DIRECTION DES SYSTEMES ORBITAUX

SOUS-DIRECTION TECHNIQUES BORD

SERVICE ALIMENTATION BORD & EQUIPEMENTS ELECTRIQUES

TECHNICAL DOCUMENTATION OF OPALIS SOFTWARE

	Nom et Sigle	Date et Signature
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DIFFUSION INTERNE	
Sigles	Noms

DIFFUSION EXTERNE	
Sociétés	Noms

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1. LIST OF THE ACRONYMS

Acronyms	Definition
DET	Direct Energy Transfer
DOD	Depth Of Discharge
LEO	Low Earth Orbit
MPPT	Maximum Power Point Tracking
NRB	Non-Regulated Bus
S3R	Sequential Switching Shunt Regulator
SA	Solar Array
SADM	Solar Array Drive Mechanism
SOC	State Of Charge

2. OVERVIEW

The OPALIS software is a simulator of spacecraft power system for all types of orbits. It is used to pre-sizing purpose and quick tests of power supply system.

For instance, OPALIS enables to define the global efficiency of the power system and to compute the battery state of charge during a simulation.

The spacecraft power system includes the following equipment:

- several “solar array section”/” regulator” pair
- a “battery”/” charging/discharging system” pair
- wiring resistances
- a bus which can be regulated or not
- the rest of the spacecraft which is regarded as an electrical load to supply and represented by a consumption profile

There are three types of inputs:

- The static inputs are the parameters needed to describe the equipment used
- The simulation inputs allow the initialization of the test run
- The ephemerides of the power consumption and of the various flow received by the solar array

All of these data need to be manually filled by the user in the OPALIS human-machine interface.

Thanks to this, OPALIS is able to plot the evolution as a function of the time of the main variables of a spacecraft power supply system. Furthermore, this tools permits to validate or not the power system sizing by analysing the results obtained for the electrical balance or by comparing the initial and final battery properties.

3. SOFTWARE INTERFACE

The software consists of several tabs containing the schematic, the simulation parameters, the input profiles, the results synthesis, the set of simulation results in tabular form and the graphs.

3.1. THE SCHEMATIC

This first tab gives an overview of the composition of the simulated power supply system. Some of the characteristic electrical variables are indicated on the schematic.

The notations in red correspond to the input data of the simulation.

3.2. THE SIMULATION PARAMETERS

This tab is intended to the parameters entry of the simulated system. It is necessary to fulfil:

- the simulation parameters for the overall configuration
- the simulation mode
- the initialization
- the spacecraft parameters
- the data of the battery and the accumulator
- the data of the charging/discharging system if there is one
- the data from solar array and cells
- the regulator data
- the data of the solar array sections

It contains also information on the value of some simulation modes to fill. For instance, it is possible to find the parameters for the choice of the thermal model of the solar array or for different kinds of regulator (boost DET, boost MPPT, buck DET…).

3.3. THE INPUT PROFILES

All the values of the input data have to be fill in this tab (the ephemerides of the spacecraft consumption and of the illumination for each SA section).

The number of the columns in the table depends on the number of the SA sections selected in the “Simulation” tab. It is not mandatory to fill in the “Days” column.

These data can be filled out in different ways:

- by copying/pasting directly from an Excel sheet
- by importing some files of power and/or of flux in CCSDS format with these icons:

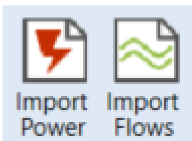


Figure 1 : Icons for the ephemerides import

The ephemerides are a list of number corresponding to variables' value of each time step. The variables are:

- The electrical consumption of the spacecraft
- The solar flux received for each section on the front face of the solar array
- The solar flux received for each section on the rear face of the solar array
- The front face albedo flux received on each SA section
- The rear face albedo flux received on each SA section
- The earth's infrared radiation received on front face of each SA section
- The earth's infrared radiation received on rear face of each SA section

Whatever the method used to fill the ephemeris inputs, some data can be missing. The default behaviour to treat missing values in the simulation computation is to take the last known value or 0 if no previous value is specified (for example, if a data of the first row is not specified).

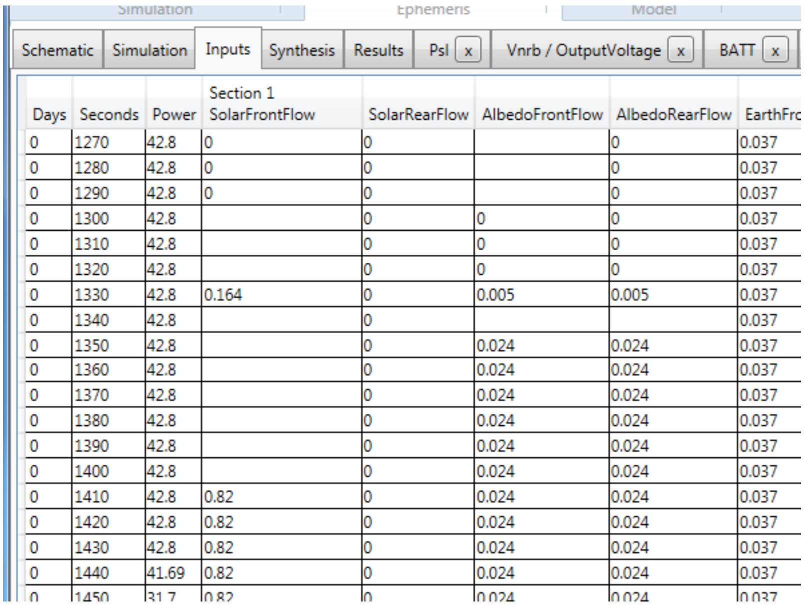
However, it is also possible to use the ephemerides consolidate function. The consolidation functionality performs a linear regression on the missing values, except for the power consumed which keep the default behaviour (if there is a missing data the simulation takes the previous value).

Clicking on the "Consolidate" button in the ribbon performs this task.

