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DYNAMIC CHARACTERISTICS OF PARASITIC-LOADING SPEED CONTROLLER FOR 10-KILOWATT BRAYTON CYCLE TURBOALTERNATOR

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SUMMARY

An investigation was conducted to determine the operating characteristics of a static parasitic-loading speed controller, including the transient and off-design characteristics, when operating with an air-driven turboalternator. The speed controller was designed to be used with the turboalternator in a 400-hertz Brayton-Cycle power conversion system.

The speed controller begins to deliver power to the parasitic load when the turboalternator output frequency increases above the rated frequency of 400 hertz, and it delivers maximum power to the load when the frequency reaches 406 hertz.

With this controller, the system speed was maintained within 2 percent for voltage variations from 140 to 92 volts and step load changes of 10 kilowatts, with an alternator output of 10.5 kilowatts.

INTRODUCTION

In a Brayton Cycle turboalternator power-generating system, speed control is accomplished by controlling the input-output energy balance. In ground-based systems this balance is normally accomplished by controlling the turbine-input power through the use of valves. Another method of maintaining the desired energy balance is to control the amount of output power the turboalternator must supply, to properly balance the input power of the turbine. This latter method has certain advantages for space power systems since it allows the use of a completely static control.

The technique of matching the alternator load to the turbine input power is accomplished by increasing or decreasing the parasitic load as the useful load changes, so as to keep the alternator load constant and essentially equal to the turbine input.

In reference 1 a controller was designed, constructed, and evaluated in a bench test at low power. This report extends that effort into a full-load, transient, and off-design performance evaluation.

Loads were varied from 1.0 to 1.8 per unit, or 100 to 180 percent of the rated load, and line-to-neutral voltage V_{L-N} from 40 to 150 volts. Response time, frequency variation, and stability are studied.

Previous parasitic-loading controls have used magnetic amplifiers and saturable reactors, which normally have a high loss when compared with solid-state systems. A different approach was taken with this speed controller, in that silicon-controlled rectifiers (SCR's) are utilized as the power handling stage to minimize "off" losses.

For the expression of the magnitude of many variables, the accepted per unit (P. U.) system is used herein, for which 1.35 P. U., for example, represents 135 percent of a rated, or fiducial, value for a given variable.

APPARATUS

The speed controller consists of three identical units, each tuned to a control range of approximately 2 hertz. A block diagram of the speed controller is shown in figure 1. The control ranges of the units are staggered in relation to one another so that power is delivered to the parasitic load over the frequency range of 400 to 406 hertz, with full parasitic load power being delivered at 406 hertz and higher. Each unit consists of a frequency discriminator, a magnetic preamplifier, six magnetic amplifiers, and six SCR's arranged so that the single-phase discriminator controls a three-phase parasitic load. Since the system operates on the high-frequency side of the discriminator response characteristics, the loss of turboalternator control at high frequencies is possible. To overcome this possible loss of control, an overspeed subcircuit, which essentially consists of a saturating core to drive the SCR's, was incorporated in the speed controller. Multiple three-phase loads were selected to reduce harmonic current generation and to provide component redundancy.

The parasitic-load resistors used for testing the controller were three three-phase load banks, each load bank having a maximum capacity of 11.3 kilowatts at unity power factor, 208/120 volts, and 400 hertz. The useful load was a single three-phase load bank rated for a maximum of 100 kilowatts, a power factor adjustable for 1.0 to 0.75 lagging, 200/115 volts, and 400 hertz.

The 400-hertz power source used in determining the dynamic characteristics of the speed controller was an existing turboalternator system. The system utilized an aircraft turbosupercharger turbine modified to operate at a reduced power level. The alternator used in the system is a commercial aircraft alternator rated at 40 kilowatts, 208/120 volts, 0.75 power factor lagging, 400 hertz, and 6000 rpm.

