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VOLTAGE DISTORTION EFFECTS OF SNAP-8 ALTERNATOR SPEED CONTROLLER AND ALTERNATOR PERFORMANCE RESULTS

by David S. Repas and Martin E. Valgora

Lewis Research Center
Cleveland, Ohio

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SUMMARY

The results of the SNAP-8 alternator tests that were performed at the Lewis Research Center are presented in this report. This alternator is rated 80 kilovolt-amperes at a power factor range of 0.75 (lagging) to 1.0, 120/208 volts, 400 hertz, and 12 000 rpm.

Loads corresponding to typical alternator power outputs were studied to determine the effect of the saturable-reactor - parasitic-load type of speed controller on the harmonics present in the alternator and load voltages. It was found that the maximum total harmonic distortion of the load voltage is 7.5 percent. For certain loads, the alternator kilovolt-ampere rating was exceeded because of the reactive power required by the speed controller. The overload on the alternator can be as much as 13 kilovolt-amperes, or 16 percent.

Saturation curves were obtained and the alternator efficiency was determined by the method of separation of losses. Calculated efficiencies from the latter test were compared with data obtained from the alternator manufacturer and were found to agree within 1 percent.

INTRODUCTION

The SNAP-8 electrical generating system is being developed by the NASA for use in various space applications. The system provides 35 kilowatts of useful electrical power by converting heat from a nuclear reactor into electrical energy.

This report presents the results of the SNAP-8 alternator tests that were performed at the Lewis Research Center. The unit tested was the first experimental alternator that was delivered under contract. Since these tests, actual flight-type alternators have been delivered. The SNAP-8 alternator is rated 80 kilovolt-amperes at a power factor range of 0.75 (lagging) to 1.0, 120/208 volts, 400 hertz, and 12 000 rpm.

The test was conducted primarily to study the effect of the saturable-reactor - parasitic-load type speed controller on the harmonics present in the alternator voltage, alternator current, and vehicle load voltage. The effect of the speed-controller reactive power on the required kilovolt-ampere output of the alternator was also determined.

The two main conditions studied were for total electrical loads on the alternator of 54.2 and 60 kilowatts. These values are typical alternator steady-state outputs as obtained from a progress report written by the SNAP-8 prime contractor.

The electrical load consists of four components: pump motors, system controls, vehicle (useful) load, and the speed controller. A load representing the pump motors and system controls was held constant. Vehicle load was varied from 0 to 35 kilowatts at a 0.75 (lagging) power factor. The speed controller was adjusted to obtain the desired total power for each of these two conditions. Curves of alternator kilovolt-ampere output, power factor, and total percent harmonic distortion, and tables of individual voltage and current harmonic magnitude breakdowns were obtained as functions of vehicle load.

For comparison, the effects of linear loads of 54 and 60 kilowatts at 0.75 (lagging) and 1.0 power factors were investigated. In this report, a linear load is defined as a load for which applied voltage and resultant current waveforms have essentially the same shape. The speed controller was also tested alone to determine its kilovolt-ampere and reactive-power characteristics as a function of real power loading.

Two secondary test objectives were (1) to determine alternator efficiency and (2) to obtain saturation curves. The results of the efficiency tests were used primarily to confirm data received from the alternator manufacturer.

The following saturation curves are included in the report: open-circuit, short-circuit, and rated load current at 0.75 (lagging), 0.0 (lagging), and 1.0 power factors.

Alternator efficiency was determined by the method of separation of losses. The different losses were measured or calculated from other pertinent data. The following individual losses were considered: open-circuit core, stray load, field copper, armature copper, windage, and bearing and seal friction. From these data, curves of efficiency as a function of alternator output and power factor were plotted.

EXPERIMENTAL COMPONENTS

The SNAP-8 alternator and associated controls tested consisted of an alternator, a voltage-regulator - static-exciter, and a speed controller. A block diagram of these components and the auxiliary test equipment is shown in figure 1.

Alternator

The alternator is an oil-cooled, brushless, solid-rotor, radial air-gap, homopolar inductor generator with the following continuous rating: 80 kilovolt-amperes, a power-factor range of 0.75 (lagging) to 1.0, 120/208 volts, 222 amperes, three phase, 400 hertz, and 12 000 rpm.

It was the first alternator delivered for the SNAP-8 program.

Voltage-Regulator - Static-Exciter

The voltage-regulator - static-exciter provided for these tests is a rack-mounted, air-cooled, experimental model. Figure 2 is a block diagram of the voltage regulating portion of the SNAP-8 system.

Static exciter. - The static exciter provides power for the alternator field. The main component of the static exciter is a saturable current potential transformer (SCPT). This is a combination three-phase current transformer, potential transformer, and saturable reactor.

The SCPT provides power to the alternator field from the alternator output by means of a combination of voltage and current feedback. The functions of the current feedback are to provide load compensation and to maintain field excitation during short circuits. A linear reactor in series with each potential primary winding is included to compensate for load power factor variations. The output of the SCPT is rectified and fed to the alternator field winding.

For normal loads, the static exciter alone is nearly capable of supplying and controlling the correct amount of field power. However, to obtain closer control, provide fast response, and improve stability, a saturating winding feed from a voltage regulator was added to the SCPT. The exciter output could be adjusted from minimum to maximum by varying the current in this control winding. (For detailed information on this type of exciter see ref. 1.)

Voltage regulator. - The voltage regulator supplies the control signal for the SCPT. The alternator terminal voltage is maintained at 120/208 volts at 400 hertz and constant voltage per cycle at lower frequencies. (For circuit details see ref. 2).

Speed Controller

The speed of the SNAP-8 system is controlled by parasitic loading of the alternator. The total electrical load is kept constant by means of the speed controller. Since both the electrical load and the power developed by the turbine remain essentially constant during steady-state operation, the system speed and frequency will vary no more than 1.0 percent.

The speed-control system consists of an amplifier assembly, a saturable reactor, and a parasitic load resistor (fig. 1). In the amplifier assembly, a stagger-tuned frequency circuit detects frequency changes and supplies a control signal to the saturable reactor, which controls the power flow to the parasitic load resistor. The amount of power dissipated in the parasitic load resistor is determined by the portion of the cycle in which current is conducted. This method of controlling speed is similar to that used in the SNAP-2 program (ref. 3).

The experimental speed controller used in these tests is a rack-mounted, air-cooled model.

TEST SETUP

Drive Stand

For these tests, the SNAP-8 alternator was driven at 12 000 rpm by a variable-speed induction dynamometer rated 300 horsepower at 20 000 rpm. The dynamometer reaction torque was transmitted to a force transducer located at the end of a 1-foot level arm and read out directly on the transducer-amplifier indicator. Speed was indicated directly on an electronic counter by a signal from a tachometer generator on the dynamometer shaft.

Alternator Cooling

The SNAP-8 alternator was designed to be cooled and lubricated with polyphenyl ether oil at a 210° F inlet temperature. This coolant was selected for its radiation-resistant properties. Because of the complexity and problems associated with a polyphenyl ether oil supply, an existing MIL-L-7808 oil supply was used for the tests. This substitution resulted in a one-third reduction in bearing and seal losses because of the decreased viscosity and density. This did not affect the electromagnetic efficiency, which is discussed in this report. The heat-transfer characteristics of MIL-L-7808 oil resulted in a slightly different temperature profile that had a negligible effect on efficiency and no effect on harmonics and saturation. The oil supply controlled the inlet oil temperature to within ±5° F of the selected value and provided preheating capability.

The alternator and oil supply temperatures were indicated on 16 temperature meter relays with audible alarms using iron-constantan thermocouples.

Auxiliary Equipment

All contactors are of the type used in advanced aircraft. The vehicle and parasitic load banks are commercial air-cooled equipment. An auxiliary direct-current power supply was used for manual field control in obtaining saturation curves and when the field excitation requirement exceeded the capability of the static exciter.

For the speed-controller tests, variations in turbine-alternator speed were simulated by driving the frequency sensing circuit with an external oscillator. For harmonic analysis, a wave analyzer was used with a sweep drive and an x, y-recorder to plot harmonic voltages against frequency.

All alternating-current meters were amplifier-detector type instruments designed primarily for the measurement of the true root-mean-square value (effective value) of voltages. This type of meter was necessary because of the distorted waveforms caused by the nonlinear effect of the speed controller. Before each test run, the meters were calibrated to within 1.0 percent accuracy at 400 hertz.

RESULTS AND DISCUSSION

Harmonic Analysis of Load Conditions

The saturable reactor speed controller used in the SNAP-8 alternator electrical system introduces harmonics into the line current. For certain actual loads, these harmonic currents increase the distortion of the alternator terminal voltage over that present with no load or with linear loads. In addition, reactive power must be supplied to the speed controller. This reactive power requirement causes the alternator kilovolt-ampere rating to be exceeded for certain actual load ranges. Data on harmonics are necessary to determine heating effects on components, filtering requirements for loads (especially electronic), and possible interference with communications equipment. The increased alternator rating due to parasitic type loading is of interest in the design of similar systems.

