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Electrical Design of a Solar Array for LEO Satellites

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Abstract

During daylight, the solar array of low earth orbit satellites harvests electrical power to operate satellites. The power conversion of the solar array is carried out by control of the operation point using the solar array regulator when the solar array faces the sunlight. Thus, the design of the solar array should comply with not only the power requirement of satellite system but also the input voltage requirement of the solar array regulator. In this paper, the design requirements of the solar array for low earth orbit satellites are defined, and the means of satisfying these requirements are described. In addition, the architecture of a multi-distributed interface is suggested to maximize the power harvested from a solar array having high temperature deviation between each panel. The power analysis in this paper shows the optimal number of multi-distributed interfaces with a converter.

Key words: Solar array, LEO satellite, Regulator, Interface

1. Introduction

The solar array of satellites performs a function of converting solar energy into electrical energy. The solar array should produce maximum electricity during daylight in order to secure the electricity used at eclipse because Low Earth Orbit (LEO) satellites are repeatedly exposed to intervals of daylight and eclipse. In order to harvest the maximum power from the solar array, the Solar Array Regulator (SAR) should control the operating point of the solar array. Thus, the design of the solar array should comply with not only the power requirements of the satellite system but also the input voltage requirements of the solar array regulator. As the solar array is placed in space environments without any thermal control or radiation protection; therefore, its electrical characteristics exhibit large variations due to the changes in temperature, sun intensity, and radiation according to the conditions of the space environment [1]. For the proper design of a solar array, an analysis of the conditions in the space environment is necessary.

In this paper, the requirements for the design of the solar array are defined considering the all loss factors at specific a LEO satellite using the developed example. In addition, the power capability of the solar array is analyzed considering the interface between the solar array and the SAR.

2. Definition of Requirements

The requirements for the design of the solar array are divided into two factors. The first comes from the input voltage constrains of the SAR, and the second comes from the power budget for the satellite operation during mission life. The number of cells in series is determined by the first requirement and the number of strings in parallel is determined by the second requirement. Both requirement factors are subject to the harsh exposure conditions of a satellite in the space environment.

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In this chapter, the precondition for these requirements are defined and described.

2.1 Precondition

There are three major factors that affect the characteristics of the solar array. The first factor is an extended temperature range. In the LEO satellite, the satellite is repeatedly placed in eclipse and sunlight by the shadow of the earth, thus the power capability of the solar array varies widely [1-3]. The second factor is radiation. Radiation degrades not only the performance of the solar cell but also the loss rate of temperature [4]. The third factor is sun intensity. The current output of the solar cell varies with sun intensity, which differs regarding to the season [1]. These are related to both the orbit and mission life of the satellite; therefore, the definition of the orbit and mission life is necessary for proper design of the solar array. The precondition of this study is here:

- End of Life : 5 years
- Orbit : Sun synchronous, Dusk-dawn
- Altitude : Mean 505 Km
- Nodal period : 94.85 Minutes

2.2 Requirements for a SAR

Owing to increasing demands of satellite usage, satellites are often equipped with multiple payloads. In this case, the power to fulfill the mission life of the satellite is accordingly being increased. In this trend, the bus voltage design tends to increase for minimizing both power loss and the mass of the wiring harness. This higher voltage can be realized by increasing the pile cells of batteries [2].

In this study, the solar array regulator is placed between the solar array and the bus including the battery, as shown in fig 1. The bus in this design has an unregulated bus voltage (69.0 V ~ 98.4 V) that is about twice the level of a previous satellite program [5]. The level of voltage comes from the requirements of payload input voltage and the need of power loss reduction. For a buck topology, as used in a previous program [5], the voltage of solar array must be higher than the bus voltage. This design, however, has two disadvantages. One is the difficulty of selecting electrical parts for the converter design. The other is the increase of loss when the string has fault. Thus, the buck-boost topology is employed to meet system requirements while not increasing the solar array voltage more than necessary.

