Control and Power Electronics for a Two-Stage Turbo-Brayton Cryocooler for Space Applications

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ABSTRACT

Last year saw the successful demonstration of an autonomously controlled two-stage turbo-Brayton cooler. The electronics developed for this demonstration evolved from the seminal work of the NICMOS cryocooler, the first flight-qualified turbo-Brayton cryocooler. Two key features of the electronics are the ability to control temperature without the use of trim heaters and the ability to recover expander power back to the main power bus. The development of the control and power electronics for this two-stage cooler was the first step toward a space qualifiable design. The technical challenges, solutions and performance of the electronics for the two-stage turbo-Brayton cooler are presented.

INTRODUCTION

Turbo-Brayton cryocoolers are attractive options for a variety of space applications because they have demonstrated long-life, produce no significant export vibrations, and simplify integration with payloads and spacecraft systems. In 2002, the first space-qualified turbo-Brayton cryocooler was installed on the Hubble Space Telescope to cool the NICMOS detector.[1,2] This cryocooler uses a high-frequency centrifugal compressor operating between 5000 and 7500 rev/sec driven by a power inverter that converts the variable dc bus voltage to a regulated three-phase ac voltage. The inverter uses conventional pulse width modulated circuitry to provide the necessary power and control to the compressor. It also incorporates filters to correct the power factor to the motor and to reduce EMI. The inverter supplies approximately 350 W to the compressor motor. There is a single turboalternator stage providing refrigeration at 72 K. Refrigeration power produced by the turbine, on the order of 12 W, is absorbed in a resistor bank.

In 2004, Raytheon teamed up with members of the NICMOS cooler development team, Creare Inc. and Jackson and Tull Engineering, to extend the capability of turbo-Brayton technology. A two-stage design was undertaken, in which turbine stages at 100-120 K and 65-75 K would be controlled independently while driven in parallel by a single compressor. In late 2007, this two-stage development effort culminated in the successful demonstration of autonomous temperature control at two different heat loads.

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Though functionally similar to the NICMOS design, the electronics for the two-stage system incorporated some significant advances. Table 1 summarizes the key differences between the two systems. An advance in the electronics hardware is the change in switching logic for the power electronics from discrete components in the NICMOS system to FPGA logic in the two-stage system. The change from the classic PWM inverter topology for the compressor drive to the transformer-coupled rotating field inverter (RFI) was necessitated by the need for higher ac power and voltage levels in the two-stage system.

The important advances over the NICMOS system were in turbine power recovery and speed control. As a single stage system with a single temperature to control, NICMOS only required one control input, which was the compressor speed. There was no direct control of the turbine speed, which changed modestly with commanded changes in the compressor speed. This was perfectly acceptable in the one-stage system. The two-stage system, with two temperatures to control, requires a minimum of two control inputs. Three are provided to obtain maximum control authority, compressor speed, and two turbine speeds. In addition, the power electronics that load the two turboalternators return the generated power to the dc bus; reducing the system input power by about 20 W. In the NICMOS system, this generated power, which was about 12 W, was dissipated in load resistors.

The following sections of the paper describe the electrical drives, control and telemetry for the three turbomachines in the two-stage system, followed by a review of preliminary test results that demonstrate the two-stage temperature control. The mechanical cryocooler design and thermodynamic performance are described in another presentation at this conference.[3]

