ENGINEERING EXPERIMENT STATION
Georgia Institute of Technology
Atlanta, Georgia

FINAL REPORT

PROJECT NO. A-268

PART ONE AND TWO

TESTING OF BOGUE MOTOR GENERATOR SETS MANUFACTURED BY BOGUE ELECTRIC MANUFACTURING COMPANY UNDER CONTRACT DA-01-076-ENG-1923 EGLIN AIR FORCE BASE, FLORIDA

by

B. J. DASHER AND A. W. STALNAKER

- o - o - o - o -

PREPARED FOR CORPS OF ENGINEERS
U. S. ARMY MOBILE DISTRICT

- o - o - o - o -

MARCH 1, 1956

TABLE OF CONTENTS

PART ONE

PART TWO

LIST OF TABLES

LIST OF FIGURES

PART ONE

I. OBJECTIVE

The objective of these tests was to determine the rms harmonic content of the output of a 400-cycle generator and the rms ripple in the output of a dc generator.

II. BACKGROUND

The machines tested were supplied as representative of a group of motor-generator sets manufactured by the Bogue Electric Manufacturing Company for use by the Air Force Armament Center, Eglin Air Force Base, Florida. The characteristics of these machines are in controversy with respect to the harmonic and ripple content.

III. EXPERIMENTAL PROCEDURE

A. 400-Cycle Generator

This machine, set No. 172,617, is rated 12.5 kw at 0.8 power factor. Measurements were made at full rated load 0.8 power factor lagging; at 12.5 kw output, unity power factor; at 10.0 kw output, unity power factor; and at no load. In each case rated output voltage was maintained and the load was a balanced three-phase load. Lagging power factor was obtained by connecting low-power-factor inductors in parallel with resistance grids. The instruments used for measuring power output, voltage, and current were General Electric type P3 portable instruments which have an accuracy of 0.2 per cent of full scale. Harmonics were measured with a General Radio type 736A wave analyser. The wave analyser was calibrated by comparison with a General

Electric voltmeter. A schematic circuit diagram showing the connections used is shown in Figure 1.

Errors which might be introduced by the current transformers were estimated to be less than 0.5 per cent. The calibration of the wave analyser was estimated to be correct to within one per cent except where readings were made at less than half-scale deflection. In this region this instrument read low by as much as 2.5 per cent. However, since these low-scale readings contribute relatively little to the rms voltage, the over-all results are probably correct to within 2.0 per cent.

The first data were taken at full load, 0.8 power factor after a warm-up period of a little more than two hours. There was no observable change in the performance during this warm-up period. The first run required approximately two hours, and readings obtained at the beginning were repeated at the end to see whether there was evidence of drift. These data agreed quite well and it was concluded that the machine, as well as the laboratory set-up, was very stable with respect to drift caused by heating. (These data were spot-checked again on the following day without any warm-up period, and the agreement was entirely satisfactory.) Each of the three line-to-line voltages was analysed.

The second run was made at unity-power-factor, full load current (75 amperes). Under these conditions it was found that, in addition to harmonics of the 400 -cycle frequency, the output contained numerous other components. Since this was an unexpected result, an investigation was made to determine the source of the spurious components. The field excitation was immediately suspected. Examination by means of an oscilloscope disclosed that the excitation voltage contained a large ac component consisting of harmonics of 400-

