

Modeling of Solar array and Analyze the Current Transient Response of Shunt Switch Voltage Regulator in Spacecraft Power Conditioning Unit

By

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Abstract— Spacecraft bus voltage is regulated by power conditioning unit using switching shunt voltage regulator having solar array cells as the primary source of power. This source switches between the bus loads and the shunt switch for fine control of spacecraft bus voltage. The effect of solar array cell capacitance [5][6] along with inductance and resistance of the interface wires between solar cells and power conditioning unit[1], generates damped sinusoidal currents superimposed on the short circuit current of solar cell when shunted through switch. The peak current stress on the shunt switch is to be considered in the selection of shunt switch in power conditioning unit. The analysis of current transients of shunt switch in PCU considering actual spacecraft interface wire length by illumination of solar panel (combination of series and parallel solar cells) is difficult with hardware simulation. Software simulation by modeling solar cell is carried out for a single string (one parallel) in Pspice [6]. Since in spacecrafts number of parallels and interface cable length are variable parameters the analysis of current transients of shunt switch is carried out by modeling solar array with the help of solar cell model[6] for the actual spacecraft condition.

Index Terms— Shunt regulator, Shunt switch, Current transients, power conditioning unit

I. INTRODUCTION

In space application, solar energy is the main sources of power apart from nuclear alternatives used for inter planetary missions. With increase in power demand the solar array size is increased with more number of series and parallel cells. In spacecraft bus voltage regulation, several strings of different ratings and shunt switch combination as shown in the input of Fig-1 are paralleled to meet the required load power. At any point of time only one string is switching and others are either ON or OFF depending on the load power requirement in sequential shunt switching regulator [1]. The solar cell capacitance and resistance along with the interface cable line inductance, plays major role in causing current stress on the shunt switch. This current transient study is important in the selection of shunt switch. The effect of solar cell capacitance and cable inductance on the performance of power conditioning unit should be considered in the design. The effect of solar array cell capacitance has been considered in [2]–[4] for the design of shunt power regulators. The stress on the shunt switch due to cell capacitance and

cable inductance effect has not been addressed. The solar array strings and shunt interface is through cables of different length for

each circuits. Considering the wiring on the panel, the current transients are not same for all circuits.

Hardware simulation for all combinations (various string rating and cable length) wired in the spacecraft is a complex approach. This is achieved with software simulation through solar cell modeling by deriving internal cell capacitance and resistance. The equivalent

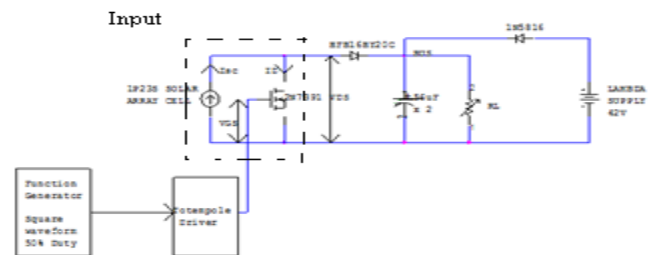


Fig 1. Schematic of shunt switch regulator

circuit of solar cell is as shown in Fig-2. Measurement of solar cell capacitance[5] based on the extra output voltage ripple due to cell capacitance is not an accurate method since cable line inductance has not been considered in the rise time of shunt switch. The first step for cell capacitance derivation is the hardware simulation with a single string and known cable length in the switching path. Many parameters are available in the current transients of shunt switch to create a cell model for software simulation, when compared with the output voltage extra ripple due to rise time of shunt switch.

