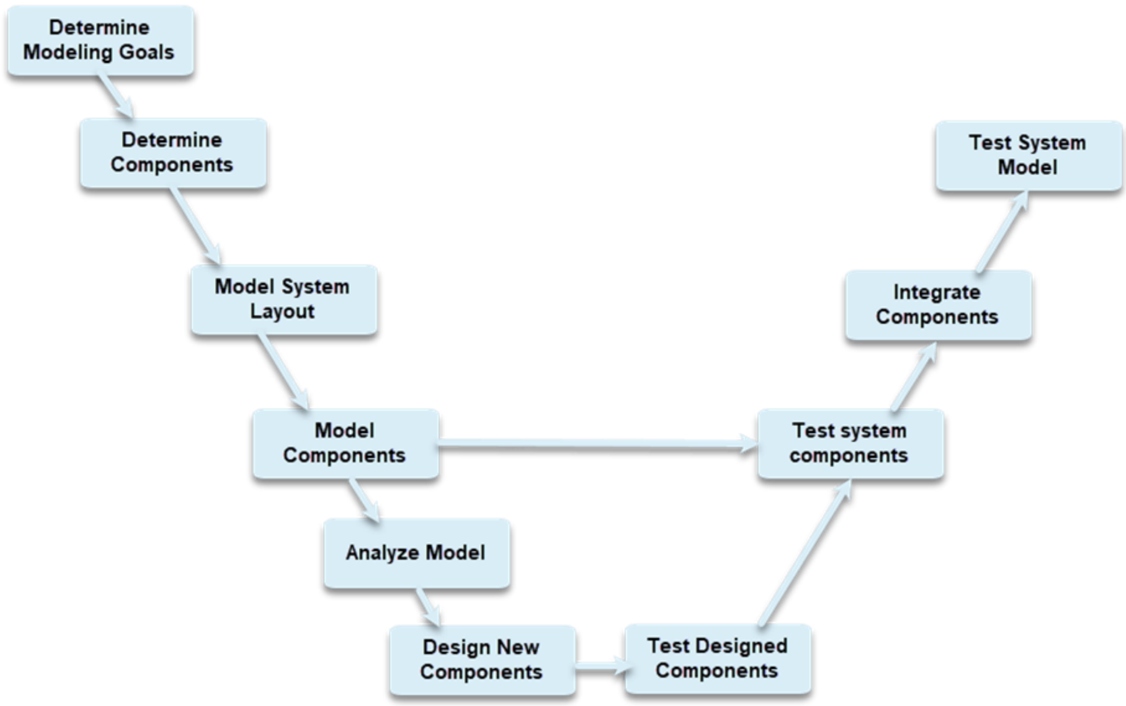


Figure 2: Model-based design task considering the workflow

Simscape block diagrams use physical signals instead of regular Simulink signals. We need converter blocks to connect Simscape diagrams to Simulink sources and scopes. Simulink-PS converter block to connect Simulink sources or other Simulink blocks to the inputs of a Simscape physical network, also used it to specify the input signals units. PS-Simulink converter block is used to connect outputs of a Simscape physical network to Simulink scopes, an example is shown in Figure 3.

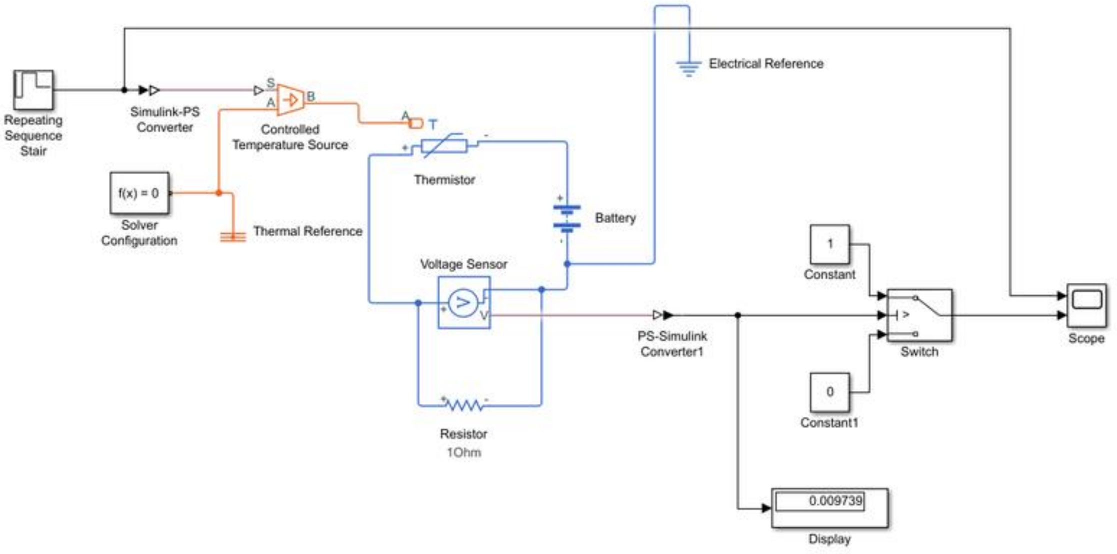


Figure 3: Connecting Simscape diagrams to Simulink sources and scopes

Simscape Battery offers a range of design tools and parameterized models specifically designed for battery systems. It enables the creation of digital twins and facilitates virtual testing of battery pack architectures. With Simscape Battery, users can design battery management systems, assess battery system behaviour under normal and fault conditions, and model various battery pack operations.

The parameterized models provided by Simscape Battery showcase functionalities such as cell balancing and state of charge estimation. Users can effectively build battery pack models and implement control strategies for battery management systems (BMS) using controllers, estimators, monitors, and balancers. Additionally, the software allows for the simulation of battery cooling systems, enabling the evaluation of thermal management for individual modules or packs.

2.2 Model requirements

When developing components models for ESS like for example solid-state batteries, several key requirements need to be considered in general. Energy density is a crucial factor, determining how efficiently energy is stored. Power density is also important, as it indicates how quickly the battery can deliver energy. The desired operating voltage range, also the operating temperature and charging time should be specified to ensure compatibility and efficient rechargeability. Additionally, the physical dimensions need to be determined for seamless integration.

For modelling supercapacitors, capacitance plays a vital role in efficient energy storage. Power density is important to meet high-power demands. The operating voltage range and the operating temperature range should be defined to ensure compatibility. Moreover, the physical dimensions and form factor must be specified for integration purposes.

Three different tools, ConfigTool, Simcenter Amesim, and Matlab/Simulink, offer distinct approaches to modelling solid-state batteries (SSB) and supercapacitors (SC).

ConfigTool is a tool that provides a fast and simplified modelling approach. It allows for quick prototyping and initial assessments, making it suitable for rapid concept exploration and numerical optimization of concept variants.

Simcenter Amesim takes a more comprehensive approach by utilizing electrical circuit models for each component. This method enables detailed analysis and optimization, considering electrical characteristics and component interactions. Simcenter Amesim offers higher accuracy and precision in the modelling process.

Matlab/Simulink is a versatile tool widely used for system modelling and simulation. It provides a flexible platform to incorporate various physical and mathematical models. With Matlab/Simulink, complex and dynamic models of solid-state batteries and supercapacitors can be developed, allowing for detailed analysis, control system design, and performance evaluation.

2.3 Solid state battery (SSB) models

2.3.1 Input data

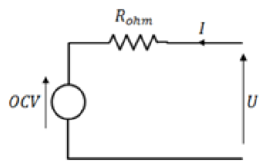
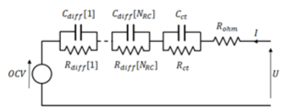
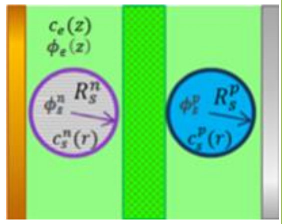
All three different tools, ConfigTool, Simcenter Amesim, and Matlab/Simulink are used for modelling SSBs. With regards to Simcenter Amesim there are three types of battery model in Simcenter Amesim as shown in Table 1

• Simple equivalent circuit model, which consists of a voltage source to represent the open-circuit voltage (OCV) and a resistance. This model would only represent the basic electrical and thermal behaviour of the battery, with few functional parameters and no coupling to other advanced features such as thermal runaway modelling.

• Advanced equivalent circuit model, which in addition can include RC circuits to accurately represent the battery dynamic behaviour related to the diffusion and the charge transfer phenomena inside the battery. This model can be used when you need to simulate the dynamic behaviour, the aging or the thermal runaway of the battery. Note that depending on the selected options, the model can have a less complex equivalent circuit.

• Electrochemical model, which describes in detail the chemical process taking place inside the battery cell, such as the charge transfer, the diffusion, etc. The electrochemical models do not produce a better fidelity than the advanced equivalent circuit model. However, their parameters define the battery geometry and the electrochemical characteristics of its materials. They can therefore be used to predict battery behaviour before it is manufactured.

Table 1: Overview of the battery models in Simcenter Amesim

Modelling approach	Simple equivalent circuit	Advanced equivalent circuit	Electrochemical
Schema			
Thermal loss	Yes	Yes	**Yes**
Thermal runaway	No	Yes	**No**
Aging	Yes	Yes	**Yes**

For the ConfigTool the main input parameters for such battery models are:

- Cell voltage: U_{iC}
- Internal cell resistance: R_{iC} (SoC, T)
- Capacity of a cell: E_C
- Heat capacity of a cell: C_C
- Thermal coefficient: C_{thC}

The model is similar like the simple equivalent circuit as describe above for Simcenter Amesim. Especially state variables, namely state of charge and temperature, will be taken into account for e.g., the internal cell resistance.

