IS454 Satellite Electrical Systems

Battery and Solar Array Sizing of Telecom Satellites

TAS ASTRO 2018-19

February 2019

Ahmet Burak KOÇ

Ömer Eren Can KOÇULU

Contents

Figure List

Diagram List

Graph List

Table List

1 Introduction

The objective of this exercise is to complete power architecture assessment of a Telecom satellite. In particular, AIRBUS's E3000 power architecture with 100V regulated bus is sized.

2 Requirements

The following requirements have been taken into account in this exercise.

- Geostationary orbit
- 15 years lifetime
- 100V regulated bus
- 12kW payload consumption + 3 kW platform consumption
- Margin on battery: maximum DoD = 80%, including possible failures
- Margin on solar array: 7% on power required by customer

The power architecture of the E3000 platform is designed as 100V regulated. The diagram where below shows the system's power architecture.

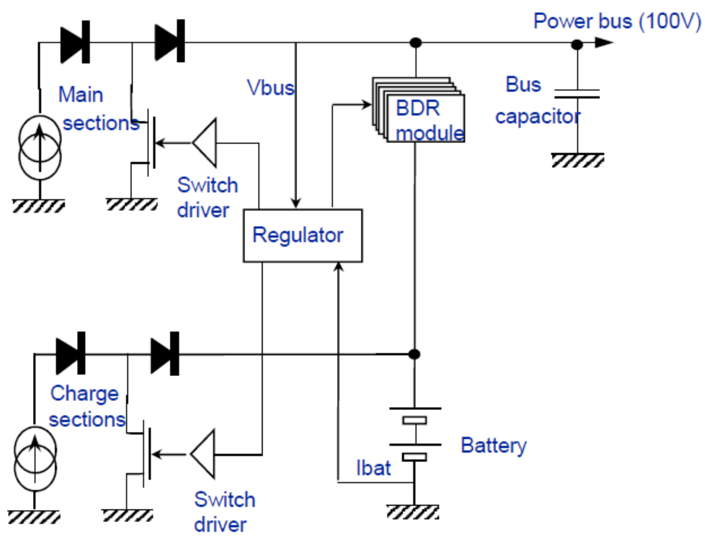


Diagram 1 E3000 architecture – 100V regulated bus

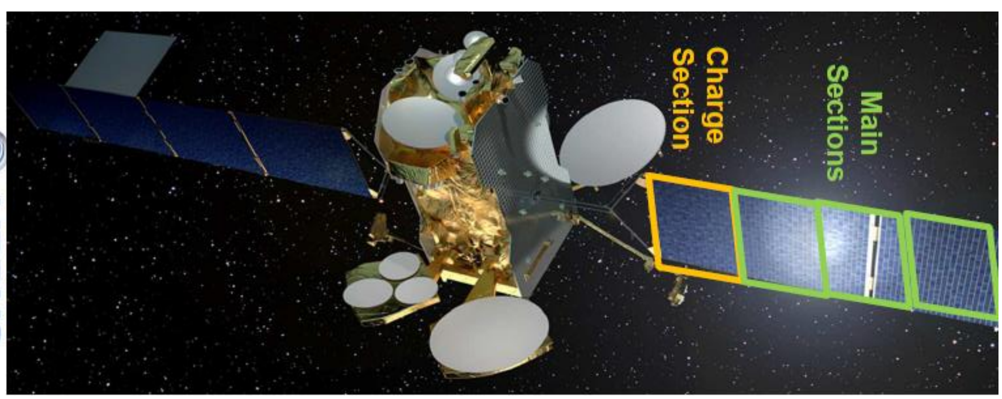
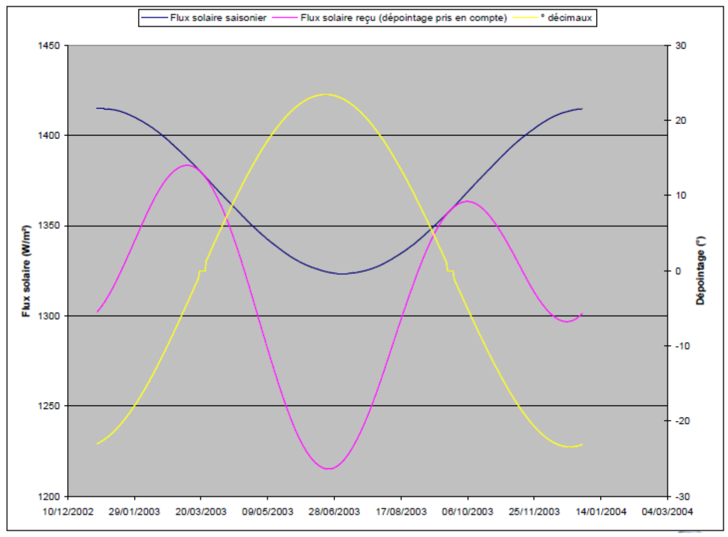