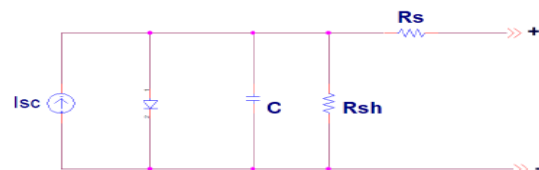


Fig 2. Solar cell equivalent circuit

II. HARDWARE SIMULATION AND ANALYSIS

A solar string with a minimum generation of 0.5A at 42V (23 cells

in series) is interfaced with the shunt circuit with definite cable length. The schematic shown in Fig 1 is for the 42V spacecraft bus voltage. Instead of closed loop operation a fixed 42V supply is used as bus voltage. Shunt switch is driven by function generator to observe the current transients at different switching frequency. String isolation diode is connected between the solar array and the load. Solar cells are illuminated by large area pulsed solar simulator providing sun intensity of 2ms duration. The current and voltage transients are as shown in Fig 3 and Fig 4 for 15 KHz switching.

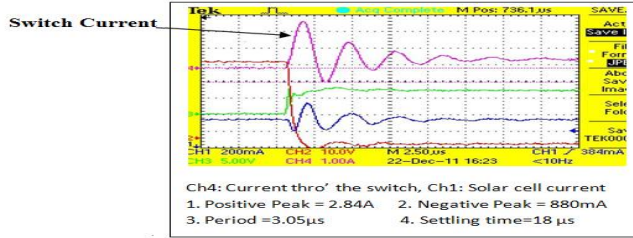


Fig 3. Current transient response

The current through the switch when shunted is a damped sinusoidal with a settling time of 18 μs as shown in Fig 3. Whereas the voltage rise across the switch when open is ringing and not a smooth exponential as shown in Fig 4. However these dynamics are not the actual transients present in the spacecraft since the solar string rating and harness length are different in the setup. Modeling of solar cell is essential to carry out software simulation incorporating solar array circuit connected to shunt switch with required cable length inductance. A single string is considered in the hardware setup for derivation of cell capacitance and resistance to model solar cell.

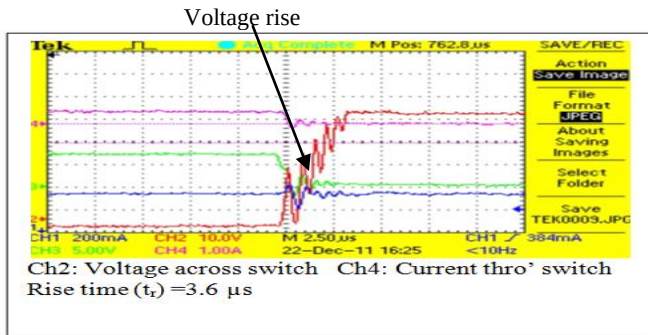


Fig 4. Voltage transient response

A method for finding solar array capacitance is discussed in [5] considering the voltage rise across the switch where cable inductance which also contributes for the voltage rise as shown in Fig 5 is ignored. This method will not give exact cell capacitance value. Hence extra ripple is due to cell capacitance as well as cable inductance in the switching path. Current transient through shunt switch is taken as input for modeling of solar cell since many parameters are available compared to voltage rise in the voltage transient response.

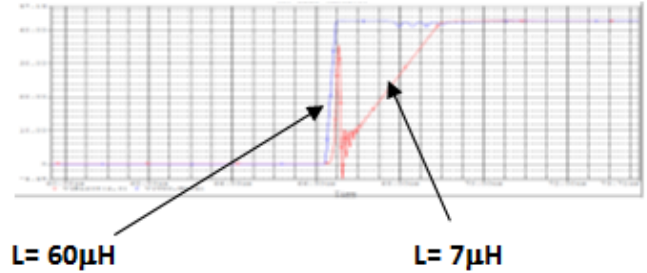


Fig 5. Inductance effect on Voltage rise across switch

The most efficient way of deriving solar cell capacitance, resistance and interface cable inductance is using current transient parameters like first peak current, second peak current and damped frequency. At switching frequency <15 KHz the variation of current parameters are very minimal as shown below for 10 KHz. Hence the above mentioned values for 15KHz is considered for derivation.

