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PERFORMANCE OF THE ELECTRICAL CONTROLS FOR THE MINI-BRAYTON SYSTEM

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SUMMARY

The design theory and performance of a breadboard of the proposed Mini-Brayton electrical control system is presented. The Mini-Brayton is a nuclear isotope powered dynamic power conversion system. Testing was performed with an electronic simulation of a turbine alternator. Data on the voltage regulation, speed control, power consumption, reliability, and transient response are presented for the breadboard.

INTRODUCTION

The Mini-Brayton Power System can provide up to 2-kilowatts of conditioned electrical power for space applications by conversion of heat to electricity at an expected overall system efficiency of about 30 percent (ref. 1). The heart of this thermodynamic conversion system is a turbine-compressor-alternator operating on a single rotating shaft which is supported on bearings lubricated by the inert working gas of the system.

The system uses as primary energy the heat of decay of radio isotopes and is presently conceived to utilize the AEC multi-hundred-watt heat source. Electrical power is delivered to the user bus at a conditioned 120 volts dc (±0.5 percent). The system has an anticipated specific power of about 1.5 watts per kilogram (3 W/lb) at 2 kilowatts electric output.

The Lewis Research Center has been involved in Brayton cycle power systems since 1963. A 2- to 15-kilowatt Brayton engine was developed (ref. 2) and has operated for over 20 000 hours. The Mini-Brayton system is a continuation of this technology for the 500- to 2500-watt power range.

One component of the Mini-Brayton is the electrical control system which performs the several functions of user bus voltage regulation, turbine-compressor-alternator rotating unit speed control, and system startup control (not including the startup power source). The technology for Brayton control systems has been an active program at the

Lewis Research Center since 1964. The concept and circuitry for this Mini-Brayton electrical control system represents the most advanced of this technology to improve reliability, reduce complexity, reduce the electrical power consumed by the controls, reduce the weight, and lower the cost.

This report presents the design and measured performance (laboratory breadboard model) of this Mini-Brayton electrical control system. The report discusses the approach used to achieve the design technology goals, functionally describes the control system, and presents measured performance data. The report is directed to the systems engineer interested in the overall concepts and performance of this Mini-Brayton component.

DESIGN OBJECTIVES

In the design of the electrical control system, the following objectives were adopted:

(1) High reliability
(2) Minimum complexity
(3) Low power loss
(4) Light weight
(5) Low cost

These objectives are highly interactive, and are listed in the order of importance.

Reliability being most important, a no single failure criteria was adapted. That is, essentially any single component failure will not noticeably affect the normal operation. Implementation of this concept, although increasing the complexity, power loss, weight, and cost objectives, provides an order of magnitude improvement in the calculated 10 year reliability over a nonredundant approach. In addition, component derating, in terms of voltage, current, power, temperature, gain, and safe-operating area, was used to further improve the reliability. Finally, circuit concepts were chosen in which component tolerances were not critical and, therefore, degradation during operation is not serious, and the use of precision, matched, or adjustable components is minimized.

Complexity is minimized by the extensive use of integrated circuits, and multifunction use of circuits. For example, one speed sensor is used to control alternator speed, provide overload capabilities, underspeed shutdown, and automatic sequencing during startup. Also, standardization was used to the maximum extent possible, resulting in a minimum of different component types being used. This latter approach would ease conversion to hybrid circuits which would yield significant size and weight improvement.

Low power loss is desirable for three major reasons. The lower resulting temperatures of the components improves reliability and allows more compact packaging. Also, more power is available at the output, and low power loss reduces the size of the radiator required to cool the system. Low power loss is provided primarily by the use of low power integrated circuits and high efficiency switching in power control circuits.

Weight and cost are secondary considerations to all the aforementioned objectives and the design was not compromised to achieve these. However, many of the techniques discussed under complexity and power loss contribute to light weight and low cost. Using these techniques the weight and cost of the electrical system will be only a small fraction of the total power conversion system.