Figure 2 : "Consolidate" button

The following example presents the consolidate operation.

Before consolidation:



Days	Seconds	Power	Section 1 SolarFrontFlow	SolarRearFlow	AlbedoFrontFlow	AlbedoRearFlow	EarthFrc
0	1270	42.8	0	0		0	0.037
0	1280	42.8	0	0		0	0.037
0	1290	42.8	0	0		0	0.037
0	1300	42.8		0	0	0	0.037
0	1310	42.8		0	0	0	0.037
0	1320	42.8		0	0	0	0.037
0	1330	42.8	0.164	0	0.005	0.005	0.037
0	1340	42.8		0			0.037
0	1350	42.8		0	0.024	0.024	0.037
0	1360	42.8		0	0.024	0.024	0.037
0	1370	42.8		0	0.024	0.024	0.037
0	1380	42.8		0	0.024	0.024	0.037
0	1390	42.8		0	0.024	0.024	0.037
0	1400	42.8		0	0.024	0.024	0.037
0	1410	42.8	0.82	0	0.024	0.024	0.037
0	1420	42.8	0.82	0	0.024	0.024	0.037
0	1430	42.8	0.82	0	0.024	0.024	0.037
0	1440	41.69	0.82	0	0.024	0.024	0.037
0	1450	31.7	0.82	0	0.024	0.024	0.037

Figure 3 : Example of ephemerides before the use of the "consolidate" function

After consolidation:

Days	Seconds	Power	Section 1 SolarFrontFlow	SolarRearFlow	AlbedoFrontFlow	AlbedoRearFlow	EarthFrontFl
0	1270	42.8	0	0	0	0	0.037
0	1280	42.8	0	0	0	0	0.037
0	1290	42.8	0	0	0	0	0.037
0	1300	42.8	0.041	0	0	0	0.037
0	1310	42.8	0.082	0	0	0	0.037
0	1320	42.8	0.123	0	0	0	0.037
0	1330	42.8	0.164	0	0.005	0.005	0.037
0	1340	42.8	0.246	0	0.014	0.014	0.037
0	1350	42.8	0.328	0	0.024	0.024	0.037
0	1360	42.8	0.41	0	0.024	0.024	0.037
0	1370	42.8	0.492	0	0.024	0.024	0.037
0	1380	42.8	0.574	0	0.024	0.024	0.037
0	1390	42.8	0.656	0	0.024	0.024	0.037
0	1400	42.8	0.738	0	0.024	0.024	0.037
0	1410	42.8	0.82	0	0.024	0.024	0.037
0	1420	42.8	0.82	0	0.024	0.024	0.037
0	1430	42.8	0.82	0	0.024	0.024	0.037
0	1440	41.69	0.82	0	0.024	0.024	0.037
0	1450	31.7	0.82	0	0.024	0.024	0.037

Figure 4 : Same example of ephemerides after the use of the "consolidate" function

3.4. RESULTS SYTHESIS

Once the simulation performed, an overview of the results is displayed in the « Synthesis » tab. More details are available in section "3.5.1. Data Synthesis".

3.5. GRAPHS

The following variables can be plotted:

- P_{SL}: Spacecraft power (W)
- V_{NRB}: NRB voltage (V)
- V_{SA}: Output voltage of the SA (V)
- V_{BATT}: Output voltage of the battery (V)
- Ebat: Internal voltage of the battery (V)
- I_{BATT}: Output current of the battery (A)
- $I_{SA\_supplied}$: Current provided by one section of the solar array (A)
- I_{O_regT}: Total current at the output of the SA regulator (A)
- $Temp_{SA\_front}$: Temperature on the front face of one SA section (°C)
- $Temp_{SA\_rear}$: Temperature on the rear face of one SA section (°C)
- Irradiance: Solar irradiance (unitless)
- $SOC_{BATTERY}$: Battery state of charge computes from the present capacity (and not from the capacity at the beginning of life), (unitless, value between 0 and 1)
- DOD: Depth of Discharge (= 1-SOC), (unitless, value between 0 and 1)
- V_{ER}: Input voltage of the regulator of one SA section (V)

By default, some of these outputs are automatically plotted in graph tabs. It still is possible to display on specific tabs or add in existing graphs new results.

The values of all the outputs are also indexed in table form in the "Results" tab. In this way it can be easily shift in Excel.

4. SIMULATION OF THE ELECTRICAL SUPPLY OF A SPACECRAFT

4.1. INPUT DATA

The input data of the simulation are the consumption profile of the spacecraft and the irradiation profiles of the solar array.

The consumption profile (power in Watts) characterize the spacecraft system to supply.

The irradiance profile of the solar array takes into account six fluxes:

- Solar flux received on the front face of the solar array (W/m²)
- Solar flux received on the rear face of the solar array (W/m²)
- Front face albedo flux received on the SA (W/m²)
- Rear face albedo flux (W/m²)
- Earth's infrared radiation received on front face of the SA (W/m²)
- Earth's infrared radiation received on rear face of the SA (W/m²)

In LEO orbit, the straight solar illumination is defined by the following equation:

$$ecl = \cos(\theta).irrad.(1-u)$$

With:

- θ: angle between the sun direction and the normal to the solar array, in degrees
- u: solar and lunar eclipses indicator (day value: 0; night: 1; shadows: 0.7), unitless
- irrad: relative irradiation, unitless

$$irrad = \frac{C_S}{1361}$$

- and C_S: solar constant, function of the day of the year, W/m²

The straight solar irradiation expresses the solar flux received by the SA. Many factors impact this irradiation profile: spacecraft altitude, orbit parameters, tilt angle of the SA, SADM motion, date…

The albedo corresponds to the solar irradiation reflected by the earth on the solar array.

The infrared flux emitted by the earth is also considered. This flux impacts on the SA temperature and thus on solar cells efficiency. In the same way, the straight solar irradiation and the albedo flux received on SA rear face are considered only for thermal computes.

For other type of orbits or spacecraft mission's irradiance profiles shall be defined according to these particular needs.

