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PERFORMANCE OF A DIRECT-CURRENT POWER SUPPLY FOR THE 2- TO 15-KILOWATT BRAYTON CYCLE SYSTEM

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16. Abstract

Some of the performance characteristics of a Brayton cycle dc power supply were determined. The dc supply is a transformer rectifier set that supplies ±28 volts dc to a dc bus and ±42 volts dc for battery charging. The maximum output power is 1400 watts. The supply was tested over a range of input voltages and frequencies and a range of output currents. The efficiency was 89 percent at the design point and the power factor was 0.89 for all tests. The output voltage was approximately a linear function of the input voltage and had a load regulation of 6 percent. The overall performance of the dc supply was judged satisfactory.

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SUMMARY

Some of the performance characteristics of a Brayton cycle dc power supply were determined. The dc supply is a transformer rectifier set that supplies ±28 volts dc to a dc bus and ±42 volts dc for battery charging. The maximum output power is 1400 watts.

The supply was tested over a range of input voltages and frequencies and a range of output currents. The efficiency was 89 percent at the design point and the power factor was 0.89 for all tests. The output voltage was approximately a linear function of the input voltage and had a load regulation of 6 percent. The overall performance of the dc supply was judged satisfactory.

INTRODUCTION

A Brayton cycle space power system is being investigated at the NASA Lewis Research Center. This system has a useful electric power output of 2 to 15 kilowatts and is completely self-contained in that it requires no external inputs other than a heat source. The output of the system is regulated 120/208-volt, three-phase, 1200-hertz power. For more information on the Brayton cycle system, see references 1 and 2.

The Electrical Subsystem of the Brayton cycle system regulates and distributes the generated electrical power; in addition, it provides all control and logic functions required to operate the Brayton system. The primary tasks of the Electrical Subsystem are

(1) Control of the alternator voltage and frequency
(2) Supplying its own internal source of dc power during transient and steady-state operation
(3) Supplying signal conditioning for instrumentation

(4) Providing fully automatic system operation and protection

Figure 1 shows each of the items of hardware used in the Electrical Subsystem. For more information on the Brayton Electrical Subsystem, see reference 3.

Internal dc power for the Electrical Subsystem is required for instrumentation, control, battery charging, and startups and for input power to inverters. The dc power supply converts three-phase ac power to ±28 volts dc. The supply also contains a pair of 28-volt batteries, battery chargers, and control logic which supply dc power when ac

