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ELECTROMAGNETIC PERFORMANCE LIMITS OF A 1200-HERTZ LUNDELL ALTERNATOR FOR A BRAYTON-CYCLE POWER SYSTEM

by Gary Bollenbacher and Heinz L. Wimmer
Lewis Research Center
Cleveland, Ohio

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ABSTRACT

Overload tests were performed on a 10.7-kilowatt 1200-hertz Lundell alternator in order to determine its electromagnetic limitation on output power. The maximum output powers were 26 kilowatts at 0.85 power factor and 44 kilowatts at 1.0 power factor. Extrapolation from data available for lower powers indicates an 88-percent electromagnetic efficiency at 26.6 kilowatts and power factor of 1.0.

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SUMMARY

Overload tests were performed on a 1200-hertz Lundell alternator designed for 10.7 kilowatts. Within the alternator's electromagnetic capabilities, the maximum power outputs were 26 kilowatts at 0.85 power factor and 44 kilowatts at 1.0 power factor. Severe alternator heating required limiting the test duration. Estimates of losses and efficiency, based on experimental data at lower power levels, indicate that efficiencies are 88 percent at 26.6 kilowatts and power factor of 1.0, and 85 percent at 24 kilowatts and power factor of 0.85.

INTRODUCTION

The 1200-hertz Brayton-cycle system (refs. 1 through 6), rated at 10.7 kilowatts and 0.75 power factor, has the potential to produce higher powers with minor modifications. These modifications include changes in operating pressures and temperatures of the turbine and compressor and improvements in alternator cooling. To avoid problems with the gas bearings and rotor dynamics, it is desirable not to change the rotor of the turbine-compressor-alternator unit.

One step to define a feasible rating of an improved system was to experimentally determine the electromagnetic power limits of the alternator. In addition, as an aid to establishing the requirements of a modified cooling system, electromagnetic efficiencies for higher powers were estimated. The estimates are based on extrapolations of experimental data obtained from alternator tests at lower power levels.

APPARATUS AND PROCEDURE

The research alternator (refs. 4, 5, and 6) used for the tests described in this report is identical electromagnetically and thermally to the alternator used with the Brayton-cycle system rotating unit (refs. 2 and 3). It is a Lundell machine having a solid rotor and two stationary field windings for series and shunt excitation. It is rated for 14.3 kilovolt-amperes at 0.75 lagging power factor, 120/208 volts. The design frequency is 1200 hertz with a rotor speed of 36,000 rpm.

The alternator was connected to a turbine as shown in figure 1. An analog speed controller regulated turbine speed by adjusting a throttle valve at the turbine inlet. The two field windings of the alternator were connected in series, with field excitation being provided by a manually adjusted dc power supply.

Since the alternator cooling system had been designed for power levels near the 14.3 kVA rating, the alternator could not be operated continuously at the power levels necessary for these tests. This cooling limitation required that all load-bank settings be made at one half (60 V) of rated voltage. Field voltage was then rapidly increased and manually regulated until the required data could be recorded. The time required to record all the data was typically less than 30 seconds. After a reading was complete, alternator voltage was returned to 60 volts and the load was removed in order to allow the alternator to cool to near normal operating temperatures before taking the next set of data.

During the interval in which the alternator operated at high power levels, temperatures were closely observed. Temperatures rose very rapidly, and the end turns at times exceeded 500° F (260° C), which was the maximum temperature that could be measured with the available instrumentation. Because the alternator operated at high loads for only short times, alternator temperatures could not stabilize. To the extent that field excitation is a function of temperature, the values of field excitation reported here are only approximate. To assess the effect of temperature on field excitation, several data points were obtained with the alternator at ambient temperature prior to the application of load and field excitation. For these data points the temperature did not rise as high as it did for all other points, which were taken with the alternator already heated up.

RESULTS AND DISCUSSION

Alternator Electromagnetic Performance Limits

Load saturation curves. - Load saturation curves were obtained for 0.85 (lagging), 0.90 (lagging), and 1.0 power factors. These curves are shown in figures 2 through 4. Figures 2 and 3 show several points which were obtained with the machine initially at ambient temperature, as discussed previously. These points provide some measure of the effect of temperature on the saturation curves. The shaded band indicated on these curves is approximate but it serves to emphasize the temperature dependence. The highest current level for which a saturation curve was obtained is 120 amperes at 1.0 power factor. At that current level the ability of the alternator to generate 120 volts was marginal.

Alternator power characteristics. - The alternator's power characteristics, which are curves of output power against field excitation, are shown in figure 5. These curves clearly define the maximum powers that the alternator can produce and the corresponding values of required field excitation. The results are summarized in the following table.

Power Factor (Lagging)	1.0	0.9	0.85
Maximum Output Power, kW	44	30	26
Required Field Excitation, A-Turn	10,500	8100	7500

The values of field excitation required for maximum output power are much higher than the 2500 ampere-turns needed at design conditions of 10.7 kilowatts and 0.75 (lagging) power factor.

Short-circuit curve. - A short-circuit curve for the alternator was obtained in order to determine if, for an upgraded system, the short-circuit current would be sufficient for fault descrimination and for operation of protective devices. The data presented in figure 6 demonstrates that a short-circuit current of 177 amperes can be produced with a field excitation of 11,400 ampere-turns.

The table below gives the short-circuit current in per-unit for several hypothetical power levels at which the alternator might be rated.

Hypothetical Alternator Rating, kW at 1.0 Power Factor	Short-Circuit Current, Per-Unit (Approximate)
20	3.0
25	2.5
30	2.0
35	1.8

It should be possible to design a protection system for an alternator capable of producing a 2.0 per-unit short-circuit current. With this criterion it is permissible to rate the alternator at 30 kilowatts and 1.0 power factor.

Losses and Efficiency

Alternator losses and alternator electromagnetic efficiency were estimated to assess the cooling requirement for an upgraded version of this alternator. The estimate is based on experimental data presented in this report and given in reference 5. Extrapolations and assumptions were made when necessary.

Efficiency was calculated by using the equation

$$\eta = \frac{100\ W}{W + L_T}$$

where η = alternator electromagnetic efficiency, percent
W = alternator power output, W
L_T = alternator electromagnetic losses, W

The loss L_T is given by

$$L_T = L_C + L_S + L_A + L_F$$

where L_C = open-circuit core loss, W
L_S = stray-load loss, W
L_A = armature copper loss, W
L_F = field copper loss, W

Each of these losses will now be discussed.

<u>Open-circuit core loss</u>. - The open-circuit core loss, as reported in reference 5, was 340 watts. Although the open-circuit core loss will increase due to lower alternator temperatures resulting from an improved cooling system, this increase will be neglected.

