2nd International Conference on Current Research Trends in Engineering and Technology
© 2018 IJSRSET | Volume 4 | Issue 5 | Print ISSN: 2395-1990 | Online ISSN : 2394-4099
Themed Section: Engineering and Technology

Investigation of Primary Arc behaviour at Spacecraft Solar panel using Circuit Model

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ABSTRACT

This article presents the single string circuit analysis of a high voltage solar array used in spacecraft for two standard modes namely decoupled mode and limited current mode of ground test ESD experiment. A linear circuit model is used to characterize the cover glass, solar cell interconnect, wiring by an LCR circuit and the primary arc by an equivalent LR circuit. This work discusses the effect of bias voltage and body capacitance in terms of discharge current profile, charge loss, primary arc current amplitude and duration.
Keywords: High Voltage Solar Array, Decoupled mode, Limited current mode

I. INTRODUCTION

Size and power of recent spacecrafts, especially GEO (Geosynchronous Orbit) satellites, increased intensely to the level of more than 10kW or even to 20kW [1]. When a spacecraft encounters energetic electrons in orbit, such as substorm or auroa, it may have a different potential from the surrounding space plasma, which is so-called spacecraft charging. Once the solar panel surface is charged and the potential difference between the surface insulator and conductor go beyond a certain level, ESD may occur [2]. An ESD on the solar panel gives various detrimental effects on the spacecraft power system. Once an ESD occurs, a blow-off current flows first, which is the release of charge stored in the capacitance between the spacecraft chassis and the surrounding plasma. A flashover current follows the blow-off. The flashover is the release of charge stored in the capacitance between the spacecraft surface insulator and the spacecraft chassis [2]. The flashover current may induce a large current and voltage that may damage spacecraft electronics.

The concentration of the arc current to a small spot on a solar cell may damage the solar cell. There are various types of capacitance existing between ambient plasma and the different components of the solar array. It has been observed that at higher bus voltages the accumulated charge gets a leak off which is termed as a primary arc or minor arc [3]. In the worst case, the ESD may be coupled with the current generated by the power system and may destroy a part of or even entire solar array string circuits, which is often called secondary arc or major arc[3]. The minor arc induces less damage to the solar panels compares to major arc but it is observed that the minor arc is the cause of major arc.

Spacecraft charging has become a serious threat to its operation. In 1991, MARECS-A spacecraft was damaged due to electrostatic discharge[4]. Anik-E1, E2, Geo-stationary satellites had a system failure due to the electrostatic discharge [5]. Recently, in 2010, Galaxy 15; and in 2011, Echostar had a loss of mission due to variations in potential on surfaces of a satellite. About 12,640 million USD have been claimed for the spacecraft anomalies and failures from 1994-2013[6]. 'Chandra X-ray Observatory star tracker anomalies' in spring 2010 was caused by the outer radiation belt of the energetic electron[6]. Recently, various institutes including Japan Aerospace Exploration Agency (JAXA) concluded the power system failure in ADEOS-II as a result of arcing; compelling JAXA to increase its efforts to prevent electrostatic discharge[7,8]. Moreover, It is reported in the literature [9, 10] that the effect of ESD is observed around 33% on solar panels.

In the past, numerous experimental and theoretical works were done in the modeling and analysis of ESD shaped at the solar array. R. T. Robiscoe and Zhifeng Sui [11] constructed a simple RLC circuit model for an arc. The prioriestimates of R, L, and C values are in good agreement with observation, for both typical magnitudes and areal scaling. They also analyzed the effect on the areal scaling of allowing the arc resistance R to "switch" during the growth of the arc, from a small value typical of the arc plasma to a large value characteristic of the dielectric surface. Daniel E. Hastings et.al [12] introduced theory for arcing on high voltage solar arrays that ascribe the arcing to electric field runaway at the interface of the plasma, conductor, and solar cell dielectric. The equivalent circuit of solar array describes for one string of six solar cell. The theory was compared in detail with the experiment and shown a reasonable elucidation for the data. The combined theory and ground experiments were then used to develop predictions for the SFU flight. Mengu Cho et.al [1] presented an equivalent circuit of solar array string by a combination of simple RLC circuit, suitable for simulation via an electronic circuit simulation software (SPICE). The circuit is verified against the impedance over the wide range up to several megahertz. They formulated an equivalent circuit of solar panel made of nearly 1000 solar cells based on measurement carried out in the dark condition. Bhoomi K Mehta et. presentedlinear circuit analysis for minor arcs on solar panels and predict the arc current which flows through the arc plasma [13]. In this, the value of the free spacecraft capacitance and the biasing voltage are 30 pF and -500V, respectively. The biasing voltage of -500V represents the critical value for initiating arcing in GEO. However, the value of the spacecraft capacitance is in the rage of 500-1000pF [14] and the saturated potential at the spacecraft surface is of several thousands of kV [15]. Due to this underestimation, the primary arc current amplitude and its duration are not appropriately evaluated.

