Health Monitoring of digitally controlled flexible converters – Executive Summary Report

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The current power subsystem in spacecrafts rely either on a battery bus or in a regulated bus.

For the battery bus the voltage is the battery voltage, which depends on the state of charge. The battery is charged extracting the energy from a Solar Array (SA) through a Solar Array Regulator (SAR). The SAR regulates the bus voltage once the battery is fully charged.

For the regulated bus the SAR works alongside a Battery Charge Regulator (BCR) and a Battery Discharge Regulator (BDR). These 3 are the 3 different roles that the power conversion subsystem must fulfil. Given that both the BCR and the BDR interface both the battery and the bus, these two are often merged into one called Battery Charge and Discharge Regulator (BCDR).

The bus voltage is kept constant by means of the Main Error Amplifier (MEA) which commands the SAR and BCDR to deliver or extract the power need to regulate the bus voltage regardless of the electrical power demand coming from the rest of the spacecraft. To ensure reliability, the power converters inside SAR and BCDR work in redundant configurations. The MEA, as a critical centralized point is triple majority voted. The MEA command must be distributed to the different elements inside SAR and BCDR in a reliable way.

Leveraging the fact that all the SAR, the BDR and BCR are based on DC/DC power converters one of the objectives of the project is to design a single piece of hardware, called power module, that can act in the three roles. Sharing the same hardware, the SAR, BCR or BCDR role is determined by the programming in the digital inside the power module. Therefore, the module is formed by the power converter and the digital control platform, in the current state the digital control platform is a single FPGA per module.

Reliability is assured by having a decentralized control. This control is privy to each of the modules. Bus voltage regulation, regardless of the demand and the power source nature, battery or SA, is achieved through a distributed control strategy. In this strategy the modules do not share any communication line. The only common point is the bus. The strategy relies in setting the bus voltage is a small voltage range. This voltage range is wider than the allowed one in the regulated bus strategy but much smaller than in the battery bus, which depends on the state of charge. One of the objectives of the project is to evaluate the power quality in terms of voltage range and bus impedance to compare it against the well stablished battery and regulated buses. Additionally, the decentralized control allows for a simplified power scalability. More power modules could be added to increase the spacecraft installed power and to enhance the reliability. The loss of one module will represent a smaller impact if there are many more to share its processed power.

Additionally, to assess the status of the power system during the mission health monitoring techniques are researched. These techniques shall allow to estimate if a power module is prone to failure and will serve to inform the operational decisions, such as command said module to reduce its power or even disconnect it. These health monitoring techniques shall not introduce additional hardware in the converters and shall operate along the control tasks without interfering with the main functionality of the power subsystem. To deliver enough power with the right quality to fulfil the demand.

A complete review of the technical literature was performed, and a quantitative and qualitative evaluation of the different power converter options was carried out. To fulfill the 3 roles, SAR, BDR and BCR the converter must be capable of both stepping up and down the input voltage. Moreover, to discharge and recharge the battery the converter must be able to source and sink power, thus being bidirectional. The review included isolated and non-isolated topologies. Special care was taken in addressing multiport, essentially three port, topologies. After the survey, a well known topology, the four switch Buck-Boost was selected. Then an optimized design process was carried out. The power stage was designed to maximize its power conversion efficiency whilst minimizing the size and mass. State of the art Gallium Nitride (GaN) power transistors were selected as the power switches. To achieve a very high reliability isolation switches were introduced both at the input and the output of the module. These switches are based on Silicon (Si) MOSFETs. Upon a failure, these switches are commanded off and the module is safely removed from the power system. Apart from the typical protections of input and output over current and input undervoltage, a dedicated protection for detecting a failure in the digital control platform is introduced, so upon a failure in the digital platform the module is also removed from the power system. Finally analog interfaces to the digital control platform are included. These interfaces provide input an output voltage and current measurements and inductor current measurements. These interfaces are both used for bus regulation and telemetry purposes. Several prototype design and manufacturing iterations have been carried out. Comprehensive test encompassing the three roles through the full operating range have been carried out. All the requirements regarding the module design have been met.

The control strategy must be tailored to the 3 different roles. Special care must be taken for the SAR role, in which the control must perform Maximum Power Point Tracking (MPPT). This technique allows for extracting the maximum possible amount of power from a SA given the environmental conditions. Decentralized control techniques have been widely researched in the literature, especially in the DC microgrid application. After a full review an interesting technique was selected, simulation and ultimately implemented. This technique is known as DC bus signalling and uses the DC voltage on the bus to command the modules to inject the desired power. The main concept is that all the installed modules will try to regulate the bus at slightly different maximum set-point voltages. The set-point voltage of each module is also reduced with the amount of current that the module must deliver to the bus, thus programming a resistive output impedance. Control is based on the average current or transconductance control. As it is well known, this uses a voltage contralto loop which sets the current reference for a current control loop. The voltage control loop reference is set by a predefined DC voltage minus a quantity depending on the current processed, thus programming an output resistance. Therefore, module with the highest set-point voltage will provide for the full load demand while this demand is lower than the module rating. In this situation the rest of the modules in the system do not process power. Once the demand exceeds the power rating of module, the said module limits its output power, then the bus voltage decreases entering in the regulation range of the second module, which then regulates the bus voltage injecting the needed power to compensate the demand. The BDR role must be treated with care. If the battery needs to recharge and the module behaves as a load to the power bus. The control system has been implemented in one FPGA per module. Each of them is programmed to fulfil the 3 roles. The final role (SAR, BDR or BCR) is configured by command. The full system, control and power stages have been tested in a laboratory environment meeting all the requirements.

Finally, several health estimation techniques have been conceptualized. From a literature survey it was deemed that the most relevant health estimation indicator is the variation of the on-state resistance of the switching power transistors. This resistance is very low and the variations that are a degradation indicator amount for a very low percentage of the nominal value. Moreover, this resistance is also dependant on the temperature of the device, and the variation induced by the temperature surpass the degradation one. Estimating the resistance value and its variations in operating conditions without a dedicated hardware, only using the measurements related to the bus regulation proved to be a challenge. Three techniques were conceptualized. The first one is based on a Kalman filter that can estimate said resistance. By tracking its variations, the health of the module could be assessed. As this resistance increases the efficiency of the converter decreases. By mapping this efficiency in the different operation conditions, it could be possible to identify what transistor is being degraded and how much the degradation has deteriorated the operation. Finally, a machine learning approach was tried. In it a neural network is trained in all operating conditions. The output of such model is then compared to the real measurements. Then this model is subjected to operating conditions in which the transistors have been degraded. If the model output differs by a relevant amount from the measurement, it will be decided that the converter is degraded. All the three techniques were proved through theoretical analysis and simulations. However, only the results with the Kalman filter were good enough to test them with a dedicated test platform. This test platform includes additional hardware to measure such a resistance and thus compare the Kalman estimation with it. It also allows for changing this resistance, by varying the transistor driving voltage. Whilst the results were encouraging, they were very preliminary, and it was decided not to implement it in the final hardware.

At the end of the activity the objectives regarding the decentralized control strategy implemented together with common power hardware modules were all achieved. Thus, a demonstrator of a modular, reconfigurable power system has been met and demonstrated. Regarding the health estimation techniques some promising approaches were identified. These will serve as a basis for future works.