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MOTOR-STARTING CHARACTERISTICS OF TWO INDUCTOR ALTERNATORS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • OCTOBER 1969

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SUMMARY

Two inductor alternators were started as induction motors. One machine had a 5.2-inch (13.2-cm) diameter rotor with amortisseur windings and laminated pole tips, and the other had a 7.38-inch (18.7-cm) diameter rotor with solid poles. Armature current, rotational speed, and field voltage were measured. Torque was computed from its relation to measured angular acceleration and moment of inertia. Both machines exhibited reasonable torque at standstill. Torque decreases gradually to about 50-percent speed when an inflection occurs. Above 50-percent speed, the torque is low. These machines require about 3.5 per unit current at full voltage and rated frequency, which is typical of low-starting-current induction motors. Based on worst-case assumptions, these machines will start Brayton cycle power systems with 100-percent voltage applied.

INTRODUCTION

In the single-shaft Brayton cycle space power system, one method of startup being considered is motoring of the solid-rotor alternator. However, data on the motor-starting characteristics of solid-rotor alternators are limited. Since the motor-starting characteristics could not be predicted analytically, an experimental program was conducted. The results of this investigation are presented herein. These results are then compared with the system starting requirements.

Conventional induction motors are well described in the literature (refs. 1 and 2). Their characteristics are highly predictable and can be optimized for most, if not all, applications. Investigations (refs. 3 to 6) of induction motors with solid cyclindrical rotors have also been performed; the major conclusion of these investigations is that poor performance precludes the use of such motors in essentially all applications. A comprehensive analysis of the starting characteristics of synchronous machines is presented by Concordia in reference 7. This analysis clearly shows that torque inflections occur at 50-percent speed because of saliency in the rotors. However, motor-starting information on machines with solid salient poles, with or without amortisseur windings, is limited to qualitative descriptions (ref. 8).

Alternators for use in dynamic space power systems will be brushless solid-rotor stationary-coil machines. The inductor, or homopolar, alternator is a machine of this type. An alternator of this type (ref. 9) with a 5.2-inch (13.2-cm) diameter rotor having amortisseur windings was constructed for the two-shaft Brayton cycle program. In addition, a similar alternator (refs. 10 and 11) with a 7.38-inch (18.7-cm) diameter rotor and solid poles was developed for the SNAP-8 program. These machines were utilized in this investigation.

APPARATUS

Description of the Alternators

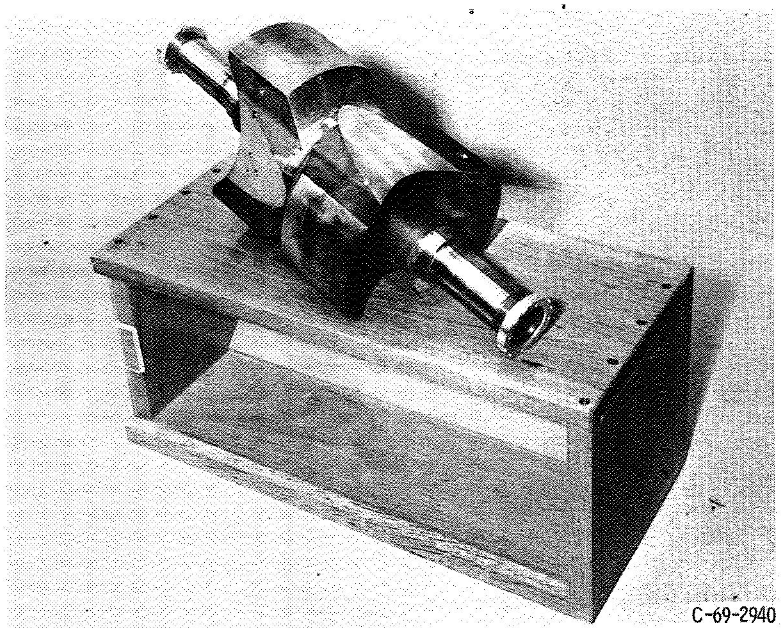
The inductor alternators used in this investigation are thoroughly described in references 9 to 12. The 60-kilowatt unit with a 7.38-inch (18.7-cm) diameter rotor was developed for the SNAP-8 program while the 12-kilowatt machine with its 5.2-inch (13.2-cm) diameter rotor was developed for the Brayton cycle program. For convenience the most significant design parameters of the two machines are shown in table I. The relative performance of electric machines of similar design, operating at the same speed, will be comparable if the product of the bore diameter squared and the stack length (D^2L) of each machine is proportional to the kilovolt-ampere (kVA) rating. The data of table I indicate that the machine with the 5.2-inch (13.2-cm) diameter rotor has a relatively large D^2L. As an alternator this machine had higher efficiency and greater overload capability. The 5.2-inch (13.2-cm) machine has amortisseur windings installed in the laminated pole tips while the 7.38-inch (18.7-cm) machine has solid poles. In this case, the amortisseur windings were designed to minimize the voltage unbalance due to unsymmetrical loads. The rotors of the experimental alternators are shown in the photographs of figure 1.