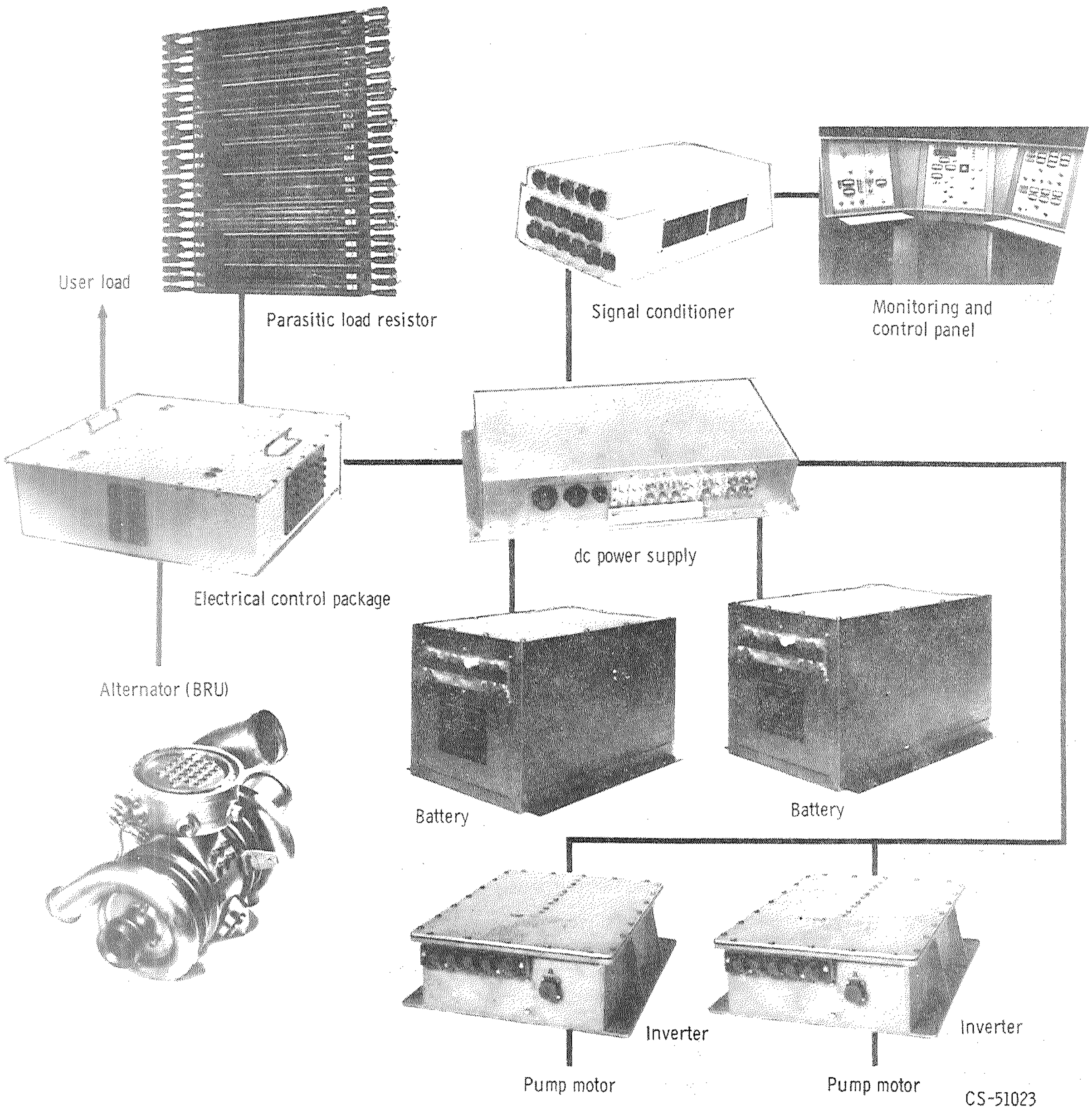

Figure 1. - Brayton cycle Electrical Subsystem components.

power is not available for conversion.

This report presents the performance test results of the dc supply. The load used was a variable resistor network. The results present the effect of input voltage, frequency, and output load on output voltage, efficiency, and power factor. Other tests involve the operation of the battery chargers, the harmonics of the input voltage and current, and the effect of unbalanced loads and on-and-off transients. These tests were conducted at room temperature and at atmospheric pressure. The effects of temperature and of operation in a vacuum were not determined.

DIRECT-CURRENT SUPPLY DESCRIPTION

The dc power supply was made by Gulton Industries under NASA contract NAS3-10936. Figure 2 presents a block diagram of the dc power supply. Two multiple-

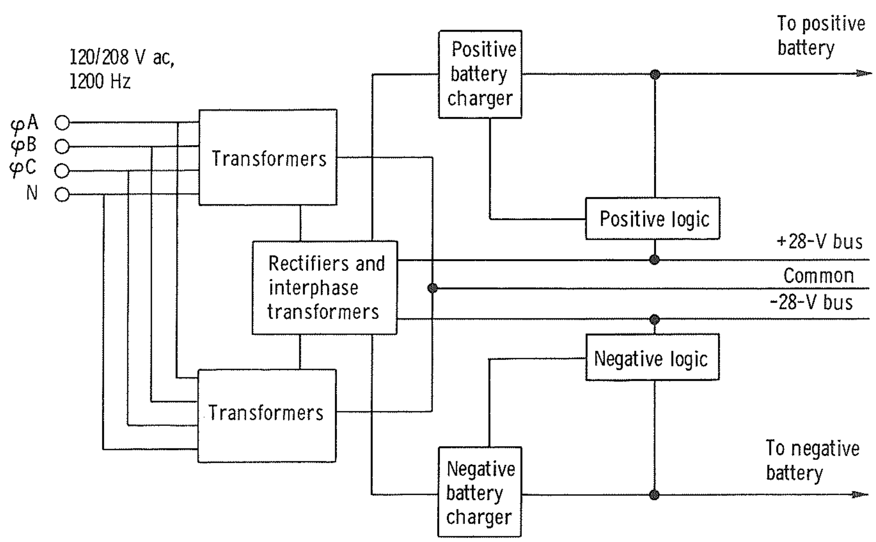

Figure 2. - Block diagram of Brayton cycle dc power supply.

winding transformers and a diode assembly change the 120/208-volt ac, 1200-hertz input to ±28 volts dc and ±42 volts dc. The ±28 volts dc is used for dc bus power and the ±42 volts dc is for battery charging. The ±28-volt dc bus has a rated output of 1100 watts (±20 A) and a maximum output of 1400 watts (±25 A).