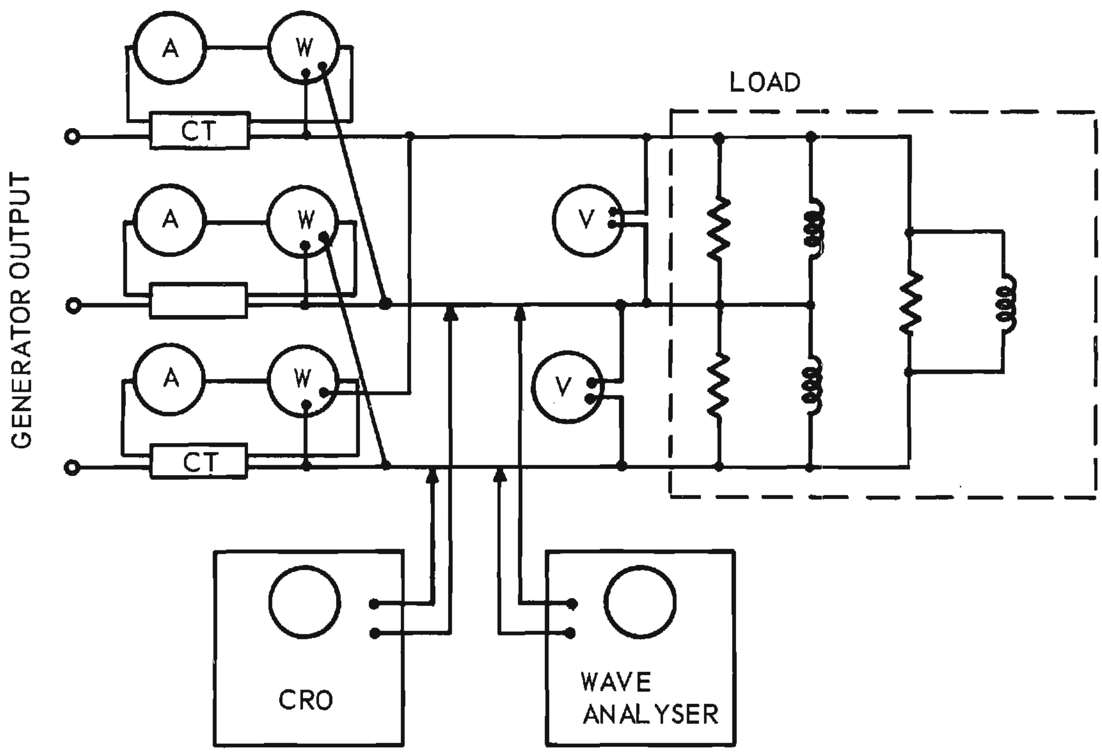


Figure 1. Schematic Diagram of Instrument Connections.

cycles and, in addition, an oscillation at a frequency near 90 cycles. It was decided to make a more complete investigation later. However, the oscilloscope examination afforded a plausible explanation for the spurious frequencies so the harmonic analysis was continued. It was necessary to search very carefully since components were present at intervals of approximately 100 cycles. However, voltages less than 0.05 volts were not recorded since they contribute so little to the total rms voltage. (One component of 0.05 volts magnitude contributes approximately 0.0005 volts to the total rms voltage.)

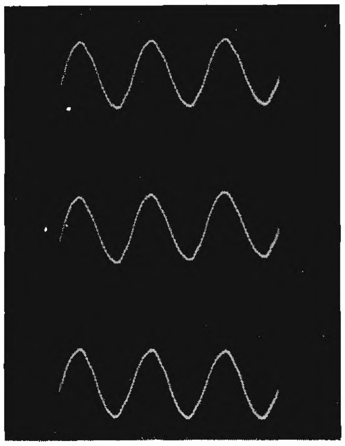
The wave-shapes of each phase voltage were observed during the measurements by means of a cathode-ray oscilloscope. Several photographs of these waves are shown in Figure 2.

A third run was made at no load. In this case the oscillating nature of the field voltage was more noticeable than before and the frequency of the oscillation was unstable. Although it was close to 100 cps it was so variable that photographs of the wave-shape could not be obtained. Frequency components were scattered about, appreciable values being found at intervals of approximately 100 cps. Data were taken on only one phase. Some readings were made with one line connected to the frame of the generator. This connection had no effect on the performance.

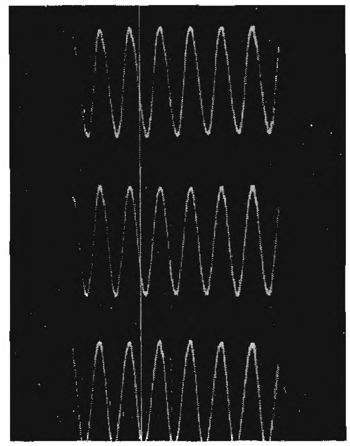
Additional tests were later made at no load and also with separately excited field. These tests are described in Part Two of this report.

B. D. C. Generator

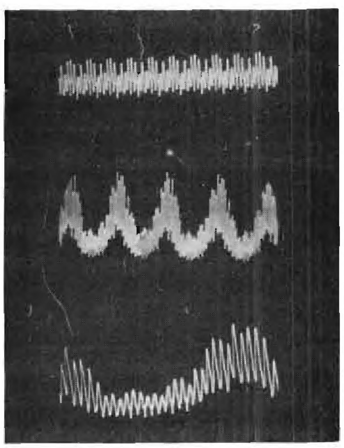
This machine, set No. 172,647, is rated 125 v, 20 kw. The rms commutator ripple was measured at full load and at no load. Because of the fluctuating nature of the ripple it was not possible to make a harmonic analysis. Instead,



(a) Output voltage waveforms at full load, 0.8 power factor. Top-to-bottom: phase 3–1, phase 1–2, phase 2–3.



