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AN ANALYSIS OF A TRANSISTORIZED
AIRCRAFT VOLTAGE REGULATOR

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This work is accepted as fulfilling

the thesis requirements for the degree of

MASTER OF SCIENCE

IN

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from the

United States Naval Postgraduate School

ABSTRACT

Since the advent of power electrical machinery, the problem of improved voltage regulation has always been a dominant factor. Recently, the Bendix Corporation has designed a new aircraft voltage regulator using transistorized components.

This regulator was considered to be a non-linear degenerative feedback unit. Using the well defined procedures of servo analysis, dynamic and frequency response tests were taken of the regulator and the regulator-generator system. These tests were evaluated with a view toward developing a regulator describing function and a system function.

The writers wish to express their appreciation for the assistance and time given them by Doctor George J. Thaler, of the U. S. Naval Postgraduate School in the experimental research of this paper.

PAGE

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Cont'd)

CHAPTER I

THE PROBLEM OF VOLTAGE REGULATION IN AIRCRAFT ELECTRICAL SYSTEMS

Voltage regulation has long been a problem encountered by the systems design engineer. Maintenance of closely regulated voltages has required equipment beyond the generation stage and has necessitated load equipments which could withstand input voltage variations. For many years a serious limit has been placed upon the performance of aircraft electrical systems due to inadequate voltage regulation. With the advent of the modern day high performance aircraft and the equally intricate weapons systems, the need for good regulation has been greatly increased.

The need for voltage regulation is readily apparent with considerations of a generator's performance. Every generator has resistance and reactance in its armature winding. If it is considered that the internally generated voltage is constant, then the terminal or output voltage of the generator is the generated voltage less the voltage drops in the armature resistance and reactance. Hence, the terminal voltage variations depend upon the current supplied by the generator. By varying the internally generated voltage of the generator, the terminal voltage may be adjusted to the desired value. Herein lies the function of the external voltage regulator.

In the past the voltage regulation problems have been met with either carbon pile regulators or circuits employing magnetic elements in the amplifier. However, both these types of regulators have imposed limitations upon the performance of aircraft due to the time delays inherent to these designs. The advances made in recent years in aircraft and airborne equipment have demanded better stability of line voltage and a reduced delay time.

1

There are many particular instances in which the performance of a quick acting regulator with narrow steady state limits can be of value to the design of electrical and electronic equipment. For instance, semiconductor components such as rectifiers, diodes and switching transistors used in a-c circuits, can have a lower peak-inverse-voltage and hence a lower cost if transient overshoots on the primary a-c bus are kept to a low value. In many of these applications the power handling capability of the semiconductor is directly proportional to the PIV; hence, a better transient response would give maximum utilization of the power handling capacity of these components.

Where a regulated d-c supply is required, using semiconductor rectifiers and well designed transformers (with sufficiently good regulation) with close regulation of the primary a-c supply, the need for regulated transformers is eliminated. Where thermal characteristics of components are designed to close limits, close control of the rms value of the a-c supply is essential.

Where the a-c system is used for timing or waveform selection processes as in radars or computers, excessive transient variations can cause intolerable computational errors.

Low frequency amplitude modulation cannot be tolerated in aircraft, for it can appear as an erroneous command for equipment such as an autopilot.

The above examples are pertinent to aircraft, but in general they apply to all installations. Taken as considerations in design of a system, it is evident that both transient and steady-state voltage deviation from the optimum operating point should be as small as possible and that voltage modulation must be avoided.

Ideally, airborne voltages should remain at some predetermined, fixed value at the alternator output. This is not possible. Hence, designs must be compromised in weight or performance or both to tolerate a degree of voltage variation. That is to say, additional equipment must be added to the alternator to limit voltage transients and to maintain the steady-state output constant or nearly so. Most electronic circuits will operate satisfactorily to acceptable limits of accuracy within a reasonable voltage spread; however, one given voltage will give the best performance. In order to achieve satisfactory performance of a particular radar set it has been estimated that 14% of the vacumn tubes and 6% of the weight were used to stabilize a $\pm$ 5% variation in the input voltage. In another radar set it was required to use a 37.5 pound voltage regulator to operate the magnetrons at maximum rating regardless of the line voltage variation due to a transmitted power variation of 22% with a line voltage variation of 12-1/4%. Using equipment voltage regulators which require such large space, weight and heat dissipation provisions, penalizes the weapon system design. To set general limits under which a power system must operate in all circumstances, Military Specifications are established as a criterion for performance. The specifications which apply to a-c aircraft systems require that the a-c system shall be a 3-phase, 4 wire "Y" system having a nominal voltage of 115/200 volts rms and a nominal frequency of 400 cycles per second. The neutral point of the source of power shall be grounded. With a balanced load the steady-state average voltage for the three phases shall be within the limits of 114.0 to 116.0 volts rms. The phase voltage is the voltage from line to neutral. The steady-state voltage for each phase under balanced conditions shall be within the limits of 113.5 to 116.5 volts rms.