Three types of load conditions were studied:

(1) Actual alternator electrical loads

(2) Linear loads

(3) Speed controller alone

Table I gives the total vehicle-load-voltage harmonic distortion for each of these load conditions. When the speed controller was used alone, the load voltage data were not recorded. Therefore, the alternator terminal-voltage distortion is presented instead. The maximum total-voltage harmonic distortion observed was 7.5 percent.

Harmonic distortion for nonsinusoidal waves is defined as

$$\text{total percent distortion} = \left(\frac{\sqrt{\sum_{i=2}^{n} A_i^2}}{A_1}\right) \times 100 \text{ percent}$$

where

A_i magnitude of i^{th} harmonic (i = 2, 3, 4, . . ., n)
A_1 magnitude of fundamental

All the odd harmonics through the 39th were used to calculate the total harmonic distortion of each waveform. The 35th and 37th slot harmonics, which are significant for this alternator, are thus included.

Other definitions for nonsinusoidal waves that are applicable for this report are

$$\text{kilovolt-amperes} = \frac{\text{rms voltage (V)} \times \text{rms current (A)}}{1000}$$

$$\text{power factor} = \frac{\text{real power (kW)}}{\text{kilovolt-amperes}}$$

Linear loads. - Data showing the distortion effect of loading the alternator were obtained for the following linear loads: no load, 54 kilowatts at 0.75 (lagging) and 1.0 power factors, and 60 kilowatts at 0.75 (lagging) and 1.0 power factors. These results are summarized in table II.

Data on harmonics for alternator terminal voltage, load voltage, and line current, together with photographs of their waveforms, are presented in the appendix. Photographs presented in this report are not calibrated; they are intended only to show the shapes of the various waveforms.

Speed controller only. - Figure 3 shows the reactive power and kilovolt-ampere demand of the speed controller as a function of its real power input. For this test, the SNAP-8 alternator supplied the necessary power. The speed-controller load resistor was set at the design value of 0.745 ohm per phase. The detailed data on harmonics and the waveform photographs are presented in the appendix.

The greatest distortion of voltage and current and the largest reactive power demand occur in the range 25 to 75 percent of the maximum speed-controller power load. Outside this range, the speed-controller current has less effect on the alternator terminal voltage. Below 25 percent, the magnitude of the current is relatively small. Above 75 percent, the current waveform is more nearly sinusoidal because the saturable reactor conducts for almost the entire cycle.

Actual system. - The two main conditions studied were for total loads on the alternator of 54.2 and 60 kilowatts. These values are probable alternator outputs as obtained from a contractor's progress report.

For certain loads, it was necessary to excite the alternator separately because the output of the voltage regulator was not sufficient to maintain a rated terminal voltage of 120/208 volts. These cases were for vehicle loads of 30 kilowatts and greater for the 54.2-kilowatt condition and for vehicle loads of 20 kilowatts and greater for the 60-kilowatt condition. For all studies, the static exciter remained connected to the alternator terminals even if it was not used to excite the field.

Figure 4 shows alternator kilovolt-ampere output and power factor as a function of vehicle load for each of the alternator load conditions. A simulated pump motor and control load was held constant at 13.2 kilowatts and 17.9 kilovars. Results indicate that the alternator rating (80 kVA) will be exceeded under normal operating conditions for each of the alternator loads studied.

Data were taken of individual harmonic magnitudes (relative to the fundamental) for alternator phase current, vehicle load voltage, and alternator terminal voltage for each load point. These data, together with photographs of the various waveforms, are presented in the appendix.

Figure 5(a) is a plot of total-load-voltage harmonic distortion against vehicle load for the 54.2- and 60-kilowatt load conditions. Figure 5(b) shows the load-voltage distortion as a function of speed-controller load. For both alternator load conditions, the voltage distortion depends primarily on the speed-controller power load.

Saturation Curves

Several saturation curves were determined. Figure 6(a) is a plot of the open-circuit and short-circuit saturation curves. The short-circuit saturation curve includes the effect of some lead resistance from the alternator terminals to the shorting switches (approximately 0.0035 ohm per phase). Figure 6(b) shows the saturation curves for rated load current at 1.0, 0.75 (lagging), and 0.0 (lagging) power factors.

Efficiency

Alternator efficiency was determined by the method of separation of losses. The following is a list of the individual losses, either measured or calculated from other experimental data:

(1) Open-circuit core
(2) Stray load
(3) Field copper
(4) Armature copper
(5) Bearing and seal friction losses
(6) Windage

The curve of open-circuit core loss plotted against alternator terminal voltage is given in figure 7(a). Stray load loss plotted against armature current is shown in figure 7(b).

Figure 8 gives the field power loss plotted against alternator kilovolt-ampere output for 0.75 (lagging) and 1.0 power-factor loads. These curves were obtained by loading the alternator to the desired value and then measuring the field power requirements. The stator oil inlet temperature was held between 200° and 210° F for all cases. Alternator temperatures were allowed to stabilize for each test point before the data were recorded.

In conjunction with these tests, the stator end-turn and tooth temperatures were recorded. From these measurements, the stator copper temperature and loss can be estimated for any of the loads considered.

The bearing and slinger losses with MIL-L-7808 oil are 2.66 kilowatts. At atmospheric pressure, the windage loss is 1.02 kilowatts.

Figure 9 shows the SNAP-8 alternator electromagnetic efficiency as a function of kilovolt-ampere output for 0.75 (lagging) and 1.0 power-factor loads. The following formula was used to calculate electromagnetic efficiency:

$$\text{percent efficiency} = \frac{\text{output}}{\text{output} + \text{losses}} \times 100 \text{ percent}$$

For this study, losses (1) to (4) listed previously were included; bearing friction and windage losses were omitted. Actual bearing and seal friction losses could not be determined because MIL-L-7808 oil was used instead of polyphenyl ether oil. Windage loss was omitted because it is intended to vent the SNAP-8 alternator rotor cavity to space.

The calculated efficiencies were compared with data obtained from the alternator manufacturer and were found to be within 1 percent of these data (ref. 4).

SUMMARY OF RESULTS

The following significant results were obtained from a test of the first experimental SNAP-8 alternator, voltage-regulator - static-exciter, and speed controller:

1. For some possible SNAP-8 alternator load conditions, the reactive power requirements of the speed controller will cause the alternator rating to be exceeded. This overload can be as much as 13 kilovolt-amperes, or about 16 percent.

2. The maximum total-voltage harmonic distortion observed for the SNAP-8 alternator electrical system was 7.5 percent.

3. The efficiencies calculated for the alternator agreed with data determined by the alternator manufacturer. The calculated efficiency figures were within 1 percent of the manufacturer's data for the same actual load points.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 17, 1967,
701-01-00-06-22.

APPENDIX - HARMONIC DATA AND ANALYSES

Tables III and IV present data on the voltage and current harmonics for the various load conditions studied. Included is information on the load distribution and the alternator output characteristics.

Percent distortion includes the effect of all the odd harmonics through the 39th. The magnitude of each individual harmonic is given as a percent of the fundamental.

Photographs of the voltage and current waveforms are included in figures 10 to 12. These photographs are not calibrated.

REFERENCES

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4. Osborn, G. A.; Wimsatt, J. M.; Whipple, E. R.; Balke, R. L.; and Luddy, C. T.: Alternator Design and Development for the SNAP 8 Electrical Generating System. Rep. No. 30-12-15-65, General Electric Co., Dec. 15, 1965.

TABLE I. - TOTAL HARMONIC DISTORTION[a]

Linear loads					
Load power, kW	0	54	54	60	60
Load power factor (lagging)	----	1.0	.75	1.0	.75
Load-voltage distortion, percent	3.81	4.68	5.06	4.75	5.36
Actual loads					
Vehicle load power, kW	0	10	20	30	35
Alternator output power, kW	60	60	60	60	60
Load-voltage distortion, percent	6.65	6.66	7.34	6.22	4.93
Vehicle load power, kW	0	10	20	30	35
Alternator output power, kW	54.2	54.2	54.2	54.2	54.2
Load-voltage distortion, percent	7.52	7.36	6.64	5.21	3.28
Speed controller only					
Parasitic load power, kW	1.3	13.8	27.4	40.9	54.6
Alternator-voltage distortion, percent	4.30	8.24	7.02	6.74	4.69

[a]Line to neutral voltages.