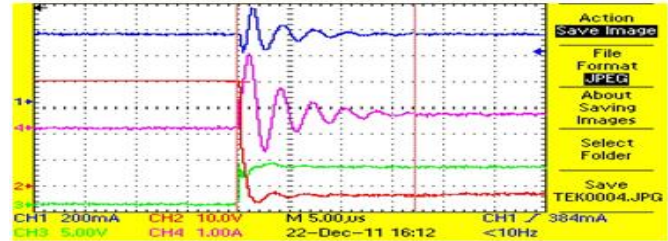


Fig 6. Current response for 10KHz

III. DERIVATION OF R, L, C USING MATHEMATICAL MODEL

When the shunt switch is open, solar cell capacitor starts charging and discharges through the switch when closed. The mathematical model and circuit for this action, including resistance and inductance in the path is as shown in Fig 7.

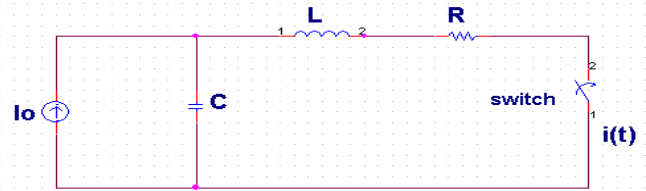


Fig 7. Circuit diagram for model

Equation for the given circuit, when switch is shunted

$$C \frac{dV_c}{dt} + I_o u(t) = I(t) \quad (\text{KCL})$$

$$sCV_c(s) + \frac{I_o}{s} + CV_o = I(s) \quad (1)$$

$$V_c(t) = I(t) R + L \frac{di(t)}{dt} \quad (\text{KVL})$$

$$V_c(s) = I(s) (R + Ls) \quad (2)$$

From (1) and (2)

$$sC I(s) (R + Ls) + \frac{I_o}{s} + CV_o = I(s)$$

$$I(s) = \frac{I_o W_n^2}{s(s^2 + 2\zeta W_n s + W_n^2)} + \frac{k W_n^2}{(s^2 + 2\zeta W_n s + W_n^2)}$$

$$\text{Where, } W_n = \frac{1}{\sqrt{LC}} \quad \text{---- natural frequency,}$$

$$Wd = Wn\sqrt{1 - zi^2} = \sqrt{\frac{1}{LC} - \frac{R^2}{2L}} \quad \text{-- damping frequency}$$

$$Zi = \frac{R}{2} \sqrt{\frac{C}{L}} \quad \text{---- damping factor}$$

$$\text{In time domain } I(t) = I_o \left(1 - \frac{e^{-zi*Wn*t}}{\sqrt{1-zi^2}} \sin[Wd*t + \text{atan}\left(\frac{\sqrt{1-zi^2}}{zi}\right)t \right] + \frac{V_o}{WdL} e^{-zi*Wn*t} * \sin(Wd*t) \quad (3)$$

To derive R, L and C, the steady state current I_o is considered as zero for simplicity.

Equation (3) reduces to

$$I(t) = \frac{V_o}{WdL} e^{-zi*Wn*t} * \sin(Wd*t) \quad \text{---- (4)}$$

Substituting 1st positive peak, 2nd positive peak and damping frequency in eq (4) for different time, the values of R, L and C obtained are----

Total cell capacitance **C= 0.032μF**, Total series resistance **R = 4.05Ω** and Total Inductance **L= 7μh**. ----- (5)

A. INDUCTANCE:

One meter wire will have an inductance of 1.1μH (straight or looped). With varying diameter of 500mil (0.49 inches) to 5mil (0.0049 inches) the change in inductance is from 1μH to 1.8μH only. In the hardware setup two wires (spacecraft cable requirement) of 8 meters length was used between cell positive and negative. Mutual inductance for this setup is given by $M=k\sqrt{L1L2}$ --- (6)

Where k is the coupling coefficient with $0 \leq k \leq 1$, L1 is the inductance of the first wire and L2 is the inductance of the second wire. The measured effective inductance of two parallel wires of 1 mt length when closely placed is 0.9μh. Where $L_{eff} = (L1*L2/(L1+L2))*(1+k)$ --- (7). Hence $k= 0.636$. For 8 mts cable length effective L is given by $4.4*(1+0.636) = 7.19\mu H$ which is closely matching with the value in (5).