Figure 1 Location of main and charge sections of Solar Array

3 Solar Array Sizing

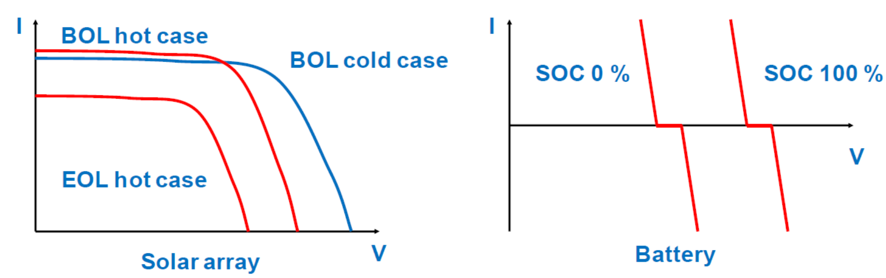
Solar array sizing has been made according to the characteristics of the orbit of the satellite and the specification of the system. The desired specifications for this system are listed in the Table 1.

<table>
<tr><td>Solar Cell: Azurespace 3G30C</td><td>Max mission duration: 15 years</td></tr>
<tr><td>Loss factor: 0.9707</td><td>Radiation dose: 1E+15 MeV</td></tr>
<tr><td>Total SA line Vdrop: 2.5V</td><td>Fill factor: 80%</td></tr>
<tr><td>Temperature range
• Hot case: 50 °C
• Cold case: 40 °C</td><td>Solar Flux


Graphic 1 Solar flux</td></tr>
</table>

Table 1 Solar array specification table

The worst-case scenario is considered when sizing the solar array. In order to determine this scenario, the variation of the current-voltage curve according to the temperature is taken into consideration. As can be seen in the Graphic 2, even at the end of the life of the satellite 100V to be provided to the system EOL hot case situation is taken into account.



Graphic 2 Current-Voltage graph for solar array and batteries of satellite

First, <u>it is calculated how many solar cells should be used in a series at the worst case</u> (hot case: 50 °C). In this calculation, the attached <u>solar cell datasheet</u> and system specifications are used. The power required to reach the satellite from the solar panels is;

$$V_{bus} + V_{drop} = 100 + 2.5 = 102.5\ [V]$$

To find the power provided by a solar cell, the "Voltage at max. Power Vmp" value (2246 [mV]) from the enclosed datasheet of the solar cell is taken according to the radiation value 1E15. Besides in order to calculate the effect of the temperature gradients, the "Voltage at max. Power" value (-6,4 [mV/ ^{o}C]) is taken according to the 1E15 radiation value.

$$2246\ [mV] + \left(-6.4\left[\frac{mV}{C}\right]\right) * (50\ [C] - 28\ [C]) = \mathbf{2015.2}\ [mV]$$

The following equation is applied to calculate how many solar cells will be in a series.

$$\#\ \boldsymbol{of\ cells\ in\ series}: \frac{102.5[V]}{2.1052[V]} = 48.7\ \longrightarrow \boldsymbol{49\ cells\ in\ series}$$

Afterward, it is calculated how many series should be used in the parallel at the worst case. This calculation is obtained by dividing the current power that the system needs with the current power that a series can provide. As the lowest current value required by the system occurs in the cold case according to Graphic 2, the worst-case scenario is taken as cold case (40 ^{o}C). In this case, firstly the current value that a solar cell can provide is calculated depending on the system specifications and attached datasheet.

$$I_{mp} = 486\ mA\ (Spectrum: AMO\ WRC = 1367\ W/m^2\ ; T = 28\ C\ per\ datasheet)$$