TABLE II. - TOTAL PERCENT HARMONIC DISTORTION

FOR LINEAR LOADS[a]

Alternator load					
Kilowatts	0	54	54	60	60
Kilovars	0	7	48	4	52
Kilovolt-amperes	0	54.5	72	60	79.5
Power factor (lagging)	----	.992	.748	.998	.755
Distortion, percent					
Load voltage	----	4.76	5.01	4.83	4.83
Alternator voltage	3.81	4.68	5.06	4.65	5.36
Alternator current	----	3.56	2.95	3.71	2.95

[a]Line to neutral voltages.

TABLE III. - VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(a) Linear load only. No-load; rated voltage; alternator output, 0 kilowatt, 0 kilovar, 0 kilovolt-ampere; alternator voltage, 121.77 (line to neutral); line current, 0; total percent distortion, 3.81[a]

Harmonic order	Alternator voltage, percent
1	100.00
3	2.33
5	.97
7	1.87
9	1.34
11	0
13	.33
15	.82
17	.09
19	.03
21	.48
23	.17
25	0
27	.24
29	.28
31	.10
33	.11
35	1.15
37	.58
39	0

[a]See fig. 10(a) for waveform photographs.

TABLE III. - Continued. VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(b) Linear load only. Alternator output, 54 kilowatts at 1.0 power factor, 6.99 kilovars, and 54.45 kilovolt-amperes; alternator voltage, 121.00/209.67 volts; line current, 150.00 volts[b]

Harmonic order	Total distortion, percent		
	4.60	4.68	3.56
	Alternator voltage, percent	Load voltage, percent	Line current, percent
1	100.00	100.00	100.00
3	4.14	4.20	3.25
5	.91	1.06	.23
7	.95	.92	.81
9	1.22	1.22	.82
11	.34	.38	.30
13	.32	.34	.15
15	.55	.54	.41
17	.19	.21	.22
19	.12	.15	.11
21	.22	.21	.18
23	.04	.09	.11
25	.05	.08	.04
27	.08	.08	.06
29	.01	.04	.11
31	.04	.06	.05
33	.09	.08	.05
35	.23	.16	.47
37	.26	.20	.36
39	.10	.07	.14

[b]See fig. 10(b) for waveform photographs.

TABLE III. - Continued. VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(c) Linear load only. Alternator output, 54 kilowatts at 0.75 power factor, 47.93 kilovars, and 72.20 kilovolt-amperes; alternator voltage, 120.33/209.00 volts; line current, 200.00[c]

Harmonic order	Total distortion, percent		
	4.97	4.93	2.95
	Alternator voltage, percent	Load voltage, percent	Line current, percent
1	100.00	100.00	100.00
3	4.51	4.51	2.36
5	.70	.83	.46
7	.67	.57	1.39
9	1.59	1.46	.72
11	.33	.46	.29
13	.23	.29	.27
15	.66	.56	.31
17	.27	.27	.05
19	.20	.22	.08
21	.19	.16	.11
23	.15	.15	0
25	.08	.09	.02
27	.04	.04	.02
29	.10	.06	.02
31	.02	.03	.02
33	.01	.02	.01
35	.20	.12	.28
37	.30	.22	.29
39	.10	.06	.08

[c]See fig. 10(c) for waveform photographs.

TABLE III. - Continued. VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(d) Linear load only. Alternator output, 60 kilowatts at 1.0 power factor, 3.80 kilovars, and 60.12 kilovolt-amperes; alternator voltage, 120.00/208.33 volts; line current, 167.00[d]

Harmonic order	Total distortion, percent		
	4.65	4.83	3.71
	Alternator voltage, percent	Load voltage, percent	Line current, percent
1	100.00	100.00	100.00
3	4.22	4.37	3.44
5	.88	1.04	.26
7	.99	1.02	.65
9	1.18	1.17	.91
11	.34	.41	.22
13	.33	.36	.11
15	.48	.44	.45
17	.17	.19	.15
19	.14	.16	.08
21	.15	.14	.20
23	.07	.08	.08
25	.05	.09	.02
27	.02	.04	.08
29	.03	.04	.06
31	.01	.03	.05
33	.05	.04	.08
35	.23	.16	.34
37	.23	.17	.40
39	.14	.10	.11

[d]See fig. 10(d) for waveform photographs.

TABLE III. - Continued. VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(e) Linear load only. Alternator output, 60 kilowatts at 0.75 power factor, 52.12 kilovars, and 79.48 kilovolt-amperes; alternator voltage, 119.33/206.33 volts; line current, 222.00[e]

Harmonic order	Total distortion, percent		
	5.36	4.83	2.95
	Alternator voltage, percent	Load voltage, percent	Line current, percent
1	100.00	100.00	100.00
3	4.89	4.42	2.52
5	.75	.82	.60
7	.79	.53	1.15
9	1.64	1.40	.63
11	.27	.46	.21
13	.32	.28	.26
15	.71	.53	.21
17	.26	.33	.04
19	.19	.23	.04
21	.22	.19	.04
23	.18	.17	0
25	.12	.12	.01
27	.08	.09	0
29	.12	.10	0
31	.03	.05	.03
33	.01	.05	0
35	.21	.10	.15
37	.27	.19	.29
39	.08	.05	.04

[e]See fig. 10(e) for waveform photographs.

TABLE III. - Concluded. VOLTAGE AND CURRENT HARMONICS

[All voltage harmonics are for line to neutral voltages.]

(f) Speed controller only. Load resistor, 0.745 ohm[f]

Harmonic order	Alternator output, kW					Alternator output, kW				
	1.26	13.80	27.36	40.90	54.60	1.26	13.80	27.36	40.90	54.60
	Alternator output, kilovars					Alternator output, kilovars				
	6.30	24.57	27.57	26.11	14.32	6.30	24.57	27.57	26.11	14.32
	Alternator output, kVA					Alternator output, kVA				
	6.42	28.18	38.84	48.52	56.45	6.42	28.18	38.84	48.52	56.45
	Power factor					Power factor				
	0.196	0.490	0.704	0.843	0.967	0.196	0.490	0.704	0.843	0.967
	Alternator voltage (line to neutral), V					Alternator voltage (line to neutral), V				
	120.00	122.00	121.00	121.00	121.00	120.00	122.00	121.00	121.00	121.00
	Alternator voltage (line to line), V					Alternator voltage (line to line), V				
	210.00	211.00	209.67	210.00	210.00	210.00	211.00	209.67	210.00	210.00
	Line current, A					Line current, A				
	17.83	77.00	107.00	133.67	155.50	17.83	77.00	107.00	133.67	155.50
	Total distortion, percent					Total distortion, percent				
	4.30	8.24	7.02	6.74	4.69	64.21	51.04	35.42	20.37	4.00
	Alternator voltage, percent					Line current, percent				
1	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
3	1.73	4.03	4.67	4.97	3.99	58.50	49.83	34.22	19.07	3.78
5	2.09	4.95	3.75	3.91	.85	24.91	9.39	8.02	6.54	.65
7	2.53	4.73	2.91	1.24	1.44	7.09	4.96	3.73	2.80	.49
9	1.30	1.22	1.59	1.47	1.36	4.12	2.43	2.17	.78	.92
11	.48	.90	.54	.29	.31	2.73	1.54	.60	.26	.15
13	.27	.42	.29	.06	.30	.78	.82	.31	.12	.09
15	.85	.83	.84	.82	.63	1.60	.33	.25	.17	.32
17	.13	.26	.08	.10	.13	.69	.36	.09	.09	.04
19	0	.22	.07	.05	.15	.15	.26	.02	.01	.05
21	.48	.49	.40	.33	.24	.54	.02	.13	.09	.10
23	.17	.07	.18	.13	.16	.06	.20	.10	.01	.01
25	0	.17	.05	0	.05	.04	.19	.02	.01	.02
27	.27	.19	.14	.11	.07	.18	.05	.08	.01	.01
29	.26	.27	.22	.12	.14	.04	.04	.05	.04	.01
31	.10	.22	.12	.01	.05	.01	.11	0	.03	.01
33	.06	0	.04	.04	.10	.44	.22	.13	.05	.02
35	1.16	1.02	.97	.79	.62	.42	.30	.26	.27	.25
37	.45	.19	.27	.41	.53	.32	.23	.21	.21	.15
39	.05	.09	.12	.19	.17	.33	.06	.03	.03	.04

[f]See fig. 11 for waveform photographs.