ELECTRICAL CONTROL SYSTEM

The electrical control system performs the functions of alternator output rectification, output voltage filtering, output voltage regulation, overload control, alternator speed regulation, and control of the system startup.

Rectification converts the three-phase alternator output to dc for the user loads. Filtering minimizes the noise on the user bus generated by the rectification and speed control.

The voltage regulator maintains constant user bus voltage with a feedback system sensing the output voltage and controlling alternator field current. Overload protection for the user is provided by reducing the bus voltage whenever the user bus is overloaded. During severe overloads, the user bus is turned off momentarily to protect the alternator and maintain operation of the power conversion system.

During normal operation the power conversion system may be producing more power than is required by the user. Any excess power is dissipated in a parasitic load, holding the total alternator load (user load plus parasitic load) constant, maintaining the alternator speed constant at the design point.

Startup is mainly controlled by the motor starting inverter, which is not discussed in this report. However, at the appropriate times in the startup sequence the field is automatically flashed, and the voltage regulator and speed control are enabled by the electrical control system.

A block diagram of the electrical control system, providing all the above functions, is shown in figure 1. The alternator is a 4 pole modified Lundell, or Rice, alternator, operating at 52 000 rpm, 1733 hertz (ref. 3). The voltage regulator preamplifier senses the output voltage and controls the field driver which regulates field current. The speed sensor senses rotation of the alternator by magnetic pickups at the compressor wheel. The speed sensor controls the parasitic load through the parasitic load driver and the voltage regulator for overload control. During an overload, the alternator slows down. The regulated output voltage is reduced as the speed decreases, thereby reducing the power to the user load. If the overload reduces the speed too far, the underspeed voltage-cutoff circuit turns off the voltage regulator completely, allowing the alternator to regain speed. The power supply and modulation oscillator (not shown) supply operating power to the circuits and control the switching of the field and parasitic load drivers.

Testing of a laboratory breadboard of this circuit was performed, using an electronic simulator for the turbine-alternator-compressor assembly. The simulator could not provide short circuit data, but provided a nonlinear dynamic simulation of the predicted turbine-alternator assembly performance. The electrical performance goals were based on MIL STD 704. MIL 704 describes 28-volt dc systems, and the specifications were developed by translating MIL 704 to 120 volts dc, for the voltage regulation and transient performance goals. All testing was done in a room ambient, but separate subcircuit tests have indicated the expected temperature variation (0° to 50° C) will not affect the performance. The breadboard electrical control system is shown in figure 2. It mounts in a standard 48-centimeter (19-in.) relay rack.

Test results in figure 3 show the output voltage as a function of gross alternator power and as a function of user load for a constant alternator output of 2 kilowatts. In both cases, the variation from 120 volts dc is less than 0.5 percent. Figure 4 shows the overload characteristics. Output voltage is plotted against the nominal load power (if 120 V dc was maintained) for a nominal 400-watt alternator power output. As the load is increased above 400 watts, the output voltage decreases to maintain the actual output power at 400 watts. The underspeed shutdown turns off the voltage regulator at approximately one-half voltage (66 V dc). Thus, continuous reduced voltage operation is obtained for better than three times rated load. This figure is similar for any gross alternator power level.

Figure 5 shows the envelopes of the transient performance during user load switching. The translated MIL 704 specifications are also shown. Short circuit performance was not tested because of the alternator simulator limitations, but is not expected to exceed the design limits. Load switching was accomplished with a transistor controlled load bank providing microsecond switching times.

Figure 6 shows a typical (10 to 85 percent load) switching transient. Worst case transients (100 percent overload to 1 percent load) were 23 volts peak, and required less than 20 milliseconds to recover to the steady-state regulation limits.

MIL 704 ripple voltage specification is 2 volts peak for a 28-volt system. This system's ripple is typically 1 RMS, 6 volts peak. The main frequency component is approximately 5 kilohertz, the switching frequency of the parasitic load and field controller.