In this paper, the single string solar cell equivalent circuitrepresents the cover glass, solar cell interconnect, wiring by an RLC circuit and the primary arc by an equivalent RL circuit. The equivalent circuit is analyzed in terms of arc current, individual currents through each branch, and charges of various capacitors. The effect of free space capacitance and biasing voltage (Saturated potential) for the assumed plasma parameters on the discharge current profile, charge loss, primary arc amplitude and its duration are evaluated for decoupled and limited current mode.

II. SOLAR CELL STRING DESCRIPTION

The equivalent circuit of High Voltage Solar Array (HVSA) string for a ground test is given in Figure 1[13]. This equivalent circuit and its analysisare reported in [13].

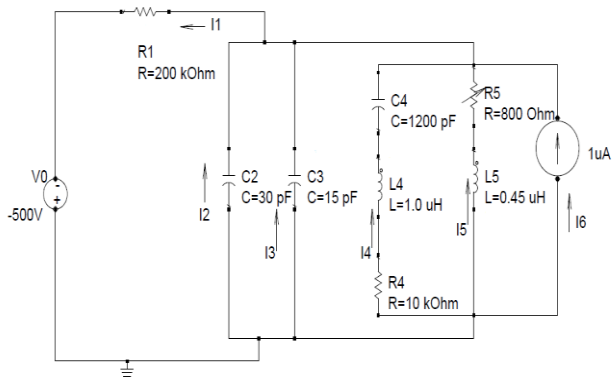


Figure 1. Equivalent circuit of HVSA string

The aim of the present circuit analysis is to predict the arc current which flows through the arc plasma. The V_{32}represent potential difference between the solar cell circuit and the chamber wall,R_1 is inserted in front of the power supply,C_2 represents the additional capacitance,C_3 represents the sum of capacitance of the wires inside the vacuum chamber and solar panel,C_4 represents the total capacitance of cover glasses and adhesives,L_4 represents the inductance of the plasma flux of coverglass front surface,R_4 is the resistance of plasma between chamber wall and coverglass surface,R_5 is the resistance of arc plasma,L_5 is inductance of arc plasma,I_6 is the steady-state current due to ambient ions when there is no arc.

In this analysis decoupling mode and limited current mode simulation operation of the system are used. In a Decoupled mode, the approximately 200kΩ resistor (R_1) is inserted between the power supply and the solar panel coupon. This resistance is adequately large so that in the event of an arc discharge, the power supply would be decoupled from the solar panel coupon to protect the power supply. However, for modeling the arc performance in space, this configuration is impractical since the bias is supplied by the solar panel coupon itself, which cannot be expected to expediently cut off whenever an arc occurs.

Since the power supply is decoupled from the arc in the standard configuration, the arc supplied only by the stored energy in the coverglass capacitances. This limits the arc current and gives an underestimate of the arc-induced damage. Therefore the second mode of operation the limited current mode is used. In this mode, an approximately 1.64kΩ resistor is chosen to allow the passage of current under discharge conditions [13]. In addition, spacecraft capacitance is added to the circuit to simulate the electrical attachment to the larger spacecraft structure. The decoupled mode is useful for understanding the mechanism of the arc time profile.

III. PROBLEM FORMULATION

By applying KVL Equations for the voltage across the first branch can be written as,

$$-V_{32}-V_0=I_1R_1 \tag{1}$$

Similarly, the voltage across the second branch, the third branch, and fourth branch can be written as

$$V_{32}=\frac{Q_2}{C_2} \tag{2}$$

$$V_{32}=\frac{Q_3}{C_3} \tag{3}$$

$$V_{32}=\frac{dI_4}{dt}+I_4R_4+\frac{Q_4}{C_4} \tag{4}$$

The reduced equations given below are providing: (1) the definition of I_4 (2) the evolution of current at the coverglass surface (3) the evolution of the arc current between the interconnector and the plasma and (4) the evolution of the voltage drop between ground and the solar panel.

$$\frac{dQ_4}{dt}=I_4 \tag{5}$$

$$\frac{dI_4}{dt}=\frac{V_{32}}{L_4}-W_{4a}I_4-W_{4b}Q_4 \tag{6}$$

$$\frac{dI_5}{dt}=\frac{V_{32}}{L_5}-W_{5a}I_5 \tag{7}$$

$$\frac{dV_{32}}{dt}=\frac{1}{C_{23}}\left[\frac{-(V_{32}+V_0)}{R_1}-I_4-I_5-I_6\right] \tag{8}$$

In the above equations$W_{4a}=\frac{R_4}{L_4}$,$W_{4b}=\frac{1}{L_4C_4}$,$W_{5a}=\frac{R_5}{L_5}$ and $C_{23}=C_2+C_3$

The system of equation is solved subject to the initial conditions prevailing just before the arc occurs.