Voltage amplitude modulation is the cyclic variation or random dynamic variation about an average value of the a-c peak voltage during steady-state operation such as that caused by voltage regulation or speed regulation. The modulation amplitude shall not exceed an amplitude of 2.0 volts when measured as the peak-to-valley difference between the minimum voltage reached and the maximum voltage reached on the modulation envelope over a period of at least one second.

Transient voltage variations shall be maintained within the limits shown in Fig. 1.

Though these specifications are explicit, they are a compromise to the performance of the regulation devices used in the past and are not a criterion for better performance.

The advances made in the semi-conductor art in recent years led the Red Bank Division of the Bendix Aviation Corporation to begin a development program in 1957 on an all-transistor amplifier for voltage regulation. The inherent short delay time of the transistor in many applications proved to be well adapted to use in a quick acting voltage regulator. In addition, a transistorized regulator was designed to be of minimum size and weight. Bendix successfully completed their design and now is in limited production of several transistor regulators. The regulator, type 20B63, has the following particulars:

> Nominal voltage setting.................115v
>
> Voltage Adjustment Range................105-125v
>
> Regulation Tolerance...................± 2%
>
> Weight (maximum).......................3 pounds

The basic concept for this thesis lay in voltage regulation as a feedback control system. Though this is not a startling proposal, it

