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doi:10.1017/aer.2020.60

Design and implementation of a power distribution system adopting overcurrent protection

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ABSTRACT

One of the most critical aspects of a small satellite is the electrical power system (EPS) since the electrical power is necessary for the satellite to operate correctly during its predefined lifetime. The electrical power system consists mainly of solar cells, batteries, voltage converters and protection circuits. The electrical power system is responsible of providing stable power to the rest of the satellite subsystems.

In satellite electrical power systems, overcurrent protection is now becoming an important function handled by the power distribution module (PDM). This paper proposes a method to evaluate the suggested protection. With the proposed procedure we should be able to verify that every possible failure does not travel through the EPS and cause a fatal degradation of the electrical power system. This will allow a complete evaluation of functionality of the protection hardware.

This paper discusses the design and implementation of the power distribution module (PDM) for the coming generation of small satellites for the Algerian Space Agency (ASAL). The design must provide a reliable protection for the subsystems from the overcurrent associated with a device failure.

Keywords: Power system; small satellites; bipolar junction transistor (BJT) switch; field effect transistor (FET) switch; hard wire switch; fuses; resettable fuses; power distribution module.

NOMENCLATURE

Cmd	Command pulse
Fcut-off	filter cut-off frequency
Hfe	Transistor amplification factor
In	Switch input current
Itrip	Switch trip current

Received 3 September 2019; revised 11 April 2020; accepted 18 June 2020.

https://doi.org/10.1017/aer.2020.60 Published online by Cambridge University Press

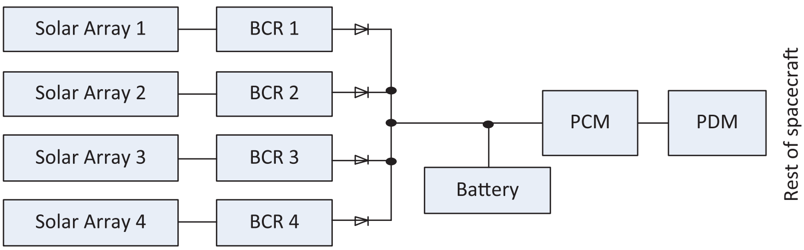

Figure 1. Standard microsatellite power system diagram.

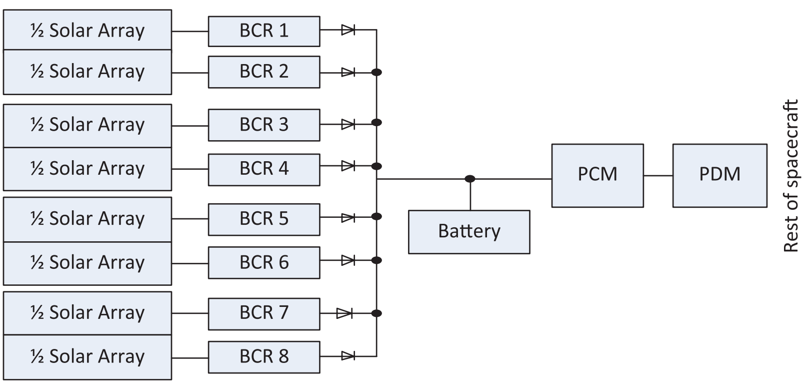

Figure 2. New configuration for microsatellite power system.

1.0 INTRODUCTION

A spacecraft needs power to carry out its various functions. Satellites in low earth sun synchronous orbits (SSO) experience about 35minutes eclipse period out of the 98minutes average orbital period.[(1)]

For spacecrafts, the primary source of energy comes from the solar cells. These latter provide power to recharge the onboard battery through a battery charge regulator BCR circuitry. In our design, each solar panel has its own battery charge regulator circuit (Fig. 1). Nowadays, new topologies exist. Each solar panel is split into two identical parts. Each half of a panel has its own BCR circuit. This way, a failure of a BCR circuit only affects half of a solar panel, as shown in Fig. 2.

A power conditioning module (PCM) regulates the battery voltage (14V) to provide regulated voltages (+10V, −10V, +5V and −5V) for the spacecraft subsystems and the payloads (primary and secondary).