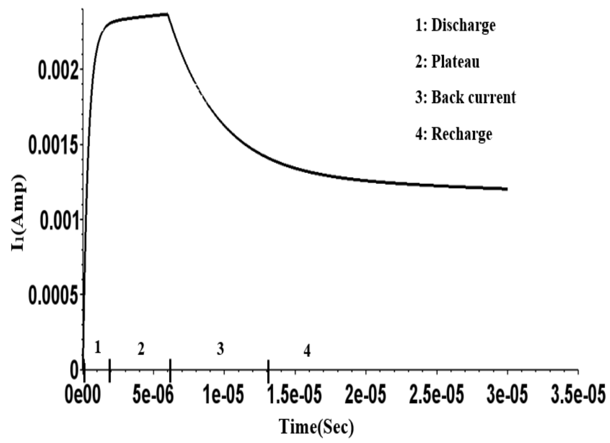
$$Q_4(0)=C_4V_{32}(0)I_4(0)=0,I_5(0)=0,V_{32}(0)=-V_0-I_6R_1$$

Use the fact that $I_1=I_6$ in steady state. The arc is triggered by a sudden drop in the parameter R_5, (the arc-resistance) which is given a value of

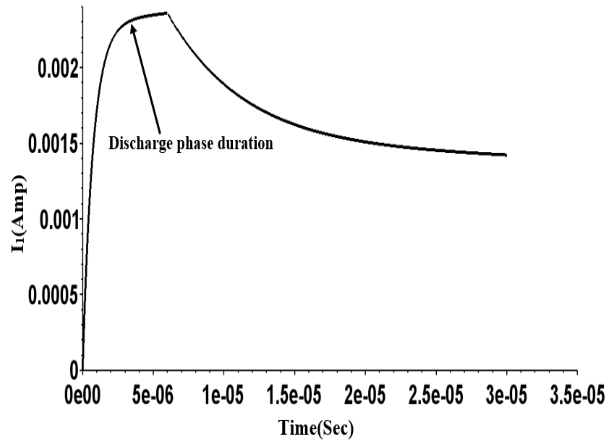
800Ω during the arc. After τ_1 seconds, the arc is assumedto be terminated, by artificially increasing the value of R_5 by a factor of 10^6.

A. Effect of spacecraft Capacitance in Decoupled mode

The structure of the discharge current profile seen due to the effect of spacecraft capacitance for thedecoupled mode is illustrated in Figure 2.



(a)

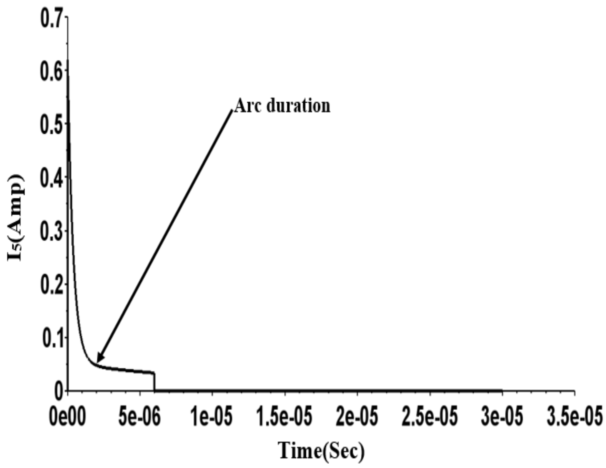


(b)

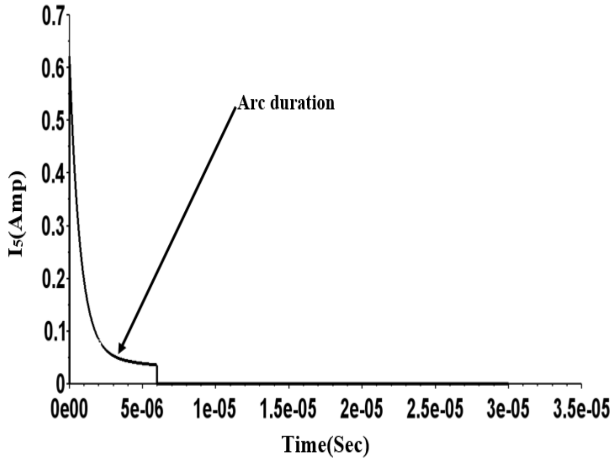
Figure 2. Discharge current profile and spacecraft capacitance effect into the resistance inserted into thefront of the power supply at (a) 500pF(b)1000pF

The discharge current profile for decoupled mode and the limited current mode is divided into four phases: discharge, plateau, back-current, and recharge phases. During the discharge phase just after the initiation of the arcing the external power supply supplies current according to the potential difference between the power supply and the solar cells. After the full discharge of the capacitance, there is plateau phase of length, where the interconnector has potential φ. In the back current phase where a reverse current is notified and the electric potential of the interconnector is found to recover quickly. Finally, the potential of the interconnector recovers gradually to the original value V_0 as the current I_1 discharge phase duration increases with a time constant determined by R_1 and the capacitance of the circuit shown in above Figure 2 (a) & (b).