To find the maximum current provided by a solar cell, the "Current at max. Power Imp" value (2246 [mA]) from the enclosed datasheet of the solar cell is taken according to the radiation value 1E15. Besides in order to calculate the effect of the temperature gradients, the "Current at max. Power" value (0,29 [mA/ ^{o}C]) is taken according to the 1E15 radiation value.

$$I_{mp_{(\mathbf{1}\ \boldsymbol{string})}} = 486\ [mA] + 0{,}29\ [\mathrm{mA/C}] * (40\ [C] - 28\ [C])\ = 490.1[mA]$$

When Graphic 1 in the system specifications is taken into consideration, the lowest solar flux value is taken as 1225[W/m^2]. In addition, loss factor specification (0.9707) comes from Table 1 and Average Efficiency (%26.5 according to 1367 W/m^2) comes from datasheet.

$$\boldsymbol{I_{mp_{(1\ string)}}} = 490.1\ [mA] * \frac{1225\ [W/m^2]}{1367\ [W/m^2]} * \frac{26.5}{100} * 0.9707 = \mathbf{426.3}[mA]$$

The current value required for the system is calculated as follows. (Customer requirements (Solar Array margin: %7) are taken into account.)

$$P_{load} = 12 + 3 = 15kW$$

$$P_{required} = 15[kW] + 15[kW] * \frac{7}{100} = 16050\ W$$

$$I_{reqired_{system}} = \frac{P_{required}}{V_{bus}} = \frac{16050[W]}{100[V]} = \mathbf{160.5}\ [A]$$

To calculate how many series should be connected in parallel, the current value that the system needs is divided by the current value of a series.

$$\#\ \boldsymbol{of\ strings\ in\ parallel}: \frac{160.5[A]}{0{,}4263[A]} = 376.5\ \longrightarrow \boldsymbol{377\ strings\ in\ parallel}$$

4 Battery Sizing

Battery sizing has been made according to the characteristics of the orbit of the satellite and the specification of the system.

Figure 2 shows the time duration that the satellite sees the sun in the geostationary orbit. GEO orbiting satellites enter the eclipse period twice a year for 45 days. In these periods, the satellite cannot see the sun for 72 minutes every day.

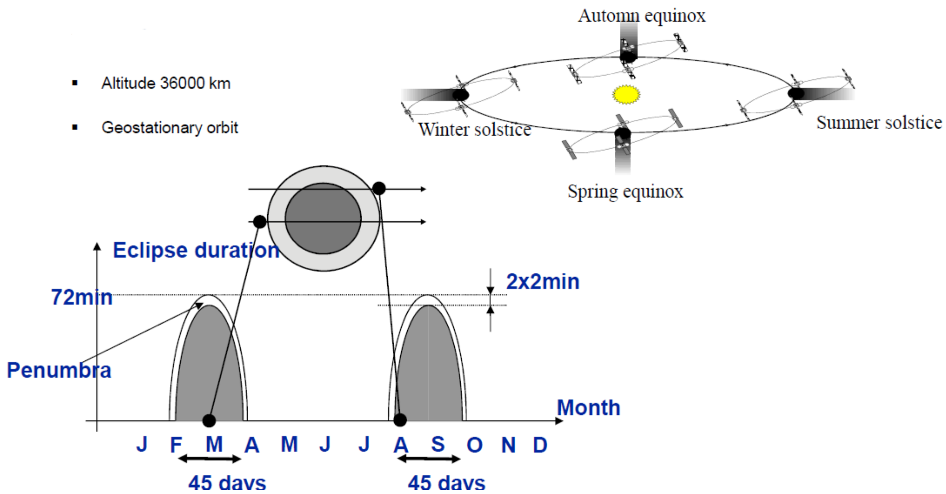


Figure 2 Effects of geostationary orbit on the satellite

Since eclipse's longest duration is 72 minutes, batteries need to supply sufficient power to the load for 72 minutes.

Power calculations are started from Load side. By using given information, load total power consumption with margin is calculated by following formula

$$P_c(margin) = P_c + P_c * margin$$

and tabulated in Table 2.