4
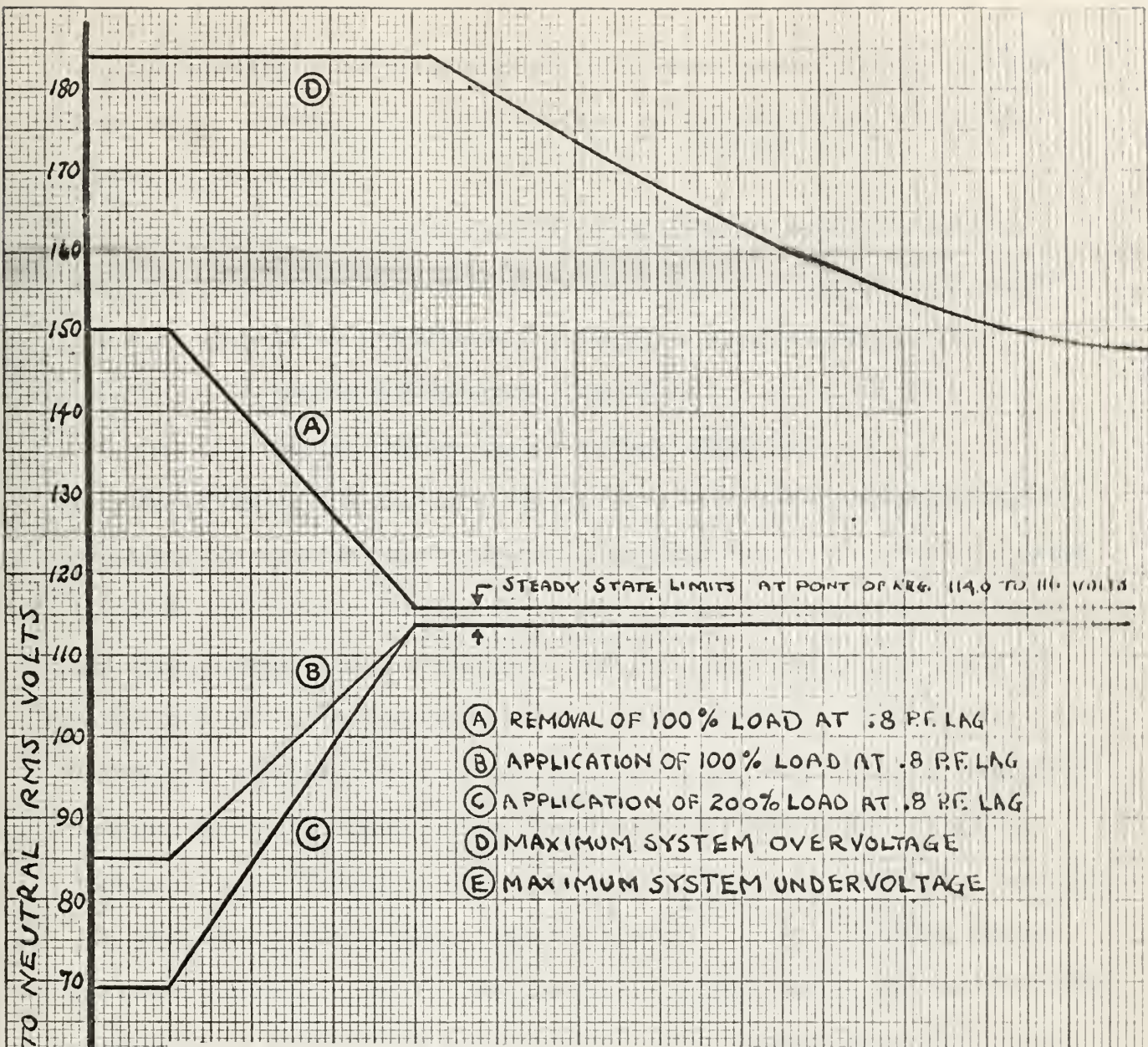
FIGURE 1

TRANSIENT AND STEADY STATE
OVERVOLTAGE AND UNDERVOLTAGE LIMITS

Steady state limits at point of reg. 114.0 to 116 volts

(A) REMOVAL OF 100% LOAD AT .8 P.F. LAG
(B) APPLICATION OF 100% LOAD AT .8 P.F. LAG
(C) APPLICATION OF 200% LOAD AT .8 P.F. LAG
(D) MAXIMUM SYSTEM OVERVOLTAGE
(E) MAXIMUM SYSTEM UNDERVOLTAGE

LINE TO NEUTRAL RMS VOLTS

TIME IN SECONDS

was decided that an investigation of the transistorized voltage regulator
alone and in a compatible system would be an interesting and worthwhile
experimental project.

To investigate a system that is in satisfactory operation and that
employs a late model alternator and a transistorized regulator the follow-
ing components which are matched for operation together were obtained.

Bendix A-C Generator Type 28E20

Bendix Voltage Regulator Type 20B63-1-A

Since the system is a three phase, four wire system, experimental
procedures as well as objectives had to be determined. In order to utilize
the theory of servo-mechanisms and its procedures for handling nonlinear
and approximately linear components, the tests were designed to parallel
those used for the conventional a-c or d-c servo-system. Experimental pro-
cedures as described later in the text, were designed to give the frequency
response of the regulator and to check the time constant with transient
response tests. Through a series of tests a transfer function or a describ-
ing function for the regulator was anticipated. After developing the ap-
proximately linear transfer function for the alternator in the desired opera-
ting range, a mathematical representation of the closed loop system was ob-
tained. From the mathematical approach, prediction of the closed loop re-
sponse of the system was made. Closed loop frequency and dynamic tests
were used to verify all results. Since the regulator contains a complex-
ity of non-linear components as seen in the next chapter, no quantitative,
analytic analysis was deemed feasible. The qualitative analysis of the
regulator provides a complete insight to its operation.

OPERATION OF THE VOLTAGE REGULATOR

A. General Operation.

The primary component of this thesis analysis was a type No. 20 B 63-1-A transistorized aircraft voltage regulator, manufactured by the Bendix Aviation Corporation. Photographs of the inside and outside of the regulator may be seen in Figures (2), (3), (4), (5), (6), and (7). The regulator is light weight and compact, although the internal circuitry is quite intricate. The size of the regulator may be seen by comparison with the ruler in the photographs.

This regulator was designed to service a type 28E20, 20KVA aircraft generator. This generator is a 115/200 Volt, 400 CPS machine.

The principle purpose of the regulator is to sample the three phase generator output and to convert any deviations from the base voltage by changing the voltage across the generator exciter.

Figure (8) shows the circuit diagram and the list of components for the 20B63 regulator. Basically, the three phase, WYE connected voltage enters the primary side of the regulator transformer at terminals F, G, H and D (neutral). A WYE-DELTA voltage transformation takes place. The Delta secondary output is then rectified, partially filtered and goes to the detector circuit. In the detector circuit, the voltage is compared with a pre-set level, so constructed that the detector output signal is inversely proportional to the voltage supply.