Turbine-Alternator Power Supply

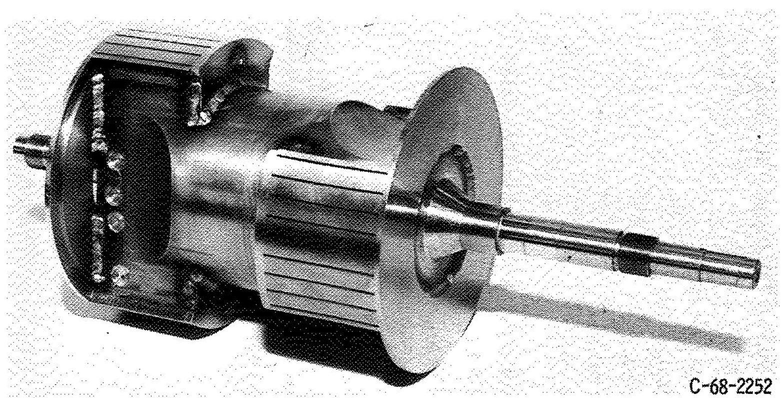
Electric power for the motor-starting tests was supplied by an air turbine-driven alternator. Figure 2 is a photograph of the turbine-alternator installed in the test facility. The duct at the bottom of the photograph provides cooling air for the alternator. The turbine was adapted from an aircraft turbosupercharger. The alternator is a brushless rotating-rectifier machine for use in aircraft. The turbine-alternator operates at 6000 rpm and has an output of 40 kilovolt-amperes at 0.75 power factor, 120/208 volts, 3 phases, and 400 hertz.

TABLE I. - DESIGN SUMMARY

	Rotor outside diameter, in. (cm)	
	5.2 (13.2)	7.38 (18.7)
Rating, kW	12	60
Power factor	0.8	0.75
Phases	3	3
Voltage, V	120/208	120/208
Current, A	41.7	222
Speed, rpm	12 000	12 000
Rotor pole pitch	2/3	2/3
Amortisseur	Zirconium-copper	None
Pole tips	AISI M-19	Solid
Rotor material	4620	4130
Stator inside diameter, in. (cm)	5.28 (13.4)	7.5 (19.0)
Length of one stack, in. (cm)	2.0 (5.08)	3.3 (8.38)
Length between stacks, in. (cm)	2.2 (5.59)	2.75 (7.0)
Lamination material	Silicon steel	3.5 percent silicon steel
Lamination thickness, in. (cm)	0.007 (0.018)	0.014 (0.036)
Slots	48	72
Turns per coil	4	1
Effective turns	26.55	10.32
Strand per turn	2	1
Circuits	2	2
Coil pitch	0.667	0.722
Field outside diameter, in. (cm)	8.68 (22.05)	10.0 (25.4)
Field inside diameter, in. (cm)	6.48 (16.46)	9.25 (23.4)
Turns	515	294
Resistance, ohms	4.97 at 160° C	2.2 at 150° C
Saliency (pole height/gap)	20	12.5
Diameter squared × length (D^2L), in.^{3} (cm^3)	111.52 (1838)	371.26 (6080)



(a) 7.38-Inch (18.7-cm) diameter rotor with solid poles.



(b) 5.2-Inch (13.2-cm) diameter rotor with laminated pole tips and Amortisseur windings.

Figure 1. - Rotors of experimental alternators.

