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Estimate Filter Tank Fault Effects for Satellite Power System

Che Cheng Huang, Jia Jing Yeh, and Chien Kai Tseng

***Abstract*—Main functions of the Power Control and Distribution Unit (PCDU) in FORMOSAT-5 satellite are to condition energy from the solar arrays and distribute power for all subsystems on the satellite. One of the modules in the PCDU, named the Bus Filter (BF) module provides a low impedance filter tank which shunted with the bus battery, to reduce the primary bus power line noise. The filter tank is consisted of capacitors in parallel. If a flaw or weak spot in the capacitor's dielectric results in filter tank a short fault, the primary bus voltage will be shorted to ground. The satellite power drops below a specific threshold, undervoltage-lockout (UVLO) protector is enabled to turn off the PCDU. At this moment in time, the satellite loses power supply and leads into the emergency situation (idle mode). Choosing polyester film capacitors with self healing properties can avoid a short condition. In this paper, we will discuss the filter tank design and estimate three fault effects to the satellite power system.**

***Index Terms*—PCDU, Bus Filter, polyester film capacitor, self-healing**

I. Introduction

FORMOSAT-5 is the first space program that National Space Organization (NSPO) takes full responsibility for the complete satellite system engineering design. An extension of FORMOSAT-2, FS-5 is currently being developed at NSPO to provide global Images of 2-meterresolution in panchromatic (PAN) and 4-meter in multi-spectrum (MS). The multi-million dollar program is scheduled to be launched in 2015 into a two-day revisit Sun-synchronous orbit with 720 km altitude and 98.28 deg inclination angle [1].

Power Control and Distribution Unit (PCDU), one of the FS-5 satellite key components is developed by NSPO. The PCDU is in charge of receiving solar power from Solar Arrays and regulating battery charging current [2] according to the Command and Data Management Unit (CDMU) commands. It also control and distribute power to various satellite load users upon the request of CMDU command. For some users, secondary voltage buses are required by means of DC-DC converters. PCDU is designed as a cold redundant unit.

The PCDU consists of a few modules: 1) Charge Regulator; 2) Power Distribution; 3) DC-DC Converter; 4) Control Interface; 5) Power Relay; 6) Bus Filter.

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II. Bus Filter

The Bus Filter (BF) module in the PCDU is in charge of the primary bus noise reduction function and switching relay of
battery charging path. It provides a low impedance filter tank, and shunted with the bus battery, to reduce the primary main bus power line noise that come from charge regulator, DC converter, or other payloads. In ground operation, the power relay is controlled by Electrical Ground Support Equipment (ESGE). After launching, the power relay is always closed for allowing primary power bus to charge the battery.

The following as shows in Figure 1 is a list of hardware features of BF module:

1. Supply low impedance vs. frequency to match for primary power bus Impedance.
2. The overall capacitance is composed by low ESR capacitors; they are connected in series, and then parallel for redundancy purpose.
3. Two paralleled power relays are connected between BF and battery. The power relays control the battery charging path from Solar Array or EGSE.
4. Provides 3 current measurement circuits for battery charge/discharge current monitoring. The analog signal output of the two circuits is connected to INTF-A and INTF-B respectively.
5. External I/O interfaces are consisted of two D-type connectors from board front panel
6. Signal lines, internal logic power supply and main bus power line are connected to Back Plane by two 96 pins connectors

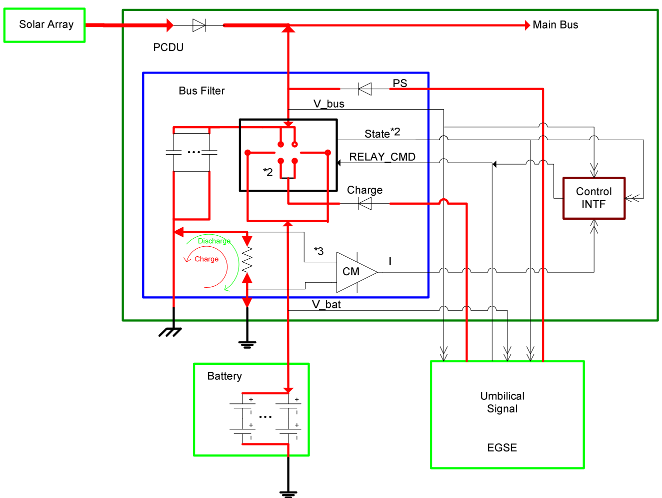

Fig. 1. The functional block diagram of BF module

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III. Filter Tank Design

The first and the main purpose in the BF module, is to reduce noise in the primary bus. Filter design focuses on choosing appropriate capacitors which are characterised by very low dielectric losses, small dielectric absorption, high dielectric strength, very high insulating resistance and a practically linear temperature coefficient in all temperature ranges.