To obtain high efficiency, low ripple, and low output impedance, the equivalent of a 12-phase output transformer was used. The most straightforward technique of obtaining a 12-phase output is to use two six-phase star output windings - one powered by a

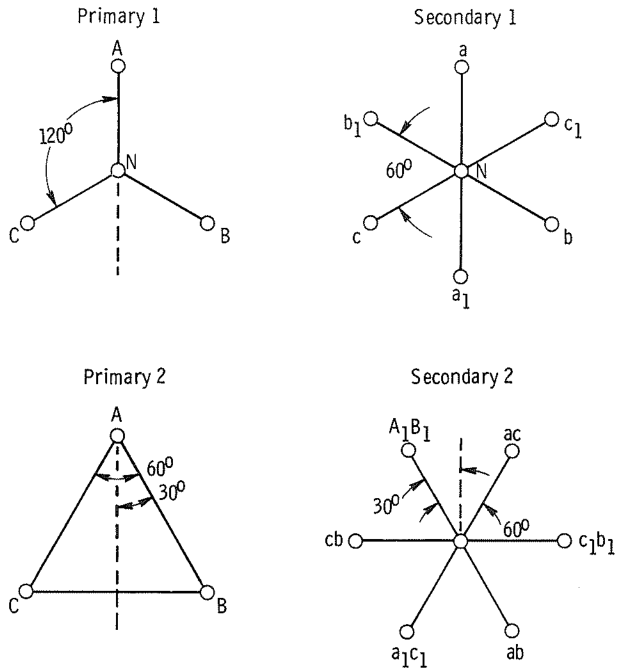

Figure 3. - Possible transformer circuit to develop 12-phase output.

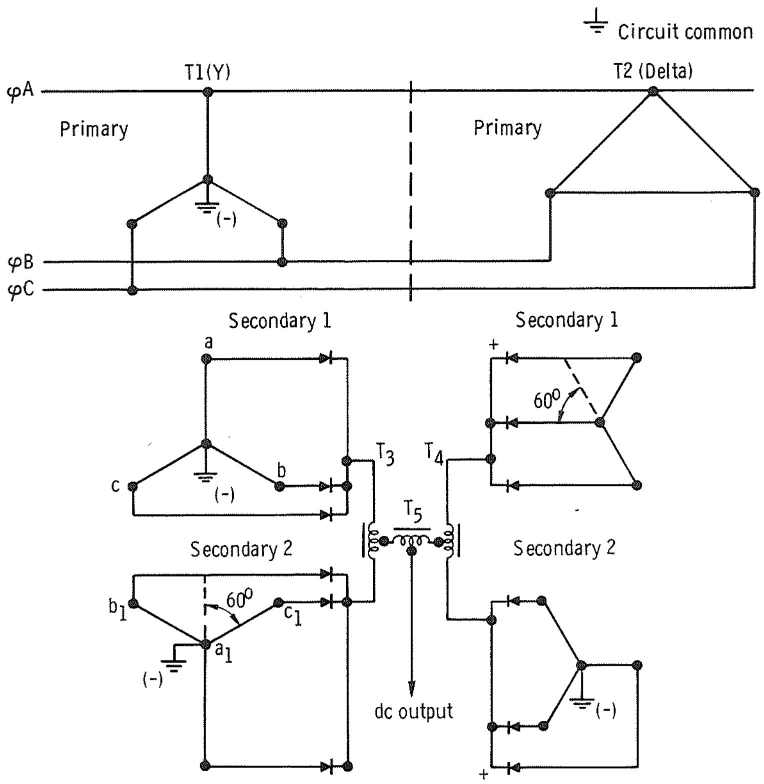

Figure 4. - Transformer circuit used for +28-volt dc output.

three-phase Y primary and the other powered by a three-phase delta primary. The vector diagram is presented in figure 3.

The resultant output is the sum of the secondaries and is a 12-phase output. The disadvantage of this circuit is that if rectifiers are connected to the output windings, each rectifier conducts for only 30°, or one-twelfth of the time. Each diode is subjected to high surge currents, and the output impedance is the series sum of one winding and one diode. For these reasons, this was not the technique used by Gulton Industries.

A better way was used by Gulton. Figure 4 shows four secondary windings where the outputs are rectified and connected to three interphase transformers. The conduction time for each rectifier increases to 120° (one-third of the time) and the output impedance is the parallel connection of four windings and diodes. This is a reduction of output impedance by a factor of 4.

The ±42 volts for battery charging is developed the same way. The secondary windings were extended by the proper number of turns to develop 42 volts instead of 28 volts. A completely separate transformer rectifier system was used to obtain the negative bus voltage and the negative battery charging source. A complete description of the circuit and its operation can be found in reference 4.

Physically, the prototype dc supply is installed in an aluminum container 28 centimeters by 53 centimeters by 12 centimeters high. The unit weighs 14 kilograms. The supply used flight-type hardware but was packaged as a development package rather than a flight package.

TEST CONDITIONS

The dc supply was mounted on a cold plate whose temperature was held constant at 24° C. The tests were conducted at atmospheric pressure and at a room temperature of approximately 24° C. The ac power supply was a variable-frequency, variable-voltage motor generator (MG) set. This MG set was used to test the dc supply at frequencies of 1100, 1200, and 1300 hertz and at input voltages of 105, 120, and 135 volts rms. This MG set has the same output impedance and approximately the same speed-torque characteristics as the Brayton cycle alternator.