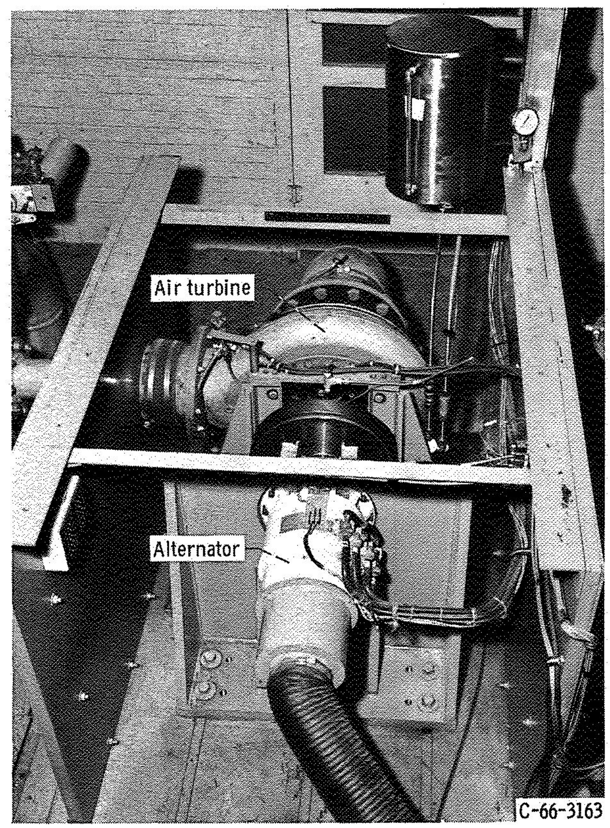


Figure 2. - Turbine-alternator power supply.

Instrumentation

The instrumentation consisted of an oscillograph with 24 recording channels having a frequency range of 0 to 5000 hertz, depending on the galvanometer used. The linearity was ±2 percent of the reading with deflections of 4 inches (10 cm) or less.

Procedure

The test alternator with the 5.2-inch (13.2-cm) rotor was accelerated from zero to full speed at essentially constant voltages of 60, 90, and 120 volts. However, the test alternator with the 7.38-inch (18.7-cm) rotor was accelerated with the current manually limited to a safe value. This procedure was necessitated by limitations of the power supply.

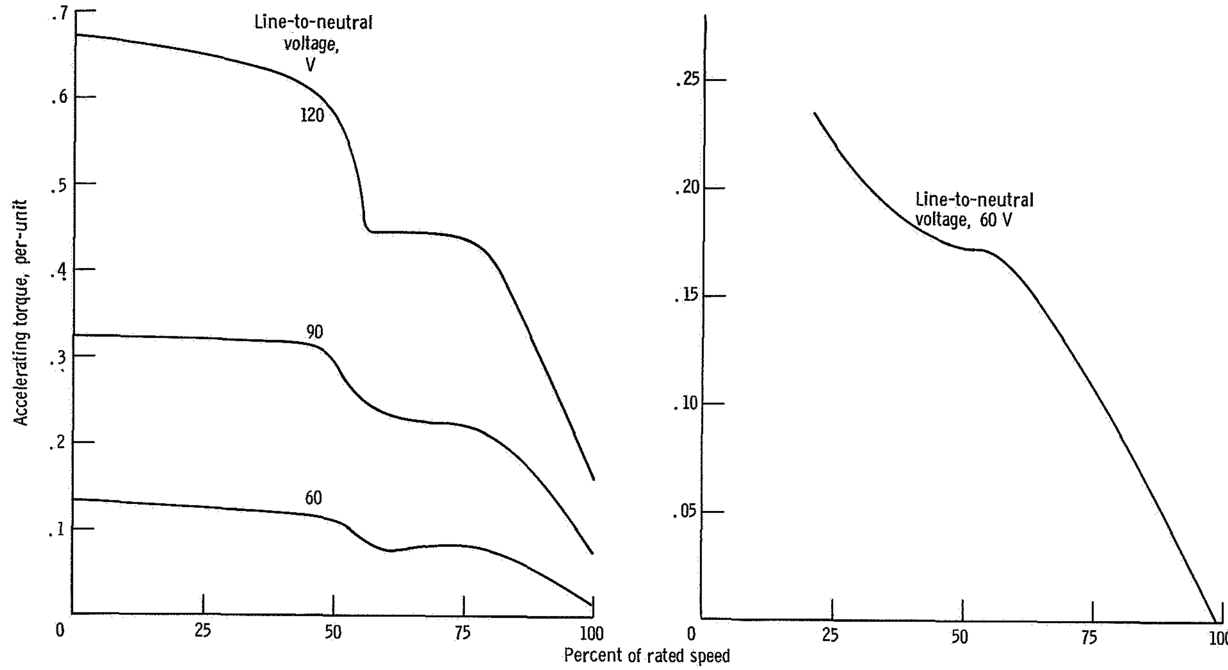
Armature current, line voltage, field voltage, and speed were recorded as functions of time. Torque was computed from its relation to moment of inertia and angular acceleration. For the smaller machine, torque and current were then corrected to 120, 90, and 60 volts. For the larger machine, torque and current were corrected to 60 volts.