The output from the detector circuit is then sent to the first of four cascaded transistors. This transistor amplifies the signal and sends it on to the second transistor which again amplifies the signal and sends

FIGURE 2   EXTERNAL VIEW OF REGULATOR

FIGURE 3   INTERNAL VIEW OF REGULATOR

FIGURE 4   HORIZONTAL SECTION OF REGULATOR
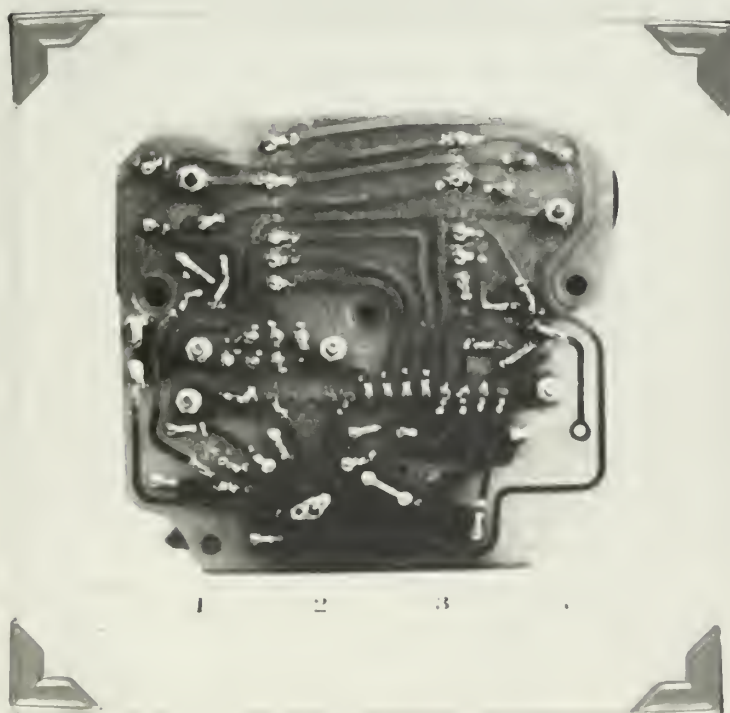
FIGURE 5   HORIZONTAL SECTION OF REGULATOR
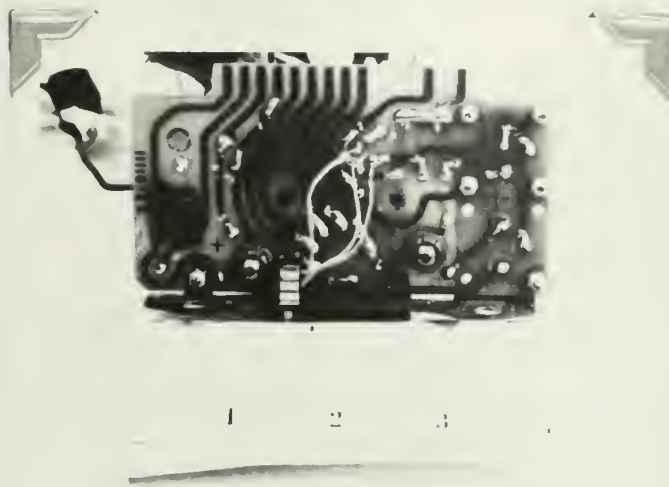
FIGURE 6   VERTICAL SECTION OF REGULATOR
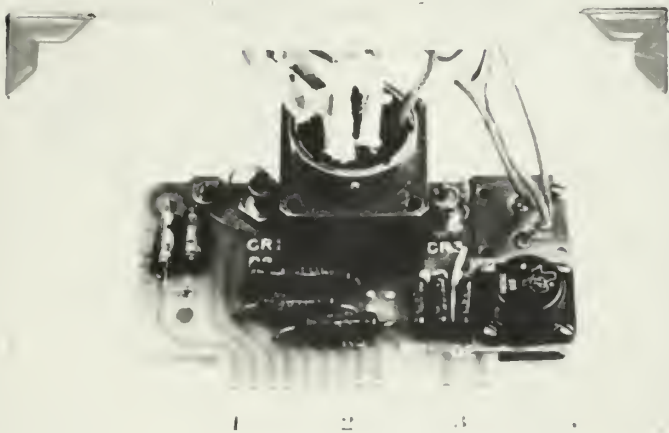