INSTRUMENTATION

The data were taken and partially reduced by a digital data acquisition system (DDAS). The input voltage and current were measured by a true rms voltmeter and recorded by the DDAS. The input power was measured by a special high-frequency wattmeter developed at Lewis (see ref. 5). The resultant volt-amperes and power factor were calculated by the DDAS.

The output voltage and current from the dc supply and battery chargers were measured by a digital voltmeter.

The dc power and overall efficiency were calculated by the DDAS. Several hot-spot temperatures and the input frequency were also monitored as a precautionary measure. A typical DDAS output is as follows:

```
  79 DAYS   14 HOURS 46 MINUTES 51 SECONDS

INPUT   VOLTS      AMPS       POWER      KVA       PF

A       119.78     1.13     118.09    135.81      Ø.86
B       121.ØØ     1.21     128.84    146.93      Ø.87
C       12Ø.81     1.3Ø     142.75    157.46      Ø.9Ø
                    Ø.75     389.69    44Ø.21      Ø.88

OUTPUT  VDC        IDC        PDC        VBC       IBC        PBC       TOTPOW

+       31.Ø5      5.Ø2     155.88     33.71      Ø.ØØ       Ø.ØØ    155.88
-      -31.Ø6     -5.Ø1     155.85      Ø.54     -Ø.ØØ       Ø.ØØ    155.85
Ø                 -Ø.ØØ    311.73                          Ø.ØØ   311.73

EFFICIENCY          Ø.79
TEMP1 DEG F          76.15
TEMP2 DEG F         149.81
TEMP3 DEG F          77.66
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TEST DESCRIPTION AND RESULTS

The dc power supply was tested at all combinations of three input voltages, three input frequencies, and six output current levels. The input voltages were 105, 120, and 135 volts rms. The frequencies were 1100, 1200, and 1300 hertz. The output current levels were 0, 5, 10, 15, 20, and 25 amperes. The design point for the dc supply is 120 volts rms, 1200 hertz, and a load of 20 amperes.

Output Voltage Characteristics