RESULTS AND DISCUSSION

Torque

It can be shown (ref. 13) that the torque of an electromechanical machine is proportional to the vector product of the gap flux density and the stator magnetomotive force. In the particular case of inductor alternators, the magnitude and form of the flux wave are significantly affected by the salient poles and by currents circulating in the pole faces or in the amortisseur windings. To a lesser degree, the flux waveform is modified by the currents induced in the stationary field coil. It has been shown (ref. 14) that an induction motor having a cylindrical rotor with unbalanced rotor impedance produces a component of torque which provides motoring action from standstill to 50-percent speed and generating, or retarding, torque from 50- to 100-percent speed. This torque characteristic is due to negative-sequence currents in the machine. Further, in reference 7, it has been shown that the saliency of the poles produces forward and backward currents and fluxes. The forward and backward components are analogous to the positive- and negative-sequence components of reference 14 and produce the same torque characteristics.

Figure 3(a) shows the torque-speed performance of the 5.2-inch (13.2-cm) machine with voltage as a parameter. Figure 3(b) shows the torque-speed characteristic of the



(a) Rotor diameter, 5.2 inches (13.2 cm); 1 per-unit torque is 7.04 pound-feet (9.5 N-m).

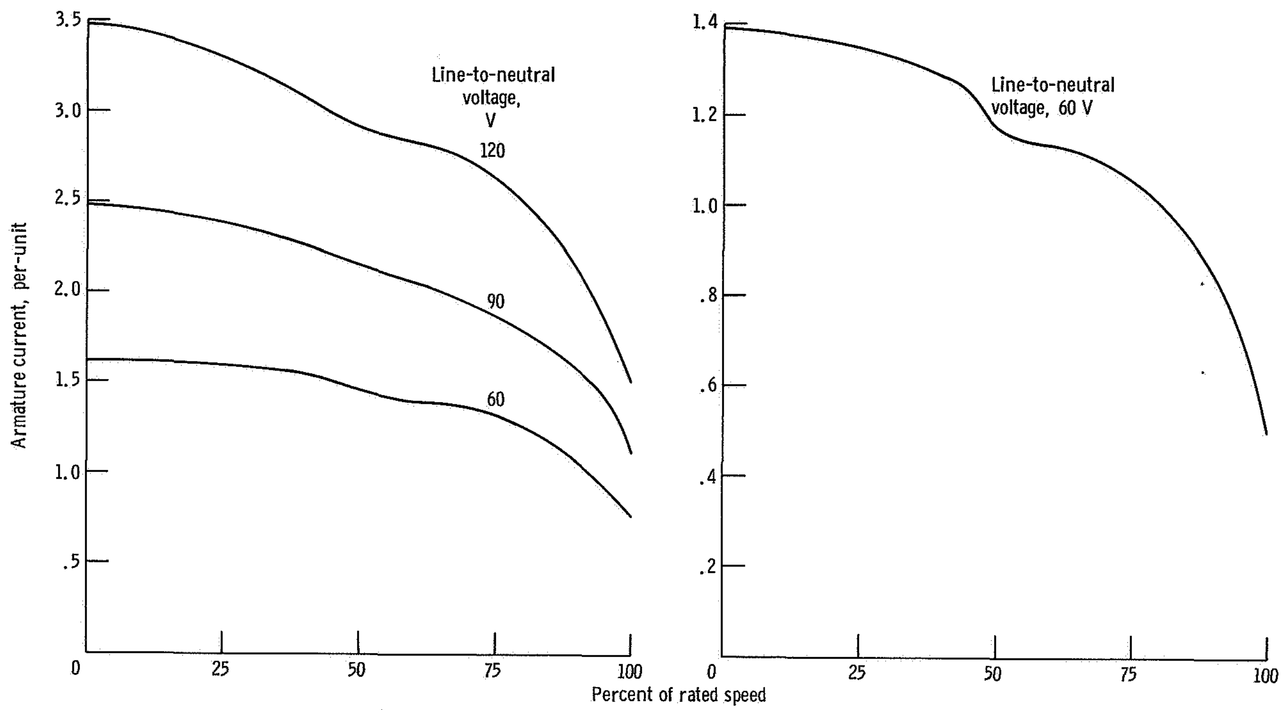
(b) Rotor diameter, 7.38 inches (18.7 cm); 1 per-unit torque is 35.2 pound feet (47.5 N-m).

