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Review Article

A Conceptual Solar Array Design for a Geostationary: Mini-communications Satellite for Algeria

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Abstract

Photovoltaic solar arrays are the principal means of converting solar energy to electrical energy for satellites. However, array configurations depend on the spacecraft stabilization concept, orbit parameters and power requirements.

The preliminary design of a geostationary communication satellite solar array is introduced in this work. Several of the considerations in the design of solar arrays are discussed: radiation effects on solar cells, substrates, selection of array voltage, analysis of shadows and overall performance.

Based on the power requirements for end of life EOL, power margin requirements and performance requirements, the number of panels, strings architecture and solar cells used on the solar array will be investigated.

Keywords: Solar Cell Arrays; Bus Voltage; Radiation Degradation; Solar Cell Efficiency; Conceptual Design; Aluminium Honeycomb Substrate; Temperature; Interconnectors and Wiring

Introduction

The increasing demand for geostationary communications satellites with high subsystems reliability and the increasing complexity of satellite power subsystems that use large area deployable solar panels and appropriate electronics modules, with increasing embedded satellite payloads, are needs that make the design even more complicated.

One of the most important requirements in each space mission is the design of a power system to provide uninterruptible energy with desired quality and quantity. The power subsystem must satisfy the satellite's demand for energy during the entire mission/lifetime.

Array sizing is an analytical process, by which the physical and electrical properties are established, that describes a solar array that meets a specific performance (output) requirement at some critical mission time, generally, end of life. The objective of array sizing during a conceptual phase is to establish the required number of solar cells, array area and array mass.

Degradation is an important factor in space missions, which, compared to terrestrial applications, has direct effects on the performance of solar cells. Taking into account the degradation factor, the generated power of a solar array can be estimated more accurately in space missions for end of life.

The production of solar energy necessary to supply large satellites with high power demand is ensured by the deployment of large solar panels with highly reliable mechanisms, also robust distribution and conditioning electronics, and finally a powerful energy storage system.

Conceptual solar array design

The solar array sizing process is, generally, carried out for a number of different candidate combinations of solar cells, solar cells covers and substrates. The process is repeated again during all design phases to reach satisfactory mission design requirements in the determination of the number of solar cells connected in series/parallel.

Sizing procedure

- Select solar array components intended for the design of the solar array (solar cells types, solar cells covers and substrates),
- Determine the maximum power output P_C of a single solar cell as outlined in (1):

$P_c = P_0 * S' * F_{RAD} * F_{Top} * F_M * F_H * F_{BD} * F_{CONF}$ --- (1)

Where:

Po: Single solar cell output (unglassed, undegraded) at normal incidence at AM0 solar constant intensity and at ambient temperature 25°C,

S': Solar intensity (including effects of cover glass transmission degradation, solar distance and non-normal incidence),

F_{RAD}: Solar cell radiation degradation factor where P_D =% orbital solar cell degradation,

F_{TOP}: Operating temperature degradation factor where $F_{TOP} = P_{mo\text{-}TOP}/P_{mpo,}$

F_M: Assembly and degradation factor. For most array designs F_M will range from 0.95 to 1.00,

F_{SH}: Shadowing factor. For unshadowing arrays F_{SH} = 1.00,

F_{BD}: blocking diode and wiring loss factor prorated for a single cell and defined as in (2):

$F_{BD} = \frac{V_D+V_W}{V_D+V_W+V_B}$ -------- (2)

Where:

V_D: Diode voltage drop,

V_W: Wiring voltage drop between the array and the load of the spacecraft,

V_B: Array bus voltage,

F_{CONF}: Configuration factor. For flat plate arrays, F_{CONF} = 1.0. For cylindrical, spinning arrays, $F_{CONF} = 1/\pi$

Note: If the blocking diodes and wiring losses are not defined () = 1.4V is a good figure for silicon diodes on arrays below 1Kw size. For higher power levels) = 2.4V.

Determine solar cell array characteristics as follows:

Number of solar cells can be found (3):

$N = P_A/P_C$--------- (3)

Where:

N: Number of solar cells,

P_A: Required output power (W),

P_C: Single cell power output (W).