OPALIS tool allows to perform a simulation with several SA section. Hence the irradiance profiles have to be defined for each section. These input data can be different from one section to another.

Note: There are two possibilities to consider the spacecraft power consumption: OPALIS can use the power consumption ephemeris filled in the « Input » tab or chose a mode where this power is fixed during all the simulation.

4.2. POWER SUPPLY MODEL

The power supply is composed of the following equipment:

- The solar array
- The regulator
- The battery
- The battery charging/discharging module
- The spacecraft to supply

The charging/discharging module is used only if the bus is regulated. For a non-regulated bus, this module will have an efficiency of 100%.

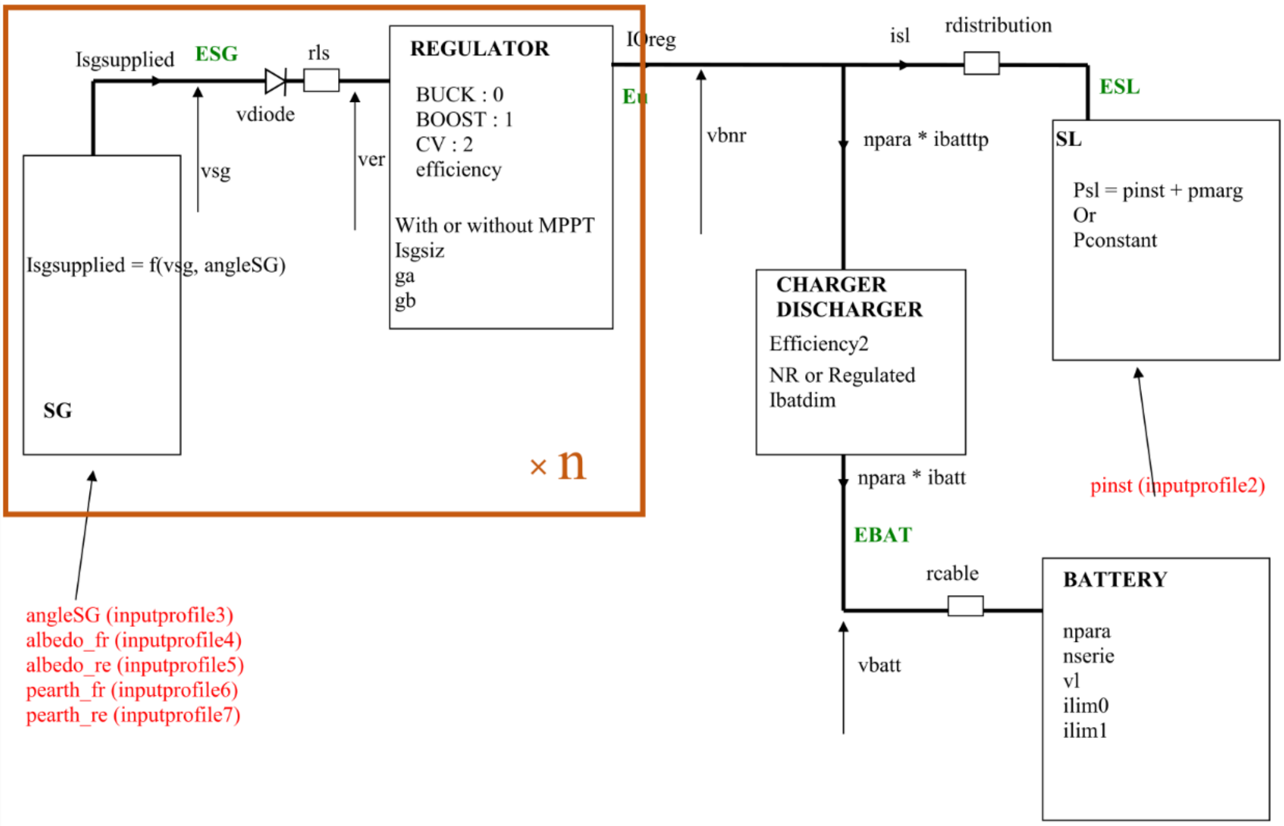


Figure 5: Power supply schematic

It is possible to simulated solar array composed of several sections. A regulator is linked with each SA section. There are different kinds of regulators (boost, boost_mppt, cvl_mppt, buck, buck_mppt or cvr_mppt). Converter types can be different from one section to another but it is mandatory that all converters of the entire solar array have to be either solely down converters (buck, buckmppt, cvrmppt) or solely up converters (boost, boostmppt, cvlmppt).