Figure 3. - No-load motor-starting torque characteristics.

7.38-inch (18.7-cm) machine at 60 volts. In these figures torque is presented in the per-unit system in order to compare the characteristics of machines with different ratings. Per-unit torque is defined as the actual torque divided by the torque as an alternator at rated speed and power. For the larger machine 1 per-unit torque is 35.2 pound-feet (47.5 N-m); for the smaller machine 1 per-unit torque is 7.04 foot-pounds (9.5 N-m). As mentioned previously, the data for the larger machine are limited by the current restriction on the power supply. A comparison of the data shown in figure 3 indicates that at 60 volts the larger machine has higher per-unit torque over the entire speed range. This is due to the laminated pole tips, unoptimized amortisseur windings, and the greater saliency of the smaller machine. Figure 3(a) shows severe points of inflection at 50-percent speed. This is the classical reversal of torque component produced by negative-sequence current which, to a large degree, is dependent on pole saliency.

At 120 volts line-to-neutral, the torque at standstill is 0.67 per-unit. As the machine speed increases to 50 percent of rated speed, the torque decreases gradually. At 50-percent speed there is an inflection in the characteristic. Above 50-percent speed the torque decreases rapidly. The torque-speed characteristics are similar at 90 and 60 volts line-to-neutral. As will be shown, the self-sustaining speed for Brayton cycle power systems is 50 percent or less. Therefore, these systems do not require motoring torques above 50 percent of rated speed.

Figure 3(a) also shows that the machine with the 5.2-inch (13.2-cm) rotor produces



(a) Rotor diameter, 5.2 inches (13.2 cm).

(b) Rotor diameter, 7.38 inches (18.7 cm).

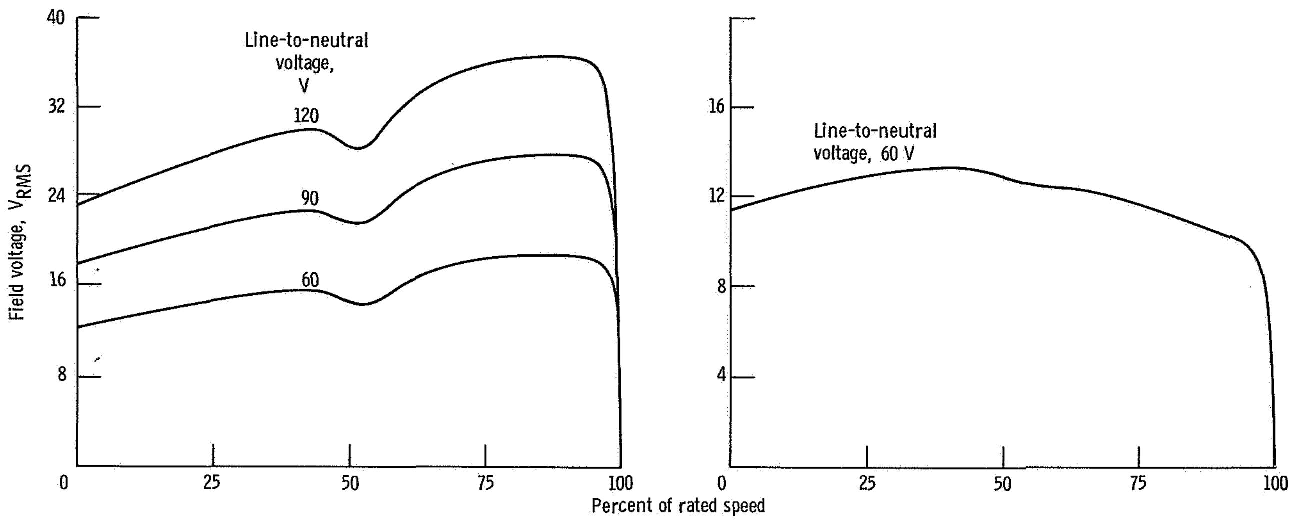
Figure 4. - No-load motor-starting armature current.

torque at 100-percent speed. This is reluctance torque which is due to the saliency of the poles.

