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# IMPROVEMENTS IN AND TEST RESULTS FOR THE 2- TO 15-KILOWATT BRAYTON CYCLE ELECTRICAL SUBSYSTEM

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16. Abstract

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# IMPROVEMENTS IN AND TEST RESULTS FOR THE 2- TO 15-KILOWATT BRAYTON CYCLE ELECTRICAL SUBSYSTEM

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Lewis Research Center

## SUMMARY

The electrical subsystem of the 2- to 15-kilowatt Brayton power conversion system consists of the auxiliary electrical equipment required for an integrated, self-contained system.

For the last 2 years the electrical subsystem has been undergoing extensive tests at the NASA Lewis Research Center. The first year of testing resulted in determining the performance characteristics of the electrical subsystem. During the second year several significant changes and improvements were investigated.

An inverter designed for motor starting the alternator performed successfully. Some of the changes that have been made are a new alternator speed pickup, which is independent of the alternator output voltage; new, more efficient power supplies for the control system; and a volts-per-hertz reference for the alternator voltage regulator.

Test data were taken on the temperature distribution of the electrical subsystem at startup conditions over a cold-plate temperature range of $25^{\circ}$ to $-50^{\circ}$ C.

## INTRODUCTION

The NASA Lewis Research Center is investigating Brayton cycle electric power generating systems capable of operation in a space environment. This program has resulted in the design and construction of a complete power system capable of producing from 2 to 15 kilowatts of 1200-hertz electrical power. The speed of the turbine-driven alternator and, thereby, the frequency of the generated ac power are maintained by a parasitic-loading speed controller which utilizes phase-delayed conduction in the power control stages. Reference 1 describes the performance of the Brayton power system.

As part of the overall Brayton cycle system, the electrical subsystem provides the required regulation and control of the generated electrical power as well as control of the overall system. It also provides electric power for auxiliary-system components such as the coolant pumps. Reference 2 describes the electrical subsystem and its performance as determined from early tests.

Data on the complete electrical subsystem as of February 1971 are presented in reference 3. This report discusses the changes and improvements to the Brayton electrical subsystem made since that time. These changes include (1) a motor starting inverter, (2) magnetic speed pickups, (3) improved control system power supplies, and (4) a volts-per-hertz reference for the alternator voltage regulator.

Also, a section on low-temperature performance and startup data is presented along with the current results of the continuous life test being performed on the subsystem. The data presented are an extension of those in reference 3 in that they were obtained from the same set of equipment, with modifications, operated in the same test facility.

## DESCRIPTION OF ELECTRICAL SUBSYSTEM

The Brayton electrical subsystem is designed for space operation and consists of the alternator, the electrical control package (ECP), the parasitic-load resistors (PLR), the dc power supply, two batteries, two inverters, the Brayton control system (BCS), and the motor start inverter.

For this evaluation, the two coolant pump-motor assemblies (PMA's) together with the cold plates and other coolant loop items required for the removal of heat from electrical subsystem components are considered parts of the electrical subsystem. Figure 1 shows a pictorial block diagram of the electrical subsystem.

The alternator is a brushless, Lundell, solid rotor machine. Its three-phase 120- to 208-volt output power is generated at 1200 hertz. The turbine-alternator-compressor assembly is referred to as the Brayton rotating unit (BRU).

The ECP contains the speed controller, the alternator voltage regulator, the main load contactor, and current transformers for measurement of alternator and load currents. It also contains the power conversion circuits for the excitation of the alternator fields and several additional contactors used for system control.

The parasitic-load resistors dissipate the excess power developed by the turbine-driven alternator. The amount of power diverted to the PLR is controlled by the speed controller in the ECP so that the total load on the alternator is maintained relatively constant regardless of the user (vehicle) load. The speed controller, together with the PLR, has three three-phase channels. Each channel is rated at 6 kilowatts. The control of the power in these channels is by means of phase-delayed conduction of silicon-controlled rectifiers in a bilateral connection. The channels are energized sequentially with increasing frequency. Reference 4 describes the functioning of the speed controller, PLR, and voltage regulator in more detail.

The dc power supply converts ac power from the alternator to ±30 volts dc to supply the electrical subsystem components. It is a polyphase, unregulated, transformer-rectifier device without output filters. The dc power supply also contains battery charger circuitry. Changeover of the dc busses from alternator-supplied power to battery power is automatic on loss of alternator power or failure of the transformer rectifier. Manual override controls are provided. Reference 5 describes the performance of the dc power supply in more detail.

The two batteries are included in the subsystem to provide dc power for subsystem operation during Brayton system startup and shutdown and for short-term backup power in the event of transformer-rectifier or alternator malfunction.

The Brayton power system uses two coolant loops to provide redundancy for component cooling. The electrical subsystem components are mounted on four dual-path cold plates connected in series. The coolant fluid is dimethyl polysiloxane. Normally, one loop operates while the other serves as a standby. Each loop is independent and complete with a separate pump. The inverters convert power from the ±30-volt dc busses (60 V) to 400 hertz, three-phase ac power for driving the induction motors of the PMA's. These inverters do not have output transformers and provide a nominal line-to-line root-mean-square output voltage of 47 volts. The output waveform is a quasi-square wave. The inverters are permanently connected to the dc busses and to the PMA's. Start and stop control is obtained by furnishing a pulse to control circuits internal to the inverters. An experimental evaluation of the pump is reported in reference 6 and of the inverters in reference 7.