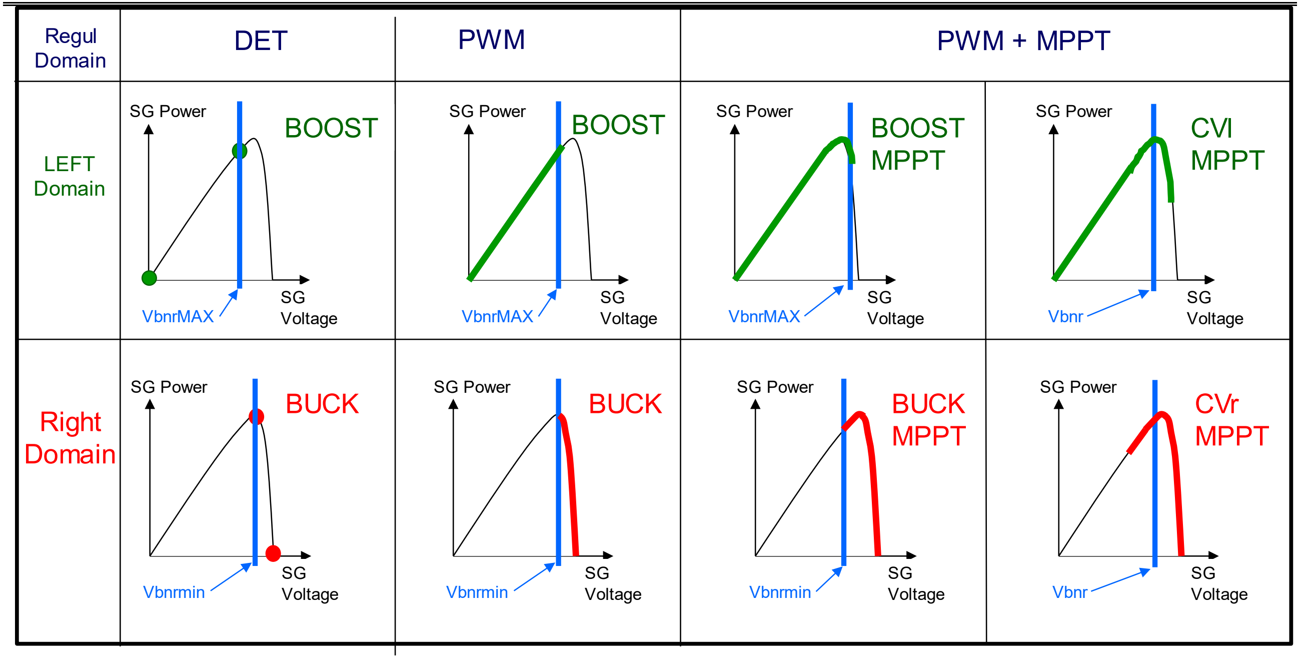


Figure 6: Different kinds of regulator

Note: Throughout the document, the variable 'n' will be used to indicate the number of the SA section considered. It is then an integer between 1 and the total number of SA sections.

4.3. SIMULATION DATA AND DETAILS OF DIFFERENT SIMULATION MODES PERMITTED

The simulation data are:

- The maximal duration of the simulation
- The simulation step
- Information on the simulation initialization (battery state of charge, battery voltage, limit voltage of the battery…)
- Information on the global power system of the spacecraft (regulated or non-regulated bus, regulator mode, thermal model…)
- Information on the equipment parameters (SA, battery, regulator…)

4.3.1. SIMULATION PARAMETERS

Parameter name	Definition	Unit
Simulation duration	Duration of the power system simulation	s
Time step	Simulation step	s
Orbit duration	Duration of one orbit	s
Max orbit number	Maximal number of orbit to simulate	/

The information on orbit duration enable computation of the overall results in the tab "Synthesis". The simulation duration is generally a multiple of the orbit duration.

4.3.2. SIMULATION MODE

This part allows several simulation choices.

The "Regulated" parameter indicates if the power system has a regulated or a non-regulated bus.

The "Consumption profile" parameter enables the choice of the consumption profile:

- "Psl" significates the spacecraft power is determined by the ephemeris fills in the "Input" tab.
- "pConstant" significates the consumed power will be constant during all the simulation and its value is filled in the "Constant consumption" cell.

The "RegulDomain" parameter determines if the SA regulators will be all shunt (left domain) or all series (right domain).

Note: The converter types can be different from one section to another but it is mandatory that all the converters of the entire solar array have to be either solely down converters or solely up converters.

4.3.3. SIMULATION INITIALIZATION

Satellite name	Name of the spacecraft	
SOC battery	Battery state of charge, 0 corresponding to a fully discharged battery and 1 to a fully charged battery.	Without unit, value between 0 and 1
Battery Voltage	Voltage of the battery	V
Vcint	Voltage of the internal resistor (rint) of the battery. The resistor rint vary if the battery is charging or discharging. The value of vcint is then continuously calculated in relation to rint.	V
Delta Vbus	In case of a s3r regulation, this parameter indicates the value of the hysteresis. This value has to be 0 if the s3r regulator is not used.	V
Power margin	System margin applied to the power consumed. In case it has been chosen to use the power profile filled in the "Input" tab, the power margin value is added to this power profile at each simulation time step. In case it has been chosen to use a constant value of power consumed during all the simulation duration, this parameter is not taken into account.	W

Constant consumption	Power consumption value in the case of simulation with constant consumption profile.	W

4.3.4. GLOBAL ARCHITECTURE

vBus	Bus voltage	V
rDistribution	Resistor of the harness between the bus and the spacecraft system to supply.	Ω

4.3.5. BATTERY

nparallel	Number of accumulator strings putted in parallel	/
nSerie	Number of accumulators putted in series	/
rcable	Harness resistor between the battery and the bus	Ω
vl	Limit voltage allowed for the battery (taper value of the voltage).	V
ilim0	If accumulators need current even though they are fully charged, this parameter define this current value.	A
ilim1	Maximal current value allowed for charging the battery (battery charging current until vl is reach).	A
eBatMin	Minimal acceptable value of the battery electromotive force. If the simulation goes under this value, the software detects an issue and stops the simulation.	V

4.3.6. CHARGER/DISCHARGER

ibatsiz	Current value used to the sizing of the charging/ discharging module (see 4.4. Charging/discharging module)	A
kb0	Parameter used for the computation of the charger/ discharger efficiency (see 4.4. Charging/discharging module)	/
kb1	Parameter used for the computation of the charger/ discharger efficiency (see 4.4. Charging/discharging module)	/
kb2	Parameter used for the computation of the charger/ discharger efficiency (see 4.4. Charging/discharging module)	A^{-1}

4.3.7. ACCUMULATOR

ebat0	Parameter used for the computation of the internal voltage of the accumulator model (see 4.2. Battery)	V
ebat1	Parameter used for the computation of the internal voltage of the accumulator model (see 4.2. Battery)	V
ebat2	Parameter used for the computation of the internal voltage of the accumulator model (see 4.2. Battery)	V
ebat3	Parameter used for the computation of the internal voltage of the accumulator model (see 4.2. Battery)	V
ebat4	Parameter used for the computation of the internal voltage of the accumulator model (see 4.2. Battery)	V
rsint0	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
rsint1	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	A^{-1}
rsint2	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
rsint3	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	V^{-1}
rsint4	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	V
capaBatNom	Nominal capacity of the accumulator (nameplate)	Ah
capaBat	Effective value of the accumulator capacity (here the accumulator ageing is considered)	Ah
ebatEffective	Effective value of energy in the accumulator (here the accumulator ageing is considered)	Wh
dint0	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
dint1	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
dint2	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
dint3	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω

dint4	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
dint5	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
dintch	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	Ω
tau	Parameter used for the computation of the internal resistor rint of the accumulator model (see 4.2. Battery)	A/V