Table 1. Comparison of NICMOS and Two-Stage Systems

	NICMOS	**2-Stage System**
Compressor Inverter	Classic 3-Phase PWM 3 MOSFET half-bridges No Transformers	Rotating Field Inverter 6 MOSFET half-bridges 6 Transformers
Inverter Switching Logic and Controls	Discrete Electronics	FPGA
Compressor Voltage Regulation	PWM Modulation Index	Switching Duty Cycle
Compressor AC Voltage Upper Limit	28 V Bus Voltage	Tailor to Motor Design with Transformer Turns Ratio
Compressor Slip Control	Sense Shaft Speed Adjust AC Voltage	Sense Shaft Speed Adjust AC Voltage
Compressor Power Factor Correction	Capacitors Cancel Motor Inductance Filter Inductors Block Switching Harmonics	Capacitors Cancel Motor Inductance Filter Inductors Block Switching Harmonics
Refrigeration Loads	Single Stage (70-75 K)	Two Stages (100-120 K, 65-75 K)
Turboalternator Power Transfer	Dissipated in Load Resistors at Heat Rejection Temperature	Recovered at DC Bus via Rectifier and Voltage Boost Electronics
Turboalternator Speed Regulation	None	Voltage Boost Duty Cycle
Temperature Control Strategy	Vary Compressor Speed to Regulate Single Load Temperature	Vary Compressor Speed, Stage 1 TA Speed, and Stage 2 TA Speed to Regulate Two Load Temperatures and Minimize Compressor Power
Temperature Control Implementation	8051 Microprocessor	8051 Microprocessor
Turboalternator Startup	Pressure Differential at Compressor Start	Low Voltage PWM Inverter or Pressure Differential at Compressor Start

Overview of the Electronics for Two-Stage Systems

Figure 1 shows a block diagram of the electronics system for the present two-stage turbo-Brayton cooler. The system consists of three turbomachines: a compressor and two turboalternator (TA) expanders, one for each stage. The compressor is driven with an induction motor. The turboalternators have permanent magnet motor/alternators. The electronics unit consists of power electronics modules that drive the three machines, logic modules that provide switching signals to the power electronics, and a microprocessor-based controller that processes telemetry and provides top level commands for speed and voltage to the logic modules.

A fully-redundant flight version of the electronics unit is expected to weigh approximately 18.6 kg (41 lbs) or 9.3 kg (20.5 lbs) per cooling stage. The dimensions are expected to be 14.00 in. x 8.25 in. x 12.35 in. Table 2 shows the projected power levels and losses for the electronics in a flight system at a typical operating condition.

Turboalternator Control

During normal operation, refrigeration power produced by the expansion of the cycle gas in the turbine rotors is absorbed by the alternators and transferred to an electrical load at the cycle heat rejection temperature. The electrical load for the NICMOS system was a bank of fixed resistors. Though this arrangement was simple and reliable, the power (about 12 W) was not recovered and there was no means to vary the speed of the turbine during normal operation. The electrical loads in the two stage system consist of conventional bridge rectifiers to convert the ac alternator output to dc, followed by a dc-dc converter to boost the dc level to the 28 volt bus. This Rectifier-Boost Converter (RBC), shown as the speed control module in Figure 1 and in the simplified schematic form in Figure 2, recovers the turbine power at the dc bus, effectively reducing the system input power by 10-20 W. Furthermore, it allows the turbine speed to be varied through variation of the switching duty cycle of the boost converter. The duty cycle sets the ratio of output voltage (28 V bus) to input voltage (rectifier). Since the output voltage is set by the input supply bus, the duty cycle determines the rectifier voltage which sets the ac voltage at the alternator terminals. The ac voltage is approximately proportional to speed.

With turbine speed variation being used to vary refrigeration power, the control system can accurately maintain constant load temperatures as the cooling loads are varied from 0 to 100% of their design values. This avoids the need for trim heaters at the loads, which are normally used in Stirling-class cryocoolers where the refrigeration produced by the cryocooler tends to be fixed.