The Brayton control system (BCS) provides the necessary control and monitoring for overall Brayton power system operation. It consists of two major assemblies, a signal conditioner and a control and monitoring console. The signal conditioner is designed for a space environment and is located with the Brayton power system. The control and monitoring console is designed for operation with convection cooling in a room-temperature environment. Its circuits, however, were designed for ready adaptation to a space environment. The signal conditioner accepts power system instrumentation and logic signals and converts them to 0- to 5-volt signals for transmission to the control console. It also acts as the interface for control commands originating at the control console. The present system uses a multiconductor, wire link between the signal conditioner and the control and monitoring console. The design is such, however, that a telemetry link could be used. The BCS is described fully in reference 8.

The inverter is discussed in the section Motor Start Inverter.

## EXPERIMENTAL APPARATUS AND PROCEDURE

### Brayton and Support Equipment

The Brayton electrical subsystem, less the alternator, was assembled on a frame in a manner that simulates the actual Brayton system assembly, as described in reference 2. For all evaluations discussed in this report, the Brayton alternator was simulated with a variable-frequency motor-driven alternator. The dynamic output impedances of the motor-driven alternator are approximately the same as those of the Brayton alternator. This simulation allows a high degree of flexibility in test conditions. The subsystem is operable both inside a 1.8-meter-diameter vacuum tank and in a room environment. The variable-frequency alternator is located external to the tank. Also, for flexibility, power to individual Brayton components can be disconnected by remotely controlled latching relays. Auxiliary power sources and loads are available to allow most components to be operated independently.

In order to be completely functional, the Brayton control system requires input signals from temperature, flow, pressure, and other transducers located on Brayton components which are not a part of the electrical subsystem. Such inputs come from the gas heat exchanger, turbine, and so forth. All control functions which are operated by the BCS are within the electrical subsystem with the exception of electrically operated valves. The inputs to the BCS which are not available from the electrical subsystem are simulated with electrical signals. The electrically operated valves are simulated with relays. This simulation equipment is located external to the vacuum tank. Also, the Brayton alternator fields (series and shunt) are simulated with a dual-winding reactor which provides loads for the alternator excitation circuits in the ECP.

All power, load, control, simulation, and instrumentation leads are brought through the vacuum tank bulkhead in connector-type feed throughs.

### Data Acquisition

The bulk of the performance data was taken and partially reduced by a computer-controlled automatic data acquisition system. This system is similar to that described in reference 9. It contains a small, 12 000-word digital computer, a teletype, two reed-relay scanners, two digital voltmeters (one dc and one ac true rms), a digital clock, and a special high-frequency wattmeter. The wattmeter was developed at the Lewis Research Center and is described fully in reference 10.

# TEST PROCEDURE

To simulate a space environment and to allow evaluation of the effectiveness of the coolant loops, the electrical subsystem was operated in the vacuum tank for the tests described in this report. The pressure in the tank was maintained at less than $1\times10^{-5}$ torr ($1.33\times10^{-3}$ N/m$^2$). For evaluation of the subsystem modification, the shroud walls of the tank were maintained at 25$^{\circ}$ C. Also, the subsystem was operated down to -50$^{\circ}$ C temperatures to determine the effects of low temperature on subsystem startup and operation.

The endurance of the Brayton electrical subsystem is being demonstrated by nearly continuous operation in a vacuum. Various system power levels between 2 and 15 kilowatts are used. The endurance test is interrupted only for detail performance tests and the incorporation and evaluation of subsystem improvements. For the endurance demonstration, the test facility operates unattended. Routine data acquisition, limit checking, and minor test control are performed by the computer-controlled data system. Sufficient protective measures have been incorporated into the facility to allow a safe shutdown in the event of a facility or electrical subsystem malfunction.

# SYSTEM MODIFICATIONS

## Motor Start Inverter

Brayton electrical power systems require some technique to start rotation of the BRU. Startup of this system has been accomplished by two methods: (1) injecting gas into the system from a high-pressure storage tank (ref. 11) and (2) operating the alternator as a motor from an auxiliary power source. This latter method of startup has the advantage of conserving gas in the system and eliminates the valves required for injection startup. Motor starting provides system restart capability without the requirement of a large gas inventory.

The feasibility of motor starting the Brayton system was investigated by first determining the motoring characteristics of the alternator (ref. 12). Testing indicated that a 400-hertz motoring frequency provided self-sustaining operation of the system, and a 20-volt root-mean-square line-to-neutral voltage provided sufficient torque to start the system. Based on these tests, a solid-state inverter was designed and fabricated. The inverter, which receives its power from the system battery source, provides the necessary ac power to operate the alternator as a motor.