A. Impedance of Filter Tank

The capacitors shunt unwanted AC variations (noise) in two directions by introducing a low-impedance path to ground. They prevent noise from entering the device from the power plane and they also suppress noise from the device being coupled into the power plane.

The capacitor is in effect a ideal capacitor in series with an inductor and a resistor, as shown in Figure 2.

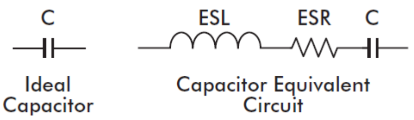

Fig. 2. Capacitor Model

The series L and R are called equivalent series inductance (ESL) and equivalent series resistance (ESR), respectively. The effective impedance of the equivalent circuit is written as the following equation, where f is the frequency. Figure 2 graphs this equation for typical parasitic ESR and ESL values found in a 1.0 µF ceramic capacitor.

$$Z = \sqrt{ESR^2 + (2\pi f * ESL + \frac{1}{2\pi f * C})^2} \quad (1)$$

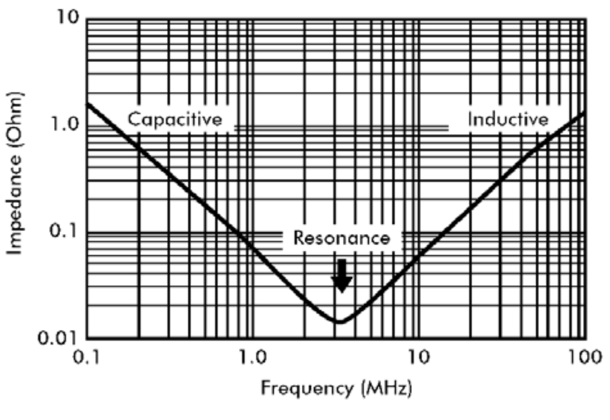

Fig. 3. Impedance of Capacitor with ESR=0.015 Ohms, ESL=2nH, C=1µF [3]

To understand the operation over frequency, manufacturers provide such curves for each capacitance value, package type, and composition. Figure 3 shows that the minimum capacitor impedance is limited by its ESR value. This impedance occurs at the series resonant frequency (f_0), which can be calculated from the equation below. On either side of this frequency the impedance increases. The ideal capacitor has zero impedance at those frequencies that need bypassing.

$$f_0 = \frac{1}{2\pi\sqrt{ESL + \frac{1}{C}}} \quad (2)$$

A common way to lower the overall impedance is to combine identical capacitors in parallel, as shown in Figure 4. Like resistors, the impedance of capacitors halves as the number of devices in parallel doubles. If the number of capacitors needed to produce the target impedance becomes unreasonable, a lower ESR capacitor may be used to reduce the total number of components.

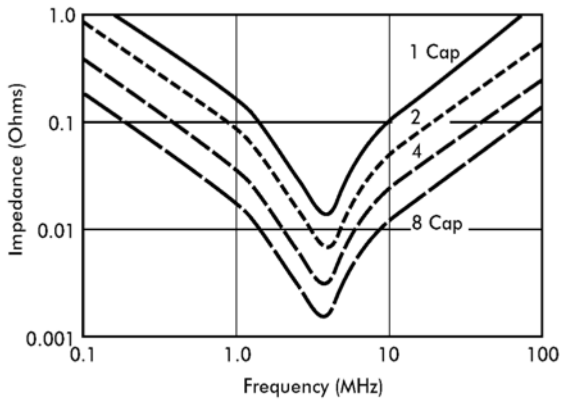

Fig. 4. Doubling the Number of Capacitors in Parallel Cuts Their Impedance in Half [3]

Figure 5 is the primary power bus impedance requirement cure. The filter tanks in the BF module are consisted segments of capacitor combinations in parallel. Connecting the filter tanks with satellite battery needs to provide a low impedance frequency response to match the primary power bus impedance.

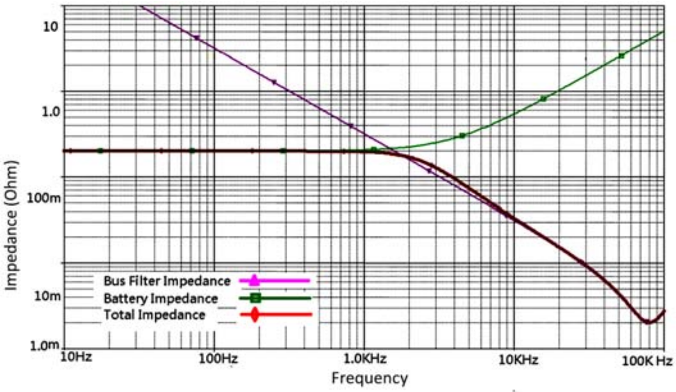

Fig. 5. Primary Power Bus Impedance Requirement

B. Polyester film Capacitor Characteristics

If a flaw or weak spot in the capacitor's dielectric results in filter tank a short fault, the primary bus voltage will be shorted to ground. When the satellite power drops below a specific threshold, undervoltage-lockout (UVLO) protector is enabled to turn off the PCDU. At this moment in time, the satellite loses power supply and leads into the emergency situation (idle mode). Choosing polyester film capacitors with self healing properties can avoid a short condition.

