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MOTORING CHARACTERISTICS OF A 2- TO 10-KILOWATT BRAYTON ROTATING UNIT

by Robert C. Evans, Sheldon J. Meyer, and Robert Y. Wong

Lewis Research Center
Cleveland, Ohio 44135

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16. Abstract

Motoring tests were performed on a single-shaft turbine-compressor-alternator designed for use in a 2- to 10-kilowatt space-power system. This report presents the results obtained in terms of starting current, torque, and acceleration time for a range of supply frequencies from 212 to 1200 hertz and a range of voltage-to-frequency ratios from 0.04 to 0.1.

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SUMMARY

A single-shaft turbine-compressor-alternator designed for use in a 2- to 10-kilowatt space-power system was motored using supply frequencies of 212 to 1200 hertz. The objective of these tests was to determine motor characteristics that could be used to select starting conditions for a closed-loop power system. The results of these tests showed that (1) the alternator when operating as a motor could generate enough torque to accelerate the Brayton rotating unit to sufficient speed to achieve self-sustaining operation; (2) the alternator maximum line current specification limit of 150 percent of rated (40 A) will be exceeded for all voltage-to-frequency ratios above 0.075 whenever the shaft speed is below synchronous speed; (3) initiation of motoring while the Brayton rotating unit is rotating backwards does not have a detrimental effect on the alternator or the gas bearings; and (4) motoring will decrease the residual magnetism of the alternator.

INTRODUCTION

The Lewis Research Center is currently engaged in a technology program to develop components for Brayton cycle space-power systems (ref. 1). As part of this program, a single-shaft turbine-compressor-alternator designed for operation on gas bearings was procured for evaluation. The turbine-compressor-alternator make up the rotating component of the Brayton cycle power system and has been designated the Brayton rotating unit (BRU).

The BRU has been tested over a wide range of operating parameters in a closed-loop facility to simulate operation in a Brayton power system (refs. 2 to 4). In these tests the BRU was always started by evacuating the loop to approximately 6 psia ($4.1\ N/cm^2$) and injecting gas into the loop through the preheated heater to spin the BRU up to a self-sustaining speed. Another method of starting the BRU in a closed loop is to use the alternator as a motor to bring the turbine and compressor up to a speed where loop operation can be self-sustaining. The alternator would function as a three-phase induction-reluctance motor. Although certain design optimizations could result in significantly improved motor performance, primary design considerations for this machine were based on its use as a generator. Its motor performance cannot be altered without some redesign. However, this assumes only secondary importance as the basic condition to be met is that its present performance be adequate for attaining BRU self-sustaining operation in the test loop.

This report presents results obtained in terms of current, torque, acceleration, and voltage-to-frequency ratio from motoring the BRU using supply frequencies from 212 to 1200 hertz and voltage-to-frequency ratios from 0.04 to 0.1.

DESCRIPTION OF BRAYTON ROTATING UNIT

A photograph and a schematic of the BRU are shown in figures 1 and 2, respectively. The turbine rotor and the compressor impeller are mounted on opposite ends of a common shaft, with the alternator rotor in the center. The two journal bearings are located just outboard of each end of the alternator rotor. The thrust bearing is located between the compressor impeller and the compressor end journal bearing.

The alternator is a brushless modified Lundell with a solid four-pole rotor, designed for an output of 10.7 kilowatts, 0.75 lagging power factor, 120/208 volts, three-phase, and 1200 hertz at 36 000 rpm. The design specifications are listed in the following table:

Power output, kW	10.7
Phase	3
Power factor	0.75 (lagging)
Voltage, V	120/208
Frequency, Hz	1200
Liquid coolant	Dow Corning 200
Liquid coolant inlet temperature, $^{\circ}C$	21
Liquid coolant flow rate, lbm/sec (kg/sec)	0.12 (0.054)
Winding insulation temperature rating, $^{\circ}C$	220
Stator winding dc resistance/phase at 25° C, Ω	0.033
Alternator poles	4
Rotor weight, lbm (kg)	21.8 (9.91)
Rotor weight (less compressor and turbine wheels), lb (kg)	16.7 (7.59)
Rotor magnetic material	SAE 4340
Rotor interpole material	Inconel 718
Shunt field resistance at 25° C, Ω	3.67
Series field resistance at 25° C, Ω	3.88

The solid rotor consists of two separate magnetic sections made of SAE 4340, brazed to a nonmagnetic spacer made of Inconel 718. A photograph of the rotor is shown in figure 3. The magnetic and nonmagnetic sections of the rotor form a salient four-pole structure comparable to those found in various simple reluctance motor designs. Induction motor (asynchronous) torque is produced when a revolving magnetic flux wave is established in the stator-rotor gap and the rotor is below synchronous speed. Although this torque reduces to zero at synchronous speed, torque continues to be produced because of the tendency of the rotor poles to maintain alinement with the poles of the revolving stator field so as to minimize the reluctance of the magnetic flux paths. This torque is called reluctance torque.

TEST FACILITY

A schematic of the closed-loop test facility is shown in figure 4. The facility is the closed-loop Brayton cycle system, which is fully described in reference 2. The gas bearing supply line is for the external pressurization of the bearings during startup and shutdown to prevent rubbing.

Figure 5 is a block diagram of the complete electrical system including the equipment used when the BRU is generating power. Only the variable-frequency motor-generator, the field loading resistors, and the auxiliary dc field supply are used for the motor tests.

The variable-frequency motor-generator has a frequency range of 212 to 2000 hertz. The auxiliary field supply is a continuously variable dc power supply that was used to excite the alternator fields to prevent reverse shaft rotation caused by externally pressurizing the gas bearings. The field loading resistors are standard 50-ohm resistors with a 100-watt power dissipation rating. These resistors were connected across the field terminals during motoring tests to reduce the magnitude of any induced voltage.

INSTRUMENTATION

Line-to-neutral voltage, line current, and induced field voltage were measured using rectifier instruments. These instruments have a response time less than 0.005 second for step input signal changes from zero to full scale. Power was measured using a three-phase Hall effect watt transducer. The response time of this transducer was less than 0.3 second from zero to full scale. This response time was slow for this type of application, but since the total motoring time was approximately 6 seconds, the power recorded after 0.3 second could be used to calculate an approximate BRU motor power factor.

BRU speed was measured using noncontact capacitance probes and conditioning equipment. The capacitance probes produced a signal that had a frequency proportional to shaft speed. The response time for the speed measurement was less than 0.003 second for full scale.

The outputs from these instruments were recorded on an oscillograph using 3300 hertz galvanometers.

PROCEDURE

It was desired to motor the BRU with as great a margin of safety as possible. Because little was certain about the motor characteristics, selections of limits for starting current, applied voltage, motoring time, and speed were based on alternator specifications and the knowledge of the loop self-sustaining speed requirements obtained from previous tests.

Because all motoring would be done with the alternator windings initially at ambient temperature (25° C), a maximum starting current limit of 120 amperes was selected. This limit is twice the line current level for the 21-kilovolt-ampere, 5-second alternator overload specification which applies at a winding temperature of approximately 250° C.