<u>Stray-load loss</u>. - The measured stray-load loss reported in reference 5, which is a function of armature current only, is plotted in figure 7 in log-log format. The data points fall essentially on a straight line. Thus linear extrapolation in a log-log plot was used to predict stray-load losses for up to 100 amperes of line current. Temperature effects on stray-load loss are ignored.

Armature copper loss. - Unreported data show that the armature resistance at 25° C is 0.0307 ohm. This resistance was adjusted for temperature change by using the temperatures shown in figure 8. These temperatures for power factors of 0.85 and 1.0 were assumed solely for the purpose of estimating alternator efficiency. The armature loss was then calculated by using the adjusted resistance value.

Field copper loss. - Field losses were calculated analogously to the armature loss. Unreported experimental data give the field resistance of the two field windings connected in series as 4.882 ohms at 25° C. This value was adjusted to the field temperatures assumed in figure 8. Field copper loss was calculated by using the adjusted value of field resistance and the values of field current obtained from figure 5.

Total loss and efficiency. - The individual losses, not including bearing and windage losses, and the total electromagnetic loss are tabulated in table I; the total electromagnetic loss is also plotted in figure 9.

As can be as can be seen from figure 9, the demands on a modified cooling system will be severe. At a 25-kilowatt alternator output, the electromagnetic losses alone are more than three times the losses of the alternator at rated conditions (10.7 kW, 0.75 power factor). To obtain the total alternator loss, bearing and windage losses must also be included; these losses, already significant at the 10.7-kilowatt power level, increase further as system gas pressure is raised in order to achieve the higher powers. The cooling system must be modified to be able to remove these increased losses and may limit the alternator to lower powers than are possible from electromagnetic considerations alone.

Estimated electromagnetic efficiencies, based on the losses shown in figure 9, are given in figure 10. The discontinuity of the efficiency curves results from assuming that the winding temperatures at 1.25 per-unit (13.4 kW) load for the high-power version of the alternator (with a modified cooling system) are lower than for the alternator used to obtain the data in reference 5. Typical efficiencies shown in figure 10 are 88 percent at 2.5 per-unit (26.6 kW) output and 1.0 power factor and 85 percent at 2.25 per-unit (24 kW) output and 0.85 power factor. Overall efficiencies, including effects of bearing and windage loss, will be considerably lower.

CONCLUDING REMARKS

A 10.7-kilowatt 1200-hertz Lundell alternator was tested for short times at power outputs far beyond its rating. The following values of maximum power output and corresponding field excitation were obtained.

Power Factor (Lagging)	1.0	0.9	0.85
Maximum Output Power, kW	44	30	26
Required Field Excitation, A-Turn	10,500	8100	7500

For rated conditions of 10.7 kilowatts and 0.75 power factor, 2500 ampere-turns of field excitation are required.

A short-circuit curve was obtained for currents up to 177 amperes; at that current, the required field excitation is 11,400 ampere-turns.

Alternator losses and efficiency were estimated from losses measured at lower powers. The estimated electromagnetic efficiencies are 85 percent at 24 kilowatts and 0.85 power factor, and 88 percent at 26.6 kilowatts and 1.0 power factor.

While the electromagnetic design of the alternator is adequate for an output in excess of 26 kilowatts, depending on load power factor, it may not be possible to cool the alternator at these loads in view of the high estimated losses.

Lewis Research Center,
National Aeronautics and Space Administration
Cleveland, Ohio, December 1969.

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2. Klann, John L.: 2 to 10 Kilowatt Solar or Radioisotope Brayton Power System. Intersociety Energy Conversion Engineering Conference. Vol. 1. IEEE, 1968, pp. 407-415.

3. Brown, William J.: Brayton-B Power System - A Progress Report. Intersociety Energy Conversion Engineering Confer nce. AIChE, 1969, pp. 652-658.

4. Ingle, B. D.; and Corcoran, C. S.: Development of a 1200-Hertz Alternator and Controls for Space Power Systems. Intersociety Energy Conversion Engineering Conference. Vol. 1. IEEE, 1968, pp. 438-447.

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Alternator Load, Per-Unit[A] (kW)	Open-Circuit Core Loss, W	Stray Load Loss, W	Armature Copper Loss, W	Field Copper Loss, W	Total Loss, W
1.25 (13.4)	340	480	168	29	1,017
1.50 (16.0)	340	715	254	38	1,347
1.75 (18.7)	340	1,020	363	51	1,774
2.00 (21.4)	340	1,380	503	66	2,289
2.25 (24.1)	340	1,830	683	87	2,940
2.50 (26.7)	340	2,300	903	114	3,657
(a) - Power Factor, 1.0					
1.25 (13.4)	340	700	241	53	1,334
1.50 (16.0)	340	1,040	366	74	1.820
1.75 (18.7)	340	1,450	533	104	2,427
2.00 (21.4)	340	2,000	747	157	3,244
2.25 (24.1)	340	2,650	1,019	251	4,260

(b) - Power Factor, 0.85 (Lagging)