The buck-boost converter of this project requires two voltage levels. One is the minimum voltage (60 V) for the maximum power point voltage of solar array, and the other is the maximum voltage (150 V) for the open connect voltage of the solar array. The minimum voltage is required to be at the near output voltage of the solar array to maximize the efficiency of the solar array regulator. The system efficiency is enhanced when at a lower voltage differential between the input and output of the solar array regulator. The maximum voltage level is limited by the availability of space related electronic components: the maximum voltage of capacitors for space application is approximately 150 V.

2.3 Requirements for System Power

In this study, the satellite system requires 2,400 W of power for two missions during 1 day. The system power requirement includes the margin of power. The power requirement that can charge the battery within 1 day orbit (about 15 times per 1 day) at worst condition is the average power during daylight.

3. Design and Analysis of a Solar Array

3.1 Power calculation of a solar array

The method of power calculation is based on the following formula, which describes the electrical characteristics of the solar cell [3]:

$$I = I_{sc} - I_0 \cdot \left(e^{\frac{V + I \cdot R_S}{V_T}} - 1 \right) \tag{1}$$

The included solar cell specific parameter I_O, V_T and R_S can be expressed as a function of the measurable electrical data of the solar cell as follows [3]:

$$V_T = V_{mp} \frac{\left(I_{sc} - I_{mp} \right)}{I_{mp}} \tag{2}$$

$$I_0 = \frac{I_{sc}}{e^{\frac{V_{oc}}{V_T}} - 1} \tag{3}$$

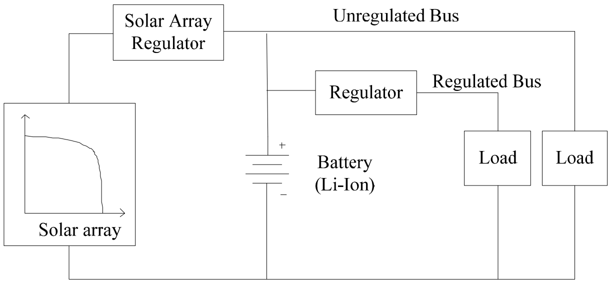


Fig. 1. EPS configuration in LEO satellites

$$R_s = \frac{V_T}{I_{mp}} \cdot \frac{ln\left(I_{sc} - I_{mp}\right)}{I_0} - \frac{V_T}{I_{mp}} \tag{4}$$

with:

I_{sc}	short circuit current
I_{mp}	current at maximum power point
V_{mp}	voltage at maximum power point
V_{oc}	open circuit voltage

The radiation dependence of the solar cell is taken into account by applying the relevant remaining factors R on the solar cell specific data (Table 2) [3]:

$$I_{sc}\left(\Phi\right) = R\left(I_{sc}\right) \cdot I_{sc} \tag{5}$$

$$I_{mp}\left(\Phi\right) = R\left(I_{mp}\right) \cdot I_{mp} \tag{6}$$

$$V_{oc}\left(\Phi\right) = R\left(V_{oc}\right) \cdot V_{oc} \tag{7}$$

$$V_{mp}\left(\Phi\right) = R\left(V_{mp}\right) \cdot V_{mp} \tag{8}$$

with Φ equivalent 1 MeV electron flus

The V-I characteristic and the solar cell specific electrical data are temperature dependent. They can be described as a function of temperature and the measured temperature coefficients (Table 3) as follows [3]:

$$I_{sc}\left(T\right) = I_{sc}\left(T_0\right) + \frac{dI_{sc}}{dT} \cdot \Delta T \tag{9}$$

$$I_{mp}\left(T\right) = I_{mp}\left(T_0\right) + \frac{dI_{mp}}{dT} \cdot \Delta T \tag{10}$$

$$V_{oc}\left(T\right) = V_{oc}\left(T_0\right) + \frac{dV_{oc}}{dT} \cdot \Delta T \tag{11}$$

$$V_{mp}\left(T\right) = V_{mp}\left(T_0\right) + \frac{dV_{mp}}{dT} \cdot \Delta T \tag{12}$$

with : $\Delta T = T - T_0$

T is the solar cell temperature and T_0 is the reference temperature.