The spacecraft capacitance value is taken 30pF which does not represent true spacecraft capacitance. Due to the underestimation of the capacitance less amount of blow off current is observed. So, to investigate the true behavior we perform the analysis by taking the value of the spacecraft capacitance 500pF and 1000pFas reported in[14]. The transient profile of arc current shown in Figure3 and charge loss with blow-off current of spacecraft capacitance is shown in Figure4.

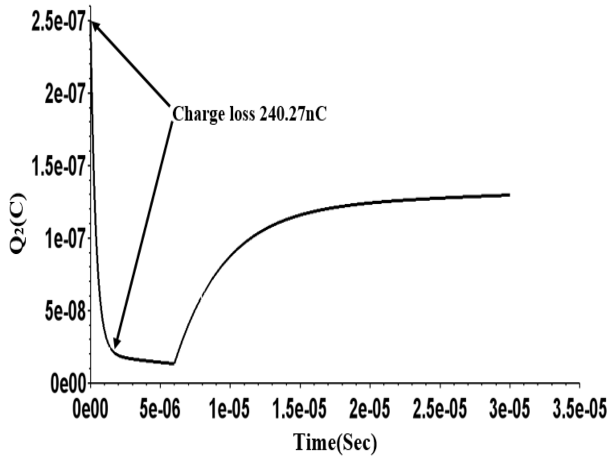


(a)

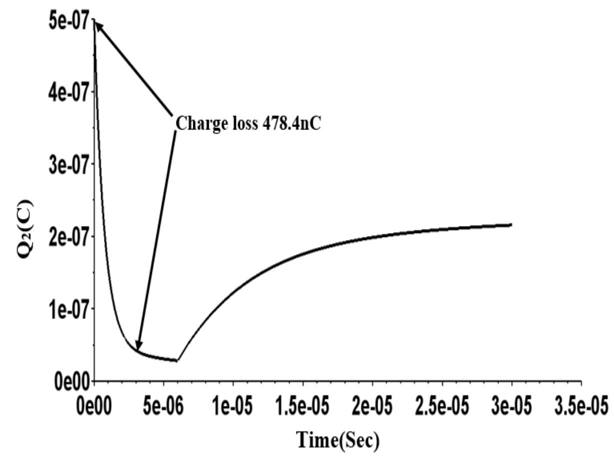


(b)

Figure 3. Spacecraft capacitance effect into the arc current at (a)500pF(b)1000pF



(a)



(b)

Figure 4. Transient response of spacecraft capacitance charge at (a) 500pF (b) 1000pF

There is a significant improvement in the arc current duration I_5 of spacecraft as shown in Figure3(a)&(b).Further, it is noticed from the Figure4(a)&(b) that, as the plateau time decreases the reverse current becomes larger and the potential differential of the interconnector at recharge phase increases also the charge loss and blow-off current of spacecraft increase up-to 478.4nCand 159.4nA,respectively.

B. Effect of saturated potential in Decoupled mode

In the auroral zone and sub-storm environment, satellite potential becomes extremely negative (several kV) because of high-energy electrons flows into the satellite. The analysis by taking the value of the saturated potential -19094V as reported in [15]. The effect of bias voltage on the front resistor discharge current profile shown in Figure5. The arc current is observed in the Figure6.

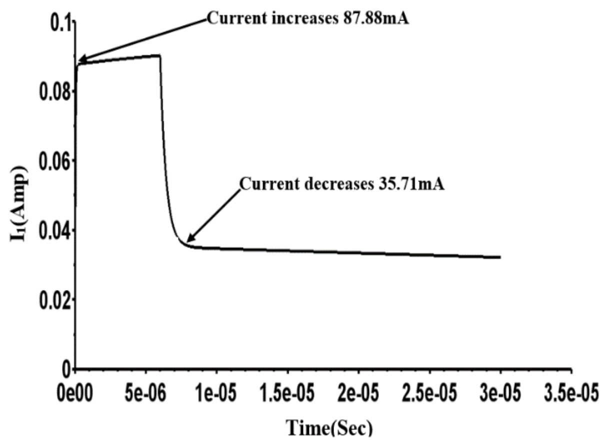


Figure 5. Current profile of front resistance of solar cell string as a function of bias voltage