Figure 5 shows the relation between the dc output voltage and the ac input voltage. The dc output voltage is actually the average of the magnitudes of the positive and negative bus voltage. The magnitudes were always within 1 percent of each other. The curves are shown for load currents from 5 to 25 amperes. The expected straight-line relationship between input and output voltage is shown. A gradual decrease in output voltage as the load increases is due to the "internal" resistance of the dc supply. At

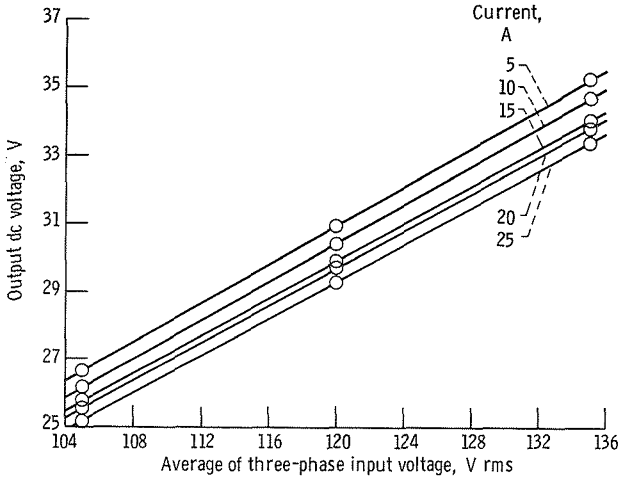

Figure 5. - Output voltage (dc) as function of input voltage (ac). Frequency, 1200 hertz.

120 volts rms input, for a change of 20 amperes the output changes 1.6 volts. This gives an approximate series resistance of 80 milliohms and a load regulation of 6 percent.

The no-load voltage was not plotted because of the large differences in positive and negative bus voltages. For instance, at 120 volts rms and 1200 hertz the bus voltages were +32.23 volts and -34.97 volts at no load. However, at 5 amperes, the voltages were +30.96 volts and -30.97 volts.

Frequency Effect

The output voltage as a function of load and frequency is shown in figure 6. The

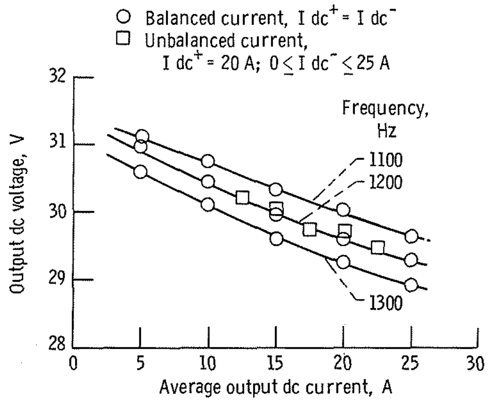

Figure 6. - Output voltage (dc) as function of output current. ac voltage, 120 V rms.

input line voltage was held constant at 120 volts rms. As expected, the output voltage decreased as the load increased. Also, the output voltage decreased as the frequency increased. The effect of an unbalanced output current is also shown in figure 5. The input voltage was held at 120 volts rms and the frequency was 1200 hertz. Positive bus current was held at 20 amperes and the negative bus current varied from 0 to 25 amperes. The relationship between the output voltage and the average load current is the same as for the balanced current condition.

Efficiency

Efficiency of the dc supply for both balanced and unbalanced currents is shown in figure 7. The input voltage was held constant at 120 volts rms and 1200 hertz and the

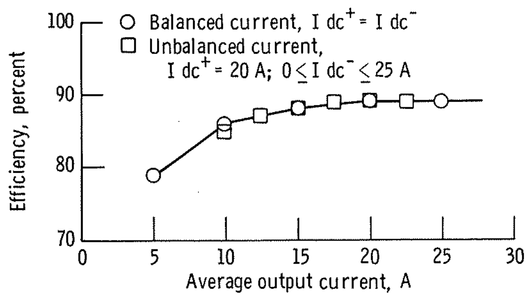

Figure 7. - dc power supply efficiency.

load was varied from 5 to 25 amperes. The efficiency rose from 0.79 to 0.89 over the load range and was essentially flat (0.875 to 0.890) from 12.5 to 25 amperes. The relationship between efficiency and the average output current shows that it is the same for both the balanced and unbalanced cases.