The strings of solar array should be connected to a converter via blocking diodes in series to prevent the reverse bias from other strings or bus when some of the string is in shadow. However, the blocking diode also has a forward voltage drop as current is flowing. For the precise power calculation, the following worst case equation is applied:

$$V_{diode} = 0.03 \cdot \ln\left(\frac{n \cdot I_{string}}{10^{-13}} + 1\right) \tag{13}$$

with :

V_{diode}	forward voltage drop of blocking diode [V]
I_{string}	string current [A]
n	number of string
0.03	thermal voltage (V_T) of blocking diode(1N5418)
10^{-13}	reverse bias saturation current (I_O) of blocking diode(1N5418)

The solar array comprises of parallel connection of strings which is connected in series of solar cells. The voltage of the solar array is decided by the number of series solar cells, and the power is decided by the number of parallel strings. As a result, the voltage and power have the step level of one solar cell or string.

The power characteristics of a solar array can be calculated by:

$$P = \left[V_{op} \cdot K_{volt} \cdot N_{ser} - \left(I_{op} \cdot K_{cur} \cdot R_{har} + V_{diode}\right)\right] \cdot I_{op} \cdot K_{cur} \cdot N_{par} \tag{14}$$

with:

V_{op}	operation voltage of SCA
I_{op}	operation current of SCA
R_{har}	harness resistance
K_{volt}	loss factor, applicable on voltage
K_{cur}	loss factor, applicable on voltage
N_{ser}	number of series SCA
N_{par}	number of parallel string

3.2 Remaining factors of a solar array

For the proper design of the solar array, the loss factors, which will affect the characteristics of solar cell, should be defined by the solar cell manufacturer.

In this design, triple junction GaAs solar cells are used. Table 1 lists the major parameters of the selected solar cells [6].

The radiation performance and temperature coefficients of the selected solar cell are shown in Tables 2 and 3, which are supplied by the solar cell manufacturer.

Table 1. Solar cell characteristics [5]

Items	V_{oc}[V]	I_{sc}[A]	V_{mp}[V]	I_{mp}[A]
CIC	2.643	0.476	2.319	0.459
Cell Efficiency	27.5%			
Condition	BOL, 28ºC, AM0			

Table 2. Remaining factors (R) as radiation performance at 1 MeV electron irradiation [6]

Fluence [e/cm^2]	V_{oc}	I_{sc}	V_{mp}	I_{mp}	P_{mp}
5E+13	0.97	1.0	0.97	1.0	0.97
1E+14	0.96	1.0	0.96	1.0	0.96
5E+14	0.92	0.98	0.92	0.96	0.89
1E+15	0.90	0.96	0.90	0.94	0.85
5E+16	0.86	0.90	0.85	0.87	0.74

Table 3. Temperature coefficients as radiation fluence [6]

Fluence [e/cm^2]	V_{oc} [mV /ºC]	I_{sc} [uA/cm^2/ºC]	V_{mp} [mV /ºC]	I_{mp} [uA/cm^2/ºC]
0	-5.48	12.0	-5.93	12.0
5E+13	-5.49	10.0	-5.68	10.0
1E+14	-5.46	11.0	-5.66	11.0
5E+14	-5.61	12.0	-5.92	12.0
1E+15	-5.7	12.0	-6.14	12.0

Table 4. Radiation prediction at EOL

Items	P_{mp}	V_{oc}	I_{sc}
Trapped Protons	9.42E+11	8.76E+12	4.36E+12
Solar Protons	4.88E+13	4.24E+13	2.48E+13
Traped Electons		8.92E+11	
Total	5.96E+13	5.20E+13	3.00E+13

Table 5. Remaining factors applied for power analysis

Loss Items		V_{oc}	I_{sc}	V_{mp}	I_{mp}
Assembly Factors	Assembly	0.995	0.995	0.995	0.995
	Cover Glass	1	0.995	1	0.995
Environmental Factors (EOL)	UV Degradation	1	0.98	1	0.98
	Micrometeorite Damage	1	0.995	1	0.995
	Radiation	0.97	1	0.97	1
	Temperature(EOL)	-5.49 mV /ºC	10.40 uA/cm^2/ºC	-5.68 mV/ ºC	7.80 uA/cm^2/ ºC
	Temperature(BOL)	-5.48 mV /ºC	12.00 uA/cm^2/ºC	-5.93 mV/ ºC	11.00 uA/cm^2/ ºC
Seasonal Factors (Sun Intensity)	Summer Solstice	1	0.967	1	0.967
	Beta 90º	1	1	1	1
Sun Angle		1	0.999	1	0.999
ETC.		Harness Loss for String/Circuit/Panel Voltage Drop of Isolation(Blocking) Diode 2 String Failure			