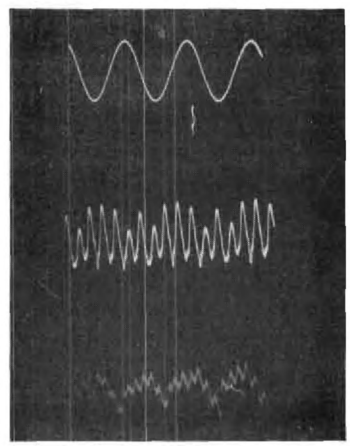
(b) Output voltage wave forms at full load, unity power factor. Top-to-bottom: phase 3–1, phase 1–2, phase 2–3. The fact that successive cycles are different is evidence that the distortion includes frequencies other than harmonics of 400 cycles.



(c) Top: Field excitation voltage with output voltage set to 105 volts. Full load unity power factor.

Center: Field excitation voltage at rated voltage, full load unity power factor.

Bottom: Same as center, expanded scale.



(d) Top: Output voltage wave with separately excited field. Full load, 0.8 power factor. Compare with 2(a).

Center: Field excitation voltage at full load, 0.8 power factor. Note absence of hunting.

Bottom: Wave form of the ripple voltage of the dc generator. The principal frequencies are harmonics of 60 cycles. This short exposure shows the general nature of the ripple but the pattern is actually not stationary.

Figure 2. Voltage Wave-forms.

the ripple was measured by means of a thermocouple voltmeter. This consisted of a large capacitor (approximately 1,4000 μfd) in series with a resistance and a sensitive thermocouple. (See Figure 3.) This arrangement was calibrated by comparison with a dc voltmeter.

IV. RESULTS AND CONCLUSIONS

The results obtained under the various conditions are tabulated in Table I for the 400-cycle generator. For the dc machine the rms voltages measured 0.82 volts at no load and 0.48 volts at full load. These correspond to 0.66 per cent and 0.38 per cent respectively. The relative error in the computed percentage value was estimated to be less than 2 per cent.

The ripple content in the output of the dc generator is well under the prescribed limit of 2.5 per cent.

The rms harmonic content in the output of the 400-cycle machine is barely within the prescribed limit of 2.5 per cent except at no load. At no load the harmonic content is greater than 3 per cent. (Additional measurements were made at no load several days later and showed even larger percentages. See Part Two of this report.)

From the nature of these results it appeared that the field excitation voltage was the main source of the harmonics. In order to check this possibility tests were made using a separate dc source for this field. These tests are described in Part Two.

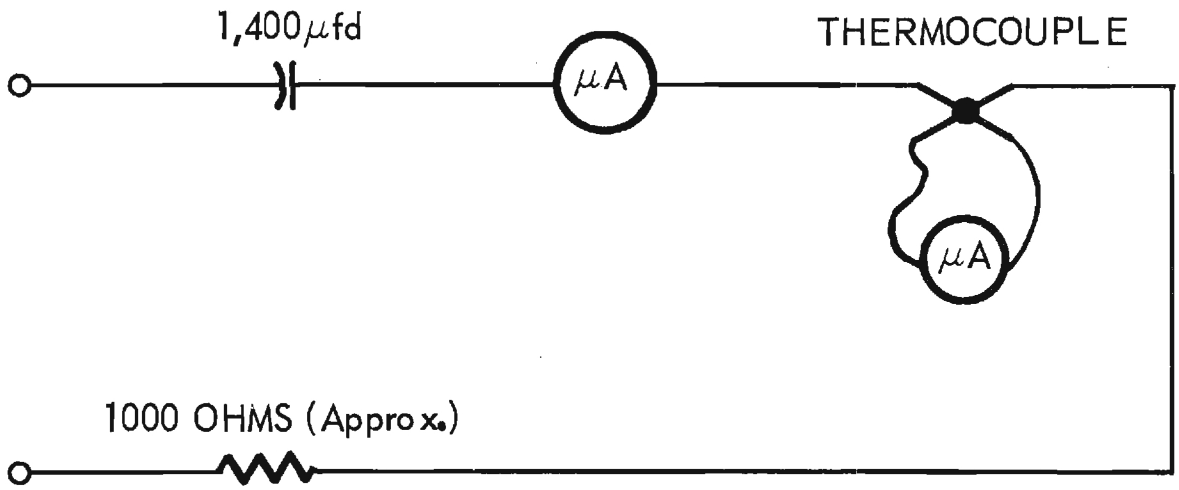


Figure 3. Thermocouple Voltmeter Circuit.