Substrate area can be expressed as in (4):

$A_S = A_C*N/F_P$ ----(4)

Where:

N: Total number of solar cells on an array,

A_C: Overall area of a solar cell (m^2),

As: Substrate area (m^2).

F_P: Packing factor.

Substrate mass is expressed as in (5):

$M = m*A_S$ -----------(5)

Where

m: Mass per unit area (kg/m^2),

A_S: Substrate area (m^2).

Packing factor is defined as in (4):

Note: Practical packing factors range from around 0.85 to 0.92. For flat solar arrays. Other types of solar arrays (conical, trapezoidal) may exhibit packing factors around 0.5 to 0.6, table 1.

Packing density

It is defined as the number of solar cells of a given size which can be fitted into a given substrate area. The packing density N' is related to the packing factor as in (6):

N' = As*Fp/Ac------------ (6)

Fp	Number of solar cells	
	2*2 cm^2	2*4 cm^2
0.8	2000	1000
0.9	2250	1125
1.0	2500	1250

Table 1: Packing densities for 2*2 cm^2 and 2*4 cm^2 solar cells.

Table 1 summarises values of packing densities for different values of packing factors.

Solar array electrical design

The electrical design activities can be summarised as follows:

- Accurate determination of the number of solar cells connected in series/parallel to form solar cells subassemblies or strings,
- Cover aluminium substrate with kapton for insulation,
- Lay down of solar cells subassemblies or strings on the aluminium substrate,
- Wiring of the solar cells circuits with considerations given to electromagnetic and electrostatic design requirements.

Series connection of solar cells

Depending on the power requirements for a spacecraft mission, a sufficient number of solar cells must be electrically connected in series to provide the bus voltage add to that any voltage drop in the blocking diodes and in the wiring. The number of solar cells in series, Ns, can be found from (7):

Ns = $(V_B+V_D+V_W)$/Vmp---------- (7)

Where:

V_B: Battery bus voltage,

V_D: Array-blocking diode,

V_W: Total wiring voltage drop between solar cells and the spacecraft load,

Vmp: Solar Cell end of life output voltage at the array maximum power point and operating temperature.

Parallel connection of solar cells

Assuming a set of Ns solar cells all connected in series to form a string of cells. The total solar cells array consists of Np strings connected in parallel to provide the required load current. Np can be found as in (8):

Np = I_L/Impav---------(8)

Where:

I_L: Load current,

Impav: Average maximum power point current output of all Np solar cells after glassing and degradation.

Solar cell array layout

The electrical array design layout activity aims to:

- Subdivide the array electrically into series strings of parallel connected solar cells,
- Arrange these strings on the available substrate area to achieve the highest possible power output per unit area,
- Define paths for the electrical conductors (harness) with different colours from the solar cells circuits to the solar panel terminals.
- Include blocking (isolation) and shadowing (bypass) diodes.

Dimensional analysis for panel layout

There are functional gaps between adjacent solar cells, as shown in figure 1, to be taken into account during layout and are determined by:

- Solar cells dimensions including (cover glass),
- Thermal expansion of aluminium substrate,
- Temperature range (-50° to +50°C),
- Interconnectors expansion coefficients
- Manufacturing process limitations.

Note

In practice, a minimum gap of 0.1 mm is adopted between adjacent solar cells in the parallel-connected group of cells. 0.5 mm between cells in the electrical series directions and 0.5 to 1.0 mm between adjacent electrical strings.

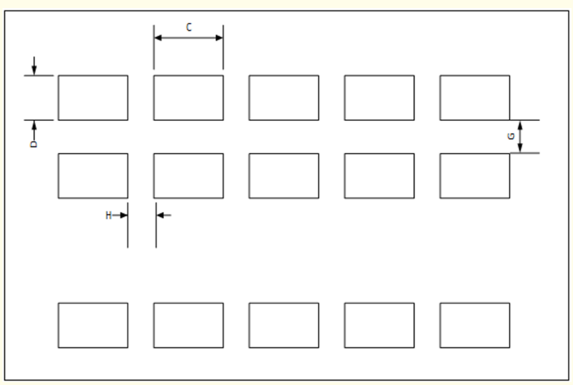

Figure 1: Solar cell array layout dimensions.