Vbus	100	V
Load power consumption	15000	W
Margin	7	%
Load power consumption + margin	16050	W

Table 2: Load Characteristics

Power consumption of load is supplied by BDR, so BDR power output must be at least 16050W. BDR characteristics are tabulated in Table 3. Total energy supplied by BDR is calculated with following formula,

$$E_{supplied} = P_{out} * Duration_{Eclipse}$$

Then, sufficient input energy and input power is calculated according to the efficiency of the BDR with following formulas

$$E_{consumed} = \frac{E_{supplied}}{efficiency}$$

$$P_{in} = \frac{P_{out}}{efficiency}$$

Vin max	60	V
Vin Min	100	V
efficiency	95	%
BDR output power	16050	W
Total energy supplied by BDR	19260	Wh
BDR input power	16895	W
Total energy consumed by BDR	20274	Wh

Table 3: BDR Characteristics

Finally, there is two requirements for battery sizing which are given in Table 4.

- Req1: Output voltage (V_{out}) is input voltage of BDR (Diagram 3) so it must be between 60V and 100V.
- Req2: In order the load to operate successfully during whole eclipse (even in the worst case), batteries must supply 20274 Wh energy to the BDR.

Requirement	Description
Req1	Vout is between [60 V; 100 V]
Req2	20274 Wh energy capacity

Table 4: Battery Sizing requirements

Vout min	3,0	V
Vout max	4,1	V
Vout avg	3,5	V
Nominal Capacity	40	Ah
Maximum DOD	80	%
Bypass resistance	100	μΩ

Table 5: Battery cell characteristics

In order to satisfy Req1, firstly, number of cells in series is calculated. In the worst case, battery cell outputs minimum 3V (Table 5) and sum of voltage outputs of cells in series must be at least 60V (Req1). Similarly, battery cell outputs maximum 4.1V (Table 5) and sum voltage outputs of cells in series must be maximum 100V (Req1).Hence,

$$Minimum\ \#\ of\ cells = round\ up(\frac{60}{3}) = 20$$

$$Maximum\ \#\ of\ cells = round\ down(\frac{100}{4.13}) = 24$$

In order to satisfy Req2, number of cells in parallel is calculated. Each cell has energy of

$$nominal\ capacity * V_{avg} = 40 * 3{,}5 = 140Wh$$

However, by considering maximum DOD (Table 5), each cell can supply

$$Total\ available\ energy\ (1\ cell) = Total\ energy(1\ cell) * DOD = 140 * 0.8 = 112\ Wh$$

Total number of batteries is calculated as

$$Total\ \#\ of\ cells = round\ up(\frac{20274}{112}) = 182$$

Number of cells in series can be selected between 20 and 24. Number of cells in parallel is calculated with following formula for all cases.

$$\# \, of \, cells \, in \, parallel = round \, up\left(\frac{Total \, \# \, of \, cells}{\# \, of \, cells \, in \, parallel}\right)$$

and results are observed if requirements are satisfied or not.

CASE	# of cells (in series)	# of cells (in parallel)	Min Vout (V) (rough)	Vdrop at bypass (V)	Min Vout (V) (Real)	Max Vout (V)	Req1
1	20	10	60,0	0,56	59,4	82,0	Vout<60V
2	21	9	63,0	0,56	62,4	86,1	OK
3	22	9	66,0	0,56	65,4	90,2	OK
4	23	8	69,0	0,56	68,4	94,3	OK
5	24	8	72,0	0,56	71,4	98,4	OK

Table 6: Req1 analysis

As it can be seen in Table 6, Req1 cannot be satisfied with 20 cells in series due to voltage drop in bypass.

CASE	# of cells (in series)	# of cells (in parallel)	Energy loss due to bypass (Wh)	Energy Output (Wh)	Energy needed (Wh)	Total number of battery cells	Req2
1	20	10	159	22241	20274	200	OK
2	21	9	151	21017	20274	189	OK
3	22	9	144	22032	20274	198	OK
4	23	8	138	20470	20274	184	OK
5	24	8	132	21372	20274	192	OK

Table 7: Req2 analysis

Also, according to the SAFT VES140 Datasheet maximum discharge current is 100A which means batteries can supply 100*8 = 800A to the BDR in the worst case (8 cells in parallel). Even in 60V input, BDR input current reaches $I = \frac{BDR \, input \, power}{60} = 282A$ which can be supplied by batteries. Hence, discharge current capabilities of the batteries satisfy required current.