The instrumentation used for the speed-control testing included analog and digital voltmeters, ammeters, wattmeters, an electronic counter, and a direct-recording oscillograph. The specifications of the instruments used are given in table I, and a block diagram of the apparatus and instrumentation is presented in figure 2. The electronic counter indicated the turboalternator shaft speed. For the conversion of this reading to frequency, the alternator rating of 6000 rpm at 400 hertz was used.

$$\text{frequency (Hz)} = \frac{\text{speed (rpm)}}{15}$$

DISCUSSION

The speed controller was designed to work with a 10-kilowatt turboalternator system that has moment of inertia of 0.051 pound-foot-second squared (7.05×10^{-3} kg-m-sec^2) and a speed of 12 000 rpm, whereas the turboalternator system used in the tests had a moment of inertia of 0.282 pound-foot-second squared (3.90×10^{-2} kg-m-sec^2) and a speed of 6000 rpm.

Since the experimental results had to represent the dynamic operation of the speed-controller in its ultimate application, it was necessary to have a power level in the test system other than the 10-kilowatt design value. This new power level was calculated as follows:

$$T = \frac{\pi^2 I N^2}{9.16\times10^4\ P} \qquad \text{(ref. 2)} \qquad (1)$$

where

T inertial time constant of turboalternator system, sec

I moment of inertia of turboalternator system, lb-ft - sec^2 = $(1/g)wR^2$; kg-m-sec^2 (ref. 2)

w weight, lb; kg

R radius of gyration

N rated speed of turboalternator system, rpm

P output power of turboalternator system, kW

The terms in equation (1) are rearranged and taken to give a ratio of power in the design system to power in the test system

$$\frac{P_d}{P_t} = \frac{I_d N_d^2 T_t}{I_t N_t^2 T_d} \qquad (2)$$

where subscripts d and t are design and test, respectively. Since the two time constants are set equal,

$$\frac{P_d}{P_t} = \frac{I_d N_d^2}{I_t N_t^2} \qquad (3)$$

Now the values previously given for the two systems may be used to give

$$\frac{P_d}{P_t} = \frac{(0.051)(12\,000)^2}{(0.282)(6\,000)^2} = 0.725$$

Therefore, if the design load is 10 kilowatts, the fiducial load for the test system must be

$$1 \text{ P.U.} = \frac{10}{0.725} = 13.8 \text{ kW}$$

If no overspeed subcircuit is used, figure 3(a) shows parasitic load power as a function of frequency. Parasitic-load power increased as frequency increased above 400 hertz, reaching a maximum of 1.8 P.U. at 406 hertz. However, as frequency is increased further, parasitic-load power begins to decrease at 412 hertz, reaches a minimum of 1.72 P.U. at 433 hertz, and returns to 1.8 P.U. at 454 hertz. Continued increase in frequency causes the absorbed power to decay, reaching 1.0 P.U. at 479 hertz. The dip in power between 412 and 454 hertz occurs because the discriminator overdrives the magnetic preamplifier circuit, and the dropoff above 454 hertz occurs because the frequency exceeds the range of the discriminator. These two characteristics are discussed in more detail in reference 1.

For the range of the controller to be extended, an overspeed subcircuit was added. The plot of parasitic-load power as a function of frequency (fig. 3(b)) then shows no dip or decay, since the overspeed subcircuit held the output full-on whenever the frequency exceeded 410 hertz. There is, however, a slight drop in parasitic-load power since the alternator being used was unable to maintain a V_{L-N} of 120 volts at these high frequencies (above 440 Hz).

The controller was designed to regulate speed with any one of the three sections inoperative. When section 1 or section 3 was inoperative, the system maintained speed with the frequency remaining at 0.15 percent or less. Figure 4 shows parasitic-load power as a function of alternator frequency with section 2 inoperative. Because of the overlap of the sensor control ranges in the three sections, there was always positive gain and the system was stable.

Figure 5 shows the time for the system to recover from a 10-percent overspeed as a function of parasitic load. As the parasitic load is increased from 1.0 to 2.0 P.U., the response time decreases substantially. Beyond 2.0 P.U. the reduction in response time is quite small. The general form of the curves is as expected, since equation (1) shows that the time constant is inversely proportional to the power. When the operating parasitic load is 1.0 P.U., the recovery is entirely dependent on system losses.