A power distribution module (PDM) distributes the regulated power from the battery via the PCM and the unregulated raw power (bus) to the subsystems and the payload. It is in the PDM where a power switching system is included. The latter can be operated by commands from the ground via the satellite telecommand system.

When designing power switches for a space mission, one needs to consider the operational environment (i.e. radiation effects and temperature variations) in orbit because it is different from that on the ground. Besides reliability and efficiency of the power switching system, over current and under voltage protection for subsystems and the payload should be considered.

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For satellites, power switches are remotely controlled. In this work, bipolar junction transistors (BJT) and field effect transistors (FET) will be investigated.[2–10]

2.0 THEORY

The objective of the power distribution module (PDM) is to distribute the different voltages to the subsystems and the payload. An important second task is the protection of the power system against faults and short-circuits in the subsystems and bus circuitry. In general, one can find that there are four different ways of power distribution:[1,11–13]

- Hard wired
- Fuses
- Resettable fuses
- Power switches

2.1 Hard wired

Hard wired means that a subsystem is directly connected to the power system, and this way there is no protection. For the subsystem this is the most reliable method. For the power system, however, this method of connection is potentially fatal. A short circuit on one of these lines will severely damage the power system, and therefore the satellite. On certain satellites, some designs have current limiting resistors, which will act as a fuse should the line stay shorted to ground.[1,11–13]

2.2 Fused lines

For fused lines, the subsystem is connected to the power system via a fuse, thereby protecting the power system from short circuits down the line. The disadvantage of fuses is that when they break, they cannot be reset. The reason for using fuses is dictated by space requirements as they take little space compared with power switches. Subsystems that must be switched on all the time, are low power, and have enough redundancy to survive an “accidental” break if one fuse are powered by fused lines.[1,11–13]

2.3 Resettable fuses

Resettable fuses have become an attractive circuit protection against overcurrent conditions due to their ability to cycle back to a conductive state after the current is removed, acting as circuit breakers. This allows the circuit to function again without having to replace it. Next-generation resettable fuses meet the standards and requirements for secure and reliable overcurrent protection within rated limits. Once system requirements are defined and circuit analysis has determined the operating parameters, selecting the right fuse for a specific design is rather simple.[5]

2.4 Power switches

Power switches are the most flexible way of distribution. The power switch has two main functions. First, it can switch the subsystem ON and OFF by means of a telecommand. This is useful when it is not necessary to have a subsystem powered up all the time. It can also be a necessity to switch off a subsystem when the power budget cannot support the power demand, e.g. the high-power transmitter. Second, the power switch is a protection. The switch is also

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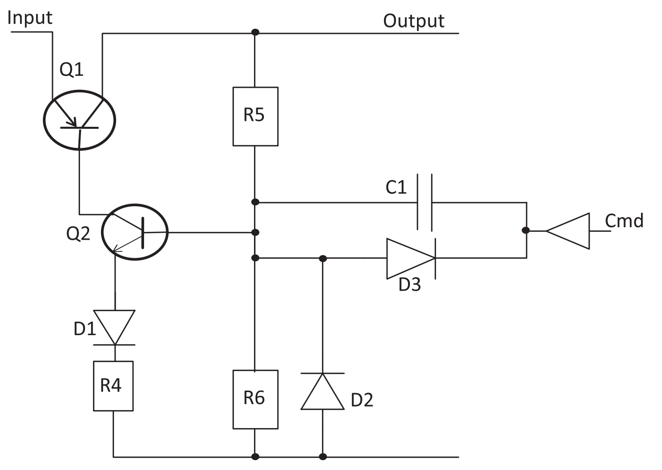

Figure 3. The positive bipolar power switch.

an electronic fuse that automatically switches OFF when the current drawn by the subsystem becomes larger than a pre-set value. There are two basic types of switches:(13–16)

- Bipolar junction transistor (BJT, positive and negative) switches
- Field effect transistor (FET) switches

2.5 The bipolar junction transistor switch

There are basically two types of bipolar switches in use: a positive switch and a negative switch. The positive switch can be subdivided into two categories:(13–16)

- Low power switch, up to 200mA trip current
- Medium power switch, up to 1A trip current
- High power switch, higher than 1A trip current

The negative switch has only a low power version because the −10V line can only support low power. (13–16)

2.6 The positive bipolar transistor switch

The positive power switch, shown in Fig. 3, works as follows: In the OFF state, the command line is low. The base of Q_2 is low, and there is no current out of the base of Q_1. Therefore, Q_1 is OFF and the output of the switch is low. Diodes D_1 and D_3 ensure that the switch stays OFF when the telecommand is low.