As it can be seen in Table 6 and Table 7, case 1 cannot satisfy all requirements so one of the cases 2, 3, 4 or 5 will be selected for battery sizing.

When one cell failed and is bypassed, number of cells in series decrease by one. If case 4 or case 2 are chosen, the system will not be fail operational because number of cells in parallel will not be enough to supply enough power. Hence, case 3 or 5 needs to be chosen.

Total number of cells is lower for case 5 (192 cells) than the case 3 (198 cells), so case 5 cost lower for financial budget and mass budget.

As a result, case 5 is chosen. 24 cells in series and 8 cells in parallel architecture of batteries will be used in the system.

5 Solar Array (Battery Charge Sections)

As it is calculated in Battery Sizing, 20274Wh energy is supplied by batteries so the same amount of energy must be charged.

Eclipse duration is 72 minutes per day so batteries must be charged fully during

24 h – 72 min = 24*60-72=1368 min

Total power consumed by batteries during charging is calculated with following formula.

$$P_{in}(batteries) = \frac{20274}{\frac{1368}{60}} = 889.21W$$

Since, efficiency of the recharge is 90%. Power output of the solar array must be at least

$$P_{out}(SA) = \frac{P_{in}(batteries)}{efficiency_{recharge}} = \frac{889.21}{0.9} = 988.01W$$

In order to supply 989W power through $100V_{bus}$, solar array needs to output $I = \frac{988{,}01}{100} = 9.8802A$ current. It is already calculated in Solar Array Sizing that one string supply 426.3 mA. In order to obtain enough current, $round\ up(\frac{9.8802}{0.4263}) = 24$ strings in parallel are sufficient.

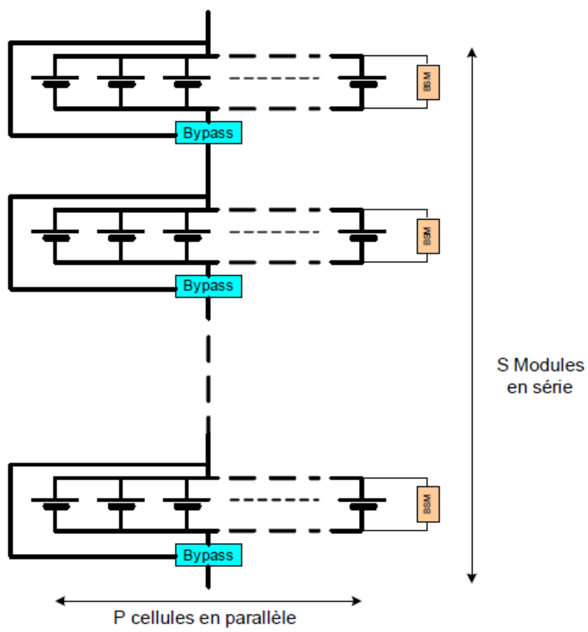


Diagram 2 Battery architecture

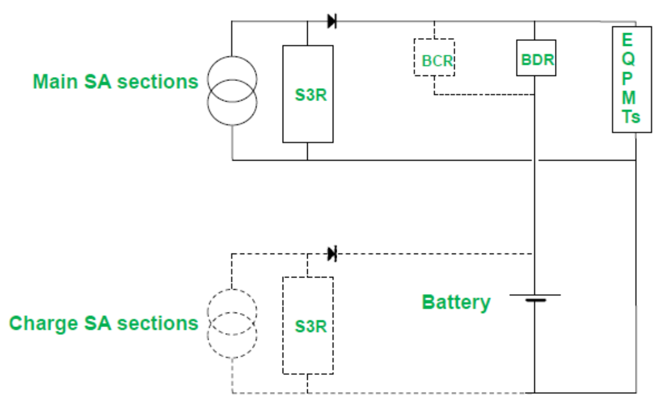


Diagram 3 Main and charge section of Solar Array

6 Physical Sizes and Mass Calculations

6.1 Solar Array

Total number of solar cells is found as 19649 (Table 8)

Main section	# of cells in series	49	18473
	# of cells in parallel	377	
Charge section	# of cells in series	49	1176
	# of cells in parallel	24	
		Total # of solar cells	19649

Table 8 Number of solar cells

According to the datasheet of the solar cell, mass of a solar cell is 86 mg/cm^2 and dimensions are 40 x 80 mm ± 0.1 mm. In addition, when calculating the weight of the solar panels, the weights of the other mass (including solar cells) are taken into account. In this case, 1.6 kg/m^2 uses for calculating to the solar panel mass.

