Development of circuit model for arcing on solar panels

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Abstract. The increased requirements of payload capacity of the satellites have resulted in much higher power requirements of the satellites. In order to minimize the energy loss during power transmission due to cable loss, use of high voltage solar panels becomes necessary. When a satellite encounters space plasma it floats negatively with respect to the surrounding space plasma environment. At high voltage, charging and discharging on solar panels causes the power system breakdown.

Once a solar panel surface is charged and potential difference between surface insulator and conductor exceeds certain value, electrostatic discharge (ESD) may occur. This ESD may trigger a secondary arc that can destroy the solar panel circuit. ESD is also called as primary or minor arc and secondary is called major arc. The energy of minor arc is supplied by the charge stored in the coverglass of solar array and is a pulse of typically several 100 ns to several 100 μs duration. The damage caused by minor arc is less compared to major arcs, but it is observed that the minor arc is cause of major arc. Therefore it is important to develop an understanding of minor arc and mitigation techniques. In this paper we present a linear circuit analysis for minor arcs on solar panels.

To study arcing event, a ground experimental facility to simulate space plasma environment has been developed at Facilitation Centre for Industrial Plasma Technologies (Institute for Plasma Research) in collaboration with Indian Space Research Organization’s ISRO Satellite Technology Centre (ISAC). A linear circuit model has been developed to explain the experimental results by representing the coverglass, solar cell interconnect and wiring by an LCR circuit and the primary arc by an equivalent LR circuit. The aim of the circuit analysis is to predict the arc current which flows through the arc plasma. It is established from the model that the current depends on various parameters like potential difference between insulator and conductor, arc resistance, stored charge in the solar cell coverglass and the external capacitor that simulates wire harness. A close correlation between the experiments and circuit model results has been observed.

1. Introduction
As space technology evolves, it is most important to develop ground and flight testing facilities for different space systems. A large number of ground and flight experiments have already been performed to understand the role played by minor and major arcs in solar cell arrays. Negatively
biased, high voltage solar arrays in Low Earth Orbit (LEO) are more prone to arcing. Arcing in solar cells due to spacecraft charging and related effects have been investigated by several authors [1-3]. Electrostatic discharges on the surface of the solar panel are undesirable and prevention of these events is of primary importance to solar panel designers. For this reason and especially due to increased demands of power systems, the development of the arc circuit model has led to a better understanding of basic principles.

Most research and development efforts have been directed to the use of computer methods for evaluation of arc and design of solar panels. This gives motivation to the creation and use of arc model to describe the arc characteristics. The use of the numerical and computational methods is the most affordable approach to the study of arc characteristics, reducing cost and time. Nowadays the fundamental problem when trying to implement existing numerical arc models is to obtain reliable values of the unknown input parameters. There is a need to estimate some of the values from mathematical calculations. However, it is possible to sacrifice much of the details and still have the model which retains sufficient information related to arcing behavior. So simulation of the arc has been done and extrapolated to regimes covering inaccessible experimentation.

The main objective of the work is to develop the linear circuit equations for arc circuit and develop a code based on SCILAB built-in function of ODE solver, which can be used to extract the unknown parameter from the estimated known parameters. The current time characteristics of arc can be found from the simulation.

2. Arcing model development

Normally, the solar cells are connected in a ‘U’ shaped string whose two ends will feed the power-bus (Figure 1). In a given ‘U’, there exist a progressively increasingly negative potential as one move from one coverglass to the next as they are connected in series. In addition to this, the whole spacecraft is typically, say, negative with respect to the plasma. The capacitive coupling between the panel-base and the coverglass will also make them negative with respect to the plasma. Thus, one expects that ions will cause the coverglass to be more positive when compared to interconnect. Survey on experiments on arcing of the negatively biased solar panel coupons with interconnects exposed to the plasma [4] reveals that

1. the rate of arcing increases with ion density,
2. the arcing rate is a sensitive function of the bias potential,
3. before the discharge, the coverglass potential swings towards negative values, which indicates electron build up on the coverglass as a precursor to discharge.

![Figure 1. Solar panel coupon](image-url)
Arcing is thought to be initiated as a result of ion neutralization and associated charge build up on a thin insulating layer over the metallic interconnect. The order of magnitude of the arc rate in some experiments is consistent with the time required for ions attracted from the plasma to build up the electric field in such an insulating layer. Calculations show that negative charge reaching the coverglass prior to arcing is due to the electron emission from interconnects.

