CellMod™ FMU

User Documentation

With Documentation for BasicPackMod™ and CellMod™ Lite

REVISION INFORMATION

Revision	Date	Description
0.1	01/24/2019	Initial version
0.2	01/28/2019	Review of the initial version
0.3	02/12/2019	Remove discussion of feedback control based on status Add recommendations on input derivatives usage
0.4	02/13/2019	Review
0.5	03/25/2019	Revisions to account for latest implementation features and limitations
0.6	04/05/2019	Review for release
0.7	06/04/2019	Update information about the input derivatives feature
0.8	08/13/2019	Add documentation on BasicPackMod
0.9	08/23/2019	Update FMU log messages chart with License status Add information on support of directional derivatives

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1. Description

This is the documentation for the CellMod™ functional mockup unit for co-simulation (FMU). This documentation covers the following products:

- CellMod™ Lithium-Ion FMU for Panasonic NCR18650A Cell v2.X: single cell simulations with cell thermal model,
- BasicPackMod™ Lithium-Ion Pack FMU based on Panasonic NCR18650A Cell v2.X: simple battery pack simulations,
- CellMod™Lite Lithium-Ion FMU for Panasonic NCR18650A Cell v2.X: single cell simulations with imposed current only.

The CellMod FMU can simulate the behavior of a single cell under arbitrary electrical and thermal loads. For battery pack simulations, the BasicPackMod FMU can be used to simulate the behavior of an arbitrarily sized pack, containing a specified number of cell modules connected in series, with a specified number of *identical* cells connected in parallel in each module. The documentation explains how to set up and use the FMU and provides description of the FMU input and output ports.

2. FMU features

- CellMod™ Lithium-Ion FMU contains an electrochemical model of a lithium-ion rechargeable cell.
- The FMU supports the following modes of charge/discharge operations:
    - imposed current,
    - imposed voltage,
    - imposed power,
    - imposed Ohmic load.
- The FMU provides a dynamical load switching capability that makes it possible to change the mode of charge/discharge during the simulation (for example, switching from imposed current to imposed power).
- The model can be exercised at varying ambient temperature conditions.
- Aging of the cell can be simulated via two dedicated parameters defining capacity loss and increased Ohmic resistance.

2.1. Lite version

The CellMod™Lite FMU version has the following limitations:

- imposed current mode of operation only (no load switching),

- no thermal input and outputs,
- no aging parameters.

2.2. BasicPackMod

The BasicPackMod™ FMU version has the following limitations:

- no thermal input and outputs.

3. FMU usage

This section discusses how to setup and use the CellMod™ FMU. For information regarding FMU import and configuration refer to the documentation of the simulation environment.

3.1. Input ports

The FMU receives its inputs from the following three ports:

- `t_amb` port receives ambient temperature value in Celsius (C) and is only available for the CellMod FMU,
- `load_type` is a *discrete* (integer) input port describing the type of electrical load conditions applied to the cell or pack,
- `load` port receives the value of the electrical load applied to the cell or pack.

The electrical load applied to the simulated cell is defined by the combination of the `load_type` and `load` input ports. The value of the `load_type` input defines the type and unit of the electrical load according to Table 1 and the value of the `load` input corresponds to the actual value of the electrical load. For imposed current and imposed power load types, a positive value for the `load` input corresponds to discharging load, while a negative value corresponds to a charging load. When the imposed conductance load type is used the FMU expects to receive a positive load value, and for the imposed voltage load type the applied voltage should be within the operating range of the cell (see 3.3.). The *rest* load type is provided for convenience and is equivalent to imposing a zero current load.

Note that the Ohmic load type actually corresponds to a *conductance* load (rather than resistive one), which implies that the load value is expected in Siemens. This is designed to provide the ability to define infinite resistance at the terminal of the cell by using a load value of 0 S.

If the value of `load_type` is set outside of the range defined in Table 1 the FMU will terminate the simulation.

load_type	Description	load units
0	Rest (zero current load)	N/A
1	Imposed current	Ampere (A)
2	Imposed voltage	Volt (V)
3	Imposed power	Watt (W)
4	Imposed Ohmic load (conductance)	Siemens (S)

Table 1: Description of load_type input values and corresponding load input units.

3.2. Output ports

The outputs ports of the CellMod™ FMU are summarized in Table 2.

Output port	Description	Units
v_cell	Cell voltage	Volt (V)
i_cell	Cell current	Ampere (A)
t_core	Cell core temperature	Celsius (C)
t_surf	Cell surface temperature	Celsius (C)
t_eff	Effective cell temperature	Celsius (C)
dod	Cell depth of discharge	1
status	Model status	N/A

Table 2: Description of CellMod FMU output ports.

The outputs ports of the BasicPackMod™ FMU are summarized in Table 3.

Output port	Description	Units
v_pack	Pack voltage	Volt (V)
i_pack	Pack current	Ampere (A)
pack_capacity	Pack capacity	(Ah)
dod	Pack depth of discharge	1
status	Model status	N/A

Table 3: Description of CellMod FMU output ports.

3.3. FMU operating ranges

During the course of a simulation the output voltage and current of the simulated cell have to remain within the operating ranges of the modeled cell. For the CellMod™ Lithium-Ion FMU for the Panasonic NCR18650A cell the operating ranges are implemented as follows:

- The initial cell voltage must be between 2.8 and 4.2 V.
- The cell voltage should not fall below 2.5 V during discharge and should not exceed 4.2 V during charge. The FMU provides a failsafe mechanism that switches the model to a *rest* state (zero current load) if the voltage reaches 2.48 V or 4.22 V at any point during operation.
- The absolute value of the cell current should not exceed 6.2 A. If at any point during operation the absolute value of the current exceeds 6.2 A, the FMU will switch the model to a *rest* state (zero current load).