2.3.2 Modelling approaches

Simcenter Amesim

The battery models are stored behind components icons for individual cell and modules/packs (Figure 4).

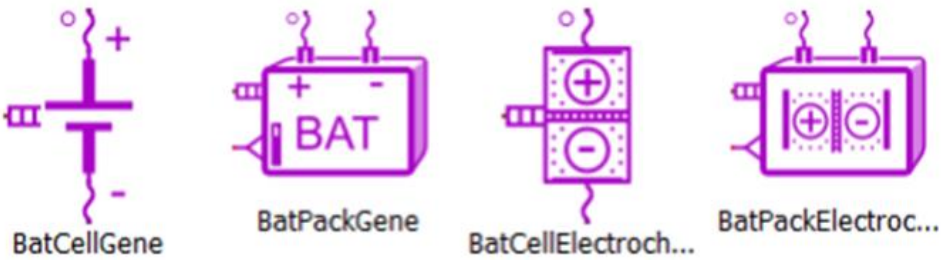


Figure 4: Battery icons

In all cases, the battery model component will exchange variables with other components through ports. There are three types of ports for these models: electrical ports, where instantaneous current and potential are exchanged, a thermal port where a temperature and a heat flow rate are exchanged. Additionally for the battery pack models, a signal port gives the state of charge as an output. Simcenter Amesim is based on a causal approach, the inputs/outputs (I/O) at the ports may vary depending on the connected elements. An example of the I/O for a battery pack is presented Figure 5.

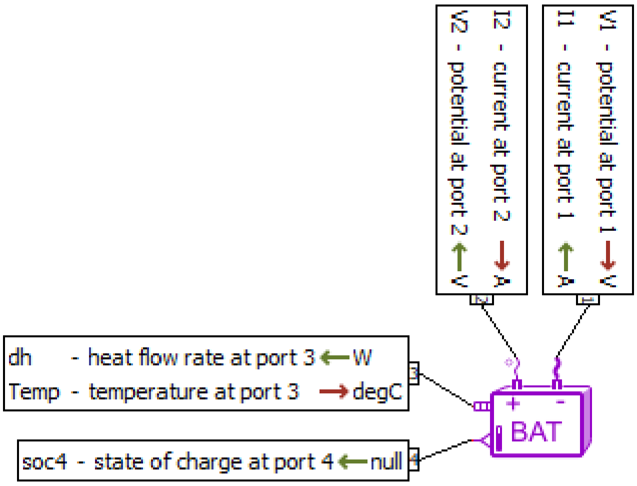


Figure 5: Example of battery pack I/O (submodel ESSBATPA01)

The battery model used in the AENEAS project will be the advanced equivalent circuit model. It is based on an equivalent circuit model such as shown in Figure 6.

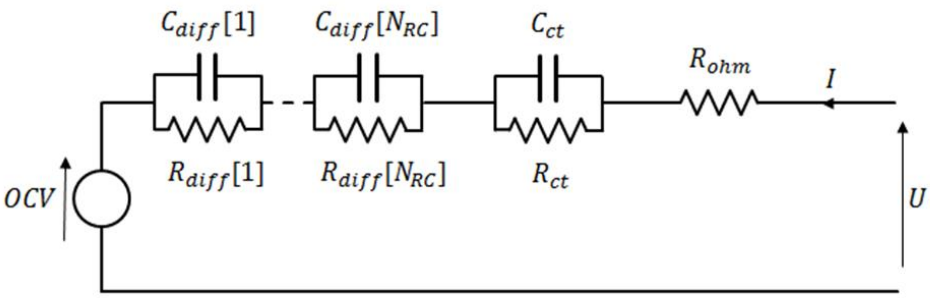


Figure 6: Dynamic equivalent circuit model of battery cell

Most of the parameters can be set as tables or expressions as a function of the battery operating condition, such as the state of charge and the temperature.

The battery representation can be very simple, taken into account only the most basic phenomena:

- Open circuit voltage, which defines the battery voltage when it is at rest.
- Ohmic resistance, which defines the instantaneous voltage drop depending on the charge or discharge current.

In addition, the modelling of different advanced phenomena can be activated:

- Faradic efficiency, which takes into account the faradic loss that occurs during charge. This will be considered in the AENEAS project only if the cell shows significant hysteresis.
- Hysteresis modelling, which takes into account the change of open circuit voltage related to the charge and discharge history. This will be considered in the AENEAS project only if the cell shows significant hysteresis.
- Entropic coefficient, which models the voltage change in OCV due to temperature change and the reversible heat flow related to this phenomenon. This will be considered in the project, in order to ensure an accurate thermal behaviour of the model.
- Diffusion and charge transfer, which capture the transient of the battery voltage drop, using RC circuits. This will be considered in the project.

- Aging, which estimates the calendar and cycle aging on the battery capacity and resistances. This will not be considered in the AENEAS project.
- Thermal runaway, which represents the exothermic reactions in the cell during a thermal runaway. This will not be considered in the AENEAS project.

In addition to the parameters of the different electric circuit, the battery model has the cell capacity as parameter, as well as the number of cells in series and in parallel in the case of a battery pack. A thermal model can be connected to the battery model. In this case, additional parameters such as thermal capacitance, convective heat exchange area and convective heat exchange coefficient will have to be set. All the parameters are accessible and can be changed by the user. The most relevant parameters to be changed for the optimization process will be identified with WP3 partners.

Simulink and Simscape

Similarly, the models used in Simscape Battery aim to replicate battery behaviour through electrical equivalent circuits, allowing for compatibility with commercial circuit simulation software. These models feature a simple structure while still providing sufficient accuracy to approximate simulated variables, even when the state of charge (SoC) and temperature exhibit dynamic variations.

The equivalent circuit battery block within Simscape Battery utilizes a resistor-capacitor (RC) circuit battery, which can be parameterized using equivalent circuit modelling (ECM). To simulate the SoC and terminal voltage, the block takes into account the load current and internal core temperature. By employing parameter lookup tables, the equivalent circuit battery block calculates the combined voltage of the battery network. These lookup tables are functions of the SoC and battery temperature and are generated using the same block.

The specific parameters implemented in the equivalent circuit battery block are represented as lookup tables, which are functions of the SoC and battery temperature. These parameters include:

- Series resistance, $R_o = f(\text{SoC}, T)$
- Battery open circuit voltage, $E_m = f(\text{SoC}, T)$
- Battery capacity, $C_{batt} = f(T)$
- Network resistance, $R_n = f(\text{SoC}, T)$
- Network capacitance, $C_n = f(\text{SoC}, T)$

To compute the combined voltage of the battery network, the block employs these equations:

$$\boldsymbol{V_T = E_m - I_{bat}\,R_0 - \sum_1^n V_n} \tag{2}$$

$$\boldsymbol{SoC = \frac{-1}{C_{batt}} \int_0^t I_{batt}\,dt} \tag{3}$$

$$\boldsymbol{I_{batt} = \frac{I_{in}}{N_p}} \tag{4}$$

$$\boldsymbol{V_{out} = N_s V_T} \tag{5}$$

$$\boldsymbol{P_{battLoss} = I_{batt}^2\,R_0 + \sum_1^n \frac{{V_n}^2}{R_n}} \tag{6}$$

$$\boldsymbol{Ld_{AmpHr} = \int_0^t I_{batt}\,dt} \tag{7}$$

Here, E_m is battery open-circuit voltage, I_{batt} is per module battery current, I_{in} is the combined current flowing from the battery network. R_o is series resistance, N_p is the number of parallel branches, N_s is the number of RC pairs in series, V_{out}, V_T combined voltage of the battery network, V_n voltage for n-th RC pair, R_n is the resistance for n-th RC pair, C_n is capacitance for nth RC pair, C_{batt} battery capacity, P_{batt} battery power, $P_{LossBatt}$ is the negative of battery network power loss, $P_{BattLoss}$ is battery network power loss, $P_{StoredBatt}$ is battery network power stored, P_{LdBatt} is Battery network power, and T is battery temperature.

The Equivalent Circuit Model (ECM) is widely used in battery numerical analysis. It typically involves a one or two RC block model, which offers computational simplicity and can be easily combined with other methods, such as coulomb counting with OCV/SOC correlation for periodic recalibration during rest. The ECM is also adaptable to advanced techniques like the extended Kalman filter.

By reducing the general ECM with multiple RC blocks to a simplified ECM with just a single RC block (Figure 7), it becomes possible to account for all dynamic characteristics of the cell. This includes nonlinear open-circuit voltage, average discharge current, and inner cell temperature. During the parameter estimation procedure, dependencies of the ECM on the state of charge (SoC) and temperature are identified. These dependencies are then implemented as lookup tables, which define the values of the equivalent circuit elements.

The ECM model undergoes thorough validation using independent experimental data to ensure accuracy. Once validated, it becomes a reliable tool for general simulation, allowing for analysing and predicting battery behaviour in various scenarios.

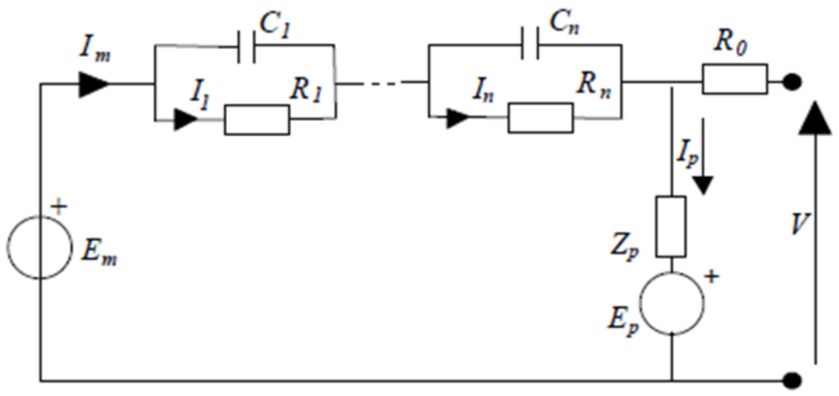


Figure 7: Equivalent circuit model

ConfigTool

In ConfigTool a model of a battery cell is done which describes the cell properties (see above). Afterwards the cell model is used to characterise a battery pack. The characterisation of the battery pack is modular, due to the parametrisation of a single cell. This modular approach enables easy adjustment and customization of the model of a battery pack.