Table 5 lists the remaining factors for design and analysis. The remaining factors of assembly and cover glass come from the manufacturer of the Solar Cell Assembly (SCA). The remaining factors of temperature, UV, micrometeorite, radiation and sun intensity come from satellite orbit and mission life. The remaining factor of sun angle comes from satellite attitude.

3.3 Selection of series cells

The number of series of solar cells should be selected to comply with the input voltage requirements of the SAR. As previously stated, the maximum voltage of the solar array should not exceed 150 V. This implies that the open circuit voltage of the solar array should not exceed 150 V at the best condition, Begin of Life (BOL). In this orbit, the best condition of the solar array is in summer. Although the sun intensity in winter is stronger than that in summer, the temperature in summer is very low. Fig 2 shows the configuration of the solar array and the temperature distribution at summer solstice. The solar array is configured with six panels and the temperature at the edge of the outer deployed panel is lowest (-26ºC). The lowest temperature includes a temperature tolerance of -11ºC.

The maximum voltage of the peak power point, which is on EOL worst condition, should be above 60 V. In this orbit, the EOL worst condition of the solar array is on beta 90º (vernal and autumnal equinox). Although the sun intensity in summer is weaker than that of beta 90º, the temperature at beta 90º is higher than 16ºC at the hot point of a structure mounted panel. The highest temperature is 116ºC, which includes a temperature tolerance of 11ºC.

The selected number of series cells is 39. Fig 3 shows the V-P curves for compliance with the voltage requirements of the SAR. The voltage of the peak power point is designed to be located near the minimum voltage level of the SAR input voltage range, which has two advantages. One advantage is the power quality of the SAR. The SAR of this project is configured with the series connection of the buck converter, and the boost converter, and each converter has a controller [10]. Therefore, when the mode is changed, the ripple of voltage and current increases because of the transition to a different controller. The low input voltage of the SAR will primarily make the SAR operate in the boost mode. Therefore, the ripple of the voltage and current caused by mode transition is minimized. The second advantage is the loss of margin. Generally, two strings failure are considered for design of satellite solar array. The power loss is less in a string with more series cells, i.e., if two strings failure have occurred during satellite launch.

3.4 Selection of parallel strings

The number of parallel strings should be selected to comply with the system power requirements. The power of the solar array should be exceeded 2,400 W at the EOL worst condition. In this orbit, the worst condition of the solar array is on summer solstice. Although the temperature of beta 90º is higher than that in summer, the solar array always faces the sun in beta 90º. The average power during one orbit is at a minimum on summer solstice.

Excepting the environmental effect, the interface between the solar array and the SAR should be considered. Most solar array of satellites, except for small satellites, are configured with a deployed configuration. In these satellites, deployed configurations, the electrical characteristics of each panel are similar because each panel has a similar temperature. However, the solar array of this project is configured with both deployed panels and structure mounted panels together (Fig. 2) because of the constraint from the satellite structure. The temperatures of structure mounted panels

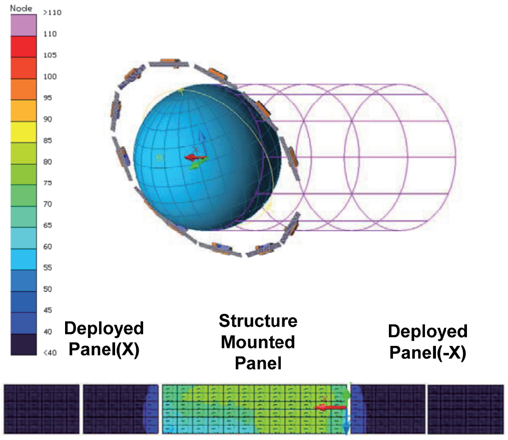


Fig. 2. Temperature distribution at summer solstice (cold case)