TABLE I

SUMMARY OF MEASURED RMS HARMONIC VOLTAGES

Load Condition	Measured rms Harmonic Voltage	Harmonic Voltage (%)
1. 120 v, 75 a, 0.8 pf lag		
Phase 2-3	2.93	2.44
Phase 1-2	2.72	2.27
Phase 3-1	2.91	2.42
2. 120 v, 75 a, 1.0 pf		
Phase 2-3	2.93	2.44
Phase 1-2	2.81	2.34
Phase 3-1	2.87	2.39
3. 120 v, no load		
Phase 2-3	3.71	3.09
4.† 120 v, 60 a, 1.0 pf		
Phase 2-3	3.02	2.51
5.† 120 v, no load		
Phase 2-3	4.05	3.37
Phase 1-2	4.85	4.04
Phase 3-1	3.65	3.04

† See Part Two for details.

Measured rms harmonic voltage = $\sqrt{V_2^2 + V_3^2 + \ldots V_n^2}$

in which V_2, V_3, ... V_n are the measured values of the various harmonic voltages.

V. TABULATED DATA

1. Full Load (120 v, 75 a, 0.8 pf lag)

Phase 2-3 Frequency	Phase 2-3 Voltage	Phase 1-2 Frequency	Phase 1-2 Voltage	Phase 3-1 Frequency	Phase 3-1 Voltage
400	120.0	400	119.5	400	119.5
800	0.32	800	0.22	800	0.18
1200	0.15	1200	0.21	1200	0.36
1600	0.33	1600	0.53	1600	0.20
2000	2.50	2000	2.00	2000	2.30
2400	0.11	2400	0.43	2400	0.54
2800	1.25	2800	1.50	2800	1.50
3200	0.33	3200	0.45	3200	0.13
3600	0.26	3600	0.30	3600	0.30
4000	0.28	4000	0.30	4000	0.02
4400	0.48	4400	0.36	4400	0.52
4800	0.04	4800	0.12	4800	0.17
5200	0.09	5200	0.20	5200	0.13
5600	0.06	5600	0.05	5600	0.02
6000	0.11	6000	0.06	6000	0.09
6400	0.04	6400	0.03	6400	0.05
6800	0.05	6800	0.07	6800	0.03
7200	0.03	7200	0.03	7200	0.05
7600	0.09	7600	0.03	7600	0.08
8000	0.02	8000	0.04	8000	0.03

2. Full Load (120 v, 75 a, 1.0 pf)

Phase 2-3 Frequency	Phase 2-3 Voltage	Phase 1-2 Frequency	Phase 1-2 Voltage	Phase 3-1 Frequency	Phase 3-1 Voltage
400	120.0	400	120.0	400	120.0
485	1.42	485	1.40	485	1.42
				560	0.37
570	0.32	570	0.35		
		640	0.11		
		720	0.10	720	0.09
800	0.35	800	0.11	800	0.10
				880	0.08
		890	0.13		
		960	0.08		
				1120	0.11
		1200	0.19	1200	0.31
				1260	0.16
				1360	0.11
				1430	0.07

Phase 2-3

Frequency	Voltage
1600	0.26
1820	0.47
1900	1.00
2000	1.40
2050	1.05
2150	0.47
2250	0.18
2400	0.11
2450	0.08
2600	0.37
2700	0.60
2800	0.50
2900	0.70
2950	0.40
3200	0.12
3300	0.12
3600	0.11
3950	0.09
4000	0.08
4100	0.15
4200	0.27
4300	0.25
4450	0.23