The characterisation of the battery is used to calculate the state variables. The thermal characteristics are implemented describing how the whole battery pack, is exchanging heat to the environment (components, cooling system...). This heat exchange is mainly determined by the mechanical pack configuration, cooling system applied as well as the operating conditions of the battery pack.

2.3.3 Modelling parametrisation

Simcenter Amesim

The Simcenter Amesim advanced battery model can be parameterized from battery tests with current, voltage and temperature data. The battery Electro-thermal Identification tool (Figure 8) can be used to identify the parameters from these measurements. The workflow is shown Figure 8. The tool takes as input the battery test profiles with current, voltage and temperature data. These test profiles can be experimental tests, or simulation of complex battery models (electrochemical models, for instance). Then the tool provides a step-by-step guide through the whole identification process. The main steps are data import, capacity calculation, electrical model identification, thermal model identification, model set-up and validation, and finally data export. The outputs of the tool are model parameters values, which are tables in function of state of charge, current and temperature. These data are sent directly to the battery model in Simcenter Amesim.

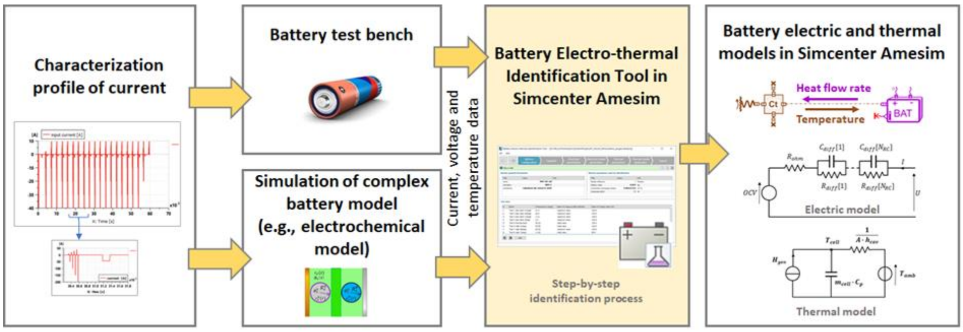


Figure 8: Workflow of the battery electro-thermal identification tool

Simulink and Simscape

In Figure 9, the parameter estimation steps are depicted, which involved running the pulse discharge curve for each temperature separately through the estimation task. This process yielded a set of one-dimensional lookup tables for each temperature, representing the four parameters (E_m, R_0, R_1, and C_1) as functions of the state of charge (SOC). By repeating this procedure at different temperatures, four sets of data were obtained, characterizing the specific cell chemistry being considered. These lookup tables and a linear interpolation process formed the two-dimensional lookup tables used to determine the values of the equivalent circuit elements during the simulation phase. It is assumed in the resulting model that the cell impedance remains relatively unchanged, regardless of the magnitude of the discharge current. This assumption simplifies the model and allows for efficient simulation of the battery behaviour.

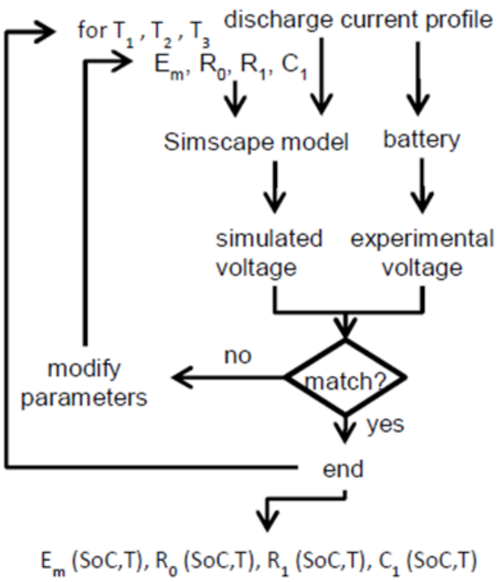


Figure 9: Flow diagram of the parameter's estimation procedure

ConfigTool

To describe a battery pack starting from a single cell the following parameters are used:

- Thermal resistance of the battery to the environment: $RI_{bat,env}$
- Total number of cells: p * s, with:
  - p = number of cells connected in parallel
  - s = number of cells connected in series

With the parameters of the battery cell and the parameters of the battery, characterisation of the battery pack model is done. The characterisation can be functions of the state variables namely the state of charge (SoC) and temperature (T). The main characterisation variables are:

- Capacity of battery: E_B
- Heat capacity of battery pack: C_B
- Average temperature of battery pack: T_{bat}
- Power of battery: P_{bat}
  - Electrical Power: $P_{el,bat}$
  - Thermal Power: $P_{th,bat}$

Example formulas:

$$E_B = psE_c \tag{8}$$

$$C_B = psC_C \tag{9}$$

The state variables get updated with each time step. Where following equations are used in the model:

$$SoC(t_i) = SoC(t_{i-1}) + \frac{P_{el,bat}(t_i)\,\Delta t_i}{E_B} \tag{10}$$

$$T_{bat}(t_i) = T_{bat}(t_{i-1}) + \frac{P_{th,bat}(t_i)\,\Delta t_i}{C_B} \tag{11}$$

In the last formula $P_{th,bat}$ is the difference between generated heat and dissipated heat, generated by the battery pack.

2.3.4 Evaluation of SSB modelling approaches

The model evaluation is done using experimental data as presented for one of the approaches below. In the previous section sketched dynamic equivalent circuit model of a battery cell can predict accurately its electrical and thermal behaviour. A comparison with experimental results for a commercial NiRich NMC-SiC 18650 battery cell with 3 Ah nominal capacity is presented in this section. Figure 10 presents the comparison for the hybrid pulse tests which have been used to identify the parameters of the battery electrical model. Figure 11 gives a zoom of the discharge phase. The model accurately represents the electrical and thermal behaviour of the real cell on the change of State of charge and temperature.

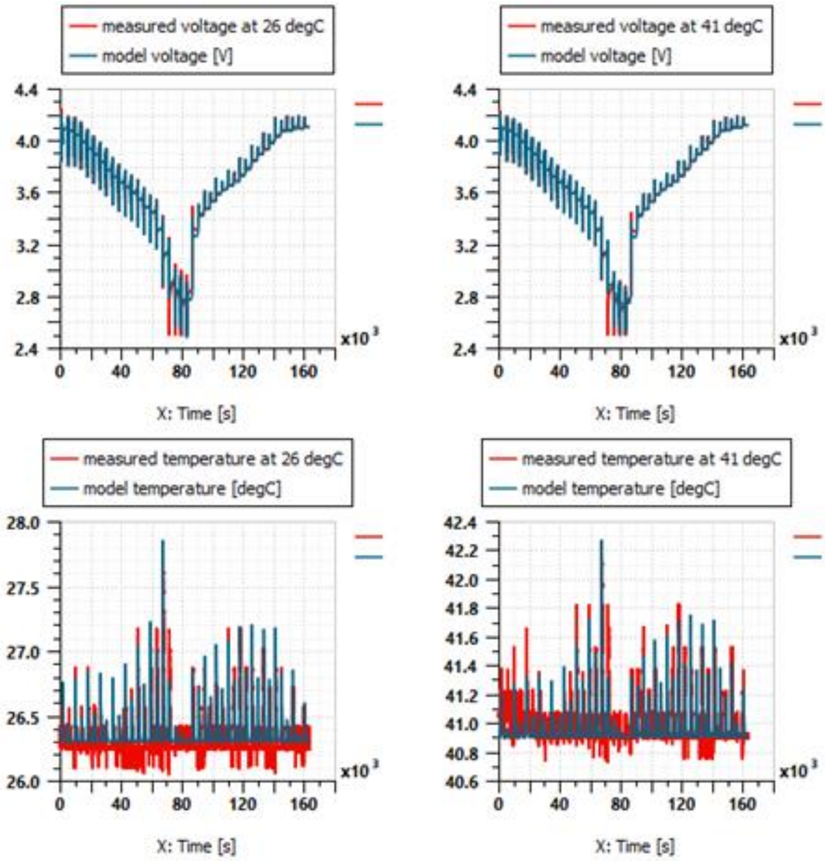


Figure 10: Voltage and temperature comparison between the experimental and model data for hybrid pulse tests at different temperatures

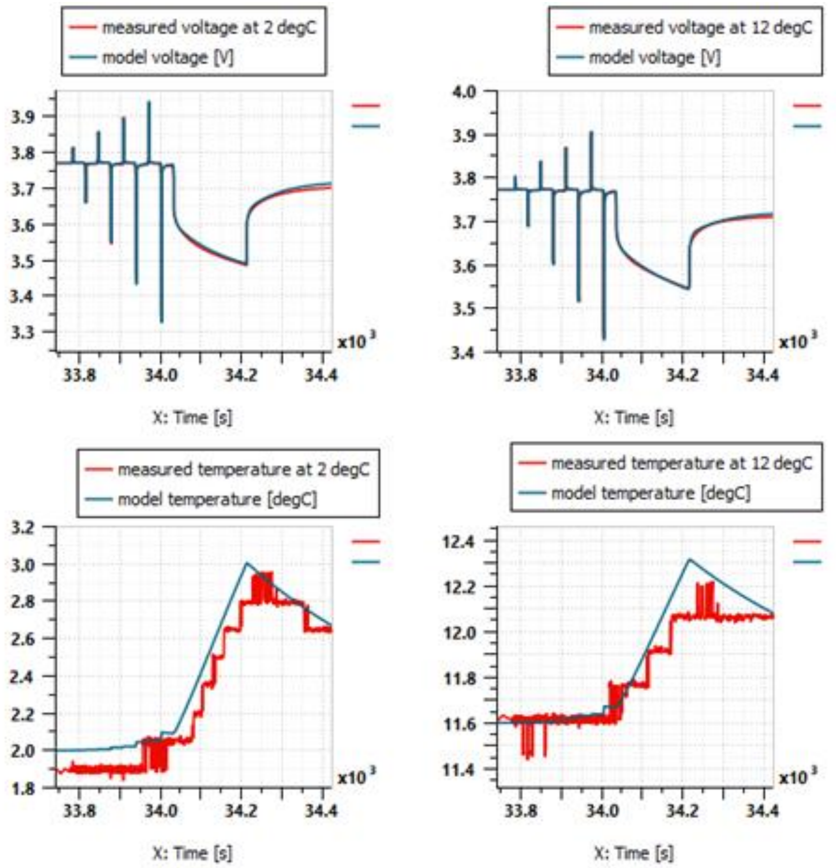


Figure 11: Zooms of the results for the hybrid pulse tests

All the battery models used within future work of ANEAS will be calibrated using the AENEAS data provided by WP3.

