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MOTOR STARTING A BRAYTON CYCLE POWER CONVERSION SYSTEM USING A STATIC INVERTER

by Joseph S. Curreri, Richard A. Edkin, and Roman Kruchowy

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16. Abstract

The power conversion module of a 2- to 15-kW_e Brayton engine was motor started using a three-phase, 400-hertz static inverter as the power source. Motor-start tests were conducted for initial gas loop pressures of 10, 14, and 17 N/cm^2 (15, 20, and 25 psia) over a range of initial turbine inlet temperatures from 366 to 550 K (200° to 530° F). The data are presented to show the effects of temperature and pressure on the motor-start characteristics of the rotating unit. Electrical characteristics during motoring are also discussed.

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SUMMARY

The power conversion module of a 2- to 15-kilowatt-electric Brayton engine was motor started using a three-phase, 400-hertz static inverter as the power source. The purpose of these tests was to obtain motor-starting characteristics that could be used to select conditions for starting the complete Brayton engine in a space environment. The tests were conducted for initial gas loop pressures of 10, 14, and 17 newtons per square centimeter (15, 20, and 25 psia) over a range of initial turbine inlet temperatures from 366 to 550 K (200° to 530° F). The results of this investigation showed the following:

(1) For the heat input rate used and over the temperature range investigated, the motoring time to attain synchronous speed (12 000 rpm) was 30 seconds or less.

(2) For the conditions tested, the bootstrap time (time required to accelerate from synchronous speed (12 000 rpm) to rated speed (36 000 rpm)) decreased with increasing turbine inlet temperature.

(3) Based on the extrapolation from several startups of the acceleration of the rotating unit over the initial 1000 rpm increase during bootstrapping (12 000 - 13 000 rpm), the minimum turbine inlet temperature required for self-sustaining operation was estimated to be about 665 K (740° F).

(4) The rotating unit could be motor started even if one of the inverter phases was open circuit (two-phase start).

INTRODUCTION

One requirement in the development of a Brayton power system (refs. 1 and 2) is to determine start procedures which minimize system complexity. Two methods of starting the Brayton power system are presently being investigated: (1) gas injection and (2) motoring of the alternator. Results of analytical and experimental studies of the gas injection method for starting the Brayton power system are presented in references 3 and 4, respectively.

The gas injection method requires control of the injection flow rate and results in additional flow control equipment for the gas management system. To reduce the size and complexity of the gas management system, the method of motor starting was considered. In this method, a lightweight static inverter is used in conjunction with the system battery source to provide the ac power to operate the alternator as a motor. During motoring, the alternator spins the Brayton rotating unit (BRU) which consists of a turbine, an alternator, and a compressor mounted on a single shaft. The compressor circulates the working gas in the preheated loop. When sufficient pressure rise is developed by the compressor and sufficient heat is absorbed from the heat source to provide enough energy to the turbine to rotate the BRU unassisted by the motor, the system becomes self-sustaining.

Motoring characteristics of the alternator alone (i.e., without any other equipment coupled to the shaft) were determined experimentally in reference 5. Motoring characteristics of the alternator coupled to the turbine and compressor are presented in reference 6. Motor starting characteristics of the BRU operating in a closed gas loop are discussed in reference 7. This gas loop was designed specifically to test the BRU over a wide range of operating conditions. Furthermore, this gas loop was not designed to duplicate the system pressure losses of the Brayton power conversion loop. Reference 8 presents the motor starting characteristics of the BRU operating in a Brayton power conversion gas loop. This gas loop consisted of a flight-type Brayton power conversion module which included the Brayton heat exchanger unit. From an operating standpoint, the major difference between the gas loops of references 7 and 8 is the system pressure losses which result from the different piping length and size and the different heat supply and heat rejection equipment. These differences have a minor effect on performance. The motoring power source used in the previous experiments was a three-phase, variable voltage, variable frequency motor-generator set. The results of these tests were used to design and fabricate a static, three-phase, 400-hertz motor-start inverter (ref. 9).

This report presents the results of motor-start testing on a Brayton power conversion module of a 2- to 15-kilowatt-electric Brayton engine using the 400-hertz battery-powered static inverter as the power source. The tests were performed in the same gas loop test facility and nearly the same range of turbine inlet temperatures as those tests described in reference 8. However, for the tests described herein, no attempt was made to maintain constant turbine inlet temperature. This more closely simulates a system start in space. The tests were also conducted over a range of initial system pressures. The data are presented to show the effects of temperature and pressure on the motor-start characteristics of the BRU. Electrical characteristics during motoring are also discussed.

BRAYTON POWER SYSTEM

The closed-loop Brayton engine shown schematically in figure 1 was designed to generate 2 to 15 kilowatts of electrical power in space. The major subsystems are the heat source subsystem, the gas management subsystem, the electrical subsystem, and the heat rejection subsystem. The Brayton power system was designed to be used with either a solar collector or with radioisotopes as the heat source. A detailed description of the system may be found in references 1, 2, and 10.