[A] 1 per-unit = 10.7 kW

TABLE I

ESTIMATED ALTERNATOR LOSSES

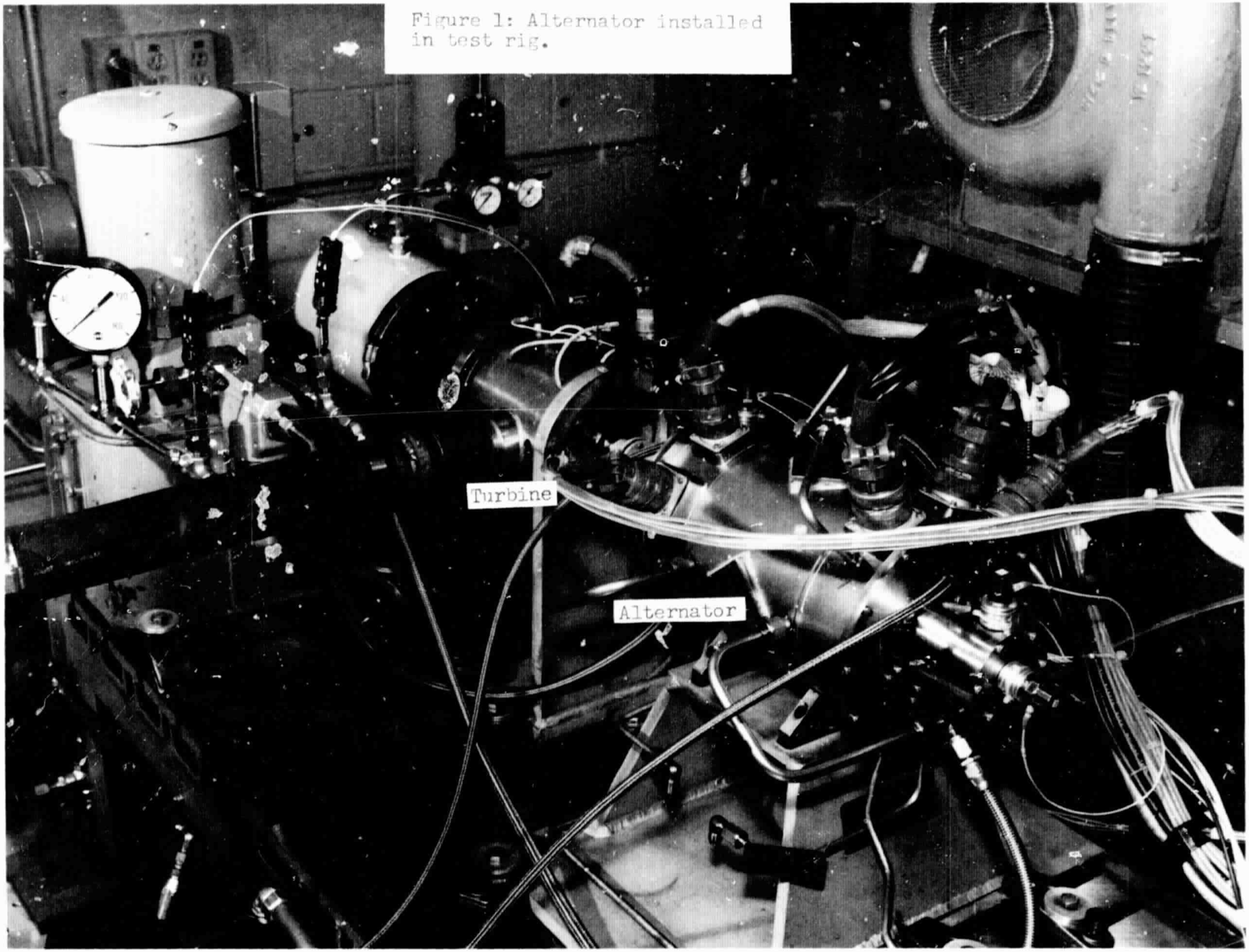

Figure 1: Alternator installed in test rig.

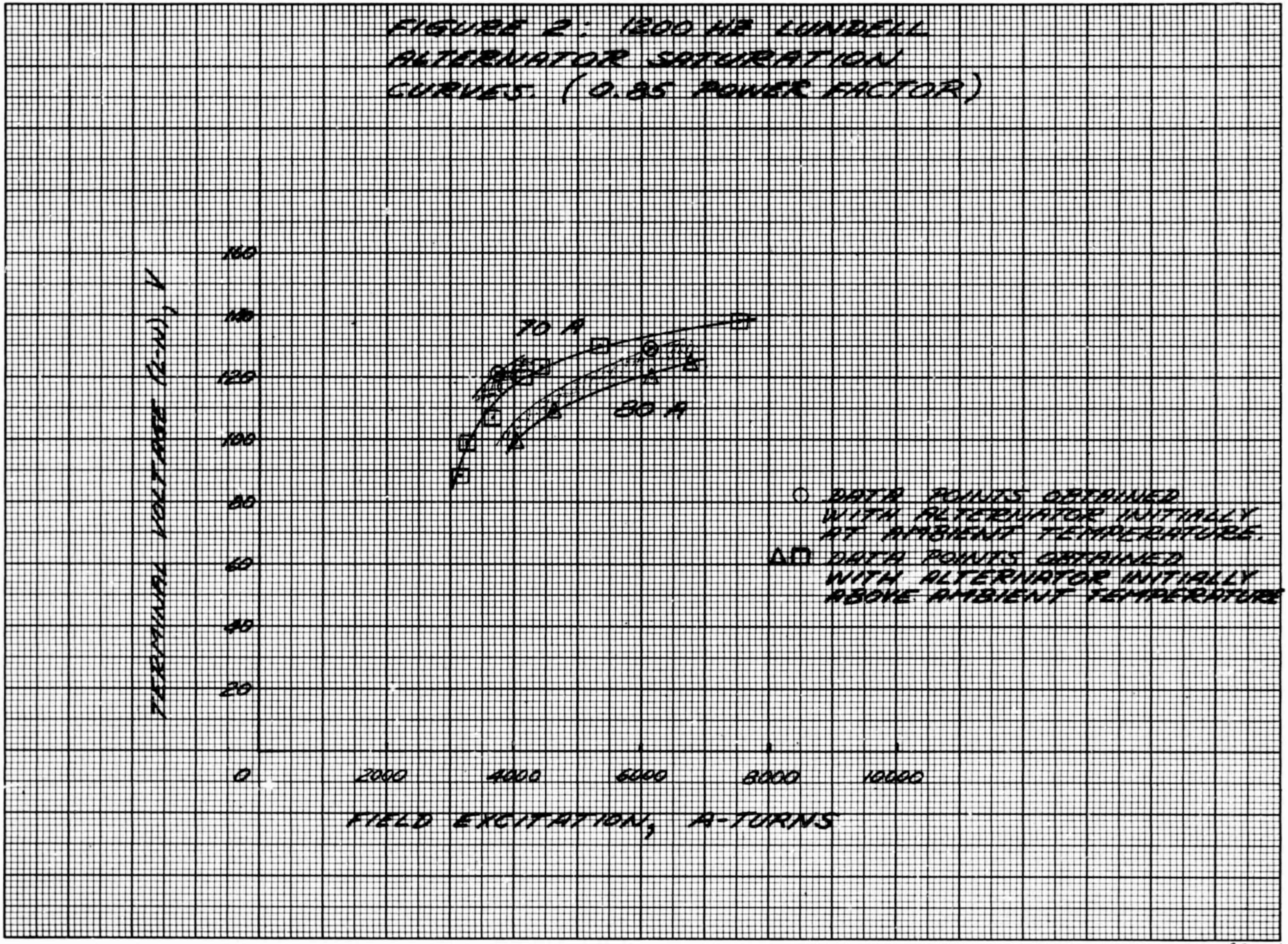

FIGURE 2: 1200 HZ LUNDELL ALTERNATOR SATURATION CURVES. (0.85 POWER FACTOR)
TERMINAL VOLTAGE (L-N), V
160
140
120
100
80
60
40
20
0
2000
4000
6000
8000
10000
FIELD EXCITATION, A-TURNS
70 A
80 A
○ DATA POINTS OBTAINED WITH ALTERNATOR INITIALLY AT AMBIENT TEMPERATURE.
△□ DATA POINTS OBTAINED WITH ALTERNATOR INITIALLY ABOVE AMBIENT TEMPERATURE