2.4 Supercapacitor (SC) models

2.4.1 Input data

Supercapacitors (SCs), also called Electrochemical double layer capacitors (EDLC) or Ultracapacitors (UCAP), are electrostatic energy storage systems, which can be used in association with battery systems to absorb or supply high electric power pulses. They prevent batteries from premature aging due to high current and high thermal losses, generated inside the cells and packs.

SCs systems store energy electrostatically in the electrochemical double layer at electrodes/electrolyte interfaces, enabling very fast energy conversion, thus providing high capability of current absorption and release.

Experimental investigations of SCs enable not only the required valuable insights into the behaviour of a SC but also serves as a crucial resource for the calibration of a mathematical/computational model of such SC. These models incorporate various parameters, equations, and algorithms to simulate the behaviour of the capacitor under different operating conditions. However, for the model to accurately and reliably represent the real-world behaviour of the capacitor, it requires calibration and fine-tuning.

By comparing the experimental data to be obtained from the experiments as foreseen in Task 3.2 with the predictions generated by the model, adjustments can be made to the model's internal parameters or equations. This calibration process aims to bring the model's predictions into closer alignment with the observed behaviour of the capacitor. For the ConfigTool, for example, the following main input parameters are used to model a capacitor:

- Capacitor voltage: U_{iCap}
- Internal capacitor resistance: R_{iCap} (SoC, T)
- Capacity of a capacitor: E_{Cap}
- Heat capacity of a capacitor: C_{Cap}
- Thermal coefficient of a capacitor: C_{thCap}
- Leakage current: I_{lCap}

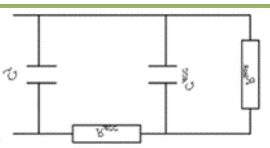
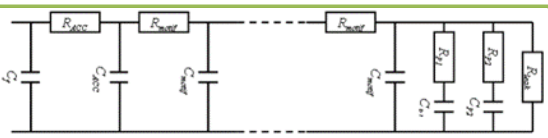
The input for the capacitor model is similar to these of a battery cell. However, one of the relevant differences between these models is the leakage current, which describes the SoC loss of the capacitor over time.

2.4.2 Modelling approaches

Simcenter Amesim and Simulink

There are two types of supercapacitor model in Simcenter Amesim (Table 2). The quasi-static model is used when the dynamic behaviour due to diffusion and charge transfer can be ignored. Otherwise, the dynamic model can be used to represent the dynamic behaviour. The two models are based on the equivalent electric circuits shown in the following table. The model can represent the electric behaviour of the supercapacitor and estimate the thermal losses as well but does not account for the aging of the component.

Table 2: Supercapacitor model

SC modelling approach	Quasi-static	Dynamic
Schema		
Thermal loss	Yes	Yes
Aging	No	No

The supercapacitor models are stored behind two components icons (Figure 12: Supercapacitor cell and pack icons), one for an individual supercapacitor, one for a capacitor module/pack.

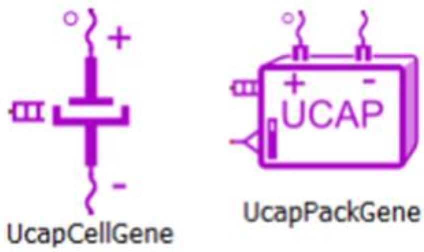


Figure 12: Supercapacitor cell and pack icons

The variables exchanged at the ports are similar to the one for the battery, as presented in Figure 12.

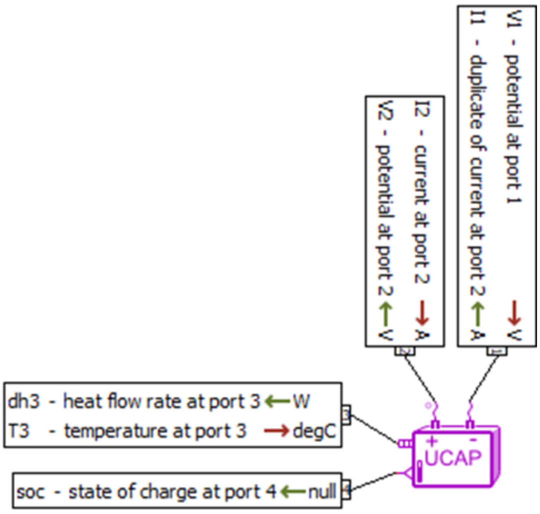


Figure 13: Example of supercapacitor pack I/O (submodel ESSUCAPPS01)

Simulink will be used for further parametrization and analysis based on the Simcenter Amesim model.

ConfigTool

The modelling approach for SCs is quite similar to the approach for SSBs. The initial step in the modelling process of the supercapacitor pack is the parametrisation of a single capacitor, which serves as the foundation for subsequent modelling of the entire pack. By defining the number of capacitors in series and parallel, the pack can be modelled, enabling the desired modularity of the supercapacitor pack. This modularity is essential for sizing the proposed initial architecture.

The supercapacitor model is based on a battery model (as described in 2.3) which is enhanced by a capacitor functionality (i.e., Voltage based on SoC). Additionally special modelling focus is put on the interaction between the modelled battery and capacitor behaviour.

The characterisation of the capacitor pack is used for calculating the state variables associated with the supercapacitor pack, particularly the temperature and state of charge. The characterisation will incorporate the representation of losses and thermal inefficiencies.

2.4.3 Modelling parametrisation

Simcenter Amesim and Simulink

The electrical equivalent circuit used to describe the Simcenter Amesim UCAP cell for the quasi-static model is shown in Figure 14. It takes into account main capacitance, internal resistance and electrical leakage.

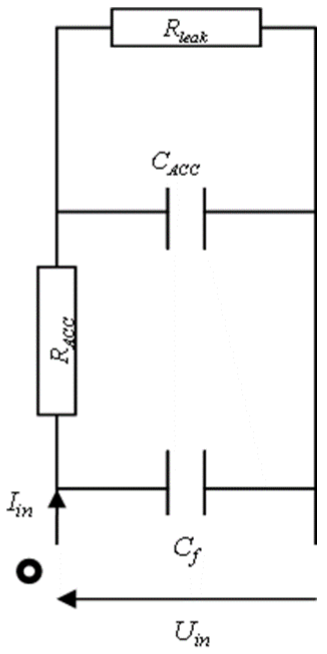


Figure 14: Electrical equivalent circuit model of the quasi-static UCAP submodel

The parameters needed to use this submodel are usually given by manufacturers' datasheets. The accumulator nominal capacitance, C_{ACC} is related to the number of charges that can be stored in the UCAP at V_{max} and is given by the manufacturer.

Leakage resistance, R_{leak} is an electrical parameter that can be evaluated thanks to experimental self-discharge tests on large time scales (Δt > 1h).

$$R_{leak} = U_{cell}(0) * I_{leak} = U_{cell}(0) * \triangle t * CACC(U_{cell}(\triangle t) - U_{cell}(0)) \tag{12}$$

where I_{leak} is the leakage current that can be approximated by the charge flow in the leakage resistance (i.e., the charges that are taken from the main capacitance). The entropic coefficient a is a constant used to describe reversible heat flow rate. Its evaluation is described in Schiffer et al. (2006) work. The filtering capacitance C_f is a numerical parameter used to break algebraic loops. It has no physical meaning and has to be small enough to be negligible.

The dynamic ultracapacitor model takes into account phenomena at different time scales, from instantaneous accumulation to electrical leakage. The electrical circuit representing the UCAP electrical behaviour is shown in Figure 15.