4.3.8. SOLAR ARRAY

Solar Constant	Value of the solar constant	W/m²
Albedo	Value of albedo used only in case of a “Reduced” thermal model.	W/m²
Earth radiation	Value of earth’s infrared flux used only in case of a “Reduced” thermal model.	W/m²

4.3.9. SOLAR CELL

tref	Reference temperature used for the solar cell model (see 4.1. Solar array)	°C
ki10	Parameter used to describe the solar cell (see 4.1. Solar array)	A
discsa	Parameter used to describe the solar cell (see 4.1. Solar array)	A/°C
ki2	Parameter used to describe the solar cell (see 4.1. Solar array)	A
ki3	Parameter used to describe the solar cell (see 4.1. Solar array)	V^{-1}
kvt	Parameter used to describe the solar cell (see 4.1. Solar array)	V/°C
surfaceParameter	Solar cell area divided by the fill factor of the solar array. This parameter is **only used** in the computation of the SA temperature.	m²
VpMaxSa0	Voltage value at maximum power point and at the reference temperature. Parameter used to describe the solar cell (see 4.1. Solar array)	V

4.3.10. REGULATOR

ga	Parameter of the controller model (see 4.3.2. PI controller)	/
gbBoost	Parameter of the controller model (see 4.3.2. PI controller)	/
gbBuck	Parameter of the controller model (see 4.3.2. PI controller)	/
Regulator control	This parameter enables the choice of regulator type (parallel command, sequential command or s3r)	/

4.3.11. SOLAR ARRAY SECTIONS

Every following parameter may have different values for each section.

Front temperature	Front face temperature of the solar array	°C
Rear temperature	Rear face temperature of the solar array	°C
nPsection	Number of solar cell strings connected in parallel on the respective SA section	/
nSsection	Number of solar cells connected in series on the respective SA section	/
alphaFront	Average absorbance of the SA front face	/
alphaRear	Average absorbance of the SA rear face	/
epsilonFront	Average emittance of the SA front face	/
epsilonRear	Average emittance of the SA rear face	/
heatCapacity	Heat capacity of the SA	W/°C
thermalModel	Define the thermal model used (Reduced, Albedo and P_earth profile, Fixed Day Night Temperature)	/
Day temperature	Fixed temperature of the SA section during the day. This parameter is used in case of « Fixed Day Night Temperatures » thermal model.	°C
Night temperature	Fixed temperature of the SA section during the night. This parameter is used in case of « Fixed Day Night Temperatures » thermal model.	°C

Conductivity	Thermal conductivity between the front face and the rear face of the solar array	W/K/m²
vdiode	The voltage drop across the diode located between the SA section and the related regulator	V
rls	Harness resistor located between the SA section et the related regulator	Ω
isasiz	Current value used for the sizing of the SA regulator (see 4.3.1. Regulator efficiency)	A
kr0	Parameter of the regulator model (see 4.3.1. Regulator efficiency)	/
kr1	Parameter of the regulator model (see 4.3.1. Regulator efficiency)	/
kr2	Parameter of the regulator model (see 4.3.1. Regulator efficiency)	/
Regulator	This parameter indicates the regulator used for the corresponding section. In case the choice “LeftDomain” has been made for the parameter “RegulDomain”, the user can select one of the following regulators: Boost, BoostMppt or CvlMppt. In case the choice “RightDomain” has been made for the parameter “RegulDomain”, the user can select one of the following regulators: Buck, BuckMppt or CvrMppt.	/
Cell	Type of solar cell used	/

The parameter “thermalModel” enables to choose the thermal model:

- “Reduced”
- “Albedo and P_earth profile”
- “Fixed Day Night Temperature”

For the « Reduced » model the illumination is set by the profile entered in the “Input” tab, however the albedo and the terrestrial infrared are calculated from fixed values (“Albedo” and “Earth radiation”) filled in the “Simulation” tab. The calculations, made for each section, are as follows:

$$albedo_{av} = illumination \times \frac{albedo}{3.14}$$

$$albedo_{ar} = illumination \times \frac{albedo}{3.14}$$

$$pterre_{av} = \frac{pterre}{3.14}$$

$$pterre_{ar} = \frac{pterre}{3.14}$$

With:

- $albedo$: corresponding to the value entered in “Albedo”
- $pterre$: corresponding to the value entered in “Earth radiation”

The model “Albedo and P_earth profile” takes into account all of the flux ephemeris (illumination, albedo and terrestrial infrared power) entered in the “Input” tab. This is the most accurate model.

The model “Fixed Day Night Temperatures” considers, to calculate the SA temperatures, only the temperature values set in the “Simulation” tab by the “Day temperature” and “Night temperature” parameters.

4.4. STOPPING CONDITIONS OF THE SIMULATION

The simulation stops when one of the following conditions is met:

- The simulation duration filled by the user is reached
- The maximal number of orbit is reached
- The end of the input profiles is reached
- The battery is completely discharged ($SOC_{battery} < 0$)
- The internal voltage of the battery is too low (ebat lower than its minimum value filled by the user)

4.5. OPALIS OUTPUTS

4.5.1. DATA SYNTHESIS

In the “synthesis” sheet, are presented all the synthesis results of the simulation.

The orbit duration is defined by the user as a simulation parameter. For each orbit, the following data are defined:

- DOD and cycled DOD in percent
- The minimum energy value E_{min} available at the end of the eclipse
- The period during which the battery is in current limitation mode (til)
- The period during which the battery is in taper voltage mode (tvl), that is during which its voltage is constant and equals V_L
- The voltage value at the end of the night, $Vbatt_{min}$

The averages of these results on the fifteen orbits are also presented.