The system frequency as a function of time is shown in figure 6 when step load changes of 1.0 P.U. are applied. These curves show the system to be underdamped (ref. 3) and stable (ref. 4). Further, the overshoot does not exceed the active range of the controller, reaching only 404.8 hertz. It was necessary to run these load-switching tests with the system operating at a power level greater than 1.0 P.U. In the case when 1.0 P.U. step load is applied to a system while operating with a parasitic load of 1.0 P.U., the system frequency undershoots the rated design value. This frequency is an entirely normal system response. Theoretically, the system should then operate at the reduced frequency. However, because of the change in turbine efficiency, the speed continues to drop. One solution to the problem is to operate the system with a power margin. For the test turboalternator the minimum margin is 0.05 P.U. power.

Figure 7 shows maximum parasitic power as a function of voltage. For this curve, the analog computer (fig. 2) was used to maintain 414 hertz while V_{L-N} was controlled manually by use of the 0- to 30-volt supply. The power varies approximately as the square of the voltage above 80 volts, but below 70 volts the effect of a decreased SCR conduction angle invalidates the squared relation. The minimum voltage V_{L-N} at which 1 P.U. power can be delivered to the parasitic load is 92 volts. This then, is the lowest voltage at which the speed controller can maintain system speed if the turbine is producing rated power.

In addition to the change in full-load power with voltage, the full-on and turn-on frequencies also change. This effect is shown in figure 8. Above a V_{L-N} of 100 volts the full-on and turn-on frequencies are essentially constant. As the V_{L-N} is reduced below 100 volts the voltage available to maintain the SCR conduction angle at 150° is reduced, and the full-on frequency begins to rise. Because of a phase shift between the line voltage and the SCR-gate-voltage, the trigger pulse is not affected until V_{L-N} drops to 85 volts. The turn-on frequency then begins to rise. As the voltage continues to drop, the magnetic amplifier begins to lose control at V_{L-N} of 53 volts; and below

V_{L-N} of 40 volts, the SCR's cannot be triggered into conduction.

Some details of the test results are given in table II.

Comparison With Design Performance

The design performance (ref. 1, fig. 14) and the observed performance (fig. 3) agree quite well. Some selected characteristics are compared in the following table:

Characteristics	Design	Test
Frequency at load of 1.8 P.U., Hz	406	406
Minimum V_{L-N} for parasitic load of 1.0 P.U., V	90	92
Minimum V_{L-N} for constant frequency control range, V	70	100
Maximum operational frequency without overspeed control, Hz	475	479
Minimum frequency for overspeed takeover, Hz	420	412

SUMMARY OF RESULTS

An investigation of the dynamic characteristics of a static parasitic-loading speed controller (designed for a 10-kW, 400-Hz turboalternator system) showed that the controller will apply 1.8 per unit load in 6 hertz. Under normal operating conditions, this controller will maintain the speed of the system with 6 hertz at all times and will require only 0.6 second to reach a new steady-state operating point. In response to step changes in load, the controller exhibits an underdamped and stable characteristic.

Line-to-neutral voltage variations from 100 to 140 volts (designed for 120 volts) have a minimal effect on the operation of the controller, and 1 per unit or a greater load can be maintained with line-to-neutral voltage as low as 92 volts.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, June 1, 1967,
120-27-03-42-22.

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2. Oldenburger, Rufus: Regulators. Control Engineers' Handbook; Servomechanisms, Regulators, and Automatic Feedback Control Systems. John G. Truxal, ed. McGraw-Hill Book Co., Inc., 1958, sec. 18, pp. 2-7.

3. Thaler, George J.; and Brown, Robert G.: Servomechanism Analysis. McGraw-Hill Book Co., Inc., 1953, pp. 86-87.

4. Lynch, William A.; and Truxal, John G.: Signals and Systems in Electrical Engineering. Part 1 - Introductory System Analysis. McGraw-Hill Book Co., Inc., 1961, p. 297.