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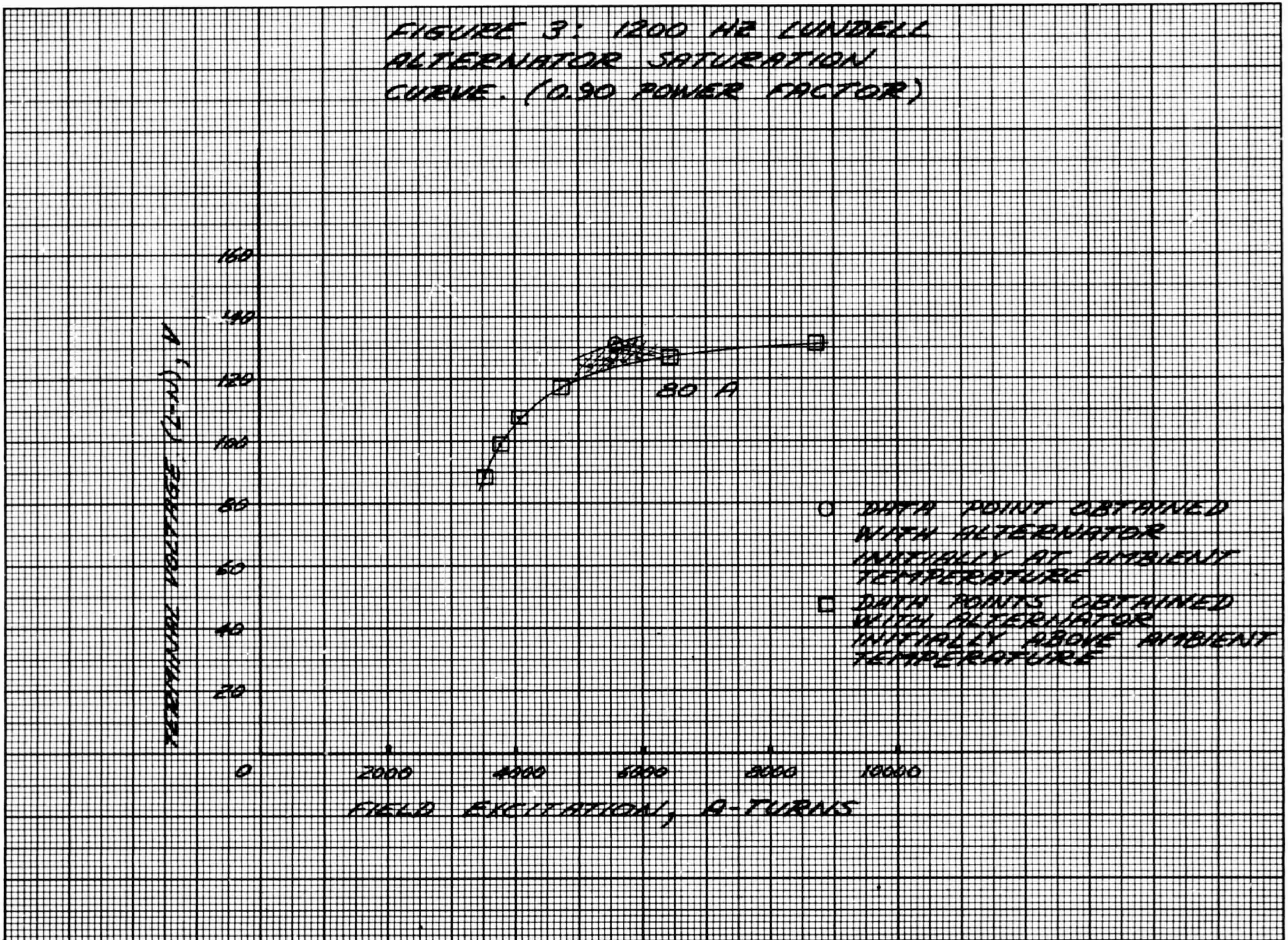
FIGURE 3: 1200 HZ LUNDELL ALTERNATOR SATURATION CURVE. (0.90 POWER FACTOR)
TERMINAL VOLTAGE (L-N), V
160
140
120
100
80
60
40
20
0
2000
4000
6000
8000
10000
FIELD EXCITATION, A-TURNS
80 A
DATA POINT OBTAINED WITH ALTERNATOR INITIALLY AT AMBIENT TEMPERATURE
DATA POINTS OBTAINED WITH ALTERNATOR INITIALLY ABOVE AMBIENT TEMPERATURE

