Measurement xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Measurement

journal homepage: www.elsevier.com/locate/measurement

Cross-model verification of the electrical power subsystem in space projects

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ARTICLE INFO

Keywords:
Requirement verification
Satellite
Electrical power subsystem
On-board software
Test case design
Satellite SW simulator
Satellite engineering model

ABSTRACT

Verification of functional and performance requirements in both government and commercial space programs is a challenging task. Nowadays, spacecraft can be regarded as complex systems, and demanding quality requirements have to be fulfilled. Verification activities are performed in different steps and by means of various test environments/spacecraft models. This paper presents a cross-model verification approach for space projects and shows its application to the Electrical Power Subsystem. Functional and performance requirements of such subsystem are verified on the spacecraft Engineering Model by reusing test cases and corresponding test scripts from the On-Board Software testing campaign. This can be achieved thanks to the above-mentioned cross-model verification approach. In particular, test cases can be conceived and implemented by means of an XML-based test procedure language, independently from the underlying test environment.

1. Introduction

Having a solid verification program ensuring that a “system is built right” plays a crucial role in both government and commercial space programs [1]. The verification effort guarantees that first the mission requirements are properly interpreted and flowed down into each product specification and that each product is built such that it is properly designed, manufactured, integrated, and tested to meet the specification. Verification of functional and performance requirements in space projects is a very complex and time-consuming task. Nowadays, spacecraft can be regarded as System-of-Systems (SoS) and demanding quality requirements have to be fulfilled [2]. Such requirements are usually allocated into different spacecraft subsystems and units, which interact each other during the mission operational phase [3]. Moreover, the On-Board Software (OBSW), installed on the satellite On-Board Computer (OBC), plays an relevant role in implementing most of the spacecraft functions [4]. Therefore, the OBSW has a central role in the spacecraft verification activities [5]. Once all the HW and SW items concurring at the implementation of the spacecraft requirements have been verified and integrated, they are globally validated at spacecraft level.

Current verification activities are labor intensive and are performed stepwise by means of different test environments/spacecraft models, e.g., satellite SW simulators, flight-like as well as flight hardware [6]. In order to avoid any serious project delay and to preserve the product quality, it is necessary to focus on the test process definition, the testing (automation) tools, and the standardization procedures since the early phases of any space project. The goal is to define a cross-model verification approach so that test environments, test case definitions, and test scripts can be reused throughout the verification activities. Migrating from one model to the next one can be very expensive, and thus it is highly recommended using test environments and test artifacts which can be easily customized along the whole project.

This paper presents a cross-model verification approach for the spacecraft Electrical Power Subsystem (EPS). The EPS is a network of electrical components and is responsible for generating, storing, regulating, and transferring electric power on board the spacecraft [7]. It consists of the solar cells, batteries, and voltage converters/regulators. The EPS has to be able to provide sufficient power to the satellite subsystems under all designed operational conditions. In our previous contribution [7], we showed how to verify OBSW requirements implementing the EPS on-board management by means of spacecraft SW simulators. In this paper, we extend such approach at satellite system/subsystem level. EPS functional and performance requirements are verified at such level on the spacecraft Engineering Model (EM) by reusing tools, test cases, and test scripts from the OBSW test campaign. We propose a testing framework which allows designing test cases, implementing the corresponding test procedures, executing a full test campaign, analyzing the corresponding test results automatically. In particular, the test case implementation can be carried out by means of

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https://doi.org/10.1016/j.measurement.2018.01.014
Received 27 September 2017; Received in revised form 6 January 2018; Accepted 9 January 2018

Please cite this article as: Zoppi, M., Measurement (2018), https://doi.org/10.1016/j.measurement.2018.01.014

an XML-based test procedure language from a more system-level/testing standpoint, independently from the underlying spacecraft model. The proposed cross-model verification approach is currently being used at OHB System AG in different space projects.

The paper has been organized as follows. Section 2 provides an overview of the EPS basic principles. Section 3 outlines the EPS architecture for geostationary satellites. Section 4 is the main contribution of the manuscript, and describes how the EPS functionality can be verified on the spacecraft SW simulators and the spacecraft EM by means of the above-mentioned cross-model verification approach. Section 5 outlines the applicability of the proposed approach for the verification of Cyber-Physical Systems (CPS), being modern space systems an example of CPS [8]. Section 6 concludes the paper.

2. An overview on the EPS functionality

The Electrical Power Subsystem (EPS) is responsible for the spacecraft on-board energy management. It has to provide sufficient power to the satellite subsystems under all the designed operational conditions. To this aim, the EPS is in charge of regulating, controlling, and distributing the power generated by solar arrays and/or batteries [9]. Its main elements are the solar array, the solar array drive assembly, the battery, the battery charge and discharge regulators (BCR and BDR), the bus voltage regulator, the load switching, the fuses, and the distribution harness. Fig. 1 shows the EPS main functions. They are briefly explained hereafter.