Phase 1-2

Frequency	Voltage
1450	0.13
1550	0.16
1600	0.50
1750	0.12
1850	0.32
1900	0.79
2000	1.15
2050	0.95
2100	0.38
2200	0.11
2300	0.24
2400	0.31
2450	0.18
2550	0.13
2600	0.43
2700	0.70
2800	0.57
2900	0.80
2950	0.35
3050	0.13
3100	0.18
3200	0.17
3300	0.20
3600	0.11
3750	0.15
3800	0.11
4000	0.09
4100	0.11
4200	0.15
4300	0.18
4400	0.09
4450	0.22

Phase 3-1

Frequency	Voltage
1520	0.08
1600	0.34
1680	0.14
1760	0.16
1820	0.39
1900	0.92
2000	1.10
2050	1.00
2100	0.37
2200	0.20
2300	0.21
2400	0.23
2450	0.13
2550	0.40
2600	0.43
2700	0.69
2800	0.57
2900	0.78
2950	0.42
3050	0.16
3100	0.11
3200	0.07
3250	0.08
3350	0.15
3450	0.13
3500	0.09
3600	0.14
3700	0.15
3800	0.10
4000	0.13
4050	0.13
4100	0.15
4200	0.15
4300	0.19
4400	0.06
4450	0.15

Phase 2-3		Phase 1-2		Phase 3-1	
Frequency	Voltage	Frequency	Voltage	Frequency	Voltage
4550	0.17			4550	0.15
4600	0.14			4600	0.17
4700	0.10			4700	0.07
				4800	0.08
				4900	0.14
4950	0.08				
				5000	0.12
		5050	0.12		
		negligible to 8000		5100	0.10
				5200	0.11
5300	0.10			5300	0.07
negligible to 8000				negligible to 8000	

3. No Load.

Phase 2-3

Frequency	Voltage
400	120
500	1.40
595	0.20
710	0.10
800	0.40
900	0.11
1200	0.07
1600	0.14
1700	0.17
1800	0.50
1900	1.20
2000	1.75
2100	1.50
2200	0.45
2300	0.13
2400	0.19
2500	0.08
2550	0.31
2600	0.55
2700	0.31
2800	0.94
2900	1.10
2950	0.50
3050	0.15
3100	0.19

Frequency	Voltage
3250	0.19
3400	0.14
3650	0.08
4000	0.15
4050	0.20
4100	0.33
4200	0.45
4300	0.57
4450	0.63
4550	0.42
4650	0.23
4800	0.12
4900	0.18
5000	0.16
5100	0.17
5200	0.16
5300	0.22
5400	0.15
5450	0.10
6700	0.17
6850	0.20
7600	0.14
8000	0.07

PART TWO

I. OBJECTIVE

The objective of these tests was to determine the rms harmonic content of the output of a 400-cycle generator with separately excited field.

II. BACKGROUND

The tests described in Part One of this report indicated that the harmonics and distortion in the output of the 400-cycle generator were caused largely by the distortion present in the field excitation voltage. It was desired to check this assumption by measuring the distortion when the field excitation was obtained from a separate dc source free of distortion.

III. EXPERIMENTAL PROCEDURE

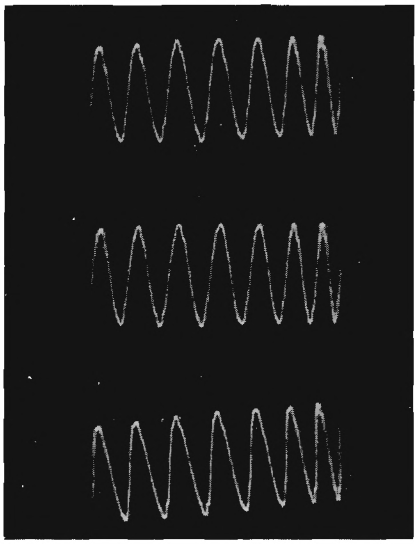
The procedure in this case was the same as in Part One except for the method of obtaining the field excitation. This was obtained from the laboratory dc supply. The internal regulated supply was connected to a dummy load so that it was unnecessary to disable the voltage-regulating circuit. The current in the dummy load could be controlled by means of the output voltage adjustment.

In addition to the tests with separately excited fields, data were taken with a unity power factor load of 60 a. Several days later it was considered advisable to make additional tests at no load, since the previous no load measurements were made on only one phase. In the second test the hunting of the voltage regulator was sufficiently stable so that it was possible to photograph the wave shape.