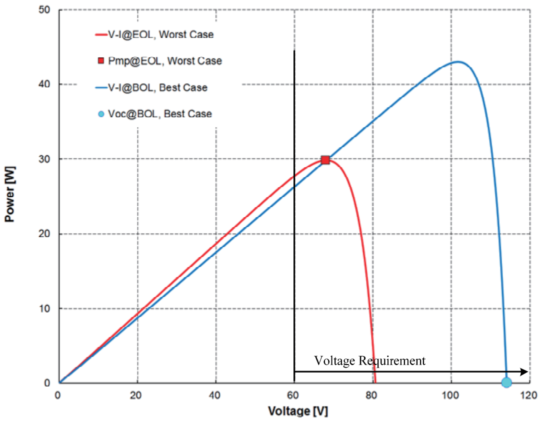


Fig. 3. P-V characteristics of one string at best and worst condition

are higher than that of the deployed panels. Therefore, each panel has its own electrical characteristics. When the panels which are at different temperature, are connected in parallel, the power capability of each panel is decreased because the voltage of peak power controlled by the SAR does not individually satisfy the voltage of peak power for each string. As such, a multi-distributed interface is suggested to harvest the maximum power from each panel and power analysis is carried out for each panel. In this analysis, the temperature of each panel used the highest temperature point, which is equaled out during sunlight. Using the highest temperature is a conservative approach, but using this method to calculate the panel power is reasonable because the deviation across one individual panel is small.

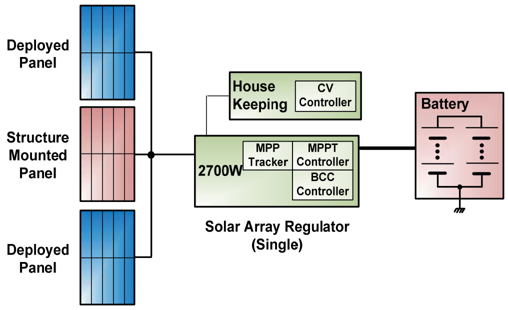
Hence, 72 strings are selected to comply with the system power requirements. Table 6 shows the electrical characteristics of each panel.

Figure 4 shows the three interface methods between solar array and SAR. Fig. 4(a) is a single distributed interface using a high-capacity SAR and (b) are three distributed interfaces using three middle-capacity SAR. Fig. 4(c) shows the six distributed interfaces using six low-capacity SAR.

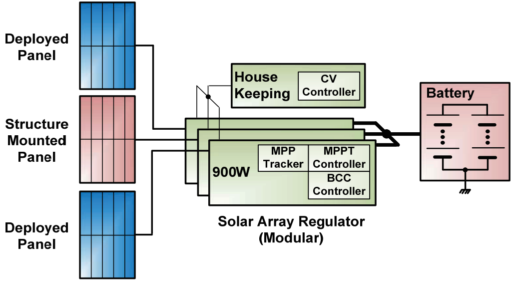
Figure 5 shows the predicted power capacity at each interface. The P-V curves of DP1 and DP2 overlap because of similar temperatures.

The power capability at the single distributed interface is far behind the other configurations because the maximum power tracker of the SAR is unable to convert the peak power of each panel. The power capabilities of the three and six distributed interfaces are similar. This condition due to the temperatures of a pair of panel slightly differing. For the best harvest of electrical power from the solar array, it is best that each string or each cell has its own converter including maximum power tracker, because the temperature and characteristics of strings and cells are different. However, it is highly unrealistic to ignore the cost and weight of the converter and harness associated with increasing electric components.