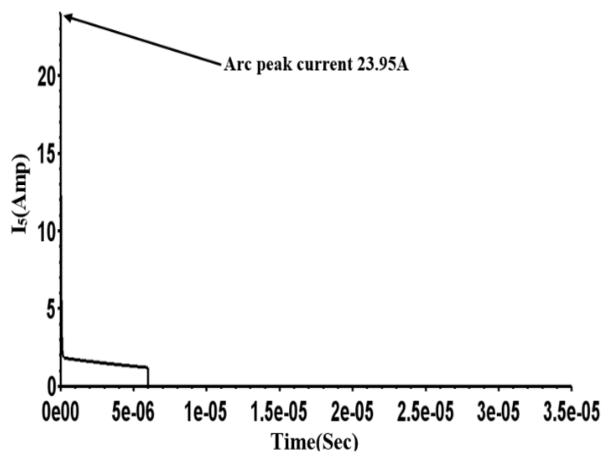


Figure 6. Behavior of arc current as a function of bias voltage

During discharge phase, current I_1increases up to 87.88mA and in the recharge phase the current I_1 decreases up-to 35.71mA that is higher than the decoupled mode that is noticed in Figure5. The arc current at discharge phase increases 23.95A is observed Figure6 means that the damage probability of the solar cells is increased. The transient behaviour of the charge for C_2 (spacecraft capacitance)&C_4(cover glass capacitance) are shown in Figure7 and 8.

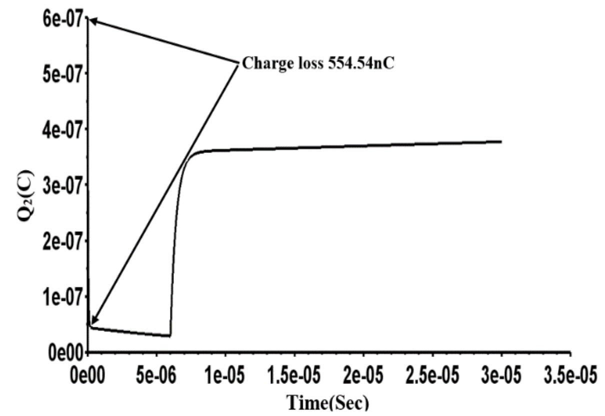


Figure 7. Transient response of spacecraft capacitance's charge as a function of bias voltage

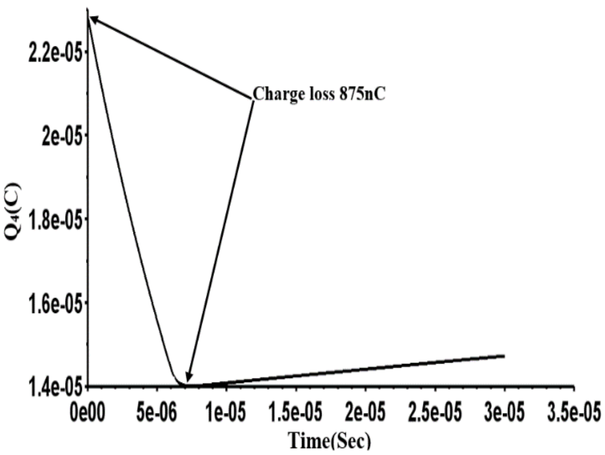


Figure 8. Transient behaviour of cover glass charge as a function of bias voltage

Figure 7&Figure 8shows that during the primary arc, capacitance c_2 (spacecraft capacitance)'s charge and capacitance c_4 (cover glass capacitance)'s charge loss increases up-to 554.54nC and 875nC, respectively compared to reported in [13].

C. The result of limited current mode

In the limited current mode, the front resistor is taken as 1.64kΩ. Figure9 & 10 shows the discharge current profile of the front resistance (R_1) and arc current profile for the limited current mode respectively.

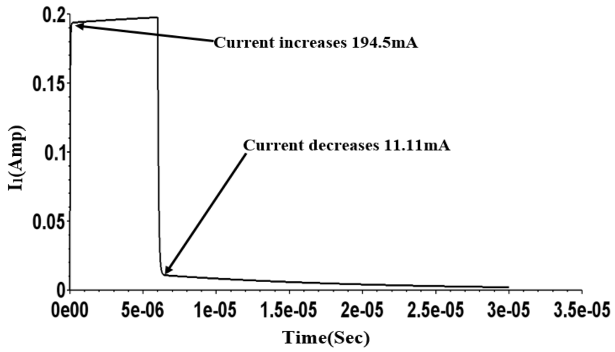


Figure 9. Discharge current profile of resistance inserted in front of the power supply