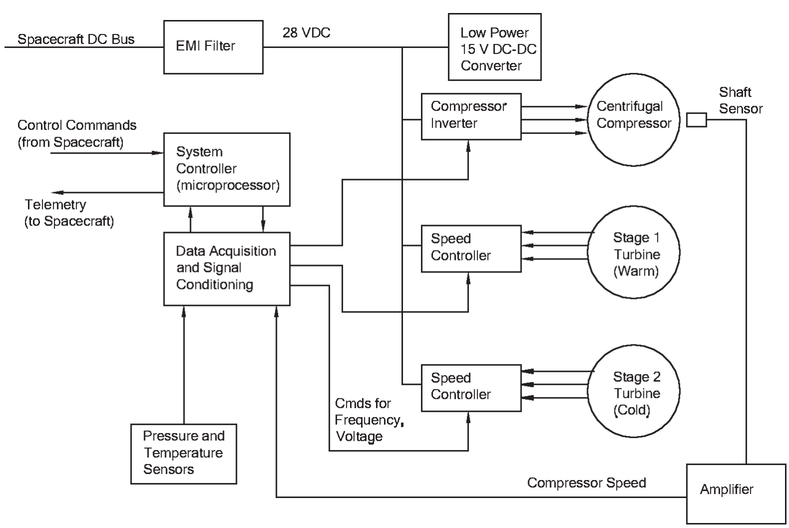

Figure 1. Electronics for Two-Stage Turbo-Brayton Cryocooler

Table 2. Projected Power Values for Flight Electronics

	Average	Max
Overhead Power (includes sensors and harnesses)	34.3 W	53.2 W
Compressor Inverter AC Output Power	251.9 W	359.9 W
Losses in compressor inverter	13.1 W	20.1 W
Turboalternator AC Power (Returned to RBC)	-13.9 W	-18.1 W
Losses in Turboalternator RBC	2.4 W	3.1 W
Total Cryocooler Electronics Input Power	**287.8 W**	**418.2 W**

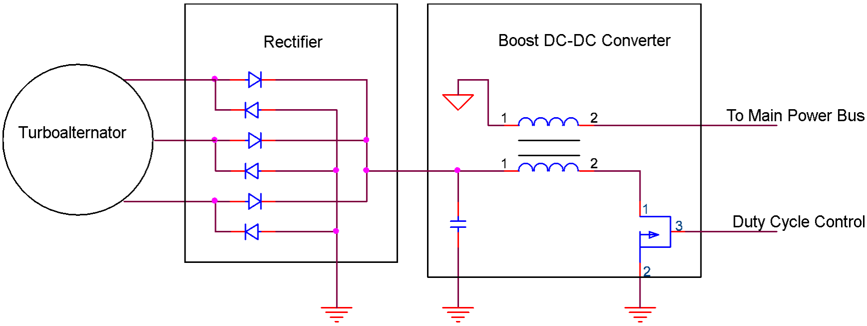

Figure 2. Simplified Schematic of Rectifier Boost Converter

The only practical limitation in the initial embodiment of the two-stage speed control electronics is the relatively coarse resolution of the boost duty cycle command, which has an increment of 0.66%, characteristic of the system clock frequency. To remedy this constraint, a closed loop current controller is under consideration where the duty cycle will be set within an analog control loop that will be closed between sensed current and a 12-bit current command. The present electronics contain the current sensors but the signal is used only for thermal protection of the turboalternators. The turboalternator speed is also sensed to ensure compliance with upper and lower limits for safe and efficient operation. This is obtained by measuring the fundamental frequency of the ac voltage; a mechanical speed sensor is not required.

Compressor Control

The compressor inverter uses the rotating field inverter (RFI) topology shown in Figure 3, in place of the PWM inverter used in the NICMOS cooler. Advantages of the RFI include lower harmonic content in the stepped sine wave voltage, and the ability to accommodate a range of motor voltage requirements through modification of the transformer turns ratios. Operational adjustments to the motor voltage to obtain changes in compressor power and speed are made through the voltage step duty cycle, which is a commanded quantity. The embedded temperature controller will command changes in compressor speed through the frequency and duty cycle commands when changes in refrigeration power are required that exceed the amount of change that can be generated by allowable turbine speed adjustments. This is done by first commanding a change in inverter frequency roughly equal to the desired change in compressor speed. Then the duty cycle is adjusted to maintain an induction motor slip (difference between frequency and speed) of around 4%.