B. RESISTANCE:

The total series resistance includes, cell internal impedance, wire resistance and shunt switch ON resistance. The split up of total resistance is as given below

- The **On resistance** of 2N7391 is **0.2 Ω**.
- **Wire resistance:** Any wire carrying alternating current will have higher resistance than wires carrying dc current due to skin effect which is given by $\frac{10^{-6}\sqrt{f}}{D}$ in Ω/ft. Where D = diameter of wire in inch, f= frequency of alternating current in hertz. Since transient response is alternating current, the AC resistance for 22 gauge wire with D=0.025 inch and f= 333 KHz (frequency is taken from the practical result from fig3) is $R_{ac} = 0.0231 \Omega/\text{ft}$ or $0.0757 \Omega/\text{mt}$. For 8 meters length $R_{ac}=0.606\Omega$. Hence for 2 wires effective AC resistance $R_{ac} > 0.3 \Omega$ and $\leq 0.6 \Omega$ because of proximity effect for closely running wires. Here maximum of 0.6Ω is considered which introduces very small percentage variation in the cell resistance calculations. Hence for 8mtr wire **$R_{ac}=0.606\Omega$** . Whereas the DC resistance of the wires (22 gauge) for 1mt length= 50m Ω. And for 8mts parallel wire $R_{dc}= 0.2\Omega$.

- **Cell internal resistance:** The internal resistance for 23 cells in series= $(4.05 - 0.606-0.2) = 3.244 \Omega$. Hence the cell internal impedance= **141mΩ**.

C. CELL CAPACITANCE:

The capacitance of each cell is derived from total capacitance. Hence individual cell capacitance is given by $(0.032*23) = 0.736\mu F$. This value closely matches with the cell data.

IV. CELL MODEL

From the value derived above, cell model is created as shown in Fig 8. The four diodes in parallel with the current source gives the open circuit voltage of 2.64 which is equal to actual open circuit voltage of onboard cells for 42V application. Manufacturer's data sheet describes the internal impedance of the cell to vary from 0.1 to

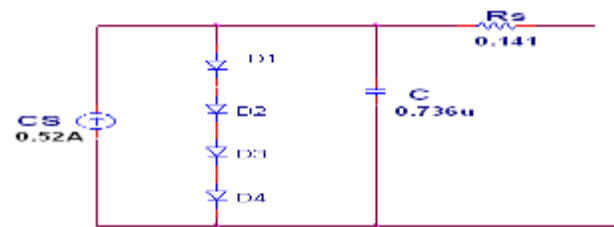


Fig 8. Solar cell model

0.5 Ω. And the cell impedance will tend towards the lower side of this range. Accordingly impedance of 141mΩ to 153mΩ (considering the small percentage error due to proximity effect) is obtained in the calculation.

V. CELL VALIDATION

The solar cell model is validated by connecting 23 equivalent circuits in series to get one parallel of 0.52A @ 42V and interface with the shunt switch circuit as shown in Fig 10. When the switch is closed the current dynamics through it as shown in Fig 9 is same as the result obtained from the hardware experiment shown in Fig 3.