Data taken from gas injection starting of the BRU in the hot test facility with the voltage regulator and series field excitor disconnected have shown that, with a turbine inlet temperature of 510° C, self-sustaining operation should occur at speeds above 8000 rpm. It was decided that a speed of 12 000 rpm provided sufficient margin to reasonably insure a system start at this turbine inlet temperature with the voltage regulator disconnected. This is synchronous speed for a supply voltage frequency of 400 hertz. Operation at synchronous speed is desirable if long motoring periods are required because of the relatively low line current at this condition. Therefore, the bulk of the motor testing was conducted at 400 hertz. Only starting characteristics such as current and torque were investigated at frequencies of 212, 800, and 1200 hertz. In order to limit the heating of the motor windings and the rotor, a motoring time limit of 6 seconds was chosen. This value was only 20 percent greater than the 5-second overload time specified for the alternator.

Before starting a series of motor tests, all circuit contactors were opened. The bearings were then pressurized and the alternator field excited to prevent reverse rotation. The motoring supply voltage and frequency were then set to the desired levels. To motor the BRU, the field supply contactor was opened and the field resistor contactors were closed. Then the motor-generator contactor was closed.

Motoring tests were conducted with frequencies of 212, 400, 800, and 1200 hertz for various voltage-to-frequency (V/f) ratios. The 212-hertz frequency was the lowest stable frequency that could be obtained from the motor-generator. The synchronous speeds that correspond to the selected frequencies are 6360, 12 000, 24 000, and 36 000 rpm, respectively.

Whenever the gas journal bearings are externally pressurized, a torque tending to rotate the rotor in the reverse direction is produced. With no flow in the loop, the windage load of the turbomachinery limits the speed produced by this torque. Reverse speeds in excess of 1000 rpm have been observed with a loop pressure below 6 psia ($4.1\ N/cm^2$). In the test facility, the auxiliary dc supply was used to excite the alternator fields to keep the shaft from rotating in the reverse direction. Approximately 2 or 3 seconds before an injection start or when motoring, the axuiliary dc excitation was removed and the shaft was then free to rotate backward. Under normal injection starts, or motoring, this rotational speed did not exceed 5 rpm. Without the braking action of the auxiliary field excitation, the reverse speed at the time of starting could be much higher. Tests were conducted at various speeds of reverse rotation to determine the effects on gas bearing behavior and the motoring operation in general. The tests were conducted in 100-rpm increments, starting at 0 rpm and ending at 600 rpm.

RESULTS AND DISCUSSIONS

The objective of this investigation was to obtain motor characteristic data for the BRU that could be used to select starting conditions for a closed-loop power system. The following discussion will present the results of the motor tests performed and relate whether the performance is acceptable for obtaining self-sustaining operation of the BRU in this loop.

Starting Current and Torque

The maximum BRU starting current was obtained at zero speed. Figure 6 shows this maximum current as a function of voltage-to-frequency ratio for constant supply frequencies of 212, 400, 800, and 1200 hertz. At a constant supply frequency, the relation between applied voltage and starting current is approximately linear, and high starting current for high v/f can be predicted. The alternator over-current limit of 58 amperes was exceeded at v/f values of 0.045 at 1200 hertz, 0.049 at 800 hertz, 0.060 at 400 hertz, and 0.073 at 212 hertz. For all applied frequencies, the current decreased from its maximum value as the BRU began to rotate and reached its minimum value at synchronous speed.

Figure 7 gives the calculated starting torque for the same v/f values as those shown in figure 6. These torques were calculated from input power measurements minus armature resistance losses (see appendix). The input power could not be accurately measured at the instant the contactor was closed because of the 0.3-second to full-scale response time of the watt transducer. Input power used to calculate starting torque was obtained by extrapolating these data. The slope of the input power as a function of time curve was determined at 0.3 second and assumed to be constant between 0 and 0.3 second. This assumption was based on the linear variation of voltamperes from 0 to 50 percent synchronous speed.

Starting torque was also calculated using the polar moment of inertia of the rotor and its acceleration. The method used in computing this starting torque is given in the appendix. Figure 8 presents this starting torque as a function of voltage-to-frequency ratio. Figure 9 shows very good agreement between the starting torques computed by input power measurements (fig. 7) and by polar moment of inertia and acceleration (fig. 8) for a supply frequency of 400 hertz. The higher torque, computed using input power measurements, could be due to not taking into consideration all internal power losses. The data in figures 7 and 8 show that at a constant v/f the torque increased as the supply frequency was increased. The starting current also increased as the frequency increased. A BRU starting torque of 15 inch-pounds (1.7 N-m) will require a starting current of 60 amperes at 212 hertz. At 1200 hertz, 72 amperes will be required to produce the same torque.

As discussed in the PROCEDURE, most of the motor tests were conducted at a supply frequency of 400 hertz. Lower speeds resulting from lower frequencies may be marginal for starting a power system. Frequencies above 400 hertz will result in higher starting currents that yield the same level of starting torque.

Figure 10 shows the variation in BRU speed with time. The loop pressure was 6 psia (4.1 N/cm^2). Curves for line-to-neutral voltages of 22, 32, and 42 volts are shown. All voltages are at 400 hertz and were applied for 6 seconds. These voltages were not constant over the 6-second motoring period because of poor regulation of the motor-generator supply. The minimum value would occur at the instant of starting (maximum line current). The line-to-neutral voltages given are the average of the voltages occurring over a complete motoring period. At an average voltage of 42 volts the BRU reached synchronous speed (12 000 rpm) in approximately 4.9 seconds. At average voltages of 22 and 32 volts, the BRU reached speeds of 6500 and 10 500 rpm, respectively, in 6 seconds.

Figures 11 and 12 give the line current and input kilovolt-amperes, respectively, for the same three line-to-neutral voltages. At 42 volts, the line current was 110 amperes (2.6 times rated alternator current) at zero speed and decreased to 33 amperes at synchronous speed. The input kilovolt-amperes decreased from a maximum of 12.8 at zero speed to 4.5 at synchronous speed. At 32 volts, zero-speed line current was only

76 amperes (1.8 times rated). Input kilovolt-amperes were 6.6 at zero speed and reduced to 5.2 at the end of 6 seconds. For 22-volt input, the maximum line current was 49 amperes (1.25 times rated). The input kilovolt-amperes was 3.1 at zero speed and reduced to 2.8 at the end of 6 seconds.

From consideration of the speeds attained during the 6-second motoring period and the maximum values of line current reached, an average supply voltage of approximately 32 volts would appear to be adequate for achieving motor start in a closed loop. Lower supply voltages will produce lower speeds for the same motoring time or require a longer time to reach the same speed obtained when applying higher voltages. Also, at lower speeds the BRU will require higher turbine inlet temperatures to become self-sustaining. Higher voltages result in much greater currents with increased stator winding and rotor heating.

Figure 13 shows the effect of speed on input power and power factor for an average line-to-neutral voltage of 42 volts at 400 hertz. At zero speed the power factor is approximately 0.56 and is nearly constant to 50 percent synchronous speed. It then decreases rather rapidly until it reaches about 0.1 power factor at synchronous speed. These power factor values are typical of induction-reluctance motors.

Inflection points may be seen at 50 percent synchronous speed in figure 11 for applied voltages of 32 and 42 volts. They also appear in the input volt-amperes and power factor as functions of speed curves in figures 12 and 13 and in the torque as a function of speed curves shown in figure 14. The results of the analysis for this type of motor using revolving field theory and symmetrical components show that these inflections occur because of rotor pole saliency and that, for slips smaller than 0.5, retarding torque produced by the resulting negative sequence currents is greater than for slips larger than 0.5. The accelerating torque is thus reduced at a greater rate (refs. 5 to 7).