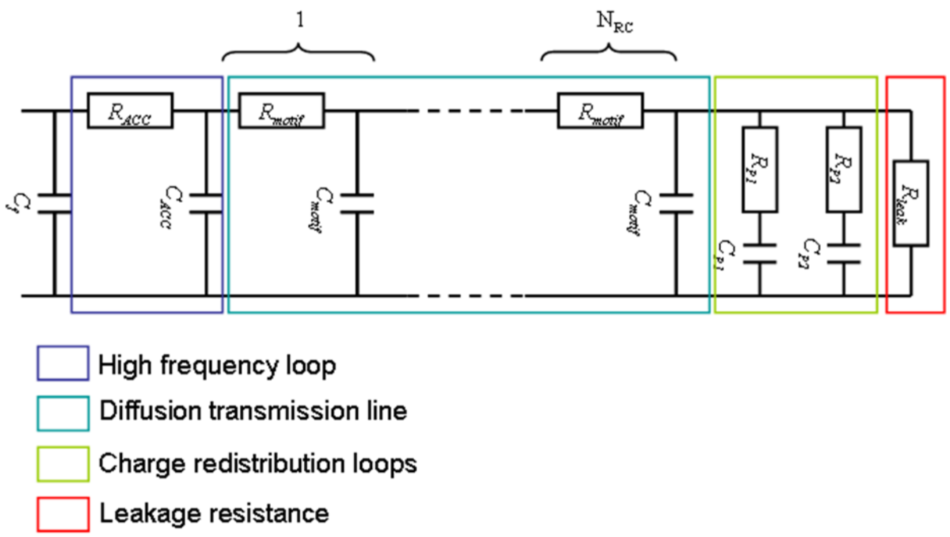


Figure 15: Dynamic UCAP phenomena modelled with an equivalent electrical circuit

The first loop (blue) composed by R_{ACC} and C_{ACC} accounts for high frequency phenomena (t<10ms) then ionic diffusion (t < 100s) is described by a transmission line (green) composed by N_{RC} loops. The two next branches are for charge redistribution phenomenon (t < 1h) and the last resistance (red) accounts for leakage, the characteristic time of which is the highest (t > 1h). The electrical parameters of this circuit are temperature dependent (R_{motif}) and/or voltage dependent (C_{motif}, R_{P1}, C_{P1}).

Electrical parameters of this circuit are estimated in order to fit Electrochemical impedance spectrum and galvanostatic measurements. The transmission line describes, in the temporal domain the diffusion impedance Z_{diff} which can be expressed in the frequential domain as follows:

Electric resistances R_{motif} and capacitances C_{motif} of the transmission line are, respectively, temperature and voltage dependent. The C_{motif} capacitances follow a linear law as a function of applied voltage modelling variable capacitance of the UCAP.

ConfigTool

The parametrisation of the SC is driven to adequately mimic the interplay between the behaviour of the battery and capacitor interaction. Additionally, the parametrisation of the leakage current is required to model SC losses overtime.

To characterize a pack of capacitors starting from a single capacitor, the following parameters are required.:

- Thermal resistance of the battery to the environment: $RI_{cap,env}$
- Total number of capacitors: p * s, with:
  - p = number of capacitors connected in parallel
  - s = number of capacitors connected in series

By considering the parameters of both an individual capacitor and the capacitor pack, it becomes possible to perform a characterization of the SC model. This characterization involves functions that may depend on the state variables, specifically the state of charge (SoC) and temperature (T). The key variables used in the characterization process are as follows:

- Capacity of capacitor pack: E_{cap}

- Average temperature of the capacitor pack: T_{cap}
- Heat capacity of capacitor pack: C_{cap}
- Power of capacitor pack: P_{cap}
    - Electrical Power: $P_{el,cap}$
    - Thermal Power: $P_{th,cap}$

Example formulas:

$$E_{cap} = psE_c \tag{13}$$

$$C_{cap} = psC_C \tag{14}$$

The state variables get updated with each time step. The following equations are used in the model:

$$SoC(t_i) = SoC(t_{i-1}) + \frac{P_{el,cap}(t_i)\,\Delta t_i}{E_{cap}} \tag{15}$$

$$T_{cap}(t_i) = T_{cap}(t_{i-1}) + \frac{P_{th,cap}(t_i)\,\Delta t_i}{C_{cap}} \tag{16}$$

2.4.4 Evaluation of SC modelling approaches

The model evaluation is done by using experimental data as presented for one of the approaches. The previous presented dynamic Ucap model can predict accurately the electrical and thermal behaviour of an ultracapacitor. A comparison with experimental results for a 3500F Ucap is presented in this section. The electrical test performed is a succession of charge pulses of 200 A during 30 s followed by 10 min rest period and then -200 A discharge pulse during 30 s at 23 °C.

Figure 16 presents the comparison of voltage and temperature between the experimental measurements and the simulated results, obtained with the two modelling approaches. It appears that both models give a correct estimation of both voltage and temperature, compared to the experimental data.

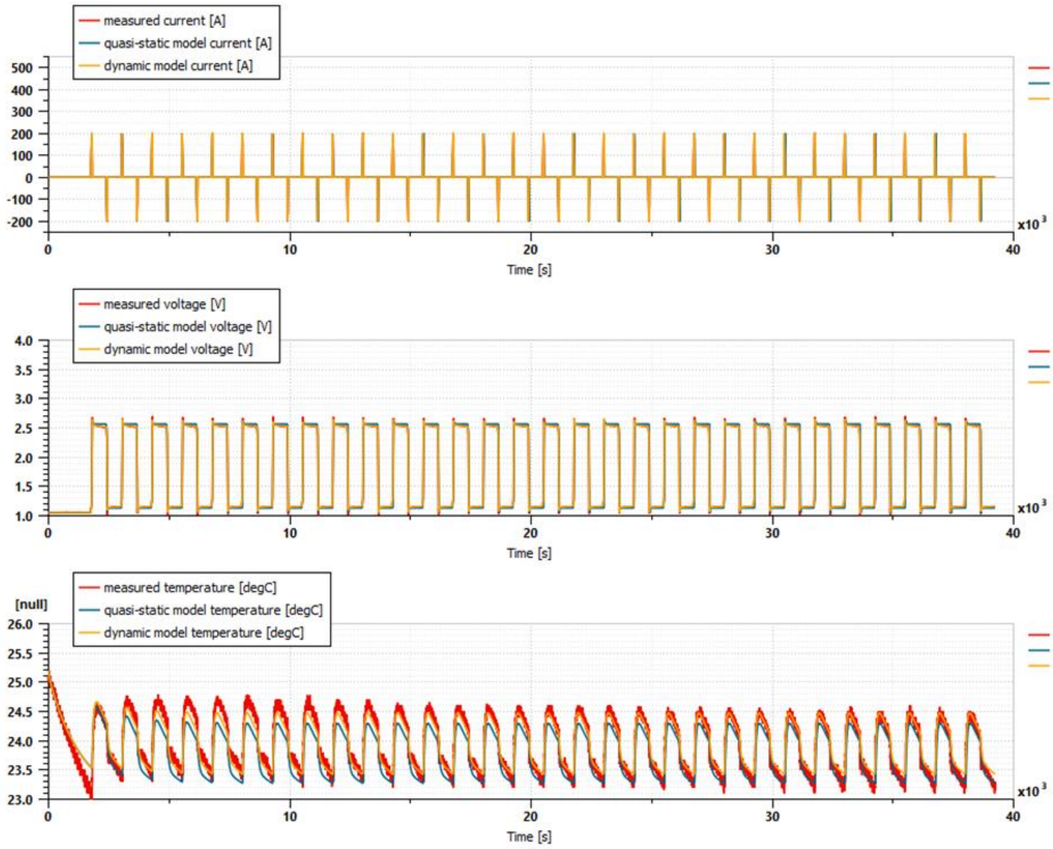


Figure 16: Comparison between experimental and modelling voltages and temperatures

A closer look on electrical behaviour shows the differences between the quasi-static and dynamic approaches. As shown in Figure 17, the relaxation during rest periods is not well predicted by the quasi-static model. It can be explained by the lack of charge redistribution modelling. Consequently, the voltage remains constant according to the quasi-static model, whereas the dynamic one is able to show the slow drop of voltage, observed in experimental results, during relaxations.

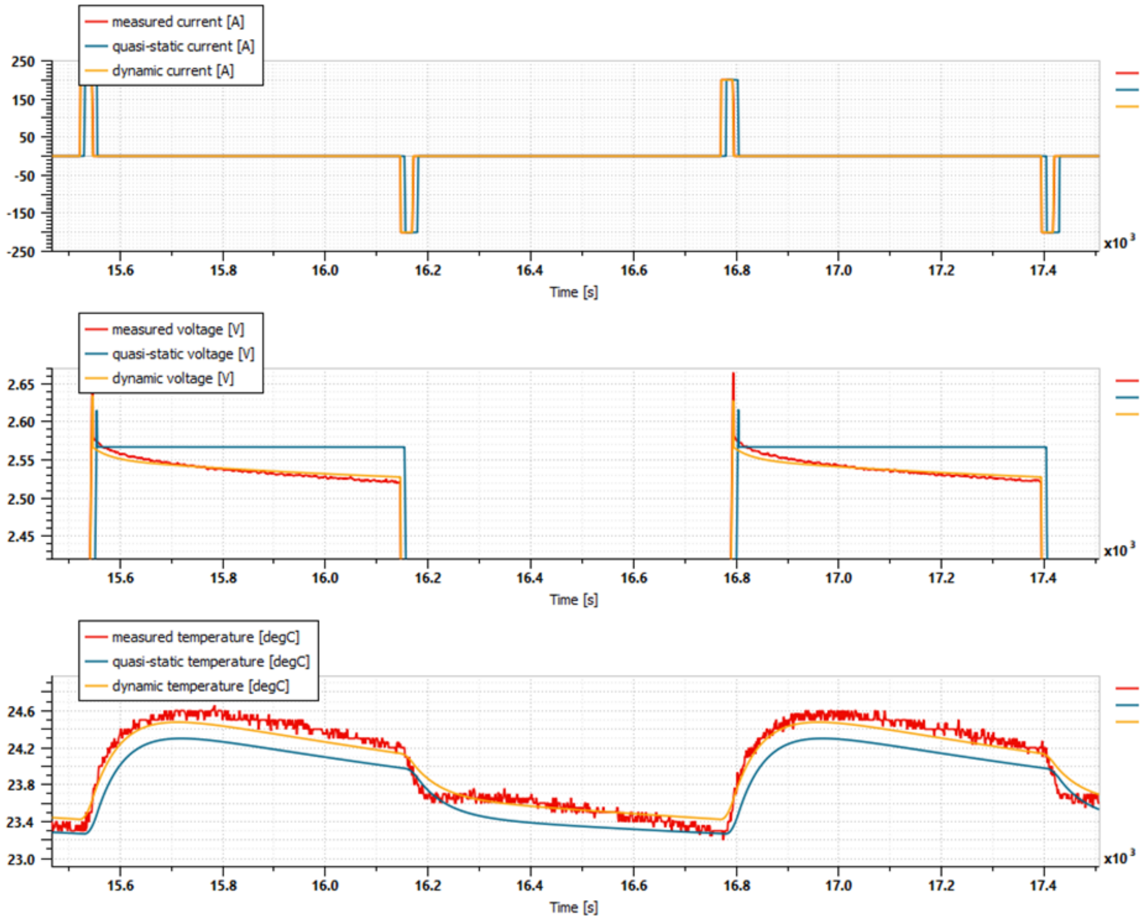


Figure 17: Detailed view of voltage and temperature

The quasi-static and dynamic models will be calibrated using the AENEAS data provided by WP3.