The facility used in the motor-start tests of the Brayton power conversion module system is described in references 8 and 11. The power conversion module is a closed gas loop that consists of a Brayton heat exchanger unit (BHXU) and a Brayton rotating unit (BRU). The working fluid in this system is a mixture of helium-xenon (He-Xe) gas having a molecular weight of 83.8. An electrical heater was used as the heat source subsystem. An auxiliary heat exchanger, cooled by a facility refrigeration system, was used to remove waste heat.

The BRU consists of a turbine, an alternator, and a compressor mounted on a single shaft designed to rotate at 36 000 rpm. The shaft is supported and restrained by gas-lubricated bearings. During startup and shutdown the bearings are operated hydrostatically by externally supplied jacking gas. During normal operation the jacking gas is turned off and the bearings operate hydrodynamically (self-supported). The motor-start inverter was designed to supply three-phase, 400-hertz power to operate the alternator as a motor. The design of the inverter is described in reference 9.

PROCEDURE

The general operating procedure for the motor-start tests was to (1) fill the gas power loop to a desired pressure level, (2) preheat the working fluid and the system, (3) externally pressurize the BRU bearings, and (4) apply motoring power to the alternator with the motor start inverter. After motoring, heat input was increased to assist in accelerating the rotor to the design speed of 36 000 rpm.

The power conversion system was first filled with He-Xe to the desired loop pressure of 10, 14 or 17 newtons per square centimeter (15, 20 or 25 psia). A prestart data scan of 200 data channels was then taken on the digital data acquisition system (ref. 12) to record all initial preheat loop conditions. The power to the electric heat source was then set to 20 kilowatts electric to preheat the gas loop by natural convection. When the heater tube temperature reached its maximum allowable limit (1283 K, 1850° F) the power to the heat source was reduced to 10 kilowatts electric to maintain this temperature for the balance of the preheat period. A turbine inlet temperature range of 366 to 550 K (200° to 530° F) was obtained by allowing the system to preheat from 1 to $3\frac{1}{2}$ hours. After preheating, the loop pressure, which increased due to increasing gas temperature, was bled back to the initial desired loop pressure. Another 200 data channel scan was then taken to record all of the actual prestart loop conditions.

A three-phase, 400-hertz, static inverter (ref. 9) was used for motor starting the BRU. This inverter was connected in the test system as shown in figure 2. The ±28-volt batteries supply the 56-volt dc input to the inverter. The three-phase output voltage is a 400-hertz nominal 28-volt rms, quasi-square-wave. Prior to motoring, the gas bearings were externally pressurized to float the shaft of the BRU and to prevent bearing rub during rotation. The contactor at the inverter output was then closed. This contactor provides an electrical interlock to open the circuit to the Brayton electrical subsystem and to connect a 50-ohm resistor across each field in the alternator. This resistance value was arbitrarily chosen to limit the induced voltage in each field. The measured induced voltage was approximately 5 volts at its peak.

Motoring was started by turning on the control to the inverter. The alternator then operated as a motor and accelerated the BRU shaft to synchronous speed (12 000 rpm for the applied frequency of 400 Hz) provided the shaft load is not too great. At the end of approximately 1 minute, the inverter was first turned off and then the output contactor was opened. This sequence is used to avoid inductive effects on the output stage transistors of the inverter. The contactor to the Brayton electrical subsystem closed and the 50-ohm resistors were removed from the alternator fields. As soon as the motoring power was terminated, the power to the heat source was raised to 23 kilowatts electric. At 12 000 rpm and with sufficient turbine inlet temperature and compressor pressure rise, the turbine develops excess torque to rotate the alternator and compressor and the BRU bootstraps (accelerates). At approximately 18 000 to 23 000 rpm, the shunt voltage regulator (VR) was manually turned on. With sufficient temperature the BRU accelerates to rated speed (36 000 rpm) and the speed control limits the BRU speed. The jacking gas was arbitrarily turned off when the turbine inlet temperature reached 922 K (1200° F).

During the start, there was an increase in system pressure as a result of the increasing gas temperature and the increasing system inventory. The inventory increase was due to the externally supplied jacking gas. The compressor discharge pressure was allowed to increase to a value between 21 and 28 newtons per square centimeter (30 and

40 psia). The compressor discharge pressure level was controlled manually by bleeding the excess gas with the vent valve located at the compressor discharge. During the start, the temperature at the compressor inlet was held constant at 300 K (80° F) by the heat rejection subsystem.

RESULTS AND DISCUSSION

A series of motor start tests was performed on the power conversion system of a 2- to 15-kilowatt Brayton engine using a motor-start inverter as the power source. The objective of these tests was to obtain motor starting characteristics that could be used to select conditions for starting the complete Brayton engine in a space environment. The tests were conducted for initial system pressures of 10, 14, and 17 newtons per square centimeter (15, 20, and 25 psia) and at initial turbine-inlet temperatures from 366 to 550 K (200° to 530° F).

The time required for a motor start of the Brayton power system is the time required to accelerate the BRU shaft from zero to rated speed (36 000 rpm). Thus, the total motor-start time is the sum of the time to reach synchronous speed (12 000 rpm), the time at synchronous speed, and the time to accelerate from synchronous speed to rated speed (bootstrap time). For each motor start, the total motoring time was varied to obtain a desired turbine inlet temperature at the end of motoring. However, because of preheat and heat input rate a nominal motoring time of approximately 60 seconds was sufficient to obtain the necessary loop conditions for bootstrap in the range of conditions tested.