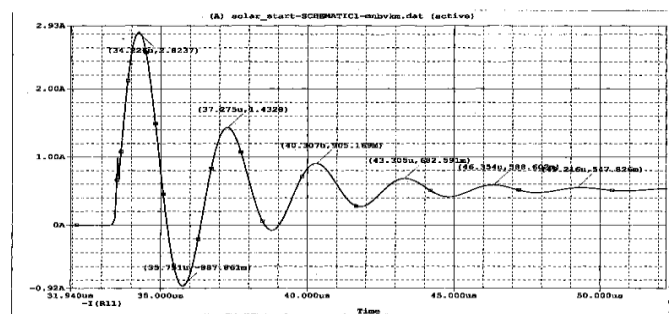


Fig 9. Simulation Result

- Initial Current $I_o = 0.52A$
- + ve Peak current = 2.838A
- -ve Peak current= -878mA
- Period= 3.04μs
- $t_r = 750ns$,
- Settling time = 20μs

Since all parameters are matching with respect to hardware results, the cell model created is validated. Using this cell model, solar string of any rating connected to shunt regulator with any harness length can be modeled in the software to analyze shunt switch current stress. In any spacecraft each string is combination of series and parallel cells to achieve required string current at required voltage.

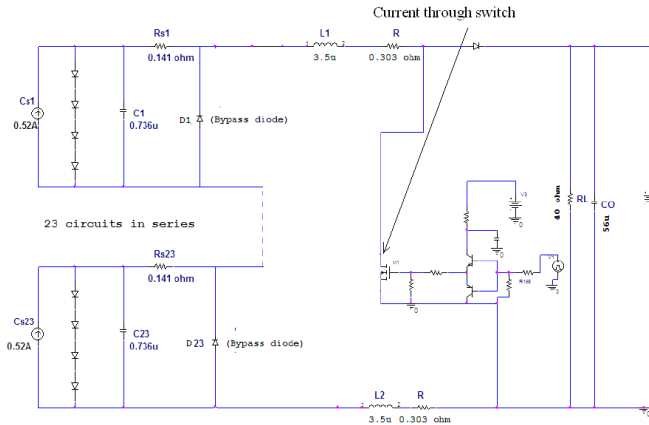


Fig 10. Circuit model

VI. ANALYSIS

When the switch is shunted, capacitor is fully charged. Current flow through the switch is due to generation current of the cell and the capacitor discharge current. This closed circuit becomes second order under damped system with damping factor ζ (ξ) < 1 given by $R/2\sqrt{C/L}$. The response of under damped system is always oscillatory with frequency of damped oscillation $\omega_d = \omega_n \sqrt{1 - \xi^2}$, ω_n = Natural frequency = $1/\sqrt{LC}$. The peak current is given by $e^{-\pi\xi/\sqrt{1-\xi^2}}$. The contribution of capacitor voltage for peak current is higher than the solar cell current. The damping occurs due to the presence of resistance in the switching path where the energy gets dissipated. Hence the amplitude of current peaks damps exponentially and settles at $4 * T$, ($T = \frac{1}{\omega_n \xi}$).

A bypass diode is connected across each cell on the panel to bypass the cell failed in open mode. The negative peak is limited at 880mA due to the conduction of this bypass diode when reverse voltage is greater than total cut in voltage for 23 diodes.

VII. EFFECT OF SERIES DIODE

For higher string rating, single parallel (minimum current) strings are diode ORed to achieve total string current thereby preventing one string failure under short circuit of any single parallel. The current transient through switch with the series diode is as shown below.