TABLE I. - INSTRUMENT SPECIFICATIONS

Instrument	Specification	Rating
Wattmeter	Accuracy	0.1% from dc to 2500 Hz; run at 40 kW full scale
Ammeter	Accuracy	2% from 20 Hz to 4 MHz; run at 1, 10, and 100 A full scale
Current transformer (used with wattmeter and ammeter)	Accuracy	0.7% from 25 to 500 Hz
Shunt resistor (used with wattmeter and ammeter)	Resistance	0.1 Ω
	Accuracy	0.04% to 25° C
Digital voltmeter	Accuracy	0.1% or ±2 digits; 30 Hz, 10 KHz (sine wave only)
Analog voltmeter	Accuracy	2% from 20 Hz to 4 MHz; run at 300 V full scale
Electronic counter	Accuracy	±1 digit
Oscillograph	Timing accuracy	2%
Galvanometers	Accuracy	2% for a deflection of 8 in. or less
A	Natural frequency	40 Hz
	Frequency response	0 to 24 Hz; flat ±5%
	Sensitivity	8 μA/in.
B	Natural frequency	400 Hz
	Frequency response	0 to 240 Hz; flat ±5%
	Sensitivity	77 μA/in.
C	Natural frequency	1000 Hz
	Frequency response	0 to 600 Hz; flat ±5%
	Sensitivity	263 μA/in.

TABLE II. - TEST RESULTS

Test	
Load application	1.8 P. U. maximum applied in 6 Hz (400 to 406 Hz) at V_{L-N} = 120 volts
Maximum control frequency	
Without overspeed	478 Hz (1.0 P. U)
With overspeed	>530 Hz (1.8 P. U.)
Voltage range	
Full control	V_{L-N} = 92 to over 140 volts (≥1.0 P. U.)
Partial control	V_{L-N} = 40 to 92 volts (<1.0 P. U.)
Overspeed recovery	1.34 sec to steady state from 440 Hz
Response to step load change	
1.0 P. U. on	0.5 Hz undershoot; 0.5 sec to steady state
1.0 P. U. off	1.8-Hz overshoot; 0.6 sec to steady state