2.1. Power source and energy storage

Photo-voltaic solar arrays are the most common power source for satellite, and convert solar radiation into electrical energy. They are made of numerous photo-voltaic cells stacked in series-parallel connections to obtain the desired voltage and current from the assembly.

The battery is made of rechargeable electrochemical cells connected in a series-parallel combination to obtain the desired voltage and current. Its terminal voltage depends primarily on the state of charge and the operating temperature [10]. The battery charge is measured in terms of the ampere-hours stored between the positive and negative plates. The voltage highest value is reached when the battery is fully charged, whereas the lowest one when it is fully discharged. Since the battery works more like a constant voltage source over the normal operating range, its terminal characteristic is generally expressed in terms of the battery voltage versus the state of charge.

2.2. Power regulation and control

If the solar array, the battery, and the loads were operated at the same constant voltage, no voltage regulator would be needed and all the equipment could be wired to the same power bus. However, this is not the case. For instance, the solar array output voltage is higher at the beginning of the satellite lifetime and after each eclipse. The battery has also a lower voltage output during the discharge phase than during the charge one. Since the system is required to provide the loads with a voltage within specified limits, a power regulator is needed to match voltages of various power components during the entire satellite operational lifetime [9].

In selecting a type of power regulation, we should focus on the minimum power losses and mass, while we should maximize reliability, survivability and power quality [10]. In the remaining part of this section, we briefly explore some typical power regulation techniques.

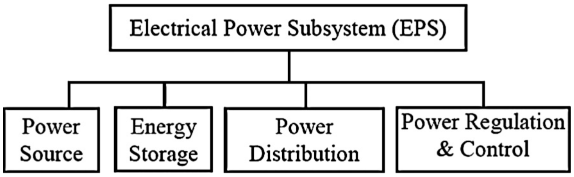

Fig. 1. Electrical power subsystem functionality.

2.3. Direct energy transfer and peak power tracker

In the Direct Energy Transfer (DET), the solar power is transferred to the load with no series component in between. In such a case, the following three configurations are usually implemented [11]:

- Shunt regulation: it dissipates the extra solar array (SA) power by shorting the corresponding amount of solar cells.
- Series regulation: it regulates the SA power delivery by means of a linear power regulator in series with the SA bus.
- String switching: it connects the solar cell strings to the power bus according to the demanded power.

The DET is a dissipative approach because it dissipates the unused power. Power subsystems with shunt regulation are extremely efficient. They dissipate little energy by simply shunting excess power at the array or through shunt resistor banks to avoid internal power dissipation. A shunt regulation solution has also the advantage of having fewer parts and lower mass [10].

The Peak Power Tracker (PPT) is a non-dissipative solution and it extracts the exact power a spacecraft requires up to the SA peak power [12]. In particular, a series DC/DC power converter between the SA and the loads changes the operating point of the SA source to the voltage side of the array and tracks the peak power point when energy demand exceeds the peak power. For this architecture to be cost effective, the power loss in the PPT converter should be less than the gain in operating the system at the peak power point all the time.

2.4. Main bus voltage regulation

There are different EPS primary bus voltage control techniques, which fall into the following categories (see [13,11,14]):

- Unregulated Bus (BU).
- Regulated Bus (BR).
- Semi-regulated Bus (BS).
- Quasi-regulated Bus (BQ).
- Hybrid Bus (BH).

Fig. 2 depicts the different techniques for power regulation. The basic approaches are the PPT, which places a regulator in series between the solar arrays and the loads, and the DET, which uses a regulator in parallel with the solar arrays and loads.

The BU topology has a load bus voltage that varies significantly [15]. Since the battery is directly connected to the bus without a discharge converter in between, the bus voltage is the same as the battery voltage, which varies about 20% from charge to discharge [12]. The BU is an approach to minimize the complexity of the power distribution from solar array and battery to the loads.

The BR topology adopts both charge and discharge regulators. The advantage of this topology is that it behaves as low-impedance power supply, and thus it facilitates the load integration. However, it is a complex power subsystem topology with an inherent low efficiency when the charge regulator uses liner technology [12].

The BS topology is a compromise between the BU and BR topologies [11]. It has the main advantage of having two independent SA buses which increase the level of solar power availability and the whole subsystem reliability. During the battery discharge phase, the bus voltage level normally remains multi volts lower than the bus voltage level during its charge when the battery is detached from the bus by a blocking diode.

In the BQ topology, the bus voltage during the battery charge is