Figure 14 shows computed motor torques as a function of speed. Curve 1 is the theoretical maximum motor torque, computed using input power measurements. This torque computation assumes no losses in the machine (input power equals stator-rotor gap power). Curve 2 is the theoretical motor torque with stator resistance power loss taken into account. Curve 3 is actual torque required to accelerate the rotor at the rate of angular acceleration computed using the experimental test data. The theoretical motor torque at synchronous speed, shown in curve 2, is composed of the windage load torque of the gas bearings, the turbomachinery and the alternator, as well as alternator stator iron losses. By assuming that these iron losses are low compared with the windage losses, curve 4 can be plotted assuming a cubic variation with speed of these windage loads. Values plotted in curves 3 and 4 must be added to obtain the actual torque output as a function of speed (curve 5). The area between curve 5 and the values plotted in curve 2 relate to power lost in heating the rotor. These losses are very high at lower speeds.

It was not possible, because of limits in instrumentation, to determine the amount of rotor heating that occurred during this period. However, if the total area between curve 2 and curve 5 is determined, the amount of thermal energy absorbed by the rotor over the 4.9-second acceleration period can be calculated. Since the specific heat for both materials composing the rotor is approximately 0.107 Btu per pound per $^{\circ}F$ (448 J/(kg)($^{\circ}C$)) and the total rotor mass (including turbine and compressor wheels) is 21.8 pounds (9.9 kg), the 19.2-Btu (20.3-J) computed energy loss to the rotor heating elevates the rotor temperature 4.6° C during the acceleration period. If the weight of the wheels is excluded, a temperature rise of 6.0° C would result. Iron losses during the acceleration period and at synchronous speed were not considered in making these calculations.

Since these high rotor losses exist only during the acceleration period, any prolonged asynchronous operation of the machine as a motor may result in substantial rotor heating as well as stator winding heating resulting from high line currents.

Figure 15 shows photographs of oscilloscope traces of line current and line-to-neutral voltage at the instant of starting. The narrow upper trace is the line-to-neutral voltage. Amplitude modulation of the line current is very apparent. The modulation relates to two simultaneously occurring effects which vary the inductive portions of the machine terminal impedance: (1) reluctance variation caused by the motion of the rotor's salient magnetic poles with respect to a stator phase winding and (2) motion of the rotor poles with respect to the peak of the synchronously revolving stator flux wave.

Although the trace covers a period of approximately 180 milliseconds, the low frequency of the initial modulation brought about by the rotor poles passing the stator windings is seen to increase as the rotor accelerates. With decreased oscilloscope sweep rate, figure 15(b) covers a period of approximately 0.5 second. One-half synchronous speed was not reached during this time.

In figure 16 photographs of current and voltage traces for an entire motor accelerating period are presented. They were not taken during the same test but are all at a frequency of 400 hertz. These photographs are not calibrated and are intended only to show the modulating of the supply voltage and current at zero, one-half synchronous, and synchronous speed. In figure 16(a), at the instant voltage was applied, the rotor was retrograding because of the action of external pressurization on the gas journal bearings. This photograph shows the initial modulation effects at and in the immediate vicinity of zero speed. Figure 16(b) shows the effects while approaching (and reaching) synchronous speed. The low frequency modulation at this point arises from the effect of the peaks of the synchronously rotating stator flux wave sweeping past the rotor poles at a decreasing rate. This frequency reduces to zero at synchronous speed as the rotor pulls into step with the rotating flux wave. The photograph indicates that for this particular test, synchronous speed was reached after a short period identified by very low frequency modulation. This corresponds to the period when the peaks of the slowly fluctuating reluctance torque were increasing in value such that the rotor could be "snapped" (pulled) into synchronism.

Figure 16(c) shows the modulations at one-half synchronous speed. The amplitude reduces because of partial cancellation, and higher modulating frequencies are observed. No modulation effects were visible on the trace of applied voltage except at starting and near synchronous speed. The disturbances were of low level. Their appearance, being of such short duration, should be of no consequence in the operation of any Brayton power system of this type.

Induced Field Voltage

Figure 17 gives the maximum level of voltage induced in one of the alternator fields for various supply line-to-neutral voltages at a frequency of 400 hertz. A 50-ohm resistor was connected across each field to limit the voltage level. The maximum induced field voltage was approximately 7 volts for a 0.1 supply voltage-to-frequency ratio. The level of the voltage induced in both field coils was approximately the same. The frequency of the induced voltage is a function of the rotor speed and the frequency of the supply voltage. At zero speed, this frequency was equal to the supply voltage frequency. The level of the voltage was approximately constant from zero speed to almost synchronous speed. It increased slightly as the rotor speed approached 50 percent of synchronous speed and then decreased slightly at speeds above 50 percent. At synchronous speed the voltage reduces to zero as the rotor becomes stationary to the stator magnetic flux wave.

Subsequent testing with the alternator functioning as a generator revealed that the residual magnetism of the alternator was reduced during motor starting. At the normal level of residual magnetism found in this particular machine, the alternator would generate enough line-to-neutral voltage to turn on the voltage regulator at approximately 10 000 rpm (ref. 4). If the residual magnetism is greatly reduced, the alternator will not generate enough voltage to turn on the voltage regulator. As a result, electrical loading of the alternator can not be established and an overspeed condition will result. As a safety precaution when motor starting the BRU, it is recommended that the shunt field of the alternator be momentarily excited by a dc power supply at the end of the motoring period.

Reverse Speed

The BRU was motored while rotating at reversed speeds of 100 to 600 rpm. No detrimental effects were found when initiating motoring at these reverse speeds. The tests revealed the following: (1) the maximum positive speed obtained for a set motoring time and v/f ratio will decrease as the reverse speed is increased; and (2) the total operating time at the maximum starting current level will increase.

Figure 18 gives the time required for the BRU to reach a forward speed equal to its initial reverse speed. This curve is intended to show the time required to reach zero speed, the time at zero speed, and the time required to reach a forward speed of 600 rpm. In order to compensate for the time loss in reversing the speed, a higher v/f ratio will have to be used if a constant maximum speed is to be obtained within a given allowable motoring time.

SUMMARY OF RESULTS

The results from motor tests on the Brayton rotating unit (BRU) are summarized as follows:

1. The alternator will perform satisfactorily as a motor to rotate the BRU to the speed required for self-sustaining operation.

2. A supply frequency of 400 hertz at an average voltage-to-frequency ratio of 0.08 to 0.1 was found to be adequate for motoring the BRU at loop pressures from 6 to 15 psia (4.1 to 10.3 N/cm^2). The alternator maximum line current limit specification of 150 percent of rated will be exceeded until the shaft speed reaches synchronous speed.

3. At a constant voltage-to-frequency ratio, the maximum starting current and torque will increase as the supply frequency is increased.

4. Varying the supply voltage to the BRU affects the starting torque to a much greater extent than it does the starting current.

5. Motoring the BRU from initial reverse speed of 600 rpm does not have a detrimental effect on the alternator or the gas bearings.

6. Motoring the BRU will reduce the alternator residual magnetism. An auxiliary field excitation source should be used at the end of the motoring period to flash the shunt field to assure the generation of enough line voltage to turn on the voltage regulator.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 30, 1970,
120-27.

APPENDIX - STARTING TORQUE CALCULATION METHODS

Based on Input Power

The starting torque was calculated from the equation

$$T \approx \frac{9.54\, V^2 R_r m}{N_s Z_e^2} \qquad \text{N-m}$$

where V is the supply line-to-neutral voltage, R_r is the resistance of the rotor/phase, m is the number of phases, Z_e is the equivalent impedance of the stator and rotor/phase, and N_s is the synchronous speed in rpm (ref. 8).