The efficiency was also studied as a function of input voltage and frequency. For a given load condition, it was found that the efficiency was not a function of either input voltage or frequency over the range of values tested.

Power Factor

The power factor of the dc supply was determined for all combinations of voltage, frequency, and load. Surprisingly, it was constant at 0.89±0.02 for all tests.

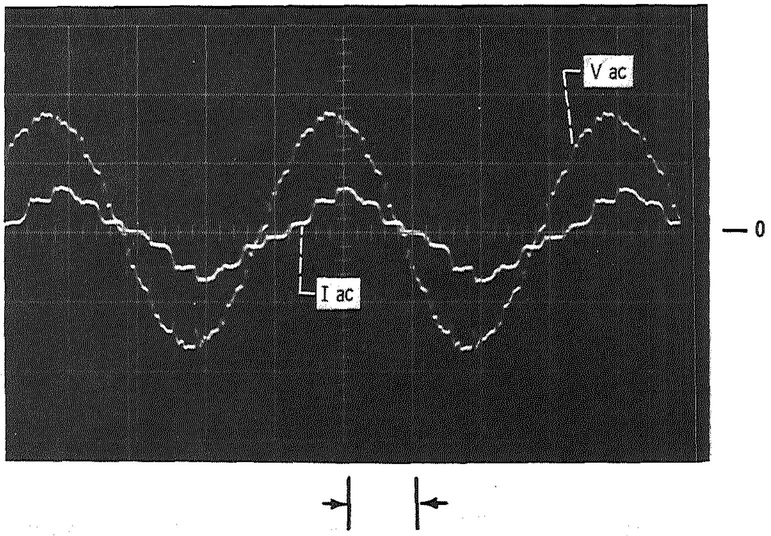

Figure 8. - Input voltage and current.

Harmonics

An oscilloscope trace of the input voltage and current is shown in figure 8. The input voltage (the larger trace) is 120 volts rms at 1200 hertz. The load current is 20 amperes dc. The input current is approximately 4 amperes rms. The current lags the voltage by about 25°. Both the voltage and the current have a large amount of ripple caused by the commutating diodes. This ripple frequency is 12 times the fundamental frequency. From modulation theory, a load that varies sinusoidally at 12 times the fundamental frequency will cause 11th and 13th harmonic distortions in the voltage waveform.

The results of a harmonic analysis of the input voltage and current are shown in table I. The input voltage is 120 volts rms at 1200 hertz. The load current is 20 am-

TABLE I. - HARMONIC VOLTAGES AND CURRENTS

[ac voltage, 120 V rms; dc current, 20 A; frequency, 1200 Hz.]

Harmonic	Voltage, percent	Current, percent
Fundamental	100	100
3rd	1.4	18.0
5th	(a)	(a)
7th	(a)	(a)
9th	(a)	5.6
11th	2.3	9.0
13th	1.4	4.4

[a]Less than 1.0 percent.

peres dc. The high third harmonic current is 18 percent of the fundamental. The 11th and 13th harmonics are the sum and the difference of the ripple frequency and the fundamental.

The total harmonic distortion in the voltage waveform is 3.3 percent and in the current waveform is 21.8 percent.

Output Voltage

The dc output voltage of the positive bus is shown in figure 9. Again, the input

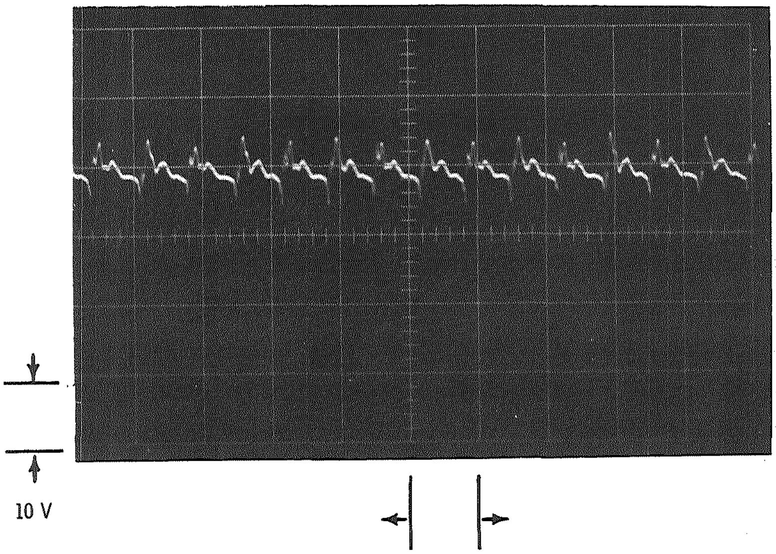

Figure 9. - Output dc voltage.