When the command line becomes high, a pulse is generated through the capacitor, which switches transistor Q_2. Transistor Q_1 is ON, and the collector goes to the same level as the emitter. When the output of the switch is ON, the resistor bridge divider (R_5, R_6) sets the base of Q_2 at 3.5volts. This keeps Q_2 ON and keeps Q_1 ON, so the switch stays ON.

Switching OFF uses the same principle as switching ON. When the telecommand line goes low, a negative pulse from the capacitor forces the base of Q_2 to go down to zero; thereby, the switch goes OFF. D_2 ensures that the base does not go below zero (−0.6V).

The automatic switch OFF of the switch is obtained as follows: when the switch is operating nominally (normal output current) transistor Q_1 is in saturation. When the current through Q_1 increases, the transistor, at a certain point, will come out of saturation. When that happens,

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the voltage drop across the collector and emitter (Vce) of Q_1 increases; this causes the output to go down and the voltage at the base of Q_2 to go down. Because of that, Q_2 will be less saturated, so the base current of Q_1 decreases, which causes Q_1 to be less saturated until the switch goes OFF.

Because a subsystem requires a higher current than normal (higher than the trip current of the switch) when switched ON (capacitor charging), the switch must be capable of large initial (in-rush) currents. This is done by the capacitor C_1. As long as the capacitor's pulse keeps the base of Q_2 above the nominal 3.5V, the in-rush current can be higher than the trip current. By increasing the capacitor, the in-rush capability is increased. A 1F capacitor is judged enough for most subsystems. Some subsystems require larger capacitors; therefore, a 10F electrolytic capacitor can be used.[13–16]

The rest of the components are estimated as follows: The transistors, Fig. 3, are chosen according to the current handling of the switch. The trip current of the switch and its components are highly dependent on the H_{fe} of the transistors. The calculation gives only an estimate, and the real values of the resistors must be selected for each switch. The resistor values of the divider chain R_5 and R_6 are chosen such that the base of transistor Q_2 is at 3.5V. To keep the trip current of the switch as independent as possible from the H_{fe} of Q_2, the current through R_5 and R_6 must be larger than the base current of Q_2. If this current is about 5 times higher and the H_{fe} of both transistors is about 100, the current through R_5 and R_6 is given in Equation (1):[13–16]

$$I = \text{trip current}/500 \qquad \ldots(1)$$

So, the resistance value of R_6 is equal to, Equation (2):

$$R_6 = \{3.5V * 500\}\ /\text{trip current} \qquad \ldots(2)$$

And the resistance value of R_5 is equal to, Equation (3):

$$R_5 = \{\text{voltage drop } R_5 * 500\}\ /\text{trip current} \qquad \ldots(3)$$

The voltage drop over R_5 is different for a 5V, 10V or 14V switch. The value of the resistor R_4 sets the trip current of the switch and depends greatly on the H_{fe} of Q_1. A lower H_{fe} requires a larger base current and thus a lower resistor value for R_4.

An approximate value of R_4 is given in Equation (4):

$$R_4 = \{\{\text{Base voltage} Q_2 - (2 * \text{ diode drop})\} * H_{fe} Q_1\}/ \text{ trip current} \qquad \ldots(4)$$

Table 1 summarises values for the resistors R6, R5 and R4 for different positive BJT switches. The resistors values are produced for different voltages, i.e. +5V and +10V and different trip currents. Note that positive BJT switches are designed in this case for a large interval of trip currents.[13–16]

2.7 The negative bipolar transistor switch

The negative switch, Fig. 4, works according to the same principles as the positive one except for the current flowing in the other direction. Also, the buffer is of the inverting type so switching ON is a negative going pulse and switching OFF as a positive pulse. The telecommand remains the same.