Armature Current

Figure 4 compares the armature current-speed characteristics of the two machines under test. At 60 volts (50 percent of rated voltage), the larger machine requires 1.4 per-unit current while the smaller machine requires 1.67 per-unit starting current. At 120 volts, the smaller machine requires 3.5 per-unit current which gives about 0.67 per-unit torque at standstill. This value is typical of low-starting-current induction motors which usually require between 3 and 4 per-unit current. These data show that the power-supply requirements will be quite severe if inductor alternators are utilized as induction motors for system startup.

The data for both machines show that the armature current has an inflection at 50-percent speed. This inflection corresponds to the inflection in the torque-speed curves, but the magnitude of the change is considerably less. Further, the inflection occurs at 50-percent speed where the negative-sequence voltage and the resulting negative-sequence current are zero.



(a) Rotor diameter, 5.2 inches (13.2 cm).

(b) Rotor diameter, 7.38 inches (18.7 cm).

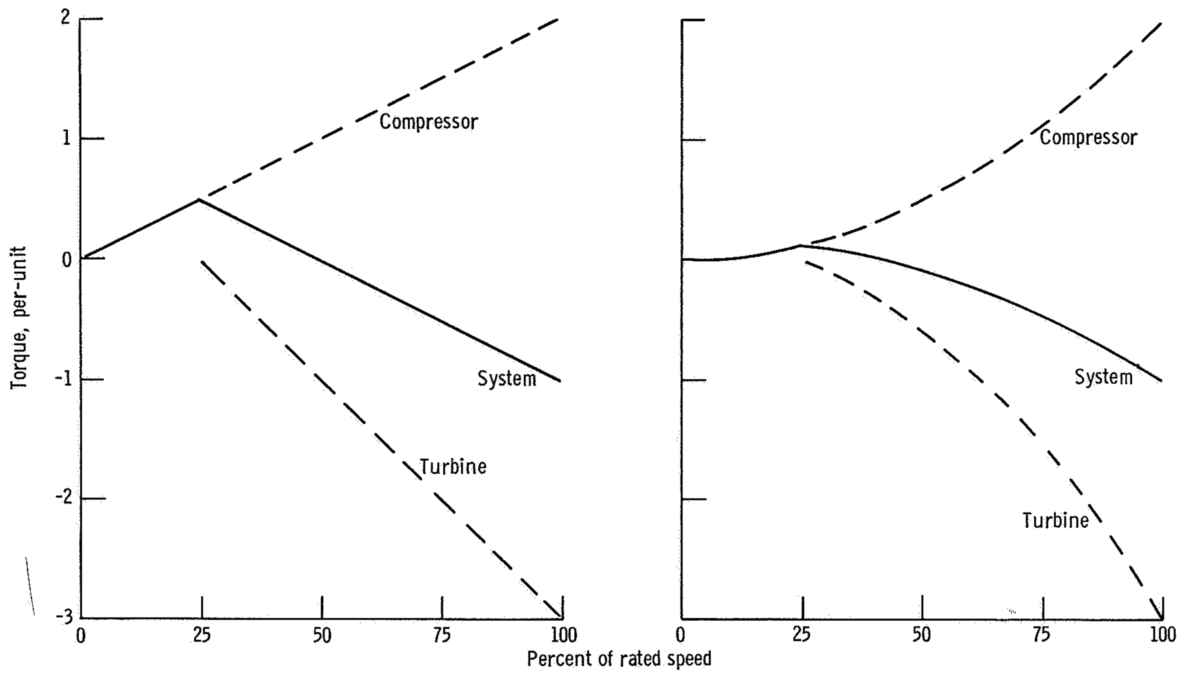
Figure 5. - No-load motor starting field voltage characteristics. (Note: 10 ohm resistor across field.)

Field Voltage

A 10-ohm resistor was connected across the field of each machine to limit the induced voltage. The value of the voltage across this resistor as a function of speed is presented in figure 5. The frequency of the induced voltage is directly proportional to rated speed minus actual speed, being 400 hertz at standstill and zero at 100-percent speed. A comparison of figures 5(a) and (b) shows that, at 60 volts, the field voltages for the two machines are approximately equal. The larger machine, with the 7.38-inch (18.7-cm) diameter rotor, has a relatively smooth characteristic which is typical of synchronous-motor starting. The smaller machine has a generally ascending characteristic with a dip at about 50-percent speed. For both machines the field voltage begins to decay rapidly at 95-percent speed and becomes zero at 100-percent speed.