The results on the energy balance, on the battery (in particular the initial and final SOC values) and the average power balance which describes the power consumed by the spacecraft, the power supplied by the solar array and all losses dissipated at each different module are also presented.

Many results need to be carefully monitored to ensure proper sizing of the supplying system, the main elements are as following:

- Once the simulation is complete, if the final SOC value is lower than the initial SOC value, the simulation has to be restart to obtain a stabilization. If after several attempts of the simulation, the final SOC is again lower than the initial value it means that the power system is not balanced (due to a sizing issue).
- It is essential to cheek that the obtained Emin is higher than the minimum value required in case of switching in survival mode. If this is not the case, the sizing of the power supply system is flawed. As a matter of fact, in case of failover in survival mode, the spacecraft would not have enough energy to ensure this survival mode.
- It is usually requested that the tvl_moy value be higher than 10min.

The meaning of all of these data results are detailed in the sections below.

4.5.1.1. SUMMARY

Date	Date on which the simulation has been made	/
Duration	Simulation duration (corresponds to the duration of the input profile in case stop condition is the end of the input flows)	s
Simultime Percent	Simulation status	%
Stop condition	Reason why the simulation is complete	/
Regulated	Indicates if the power system has a regulated or a non-regulated bus	/
Voltage control	Indicates the regulator type (parallel command, sequential command or s3r)	/
Consumption profile	Choice of the consumption profile (constant value or determined from the ephemeris)	/

4.5.1.2. SIMULATION SYNTHESIS

Initial SOC	Initial value of the state of charge	/
Final SOC	Value of the state of charge at the end of the simulation	/
PslMean	Average value of the power consumption of the spacecraft (including margin)	W
Pdiss battery	Power dissipated in the battery	W
Battery efficiency	Efficiency of the battery	%
Esl	Energy consumed by the spacecraft	Wh
E absorbed BATT	Energy absorbed by the battery	Wh

E delivered BATT	Energy delivered by the battery	Wh
E supplied SA	Energy supplied by the Solar Array	Wh
Eu (regulator output)	Energy delivered at the regulator output	Wh
Regulator efficiency	Efficiency of the regulator	%
SupplySystemEfficiency	Efficiency of the overall power system	%
E input regulator	Energy at the entrance of the regulator	Wh
Eplusp	Energy absorbed by the battery primary (meaning it includes the charger/discharger module if any)	Wh
Eminusp	Energy delivered by the battery primary (meaning it includes the charger/discharger module if any)	Wh
Edist	Energy dissipated in Rdistribution	Wh

4.5.1.3. ORBITS SYNTHESIS

The values of the following data are given for each orbit.

Number	Indicate the number of the orbit
DOD (%)	Depth Of Discharge of the battery
Emin (Wh)	Remaining energy at the end of the orbit
Til (mn)	Duration of the charging with the limitation current
Tvl (mn)	Duration of the charging at the voltage limit value
DODcycle (%)	Cycled DOD
Vbattmin (V)	Battery voltage at the end of the orbit

4.5.1.4. ENERGY BALANCE RESULT

PslMean	Average value of the power consumption of the spacecraft (including margin)	W
Pmargin	System margin applied to the power consumed in case the consumption is determined from the power profile filled in the “Input” tab	W
Pconstant	Power consumption value when using a constant value	W

Tvlmean	Mean value of the time at the voltage limit	mn
Vl	Value of the voltage limit set by the user	V
SupplySystemEfficiency	Efficiency of the overall power system	%

4.5.1.5. BATTERY

DODcyclemean	Average value of the cycled DOD	%
DOD max	Maximum value of the DOD	%
Emin min	Minimum value of the remaining energy at the end of the orbit	Wh
Capabat	Effective value of the battery capacity (taking the battery ageing into account)	Ah
Pdiss battery	Power dissipated in the battery	W

4.5.1.6. AVERAGE POWER BALANCE

PslMean	Average value of the power consumption of the spacecraft (including margin)	W
P_supplied_SA	Power supplied by the Solar Array	W
pdiss PCU	Power dissipated in the regulator	W
pdiss RPS	Power dissipated between the output of the solar array and the regulator input	W
pdiss Rdistribution	Power dissipated in Rdistribution	W
pdiss Rcable	Power dissipated in Rcable (= power absorbed by the battery - power delivered by the battery)	W
pdiss battery	Power dissipated in the battery	W
pdiss CHDCH	Power dissipated in the charger/discharger module	W
pdiss total	= Power delivered by the solar array - Power consumed by the spacecraft	W
pdiss total (sum)	Sum of all power losses (= P_{diss_PCU} + P_{diss_RPS} + $P_{diss\_Rdistribution}$ + P_{diss_Rcable} + $P_{diss\_battery}$ + P_{diss_CHDCH})	W

4.5.2. DISPLAY OF THE SIMULATION RESULTS

OPALIS uses the entrance data to perform a simulation and produces output data in tabular form, with the results at each time step.

The output data are:

- The time
- The power consumed by the spacecraft
- The current supplied by the solar array sections
- The BNR voltage
- The output voltage of the SA sections
- The front face and rear face temperatures of the SA
- The voltage and current of the battery
- The input voltages of the regulators
- The energy contained in the battery
- The total current at the output of the SA regulators
- The state of charge of the battery

The progress of each parameter are plotted in specific tabs.

Some of the output data of a simulation are returned in the initialization parameters for the next simulation:

- The state of charge of the battery
- The transient voltage of the battery model
- The voltage over the internal resistor of the battery, Vcint

5. DETAILED MODELS OF THE POWER DEVICES

5.1. THE SOLAR ARRAY

The solar array is composed of several sections. A SA section contains a number of solar cells placed in series and in parallel.

5.1.1. SOLAR CELL MODELLING

The electrical model of the solar cells used in OPALIS is characterized by the following equations.