voltage was 120 volts rms at 1200 hertz and the load current was 20 amperes dc. The scale of the photograph is 10 volts per division and a sweep speed of 0.1 millisecond per division. Measurements from the photograph indicate the commutating diode spike frequency is about 12 times the fundamental, as expected. The positive dc voltage averaged over a period of 166 milliseconds was 29.2 volts. From the photograph, the spikes are 9 volts peak-to-peak. These spikes are large because there is no output filter, however, the absence of an output filter improves the efficiency and the spikes were not a significant factor for the intended application. The effect of the lack of an output filter is also illustrated by the fast turnoff and turnon of the dc supply, as shown in figures 10 and 11. The input voltage is 120 volts rms at 1200 hertz and the load is 20 amperes dc. The output voltage rises to full output in less than 1 millisecond and falls to zero in less than

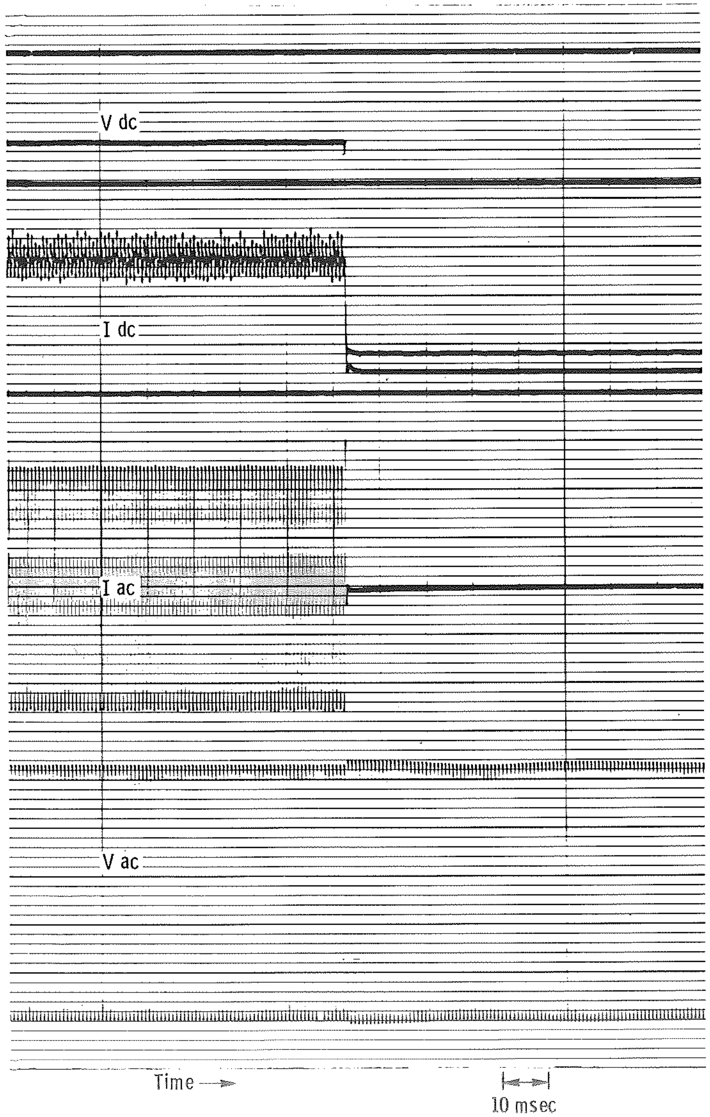

Figure 10. - dc supply turnoff characteristic. "On" conditions: ac voltage, 120 volts rms; dc current, 20 amperes; frequency, 1200 hertz.

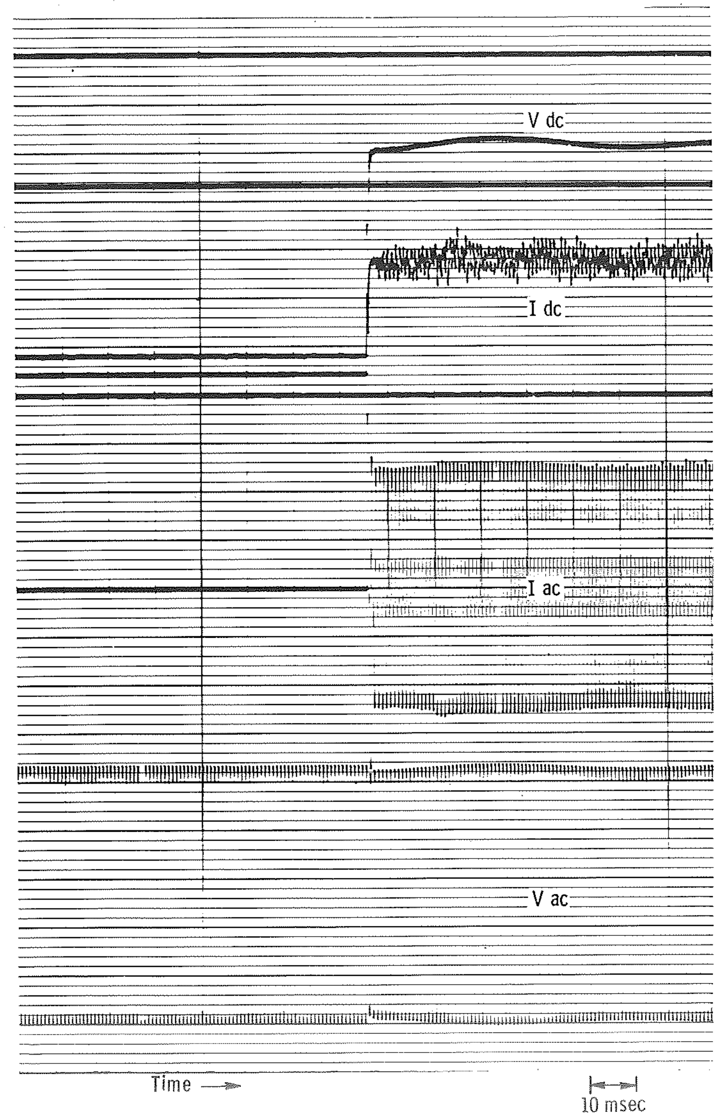

Figure 11. - dc supply turnon characteristics. "On" conditions: ac voltage, 120 volts rms; dc current, 20 amperes; frequency, 1200 hertz.

2 milliseconds. A single-pole filter with a time constant of 50 microseconds was used to filter the ripple out of the dc voltage before recording it. After turnon, the percentage of amplitude modulation in the output voltage is approximately the same as that of the line voltage, and the period is the same. This leads to the conclusion that the modulation in the output voltage is due to the modulation of the input.

Battery Chargers

The battery charger section of the dc supply was also tested. Batteries were not used but were simulated using a variable dc power supply and the circuit in figure 12.

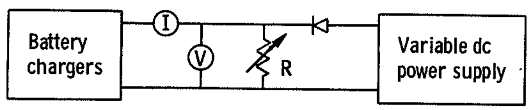

Figure 12. - Battery charger test circuit.