The time to reach synchronous speed and the bootstrap time are each discussed in terms of the turbine inlet temperature and pressure measured at the beginning of their respective time periods. Turbine inlet pressure at the start of bootstrapping (bootstrap pressure) was approximately 4 newtons per square centimeter (6 psia) higher than the initial system pressure for all pressure levels tested. The difference was due, mainly, to the increase in system inventory caused by the externally supplied jacking gas.

BRU Motor-Start Characteristics

Motor-start time responses of speed and turbine inlet temperature are shown in figure 3. The data represent typical start results obtained at low and high initial turbine inlet temperatures for each initial pressure level tested. These data are sufficient to show the characteristic shape of the speed curves and the overall temperature effects on total motor-start time. In each case, the BRU shaft accelerated to synchronous speed and remained constant for as long as the motoring power was applied. When the motoring power was removed, the BRU shaft accelerated as a result of the excess thermal energy available to the turbine. The shunt voltage regulator (VR) was applied between 18 000 and 23 000 rpm.

The overall effect of initial turbine inlet temperature on the total motor-start time is apparent. For the conditions defined, the higher this temperature, the shorter the motor-start time. Also, at the lower temperature conditions, the load from the VR was sufficient to reduce the acceleration of the BRU. At the higher temperature conditions, the VR has little effect on BRU acceleration because the load of the VR is negligible compared to the excess energy supplied by the turbine.

Figure 4 shows the time to attain synchronous speed as a function of initial turbine inlet temperature for all pressures tested. The results indicate that the time to reach synchronous speed decreases with increasing initial turbine inlet temperature. Initial system pressure has a negligible effect on this time. Synchronous speed was attained in 30 seconds at an initial turbine inlet temperature of 366 K (200° F). This time was reduced to about 18 seconds at an initial turbine inlet temperature of 550 K (530° F).

After synchronous speed was achieved, the motoring power was left on to allow the turbine inlet temperature to increase. At the desired turbine inlet temperature, motoring was terminated. The time to accelerate from synchronous speed to rated speed (bootstrap time) for all initial bootstrap pressures is shown in figure 5. The data are plotted against the turbine inlet temperatures measured at the beginning of the bootstrap period (bootstrap temperature). As expected, bootstrap time decreases with increasing bootstrap temperature. The system pressure appeared to have a negligible effect on bootstrap time. The bootstrap time was reduced from about 360 seconds at 682 K (768° F) to about 40 seconds at 825 K (1025° F). The scatter in the data is attributed to differences in the heat input rate and BRU speed at the time the VR was turned on.

The initial acceleration of the BRU during bootstrapping is shown in figure 6 as a function of bootstrap temperature. These data represent the slope of the speed curves (illustrated by fig. 3)) from 12 000 to 13 000 rpm. The slope was assumed to be a straight line over this speed range. The results show increasing initial acceleration with increasing bootstrap temperatures. The resultant curve crosses the horizontal axis, representing zero acceleration, at approximately 665 K (740° F). This implies that at the conditions tested the minimum turbine inlet temperature for self-sustaning operation at 12 000 rpm is 665 (740° F). This value is 25 K (45° F) higher than the self-sustaining temperature obtained in reference 7. The difference is attributed primarily to different system pressure losses due to the difference in pipe sizes and to the different heat exchanger equipment of the two test rigs.

Alternator Motoring Characteristics

Figure 7 shows typical motor-start armature current and BRU speed as a function of time. At zero speed, the initial rms value of the armature current is at a maximum value of approximately 60 amperes. Maximum current is equivalent to 1.5 per unit. As BRU speed increases, the transient armature current decreases to 20 amperes rms at synchronous speed (12 000 rpm). Furthermore, the input power and power factor decrease with increasing BRU speed until, at synchronous speed, they are at minimum values (ref. 6). Figure 8 shows the battery current to the motor-start inverter during motoring. At start the peak battery current to the inverter was 46 amperes. Integration of this curve showed that to reach synchronous speed the required capacity for the batteries was 0.19 ampere-hour. At synchronous speed the battery current was at the minimum value of 5 amperes.

Before beginning the test program, the BRU was motored without preheating the system to check the operation of the 400-hertz motor-start inverter. During these cold spins, it was found that the BRU would not reach synchronous speed. The maximum speed attained at this condition was between 10 000 and 11 000 rpm, depending on the initial system pressure and voltage. A nominal motoring time of 70 seconds was used for the cold spin tests.