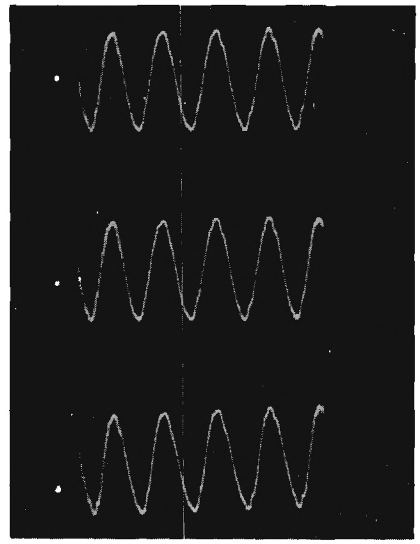
IV. RESULTS AND CONCLUSIONS

The results obtained in these tests are summarized in Table II. These data apparently confirm the assumption that the excessive distortion is caused by the distorted voltage used for field supply. A harmonic analysis of the field voltage (at full load, 0.8 pf lag) is given in section V under tabulated data, and several photographs are shown in Figure 4.

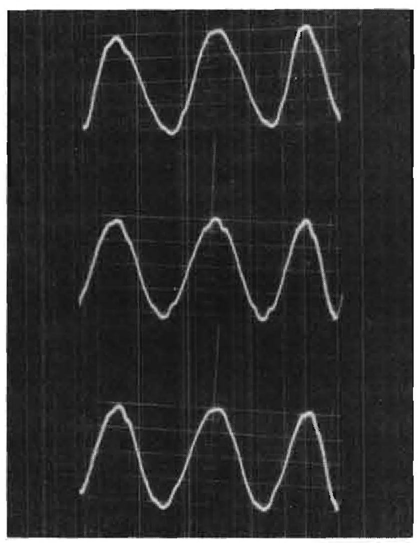
At least three different factors are involved in the relation of field excitation to harmonic output. First, the current required by the rectifier is distorted. This distorted current can introduce harmonics because of the internal impedance of the generator. Second, in spite of the large reactance of the generator field winding, the relatively large harmonic voltages impressed on the winding can result in appreciable harmonics in the exciting current which produce corresponding harmonic voltages in the output. Third, the tendency of the voltage regulator to hunt or oscillate at a frequency near 100 cps produces output frequencies which are not true harmonics. Possible interactions between these factors are so involved that considerable further investigation would be required to determine the basic cause. Filtering of the field voltage would probably help, but this would not be likely to eliminate the hunting, and the hunting is responsible for a substantial part of the difficulty. On the other hand there is little doubt that the regulator-field-supply as a whole is responsible. When separately excited, the generator produces a wave with very little distortion.



(a) Wave-forms at rated voltage, no load. Top-to-bottom: phase 3–1, phase 2–3, phase 1–2. Note variation in waveforms.



(b) Same as figure 4 (a), expanded scale.



(c) Further detail of waveform of phase 1–2. Top-to-bottom: successive frames show successive cycles in the order 1–2–3, 3–4–5, 5–6–7. Note cycle-to-cycle variations.

Figure 4. Wave-forms Showing Details of Distortion.

TABLE II

SUMMARY OF MEASURED RMS HARMONIC VOLTAGES

Load Condition	Measured rms Harmonic Voltage	Harmonic Voltage (%)
1. Separately excited field 120 v, 75 a, 0.8 pf lag Phase 2-3	0.37	0.26
2. Separately excited field 120 v, no load Phase 2-3	0.55	0.46
3. Self-excited field 120 v, 60 a, 1.0 pf Phase 2-3	3.02	2.51
4. Self-excited field 120 v, no load Phase 2-3	4.05	3.37
Phase 1-2	4.85	4.04
Phase 3-1	3.65	3.04

V. TABULATED DATA

1. Separately excited field, 120 v, 75 a, 0.8 pf lag

Phase 2-3

Frequency	Voltage
400	121.00
800	0.24
1200	0.05
1600	0.11
2000	0.14
2800	0.19
4400	0.06
5200	0.06

Negligible voltages at other harmonic frequencies.

2. Separately excited field, 120 v, no load

Frequency	Voltage
400	120.00
800	0.06
1200	0.04
2000	0.32
2800	0.30
4400	0.22
5200	0.21
6800	0.12

Negligible voltages at other harmonic frequencies.

