Single Stirling Convertor Controller Spacecraft Interface. M. E. Fraeman, D. P. Frankford, A. L. Shamkovich, R. A. Denissen, JHU/APL, 11100 Johns Hopkins Rd, Laurel, MD, mfraeman@jhuapl.edu.

Introduction: As part of an integrated product team formed in April 2009 by the NASA Glenn Research Center, The Johns Hopkins University Applied Physics Laboratory (JHU/APL) developed an active controller for a single Advanced Stirling Convertor (ASC) for potential use in a Small Radioisotope Power System (SRPS). A single ASC produces approximately 80 W_e and could potentially power a small lander to study the long-term seismology of a planetary body such as that proposed for the International Lunar Network. The JHU/APL Single Convertor Controller (SCC) regulates the alternating current (AC) produced by the linear alternator of the ASC, provides direct current (DC) output power to the spacecraft, and maintains stable piston amplitude within the convertor that can be adjusted by external command. The SCC design can supply power to a spacecraft with either battery or capacitive based power bus architectures. Recovery from a fault in the spacecraft is also supported for both types of power systems. This abstract describes the response of the SCC to both normal and abnormal loads and the SCC capabilities that allow a spacecraft to recover from power faults.

SCC Operation: The SCC consists of two identical control units in separate chassis. During normal operation, one unit actively regulates the ASC and supplies conditioned power to the spacecraft. The other is a redundant backup and is used if a fault is detected in the active controller. The DC output power lines from both units are connected together and to the spacecraft load. Similarly, the ASC AC power is connected to both control unit AC inputs. The backup side is isolated from both the ASC and the spacecraft load through internal electronic circuit breakers that are open in the backup controller. Thus only one unit is active and connected to both the ASC and the spacecraft load. After detecting an internal fault, the active controller opens its input and output circuit breakers to isolate the failure from both the ASC and spacecraft and then the backup controller closes its breakers and actively starts controlling the ASC. The entire switchover sequence occurs in less than 20 ms and simulations show that no electrical or mechanical damage occurs to the ASC or SCC during the brief interval without active convertor control.

The SCC will continue to properly control the ASC even in the presence of a variety of spacecraft load faults. These include high or low spacecraft power consumption as well as a total load open or short circuit. However, some details of the SCC internal circuitry need to be described to explain the controller's response to those conditions and understand the implications on spacecraft operation.

The key element of the SCC is an FET H-Bridge circuit that is pulse width modulated so as to provide the mathematical equivalent of the ideal ASC alternator output load. In response, the amplitude of piston motion within the ASC remains constant. The H-Bridge also acts as an AC to DC converter and boost regulator using the inherent ASC alternator inductance as the resonant element.

DC power from the H-Bridge flows through a high side electronic output circuit breaker to the spacecraft. The circuit breaker is implemented with the equivalent of a pair of series n-channel FET devices. The drain of one FET is connected to the H-Bridge output while the drain of the other FET is connected to the spacecraft load. The inherent stray source-drain diodes of the two devices blocks current flow in either direction when the circuit breaker is turned off. Thus when both FETs are on or off the H-Bridge can be connected or isolated from the spacecraft.

In addition, there is a small (compared to the alternator) inductor between the source nodes of the FETs that form the DC circuit breaker. This inductor, along with the FET whose drain is connected to the H-Bridge output, and an additional diode (connected with anode at ground and cathode at the FET source) form a switching buck regulator. This buck regulator is used to implement a soft-connect to the spacecraft load as described below.

There is also a power absorbing shunt resistor network connected to the H-Bridge output. This circuit is controlled solely by the SCC and is only activated if the DC circuit breaker is opened. While the DC breaker is open, power from the ASC is dissipated in the SCC shunt so that the operating conditions of the ASC are unchanged. The SCC shunt is totally independent of the spacecraft power systems electronics (PSE).

Spacecraft Load Response: The SCC delivers all available SRPS power to the spacecraft when its power bus voltage is between 22V and 36V DC. That voltage range was chosen for compatibility with a typical Lithium ion type battery based direct energy transfer (DET) PSE architecture. A DET design maintains the battery's state of charge by directly connecting it to the power bus and then controlling the total load so that voltage, and hence state of charge, is as desired. Excess power required by the spacecraft, beyond that available from the SRPS, is supplied by the battery. As the battery is discharged the bus voltage is reduced. Once the spacecraft power consumption is reduced below what the SRPS can supply, the PSE can use the excess power to restore the battery's state of charge. A spacecraft with a capacitive based power architecture can maintain much tighter voltage control since that design must always absorb all power in its load and PSE shunts and can never use more than is available.