Figure 9(a) is a photograph of the input voltage (line to neutral) and current to the alternator, being driven as a motor, at start. The 400-hertz, quasi-square-wave voltage is supplied by the motor-start inverter. The voltage waveforms reflect the switching of the inverter output-stage transistors. The voltage distortion on the positive and negative peaks of the waveform is produced by the combination of the transistor switching of the alternator phases to the ±28-volt batteries and the corresponding change in voltage drop due to the line impedance. The peak armature current supplied by the motor-start inverter is limited by the line impedance and the motor input impedance. At start, the line impedance of approximately 0.08 ohm per phase was significant and represent almost 18 percent of the total impedance. The photograph shows that the peak in-rush current was 100 amperes. (This peak in-rush current would be higher for a closely coupled system. These data indicate, however, that the design of the motor-start inverter is conservative since it is capable of supplying a 200-A peak current (ref. 9)). The armature current lags the applied voltage since the motoring alternator represents an inductive load on the inverter. The characteristic shape of the current waveform is produced by the inductive load which integrates the applied voltage.

A photograph showing a comparison between the neutral current and the armature current is shown in figure 9(a). The neutral current waveform has the same characteristic shape as the armature current. The neutral current is essentially a third harmonic as shown in the photograph. The peak neutral current was 50 amperes. As a result of this testing, an input filter (ref. 9) was added to the inverter to attenuate the high third harmonic neutral current. Later test results indicated that this current was reduced to approximately a 15-ampere peak.

Two-Phase Start

A two-phase motor-start test was conducted to determine the effect of an open phase of the inverter output on the starting characteristics of the BRU. The data showed that the start characteristics were similar to those of the three-phase starts with the exception that the time to reach synchronous speed was almost three times longer (58.5 sec).

The input voltage (line to neutral) and current waveform to the motoring alternator are shown in figure 10(a) for a two-phase start. The shape of the voltage waveform shows the effect of an open phase at the inverter output. The armature current waveform for a two-phase start is similar to the current waveform for a three-phase start. In both cases the peak armature currents are approximately the same. Figure 10(b) shows a comparison of the neutral current and the armature current. The peak neutral current for a two-phase start is almost three times higher than for the three-phase start. The neutral current and the armature current are both at the same frequency (400 Hz).

SUMMARY OF RESULTS

The Brayton rotating unit was successfully motor started using a 400-hertz motor-start inverter. The results of the 400-hertz, motor-start inverter tests of the Brayton power conversion system can be summarized as follows:

1. For initial turbine inlet temperatures from 366 to 550 K (200° to 530° F), the time to attain synchronous speed decreased from 30 to 18 seconds at initial gas loop pressures of 10, 14, and 17 newtons per square centimeter.

2. For the conditions tested, the bootstrap time (time required to accelerate the rotating unit from synchronous speed to rated speed) decreases with increasing turbine inlet temperature. The bootstrap time was reduced from 360 seconds at 682 K (768° F) to about 40 seconds at 825 K (1025° F).

3. Based on the initial acceleration of the BRU during bootstrapping, the minimum turbine inlet temperature required for self-sustaining operation at 12 000 rpm was estimated to be about 665 K (740° F).

4. For a three-phase start, the peak in-rush current to the motoring alternator was 100 amperes. The measured rms current was 60 amperes which is equivalent to 1.5 per unit.

5. At start, the peak battery current to the motor-start inverter was 46 amperes. To reach synchronous speed, the capacity requirement for the ±28-volt batteries was calculated to be 0.19 ampere-hour.

6. The test results demonstrated that the Brayton rotating unit could be motor started even if one of the inverter phases was open circuit (two-phase start).

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 1, 1972
503-35.

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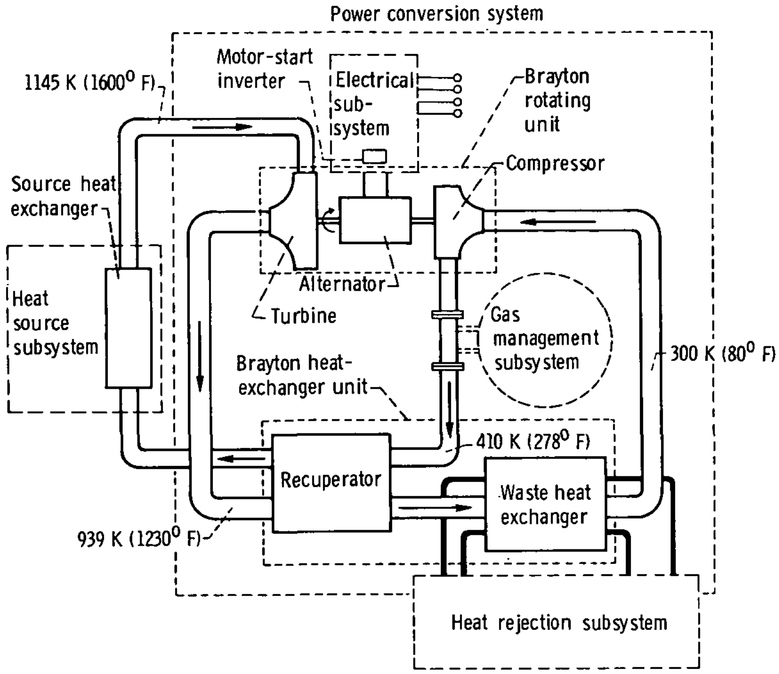


Figure 1. - Schematic diagram of Brayton engine.