3. Self-excited field, 120 v, 60 a, 1.0 pf

Phase 2-3

Frequency	Voltage
400	120.00
500	1.3
590	0.22
800	0.37
900	0.08
1200	0.14
1600	0.25
1700	0.18
1720	0.18
1800	0.41
1900	1.00

Frequency	Voltage
2000	1.50
2100	1.20
2200	0.30
2300	0.11
2400	0.12
2500	0.20
2600	0.38
2700	0.68
2800	0.65
2900	0.73
3000	0.34
3050	0.14
3100	0.10
3200	0.12
3650	0.10
4000	0.09
4150	0.27
4300	0.30
4450	0.32
4550	0.23

4. Self-Excited field, 120 v, no load

Phase 2-3		Phase 1-2		Phase 3-1	
Frequency	Voltage	Frequency	Voltage	Frequency	Voltage
				175	0.12
180	0.12				
		190	0.11		
300	0.10			300	0.11
400	120.00	400	120.00	400	120.00
500	1.2	500	1.40	500	1.20
600	0.15	595	0.16	600	0.13
800	0.50	800	0.11	800	0.27
1100	0.11	1100	0.31	1100	0.13
1200	0.40	1200	0.85	1200	0.18
1300	0.20	1300	0.37		
1400	0.15	1400	0.12		
1500	0.13	1500	0.11	1500	0.19
1600	0.30	1600	0.34	1600	0.55
1700	0.20	1700	0.17	1700	0.30
1800	0.38			1800	0.15
1900	1.20	1900	1.25	1900	0.90
2000	2.10	2000	2.10	2000	1.60
2100	1.45	2100	1.60	2100	0.98
2200	0.29	2200	0.40	2200	0.22

Phase 2-3		Phase 1-2		Phase 3-1	
Frequency	Voltage	Frequency	Voltage	Frequency	Voltage
		2300	0.34	2300	0.26
		2400	0.54	2400	0.41
2500	0.33	2500	0.48	2500	0.70
2600	0.34	2600	0.64	2600	0.38
2700	0.88	2700	1.40	2700	1.20
2800	1.20	2800	1.60	2800	1.50
2900	1.00	2900	1.50	2900	1.30
3000	0.40			3000	0.24
3100	0.14	3100	0.24	3100	0.36
3200	0.21	3200	0.30	3200	0.42
3300	0.28	3300	0.26	3300	0.42
3400	0.24	3400	0.42	3400	0.16
3500	0.24	3500	0.63	3500	0.30
3600	0.14	3600	0.34	3600	0.14
3700	0.42	3700	0.66	3700	0.10
3800	0.42	3800	0.43	3800	0.24
3900	0.18	3900	0.20	3900	0.41
4000	0.22	4000	0.16	4000	0.21
4100	0.43	4100	0.21	4100	0.41
4200	0.32	4200	0.40		
4300	0.72	4300	0.54	4300	0.43
4400	0.17	4400	0.11	4400	0.25
4500	0.65	4500	0.72	4500	0.23
4600	0.30			4600	0.22
4700	0.10			4700	0.14
4800	0.13	4800	0.17		
4900	0.14	4900	0.40	4900	0.15
		5000	0.24	5000	0.11
		5100	0.40	5100	0.31
5200	0.15	5200	0.21	5200	0.15
5300	0.20	5300	0.46	5300	0.33
5400	0.09	5400	0.30	5400	0.36
		5500	0.12	5500	0.20
		5600	0.17	5600	0.11
5700	0.12			5700	0.12
		5800	0.13		
				5900	0.13
6000	0.12	6000	0.28		
6100	0.26	6100	0.31	6100	0.12
		6200	0.20	6200	0.17
		6300	0.12	6300	0.15
		6400	0.10		
		6500	0.10	6500	0.13
		6600	0.12		
6700	0.21	6700	0.10		
6800	0.15	6800	0.14	6800	0.27

Phase 2-3		Phase 1-2		Phase 3-1	
Frequency	Voltage	Frequency	Voltage	Frequency	Voltage
6900	0.20	6900	0.08	6900	0.12
		7000	0.09	7000	0.10
		7100	0.10		
7200	0.13	7200	0.08		
		7300	0.13	7300	0.14
		7400	0.13		
7500	0.17	7500	0.13	7500	0.10
		7600	0.16	7600	0.15
7700	0.10	7700	0.14		
		7800	0.10		
8000	0.05	8000	0.02		

Submitted by:

B. J. Dasher
Project Director

Approved:

J. E. Boyd
Physics Division

Paul K. Calaway
Director, Experiment Station