TABLE IV. - SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(a) Total alternator load, 54.2 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[a]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	41.0	42.29	68.80	0.789	121.33	210.00	189.00
II	10.0	8.8	31.0	52.82	75.81	.717	120.33	209.00	210.00
III	20.0	17.6	21.0	58.70	79.92	.679	120.00	207.00	222.00
IV	30.0	26.4	11.0	65.02	84.60	.640	120.00	208.00	235.00
V	35.0	30.9	6.0	65.60	85.08	.637	120.00	208.00	236.33

Harmonic order	Total distortion, percent				
	7.52	7.36	6.64	5.21	3.28
	Load voltage, percent				
	Case I	Case II	Case III	Case IV	Case V
1	100.00	100.00	100.00	100.00	100.00
3	6.25	5.99	4.78	3.05	1.73
5	3.61	3.51	3.49	3.33	2.02
7	1.27	1.47	2.66	1.67	.88
9	1.44	1.67	1.03	1.71	1.42
11	.24	.41	.55	.39	.54
13	.12	.38	.13	.48	.24
15	.59	.61	.56	.57	.54
17	.22	.21	.22	.28	.20
19	.03	.08	.18	.16	.24
21	.24	.15	.15	.13	.15
23	.17	.18	.18	.14	.16
25	.09	.02	.06	.12	.10
27	.06	.03	.05	.08	.08
29	.12	.10	.08	.05	.05
31	0	.01	.05	.03	.03
33	0	.01	.04	.04	.05
35	.38	.23	.17	.14	.10
37	.31	.30	.27	.24	.24
39	.12	.07	.06	.07	.07

[a]See fig. 12(a) for waveform photographs.

TABLE IV. - Continued. SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(a) Continued. Total alternator load, 54.2 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[a]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	41.0	42.29	68.80	0.789	121.33	210.00	189.00
II	10.0	8.8	31.0	52.82	75.81	.717	120.33	209.00	210.00
III	20.0	17.6	21.0	58.70	79.92	.679	120.00	207.00	222.00
IV	30.0	26.4	11.0	65.02	84.60	.640	120.00	208.00	235.00
V	35.0	30.9	6.0	65.60	85.08	.637	120.00	208.00	236.33

Harmonic order	Total distortion, percent		
	6.72	6.05	4.16
	Alternator voltage, percent		
	Case I	Case III	Case V
1	100.00	100.00	100.00
3	5.48	4.19	2.95
5	3.22	3.07	2.32
7	1.01	2.62	.59
9	1.59	1.35	1.43
11	.27	.40	.38
13	.05	.18	.15
15	.78	.66	.62
17	.13	.20	.17
19	.04	.19	.22
21	.25	.20	.18
23	.14	.18	.17
25	.05	.05	.08
27	.07	.05	.07
29	.13	.10	.07
31	0	.01	0
33	0	.04	.04
35	.47	.23	.20
37	.41	.34	.31
39	.14	.09	.10

[a]See fig. 12(a) for waveform photographs.

TABLE IV. - Continued. SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(a) Concluded. Total alternator load, 54.2 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[a]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	41.0	42.29	68.80	0.789	121.33	210.00	189.00
II	10.0	8.8	31.0	52.82	75.81	.717	120.33	209.00	210.00
III	20.0	17.6	21.0	58.70	79.92	.679	120.00	207.00	222.00
IV	30.0	26.4	11.0	65.02	84.60	.640	120.00	208.00	235.00
V	35.0	30.9	6.0	65.60	85.08	.637	120.00	208.00	236.33

Harmonic order	Case I	Case II	Case III	Case IV	Case V
	Total distortion, percent				
	12.31	14.71	15.58	14.78	12.46
	Line current, percent				
1	100.00	100.00	100.00	100.00	100.00
3	11.58	14.23	15.32	14.41	11.95
5	3.58	3.00	2.31	2.43	2.62
7	2.02	1.99	.15	2.13	2.04
9	.65	.88	1.49	.26	1.08
11	.24	.15	.29	.19	.31
13	.15	.28	.20	.21	.18
15	.15	.23	.26	.29	.26
17	.06	.05	.04	.05	.02
19	.04	.05	.06	.05	.08
21	.07	.12	.07	.12	.09
23	.01	0	0	.01	.01
25	.04	0	0	.01	.01
27	0	.04	.04	0	0
29	.03	.02	.04	.04	.05
31	.03	.03	.05	.03	.02
33	.03	.01	.01	0	0
35	.22	.24	.22	.21	.20
37	.26	.24	.26	.25	.26
39	.07	.08	.07	.05	.07

[a]See fig. 12(a) for waveform photographs.

TABLE IV. - Continued. SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(b) Total alternator load, 60 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[b]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	46.8	39.98	72.10	0.832	122.00	210.67	197.00
II	10.0	8.8	36.8	52.18	79.52	.755	120.67	209.33	219.67
III	20.0	17.6	26.8	61.50	85.92	.698	120.00	208.00	238.67
IV	30.0	26.4	16.8	68.04	90.72	.661	120.00	208.00	252.00
V	35.0	30.9	11.8	71.21	93.12	.644	120.00	208.00	258.67

Harmonic order	Total distortion, percent				
	6.65	7.36	7.34	6.22	4.93
	Load voltage, percent				
	Case I	Case II	Case III	Case IV	Case V
1	100.00	100.00	100.00	100.00	100.00
3	5.69	6.21	5.63	4.08	2.93
5	2.63	3.36	3.68	3.75	3.15
7	1.51	.86	2.32	2.38	1.51
9	1.37	1.69	1.51	1.22	1.62
11	.25	.14	.51	.32	.17
13	.22	.22	.41	.43	.51
15	.62	.67	.61	.60	.59
17	.18	.14	.23	.26	.24
19	.06	.20	.14	.19	.22
21	.21	.24	.20	.19	.13
23	.15	.10	.13	.12	.19
25	.05	.07	.10	.14	.08
27	.05	.07	.10	.10	.13
29	.14	.09	.08	.09	.06
31	.02	.01	.04	.04	.06
33	0	.01	.04	.07	.07
35	.35	.21	.14	.10	.09
37	.27	.25	.22	.15	.18
39	.10	.10	.04	.04	.04

[b]See fig. 12(b) for waveform photographs.

TABLE IV. - Continued. SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(b) Continued. Total alternator load, 60 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[b]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	46.8	39.98	72.10	0.832	122.00	210.67	197.00
II	10.0	8.8	36.8	52.18	79.52	.755	120.67	209.33	219.67
III	20.0	17.6	26.8	61.50	85.92	.698	120.00	208.00	238.67
IV	30.0	26.4	16.8	68.04	90.72	.661	120.00	208.00	252.00
V	35.0	30.9	11.8	71.21	93.12	.644	120.00	208.00	258.67

Harmonic order	Total distortion, percent		
	6.09	5.98	4.83
	Alternator voltage, percent		
	Case I	Case III	Case V
1	100.00	100.00	100.00
3	5.16	4.73	3.17
5	2.27	2.59	2.61
7	1.39	1.80	1.66
9	1.53	1.56	1.68
11	.24	.45	.21
13	.16	.28	.38
15	.70	.67	.65
17	.08	.15	.19
19	.08	.18	.22
21	.22	.21	.15
23	.16	.11	.19
25	.04	.10	.07
27	.04	.08	.13
29	.14	.08	.06
31	.04	.03	.03
33	.01	.04	.07
35	.43	.21	.15
37	.40	.31	.26
39	.14	.08	.07

[b]See fig. 12(b) for waveform photographs.

TABLE IV. - Concluded. SNAP-8 SYSTEM STUDY

[All voltage harmonics are for line to neutral voltages.]

(b) Concluded. Total alternator load, 60 kilowatts. Pump motor load, 13.2 kilowatts, 17.9 kilovars[b]

Case	Vehicle load		Speed-controller load, kW	Alternator output		Power factor	Alternator voltage, V		Line current, A
	kW	kilovar		kilovar	kVA		Line to neutral	Line to line	
I	0	0	46.8	39.98	72.10	0.832	122.00	210.67	197.00
II	10.0	8.8	36.8	52.18	79.52	.755	120.67	209.33	219.67
III	20.0	17.6	26.8	61.50	85.92	.698	120.00	208.00	238.67
IV	30.0	26.4	16.8	68.04	90.72	.661	120.00	208.00	252.00
V	35.0	30.9	11.8	71.21	93.12	.644	120.00	208.00	258.67

Harmonic order	Total distortion, percent				
	7.71	12.01	13.37	13.80	13.12
	Line current, percent				
	Case I	Case II	Case III	Case IV	Case V
1	100.00	100.00	100.00	100.00	100.00
3	7.20	11.49	13.13	13.59	12.77
5	2.42	2.81	1.82	1.92	2.34
7	.99	2.05	1.12	.97	1.84
9	.81	.19	1.18	1.03	.29
11	.25	.16	.24	.18	.14
13	.11	.17	.18	.22	.20
15	.20	.16	.22	.18	.22
17	.02	.01	.01	.02	.02
19	.04	.09	.04	.04	.07
21	.03	.01	.05	.04	.06
23	.03	.02	.01	.01	0
25	.02	.02	.01	.02	0
27	0	0	0	0	0
29	.02	.01	.02	.01	.02
31	.02	.02	.05	.04	.02
33	.02	.01	0	0	0
35	.18	.16	.16	.15	.14
37	.25	.25	.25	.22	.22
39	.06	.05	.05	.05	.05

[b]See fig. 12(b) for waveform photographs.