There are two main effects of power losses in the electrical control system. Any power loss results in a decrease in system efficiency and therefore, maximum output power, and the power loss also presents an additional thermal load to the radiator, increasing system weight. Power losses in the electrical control system occur in the rectifiers, the parasitic load driver, the field driver, and in the low level control circuits.

The maximum power loss occurs at zero user load, with all the power dissipated in the parasitic load. Approximately 2 kilowatts will be dissipated directly by the parasitic load, but at a high temperature (1200^{0} F), and requires only a small area because of the high temperature. The power loss (at zero useful load) in the electrical control system under these conditions is approximately 100 watts. Fifty watts of this is from the rectifiers on the alternator output, 20 watts for control circuits and field driver loss, and 30 watts in the parasitic load driver. Electrical package cooling must be designed for this condition.

At maximum useful load (2 kW), the rectifier loss is still 50 watts, but the control power and field driver loss is reduced to 10 watts, and there is no parasitic load driver loss. For other power levels, rectifier loss is proportional to output power, so at a 400 watt level, the rectifier loss is about 10 watts, but the control power and field driver loss are constant at 10 watts. Thus, at 2 kilowatts the electrical control system is 97 percent efficient, decreasing to 95 percent at a 400-watt level.

Alternator frequency is plotted as a function of gross power and user load in figure 7. When the user load exceeds the gross alternator power, the output voltage is reduced, providing the overload capability. In the 10 to 85 percent user load region of the curves, the speed change is around 0.1 percent per kilowatt (ref. 5), resulting in a torque impulse to the spacecraft of 12×10^{-6} (m)(kg)(sec^2)/kW [0.01 (in.)(lb)(sec^2)/kW]* load change. The alternator acceleration is shown in figure 8 for 10 to 85 percent load transients at the 2-kilowatt power level. Maximum acceleration is 2.5 hertz per second. Peak torque is therefore 2.0×10^{-5} meter-kilogram (0.017 in.-lb).

Alternator speed changes, and, therefore, rotational torque applied to the spacecraft, is very small for load transients. Speed changes considerably as a function of gross power level and possibly temperature changes, but these slow changes should not have a serious effect on spacecraft attitude control.

For more critical applications, two additional concepts are under possible consideration. The first is a high accuracy digital speed control used in conjunction with the existing analog control described. This control has little effect on the transient performance, but maintains long term speed control within 0.01 percent. This system has been built and tested with the breadboard control system and performed as expected.

The second concept allows the spacecraft to exercise control of the alternator speed. By externally applying a voltage input, the alternator speed could be varied ±1 percent about its normal speed to correct for speed control deficiencies, or more usefully to provide an attitude control similar to that obtained when using a reaction wheel. Thus, attitude adjustments could be made without expending any fuel for reaction jets, and so forth. These small speed changes would have no effect on the Mini-Brayton engine performance.

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*Predicted rotor inertia = 2.54×10^{-6} (m)(kg)(sec^2) or 0.0022 (in.)(lb)(sec^2).

Electrical system reliability has been calculated to be approximately 0.99 for 10 years. This is based on complete redundancy at all points in the circuit, which has been experimentally verified in the breadboard unit. The maximum effect of any single failure is the deterioration of speed control to the ±2 percent range and changes in the overload performance.

CONCLUSIONS

A breadboard electrical control system was developed and tested on an electronic alternator simulator. The following performance was obtained:

1. Voltage regulation was approximately ±0.5 percent for power input and load variations. An overload circuit reduces output voltage during overloads.
2. Speed regulation is 0.1 percent per kilowatt for load changes, limiting the maximum transmitted torque to 12×10^{-6} (m)(kg)(sec^2)/kW [0.01 (in.)(lb)(sec^2)/kW]. This torque can be further reduced by an optional addition to the speed control or used to control attitude by a command from the spacecraft.
3. Electrical control system efficiency varies from 95 percent for a 400-watt system to 97 percent at the 2-kilowatt level.
4. An electrical control system reliability in the order of 0.99 for 10 years is attained through a highly redundant no single failure concept. Single component failures have a minimal effect on system performance.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 5, 1974,
502-25.