Neglecting the magnetic losses, Z_e was calculated from the measured supply voltage and current. The rotor resistance R_r was found from the equivalent resistance R_e and the measured stator resistance R_s where

$$R_r = R_e - R_s$$

The equivalent resistance was calculated from measured line current and power.

Based on Polar Moment of Inertia

$$T \approx \frac{0.098\, I\, \Delta\text{rpm}\; 2\pi}{60\, \Delta t} \qquad \text{N-m}$$

where I is the polar moment of inertia of the rotor and Δt is the time in seconds required for the speed to increase by Δrpm. The polar moment of inertia of the rotor was calculated to be 0.0670 kilogram-second-centimeter.

A torque-speed curve was then plotted and the starting torque obtained by extrapolating the curve to zero speed.

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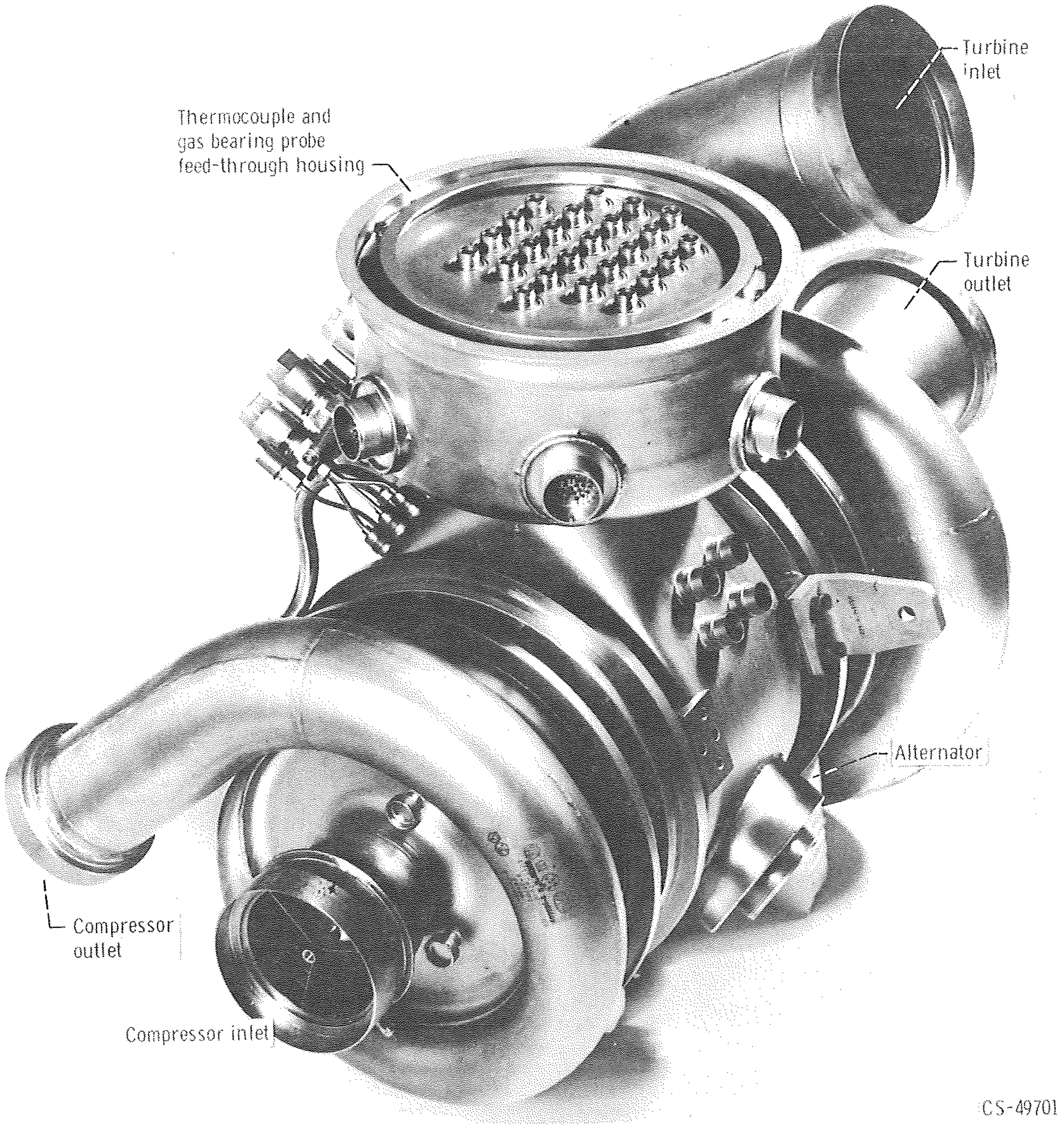


Figure 1. - Brayton rotating unit.

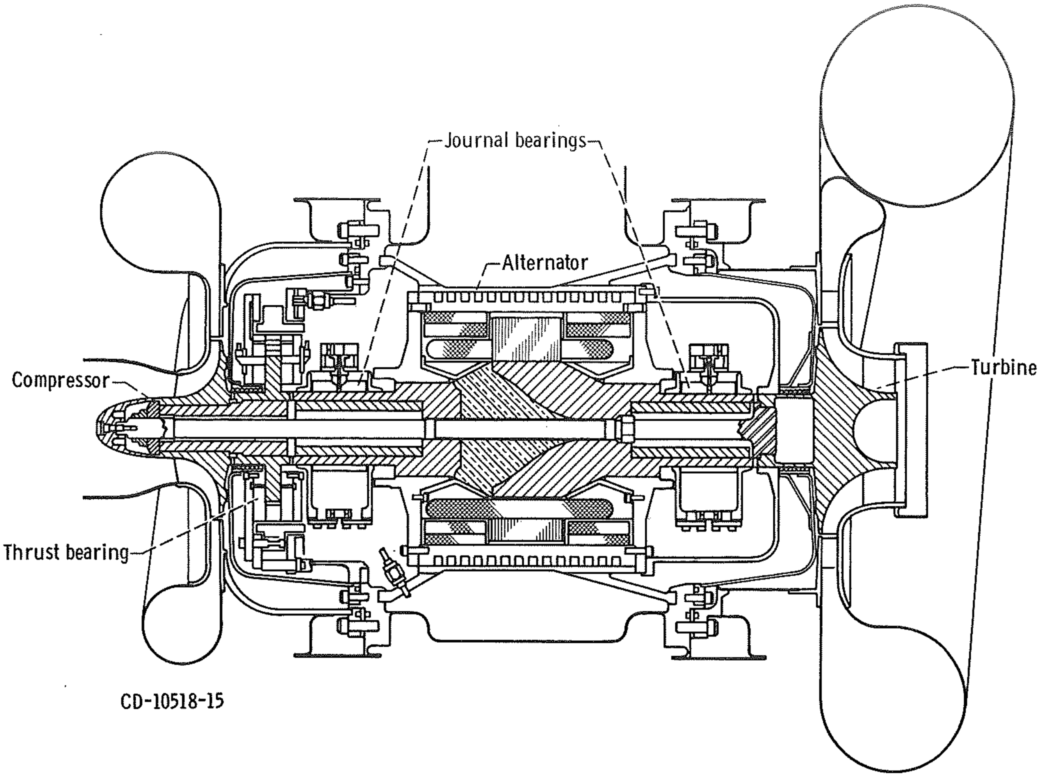


Figure 2. - Schematic of Brayton rotating unit.