To obtain an accurate measurement of slip, the compressor speed is sensed using capacitive sensors and associated amplifier electronics. A 90 V dc bias applied through a large resistance maintains a nearly fixed charge on a stationary electrode adjacent to the shaft. The run-out or a physical marking on the shaft modulates the gap between the shaft and electrode, and the capacitance varies inversely with gap. Since the charge is fixed, the capacitance variation produces a weak voltage signal at the electrode. High gain amplification of the signal allows the speed to be detected.

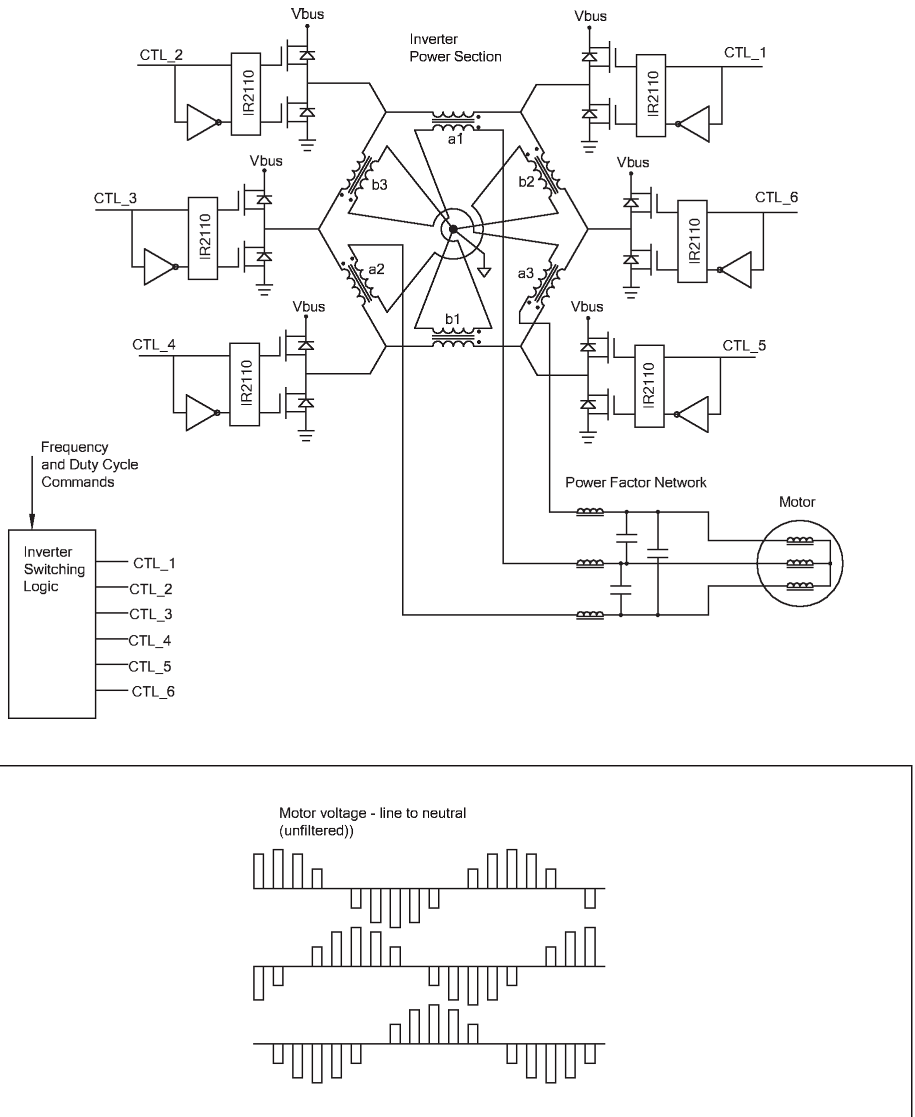

Figure 3. Simplified Schematic of Rotating Field Inverter

Due to the small signal level at the electrode and the proximity of the electrode to the motor drive, this amplification and detection process has always presented a challenge. A major improvement for the two-stage system was the addition of a JFET buffer circuit in close proximity to the compressor housing. With the buffer circuit able to drive the sensor's cable capacitance, the signal level at the amplifier input increased by about a factor of six, allowing the amplifier gain to be lowered accordingly. The result was a much cleaner signal from which speed could more easily be detected.