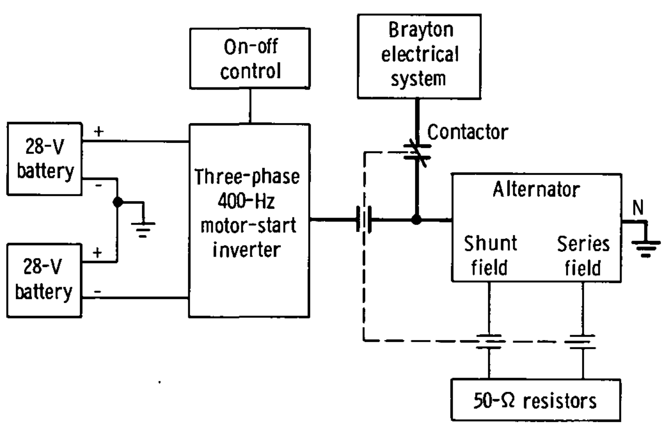
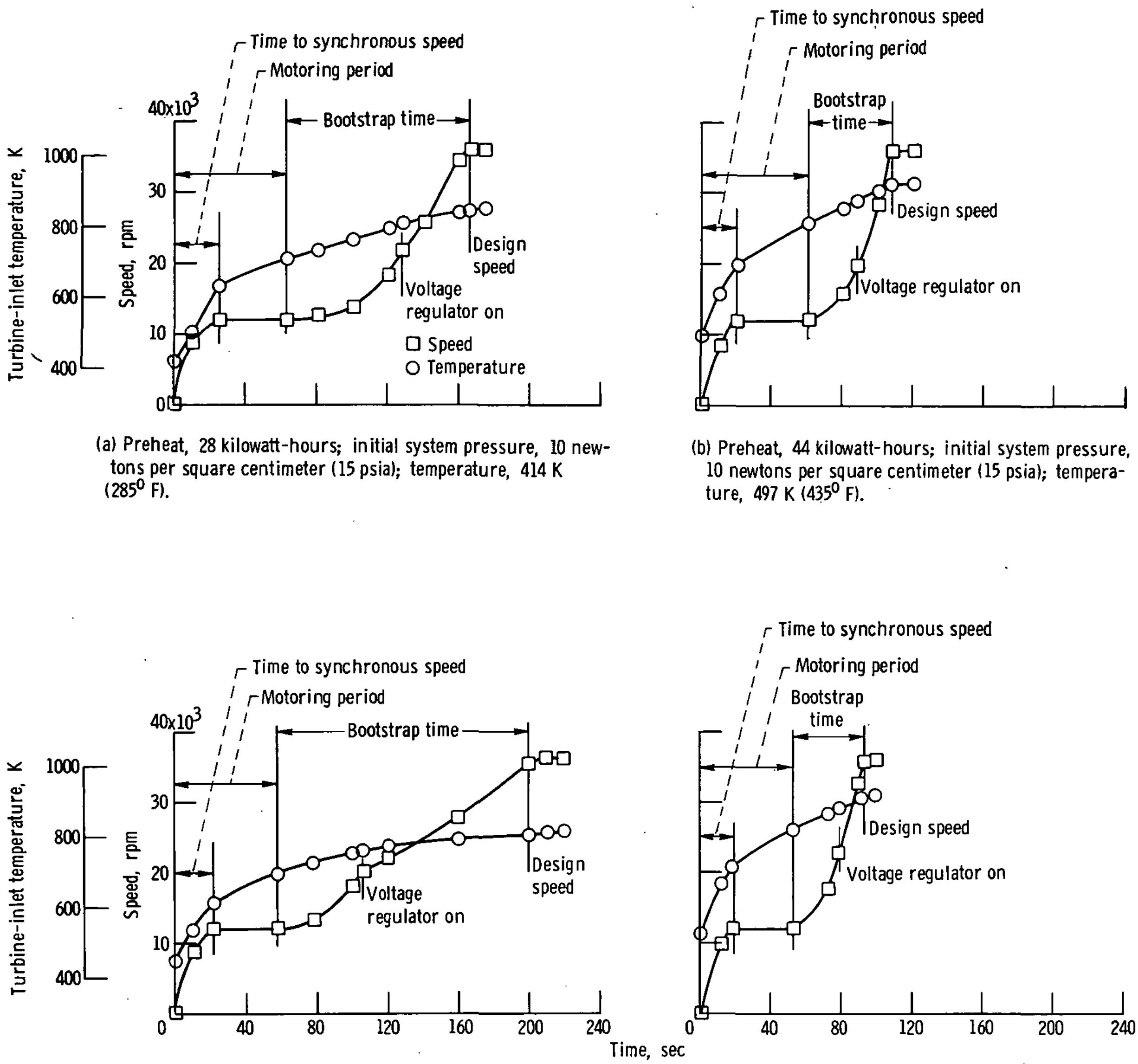


Figure 2. - Simplified schematic of motor-start inverter connected in test system.