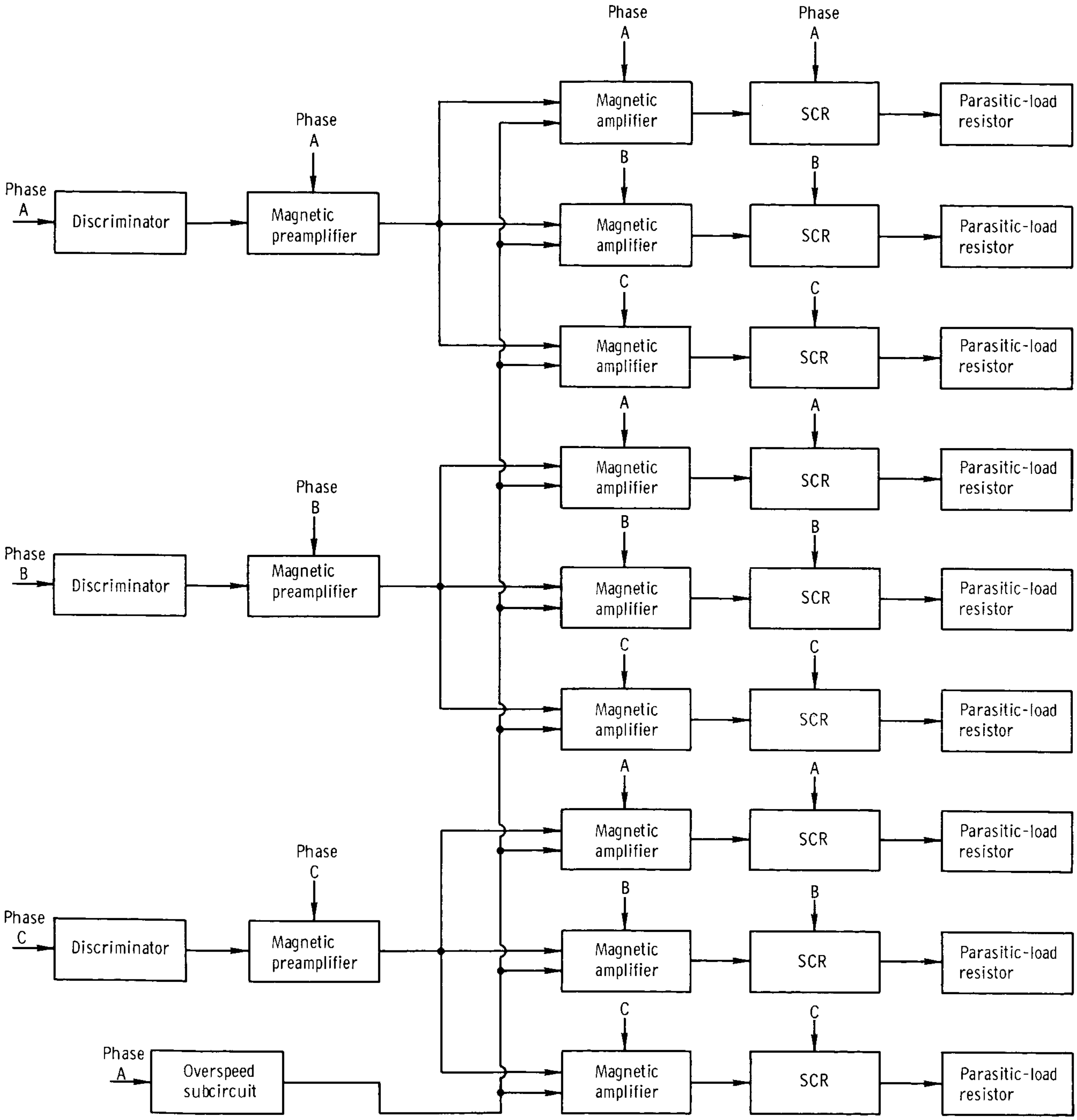


Figure 1. - Three-phase block diagram of alternator speed controller.