Where:
C: Solar cell width,
H: Solar cell gap - parallel,
D: Solar cell length,
G: Solar cell gap – series.

Solar array detailed design

The solar array detailed design phase is concerned with developing a spacecraft solar array concept for an envisioned mission. Generally, this part of the design phase is carried out as a separate study prior to the start of the project just to overcome all difficulties arising during the analysis. Also, parameters as indicated in section 4.1 (above) must be taken into account during the analysis and solar array lay down.

Subsystem requirements

From a system's point of view, the following preliminary requirements are assumed as the baseline performance for the solar arrays design:

- Mission - communications,
- Orbit - geosynchronous equatorial,
- Power requirements - 2000 Watts at EOL,
- Spacecraft lifetime - 10 years,
- Bus voltage - 50VDC,
- Satellite mass - 1000kgs,
- Array configuration - flat arrays.

For simplicity, let the baseline conceptual array be a fully oriented flat panel. For the design, we selected the following solar cells, cover glass and substrate:

- The solar cells, used in this study, were manufactured from ENE (Belgium) in the size 2*4 cm^2 using the MOCVD process and fully evaporated metals. The solar cells used single junction GaAs/Ge cells, mounted on an aluminium face sheet and an aluminium honeycomb substrate. The cells provide on average 19.8% conversion efficiency at 25°C.
- After interconnector ultrasonic welding, the 150µm thick cover glasses are attached using DC 93-500.
- The solar panels used aluminium substrates made of a 20mm aluminium core honeycomb with 0.5mm aluminium face skins front and rear. The front of the panels has an insulating layer of 75µm Kapton.

Note

The above selection was made regarding solar cells manufacturer's data available. Any other selection could have been made.

The solar cells are arranged on the aluminium panel in columns of 60 solar cells in series to allow for a bus voltage of 50 VDC. This convenient arrangement allowed the entire terminal wiring (redundant positive and negative) for each string to be located at one end of the panel. The 2*4 cm^2 GaAs/Ge solar cells were glassed and welded into solar cell assemblies (SCAs).

Cells selection

From a mission analysis point of view, super single junction SSJ GaAs/Ge cells were chosen as a high performance method of primary power generation. The following parameters were assumed as the baseline performance for the cells in the design, as outlined in table 2.

Solar cells parameters	Manufacturer's data
Isc (short circuit current)	254.6 mA
Voc (open circuit voltage)	1.022 V
Vpmax (max power point voltage)	0.9 V
Ipmax (max power point current)	0.238 A
Pmax (max power)	0.214 W
FF (fill factor)	0.82
Eff (solar cell efficiency)	19.8%

Table 2: Solar cells parameters.

The interconnectors used of gold plated molybdenum foil construction. An advantage of the gold plated molybdenum material is the complete resistance to atomic oxygen attack, which means that these are suitable for all space environments without additional protection. Molybdenum also provides mechanical strength and a good thermal expansion match to GaAs and the plating gives a ready to weld surface.

After interconnector welding, the 150 μm cover glasses are attached using DC 93-500. After an in house inspection and electrical testing, the bare cells are turned into solar cells assemblies using ultrasonic welding. The solar cells strings are then integrated onto the solar panel substrate using screen-printed CV-2566 adhesive.

Panel layout

The power system envisaged operates at a constant 50 VDC which given the above assumptions requires a minimum string length of 60 cells in order that we are at the maximum power point at the end of life EOL.

The solar cells were manufactured in the size 2*4 cm^2, using the MOCVD process and fully evaporated metals. The grids on the cells front side are obtained by evaporation through a nickel evaporation mask.