The major requirement of the inverter is the ability to supply a large peak starting current for a short period of time. The remainder of the inverter operation is a lower power motoring condition at nearly synchronous speed. The inverter was designed to produce a 400-hertz output as a result of the system testing previously mentioned. Small changes in voltage are not critical to motoring performance; therefore, the inverter was designed to operate directly from the system 56-volt, unregulated battery supply. To simplify inverter design further, a quasi-square wave inverter output was selected. Thus, the inverter was designed to produce a 15-kilovolt-ampere, three-phase, 400-hertz, quasi-square-wave output from a nominal 56-volt dc source. The root-mean-square output voltage is approximately 28 volts, while the surge current rating is 200 amperes per phase. The inverter is packaged as a prototype flight unit and is used in an environmental simulation test of the Brayton system.

The prototype flight version of the inverter without its cover is shown in figure 2. For this design, integrated circuits are used to generate the three-phase, 400-hertz reference signals. Also, a drive circuit was designed that minimized drive power loss, increased output transistor switching speeds, and eliminated the need for a drive voltage supply regulator. A pulsed on-off control circuit is provided to interface with the Brayton system controls. An input contactor is included in the design to isolate the inverter from the dc source. Detailed information on the design of the inverter can be found in reference 13.

A simplified schematic showing the use of the motor-start inverter in the Brayton system is shown in figure 3. The ±28-volt system battery supply provides the 56-volt input to the inverter. The inverter output is connected to the alternator only during the motoring period. Since the alternator neutral is always connected to the center tap of the dc source (system ground), circulating third harmonic currents are allowed to flow. The input filter in the inverter limits the current to an acceptable level.

In a separate test facility, different from the one described previously, the inverter was used to motor start an actual BRU. Approximately 50 system startups were made by using the motor-start inverter. A typical system startup occurs in the following manner. The system heat source is brought up to temperature; the alternator load contactor is opened; the voltage regulator for the alternator is inhibited; and the alternator series field is shorted. Jacking gas is turned on, and if negative rotation occurs, the inverter input contactor is closed; the contactor on the inverter output is closed; and the inverter is pulsed on. System startup then proceeds as shown in figure 4. For this startup it takes 20 seconds for the alternator to reach 400-hertz synchronous speed (12 000 rpm). The required current falls rapidly as the speed increases from zero to synchronous speed. During the motoring period, the gas in the power loop of the Brayton system is circulated through the heat source and its temperature increases. At the end of 1 minute the inverter is shut off, and the system is allowed to work its way up to rated speed (36 000 rpm). During this time, the inverter is isolated from the system by opening the contactors on the inverter input and output; the short is removed from the series field; and the voltage regulator inhibit command is removed. As the BRU approaches rated speed, the speed control assumes regulation.

The motor-start inverter was also tested under cold-soak startup conditions. After a cold soak at -50° C, in a vacuum, the inverter was turned on to an 80-ampere root-mean-square fixed load. The load was a resistor in series with an inductor with a net power factor of 0.15. This power factor was selected to simulate the alternator during startup. With the cold-plate temperature at -50° C, the inverter can operate continuously at this load without any internal temperature problems. This same test was run with a cold-plate temperature of 25° C in a vacuum, and it was found that hotspot temperatures within the inverter limited operation to approximately 15 minutes. However, a load of 25 amperes (power factor of 0.10) could be carried continuously. This leads to the possibility of the motor-start inverter replacing one of the coolant loop inverters used to supply 400-hertz power (8 A, 0.60 power factor, same voltage waveform) to the PMA's. This would reduce the weight and complexity of the overall system. Also, motor starting, by eliminating the need for gas-injection starting, will result in significant reduction in both the weight and complexity of the gas-management system and possibly of the overall system.

## Magnetic Speed Transducers

In the original design of the Brayton control system, the speed of the alternator was determined by measuring the frequency of the generated ac voltage. Because the Brayton engine is now started by motoring the alternator rather than using gas injection as originally designed (ref. 2), the alternator provides no usable voltage and frequency to measure speed during startup, that is, during motoring and until the fields are energized. Therefore, magnetic transducers were installed on the compressor scroll, as shown in figure 5. Three of these pickups were required to maintain the same triple redundancy provided by the three-phase frequency sensors of the original design. The transducers are spaced to provide three overlapping pulses. Only one of the three pulses is necessary for measuring speed. The spacing was designed such that the direction-of-rotation indication is still obtainable. The signal conditioning circuitry requires 20-millivolt input for proper operation. The new transducers have an output of 100 millivolts at 5 rpm, and tests have shown that there is sufficient output voltage to measure the speed of the BRU down to zero speed. The transducers count the 15 compressor blades to provide a 9000-pulse-per-second frequency at 36 000 rpm. This is different from the original frequency, but by changing the reference clock frequency, the original signal conditioning circuitry was maintained. System testing has proven the speed indication to be accurate to within 1 rpm at all speeds.

## Control-System Regulated Power Supplies

The control-system power supply design utilizes dc-to-dc series chopper regulators (also called switching or ripple regulators) to convert ±28 volts to the ±10- and +5-volt voltages used in the signal conditioner. The original circuitry shown in figure 6 consisted of three main blocks, a series transistor switch, an L-C output filter, and a control section. This control section used a voltage comparator which compared output voltage with the desired reference set point.