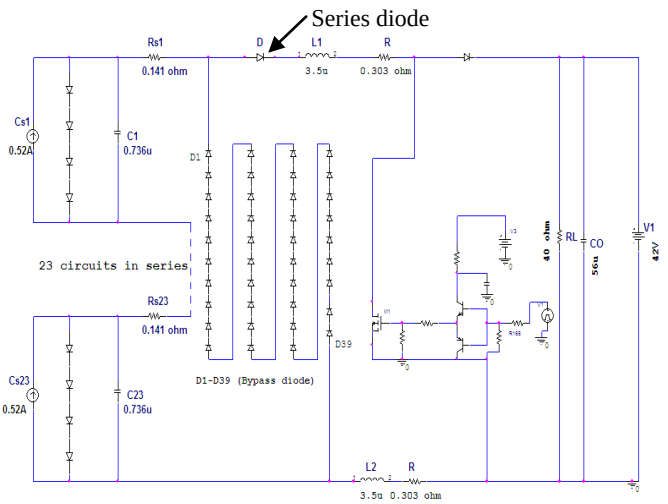
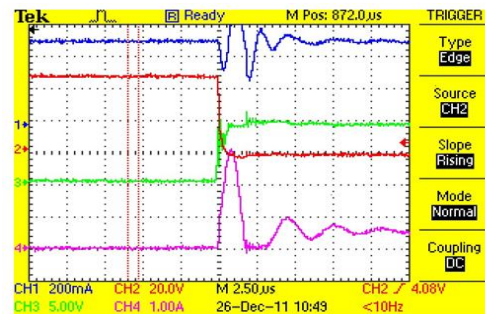


Fig.11

Hardware Simulation:



CH4= Switch Current, CH2= Drain Voltage

Fig.12

Software Simulation:

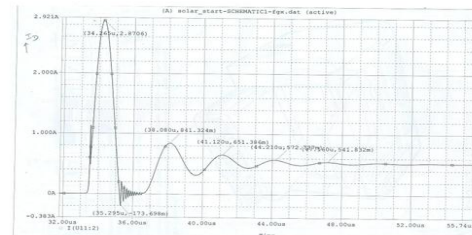


Fig.13

As observed in fig12/fig13, there is a ringing current of small magnitude when the resonating negative current flows through the diode in the switching path. Since diode blocks this negative current the reverse voltage across the diode increases for a small duration. The reverse voltage stress on the series diode for one parallel as observed in the simulation is shown in fig12.

The reverse voltage across the series diode is 157V as seen above. The reverse breakdown voltage of 1N5811 used is 160V. This series diode is blocking negative 880mA (fig9) which causes current ringing during the entire negative cycle of resonant current. At negative peak of 200mA ringing current, maximum reverse voltage is observed across the diode. This peak reverse voltage reduces with decrease in the ringing current magnitude and becomes zero at the end of the cycle. Lower the string rating higher is the voltage stress on the device.



Fig.14

VIII. SOLAR ARRAY MODEL

The shunt switch in the spacecraft is switching to regulate the bus voltage. The string current used onboard is a variable component. The effect of solar cell capacitance and cable inductance for maximum and minimum string rating is simulated and analyzed by creating solar array model. Here minimum of 1A and maximum of 3.6A (2Parallels to 7parallels) is considered.

Solar Array model is generated using solar cell model and measured cable length from panel to the shunt switch including wiring done on the spacecraft solar panel. 23 cell models are connected in series to get one parallel generating 0.52A @ 42V Vmp. The number of parallels connected depends upon the rating of the switching string to be connected to the shunt switch. Hence the extreme condition of minimum and maximum strings solar array model is generated to study the current response.

A. Maximum string current

The maximum switching current through the shunt switch considered is 3.6A.

1. Solar String Model

Maximum string is simulated by connecting seven parallels each 0.52A @42V having 23 solar cell models in series. Each parallel on the panel is running through a series diode to form one string.

2. Estimation of interface cable length

The length of the cable from solar string to the shunt switch includes

- Wiring on the panel from cell positive through diode to the panel connector
- From panel connector to SADA connector
- From SADA connector to the shunt switch in PCU

Measured cable length is as given below

- Panel wiring
 - Each parallel to the diode anode = 1mt
 - Diode cathode to panel connector maximum = 3.25mts
 - String return to Panel connector = 1.65mts
- Panel connector to SADA connector = 3mts
- SADA to shunt switch in PCU = 3mts
- Shunt switch return from the PCU to panel connector =6mts

The total harness length from solar cell live to return is 16.9mts. Hence L can vary from 16.9μH to 8.45μH since two wires are running from series diode cathode to shunt switch drain.