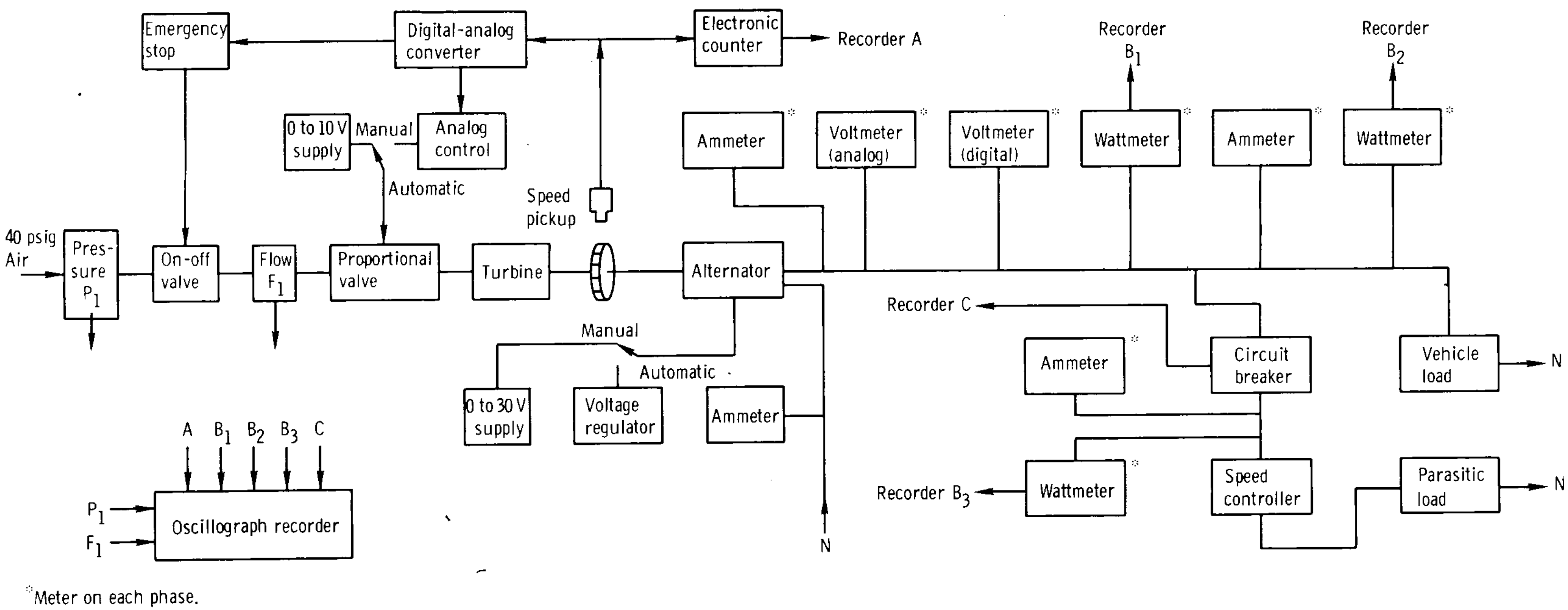


Figure 2. - Apparatus and instrumentation.

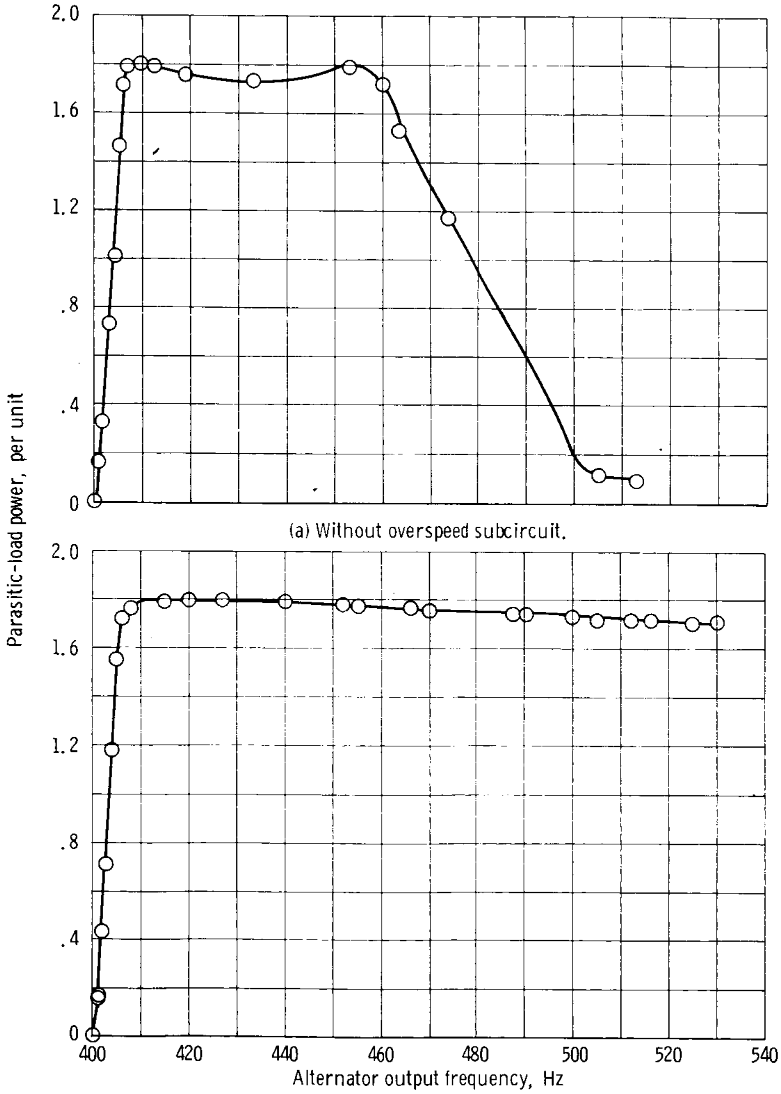


Figure 3. - Parasitic-load power as function of alternator output frequency.