FIGURE 7   VERTICAL SECTION OF REGULATOR
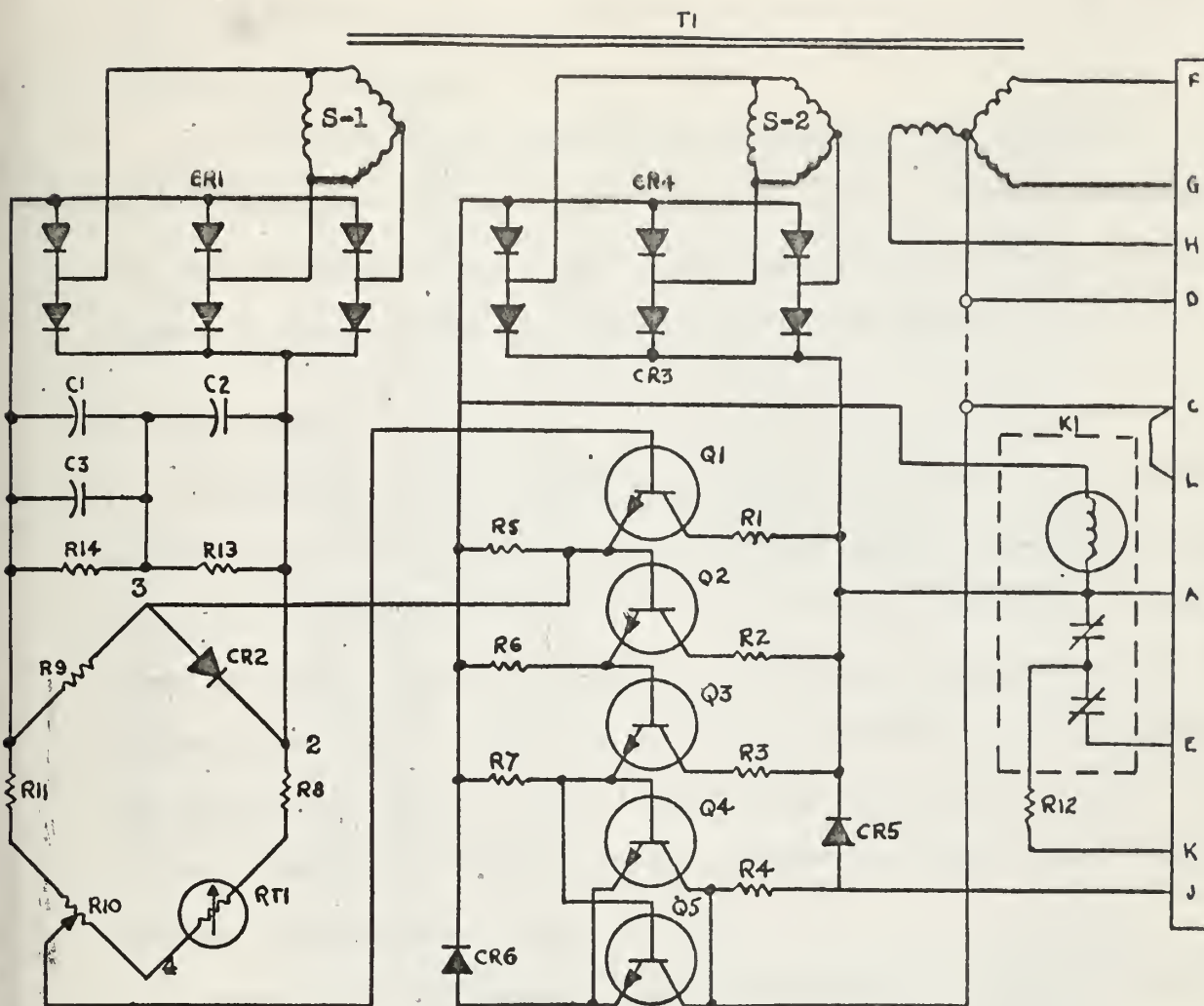
Cl 6.8 uf capacitor
C2 6.8 uf capacitor
C3 6.8 uf capacitor
CR1 Full-wave semiconductor
 device assembly
CR2 Silicon diode , SV 3097
CR3 Positive semiconductor device
CR4 Negative semiconductor device
CR5 Silicon rectifier diode , SM 224
CR6 Silicon rectifier diode , SM 224
K1 Relay
Q1 N-P-N silicon transistor, 2N656
Q2 N-P-N silicon transistor, 2N656
Q3 Silicon power transistor, 2N389
Q4 Silicon power transistor, ST7046-1
Q5 Silicon power transistor, ST7046-1