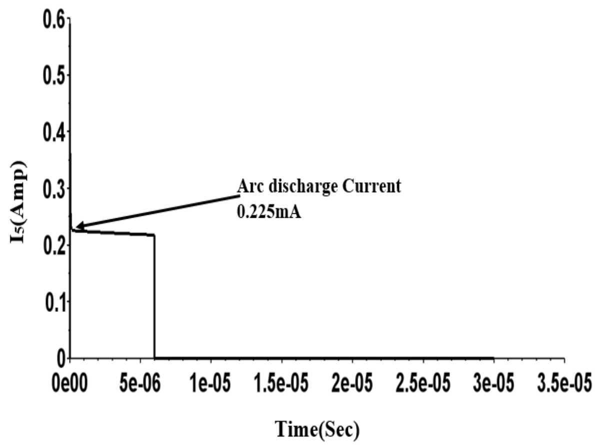


Figure 10. Profile of arc current

The above figures identified the dissimilarity of decoupled mode, here the current $I_1$is the most identical. This is happening because of the power supply in harness capacitance not visible on this scale[12].Also, the reverse current phase discussed earlier with the decoupling mode is not found here. In this mode, there is no back current in I_1, although the interconnector floats positively. This is interpreted as the arc current increases, the power into the arc increases. Therefore the speed of discharge wave increase and more easily wipe out the whole solar array before its termination shown in Figure9.In Figure10 the I_5 at discharge phase the current discharge quickly withhigh-value 0.23A compare to decoupled mode. Because of the power supply coupled to the string circuit, the resistor R_1 affects into charge loss, which is observed for spacecraft capacitance charge $Q_2$and cover glasses chargeQ_4 in Figure11 & 12.

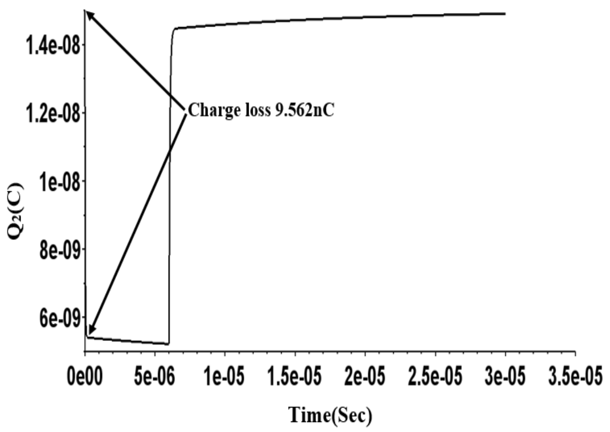


Figure 11. Transient response of spacecraft capacitance charge

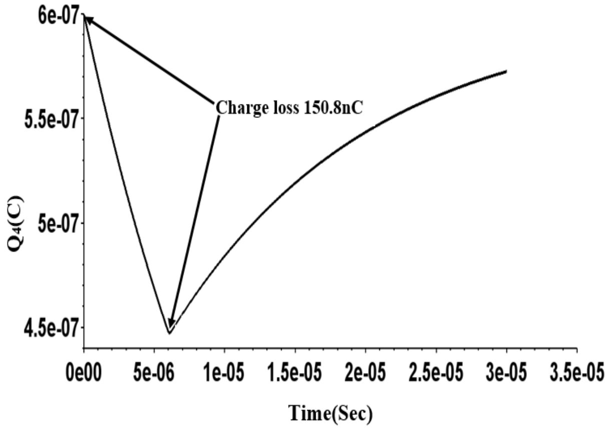
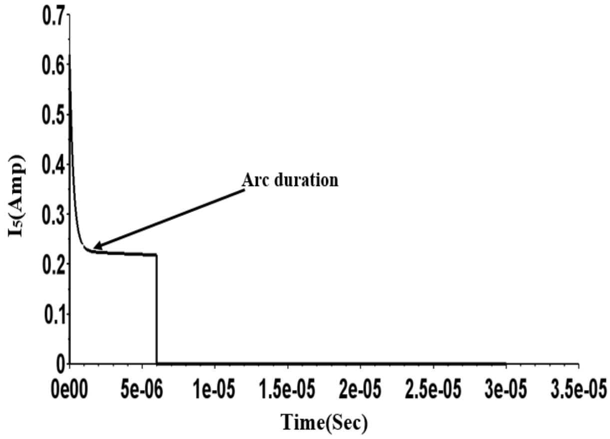