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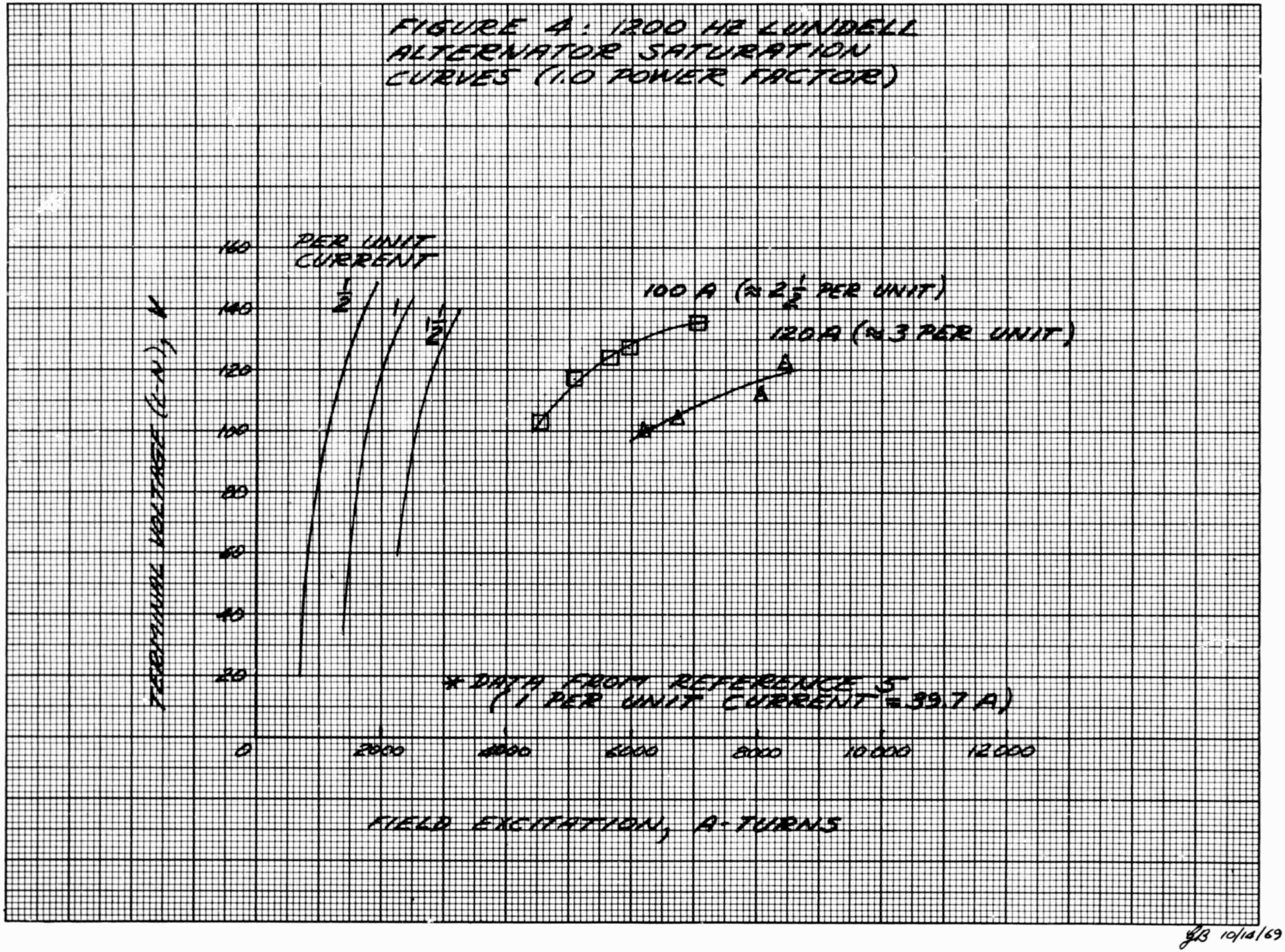
FIGURE 4: 1200 HZ LUNDELL ALTERNATOR SATURATION CURVES (1.0 POWER FACTOR)
PER UNIT CURRENT
1/2
1
1 1/2
100 A (≈ 2 1/2 PER UNIT)
120 A (≈ 3 PER UNIT)
TERMINAL VOLTAGE (L-N), V
160
140
120
100
80
60
40
20
0
2000
4000
6000
8000
10 000
12 000
* DATA FROM REFERENCE 5
(1 PER UNIT CURRENT = 39.7 A)
FIELD EXCITATION, A-TURNS
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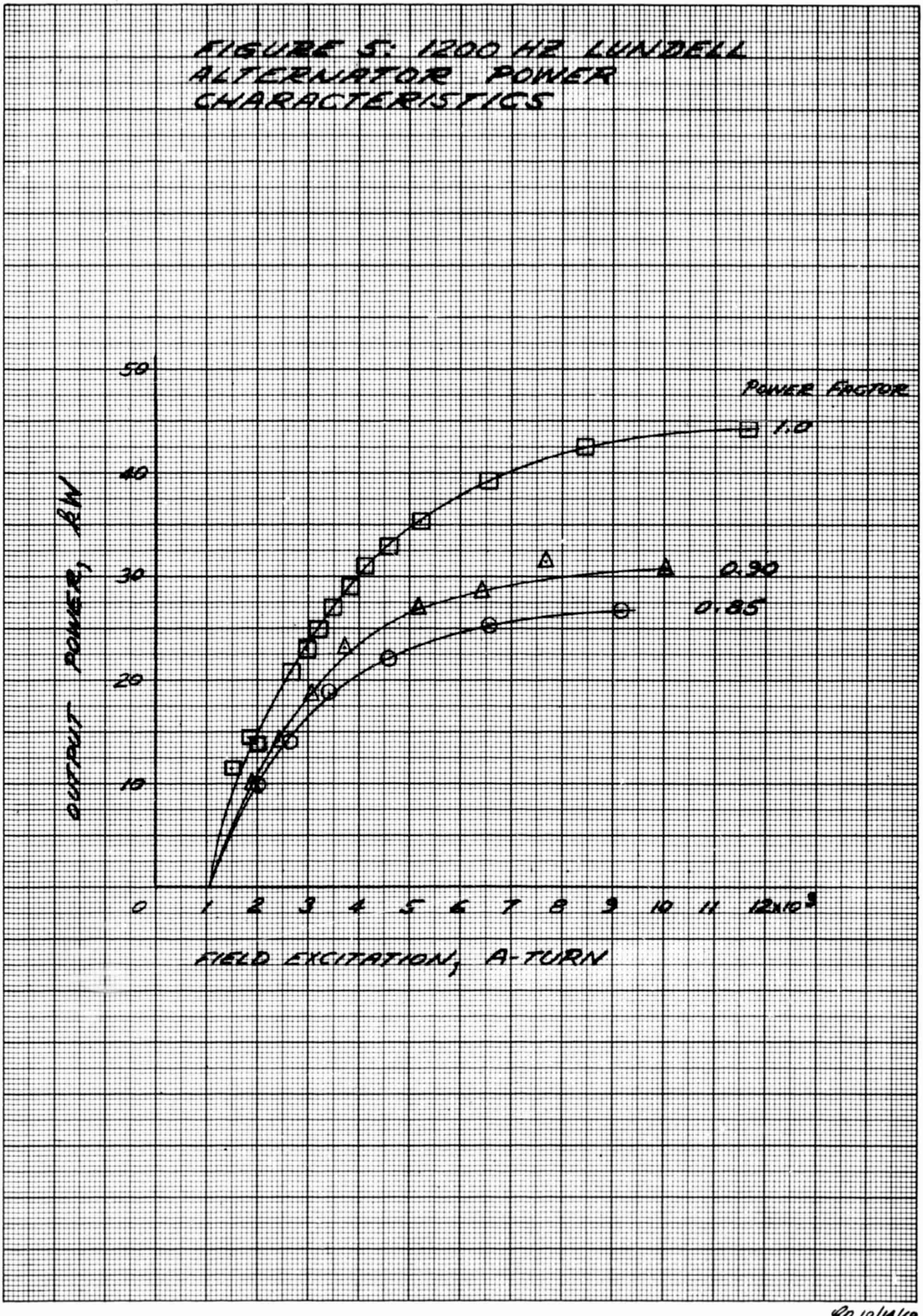
FIGURE 5: 1200 HZ LUNDELL ALTERNATOR POWER CHARACTERISTICS
OUTPUT POWER, KW
FIELD EXCITATION, A-TURN
POWER FACTOR
1.0
0.90
0.85
0
1
2
3
4
5
6
7
8
9
10
11
12x10³
10
20
30
40
50
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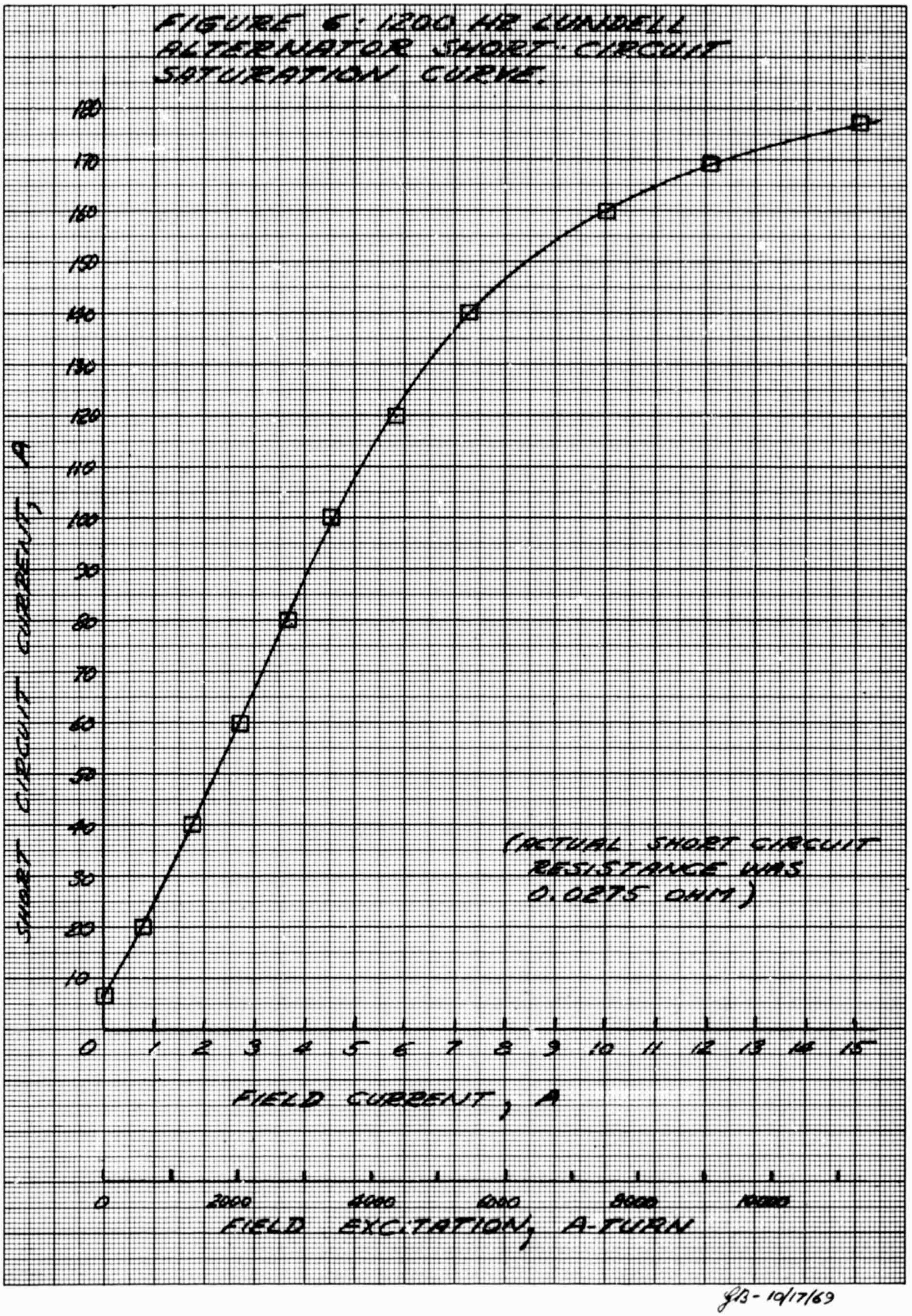