Definition of the SA section output current:

$$Isa = ki10 + discsa * (Temp - tref) + ki2 * exp(ki3 * (kvt * (tref - Temp) + Vsa))$$

With:

- tref: reference temperature (used to establish the solar cell model), in °C
- Temp: actual temperature during the solar cells use, in °C
- discsa: temperature coefficient which enables to calculate variation of the current value in short-circuit at a given temperature compared to the value established at the reference temperature, this parameter takes also into account networking coefficient and solar cell degradation, in A/°C
- ki10: short-circuit current value (Isc) at T=tref, in A
- ki2: parameter used to the SA current modelling, in A
- ki3: parameter used to the SA current modelling, in V^{-1}
- kvt: variation of the open-circuit voltage (Voc) depending on the temperature, in V/°C
- V_{SA}: SA section output voltage (upstream of its associated regulator), in V

The parameters in green depend on the type of used solar cells, they have to be filled in the “simulation” tab.

Note:

The “tref” parameter corresponds to the reference temperature, that is the temperature used to established the model.
The SA current is usually not computed from the nominal temperature of the solar cells. It is recommended to calculate it from a reference temperature closer to the actual operating temperature (“Temp”). Hence, the model will be more robust to temperature variations during the actual use of the solar array (despite these variations the model will still be representative).

Voltage at the maximum power point for the temperature Temp:

$$Vpmsa = Vpmsa0 + kvt * (Temp - tref)$$

With:

- Vpmsa0: voltage (in Volt) at Pmax for T=tref

Note:

A possibility is to determine by calculation the three main points of the curve $I_{GS}(V_{GS})$:

- at Isc (short-circuit)
- at Pmax
- at Voc (open-circuit)

Then, the coefficients ki2 and ki3 has to be adjusted so that the curve meets those previously calculated points.

5.2. BATTERY

A battery is composed of several accumulators putted in series and in parallel.

5.2.1. BATTERY ACCUMULATOR MODELISATION

The electrical model used to simulate an accumulator is detailed hereafter:

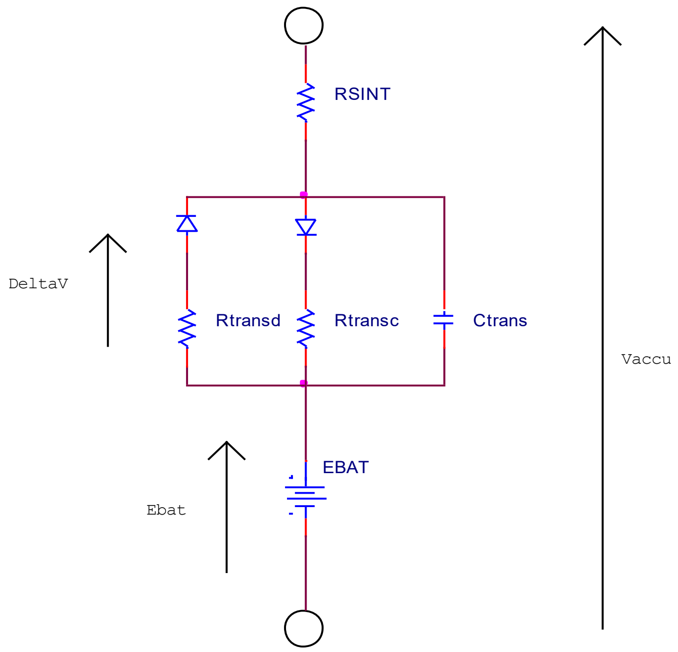


Figure 7: Electrical schematic of the battery model

With:

$$Ebat = ebat0 + ebat1 * SOC + ebat2 * SOC^\wedge 2 + ebat3 * SOC^\wedge 3 + ebat4 * SOC^\wedge 4$$

$$Rsint = rsint0 + rsint1 * Ebat + rsint2 * exp(rsint3 * (Ebat - rsint4))$$

$$RtransD = dint0 + dint1 * SOC + dint2 * SOC^\wedge 2 + dint3 * SOC^\wedge 3 + dint4 * SOC^\wedge 4$$

$$RtransC = dintch$$

$$Ctrans = tau$$

The parameters in green depend on the type of accumulators used, they have to be filled in the simulation parameters.

The parameters ebat[0..4], rsint[0..4], dint[0..4], dintch and tau could be determined from the curves of the datasheet of the accumulator or from measurement performed on this accumulator. The coefficients are deducted from the extrapolation of these curves.

The other parameters needed for OPALIS initialization regarding the battery model are listed hereafter:

- capabatnom: nominal capacity of the battery
- capabat and ebateffective: effective capacity and effective energy of the battery (which consider degradation and depend on the lifetime, the number of cycle and the cycled DOD)

5.3. THE REGULATOR

Each SA section is associated with a regulator. Regulators can be buck DET, buck MPPT, CvrMPPT (PWM), boost DET, boost MPPT or CvlMPPT (PWM) converters. OPALIS allows three type of control: parallel control, sequential control and s3r (Sequential Switching Shunt Regulator) control.

5.3.1. REGULATOR EFFICIENCY

The power losses of the regulators are represented in the model by the parameter "efficiency".

For each section, the efficiency and its maximal value (efficiencymax(n)) are initialized at 0.97 and 0.98 respectively. These values will be recalculated by simulation at each computation loop.