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Polyester film capacitors are obtained by winding two or more layers of dielectric plastic film and metal foil. The metal layers are applied by evaporation under vacuum on the dielectric. Generally, the coils of each of the metal foils are interconnected by a deposit of several metal alloy layers. The leads are connected by soldering or brazing [4].

Encapsulation (wrapped, molded, tube or metal case) ensures adequate resistance to climatic, thermal and mechanical stress.

Polyester film capacitors with smaller dimensions can be manufactured due to them high dielectric constant and excellent electrical performance of this film. Polyester film capacitors have also outstanding self-healing properties. Self-healing is a fundamental property of these capacitors.

C. *Self Healing*

The self-healing [5] feature of the metalized capacitor offers a distinct advantage over the non-metalized unit. This self-healing feature is a result of the extreme thinness of the metalized electrode material. Whenever a flaw or weak spot in the dielectric results in a short condition, the stored electrons in the capacitor and the associated circuitry will immediately avalanche and cross at the shorted point. The electron density concentration results in an extremely high current condition which in turn provides sufficient energy in the form of heat to vaporize the thin metallic electrode. The vaporized electrode forms a fairly concentric pattern away from the point of the short. As a result of the vaporization, the short condition is removed and the capacitor is again operational. This is known as a "clearing" which is the self-healing process.

To illustrate this process Figure 6 represents a greatly enlarged section of a capacitor containing an extremely thin spot in one of the dielectric sheets. In this case, it is the result of two valleys on opposite sides of the dielectric surfaces coinciding at a point. This is an example of the distance between the electrodes at a thin spot that is not capable of withstanding the voltage stresses - thus a short develops. The "self-healing" or "clearing" action vaporizes the metal electrode sufficiency; therefore, the effective distance between the electrodes increases, the short is removed, and the capacitor is again a "good" unit (shown in Figure 6B).

There are two factors to be considered relative to a self-healing or clearing action. There must be sufficient energy present to accomplish this clearing action and during the process, the circuit will experience a small, short-duration, transient voltage drop.

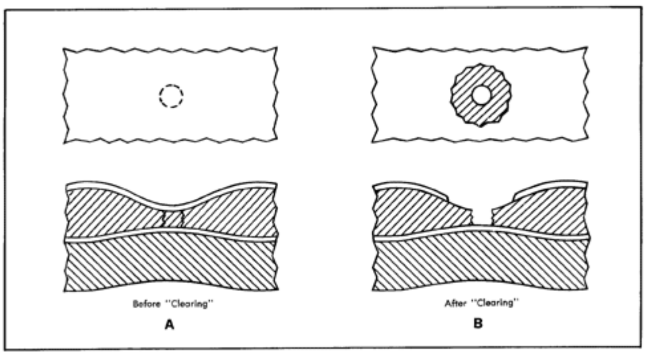

Fig. 6. Represent a greatly enlarged section of a capacitor containing an extremely thin spot in one of the dielectric sheets. [5]

D. *Energy Required To Clear*

The energy required for an average or "normal" clearing is approximately 10 microwatt-seconds [5]. This means that if energy is available only from the capacitor itself, there is a relationship between the capacitance rating and the magnitude of the charging voltage below which clearings may be questionable.

The relationship is illustrated below for both normal clearing and clearing requiring 10 times the energy.

This energy is calculated in relation to the capacitance value and the load voltage

$$W = \frac{1}{2}CE^2 \tag{3}$$

Cleaning energy available from the capacitor can be given by

$$W_0 = \frac{CE_d^2}{2} = \frac{CE_0^2}{2} - \frac{CE_f^2}{2} \tag{4}$$

Where W_0=Energy to clear (microwatt-seconds), C=Capacitance (microfarads), E_0=Charging voltage (voltages), E_f=Charging voltage after clearing (voltages), E_d= voltage drop during clearing (voltages).

And since $E_f = E_0 - E_d$ .Then

$$W_0 = \frac{C}{2}(2E_oE_d - E_d^2)$$

Rearranging: $E_0^2 - (2E_0)E_d + \frac{2W_0}{C} = 0$

We note that E_d can be derived from the quadratic formula:

$$E_d = \frac{2E_0 \pm \sqrt{4E_0^2 - \frac{8W_0}{C}}}{2} \tag{5}$$

Since the positive root is not applicable, so the voltage drop during clearing is

$$E_d = E_0 - \sqrt{E_0^2 - \frac{2W_0}{C}} \tag{6}$$

E. *Clearing During Service*

In many applications, when the actual voltage applied to the capacitor is less than the rated voltage, and the ambient temperature is less than the maximum rated temperature, the unit should function for years without clearings during its service life. This is because both voltage and temperature derating will tend to minimize the short producing condition necessary for the initiation of the self-clearing process.