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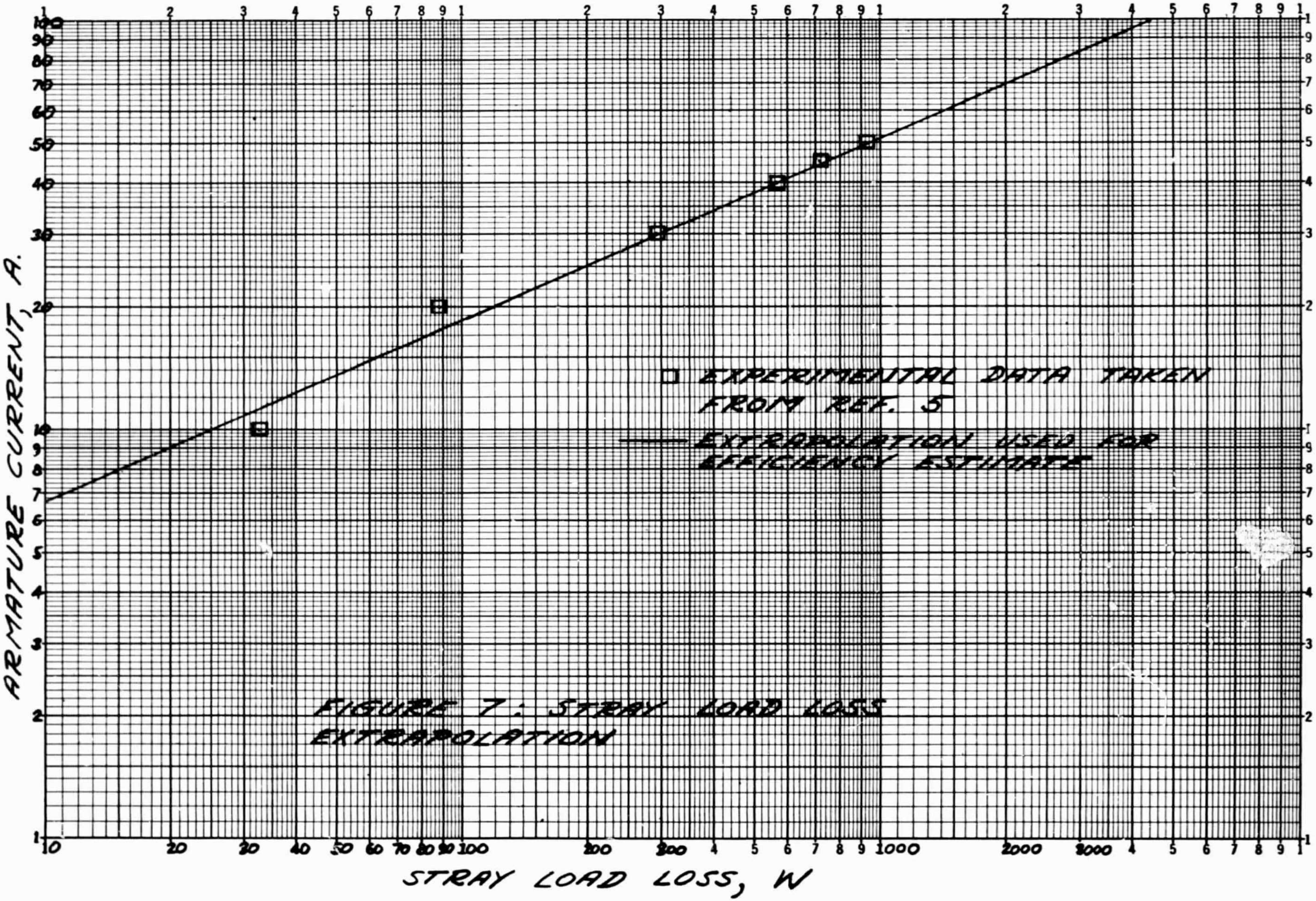