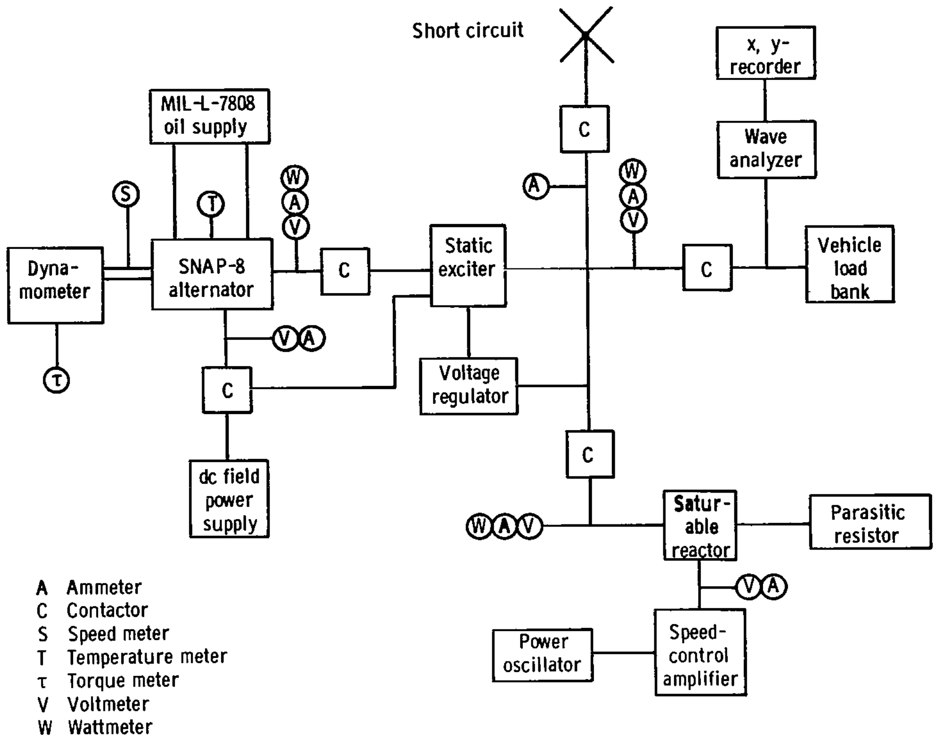


Figure 1. - Block diagram of SNAP-8 alternator test circuit.

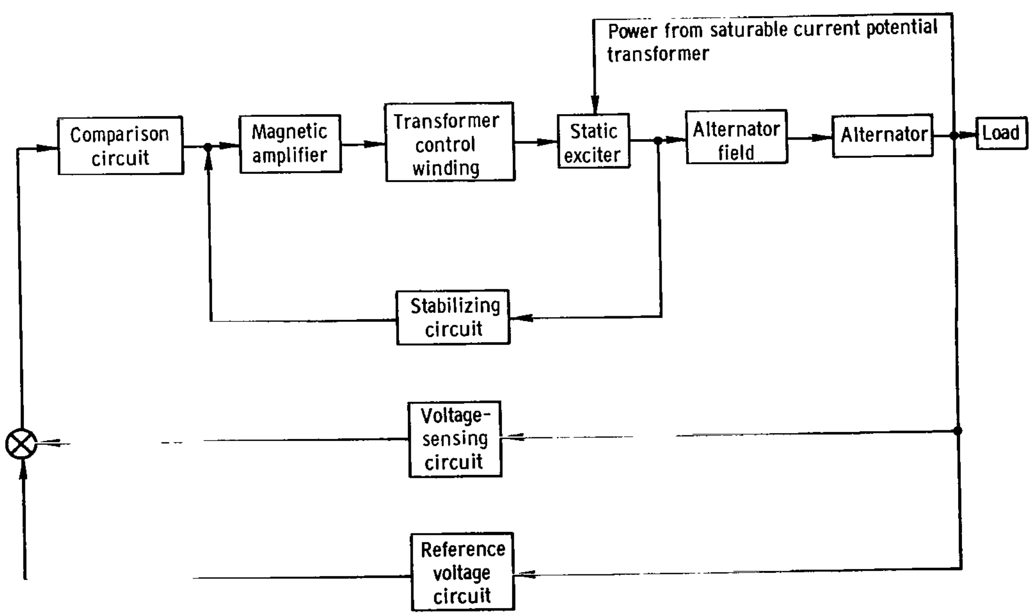


Figure 2. - Block diagram of SNAP-8 alternator - voltage-regulator - static-exciter system.

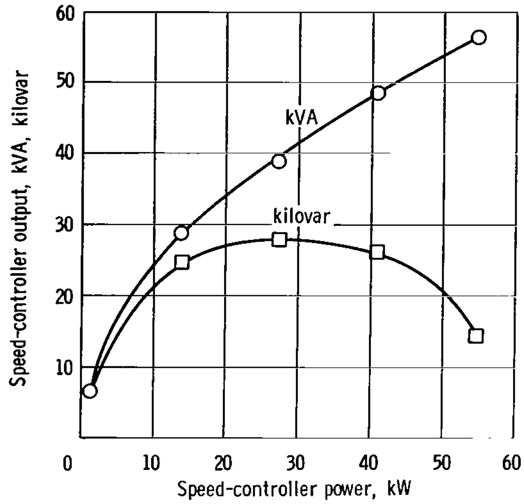
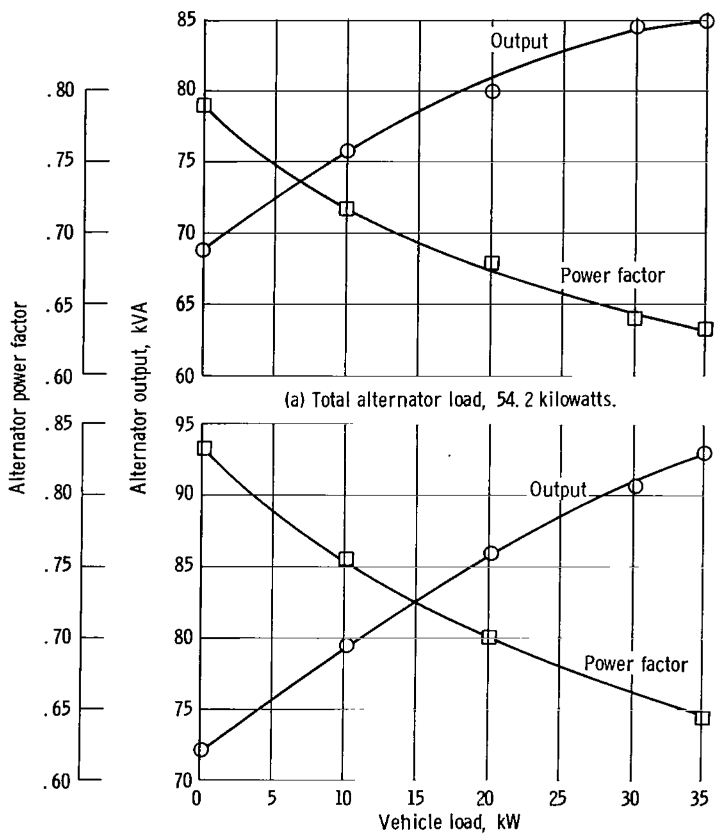
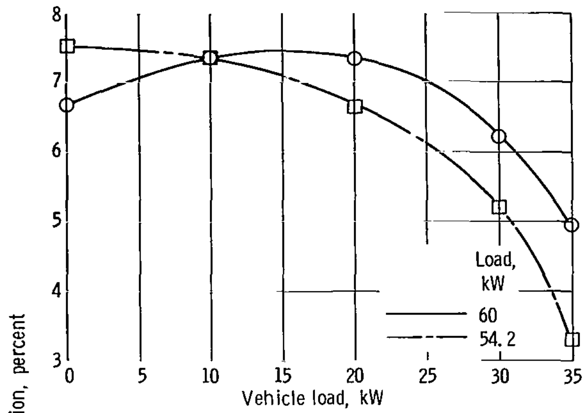


Figure 3. - Speed-controller characteristics. Load resistor, 0.745 ohm.