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Table 1
Bipolar positive power switches

Switch	Use	In (mA)	Itrip (mA)	Q1	Q2	R6	R5	R4
S1 (+5V)	Wheel	100	300	2N5153	2N2222A	6K2	3K	750
S2 (+5V)	GPS	880	1500	2N5153	2N2222A	3K	1K3	150
S3 (+5V)	MTQ	100	300	2N5153	2N2222A	6K2	3K	750
S4 (+10V)	MAG_0	15	50	2N5153	2N2222A	33K	62K	5K1
S5 (+10V)	MAG_1	15	50	2N5153	2N2222A	33K	62K	5K1

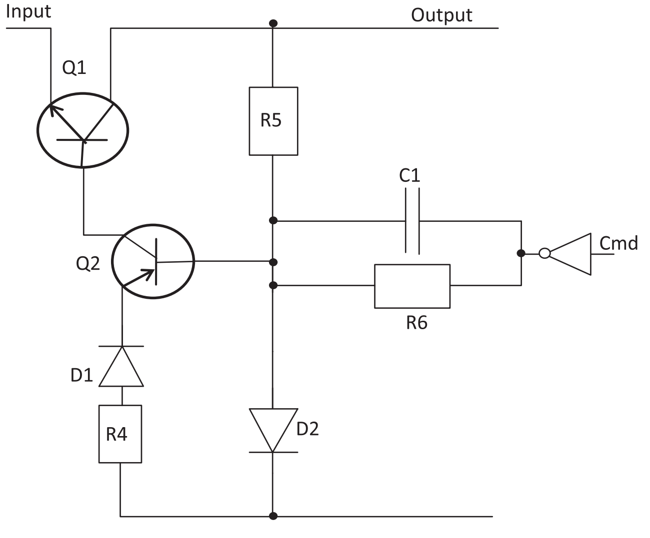

Figure 4. The negative bipolar power switch.

The power switches have one problem – they are temperature sensitive. Because the H_{fe} of the transistors drops with lower temperatures, the trip current is set approximately two to two-and-a-half times the nominal expected current. This is to compensate for the temperature coefficient of the trip current, which is about 0.5%/°C. It also incorporates the decrease in H_{fe} of the transistor and an increase in power consumption by the subsystems.

Table 2 summarises values for the resistors R6, R5 and R4 for different negative BJT switches. The resistors values are produced for different voltages, i.e. −5V and −10V and different trip currents. Note that negative BJT switches are designed in this case for lower power.[13–16]

2.8 The field effect transistor switch

Since bipolar transistor switches become inefficient at higher currents, a power switch based on a FET has been developed (see Fig. 5). The principle is the same as for the bipolar power switch. The P channel FET is ON when the gate is low (zero volts). The FET is OFF when the gate is at the same voltage as the source.

In the OFF state, the output is low, and the input is high. The positive input of the comparator is kept at approximately 3.5V by the voltage bridge divider chain R_1, R_2 and is therefore higher than the negative input. Thus, the output is high, and the FET is OFF.

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Table 2
Bipolar negative power switches

Switch	Use	In (mA)	Itrip (mA)	Q1	Q2	R6	R5	R4
S6 (−5V)	Wheel	10	50	2N2219A	2N2907A	3K	6K2	5K1
S7 (−5V)	GPS	10	50	2N2219A	2N2907A	3K	6K2	5K1
S8 (−10V)	MAG_1	10	50	2N2219A	2N2907A	33K	62K	5K1
S9 (−10V)	MAG_0	10	50	2N2219A	2N2907A	33K	62K	5K1
S10 (−10V)	MTQ	10	50	2N2219A	2N2907A	33K	62K	5K1