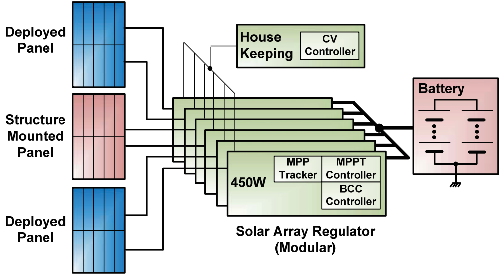
Table 7 shows the power capabilities including 2 string losses. The efficiency of the solar array which has a high temperature deviation can be increased using the multi-distributed interface. In this study, three distributed interfaces can harvest about 2% higher power than a single distributed interface can. However, the six distributed interfaces can only harvest about 0.1% higher than the three distributed interface can. These diminishing returns illustrate



(a) Single distributed interface



(b) Three distributed interface



(c) Six distributed interface

Fig. 4. Interface between the solar array and the SAR

Table 6. Electrical characteristics of each panel

Panels	Temp. [ºC]	No. String	V_{oc} [V]	I_{sc} [A]	V_{mp} [V]	I_{mp} [A]	P_{mp} [W]
DP1-Outer	44.0	12	96.06	5.36	82.78	5.16	426.93
DP1-Inner	48.2	12	95.16	5.37	81.85	5.17	423.02
SP(X)	66.6	12	91.22	5.44	77.77	5.22	405.63
SP(-X)	83.6	12	87.58	5.50	74.01	5.26	389.22
DP2-Inner	48.4	12	95.12	5.38	81.81	5.17	422.83
DP2-Outer	42.1	12	96.04	5.36	82.76	5.16	426.84

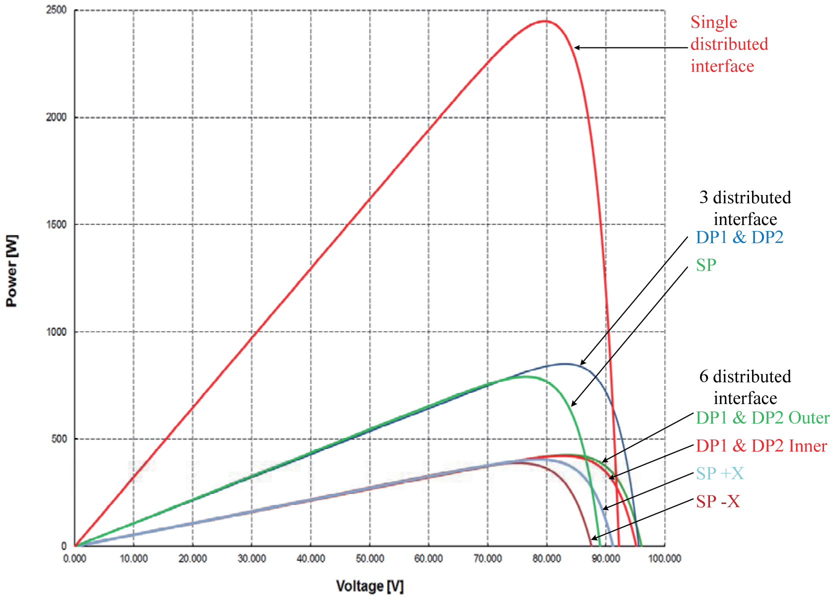


Fig. 5. Voltage-Power curves of each panel

Table 7. Power capacity of solar array

Interface	P_{mp}[W]-Normal	P_{mp}[W]-2 String Loss
Single distributed	2,449	2,378
Three distributed	2,492	2,421
Six distributed	2,494	2,423
Condition	EOL, Summer Solstice(Hot case)	

that additional interfaces, more than the six distributed shown here, are not needed to increase the power capability.

4. Conclusion

In this paper, we have proposed a method for the design and analysis of the solar array for LEO satellites, the design requirements are defined, and the means of satisfying these requirements are described. In addition, the kind of remaining factors and the quantities caused by loss factors are concretely described. The series cells and parallel strings are selected, taking into account all remaining factors and environmental conditions. Next, the utility of the multi-distributed interface is suggested to maximize the power harvested from the solar array having a high temperature deviation between each panel. The power analysis is carried out on single, three, and six distributed interfaces. Finally, the analysis results show not only the compliance with SAR requirements and system power requirement but also the need of the multi-distributed interface in the case that each panel has high temperature deviation.

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