If a minor arc occurs at a point between adjacent solar cells, it may short-circuit the two points on the solar array panel with different potentials if certain conditions are met [5]. Once they are short-circuited, a DC power supply can constantly provide energy to the arc plasma and sustain the arc. This arc is called the major arc. An arcing model has been developed to gain an understanding of the current-time characteristics of the arcs as measured in the experiment described by Meng’u Cho in [1]. In this model, we present a linear circuit analysis similar to what has been carried out in the above thesis.

The tests were conducted in a stainless steel chamber of 1m length and 1m diameter at FCIPT, IPR. (Figure 2) The chamber was pumped down with a rotary and diffusion pump with pumping speed of 3000lit/s. The setup is isolated from the pumping system by an electro pneumatic gate valve. The entire chamber is cooled by copper tubes brazed on the outer surface of the chamber. The base pressure and operating pressure are $1.7 \times 10^{-5}$ mbar and $5 \times 10^{-5}$ mbar respectively inside the chamber. Plasma is formed by using filament discharge technique. Plasma densities ranging between $10^5$ - $10^9$ cm$^{-3}$ were successfully obtained with Argon gas. Power supply used for filament heating can be operated at 32V, 30 Amp dc and for the purpose of plasma generation at 300V, 10 Amp dc. Langmuir probes were used to measure the plasma properties (density and temperature). The power for plasma production was varied to obtain various plasma densities. From the probe measurements it can be noted that as the discharge power is reduced the density decreases.

![Figure 2. Experimental set-up at FCIPT](image)

One solar cell string configuration was tested. The strings consist of 5 conventional silicon solar cells mounted on a Kapton film substrate and connected in series (Figure 1). Each had a 150 micrometer coverglass which was coated with an antireflection coating of Magnesium Flouride. The coverglass was glued to the solar cell by adhesive. The electrical circuit used in the experiment is illustrated in (Figure 2 and 3). The test samples were negatively biased. The current was monitored by the current transformer at locations CP1 and CP2 in the figure 3. The plasma density in the chamber was monitored by a Langmuir probe.
In this experiment two modes of operation of the system were used (Figure 3). The first was the decoupling mode. In this mode approximately 200kΩ resistor (R1) was inserted between the power supply and the solar panel coupon. This resistance was sufficiently large so that in the event of an arc discharge, the power supply would be decoupled from the solar panel coupon. This is the standard experimental configuration used in all previous ground based experiments usually adopted to protect the power supply. However, for modelling arc behaviour in space, this experimental configuration is unrealistic since the bias will be supplied by the solar panel coupon itself, which cannot be expected to conveniently cut off whenever an arc occurs. Since the power supply is decoupled from the arc in the standard configuration, the arc can be supplied only by the stored energy in the coverglass capacitances. This limits the arc current and will give an underestimate of the arc induced damage. Therefore a second mode of operation the limited current mode was used. In this mode a high impedance resistor was chosen to allow the passage of current under discharge conditions. In addition, additional capacitance was added to the circuit to simulate the electrical attachment to the larger spacecraft structure.

2.1. Description

A schematic diagram for the experimental setup is shown in figure 3. The equivalent circuit is given in figure 4. The linear circuit analysis using the equivalent circuit has been done. The aim of the present circuit analysis is to predict the arc current which flows through the arc plasma.

In the circuit (figure 4), we denote the potential difference between the solar cell circuit and the chamber wall by \( V_{32} \) which is positive at steady state. The resistance \( R_1 \) is inserted in front of the power supply, \( C_2 \) represents the additional capacitance, \( C_3 \) represents the sum of capacitance of the wires which is inside the vacuum chamber and the solar panel coupon, \( C_4 \) represents the total capacitance of all the cover glasses and adhesives in the sample, \( L_4 \) represents the inductance of the plasma flux due to expansion of the arc plasma to the coverglass front surface, \( R_4 \) is the resistance of plasma between the chamber wall and the coverglass surface, \( R_5 \) is the resistance of arc plasma, \( L_5 \) is inductance of arc plasma and \( I_6 \) is the steady state current due to ambient ions when there is no arc.
With this terminology the equivalent circuit (figure 4) has been solved and the circuit equations have been derived.

2.1.1. Circuit Equations
Equations for the voltage across each branch can be written as,

\[ V_{32} - V_o = I_1 R_1 \]  
\[ V_{32} = \frac{Q_2}{C_2} \]  
\[ V_{32} = \frac{Q_3}{C_3} \]  
\[ V_{32} = L_4 \frac{dI_4}{dt} + I_4 R_4 + \frac{Q_4}{C_4} \]  
\[ V_{32} = L_5 \frac{dI_5}{dt} + I_5 R_5 \]

And \( I_6 \) is the steady state current due to ambient ions when there is no arc.