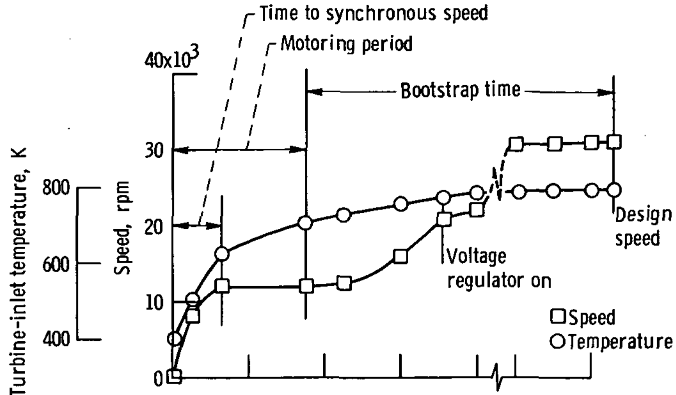
(a) Preheat, 28 kilowatt-hours; initial system pressure, 10 newtons per square centimeter (15 psia); temperature, 414 K (285° F).

(b) Preheat, 44 kilowatt-hours; initial system pressure, 10 newtons per square centimeter (15 psia); temperature, 497 K (435° F).

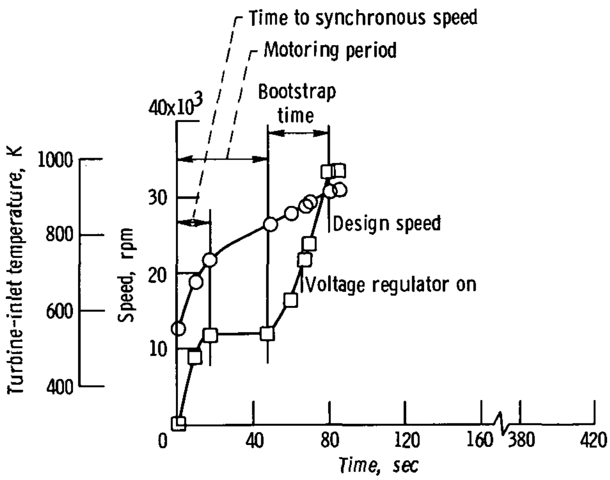
(c) Preheat, 28 kilowatt-hours; initial system pressure, 14 newtons per square centimeter (20 psia); temperature, 447 K (345° F).

(d) Preheat, 38 kilowatt-hours; initial system pressure, 14 newtons per square centimeter (20 psia); temperature, 528 K (490° F).

Figure 3. - Typical ±28-volt, 400-hertz motor-start response curves of speed and turbine-inlet temperature for lowest and highest initial turbine-inlet temperature investigated at initial system pressures of 10, 14, and 17 newtons per square centimeter (15, 20, and 25 psia).



(e) Preheat, 21 kilowatt-hours; initial system pressure, 17 newtons per square centimeter (25 psia); temperature, 400 K (260° F).



(f) Preheat, 46 kilowatt-hours; initial system pressure, 17 newtons per square centimeter (25 psia); temperature, 550 K (530° F).

Figure 3. - Concluded.

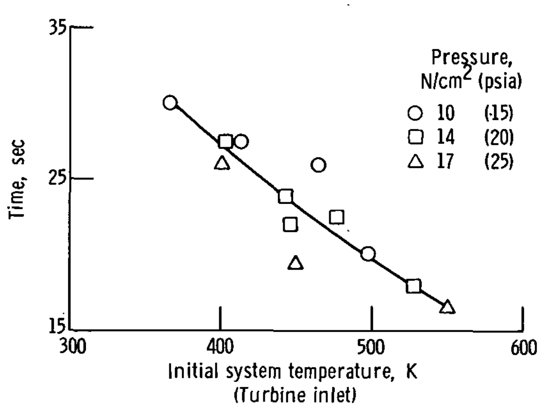


Figure 4. - Time to attain synchronous speed as function of initial system temperature. Applied frequency, ~400 hertz.

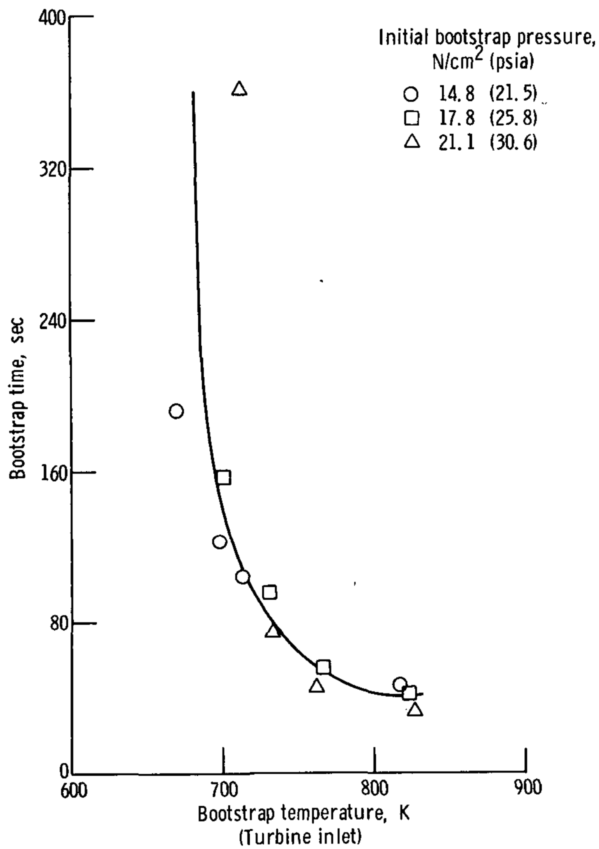


Figure 5. - Time to accelerate from synchronous speed to design speed as function of turbine-inlet temperature. Applied frequency, ~400 hertz.