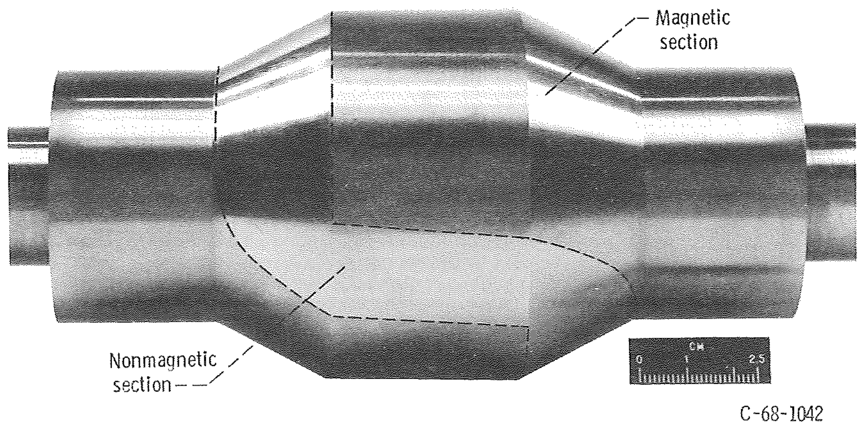


Figure 3. - Alternator rotor.

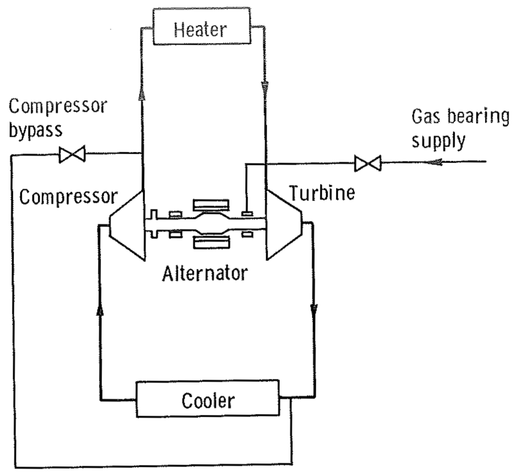


Figure 4. - Schematic of test loop.

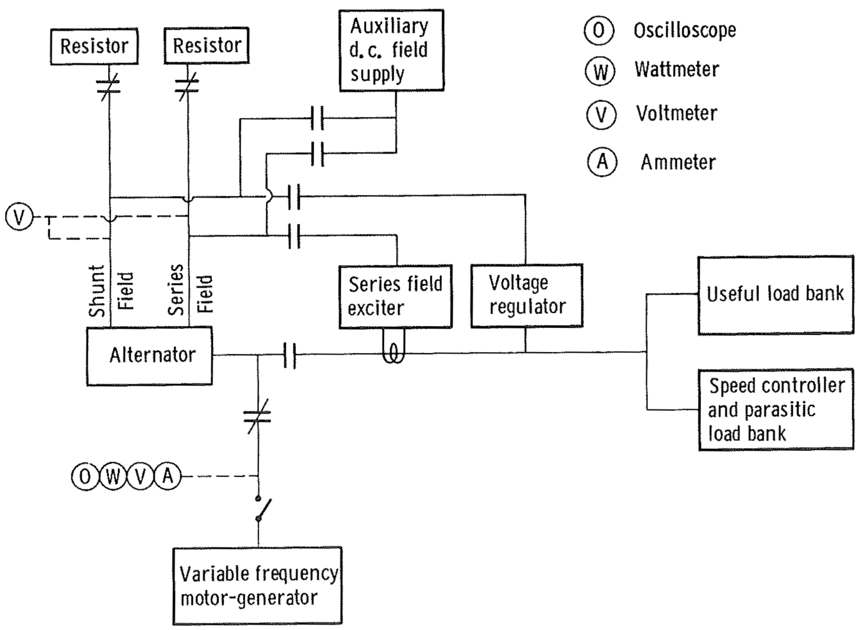


Figure 5. - Block diagram of electrical system.

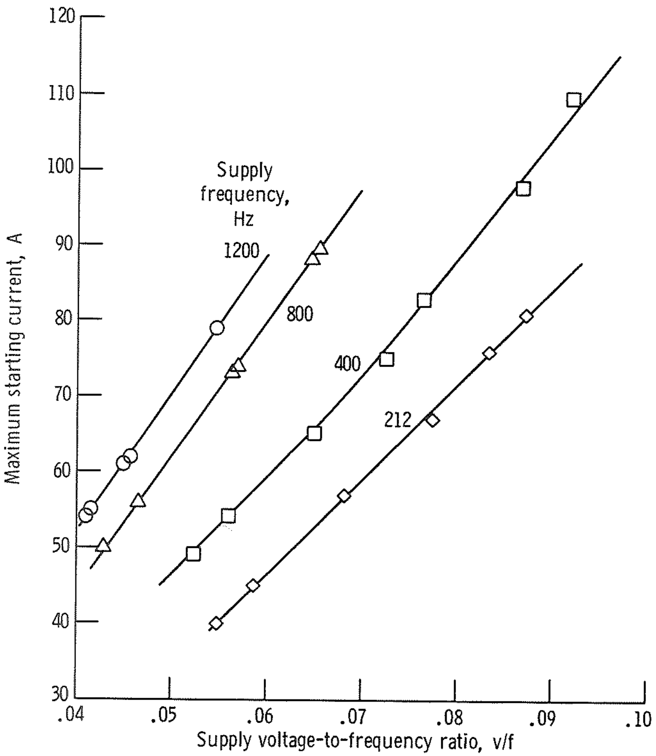


Figure 6. - Maximum Brayton rotating unit starting current for various supply voltage-to-frequency ratios.

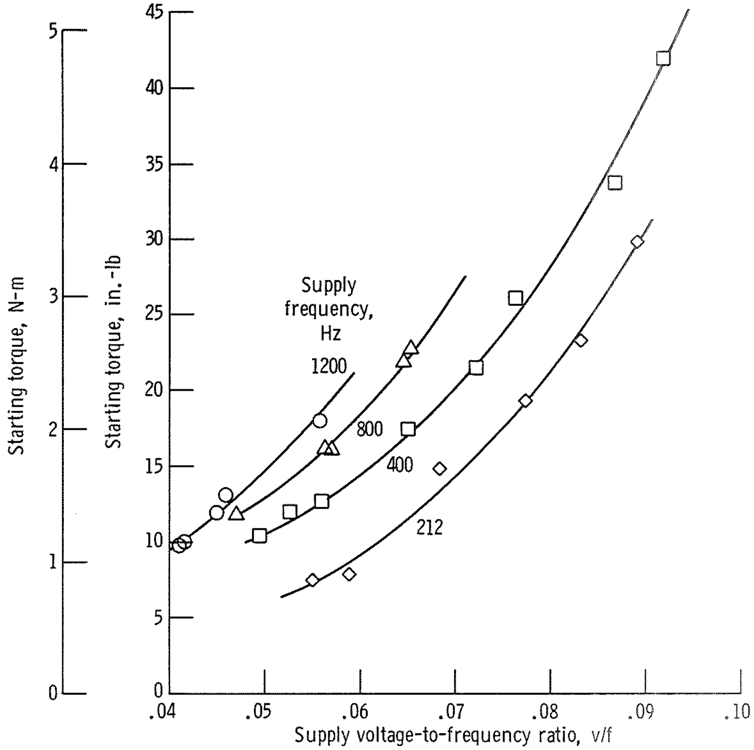


Figure 7. - Brayton rotating unit starting torque for various supply voltage-to-frequency ratios (calculated from input power).