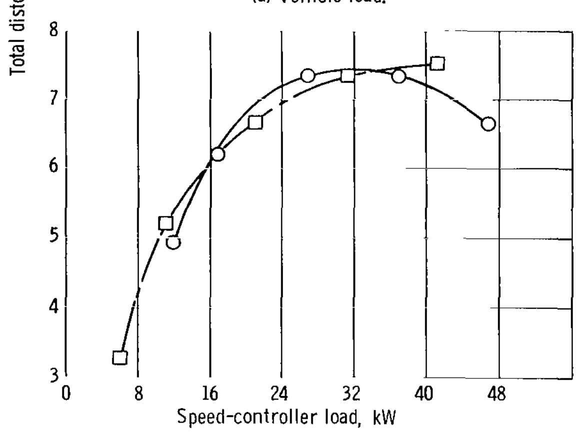


(b) Total alternator load, 60 kilowatts.

Figure 4. - SNAP-8 alternator output. Constant pump motor and control load (13.2 kW, 17.9 kilovar); vehicle load power factor, 0.75; rated output, 80 kilovolt-amperes.

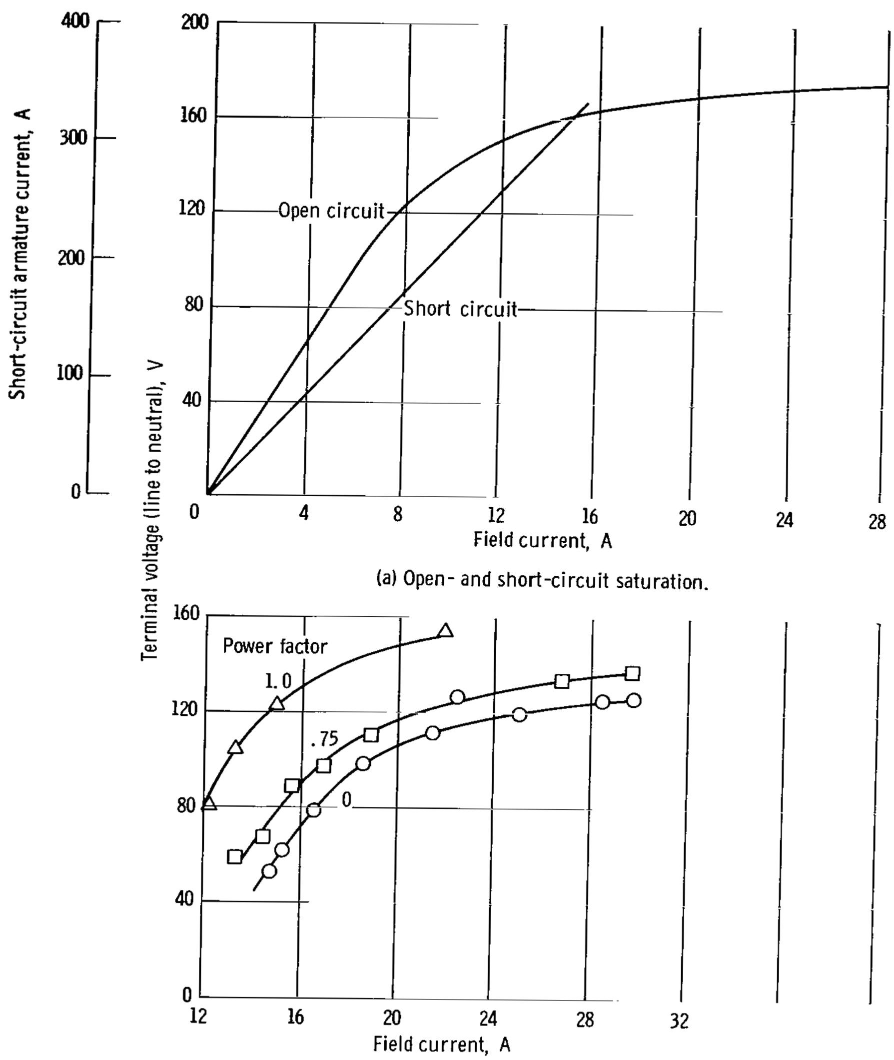


(a) Vehicle load.



(b) Speed controller.

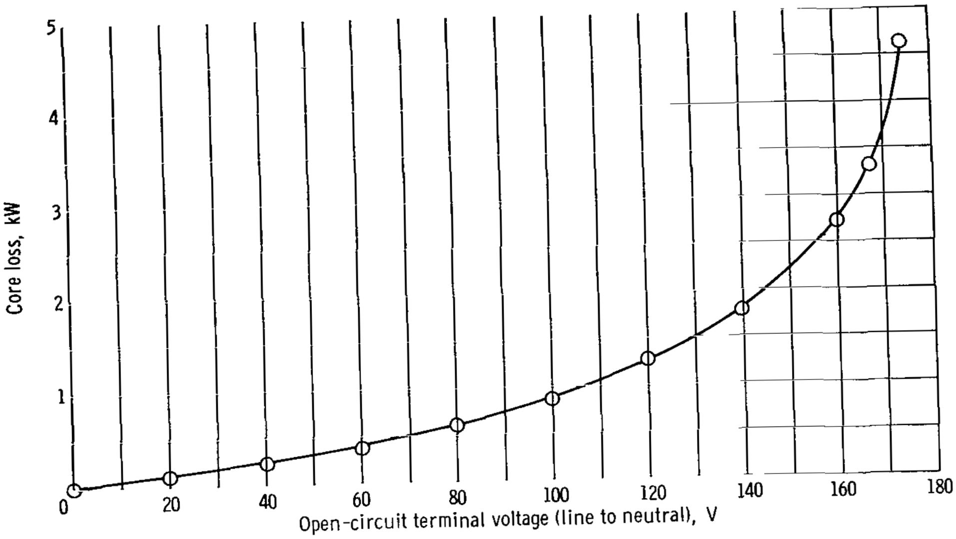
Figure 5. - Load-voltage harmonic distortion. Constant pump motor and control load (13.2 kW, 17.9 kilovar); vehicle load power factor, 0.75.



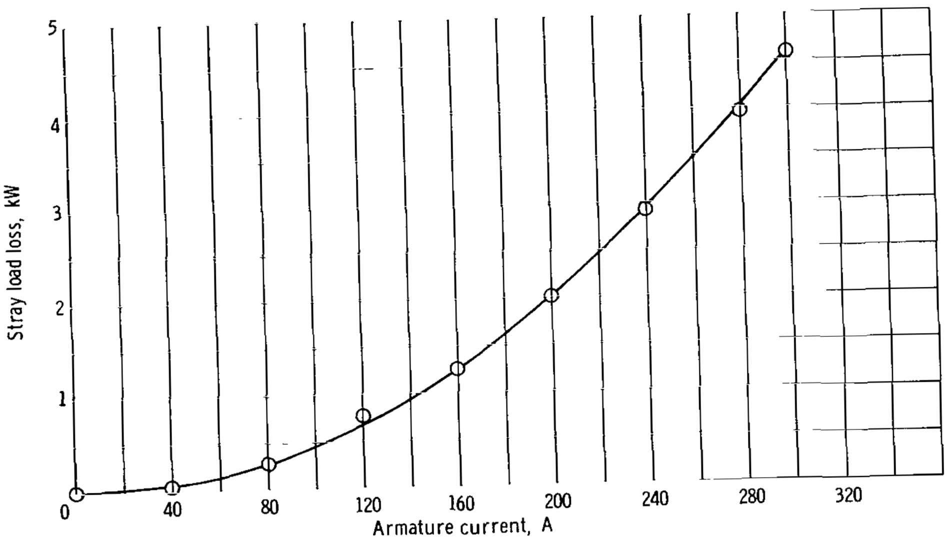
(a) Open- and short-circuit saturation.

(b) Rated armature current.

Figure 6. - SNAP-8 alternator saturation curves.



(a) Open-circuit core loss.



(b) Stray load loss.

Figure 7. - SNAP-8 alternator loss.

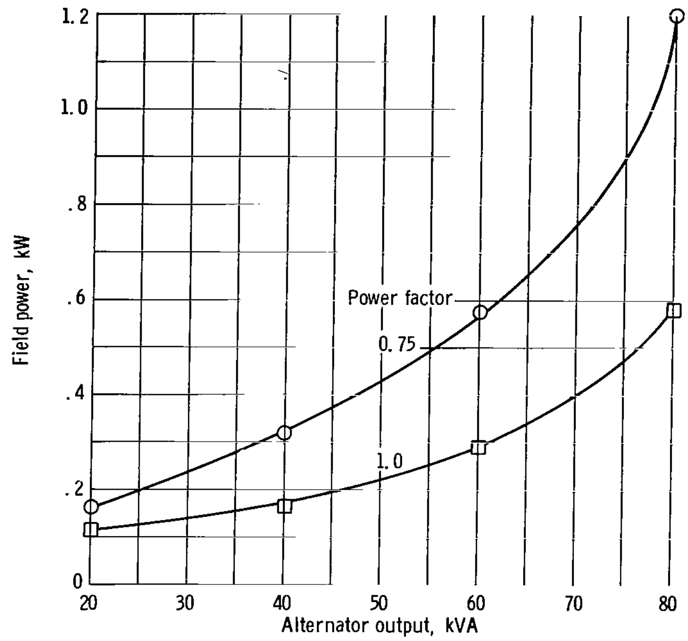


Figure 8. - Field power against output for SNAP-8 alternator. Coolant oil, MIL-L-7808; stator oil inlet temperature, 205° F.