System Requirements

Typical single-shaft Brayton cycle power generating systems include a turbine, a compressor and an alternator, assembled on one shaft. Motoring of the alternator is being considered as a method of startup for these systems. Although the torque-speed characteristics of these systems have not been determined at low speed, they can be approximately determined from the end, or rated-load point, and the torque-speed performance of the three components. At rated speed, the alternator torque is 1 per-unit. At this point, the compressor torque is 2 per-unit and the turbine torque is 3 per-unit.



(a) Torque against speed is linear.

(b) Torque against speed is squared.

Figure 6. - Torque characteristics for Brayton systems.

By assuming appropriate torque-speed relations for the compressor and turbine, the system torque requirements can be determined to fit the rated load point and extrapolated to the startup region of operation. A worst case and a more realistic case will now be determined and compared with the experimental motoring performance of the inductor alternator. It is assumed that an inductor alternator is used in the system.

Figure 6 shows torque as a function of speed for a Brayton cycle power generating system. In figure 6(a), the worst case, it is pessimistically assumed that the compressor and turbine torques are linear with speed, and that the turbine does not produce torque below 25-percent speed. System torque is the algebraic sum of the compressor and turbine torques. When the system torque is positive, the alternator must supply a counter, or negative torque, when operating as an induction motor. When the system torque becomes negative, the system is self-sustaining. With these assumptions, the system becomes self-sustaining at 50-percent speed. A more optimistic and realistic case is shown in figure 6(b). In this case it is assumed that the turbine and compressor torque characteristics are squared functions of speed. Again, the system torque is the algebraic sum of the turbine and compressor torques. With these assumptions the system becomes self-sustaining at 41-percent speed. Analog computer studies (ref. 15) have shown that for gas-injection startup the minimum self-sustaining speed is at most 40 percent of rated speed, a value in general agreement with the results herein.

For this report, system torque requirements below the self-sustaining speed and

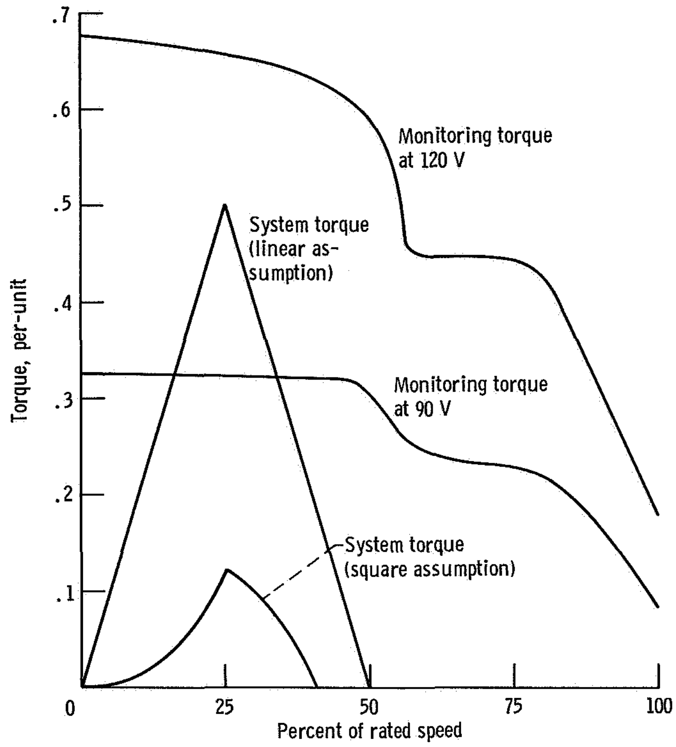


Figure 7. - System torque requirements compared with motoring torque characteristics for startup.

the motoring performance of the inductor alternator are of interest. This information is shown in figure 7 where the system torque requirements from figure 6 are superimposed on the 90 and 120 volt torque characteristics of figure 3(a). From figure 7, it is obvious that the system will start if the inductor alternator, operating as a motor, is supplied with 120 volts. At any speed, the motoring torque produced by the alternator exceeds the worst-case assumption of linear torque variation; the excess torque will accelerate the system. When the worst-case torque is compared with the motoring torque at 90 volts, the characteristics intersect; the system would not accelerate beyond this intersection since there is no net torque available for acceleration. However, the motoring torque at 90 volts is sufficient to accelerate the system when it is assumed that the compressor and turbine torques are squared functions of speed.