$$\boldsymbol{1\ cell\ area\ is}: 40.1 * 80.1 = 3212.01\ mm^2$$

$$\boldsymbol{All\ cell\ are\ is}: 19649 *\ 3212.01 * 10^{-6} = \boldsymbol{63.11}\ m^2$$

According to Table 1, the fill factor is %80.

$$\boldsymbol{Total\ solar\ panel\ area\ is}: 63.11 * \frac{100}{80} = 78.89\ m^2$$

6.2 Batteries

Total number of batteries is found as 192 (Table 9).

Number of cells in series	24
Number of cells in parallel	8
Total number of cells	192

Table 9 Number of battery cells

According to the SAFT VES140 Datasheet, mass of a cell is 1.13 kg and sizes are 53 mm diameter, 250 mm height.

Excluding additional masses (cables and other electrical equipment), total mass of batteries is

$$\boldsymbol{m_{batteries} = 192 * 1.13 = 217\ kg}$$

Excluding the volumes of other elements (cables, electrical equipment and thermal control equipment), the methods given in Figure 3, Figure 4, and Figure 5 can be used for connecting and locating cells. Geometrically, Figure 4 occupies minimum volume and Figure 5 occupies maximum volume. However, this decision depends on the other constraints of the system.

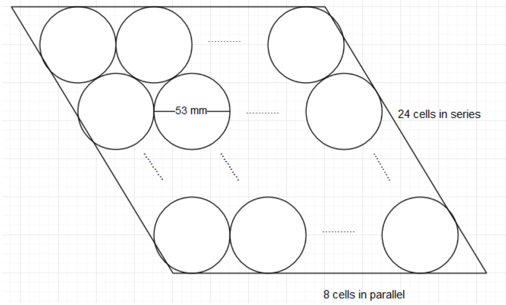


Figure 3: Diamond (24x8)

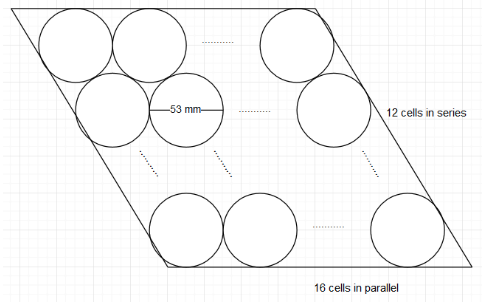


Figure 4 : Diamond (12x16)

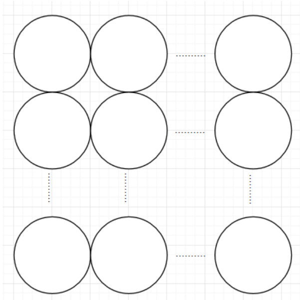


Figure 5: Rectangular (n x n)

7 Attachments

7.1 TJ Solar Cell 3G30C Datasheet

3G30 -Datasheet Azur Space.pdf

7.2 SAFT VES140 Datasheet

Battery parameters (Simplified from datasheet)	
Nominal Capacity	40 Ah
Maximum Voltage	4.1V
Minimum Voltage	3 V
Average voltage	3.5V
Bypass resistance	100 µΩ

Cell electrical characteristics	
Nominal voltage	3.6 V
Nominal capacity at C/1.5 rate at 4.1 V/3 V & 20°C	39 Ah
Maximum discharge current at 25°C	100 A (Continuous ~2 s pulse)
Specific energy (minimum)	126 Wh/Kg
Energy density	140 Wh/l
Cell mechanical characteristics	
Diameter	53 mm
Height	250 mm
Mass	1.13 kg
Mechanical environment Leak rate	Qualified all launchers 10^{-8} dm^3 atm s^{-1}
Cell operating conditions	
Lower voltage limit for discharge	Continuous (0°C to +45°C) 2.7 V
Charging method	Constant current/constant voltage (CCCV)
Charging voltage (max)	4.1 V
Recommended continuous charge current	GEO/MEO C/10 LEO (20 % DOD) C/5
Operating temperature	Charge +10°C to +35°C Discharge 0°C to +40°C
Storage and transportation temperature	- 40°C to +65°C