In the original design, the gain needed to maintain the required ±1-percent regulation was so high that, combined with the feedback dynamics, it caused the circuit to be marginally stable. This stability, in turn, resulted in high-frequency spikes in the output which interferred with the operation of the low-signal-level circuits of the control system. To maintain the desired regulation and at the same time to eliminate the spike caused by the phase-shift - gain problem, an improved control scheme was needed.

The NASA Electronics Research Center developed an electronic integrator to be used wherever conversion of an analog to digital signal is required. This circuit is called the Analog Signal To Discrete Time Interval Converter (ASDTIC). Figure 7 shows how the ASDTIC is used in our power supplies to control the switching so that the average voltage applied to the input of the filter is constant at the level required to obtain the desired output voltage. It does this by integrating the difference between the filter input voltage waveform and a reference voltage. A secondary feedback loop is provided to compensate for the voltage drop caused by the output filter. Since the secondary loop is just a trimming compensation, its gain can be small, and hence, the stability problem of the original design is eliminated.

The signal conditioner contains nine power supplies which have been redesigned to incorporate the ASDTIC. After more than 1500 hours of operation, they are functioning satisfactorily with less than 100 millivolt ripple and are well within the required ±1 percent regulation.

## Volts-Per-Hertz Alternating-Current Voltage Regulation

The alternator voltage regulator consists of a series field regulator and a shunt field regulator. The series field regulator provides alternator excitation which is directly proportional to armature current. The shunt field regulator provides additional excitation to the other field to maintain the voltage output of the alternator constant.

When the total alternator power is being used by the useful load, the parasitic load is zero. If the useful demand is greater than the power developed by the system, the alternator speed will decrease. At 90 percent of rated speed, the load breaks will automatically open and remove the overload from the alternator. At this point, the speed will return to normal but the load breaker will stay open until manually reset.

In order to permit small overloads, a volts-per-hertz reference circuit has been incorporated into the alternator voltage regulator. This circuit replaces the fixed-voltage reference in the shunt field voltage regulator. The output voltage of the volts-per-hertz reference circuit increases with increasing frequency up to the rated frequency. Above the rated frequency, the output voltage remains relatively constant. Upon an overload, the alternator voltage and frequency decreases until a new power balance is achieved.

Figure 8 is a schematic diagram of the volts-per-hertz circuit which was tested. The secondary voltage is full-wave rectified and filtered to obtain a nearly ripple-free dc voltage. The function of the Zener diode Z, the resistor $R_3$, and the transistor Q is to limit the output voltage at rated frequency, as shown in figure 9. Test results for the reference circuit by itself over the expected operating temperature range ($20^{\circ}$ to $40^{\circ}$ C) indicate satisfactory performance. The voltage decreases linearly with decreasing frequency below the rated frequency, but it remains relatively constant over the normal frequency range of 1200 to 1224 hertz. The actual output voltage is shown in figure 10. Related tests with the Brayton alternator have demonstrated satisfactory performance at room ambient temperature ($23^{\circ}$ C). The net effect on the alternator voltage when the volts-per-hertz regulator is used is shown in figures 11 and 12. The alternator voltage does not remain exactly constant at frequencies about 1200 hertz because of interaction between the speed control and the shunt field regulator.

A more detailed discussion of the volts-per-hertz regulators and the test results can be found in reference 14.

## SUBSYSTEM EXPERIMENTAL EVALUATION

In a space environment, the Brayton system might be subjected to low-temperature extremes during startups. Most, but not all, Brayton electrical subsystem components have been individually tested at low temperatures (see refs. 15 to 17). The purpose of this test was to determine the operation and performance of the complete electrical subsystem under cold-start conditions. The performance of components and system interactions was investigated over an initial temperature range of $25^{\circ}$ to $-50^{\circ}$ C. This range was achieved by cold-soaking the nonoperating electrical subsystem to the specified temperatures prior to each simulated startup.

The electrical components were mounted on Brayton cycle cold plates. These cold plates are cooled by pumping oil through them with the PMA's. Heat is rejected from the oil to gaseous nitrogen in a heat exchanger. Normally, the heat exchanger would be a radiator radiating to space. During the cold soak, the secondary Brayton coolant pump with an external 400-hertz power supply was used to pump the cold oil through the system. The Brayton cycle inverter was not used and, therefore, did not introduce heat into the system. The vacuum chamber walls were cooled with gaseous nitrogen to the same temperature as the cold plates.

To simulate cold startup conditions, the Brayton control system was turned off as the temperature test points were changed. When the desired condition was reached, the electrical subsystem was energized. All subsystem functions were available immediately, although temperature readings were not stable and the heat-source control interlock opened. This was expected because it takes time for the thermocouple calibration ovens in the signal conditioner to reach the proper temperature. When the ovens warmed up, the temperature readouts were correct. The warmup time was a function of the ambient temperature. At the coldest test point, $-50^{\circ}$ C, warmup time was approximately 30 minutes.

At steady-state operation over a temperature range of from $25^{\circ}$ to $-50^{\circ}$ C, small variations in the efficiency of some components were observed and some small changes in BCS alarm set points occurred; however, the system operated satisfactory, and component performance gave no indication that there would be any effect on the safe operation of the Brayton power generating system.