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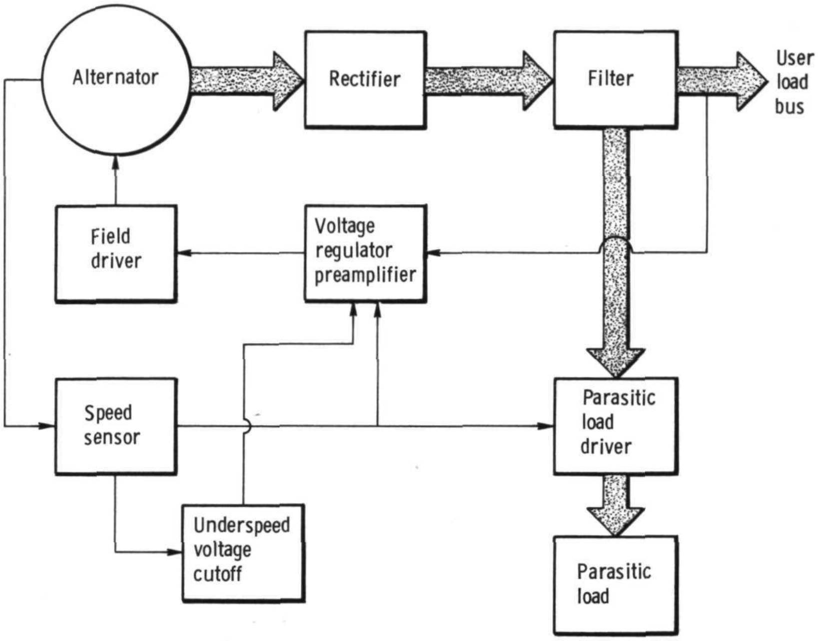


Figure 1. - Mini-Brayton electrical control system.

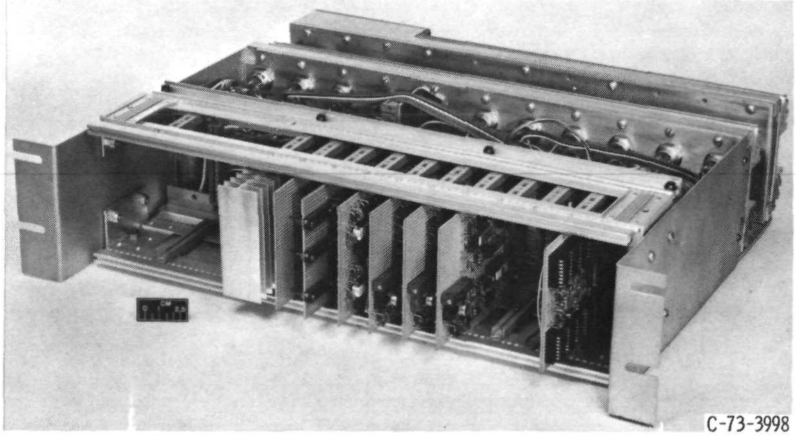
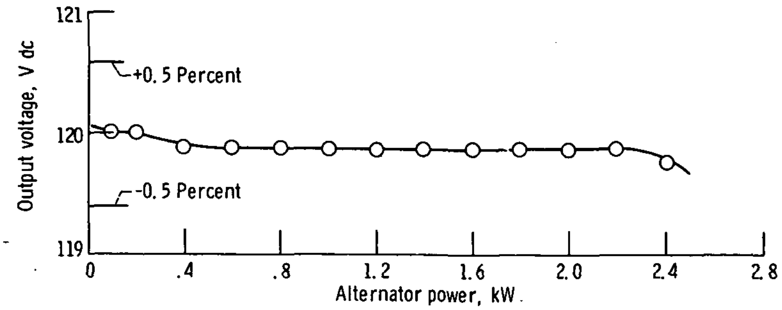
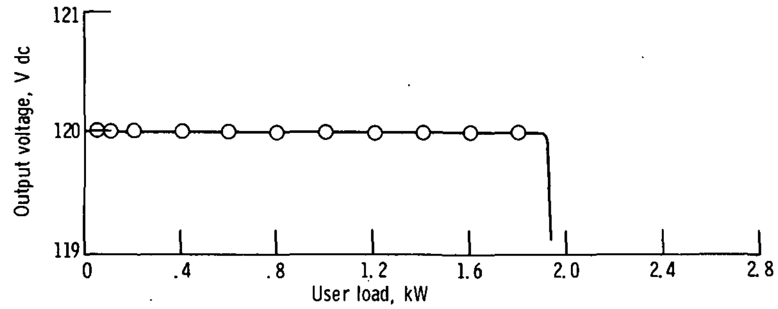