- Both the front and rear contacts are made by a silver layer at least 5 μm thick on top of which an additional 200nm gold layer was evaporated for improved welding on gold plated Molybdenum interconnects.
- Distance between the welding pads and the cell edge is 0.3mm.
- Contact length is 7.8 mm.
- Separation between the contacts is 13.725 mm.

Determine the maximum power output P_C of a single solar cell from as outlined in (1):

$P_c = P_0 * S' * F_{RAD} * F_{Top} * F_M * F_H * F_{BD} * F_{CONF}$ --- (1)

Where:

P_C: maximum power output of a single a single solar cell,

P_o: from manufacturer's data,Po = 0.9V*0.238A = 0.2142W.

Po = 0.2142W

The corresponding average solar cell efficiency:

$\eta = 0.2142/(8*10^{-4}*1358) = 19.7\%$,

$\eta = 19.7\%$

S' = 0.87 solar constant (reference solar cell array design handbook, vol.1, Oct. 1976).

F_{RAD} = 1 - PD (PD = 25%) in synchronous equatorial orbit for 10 years mission lifetime.

$F_{RAD} = 0.75$

F_{TOP} = 0.88 (reference solar cell array design handbook, vol.1, Oct. 1976).

F_M = 0.95 (assuming a 5% design margin for assembly and degradation factors).

F_{SH} = 1.00 (assuming no shadowing to be considered)

F_{BD} = (assuming a flat oriented array. Also, assume a voltage drop V_D = 0.8V and V_W = 1.6V).

For a 50VDC bus voltage:

F_{BD} = 1- (0.8*1.6)/(50*0.8*1.6) = 1 - 0.02 = 0.98

F_{BD} = 0.98

F_{CONF} = for a flat panel = 1.00

F_{CONF} = 1.00

We now can express the value of P_C. For a flat oriented array:

P_C = 0.2142*0.87*0.75*0.88*0.95*1.00*0.98*1.00 = 114.40mW

P_C =114.40mW.

The number of solar cells for the flat oriented array can be estimated to: N = 2000W/114.40*10^{-3} =17 482

N = 17 482 solar cells.

Calculating the aluminium substrate area and assuming a packing factor F_P = 0.9.A = (4*2)*10^{-4}*17482/0.9 = 15.54 m^2.

A = 15.54 m^2.

A flat plate array of 15.54 m^2 could be a square of about 3.94 m width for each side, or it could be a two-wing array with 2.79m*2.79m in size.

A comparable case study [1,35,36] concerning the design of a solar array providing 1900W required output power for end of life shows a solar array composed of six (06) panels on the -Y and +Y axis of the satellite. Hence, in our case, the solar arrays should have the same configuration as shown in figure 2. The solar arrays design dimensions are: (2.16*1.2) m^2 for each individual solar panel.

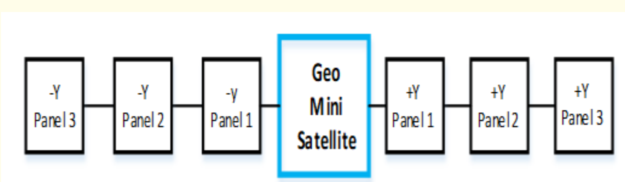

Figure 2: 6 solar arrays locationon the -Y, +Y-axis.

From the manufacturer's data sheet, we have the weight of the bear solar cell: 0.819g/cell, which gives a total mass of the solar cells used in the study as:M_{SC} = 17482*0.819 = 14.317 kgs.

M_{SC} = 14.32 kgs.

Number of solar cells: N = P_A/P_C

PA: required power output,

PC: single cell output power,

N = 17 482 solar cells.

Substrate area

As = Ac*N/F_P

As = 8*10-4*17482/0.9 = 15.54 m^2,

As = 15.54 m^2

Substrate mass

M = mAs

m = 4.3kg/m2 (reference solar cell array design handbook, vol.1, Oct. 1976).

M = 15.54*4.3 + 14.317 = 81.14 kgs.

M = 81.14 kgs

Conclusions

The work shows, in details, the system level design methodology for the solar arrays design for a geo stationary mini satellite with a 2kW satellite power requirements [1-36].

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