FIGURE 7: STRAY LOAD LOSS EXTRAPOLATION

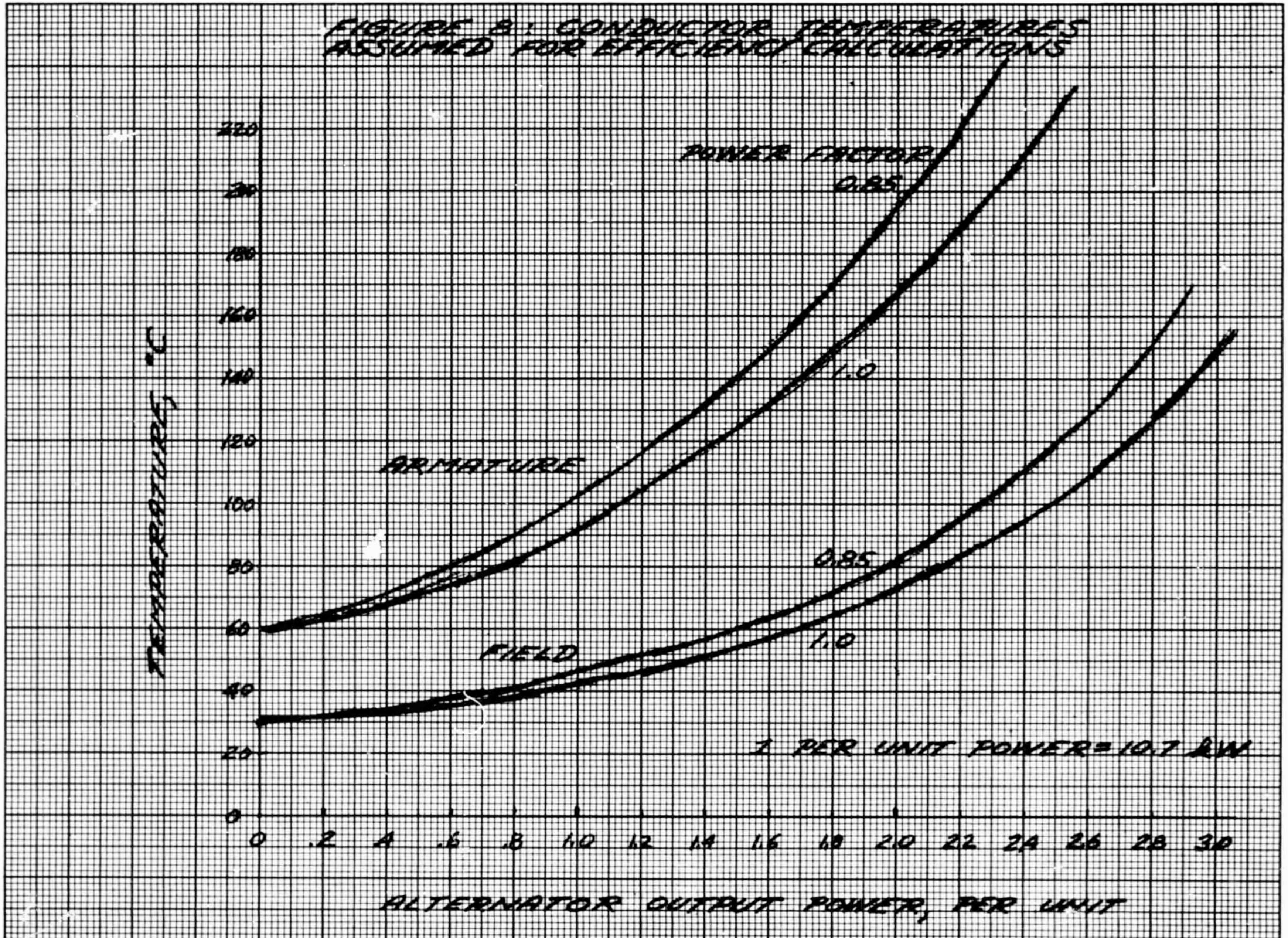
FIGURE 8: CONDUCTOR TEMPERATURES ASSUMED FOR EFFICIENCY CALCULATIONS
POWER FACTOR
0.85
1.0
ARMATURE
FIELD
0.85
1.0
1 PER UNIT POWER = 10.7 kW
TEMPERATURE, °C
ALTERNATOR OUTPUT POWER, PER UNIT
0
20
40
60
80
100
120
140
160
180
200
220
0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
2.8
3.0