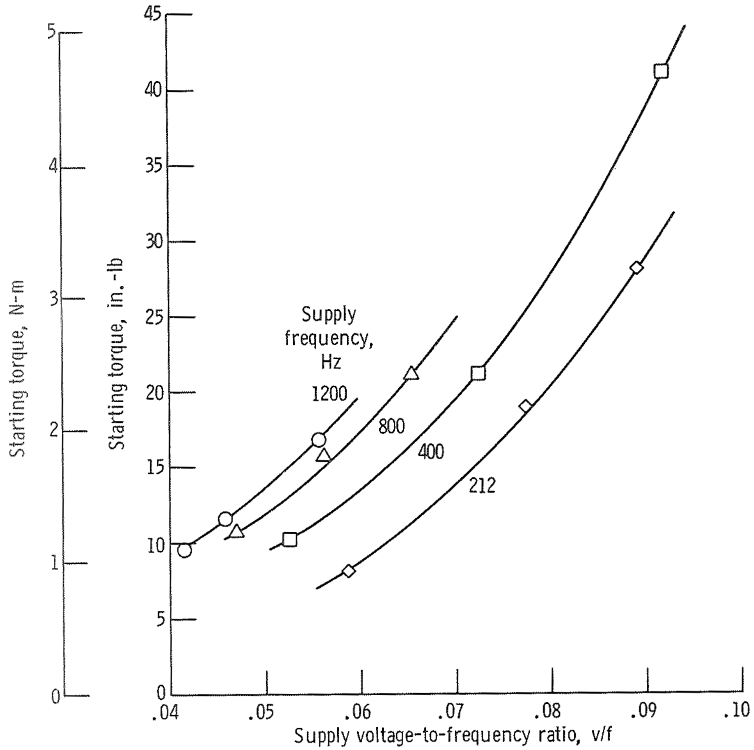


Figure 8. - Brayton rotating unit starting torque for various supply voltage-to-frequency ratios (calculated using polar moment of inertia of rotor and acceleration).

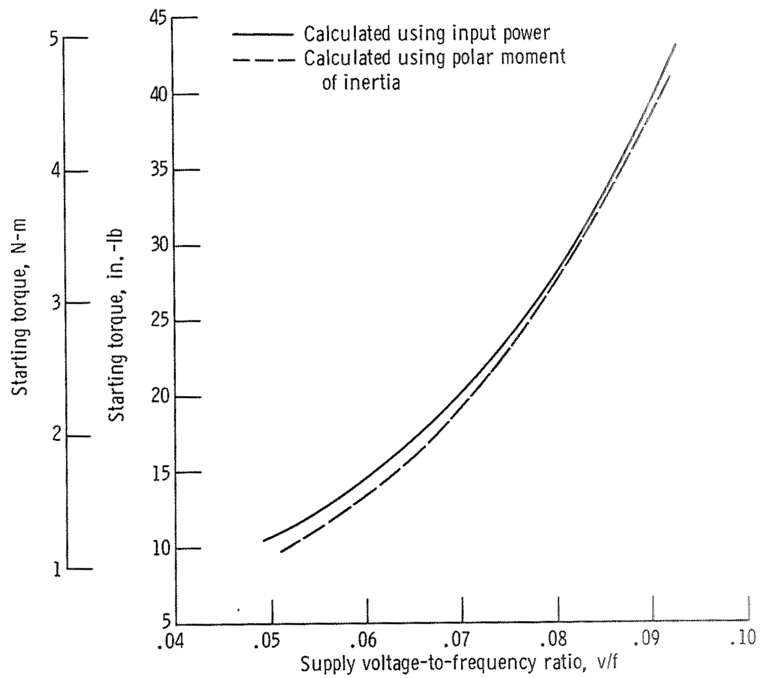


Figure 9. - Comparison of Brayton rotating unit starting torques calculated from input power and polar moment of inertia for supply frequency of 400 hertz.

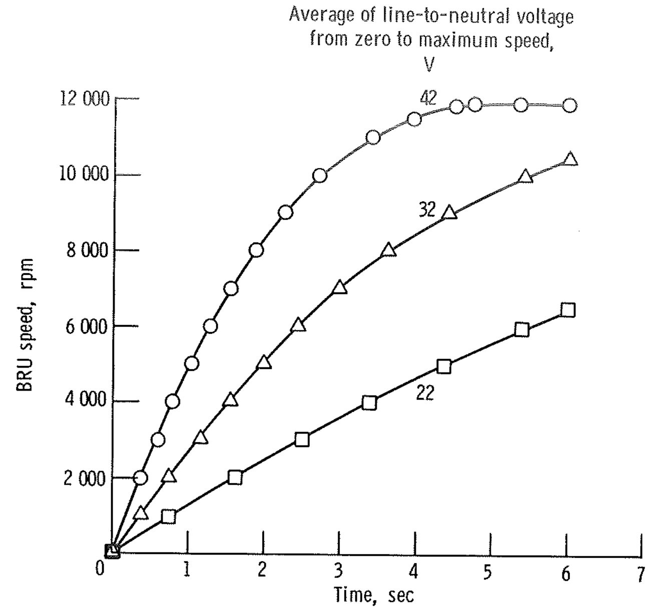


Figure 10. - Effect of input line-to-neutral voltage on Brayton rotating unit speed. Input frequency, 400±3 hertz; loop pressure, 6 psia (4.1 N/cm^2).

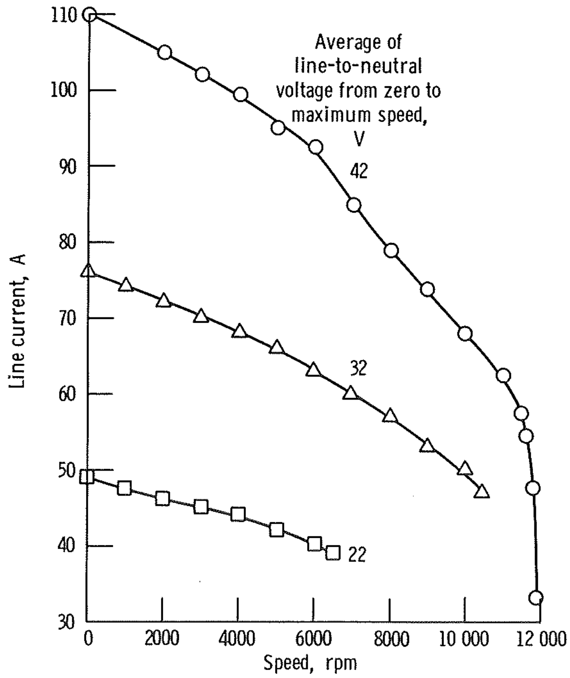


Figure 11. - Brayton rotating unit line current at various speeds for three input voltages. Frequency, 400±3 hertz; motoring time, 6 seconds.