Telemetry

Telemetry sensors for the cooler include the compressor speed sensor discussed above, cycle pressure transducers and several temperature sensors. These sensors are located close to the turboalternators and compressor motor, creating challenges to preserving signal integrity during transmission to the telemetry processor. High power 3-phase noise is the main obstacle, as the compressor requires approximately 360 W under full load. Noise is a particular concern as the temperature sensor and shaft speed sensor outputs are amplified prior to transmission to the telemetry processor. To ensure maximum signal integrity, proper bypassing of the telemetry amplifiers is critical. Additionally, cable shielding and signal routing is key for accurate sensing of telemetry in the cooler environment. A multilayer shielding scheme using both the chassis and signal grounds was employed to minimize noise coupling over the cable run. Coax and twisted shielded conductors also assisted in preserving signal integrity.

System Startup

In addition to the rectifier/boost electronics, each turbine speed control module contains a low power Startup Inverter (SUI) based on the classic 3-phase PWM topology. Although the turbines can be started pneumatically, driven by the pressure difference produced when the compressor is started, it is possible to reduce loads and resulting wear on the gas bearing surfaces at the instant of start by bringing the turbines up to speed with the SUIs prior to starting the compressor. A 3-phase motor would ideally be driven by a 3-phase sinusoidal waveform. The PWM design takes advantage of the inductance of the turboalternator windings to smooth the PWM drive signal into a pseudo-sinusoid. Because the turboalternator is a permanent magnet motor and does not contain a shaft position sensor, the SUI must be capable of starting the turboalternator from any shaft angle. To ensure successful starts regardless of shaft angle and keep the shaft synched to the PWM drive throughout the startup sequence, the SUI PWM drive must be able to smoothly transition through a frequency range from 0 to 2000 rev/s. Smooth transitions require high PWM resolution which is realized using FPGA logic and a 12 MHz clock. The SUI logic allows the startup profile to be tuned via the commanding of a final startup speed and ramp rate. The ability to smoothly move through the frequency range without large frequency jumps near zero allows startup of the turboalternator regardless of shaft position.

Once the two turboalternators and compressor are spinning at their respective initial speeds, transitioning from the SUI drive to the RBC load is a simple "handover" process in which the SUI drive is disabled and the boost converter duty cycle is enabled. To maintain a near constant turboalternator speed during handover, the appropriate duty cycle, and thus turboalternator loading, is selected to balance the pneumatic power from the compressor. A typical "handover" is shown in Figure 4. In this example, the duty cycle was selected to approximate the 2500 rev/s startup speed, yielding a turboalternator speed of 2649 rev/s after "handover".

Both pneumatic and electrical methods for starting the turbines have been used successfully to date. Further testing is planned to determine if there is sufficient benefit to the bearings from the electrical start method to justify the added complexity of including the SUIs in the system.

PERFORMANCE

The control electronics when coupled with the control software allowed very tight control of two separate temperature interfaces. The design goal for Stage 1 was ±1 K accuracy. The design goal for Stage 2 was ±0.25 K accuracy. In both cases, the cooler outperformed the design goal. As shown in Figure 4, the Stage 1 achieved ±0.1 K accuracy, and the Stage 2 achieved ±0.05 K accuracy. In Figure 5, note that the cooler control system operates on flight-like sensors with the indicated stage 1 and 2 resolutions, while the actual data plotted is from the ground support temperature sensors. The ground support sensors have a significantly finer resolution, accounting for the discrete steps visible on each temperature plot. Tighter temperature control can be achieved if needed for future applications by improving temperature sensing, signal conditioning, and duty cycle resolution.