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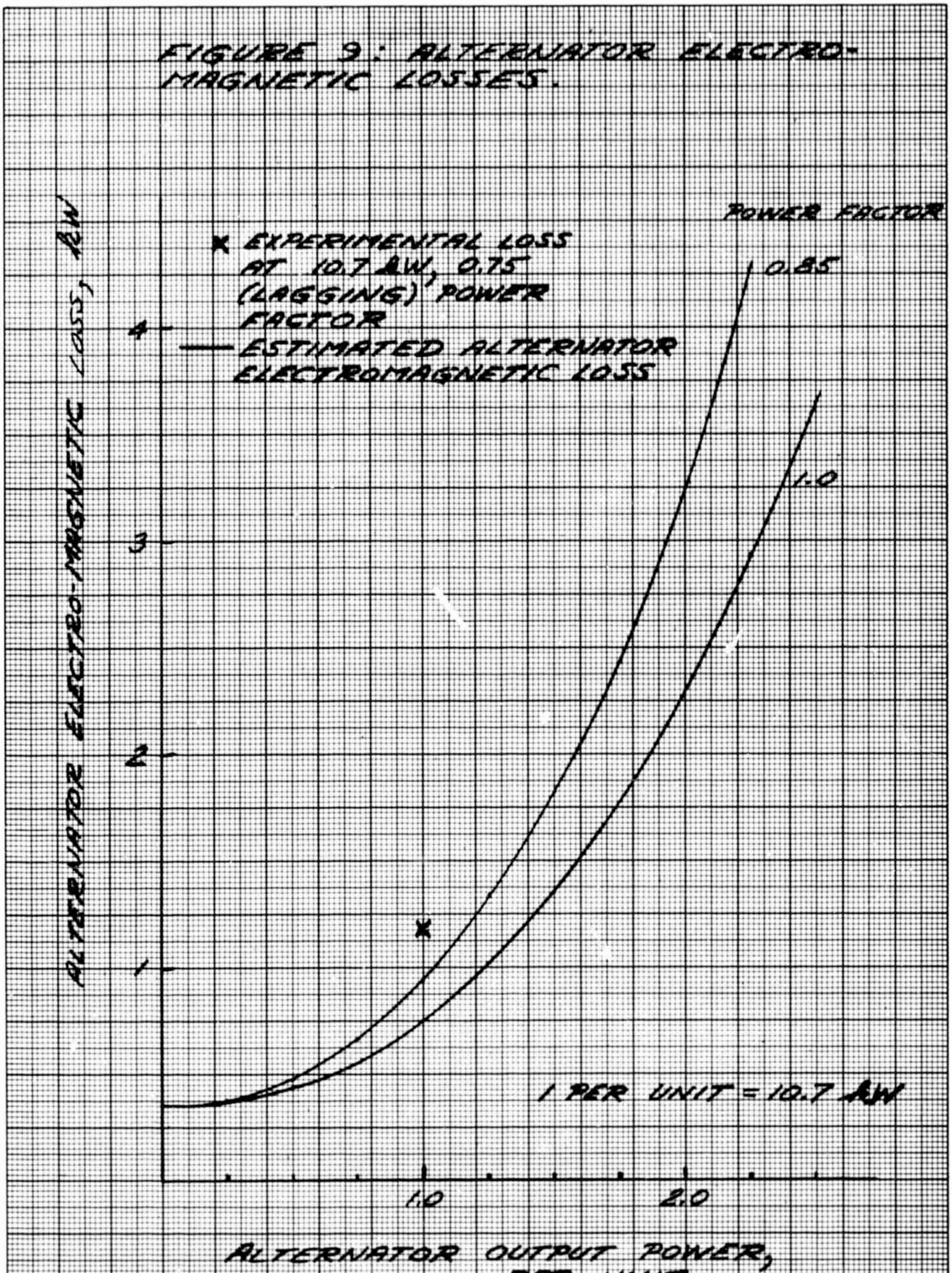

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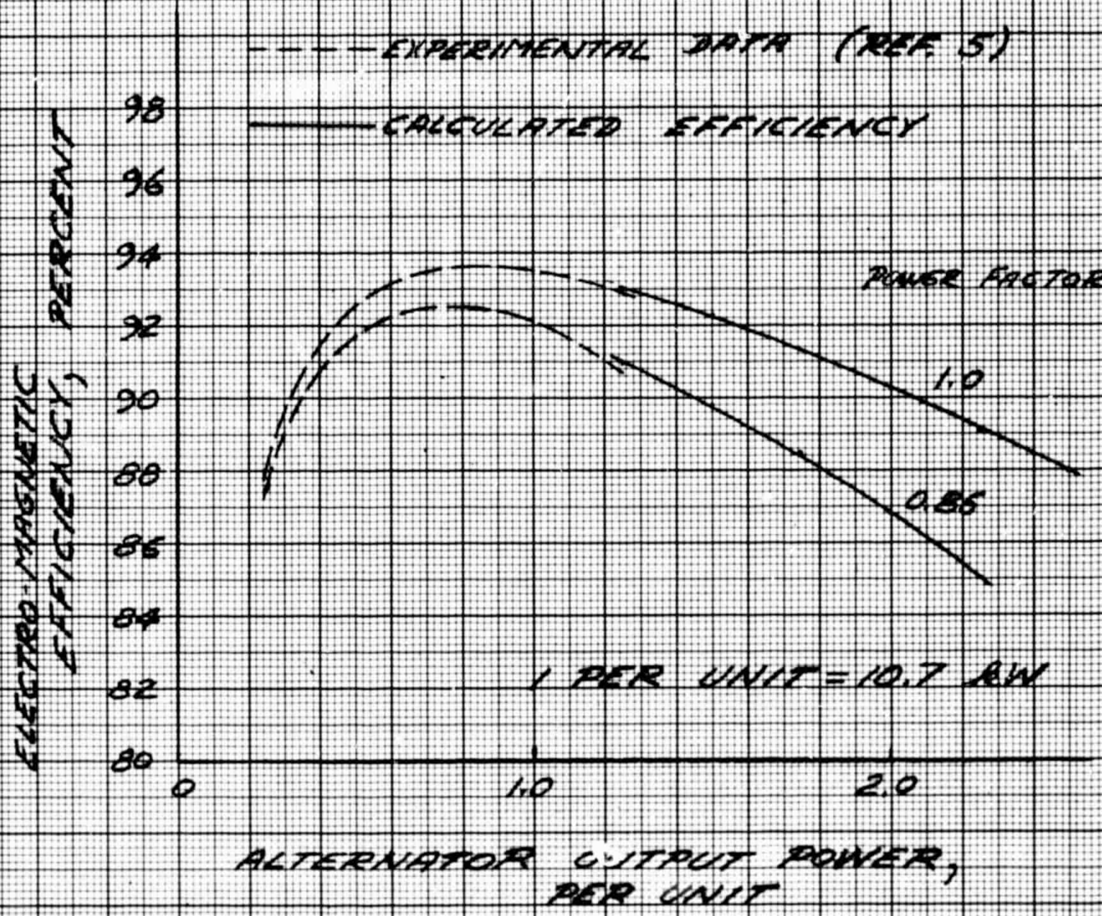
FIGURE 10: ALTERNATOR ELECTRO-MAGNETIC EFFICIENCY



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