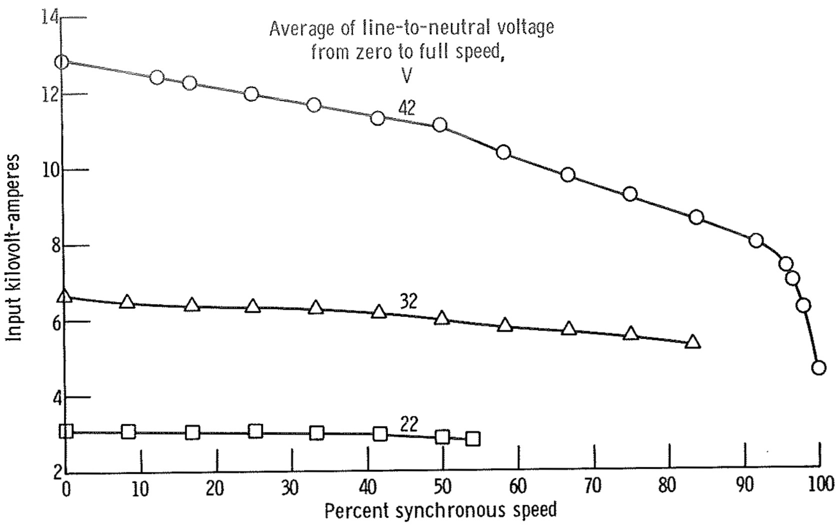


Figure 12. - Brayton rotating unit motoring kilovolt-amperage at various speeds for three input voltages. Frequency, 400±3 hertz; motoring time, 6 seconds.

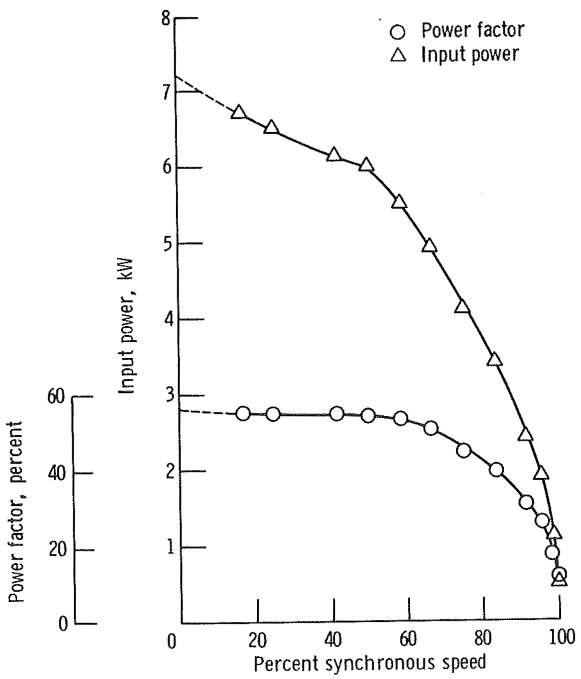


Figure 13. - Effect of speed on Brayton rotating unit motoring input power and power factor. Average of line-to-neutral voltage from zero to synchronous speed, 42 volts; frequency, 400±3 hertz.

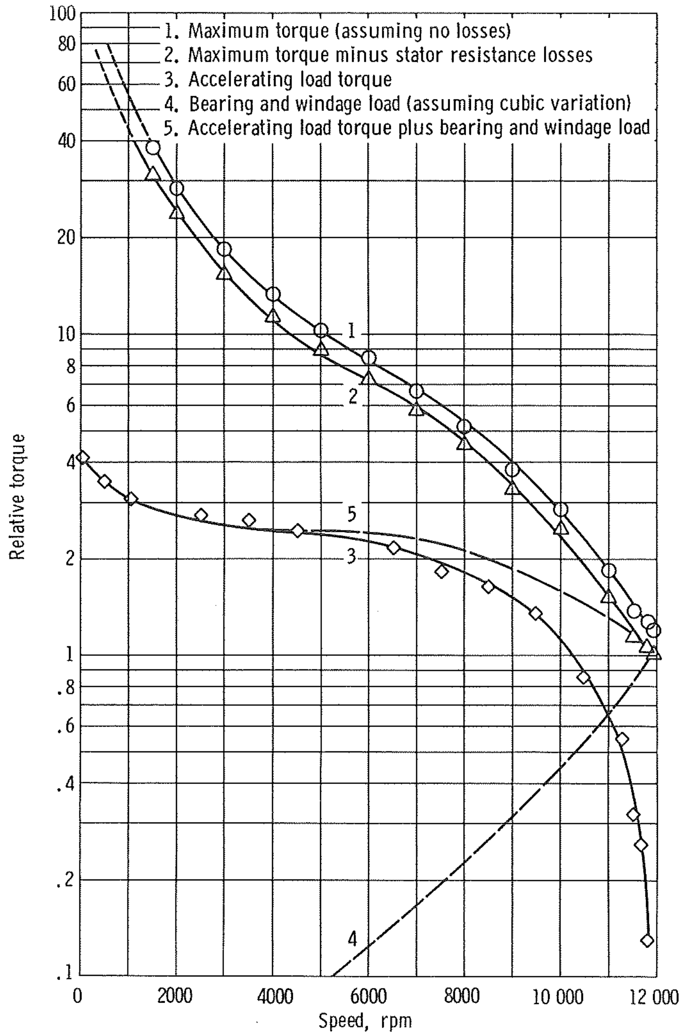
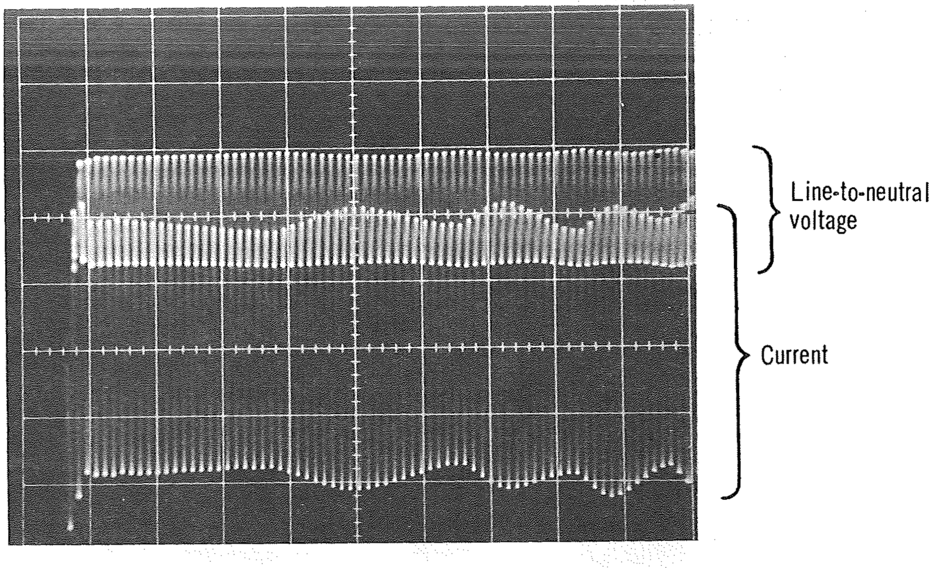
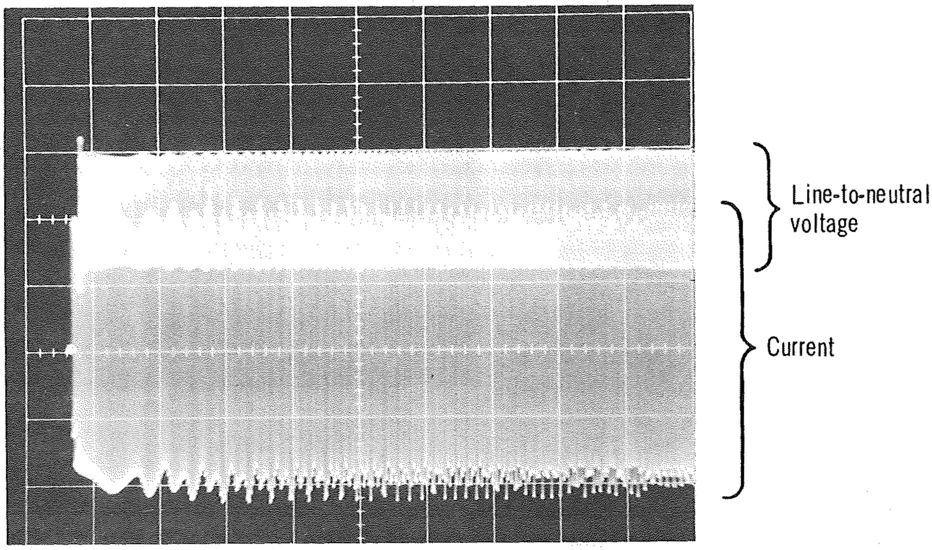