Normal load. During normal operation the SCC will be configured with the AC and DC circuit breakers of the active controller enabled and its H-Bridge controlling ASC operation and supplying DC power to the spacecraft. The spacecraft should absorb all SCC output power (power delivered to the SCC input minus conversion/control loss in the SCC circuits) and hold the bus voltage as required by the spacecraft. A common spacecraft PSE design approach sends excess power not used for other purposes through a shunt resistor network (note that this is not the SCC shunt network previously described). The PSE controls its shunt network impedance so as to maintain the desired spacecraft power bus voltage.

Low voltage or high current load. A variety of faults can occur on the spacecraft that could reduce the power bus voltage below the SCC limit. Power used by the spacecraft loads could exceed that delivered by the SRPS. A battery, if present, could supply any required extra power until the battery was discharged so far that the bus voltage fell too low. If no battery was present, the high load would quickly discharge the bus capacitance and then the bus voltage would drop. An inadvertent short circuit, such as might occur during spacecraft integration, might also cause low voltage. The SCC will respond to these low output voltage faults by opening its DC circuit breaker and thus stop delivering power to the spacecraft.

The DC breaker will also open if excessive load current (>24A) is detected. That condition may occur when connecting to a load without proper in-rush current limiting. Another cause may be a short circuit to a different voltage. The SCC continuously detects overcurrent with analog circuitry. In contrast, spacecraft bus voltage is sampled approximately every 40 μsec so the SCC is likely to respond more quickly to an overcurrent fault.

High voltage load. If the spacecraft allows the load voltage to exceed the SCC upper limit then the DC circuit breaker will also open. Since the DC breaker is open during this fault, the SCC will continue to control ASC operation while dissipating power in its internal shunt rather than supplying power to the spacecraft.

Load Fault Recovery: Recovery from a load fault requires provisions be included in both the spacecraft and the SCC.

Spacecraft response. No matter what caused the SCC to disconnect, when the spacecraft detects that it is not receiving power the spacecraft should reconfigure itself to minimize load and then wait for the SCC to attempt to reconnect as described below. A capacitive bus based spacecraft is unlikely to be able to reconfigure after a low voltage fault since no power is available to run even a minimal set of loads. In that case, the spacecraft should be placed in a state that supports initial power up when the SRPS reconnects. A battery based spacecraft should be designed to prevent bus voltage from going low enough to trip the low voltage limit. This limitation could be removed with a more complex PSE design.

SCC response. Simply closing the DC circuit breaker to reconnect to the spacecraft is impractical. The H-Bridge output voltage is unlikely to match the bus voltage, even after the spacecraft clears a load fault condition, so large currents would flow. Instead the SCC operates the switching buck regulator within the DC circuit breaker with a duty cycle that is linearly increased from 0% to 100% over 20 seconds. The buck regulator limits current during ramp up time while gradually matching the internal SCC H-Bridge voltage to the spacecraft bus. After successful conclusion of the buck ramp, the DC circuit breaker is fully closed and the SCC delivers full power to the spacecraft.

However, there are conditions that will, if detected, open the DC breaker and stop the ramp prior to its completion. If too much instantaneous current flows into the load then the overcurrent analog circuit previously described will trip and open the DC breaker. There is a minimum H-Bridge allowable output voltage required to maintain proper operation of the SCC internal circuits. Hence H-Bridge output voltage is also sampled and if it drops below 20 V, the DC breaker is opened and the reconnect ramp is terminated.

The SCC strategy for using the soft reconnect capability described above is for the active controller to make up to three soft reconnect attempts. If all those attempts fail, the SCC will switch controller sides in case there was a fault in the reconnect circuitry. The backup controller side will then repeatedly attempt to reconnect to the spacecraft without limit.

Conclusion: We have developed an active controller for the SRPS with a robust spacecraft power interface. Our controller tolerates a wide range of load faults and provides the capability to implement a robust spacecraft systems design that can autonomously recover from those faults.

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