2.1.2. Reduced Equations for the Scilab Program
Eliminating \( I_1, I_2, I_3, Q_2 \) and \( Q_3 \), we can rewrite the above system of equations in terms of only four unknown quantities which are: \( Q_4, I_4, I_5 \) and \( V_{32} \). The procedure for elimination is given below. From Equation (1) we can eliminate \( I_1 \) in terms of \( V_{32} \),

\[ I_1 = \frac{1}{R_1} [-V_{32} - V_o] \]  

From Equation (2) we can eliminate \( I_2 \) in terms of \( V_{32} \),
\[ I_2 = \frac{dQ_{32}}{dt} = C_2 \frac{dV_{32}}{dt} \]  \hspace{1cm} (7)

Similarly,

\[ I_3 = C_3 \frac{dV_{32}}{dt} \]  \hspace{1cm} (8)

Using the current conservation equation,

\[ I_1 = I_2 + I_3 + I_4 + I_5 + I_6 \]  \hspace{1cm} (9)

Equation (7), (8) and the fact that \( I_6 \) is a known constant, we obtain:

\[ \frac{dV_{32}}{dt} = \frac{I_1 - I_4 - I_5 - I_6}{C_2 + C_3} \]  \hspace{1cm} (10)

The reduced equations given below are: (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.

\[ \frac{dQ_4}{dt} = I_4 \]  \hspace{1cm} (11)

\[ \frac{dI_4}{dt} = \frac{V_{32}}{L_4} - \omega_{4a} I_4 - \omega_{4b} Q_4 \]  \hspace{1cm} (12)

\[ \frac{dI_5}{dt} = \frac{V_{32}}{L_5} - \omega_{5a} I_5 \]  \hspace{1cm} (13)

\[ \frac{dV_{32}}{dt} = \frac{1}{C_{23}} \left[ -(V_{32} + V_0) - I_4 - I_5 - I_6 \right] \]  \hspace{1cm} (14)

In the above equations \( \omega_{4a} = R_4/L_4 \), \( \omega_{4b} = 1/(L_4 C_4) \), \( \omega_{5a} = R_5/L_5 \) and \( C_{23} = C_2 + C_3 \).

2.2. Numerical Method

2.2.1. Inputs

The input parameters required are \( R_1, V_0, C_2, C_3, C_4, R_4, L_4, R_5, L_5, I_6 \).

2.2.2. Initial conditions

The system of equation is solved subject to the initial conditions prevailing just before the arc occurs. 
\[ Q_4(0) = C_4 V_{32}(0), \quad I_4(0) = 0, \quad I_5(0) = 0, \quad V_{32}(0) = -V_0 - I_6 R_1; \]

We have used 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 800 ohms during the arc. After \( \tau_1 \) seconds, the arc is assumed to be terminated, by artificially increasing the value of \( R_5 \) by a factor of 10^6.

Values of parameters used are: \( V_0= -500 \), \( R_1=2.0e5 \), \( C_2=30e-12 \), \( C_3=15e-12 \), \( C_4=1200e-12 \), \( R_4=1.0e4 \), \( L_4=1.0e-6 \), \( L_5=0.45e-6 \), \( I_0=1.0e-6 \).
3. Results
The results for $I_1$ and the current as measured by CP2 ($I_1-I_2$) are shown in the attached figures 5, 6 and 7. Figure 7 shows the zoomed results of current from CP2.

![Figure 5. Discharge current profile for output of CP1.](image1)

![Figure 6. Discharge current profile for output of CP2.](image2)

![Figure 7. Discharge current profile for output of CP2 (Zoomed scale).](image3)

The results for different currents through the circuit, variation of charges and voltages with time is also obtained. The arc current and individual currents through each branch of the circuit is shown in figure 8. The charges and voltages are also shown in figure 9. These results show very good agreement with our experimental results and earlier results of Cho.
4. Conclusions
The one dimensional arcing code from the linear circuit model was introduced and explained in this paper. Development was started as joint work of IPR and ISAC. It was expected that the code will be use in satellite solar panel designing phase by satellite engineers at ISAC. Due to this reason, the code needed accuracy in estimation of the expected output and user friendly environment for users who were not used to numerical simulation. The basic geometric set up and the mathematical formulation were also described. The basic assumptions of the model are briefly discussed. A suitable comparison with the other code was also included for showing accuracy of the code. It is evident that the code is a very good tool to assess arcing threat for materials used in the space applications and has many usages.
in the solar panel designing. By being a one dimensional code, the geometric complications can be
excluded in the computation and can determine result faster with reasonable accuracy is the other
advantage of the code. However this doesn’t mean that the code has no areas for improvement. In
particular the code needs to be validated against tests. Detailed experiments for validation of codes are
in progress.

5. References
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