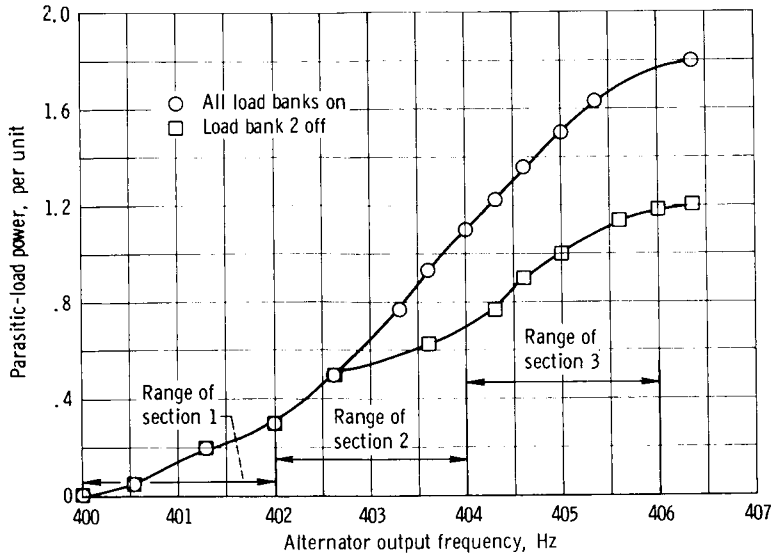


Figure 4. - Expanded parasitic-load power as function of alternator output frequency with section 2 inoperative.

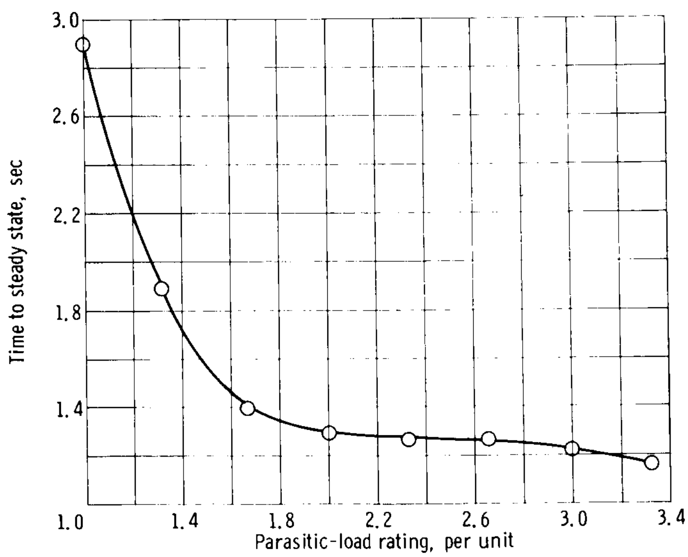
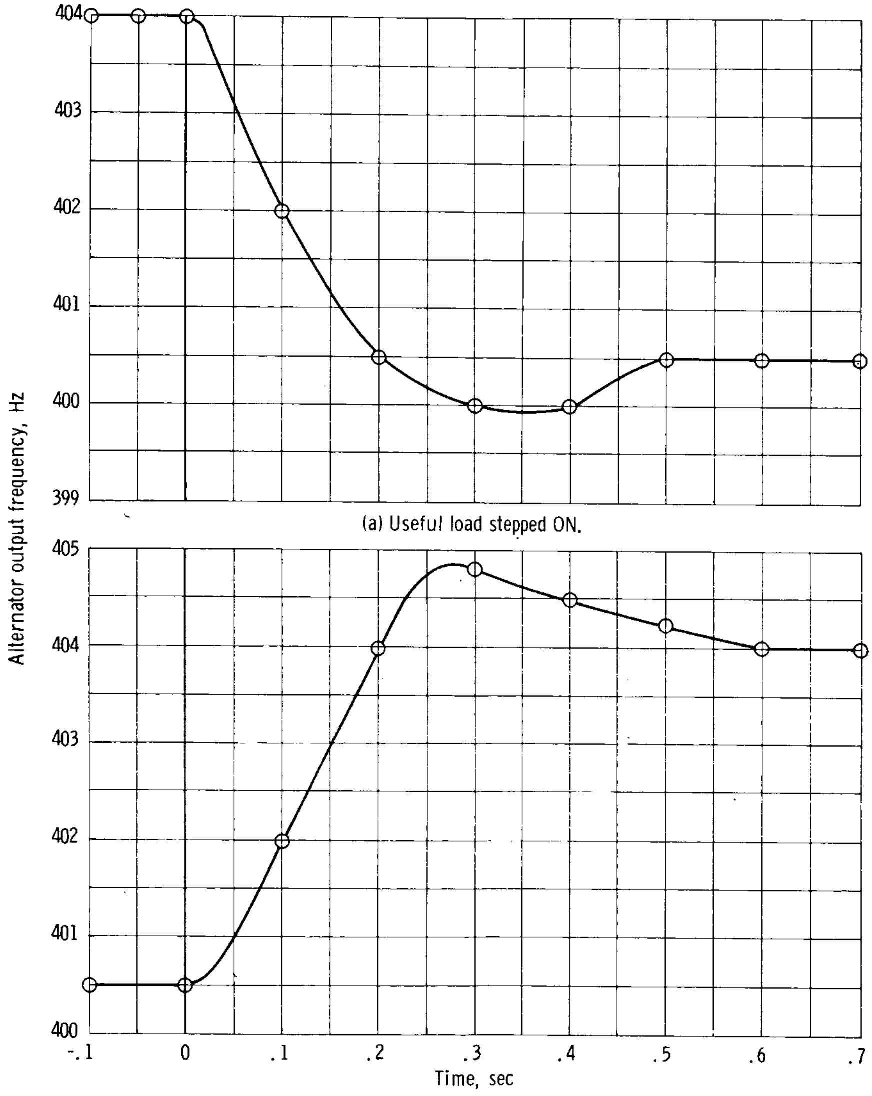