Figure 12. Transient response of cover glasses

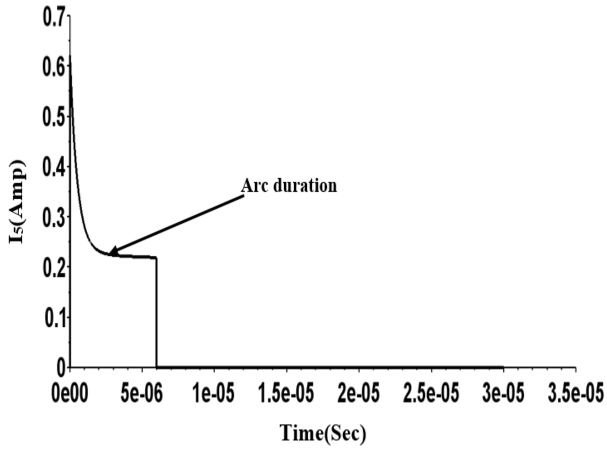
The charge loss during the discharge phase is 9.562nC and shown in Figure11. The charge loss for the capacitance C_4 is 150.8nC shown in Figure12. This result shows that the primary arc can create a path for the current to flow from insulator to the conductor at the triple junction and discharging the capacitance between the spacecraft body and the ambient plasma very quickly. The charge loss is 33% higher than the decoupled mode for capacitance C_2.

D. Effect of spacecraft Capacitance in the limited current mode

As power supply is coupled to the string circuit in the limited current mode, the stored charge of capacitance is discharged very quickly. Because of the spacecraft capacitance increases the plateau time is decreased and discharge phase increases. Figure 13 and 14 show the effect of spacecraft capacitance to the arc current and transient response of spacecraft capacitance charge.

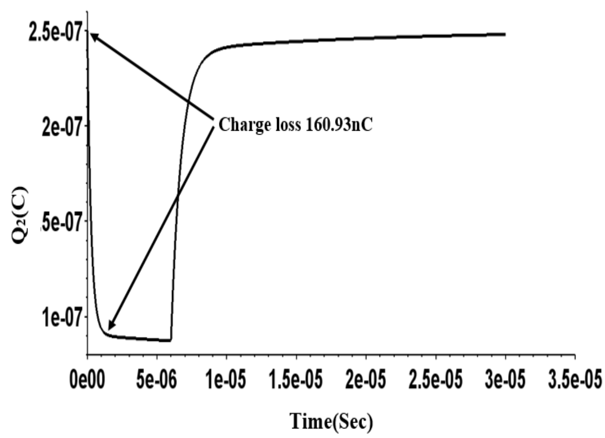


(a)



(b)

Figure 13. Spacecraft capacitance effect into the arc current (a)500pf(b)1000pf



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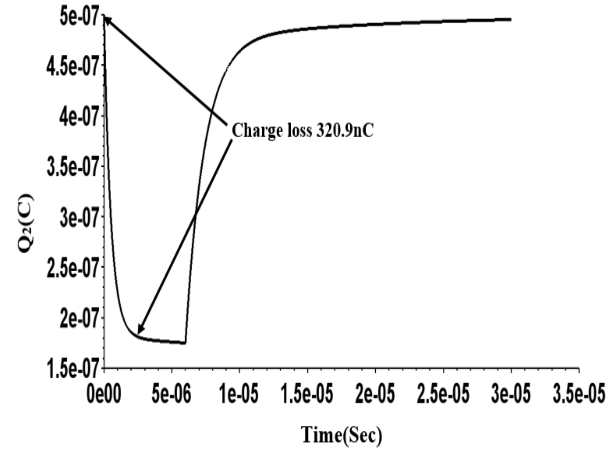

(b)

Figure 14. Transient response of charge for spacecraft capacitance (a) 500pf (b)1000pf

As shown in Figure 13 (a)&(b) by increasing the spacecraft capacitance the arc current duration increases. The charge loss and blow off current also increases up-to 320.9nCand 106.96nAas shown in Figure 14(a)&(b).The blow off current is 16% increased compared to decoupled mode spacecraft capacitance effect.

E. Effect of saturated potential in the limited current mode

In Figure 15 and 16 observed the bias voltage effect into the front resistor discharge current profile and arc current profile correspondingly.

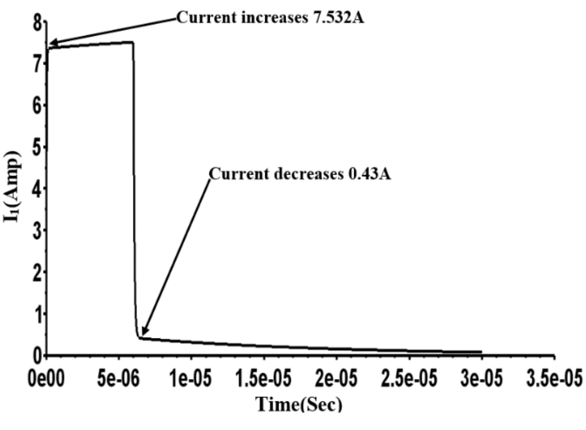

Figure 15. Current profile of front resistance of solar cell string as a function of bias voltage