The most significant results were

(1) The efficiency of the inverter - pump-motor-assembly combination decreased from 16 to 13 percent as the temperature decreased, as shown in figure 13. The inverter efficiency went up slightly because of a decrease in semiconductor losses, but pump efficiency decreased considerably because of an increase in the viscosity of the oil.

(2) The output voltages of the inverter and the dc supply were independent of temperature. Also, the speed control characteristics were independent of temperature.

(3) The set points for the Brayton control-system speed alarm showed a small increase (2 percent total) as the temperature was decreased from $25^{\circ}$ to $-50^{\circ}$ C.

For more detailed information on the cold-start and low-temperature performance of the Brayton subsystem, see reference 18.

## CONTINUATION OF ENDURANCE TESTING

The electrical subsystem has been in nearly continuous, unattended operation since November 1970 in a vacuum environment in the facility described in this report. It has been operating at various power levels with various amounts of power dissipated by the parasitic-load elements.

The batteries originally used in the subsystem were of a sealed, silver-cadmium type. These batteries failed after several cycles during the checkout phase of this program, which was approximately 1.5 to 2 years after manufacture of the cells. The subsystem is now being operated with simulated batteries.

With the exception of the battery failures and several minor, noncritical failures in the monitoring functions of the Brayton control system, there have been no significant problems experienced with the operation of the Brayton electrical subsystem.

As of November 1, 1972, 10 500 hours of subsystem operation had been accumulated. Of these hours, 10 200 were in an unattended mode. A total of 6000 hours had been accumulated with the new system modifications. It is presently planned to continue the endurance test to 20 000 hours. Also, as of November 1, 1972, several separate endurance tests had demonstrated satisfactory operation of an inverter - coolant-pump combination for 40 000 hours (one example of which lasted 20 000 hr), of a Brayton dc power supply for 25 000 hours, and of an alternator for 15 000 hours.

## CONCLUDING REMARKS

The recent improvements in the Brayton electrical subsystem include an inverter designed to motor start the turbine alternator, a new alternator speed pickup, a new control system power supply, and a new volts-per-hertz alternator voltage regulator. The overall goal of making these improvements is to improve an already highly sophisticated and reliable power conversion system.

The motor start technique allows reduced gas inventory, simplifies the gas management system, and allows repeated startup capability. The new magnetic speed pickup senses speed independently of the alternator output, which is essential for motor start operation. The new control system power supplies provide improved stability and efficiency for the control system, and the new volts-per-hertz voltage regulator gives the Brayton power system greater tolerance to transient overloads.

The low-temperature testing indicated that there would be no problem in safely and controllably starting the Brayton power system from a cold-soak temperature of $-50^{\circ}$ C.

As of November 1, 1972, 10 500 hours had been accumulated on the subsystem.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, January 9, 1973,
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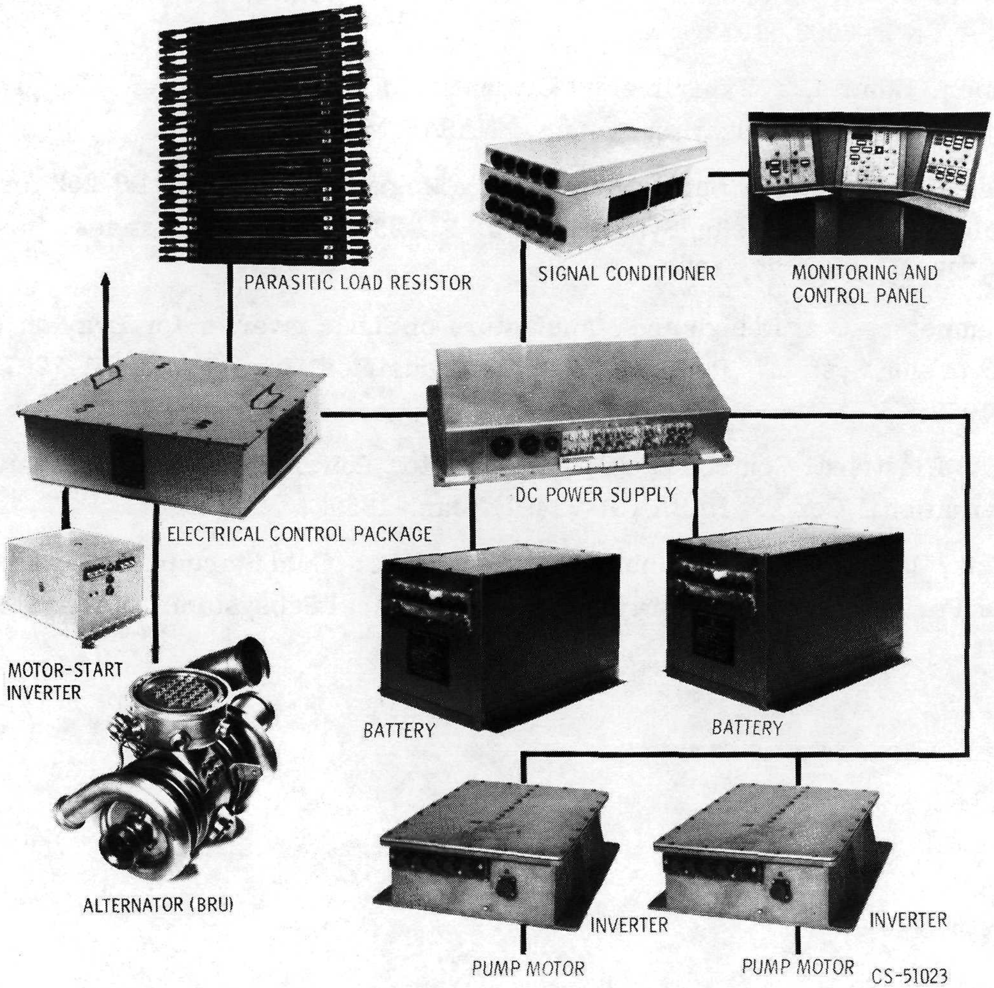