The array model, circuit connection and simulation results are as shown below.

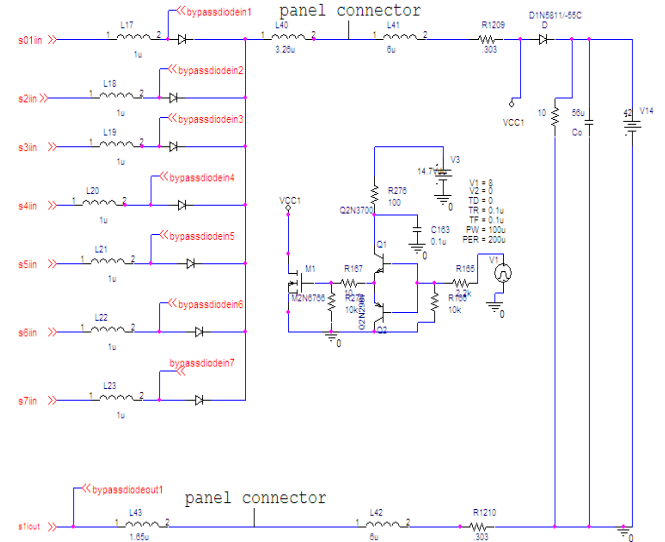


Fig.15

S1in to S7in » 23 Solar cell equivalent circuit

Bypassdiode1 to bypassdiode7 » 39diodes connected across each parallel

L17 to L23 » inductance of single wire from each cell positive to series diode

L40» Inductance from series diode cathode to panel connector

L41» Inductance from panel connector to shunt switch

1) Current transient through shunt switch for L=16.9μH (with maximum coupling between wires)

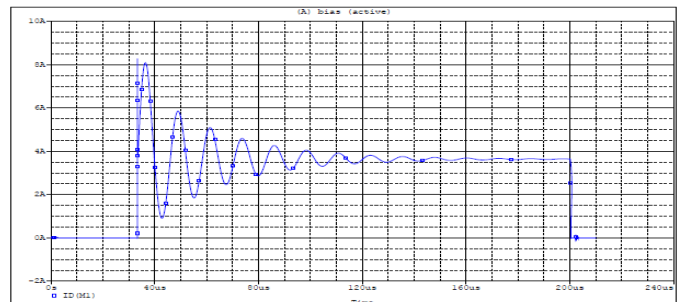


Fig.16

- +ve Peak = 8A through the switch
- -ve peak = 1A above the ground level
- Period= 12.14μs, frequency= 82Khz
- Settling time= 137μs

For 7 parallels the effective capacitance increases when compared with single parallel (0.032μ*7). The actual spacecraft harness length is more than the set up harness length (16.9mts>8mts) which increases the inductance value. The damping factor reduces since L is inversely proportional and C is directly proportional to damping factor. This low value of damping increases the settling time. The frequency has reduced because of low value of damping factor. The peak current is not very high since it is dependent on damping factor

as mentioned in page 3 analysis. Also the peak current is mainly due to capacitor initial voltage which is still at 42V. A DC shift of 3.6A is present instead of 0.5A (one parallel).

2) *Current transient through shunt switch for $L/2 = 8.59\mu H$ (with no coupling between wires)*

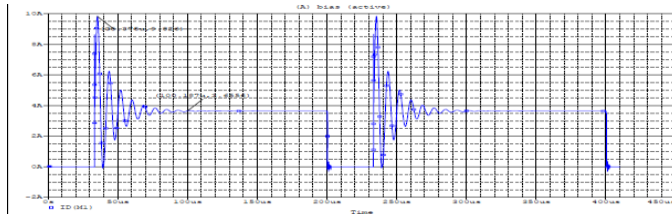


Fig.17

- +ve Peak of 9.4A flows through the switch
- Small current ringing at -ve peak at ground level
- Period= 8.71μs, frequency= 114Khz
- Settling time= 77μs