Figure 2. - Mini-Brayton electrical control system breadboard.



(a) Regulation as a function of gross alternator power. User load, 0.



(b) Regulation as a function of user load. Gross alternator power constant at 2.0 kilowatts.

Figure 3. - Output voltage regulation.

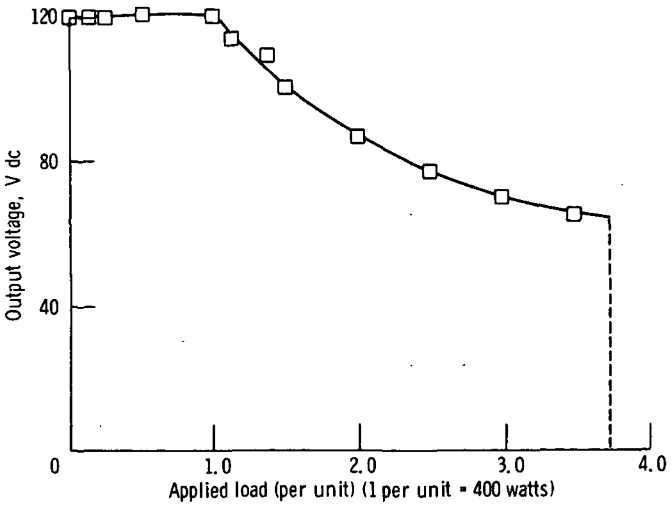


Figure 4. - Overload characteristics. Gross alternator power, 400 watts.

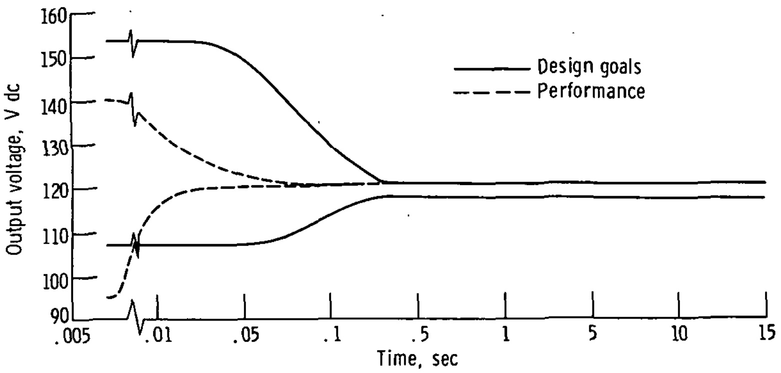


Figure 5. - Transient responses.