2.5 PMS/EMS models

2.5.1 Modelling of the PMS/EMS

Power and Energy Management Systems (PMS/EMS) models can be constructed in Simcenter Amesim from the detailed description of the functions to be represented (load levelling, boost function, peak shaving) using different capabilities:

- By a block-diagram approach using the standard “Signal, Control” library
- Using the State Chart environment to model event-driven systems
- By connecting the plant model with a control model developed in Simulink

While designing power and energy management for shipboard power system of electric vessels, it is essential to first predict the total power and energy demand of the voyage and scheduled stay of electric vessels at harbours. During manoeuvring of electric vessels, power demand may vary depending on multiple factors such as changes in torque and power fluctuation caused by drive shaft of vessels due to varying rational speed of propeller. Whereas, there is always a trade-off of power and energy densities in all energy storage systems. Besides this, energy storage systems are characterised with some specific technical features such as efficiency, life span depending on number of charge/discharge cycles, and a response time to power fluctuations. Therefore, only a single source of energy storage system for shipboard power system of any electric vessels may not be technically and economically viable solution to manage power and energy demand. Typically, a hybrid energy storage system consisting of two or more energy storage systems is a suitable solution to cope with these challenges. In our case study hybrid energy storage system consisting of solid-state battery and ultracapacitor have been proposed while considering the power and energy demand of a specific vessel. Solid state battery has a high energy density, and ultracapacitor has high power density characteristics. When both energy systems are hybridised, they are capable to deal with high energy demand as well as power fluctuations especially caused by high power demand with a rapid response time of electric vessels. The following Figure 18 presents the control algorithm to be employed for shaving peak-load demand of shipboard power system of electric vessel. This shows that in normal conditions, when load demand P_{load} is equal or less than the battery power ($p_{battery}$), battery energy storage system is only source of power supply, whereas, when the P_{load} exceeds $p_{battery}$ then the power is being supplied simultaneously by battery and ultracapacitor with hybrid energy storage solution. The above conditions are valid when the state of charge of the battery ($SoC_{battery}$) is between 20-80% or above 80%. Otherwise, only ultracapacitor will supply power when $SoC_{battery}$ is less than 20%.

The control law for the shipboard power system of electric vessels is represented by Eq. (17). According to this equation, the real power point of the entire shipboard power system of electric vessels and ESS must reach and/or follow their reference points. The power quality and limitations of the shipboard power system adhere to industrial standards such as IEEE 519-2014 and IEC 61000.

SoC_{max} and SoC_{min} indicate custom-built maximum and lowest battery SoCs limitations for the battery, respectively. When SoC touches SoC_{max}, the power charger turns to a standby manner preventing the overcharging of the battery. The SoC rise-rate is confined by the limited ΔSoC_{max} to avoid significant changing in the degree of charging over continuous intervals of time. ΔTHD_{load} is the change in total harmonic distortion on the loads side, $\Delta V_{load(rms)}$ is the RMS voltage deviation, Δf_{load} is the load frequency deviation, and $\Delta V_{dc\ bus}$ is then change in DC bus voltage.

$$
\begin{aligned}
& \bigcup_{\begin{bmatrix} Electric\ \text{Vessels} \\ ESS \end{bmatrix}} \Big|_{t\to\infty} \begin{bmatrix} P_{load}(t) \to P_{load\_ref}(t) \\ P_{ESS}(t) \to P_{ESS\_ref}(t) \end{bmatrix}, \\
& where\ P_{ESS}(t) = P_{battery}(t) + P_{ultracapacitor}(t) \\
& \text{s.t}: \\
& \qquad SoC_{\min} \le SoC_i(t) \le SoC_{\max} \\
& \qquad 0 \le | SoC(t+1) - SoC(t) | \le | \Delta SoC_{\max} \\
& \qquad \Delta THD_{load} < \pm 5\% \\
& \qquad \Delta V_{load(rms)} < \pm 6\% \\
& \qquad \Delta f_{load} < \pm 8\% \\
& \qquad \Delta V_{dc\,bus} < \pm 5\%
\end{aligned}
\tag{17}
$$

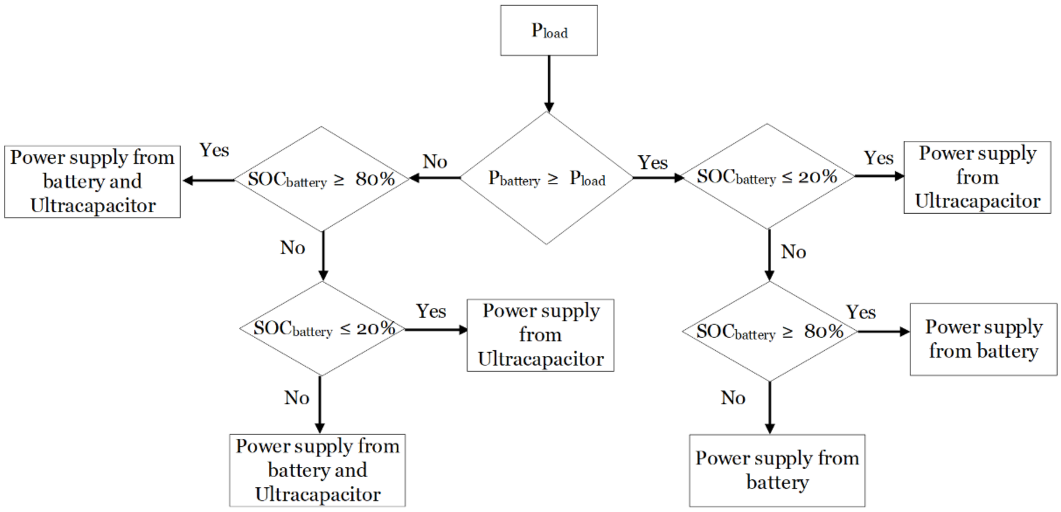


Figure 18: Control algorithm for shaving peak-load demand with hybrid energy storage systems

The PMS/EMS models can be connected to the plant model (SSB, UCAP or hybrid system) by adding the required sensors in the plant model. The power flow will typically be controlled through power converters (DC/DC). Figure 19 presents a simple hybrid storage system plant model with a battery, an ultracapacitor and a DC/DC converter, where additional sensors has been added (Power, Energy and Voltage sensors in this case) to enable a connection with a PMS/EMS system.

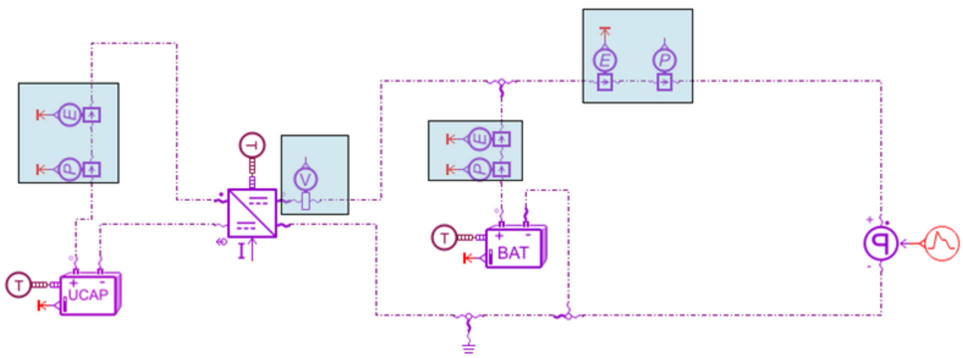


Figure 19: Example of plant model of a hybrid storage system with additional sensor for PMS/EMS connection

The Signal, Control library contains signal or block components, and makes it possible to construct block diagram models. A block diagram model represents a dynamic physical system graphically. This kind of representation comes from the Signal Processing and Control Engineering domains. This library can also be used to generate complex signals to pilot physical systems.

Figure 20 shows a very simple Peak Shaving strategy implemented with this block diagram approach: above a certain power demand threshold of the load, the DC/DC converter is commanded to provide the additional power.