SUMMARY OF RESULTS

Inductor alternators operating as induction motors have reasonably good torque at standstill. As the speed is increased to about 50 percent of rated, the torque gradually decays. Above 50-percent speed, the torque decreases rapidly. The resulting inflection in the torque characteristic is apparently caused by negative-sequence currents and fluxes in the machine. These negative-sequence currents and fluxes produce a component of torque which provides motoring action from standstill to 50-percent speed, and generating action from 50- to 100-percent speed. Pole saliency has a significant effect on the production of these negative-sequence components and the resultant torque. These machines require about 1.5 per-unit current at 50-percent voltage and 3.5 per-unit current at rated voltage. These values are typical of low-starting-current motors.

Based on worst-cases assumptions, these machines are entirely suitable for starting Brayton-cycle power systems. However, approximately full rated voltages and 3 per-unit current are required. When more realistic assumptions of the system requirements are made, the system will start with 75 percent of rated voltage and 2.5 per-unit current.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio August 22, 1969,
120-27.

REFERENCES

1. Langsdorf, Alexander S.: Theory of Alternating-Current Machinery. Second ed., McGraw-Hill Book Co., Inc., 1955.
2. Alger, Philip L.: The Nature of Polyphase Induction Machines. John Wiley & Sons, Inc., 1951.
3. Pohl, Robert: Electromagnetic and Mechanical Effects in Solid Iron Due to an Alternating or Rotating Magnetic Field. J. Inst. Elect. Eng., vol. 91, pt. II, no. 21, June 1944, pp. 239-248.
4. Gibbs, W. J.: Induction and Synchronous Motors with Unlaminated Rotors. J. Inst. Elec. Eng., vol. 95, pt. II, no. 46, Aug. 1948, pp. 411-420.
5. McConnell, H. M.; and Sverdrup, E. F.: The Induction Machine with Solid Iron Rotor. AIEE Trans., Pt. III, Power Apparatus and Systems, vol. 74, June 1955, pp. 343-349.
6. Angst, G.: Polyphase Induction Motor with Solid Rotor; Effects of Saturation and Finite Length. AIEE Trans., Pt. III, Power Apparatus and Systems, no. 58, Feb. 1962, pp. 902-910.
7. Concordia, Charles: Synchronous Machines. John Wiley & Sons, Inc., 1951.

8. Ellis, J. N.; and Collins, F. A.: Brushless Rotating Electrical Generators for Space Auxiliary Power Systems. Vol. 1: Selection Criteria. Lear Siegler, Inc. (NASA CR-54320), Apr. 26, 1965.

9. Edkin, Richard A.; Valgora, Martin E.; and Perz, Dennis A.: Performance Characteristics of a 15 kVA Homopolar Inductor Alternator for a 400 Hz Brayton-Cycle Space-Power System. NASA TN D-4698, 1968.

10. Osborn, G. A.; et al: Alternator Design and Development for the SNAP-8 Electrical Generating System. Rep. 30-12-15-65, General Electric Co., Dec. 1965.

11. Repas, David S.; and Valgora, Martin E.: Voltage Distortion Effects of SNAP-8 Alternator Speed Controller and Alternator Performance Results. NASA TN D-4037, 1967.

12. Corcoran, Charles S.; and Yeager, LeRoy J.: Summary of Electrical Component Development for a 400-Hertz Brayton Energy Conversion System. NASA TN D-4874, 1968.

13. Fitzgerald, A. E.; and Kingsley, Charles, Jr.: Electric Machinery. Second ed., McGraw-Hill Book Co., Inc., 1961.

14. Wagner, C. F.; and Evans, R. D.: Symmetrical Components. McGraw-Hill Book Co., Inc., 1933.

15. Cantoni, Dennis A.; and Thomas, Ronald L.: Analog Computer Studies of a 2 to 10 Kilowatts Electric Brayton Cycle Space Power System Including Startup and Shutdown. Paper to be presented at the Fourth Intersociety Energy Conversion Engineering Conference, AICHE, Washington, D.C., Sept. 21-26, 1969.

NASA-Langley, 1969 —— 3 E-5231

1. Report No. NASA TM X-1912	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle MOTOR-STARTING CHARACTERISTICS OF TWO INDUCTOR ALTERNATORS		5. Report Date October 1969
		6. Performing Organization Code
7. Author(s) Charles S. Corcoran, David S. Repas and Martin E. Valgora		8. Performing Organization Report No. E-5231
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		10. Work Unit No. 120-27
		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Motor starting Inductor alternator Brayton system	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	13	$3.00

*For sale by the Clearinghouse for Federal Scientific and Technical Information
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