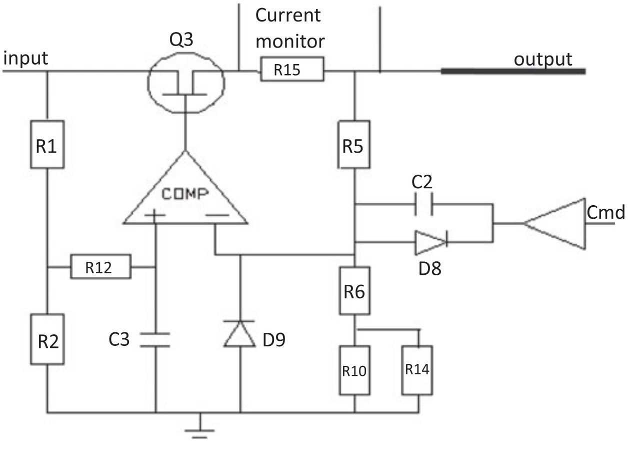

Figure 5. Field effect transistor switch.

When the command line goes high, a 5V pulse via the capacitor C_2 makes the negative input higher than the positive, the comparator output goes low and the FET switch is ON. The switch settles in normal operation with the negative input just above the positive input.

Switching OFF works the same as the bipolar switch. The low going pulse from the capacitor forces the negative input to go below the positive input, causing the switch to turn OFF.

The trip current is obtained in the following way: The FET has a fairly constant internal resistance and so with increasing current drawn through the FET, the voltage drop across the FET increases linearly. When the voltage drop increases, the output voltage decreases so does the voltage at the negative input of the comparator. When the negative input falls below the positive, the switch turns OFF.

The trip current can be set by adjusting select-on-test resistor R_{14}. By making the voltage drop across these resistors larger, the voltage on the negative input becomes higher than the voltage on the positive input and this will make the trip current larger.

A low pass filter from the positive input of the comparator to ground is incorporated to avoid quick variations on the input tripping out the switch, the cut-off frequency of the low pass filter is given in Equation (5):[13–16]

$$f_{\text{cut - out filter}} = 1/[2p^{*}(R_1//R_2 + R_{12}) * C_3] \qquad \ldots (5)$$

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Table 3
FET power switches

Switch	Use	In (mA)	Itrip (mA)	FET	Op Amp	R10	R14
S11 (14V)	MTQ	1200	2500	IRF9Z34	OP20	2K7	3K1
S12 (14V)	TX_0	500	2000	IRF9Z34	OP20	2K7	600
S13 (14V)	TX_1	1800	3500	IRF9Z34	OP20	2K7	1K3
S14 (14V)	Wheel	500	1500	IRF9Z34	OP20	2K7	1K8

With $R_1 = 68k\Omega$, $R_2 = 22k\Omega$, $R_{12} = 100k\Omega$ and $C_3 = 470$ nF, and assuming that any resistance between the battery and the switch is of no significance, the cut-off frequency of the low pass filter is given:

$$f_{cut\text{ - }out\ filter} = 2905\ \text{Hz}$$

By connecting the op amp to the 14V supply, the FET is switched OFF with 14V op amp output. The drain-gate voltage is then 0V. To switch ON the output of the op amp goes to 0V so the drain/gate voltage is −14V. The addition of R_{15} will increase the stability of the switch as the voltage difference between the comparator input increases but has the disadvantage of decreased efficiency. The resistor R_{15} is also used as a current monitor.

Table 3 summarises values for the resistors R10 and R14 for different FET power switches. The resistors values are produced for the voltage 14V and different trip currents. FET power switches in this case are designed to support current values up to 3500mA (trip current).[13–16]

3.0 CONCLUSION

The work presented in this paper summarises a design of a power distribution module for small spacecrafts. Details were given on how we can calculate and implement power switches, both positive and negative, based on BJTs. FETs power switches were also investigated when higher currents demand are requested.

The proposed method of protection has been tested and after the power switches tripping the load current was still supplied but the protection voltage was limited.

Future work is also planned to improve the reliability and efficiency of the power system. FET technology has also advanced considerably in the past few years; therefore, the use of FETs can be more efficient resulting in a greater efficiency for the power system.

Moreover, application of resettable protection for satellites power systems will examined in our future works in the perspective of new EPS designs solutions.

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