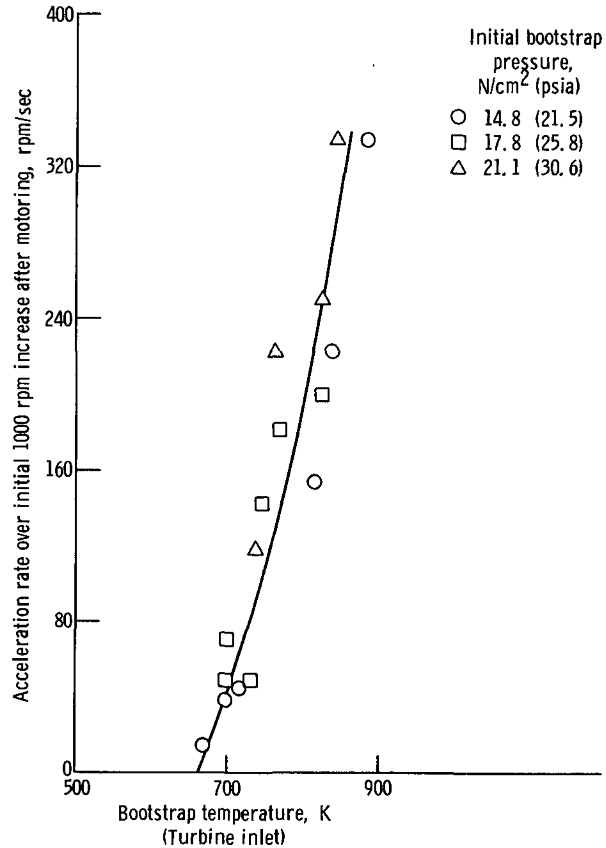


Figure 6. - Brayton rotating unit shaft acceleration from 12 000 to 13 000 rpm as function of bootstrap temperature. Applied frequency, ~400 hertz.

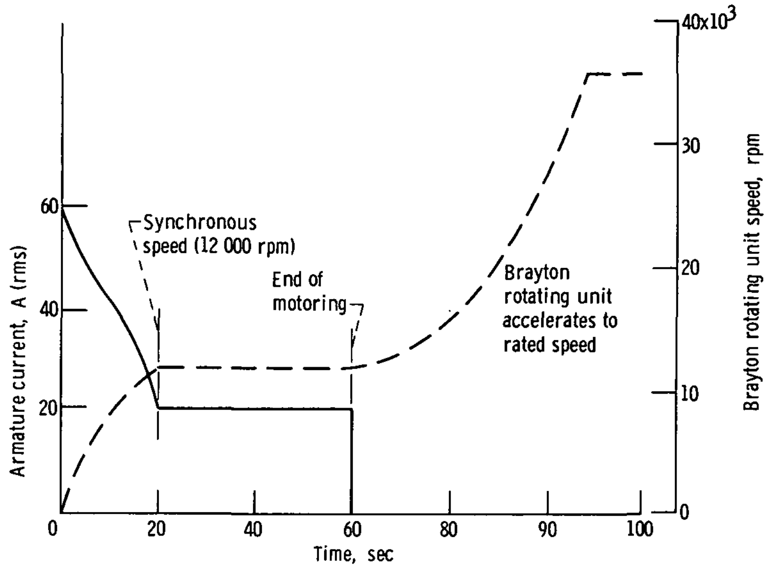


Figure 7. - Typical motor-start armature current and speed as function of time.

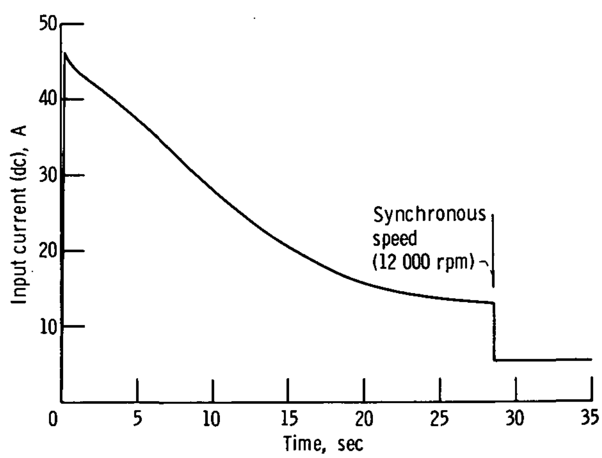
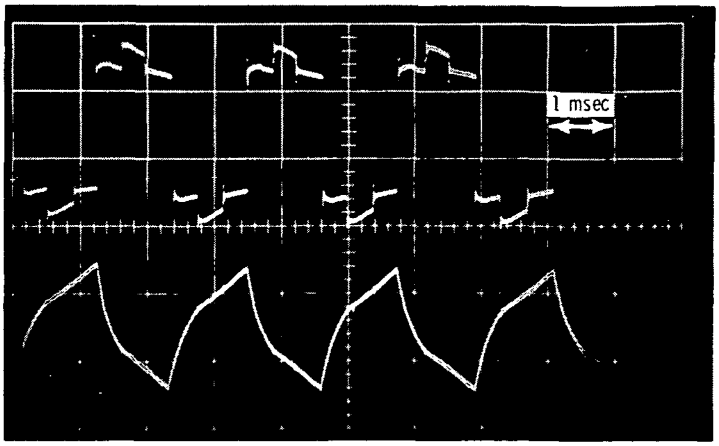