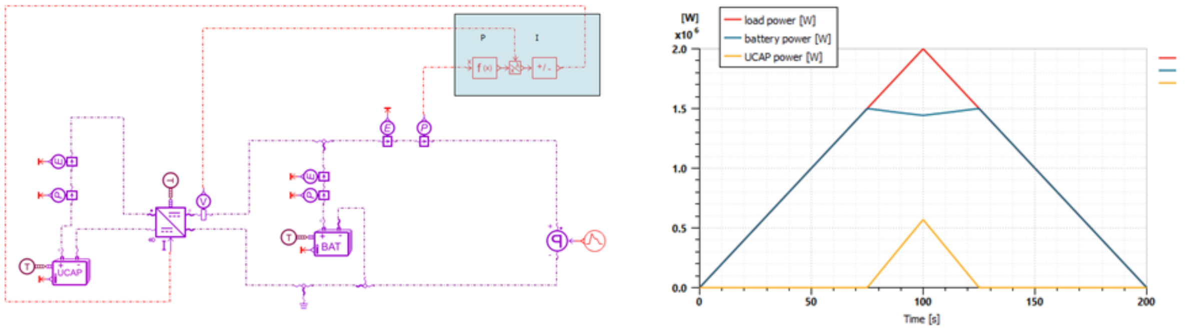


Figure 20: Simple Peak shaving strategy using Signal, Control library

The Statechart Environment is a visual formalism that can be used to describe reactive subsystems such as discrete controllers, schedulers, etc, in a more convenient way than offered by classical submodel assemblies. The Statechart Environment is designed to provide an easy-to-use graphical environment to create statecharts, integrate them in the plant model, execute them, and animate them for verification.

Figure 21 shows the same simple Peak Shaving strategy implemented with the state chart.

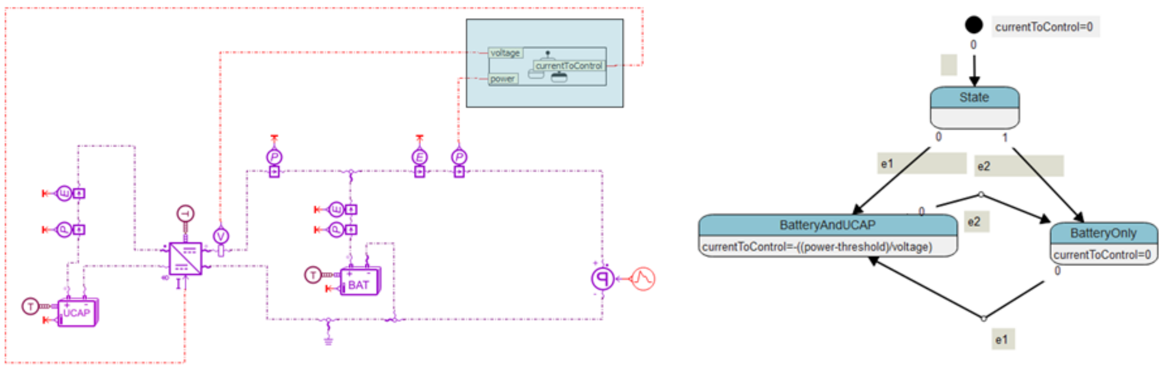


Figure 21: Simple peak shaving strategy using State Chart

As presented in part 2.1.1, Simcenter Amesim can interface with Simulink in multiple ways. If the PMS/EMS control is implemented in Simulink, it can be imported or it can cosimulate with the plant model in Simcenter Amesim. For that, an interface block defining the Input/output exchange variables has to be integrated into the plant model, as presented Figure 22.

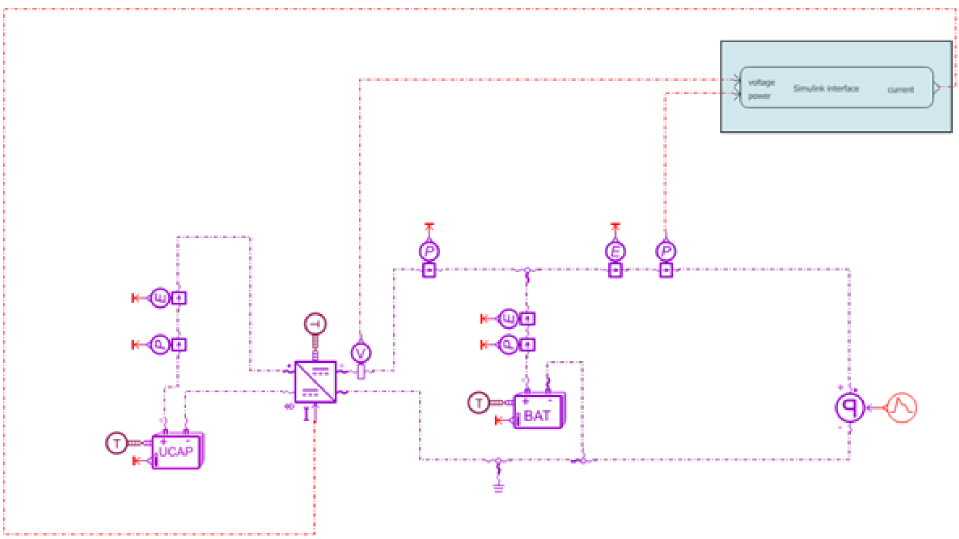


Figure 22: Simulink interface block

ConfigTool

The modelling of Power and Energy Management Systems (PMS/EMS) within AENEAS using ConfigTool will allow to optimize how the available power sources and energy storage devices are utilized the best, to meet the power demands of the system. Peak shaving is achieved through the optimization of power allocation and dynamic adjustments to the distribution. Efficient operation is enabled by effectively managing the power flow and maintaining the operating ranges (e.g. max. operating temperature, max. power load…) of each component. The optimization of such systems is made possible by very fast-computing times, compared to traditional 1-D modelling approaches.

3 Mission profiles

3.1 Introduction

Within the 3 AENEAS use-cases there are several mission profiles in addition to these already shown further down, that will be studied. For each of these mission profiles the individual best suited architecture will be elaborated (e.g., maximum battery lifetime, minimum diesel-engine usage). As a starting point for these analysis two concrete mission profiles have been already defined. The mission profiles are characterised in D1.1, via electric load energy consumptions for different operating phases, as well as battery cycle analysis of installed batteries, for two Grimaldi ships: the Eco Ship – RoRo ship and Cruise ferry. These mission profiles, that are currently managed with a specific architecture (see also D1.1), the architecture of these will be further analysed and optimised, to even better match the operating requirements (e.g., by potential integration of SCs). Furthermore, changes of the operating strategies will be investigated to deploy the full potential of the architecture used, respectively.

The averaged electrical load energy values (obtained from WP1) can be used as basis for initial sizing of ESS systems, but for optimization of the sizing and of the EMS/PMS control, a more detailed description of the energy flows on the vessels is needed. Grimaldi provided two samples of data provided by their data collector system, in order to check the relevance of the available information and data format for future WP2 activities.

The simulation and optimization of the AENEAS use cases will be done in WP2 after the selection of use cases. They will be selected among the multiple use cases defined in D1.1 and elaborated in D1.2. The details of the 3 use cases (load profiles, propulsion system, energy management…) to be used for optimising the energy/power system of each use case will be available in D2.2.

3.2 Description of Grimaldi Samples

3.2.1 Sample 1: ROPAX ship example

Grimaldi provided a set of data for a ROPAX ship for a complete week with a time stamp of 2 minutes. This data includes:

- The vessel speed;
- the power of the two main engines (and the power at the shaft)
- the power of the three Diesel generator (and the total power)
- the power of the 2-shaft generator (and the total power)
- The status of the two battery banks (charge or discharge)
- The power of the two battery banks
- The state of charge of each battery pack (2 per bank)
- the number of array available per pack
- the miles
- the port
- the position
- the status (navigation or port stay)

Figure 23 shows the data after reformatting for integration in a simulation tool (here Simcenter Amesim).

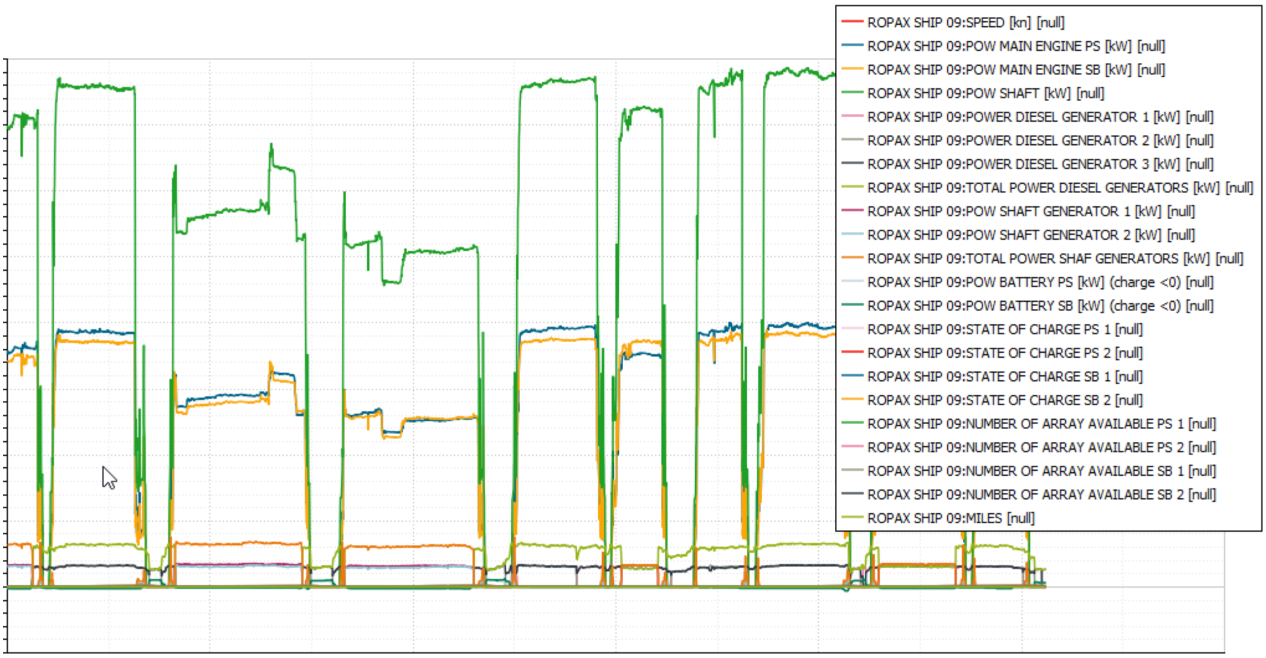


Figure 23: Ropax ship data for simulation

3.2.2 Sample 2: RORO Ship example

Similarly, Grimaldi provided the data for a RORO Ship, with the following quantities included:

- The vessel speed;
- the power of the two main engines (and the power at the shaft)
- the power of the three Diesel generator (and the total power)
- the power of the 2-shaft generator (and the total power)
- The power of the solar panel
- The power of the two battery banks
- the number of array available per bank
- the miles
- the port
- the position
- the status (navigation or port stay)

Data can be reformatted to be used in the simulation tools (Figure 24).