Figure 1. - Brayton electrical subsystem components.

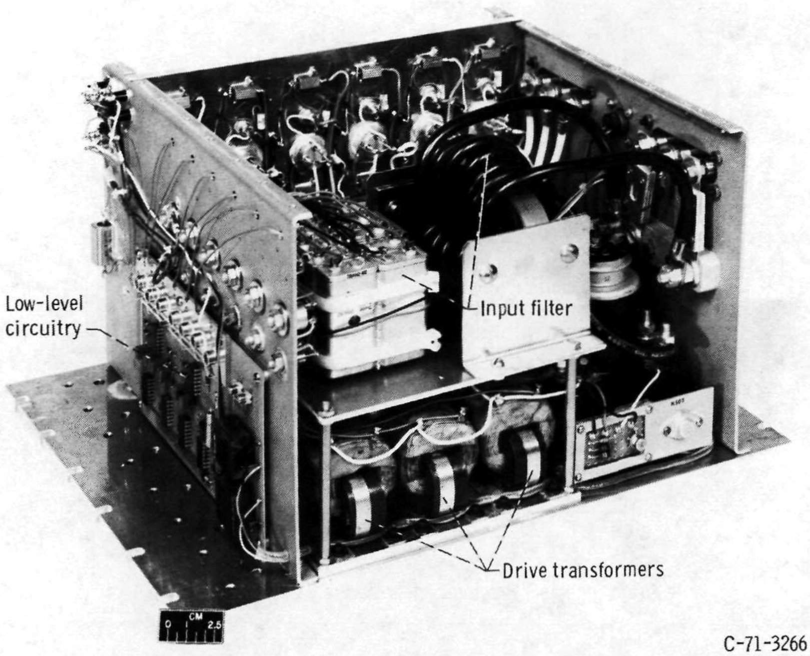


Figure 2. - Motor-start inverter.

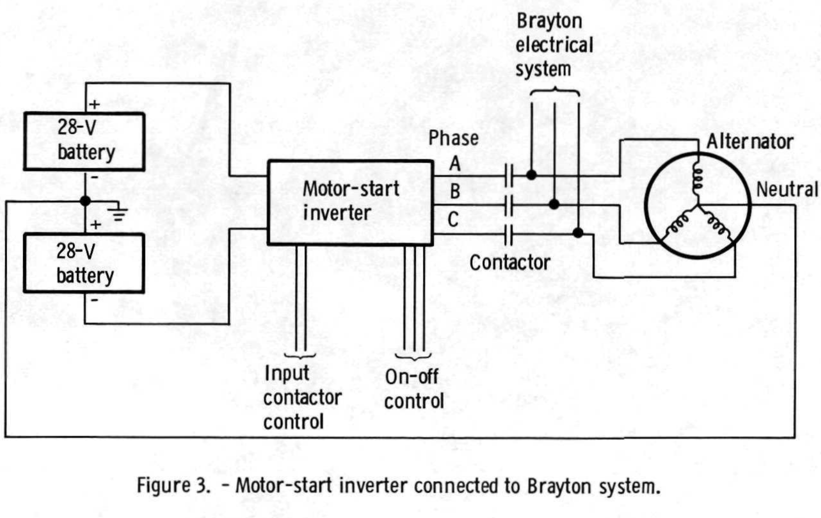


Figure 3. - Motor-start inverter connected to Brayton system.

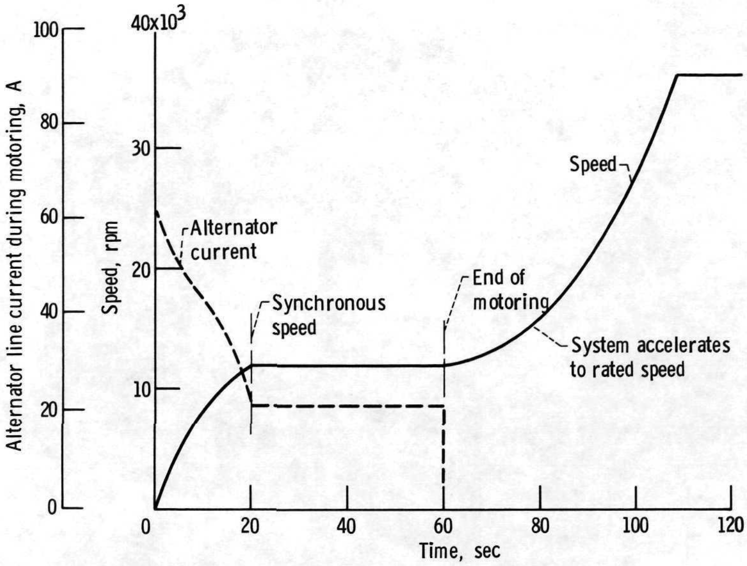


Figure 4. - Typical Brayton system startup using motor-start inverter.