The requirements for the battery charger called for two-level charging. If the battery voltage went below 30.5 volts, the charger would start to charge at a level of about 4 amperes. It would continue to charge until the voltage went above 38 volts and then turn off. If, after the battery charger turned on at 30.5 volts, the voltage continued to go down (due to a load condition or a low-charge state), the charger would switch to an 8-ampere charging level. This would occur when the voltage went below 30 volts. It would continue to charge at the 8-ampere level until the voltage went above 37 volts. The level would decrease to the 4-ampere level until the voltage exceeded 38 volts and then turn off. The maximum battery charger power was about 550 watts.

The actual performance of the battery charger is shown in figures 13 and 14. There is a slight difference between the design and the observed operation but, since the design points were not critical, the operation was judged satisfactory.

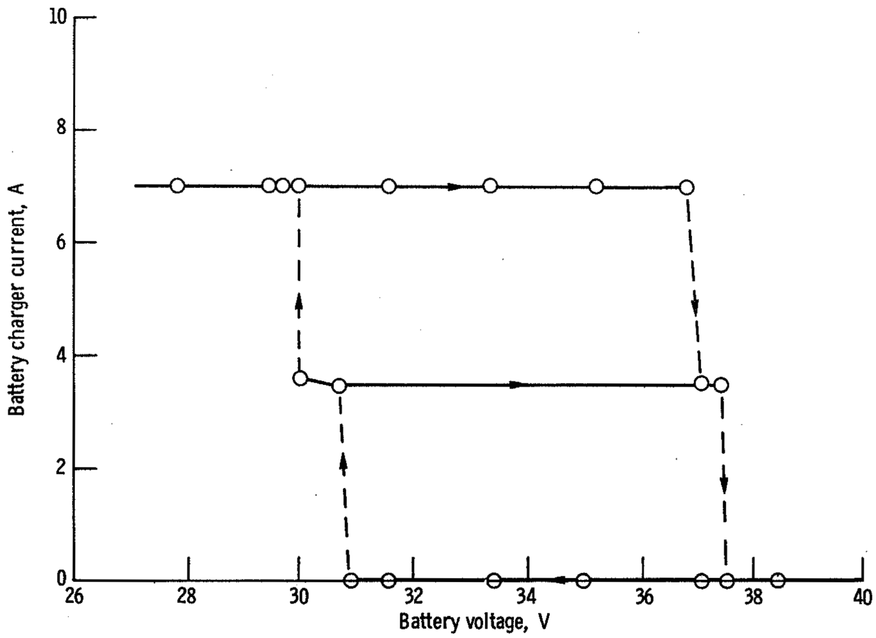

Figure 13. - Battery charger current as function of battery voltage (positive battery).

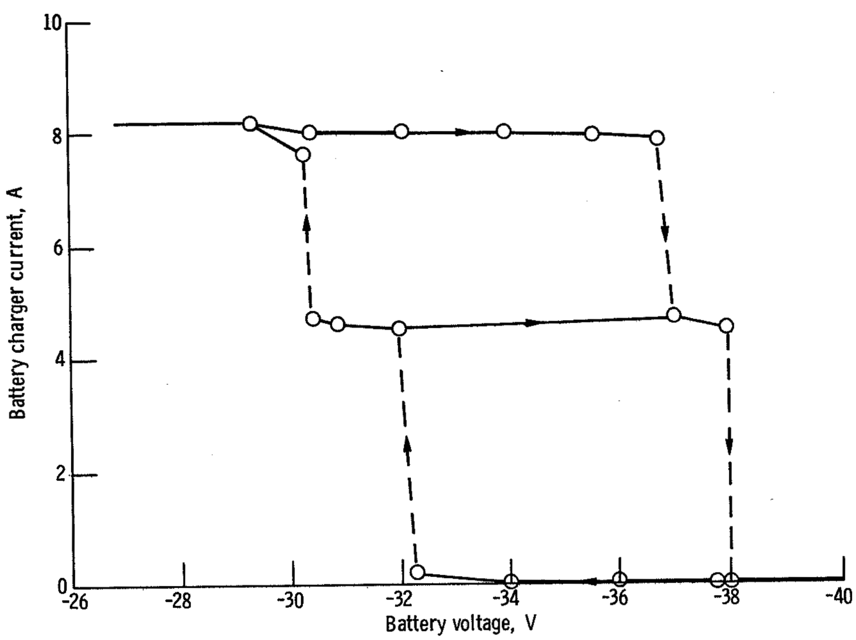

Figure 14. - Battery charger current as function of battery voltage (negative battery).

SUMMARY OF RESULTS

The dc supply was tested over a range of input voltage and frequencies and a range of output current. The design point was 120 volts ac, 1200-hertz, and a load of 20 amperes. The following results were obtained:

1. The output voltage load regulation was 6 percent over the load range of 5 to 25 amperes. The output voltage is approximately a linear function of input voltage. The output has 9-volt peak-to-peak commutation spikes at a frequency of 12 times the input frequency.

2. The power factor was 0.89±0.02 for all tests.

3. The efficiency was 89 percent at design point and flat over most of the tested range of loads. It was found to be independent of input voltage or frequency.

4. At the design point, the total harmonic content (THC) of the voltage was 3.3 percent. The THC of the current was 21.8 percent and the predominant harmonic current was the third, at 20 percent.

5. The battery charging section of the dc supply met the requirements of two-level charging.

The overall conclusion is that the dc supply operated satisfactorily for the intended purpose.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 27, 1971,
120-27.

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