R1 600-ohm resistor
R2 250-ohm resistor
R3 100-ohm resistor
R4 15-ohm resistor
R5 1000-ohm resistor
R6 500-ohm resistor
R7 125-ohm resistor
R8 125-ohm resistor
R9 2000-ohm resistor
R10 500-ohm potentiometer
R11 825-ohm resistor
R12 30-ohm resistor
R13 10,000-ohm resistor
R14 10,000-ohm resistor
RT1 35-ohm thermal resistor
T1 3-phase power conversion
    transformer

FIGURE 8   REGULATOR SCHEMATIC DIAGRAM

it on. This process is repeated through the transistor stages until a highly amplified signal is obtained at points A and C which are the output terminals to the generator exciter field.

It should be mentioned here that the output of the regulator is the only source of excitation to the generator exciter. That is, the regulator not only sends correction signals to the exciter field, but it also provides the excitation for the generator under steady state conditions.

B. The Detector Circuit.

As mentioned in the preceding paragraph, the input to the detector circuit is a full wave rectified signal which has been partially filtered by an R-C network, so that it takes on a saw tooth wave shape. Referring again to Figure 9, it can be seen that this signal is applied to the detector across points 1 and 2, with point 2, being the positive terminal. The output is at points 3 and 4 with 4 being the positive terminal. Figure 10 shows the input signal and Figure 11 shows the output signal from the detector for steady state rated voltage.

The detector consists of; a zener diode (CR02), a thermistor (RT-1) and four resistors R-8, R-9, R-10, and R-11. The resistor R-10 is a potentiometer used to adjust for the desired voltage. The thermistor maintains the detector circuit resistance constant for varying temperatures.

The voltage reference level is established by the zener diode. A zener diode is a semiconductor device which has a very high resistance until its zener voltage is reached and then for any slight increase in potential, its resistance becomes very small. To best understand how the zener diode functions in the detection bridge, it would be well to consider some hypothetical situations.

12

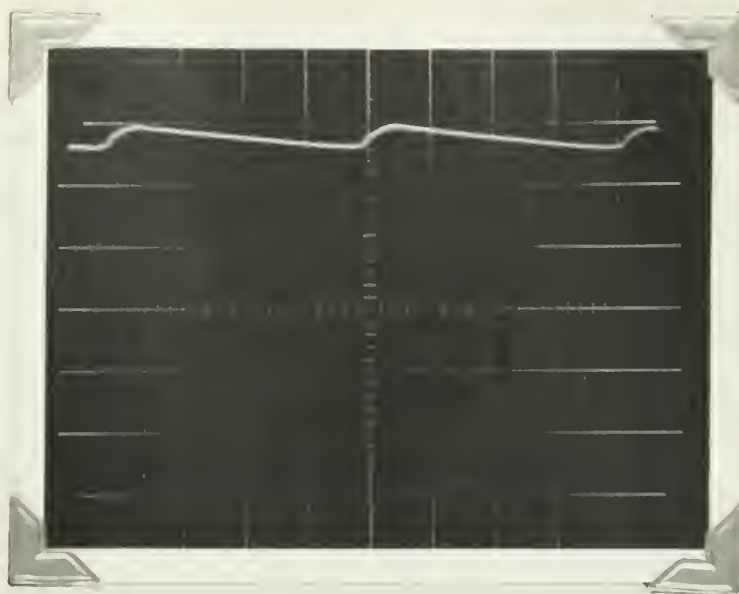FIGURE 9   OSCILLOSCOPE PHOTOGRAPH OF DETECTOR INPUT
                Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm
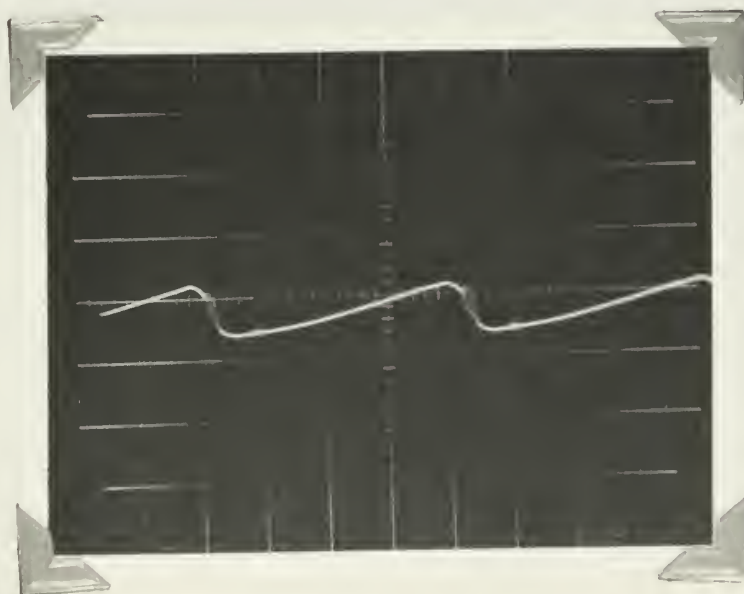
FIGURE 10   OSCILLOSCOPE PHOTOGRAPH OF DETECTOR OUTPUT
                Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