Figure 14. - Computed motor torque curves. Supply line-to-neutral voltage, 42 volts; frequency, 400±3 hertz; acceleration time, 4.9 seconds. Relative torque of 1.0 equals 10 inch-pounds (1.1 N-m).

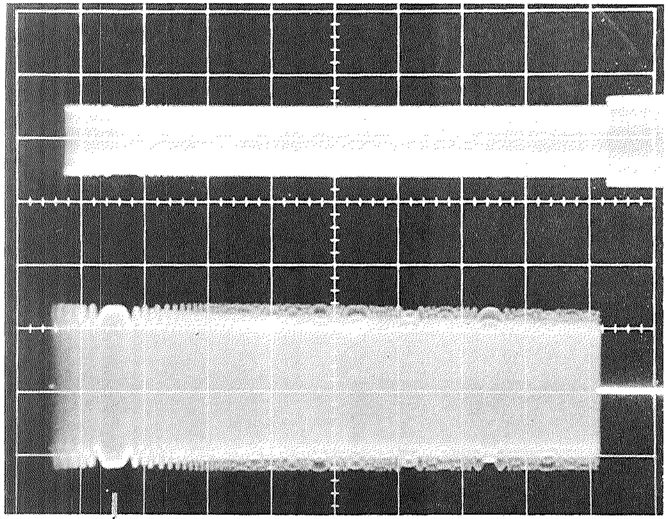


(a) Oscilloscope sweep, 20 milliseconds per centimeter.

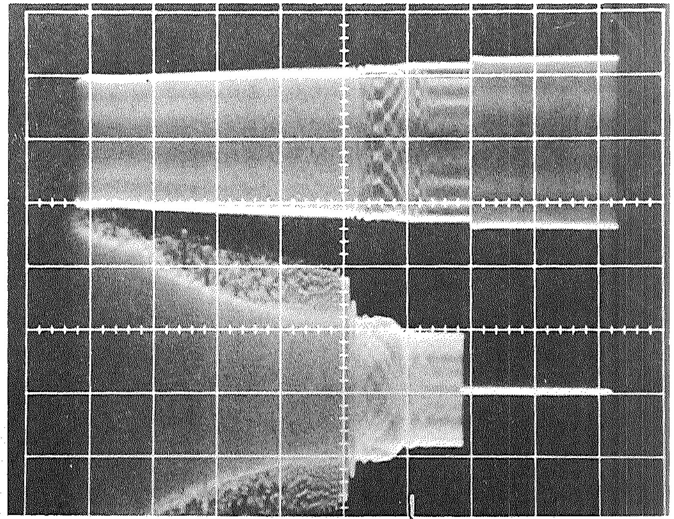


(b) Oscilloscope sweep, 50 milliseconds per centimeter.

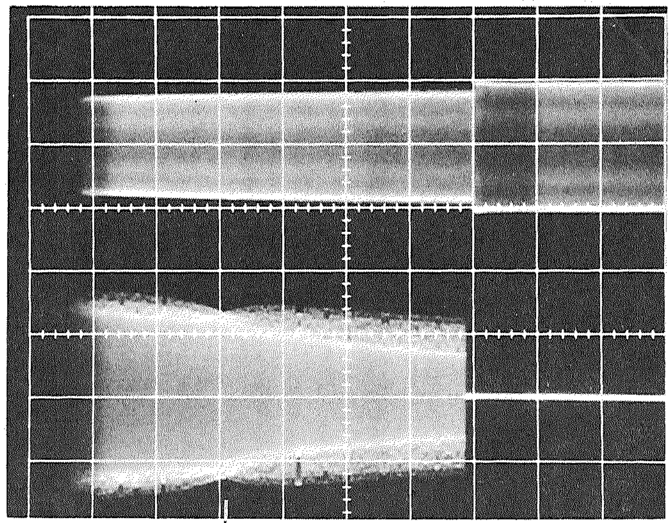
Figure 15. - Current and voltage waveforms at motor start. Frequency, 400 ± 3 hertz.



(a) Zero speed.



(b) Synchronous speed.



(c) One-half synchronous speed.

Figure 16. - Line-to-neutral voltage and line current traces for complete acceleration period. Frequency, 400 ± 3 hertz.

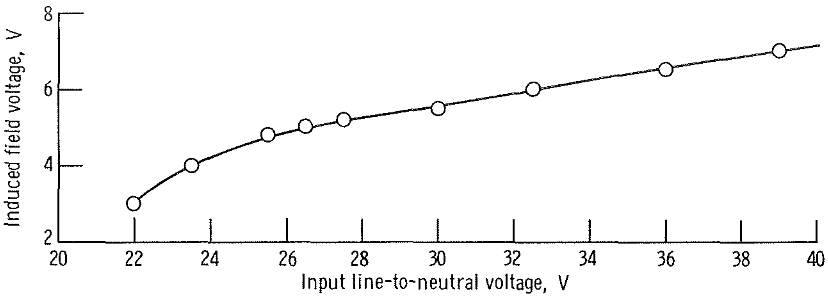


Figure 17. - Maximum voltage induced in alternator fields. 50-Ohm resistors across fields: input frequency, 400±3 hertz.

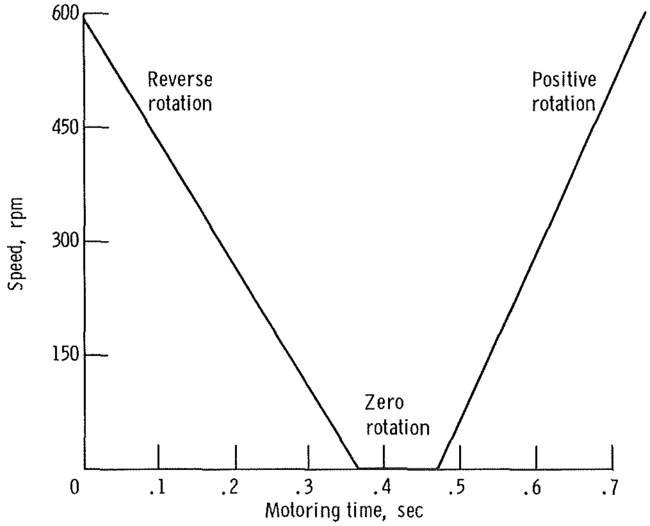


Figure 18. - Motoring time required for Brayton rotating unit to reach positive rotation equal to initial reverse rotation. Supply voltage frequency, 400±3 hertz, voltage-to-frequency ratio, 0.05.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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