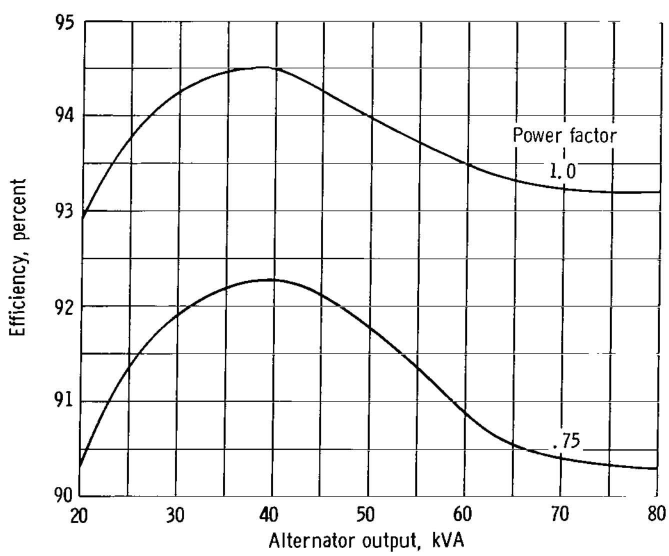


Figure 9. - SNAP-8 alternator electromagnetic efficiency.

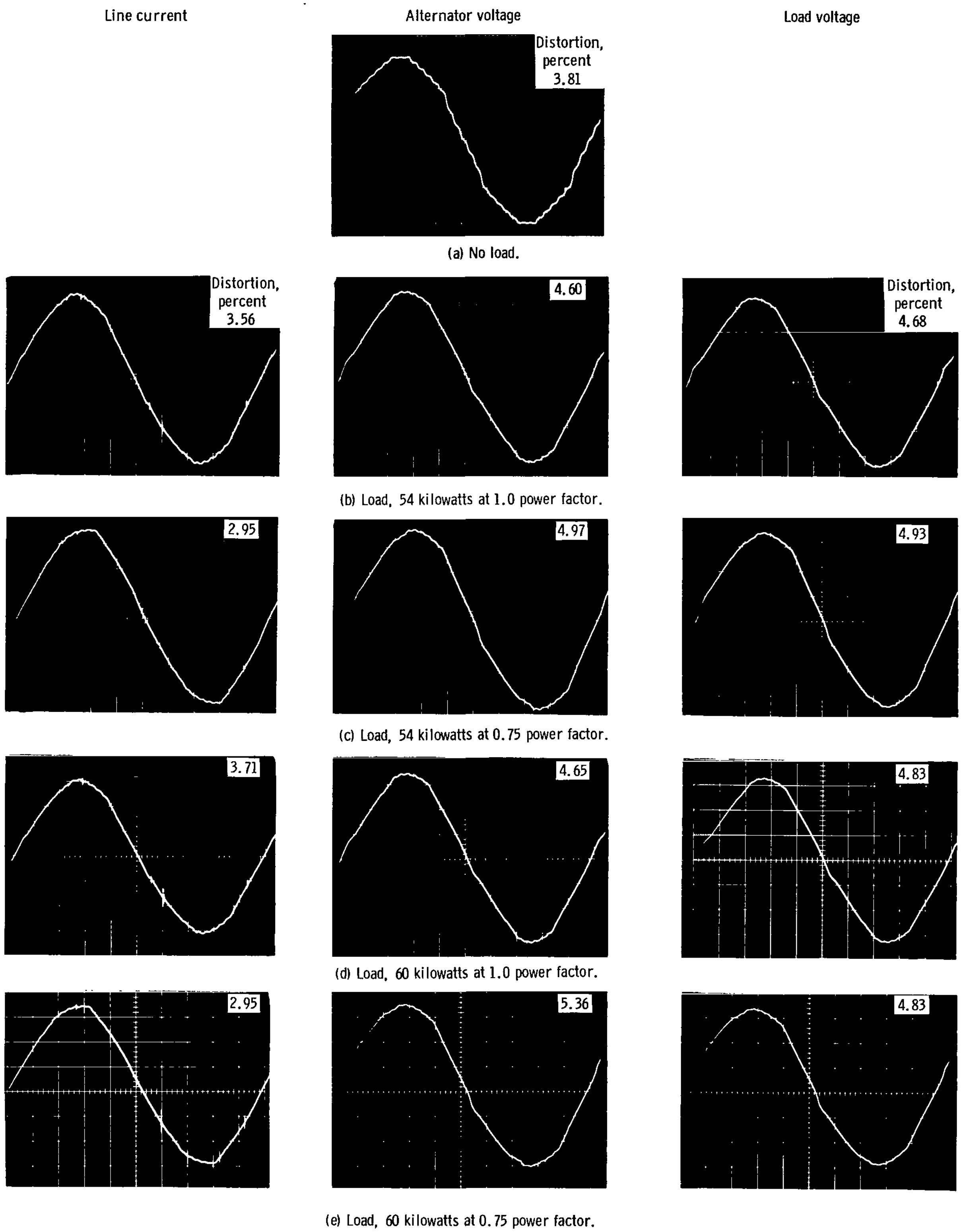
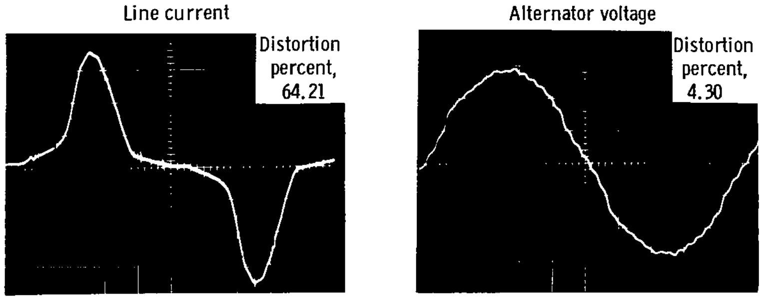
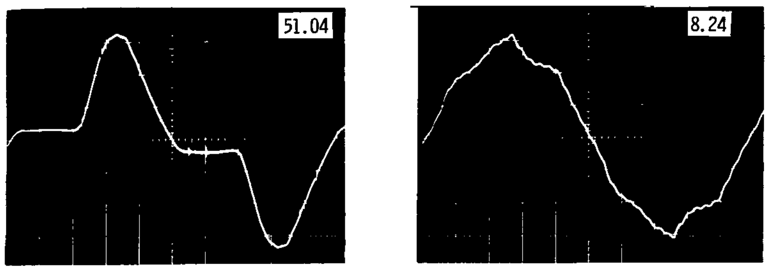


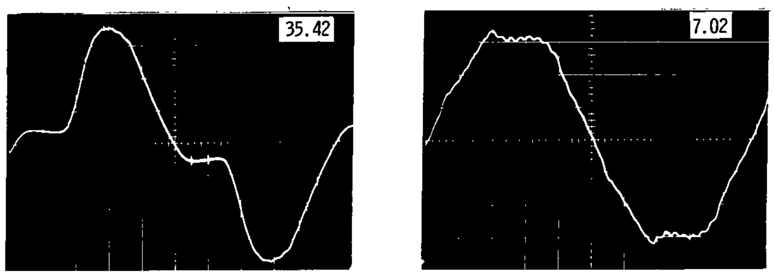
Figure 10. - Linear loads. (See tables III (a) to (e) for harmonic analyses.)



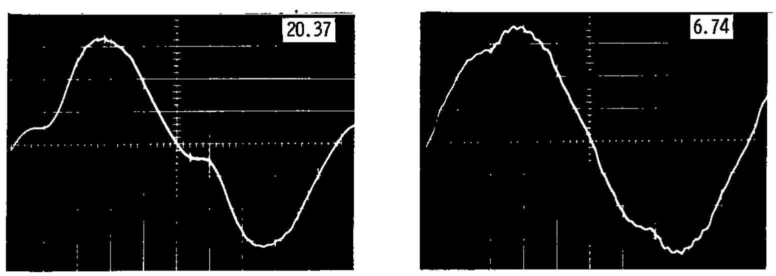
(a) Minimum load.