For the BasicPackMod™ Lithium-Ion Pack FMU based on the Panasonic NCR18650A cell the operating ranges depend on the number of cells per module N_p and the number of modules N_s and are implemented as follows:

- The initial pack voltage must be between $2.8N_s$ and $4.2N_s$ V.
- The pack voltage should not fall below $2.5N_s$ V during discharge and should not exceed $4.2N_s$ V during charge. The FMU provides a failsafe mechanism that switches the model to a *rest* state (zero current load) if the voltage reaches $2.48N_s$ V or $4.22N_s$ V at any point during operation.
- The absolute value of the pack current should not exceed $6.2N_p$ A. If at any point during operation the absolute value of the current exceeds $6.2N_p$ A, the FMU will switch the model to a *rest* state (zero current load).

3.4. Setup and initial conditions

The FMU expects the following values to be defined during initialization:

- the initial value for the cell voltage (`v_cell` or `v_pack`),
- the initial value for the load type (`load_type`),
- the initial values for the thermal and electrical loads (`t_amb` and `load`).

3.4.1. Aging parameters

The FMU provides the parameters `capacity_loss` and `aging_R` to simulate aging of the cell. These parameters should be set during the initialization of the FMU.

The parameter `capacity_loss` (value between 0 and 1) is used to indicate a fraction of the total capacity that is lost due to aging phenomena.

The parameter `aging_R` is used to indicate the *additional* Ohmic resistance (in Ohms) that can develop at the solid-electrolyte interface in the electrodes due to aging (*i.e.*, SEI build up). The additional Ohmic resistance is defined as the additional voltage drop observed at the beginning of a discharge divided by the discharge current. The CellMod™ FMU will automatically utilize this value to properly set the SEI parameters in the model.

3.5. Model status

The status of the model is indicated by the value of the `status` output port. This output port is a discrete output port with an integral value. This output should be used to monitor that the model operates without failures. Table 4 provides the list of possible status values and their meaning.

`status` value	Description
0	Normal operation
1	Max cell voltage (4.22 V) reached
2	Min cell voltage (2.48 V) reached
3	Max absolute cell current value (6.22 A) reached
4	Failsafe mode enabled (rest)
5	Model failure

Table 4: Description of the `status` output values.

Note that the min and max values for voltage and current in the above table are given for individual cell. For the BasicPackMod™ FMU, the corresponding pack voltage values must be scaled by the number of modules in the pack, and the pack current values must be scaled by the number of cells per module.

3.6. Output-dependent input

The FMU provides a load switching capability, *i.e.*, the ability to perform changes of load type and/or sudden changes of load value during simulation. This allows to exercise control of the load input based on model output. For example, one may limit or change input load if output voltage or current reaches some predefined value.

3.6.1. Notes for Altair Activate users

- When exercising output-dependent input within Altair Activate environment, one should zero out the *Direct dependency vectors for the input* for the FMU to avoid potential issues with algebraic loops. Refer to Activate documentation for more information.
- Using input derivatives with the FMU can introduce unstable numerical behavior when the inputs depend on the FMU outputs (see also Sec. 3.7.).

3.7. Input derivatives

The FMU supports the input derivatives feature of the FMI 2.0 specifications. At each communication point the derivatives of the real-valued inputs can be passed to the FMU which then use an extrapolation scheme to build the input functions for the next time step. The extrapolation scheme is based on a Taylor expansion around the communication point and input derivatives of arbitrary orders can be passed to the FMU.

Depending on the behavior of the inputs (ambient temperature and electrical load), this feature can improve the performance of the simulation. In particular, if the inputs are smoothly varying in time it is recommended to use the input derivatives feature. However, if the inputs are expected to be discontinuous or changing over very short time scales (with respect to the time step size), it may be more appropriate to not use this feature.

3.7.1. Note for Altair Activate users

For simulations, in which the load type is changing, it is recommended to disable input derivatives for the FMU, as this might introduce unstable numerical behavior. Refer to Activate documentation for more information on how to disable the input derivatives feature.

4. FMU logging

The FMU provides logging functionality that can be used to investigate the details of the simulation and to troubleshoot issues. The log messages can be categorized by the log level (Error, Warning, Info, Verbose), which allows to select messages by criticality and verbosity, and log categories (Setup, Internal, Status, Input, FMI), which allow to filter log messages as necessary.

Table 5 provides description of various types of logging messages reported by the FMU, organized by the logging levels (columns) and logging categories (rows). Logging levels are associated with the FMI status, also indicated in the column headers.

5. Compatibility with FMI specifications

The CellMod™ FMU for co-simulation is fully compatible with the FMI 2.0 standard specifications. In particular, the FMU supports the following features:

- inputs interpolation for continuous input ports (up to an arbitrary number of derivatives),
- first-order output derivatives for continuous output ports,
- directional derivatives for output voltage and current,
- multiple instantiations,
- use of custom memory functions.

The current version of the FMU does not support the following features:

- serialization functions (*e.g.*, `fmi2SetFMUState`).

	Error (`fmi2Error`, `fmi2Fatal`)	Warning (`fmi2Warning`)	Info (`fmi2OK`)	Verbose (`fmi2Discard`)
License	Checkout failure	Expiration	Checkout success	
Setup	Initialization errors Invalid initial input Out-of-range initial input		Capacity info Initial state info Initial load info	
Internal	Solver failure Load switch failure			Successful load switch Internal load switch
Status		Model status change (model limits) Failsafe mode		
Input	Invalid input Out-of-range input			
FMI	Illegal FMI calls FMU failures	FMI warnings		Log messages trace calls

Table 5: FMU log messages organization. The columns correspond to log levels, the rows correspond to log categories.