CONCLUSION

Evolved from the NICMOS cooler, the successful demonstration of autonomous temperature control at two heat loads last year proved the viability of the electronics designed for the two-stage

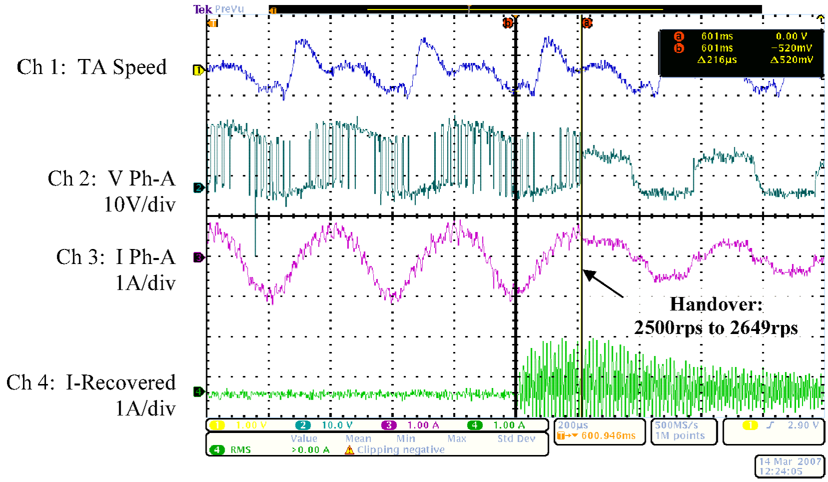

Figure 4. Turboalternator Handover

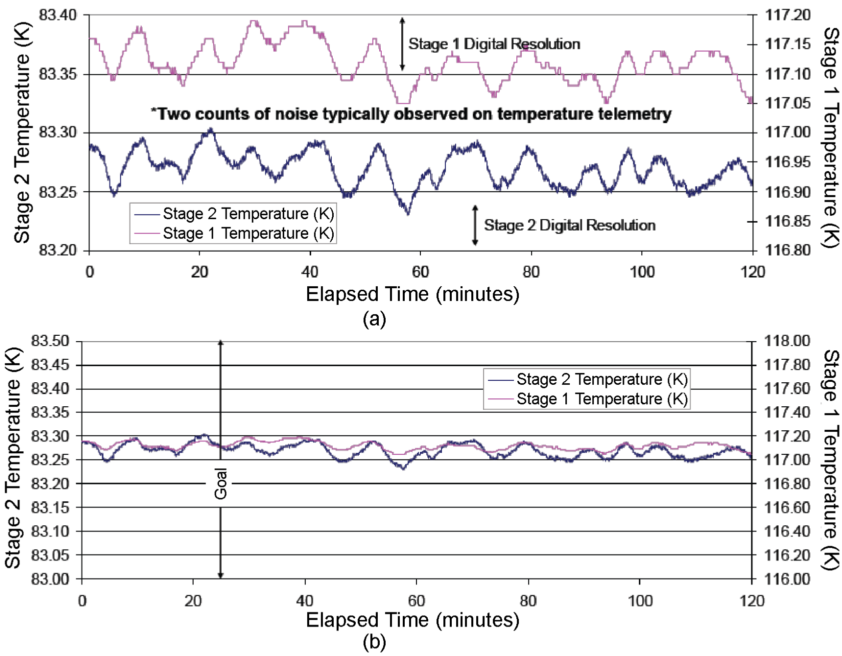

Figure 5. Temperature Performance (a) flight-like sensors, (b) ground support temperature sensors.

turbo-Brayton cryocooler. The two stage cooler achieved autonomous performance with accuracy better than +/- 0.1K at each stage without the use of trim heaters. The system was consolidated by placing discrete power control logic into an FPGA. Increased system efficiency was realized in the design of the turboalternator speed control circuitry by recovering turboalternator power as opposed to dissipating it in a resistor load bank. The RFI was implemented to accommodate the higher power and voltage required by the compressor. Lessons learned include developments in robust telemetry sensing including cable shielding and signal buffering. Future enhancements to this design include eliminating the start-up inverters with the development of means to start the turboalternators with the compressor, and the use of closed loop current control to improve the performance of the temperature control.

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