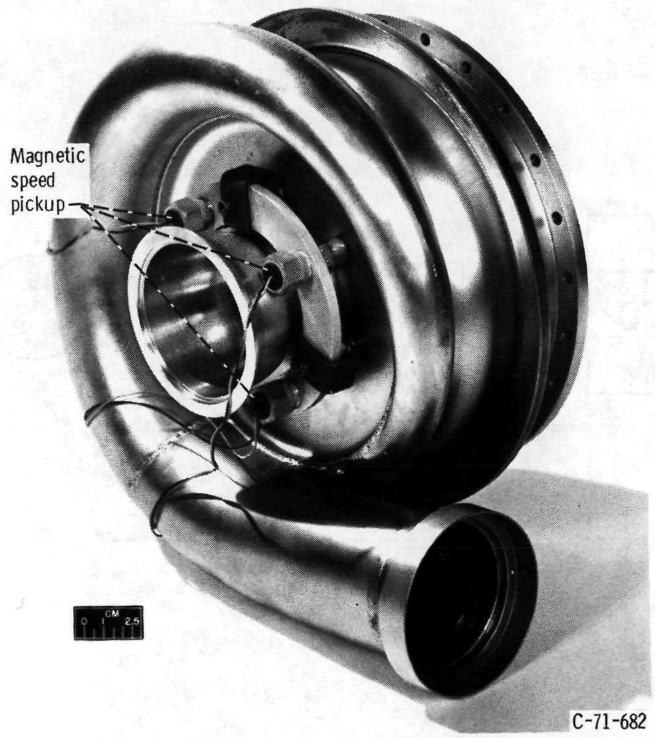


Figure 5. - Compressor scroll with magnetic pickups.

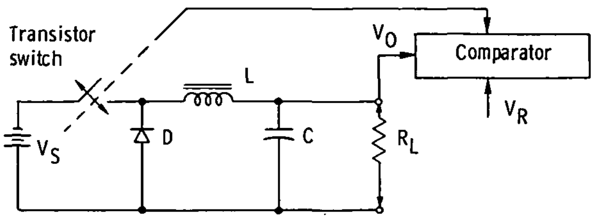


Figure 6. - Functional diagram of original control system power supply.

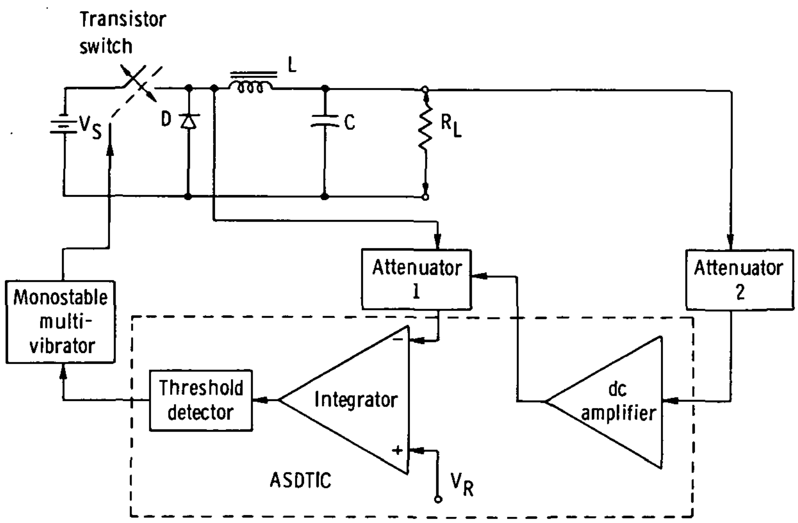


Figure 7. - Functional diagram of modified control system power supply.

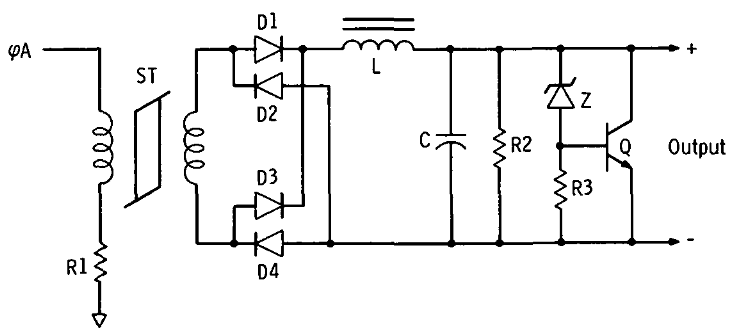


Figure 8. - Schematic diagram of volts-per-hertz reference circuit.