First, if the generator is operating at exactly the correct voltage, the signal to the voltage regulator will be slightly above the zener voltage level. Therefore, a current will flow through the zener diode side of the bridge and point 3 will be positive with respect to point 1. There will also be current flow through the thermistor side of the bridge, so that point 4 is positive with respect to point 1. The potentiometer R-10 is adjusted so that point 4 is just sufficiently positive with respect to point 3 so that the voltage output is just sufficient to furnish the correct excitation to the generator exciter after amplification through the transistor stages.

If now the generator output voltage is reduced, the voltage to detector terminals 1 and 2 will be reduced. The current through the thermistor side of the detector will be reduced as predicted by Kirchoff's Laws and point 4 will then be at some lower potential than in the previous case. On the zener diode side of the detector however, the small change in the voltage from 2 to 1 has caused the zener diode to restrict the current flow much more severely than on the thermistor side. Point 3 then will be at a much lower potential than it was before. Therefore, the net result of the undervoltage is that the potential difference between points 4 and 3 has gone up sharply.

When the generator line voltage goes above the rated level the reverse situation occurs. That is, there is a potential increase at point 4. But, at the same time there is a much greater potential increase at point 3 because the zener diode has allowed a larger current to flow through its side of the detector.

It can be seen therefore, that if the regulator is set correctly, any generator overvoltage will reduce the detector output and therefore

14

the exciter field signal and any generator undervoltage will increase the detector output and the exciter field signal. It is by this means that the regulator serves as a stabilizing feedback element to maintain a constant generator signal.

Referring again to Figures 9 and 10, it can be seen that the detector is a distortionless element with a small gain and a 180 degree phase shift, which serves to reduce the saw tooth input to the correct detector output signal.

C. The Amplifier Circuit.

As shown in Figure 8, the output from the detector circuit is put across the base (+) and emitter (-) terminals of the first of four cascaded transistors. The biasing for all of the transistors comes from the Delta Secondary of the transformer labeled S-2 in Figure 8. This voltage is full wave rectified by the diode units CR-4 and CR-3 and sent to bias the transistors. The bias voltage is varied to each of the respective transistors by the different biasing resistors shown as R-1, R-2, R-3, R-4, R-5, R-6, R-7 in Figure 8. All emitters are biased negatively.

The first transistor amplifies the detector signal and sends it from its emitter to the base of the second transistor. Because of the negative emitter biasing, the first stage transistor output is at some negative level.

The second transistor receives the input and again amplifies it. This time, however the signal is of such magnitude with respect to the voltage supply and collector resistor of the second transistor that the transistor is overdriven and its output is a modified wave with the peaks of the signals cut-off.

This procedure is repeated in transistor stages 3 and 4. That is, they are both overdriven and each time more of the peak of the signal is cut-off as the signal is amplified. This repeated overdriving of the signal

15

leads to an output of the fourth stage that resembles a series of rectangular pulses at some negative d-c level.

In Figure 8 it may be seen that the fourth transistor stage consists of two parallel ST7046 transistors. Two transistors are used at this point to increase the reliability of the regulator.

The output pulses from transistor stage number 4 are in series with the rectified voltage from the Delta Secondary S-2. These two signals then combine to give a series of pulses whose bases are at zero D. C. level. This output is present at points A(+) and C(-). These points are the regulator connection points for the leads to the generator exciter.

Figure 11 shows diagrammatically how the transistor amplifier works. Figures 12, 13, 14, and 15 show the outputs of the various transistor stages from oscilloscope pictures. Figure 16 shows the rectified voltage from the transformer secondary and Figure 17 shows the regulator output which is the sum of the fourth stage transistor output (Fig. 15) and the rectified voltage from the delta secondary (Fig. 16). All polaroid photographs from the oscilloscope were scaled at 10 volts/centimeter vertical and 100 microseconds/centimeter horizontal.