For lower value of inductance, peak currents (both +ve and -ve) increases while settling time decreases. The maximum reverse voltage across series diode during the blockage of negative swing current is 17V for <1μs as shown below

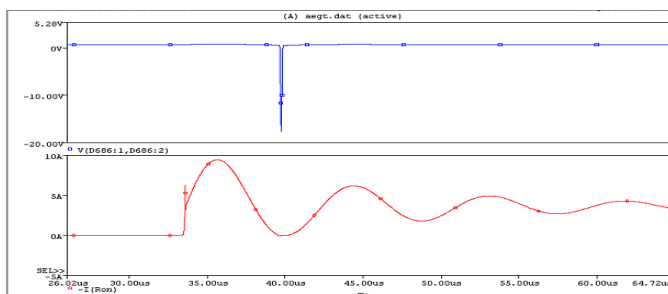


Fig.18

The AC resistance of the harness depends directly on the frequency of damping current and the harness length as described in page 3. Since length of the harness has increased and frequency is reduced as shown in the result below, the effective change in the R_{ac} value is negligible. Hence $R_{ac} = 0.606\Omega$ is considered.

B. Minimum string current

Simulation is carried out with 2 parallels connected for the same harness length.

1) *Current transient through shunt switch for $L = 16.9\mu H$ (with maximum coupling between wires)*

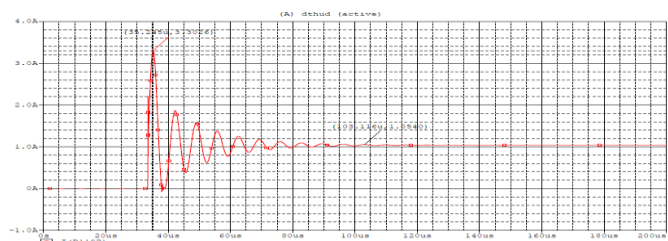
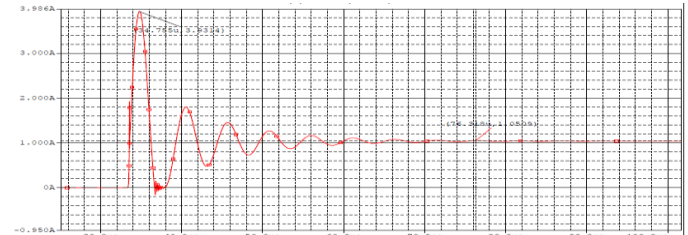


Fig.19

- The negative peak is blocked at zero level

- +ve Peak = 3.3A through the switch
- Small current ringing at -ve peak at ground level
- Period= 6.72μs, frequency= 149 KHz
- Settling time= 70μs
- Reverse voltage across series diode is 70V for 1μs

2) *Current transient through shunt switch for $L/2 = 8.59\mu H$ (with no coupling between wires)*



- The negative peak is blocked at zero level
- +ve Peak = 3.83A = through the switch
- Small current ringing at -ve peak at ground level
- Period= 4.75μs, frequency= 211 KHz
- Settling time= 34μs
- Reverse voltage across series diode is 115V for 1μs

Higher the amplitude of negative current to be blocked by the diode more is the reverse voltage across it.

IX. Conclusion

The solar cell capacitance and line inductance induces damped oscillating current through the shunt regulator when the shunt switch is closed. This peak current stress on the regulator must be considered during the selection of the shunt switch. Higher the string rating and harness length the effective capacitance and inductance increases which reduce the damping factor zeta thereby increasing the settling time. Hence during switching, the switch may open before the settling time of damping current. High peak currents are mainly due to capacitor initial voltage rather than short circuit current from solar array. A DC shift of short circuit (I_{sc}) current is present in the dynamics. For higher string rating, each parallel (minimum current) is diode ORed to achieve total string current. This series diode is stressed for a short duration during blocking of negative peak current of the transients. The reverse voltage stress also has to be considered in the selection of series diode.

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