If the regulator of the section "n" contains a voltage down converter, its efficiency is the following:

$$efficiency(n) = kr0(n) - abs\left(1 - \frac{Vbnr(n)}{Ver(n)}\right) \times kr1(n) + \left(1 - \frac{I_{GS_{provided}}(n)}{I_{GS_{siz}}(n)}\right) \times kr2(n)$$

However, if the converter of the regulator is a boost converter, the efficiency computation is defined by the following equation:

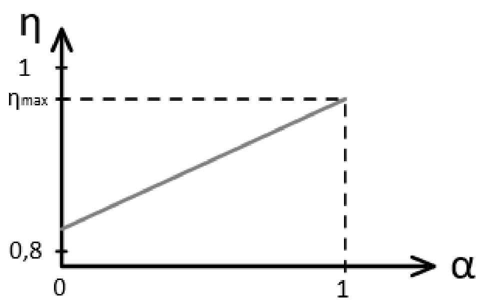
$$efficiency(n) = kr0(n) - abs\left(1 - \frac{Ver(n)}{Vbnr(n)}\right) \times kr1(n) + \left(1 - \frac{I_{GS_{provided}}(n)}{I_{GS_{siz}}(n)}\right) \times kr2(n)$$

The parameters to fill in for the efficiency computation are : $kr0$, $kr1$, $kr2$ and $I_{GS_{siz}}$.

$I_{GS_{dim}}$ corresponds to the sizing value of the current for the regulator.

The term: $kr0(n) + \left(1 - \frac{I_{GS_{provided}}(n)}{I_{GS_{siz}}(n)}\right) \times kr2(n)$ corresponds to the maximum value of the efficiency. Indeed, $V_{er}(n) = V_{bnr}(n)$ means that the regulator input is directly connected to its output (the duty cycle is 1 in case of a buck converter and 0 in case of a boost converter).

The $kr1$ coefficient sets the efficiency slope.



The efficiency of regulators is then imposed by the user via the determination of the values of the parameters.

5.3.2. PI CONTROLLER

The regulation is performed depending on the battery voltage V_{batt}. The following schematic represents, in a simplified form, the control of the regulator converter:

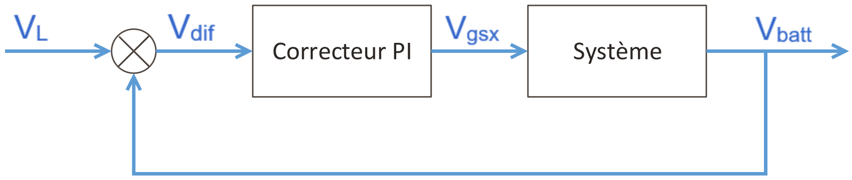


Figure 6 : Simplified diagram of the regulation

The voltage error between the reference value V_L and the measured battery voltage V_{batt} is computed as follows:

- In case of a shunt regulator: $V_{dif} = V_L - V_{batt}$
- In case of a series regulator: $V_{dif} = V_{batt} - V_L$

The value of the control voltage V_{gsx} is set with the following equation:

$$V_{gsx} = V_{gsx} + g_a(V_{dif} - V_{difm}) + g_b \times pascal \times V_{difm}$$

V_{difm} is the value of V_{dif} at the previous time step.

The parameters g_a and g_b has to be filled by the user.

The effective control voltage of the regulator is V_{com}. It may be identical or not to V_{gsx} depending on the control type used (parallel, sequential or s3r).

Parallel and sequential control involve the use of a PI controller. This is not the case with the s3r control that use hysteresis.

5.3.3. TYPES OF CONTROL

5.3.3.1. PARALLEL CONTROL

In order to regulate the voltage V_{batt}, one possibility is to use a parallel control. The same voltage is applied to each regulator. Thus, the converters of each SA section are controlled the same way at the same time. Hence, the voltage V_{batt} is the same for all the sections and is equal to V_{gsx}.

5.3.3.2. LINEAR SEQUENTIAL CONTROL

Another possibility to regulate is to use a linear sequential control. With this regulation, all of the converters are enabled sequentially.

The control of each converter is computed with the following equation:

$$V_{com}(n) = n_{sections} \times V_{gsx} - (n-1) \times ecretevalg$$

With:

- nsections: the total number of SA section
- vgsx: voltage calculated at the output of the PI controller
- Vcom: the effective control voltage
- ecretevalg: the average of all the clipped values of the control voltage of each section.

For all the sections with $Vcom(n)$ below 0, the control voltage will be set at 0. On the contrary, for the sections where $Vcom(n)$ is higher than $ecreteval(n)$, the control voltage will be set at $ecreteval(n)$. For the remaining section, the control voltage is the voltage value calculated from the given value.

5.3.3.3. S3R (SEQUENTIAL SWITCHING SHUNT REGULATOR) CONTROL

The s3r control is based on a hysteresis. The deltavbus value is set by the user during the simulation configuration. In the simulation, the internal value nsecon define the number of sections controlled at their respective ecreteval value. When the error V_{dif} exceeds the value deltavbus, nsecon is incremented by 1. On the contrary, if the error V_{dif} is lower than –deltavbus, nsecon is decremented by 1.

Thus, nsecon sections will have a control voltage V_{com}(n) equal to ecreteval(n). For the other sections, the voltage V_{com}(n) is equal to 0.

5.4. THE CHARGER/DISCHARGER

The charging/discharging battery module is only used in case of a regulated bus. In this case, it is taken into account as an efficiency value in the simulation. This efficiency can be evaluated by four parameters: Ibatdim (sizing current of the battery charger/discharger), kb0, kb1 and kb2. The values of the various parameters have to be filled in the tab “paramsimul” and are based on the efficiency formula below:

$$efficiency2 = kb0 + \frac{Vbatt}{Vbnr} \times kb1 + \left(1 - \frac{|Ibattotal|}{Ibatsiz}\right) \times kb2$$

with: $\frac{|Ibattotal|}{Ibatsiz}$ corresponding to the value of the charger/discharger current (Ichdch).

The value efficiency2 cannot exceed 0.97.

5.5. THE SPACECRAFT TO SUPPLY

In the software, the spacecraft to supply is modelled by the power consumption Psl. The first option is to fill a power consumption profile in the tab “Inputs”. The power consumption can then change at each time step. The user can add a global margin if needed during the simulation configuration.

Another possibility is to use a constant power consumption. This value has to be filled in the simulation parameters. In that case, the margin established above is not used in the simulation.

6. REFERENCES

- « OPALIS-V1 – User documentation »

- END OF THE DOCUMENT -