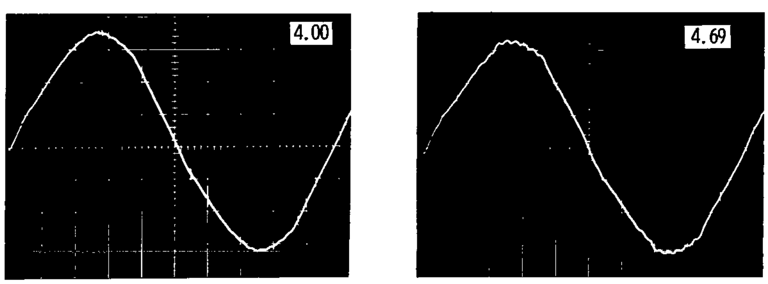
(b) Load, 25 percent.



(c) Load, 50 percent.

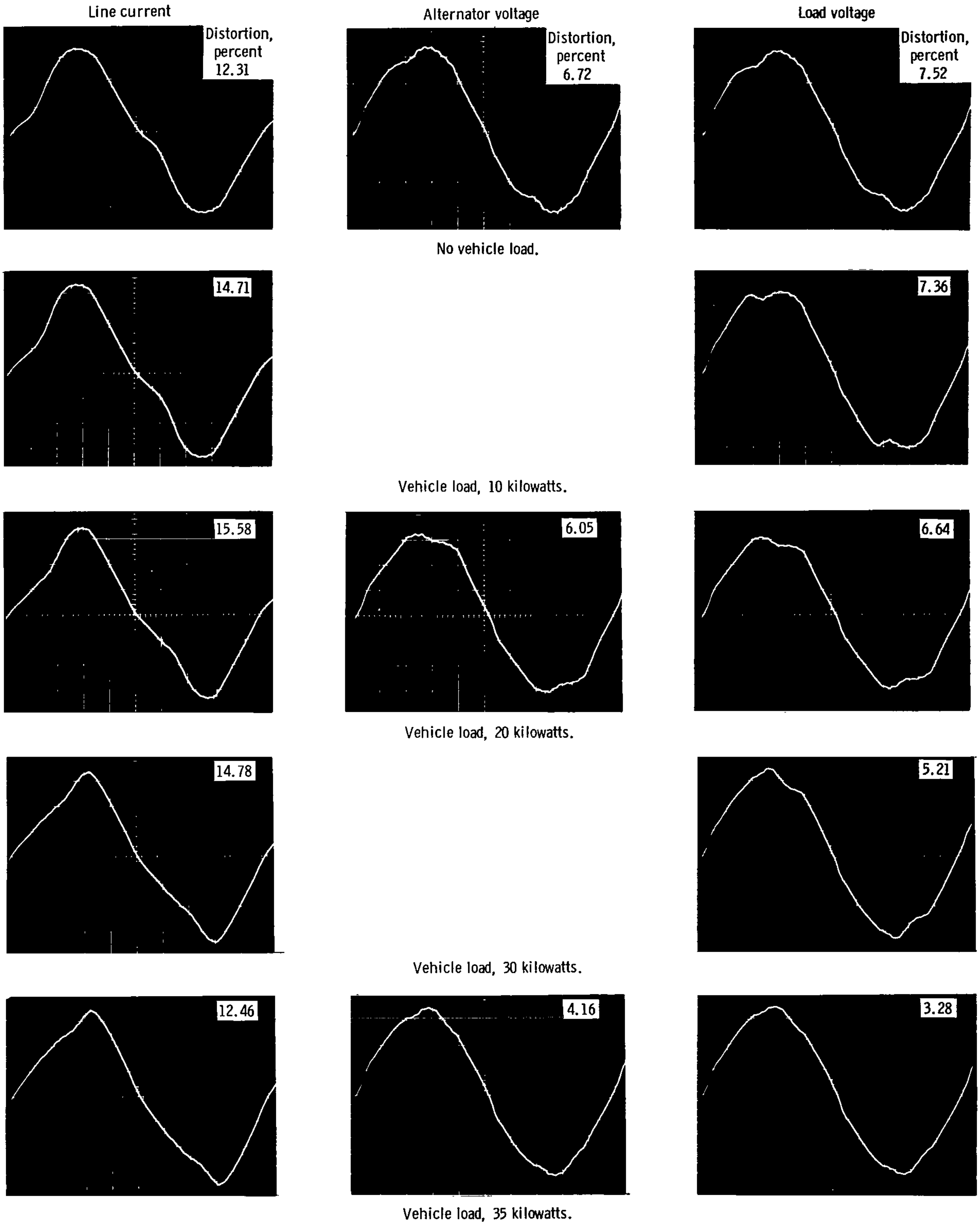


(d) Load, 75 percent.



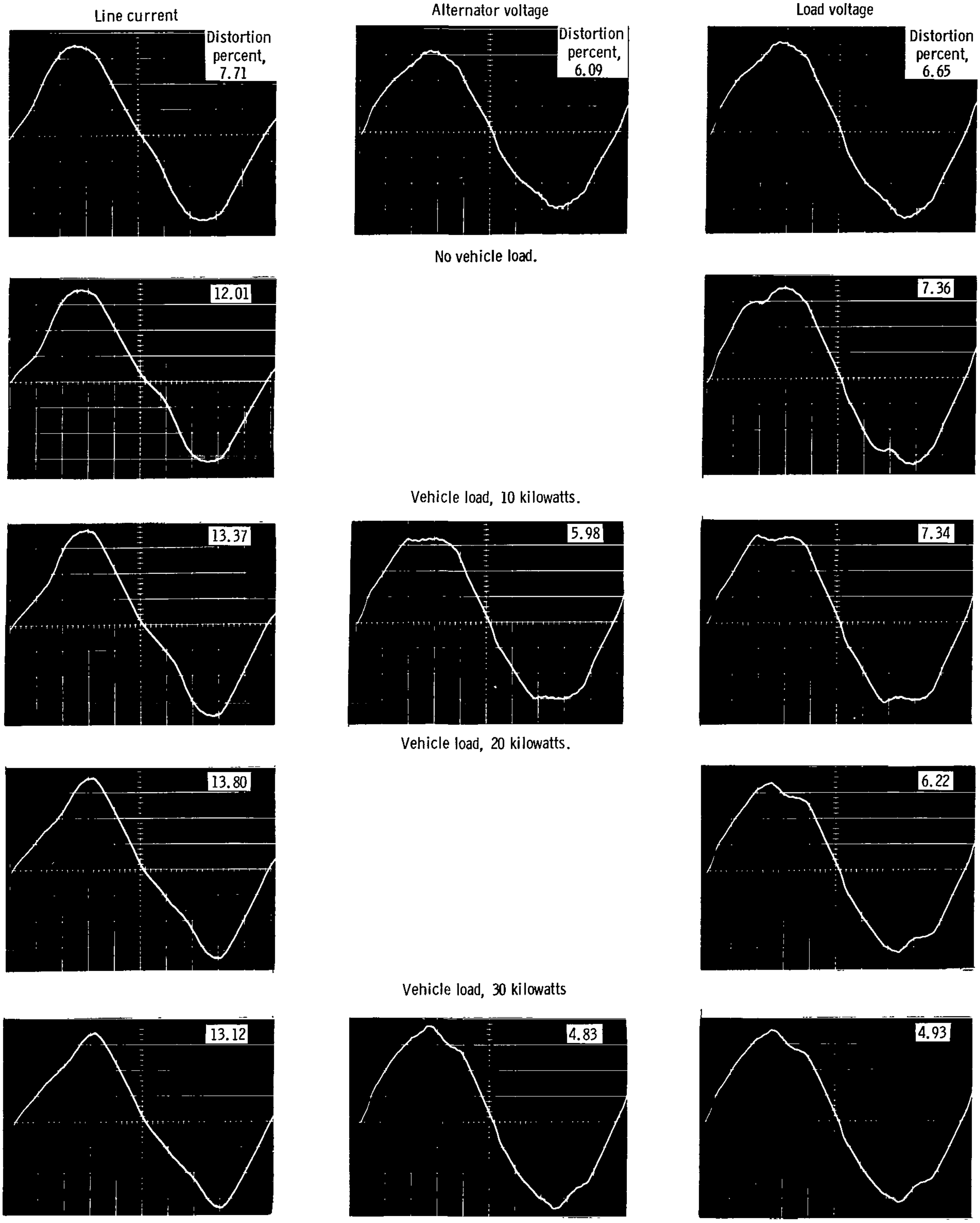
(e) Load, 100 percent.

Figure 11. - Speed controller only. Load resistor, 0.745 ohm. (See table III (f) for harmonic analyses.)



(a) Total alternator load, 54.2 kilowatts.

Figure 12. - SNAP-8 system loads. Pump motor load, 13.2 kilowatts, 17.9 kilovars. (See table IV for harmonic analyses.)



(b) Total alternator load, 60 kilowatts.

Figure 12. - Concluded.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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