The dielectric itself will have a strong controlling effect on these self-healing occurrences. For instance, under accelerated life test conditions, a metalized polyester dielectric unit will exhibit considerably less clearings than a metalized polycarbonate device.

IV. Estimate Filter Tank Fault Effects

The filter tank in the BF module is consisted of 6 segments of capacitor combinations. Each segment is composed of two serial ceramic capacitors and a polyester film capacitor in

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parallel.

When a polyester film capacitor takes place a short fault in the filter tank, the self-healing can provide a recovery to avoid the satellite mission failure. But filter tank short fault may cause some undesired effects in the satellite power system. There are three filter tank faults to be considered in the satellite power system:

A. Store energy in the polyester film capacitor is enough to execute the self healing or not, when a filter tank short fault happens.

B. Calculate the primary bus voltage drop during the self healing period.

C. Estimate for The impedance of the filter tank that still conforms to the mission demand after a short fault situation.

A. *Self Healing Energy Estimate*

Polyester film capacitor had been applied in the BF module with Eurofarad's PM90S, which possesses 100uF capacitance and 100Vdc voltage stress.

An average self-healing operation generally required only a very small amount of energy (5 to 15 microwatt seconds) and is performed in several micro seconds (<50 μ s). However, a minimum amount of energy is required below which self-healing operations are aleatory [4].

The energy required for an average or "normal" clearing is approximately 15 microwatt seconds, and clearing requiring 150 microwatt seconds (10 times the energy).Short-duration is performed in 50 μ s, the power requirement of 3 Watts. For PCDU system, there is sufficient energy to offer this requirement and the process is too short to affect the satellite's mission.

B. *Calculate Primary Bus Voltage Drop*

The primary bus working voltage in the PCDU is 22~34V, voltage drop during clearing can be calculated as follows:

Case 1：Working voltage is 22V, voltage drop during clearing from Eq. (6) is：

$$E_d = 22 - \sqrt{22^2 - \frac{2\times 150}{100}} \qquad E_d \approx 0.07\,\text{V}$$

Case 2：Working voltage= 34V, voltage drop during is：

$$E_d = 34 - \sqrt{34^2 - \frac{2\times 150}{100}} \qquad E_d \approx 0.05\,\text{V}$$

When self-healing happens, the primary bus voltage will drop about 0.05~0.07V. Compared with PCDU working voltage (22~34V), the voltage drop during the process can be ignored.

C. *Impedance Curve Measurement*

There are six segments of capacitor combinations in the filter tank. All of the 6 segments are parallel connected and obtain approximately capacitance of 600 μ F.Figure 7 shows the impedance curve measurement of the filter tanks with satellite battery. The result provides a extreme low impedance frequency response to match Figure 5, the primary power bus impedance requirement.

Suppose the worst case (Normally the short condition removed, the capacitor is again operational), the filter tank loses one capacitor after self healing process. Like resistors, the impedance of capacitors increase one-fifth as the number of devices changes to 5 segments in parallel. According to Figure 7 result, estimate the impedance frequency response; it still matches the requirement of the primary power bus impedance.

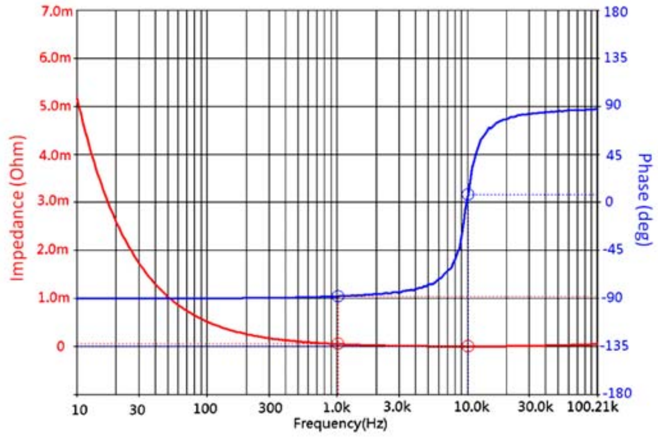

Fig. 7. The impedance curve measurement of the filter tanks with satellite battery.

CONCLUSION

The BF module design provides a low impedance filter tank shunted with the bus battery, to reduce the primary bus power line noise. When a filter tank short fault happens, the PCDU has stored enough energy in the polyester film capacitor to execute the self healing. The voltage drop during the process can be ignored and the impedance frequency response still matches the requirement of the primary power bus impedance.

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