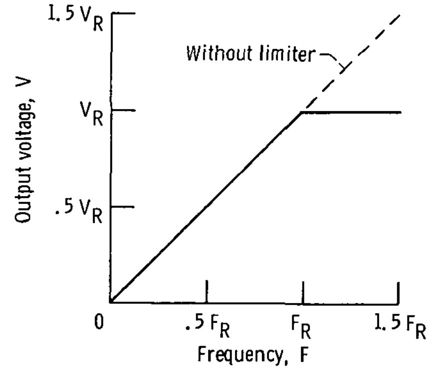


Figure 9. - Ideal volts-per-hertz characteristic. Subscript R denotes rated value.

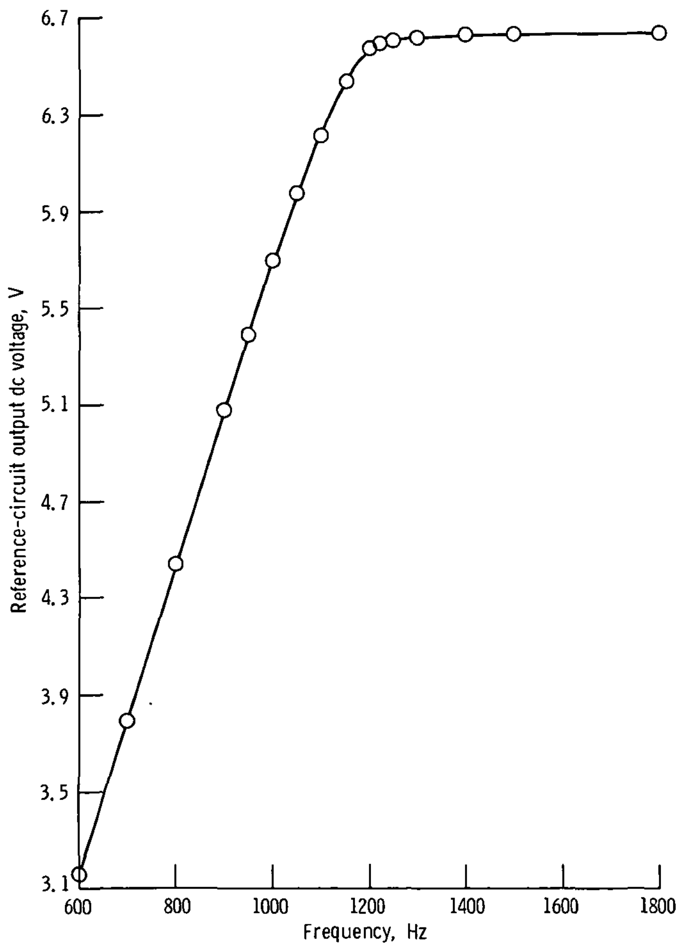


Figure 10. - Volts-per-hertz reference characteristic. Bracket temperature, 40° C; air temperature, 37° C; load impedance, 100 kilohms; ratio of input voltage to frequency, 0.1 for frequencies up to 1200 hertz.

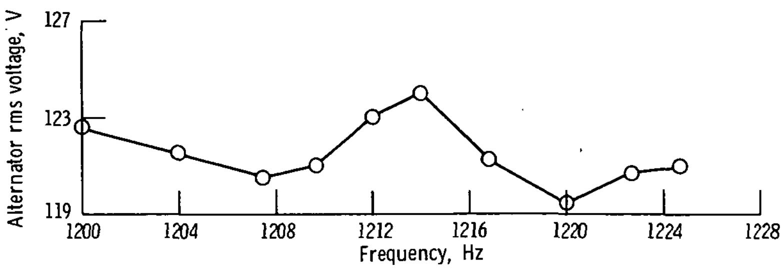


Figure 11. - Alternating-current voltage for normal operation.

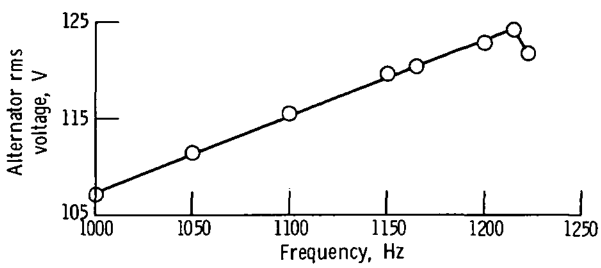


Figure 12. - Alternating-current voltage for overload condition.

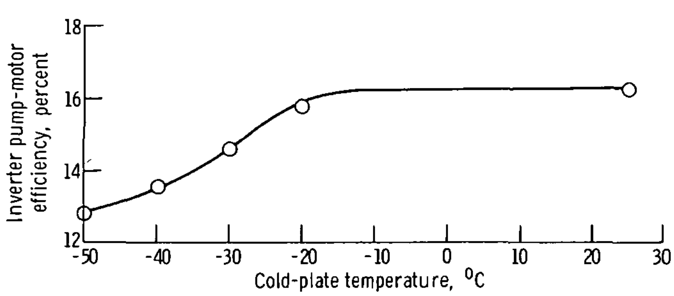


Figure 13. - Temperature effect on inverter-pump-motor efficiency (electric to hydraulic).

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