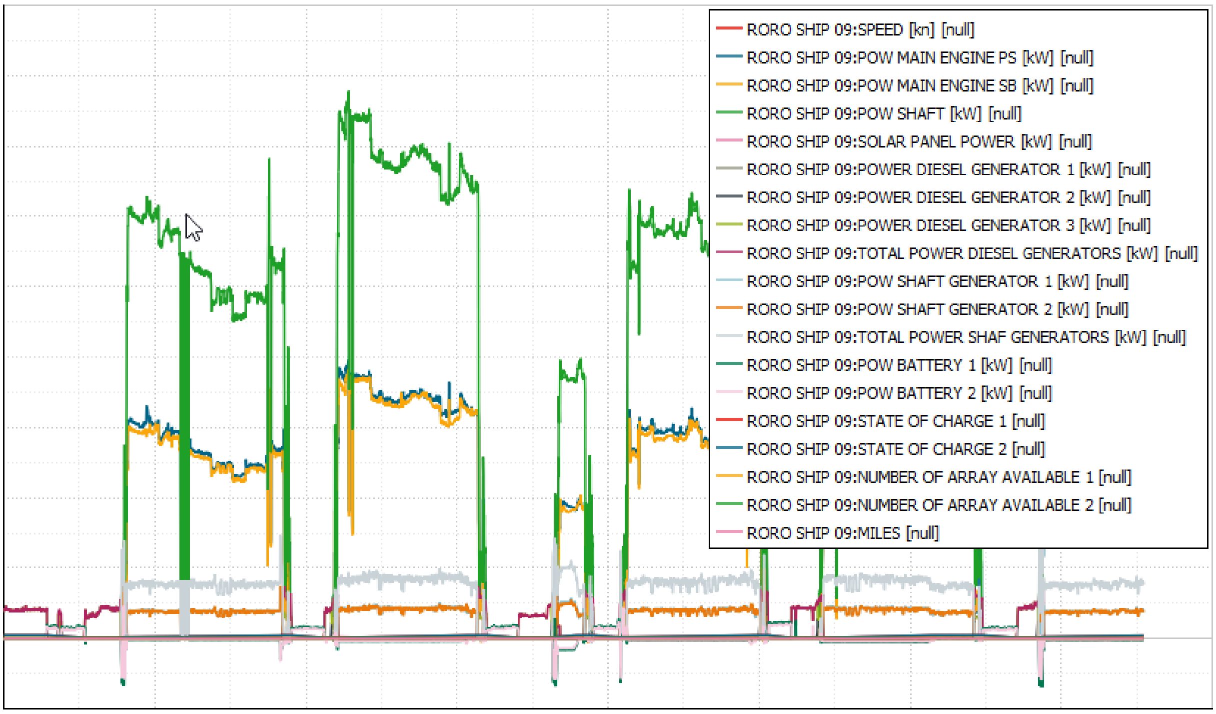


Figure 24: RoRo ship data for simulation

3.3 Example of use in a Simcenter Amesim model

Figure 25 shows an example of the use of the data (here the RoPax data) in a Simcenter Amesim model. The power request to the ship battery is read in the formatted datafile and provided as an input to the simulation model: the DC/DC converter is controlled to extract the same power from the battery model.

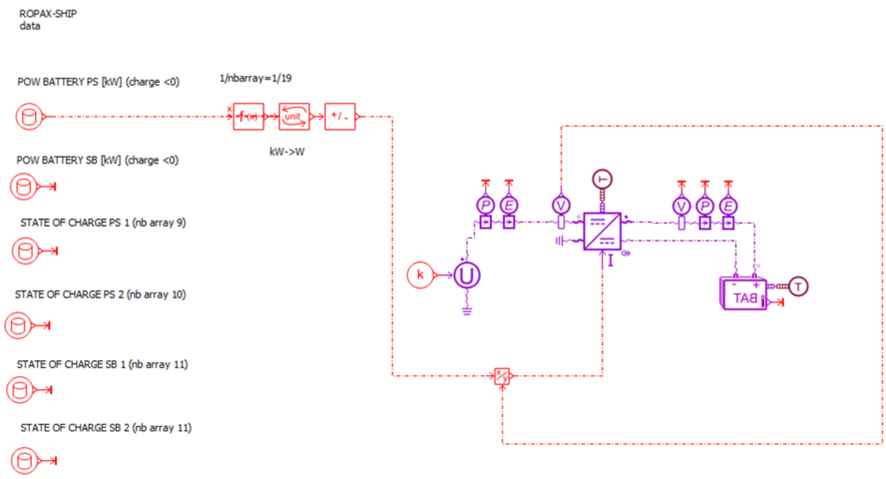


Figure 25: Example of use of RoPax data in Simcenter Amesim

In this case, a battery model has been sized to correspond approximately to the battery pack of the vessel. **Fehler! Verweisquelle konnte nicht gefunden werden.** presents the results of the model on a part of the RoPax data corresponding to a navigation phase (battery charging) a port stay (battery discharging) and a second navigation phase (battery charging). The state of charge computed by the model is in good adequation with the two estimations of state of charge available in the data sample.

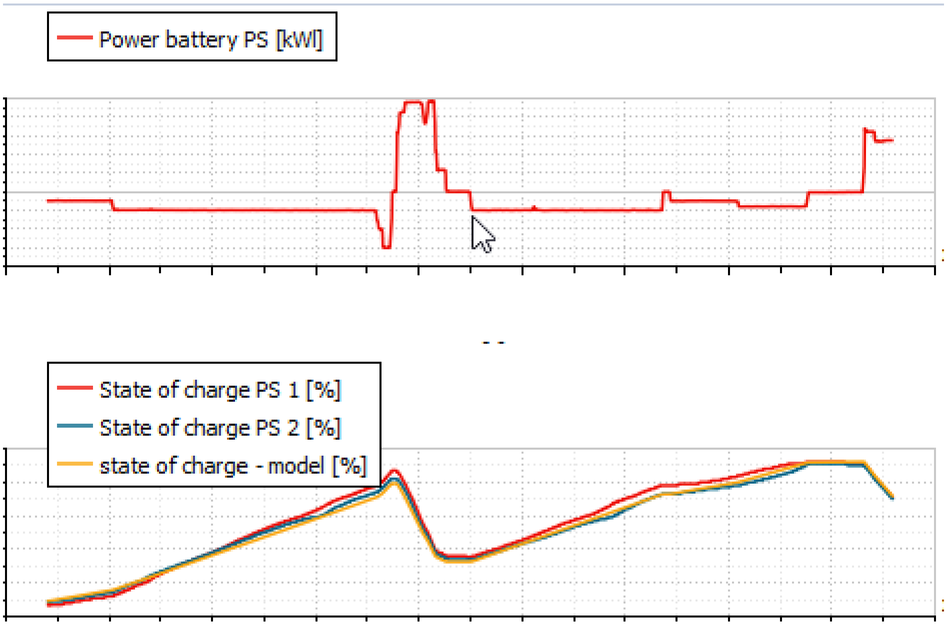


Figure 26: Simcenter Amesim results: power demand on the battery pack and state of charge comparison of the model with recorded state of charge measurements

4 Conclusions

To conclude, the different ESS simulation components that will be used in the simulation models on system level to mimic the different Energy Storage Solutions (ESS) studied within AENEAS has been presented, as well as the EMS/PMS strategies and the links to mission profiles

All these developed high-level, power-based component models will be further used in other tasks within the WP2. These components, once developed and validated, will serve as valuable building blocks for the implementation of various systems and functionalities within the project. Further implementations of the T2.1 outcomes will happen in WP5, as the models generated in T2.1 will be compatible to HIL test setup in WP5. This task has also been running in parallel with T3.1 and close collaboration and information exchange between partners has been vital during this parallel execution, ensuring smooth progress.

5 References

[1] Dean C. Karnopp, Ronald C. Rosenberg 1968 Analysis and Simulation of Multiport Systems – The Bond Graph Approach to Physical Systems Dynamics, M.I.T. press.

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6 Acknowledgements and disclaimer

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4	SIE	SIEMENS INDUSTRY SOFTWARE SAS
5	UVA	VAASAN YLIOPISTO
6	I2M	I2M UNTERNEHMENSENTWICKLUNG GMBH
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14	FS	CONSTRUCCIONES NAVALES P FREIRE SA

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Abbreviations and Definitions

Term	Definition
SC	Supercapacitor
SSB	Solid state battery
ESS	Energy storage system
BMS	Battery management system
EMS	Energy Management System
PMS	Power Management System
FMU	Functional Mock-up Unit
FMI	Functional Mock-up Interface
SoC	State of charge
RC	Resistor-capacitor
ECM	Equivalent circuit modelling
EDLC	Electrochemical double layer capacitors
UCAP	Ultracapacitors
I/O	Input/output
OCV	Open circuit voltage
HIL	Hardware-in-the-Loop

List of Figures

List of Tables