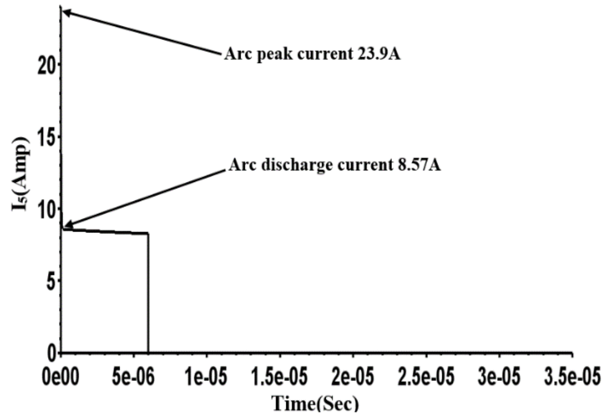

Figure 16. Behavior of arc current as a function of bias voltage

In the discharge phase, current I_1 increases up-to 7.532A. The recharge phase the current I_1 decreases up-to 0.43A means the discharge current and recharge current is higher than the decoupled mode shown in Figure15. In Figure16 the arc current at discharge phase is increased up-to 23.9A and arc current is discharge rapidly with less current means that the damage probability of the solar cells is increasedcompared to decoupling mode.

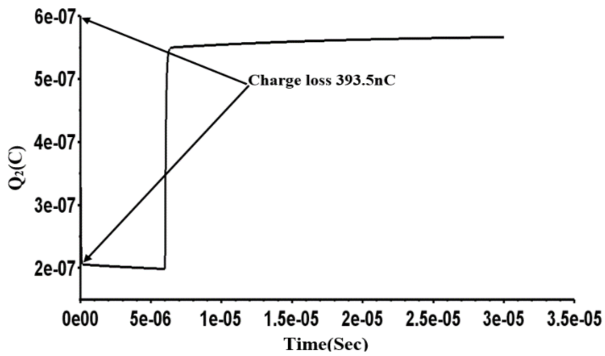

Figure 17. Transient response of spacecraft capacitance's charge as a function of bias voltage

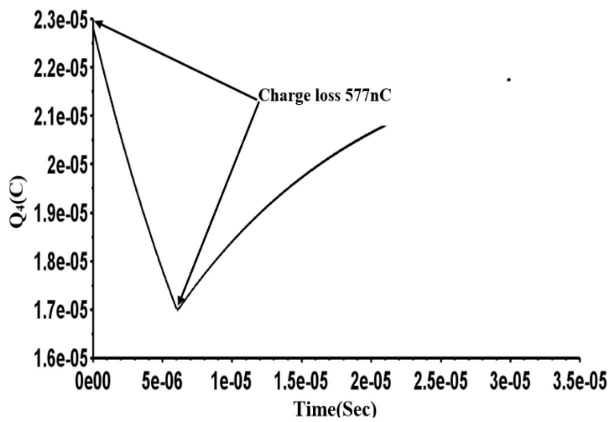

Figure 18. Transient response of cover glass charge as a function of bias voltage

As shown in Figure17&18, the charge loss of the spacecraft capacitance's and cover glass capacitance's charges increased up-to 393.5nC and 577nC compare tolimited current mode result.

IV. CONCLUSION

Following observations are made for the decoupled mode of ground test ESD experiment.

(i)After taking the true estimate of spacecraft capacitance the discharge phase duration, charge loss and blow of current are increased compared to reported literature earlier.

(ii) The increment in the discharge phase reflects the increased probability for the conversion of the primary arc to secondary arc.

(iii) After taking the true estimate of bias voltage, we observed, the discharge phase current I_1 increases and the in the recharge phase, the current I_1 decrease means the external power supply supplies current according to the potential difference between the power supply and solar cells are increased. The arc current at discharge phase is increased up to 23.9A means that the damage probability of the solar cells is increased. Also, from the charge loss, the blow off current for spacecraft capacitance is notified. This can accurately define the damage probability of the solar panel.

(iv)The decoupled mode is useful for understanding the mechanism of the arc time profile.

Following observations are made for the limited current mode of ground test ESD experiment.

(i)From the effect of spacecraft capacitance we observed an increase in the arc duration and charge loss compare to limited current mode reported literature earlier.

(ii)From the effect of saturated potential we observed that the discharge current I_1 is increased in discharge phase anditdischarges very promptly. Also, The arc current discharges less compared to the decouple mode. Because of the discharge current increased the charge loss and blow of current are also increased. From this, we conclude that the test circuit in the limited current mode is a good simulation for the arcing of the solar array, though it cannot simulate the effect of the potential distribution on the actual solar array.

(iii) Compare to the decoupled mode the string capacitance increases charge loss and arc duration in limited current mode. The duration of discharge time increase means the possibility of conversion from primary arc to the secondary arc increases. The secondary arc can damage the solar panel and it leads to spacecraft failure. The saturated potential increases the discharge current and recharge current compared to the decoupled mode.

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