Figure 5. - Time to steady state from 10 percent overspeed as function of parasitic-load rating.



(a) Useful load stepped ON.

(b) Useful load stepped OFF.

Figure 6. - Frequency as function of step changes in load ON and load OFF. Load, 1 per unit (13.8 kW).

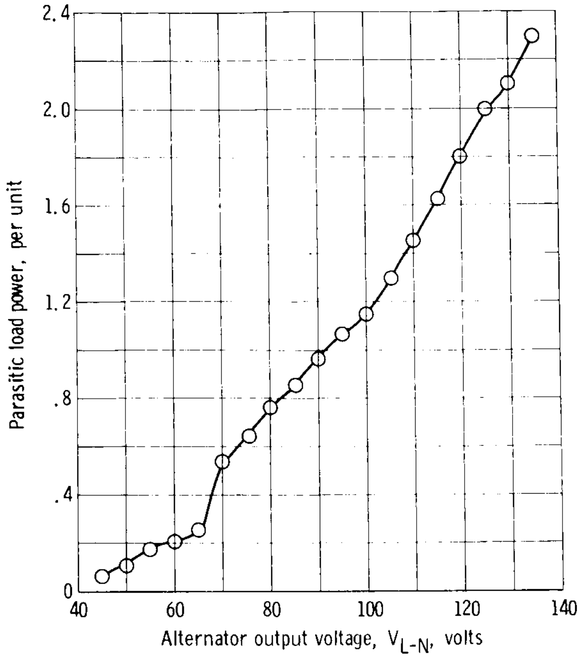


Figure 7. - Parasitic-load power as function of alternator output voltage.

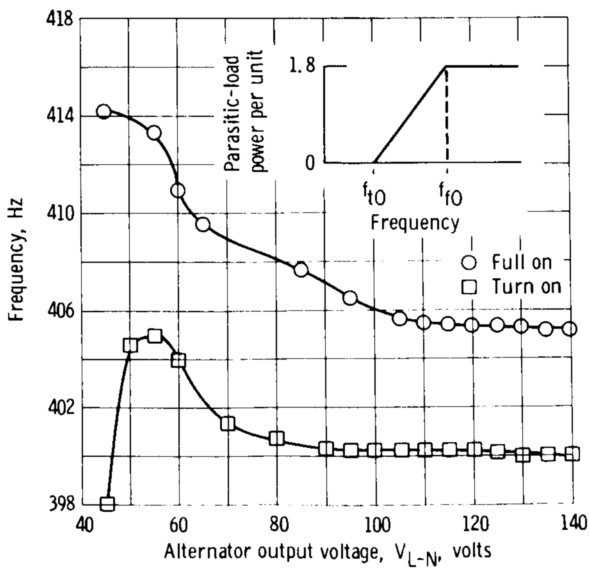


Figure 8. - Turn-on and full-on frequency as function of alternator output voltage.

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