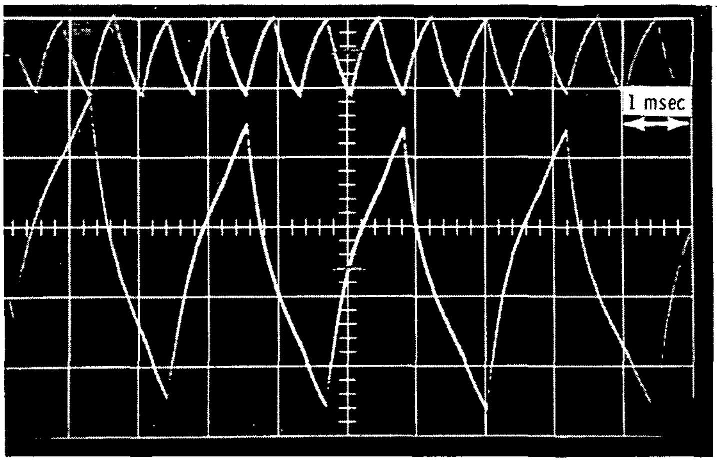
Figure 8. - Battery current to motor-start inverter as function of time.



t = 0

Time →

(a) Alternator line to neutral voltage, 20 volts per centimeter; armature current, 100 amperes per centimeter.

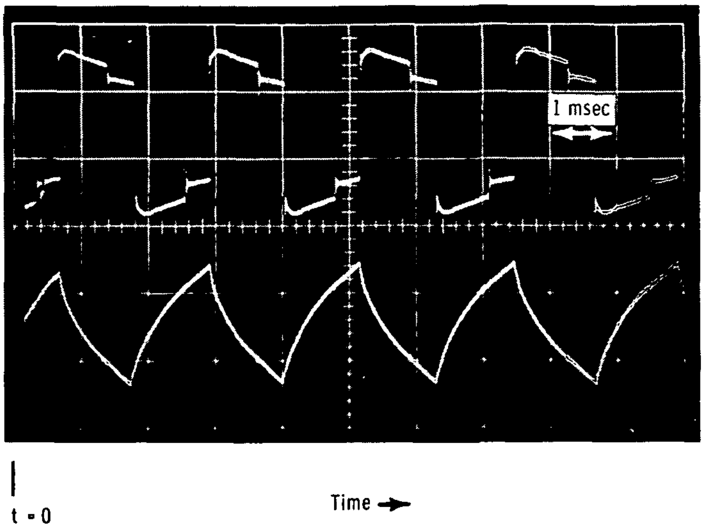


t = 0

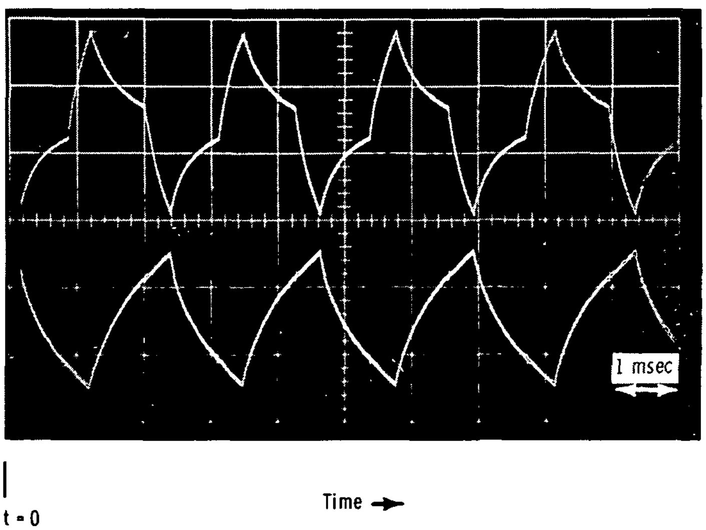
Time →

(b) Neutral current, 100 amperes per centimeter; armature current, 50 amperes per centimeter.

Figure 9. - Typical waveforms for three-phase start using motor-start inverter.



(a) Alternator line to neutral voltage, 20 volts per centimeter; armature current, 100 amperes per centimeter.



(b) Neutral current, 100 amperes per centimeter; armature current, 100 amperes per centimeter.

Figure 10. - Typical waveforms for two-phase start using motor-start inverter.

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