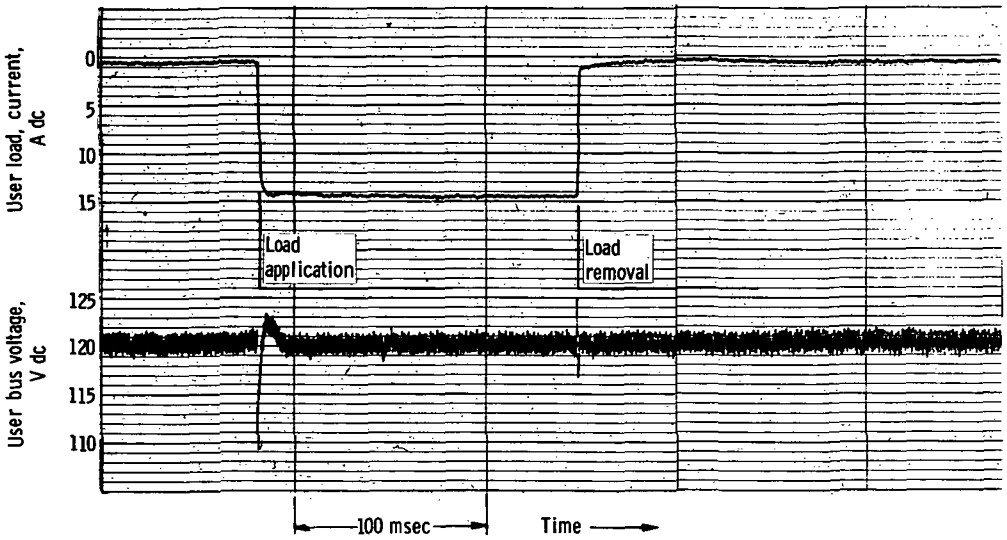


Figure 6. - Bus voltage transient response. Load switching, 10 to 85 percent; gross alternator output, 2 kilowatts.

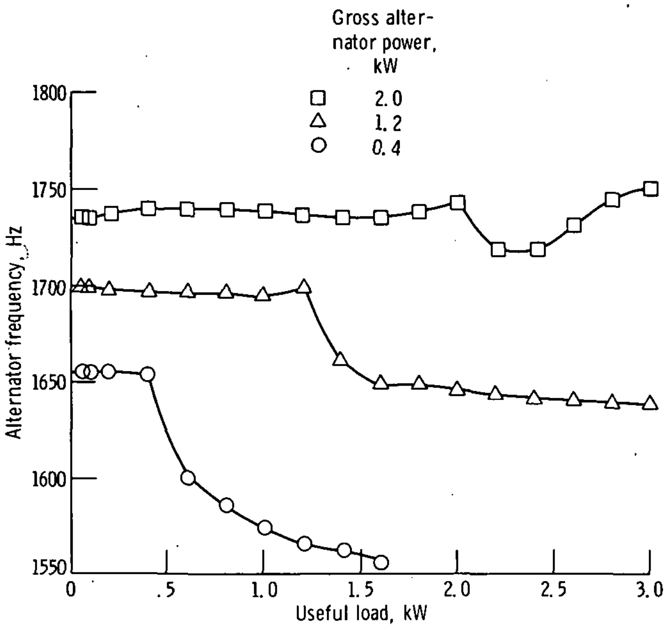


Figure 7. - Speed control characteristics.

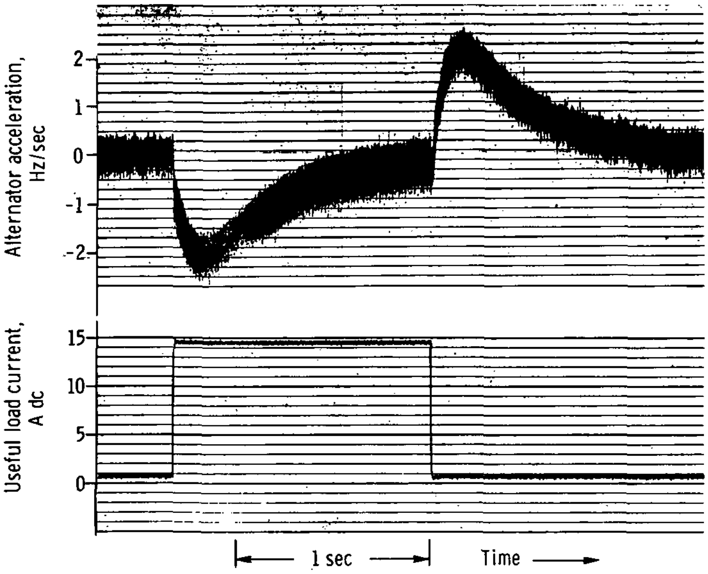


Figure 8. - Transient speed control characteristics.

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