Because of the cut-off restrictions on the transistor stages, the amplitude the fourth stage output is always constant for any magnitude of signal from the detector. The width of these pulses is, however proportional to the output signal from the detector. The fourth stage transistor output is, therefore, a constant amplitude pulse whose width is dependent on the error signal from the detector circuit.

D. Regulator Starting.

Since the regulator transistor circuit is designed to operate about a very narrow range on either side of the 115V line to neutral operating

16

FIRST STAGE OUTPUT | SECOND STAGE OUTPUT | THIRD STAGE OUTPUT | FOURTH STAGE OUTPUT
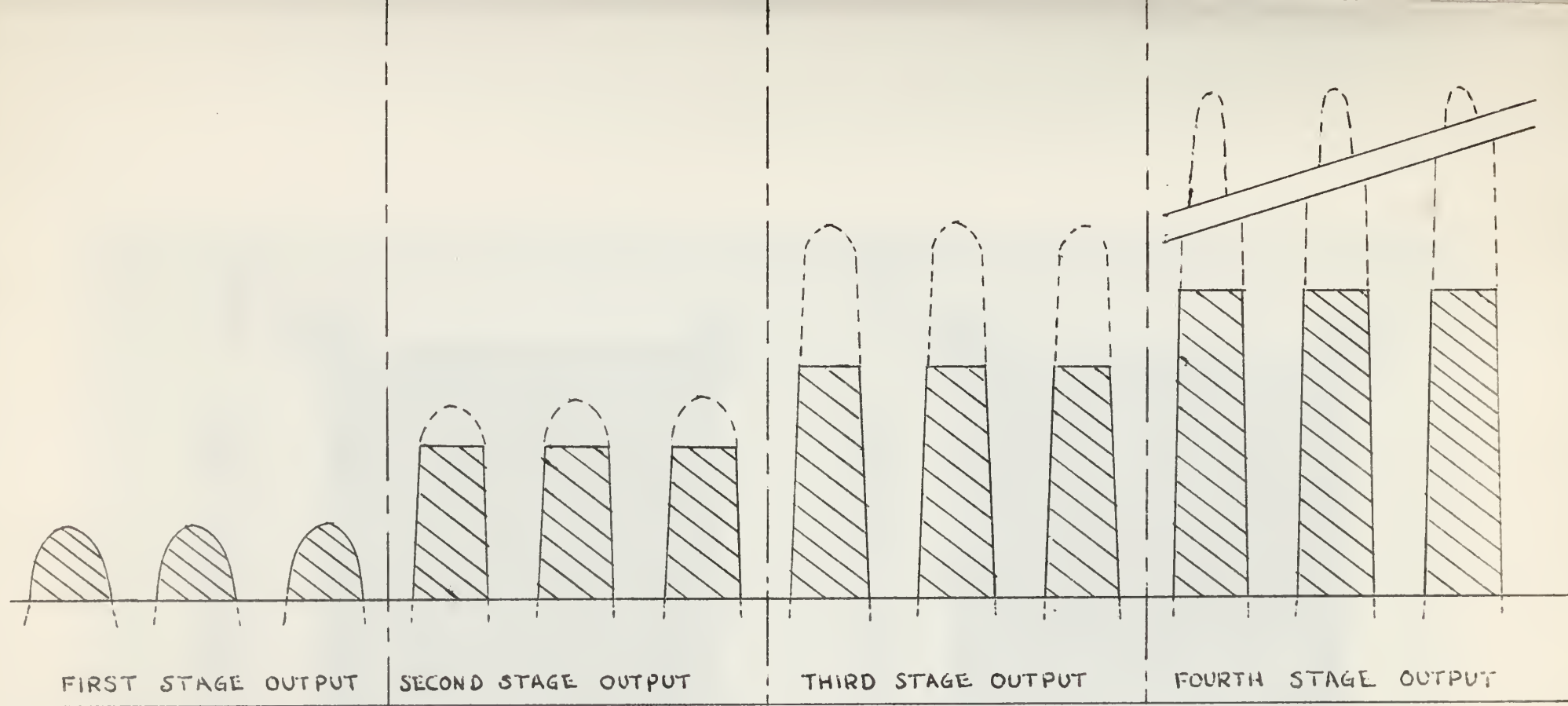
DIAGRAMATIC REPRESENTATION OF

TRANSISTOR STAGE PERFORMANCE

FIGURE 11
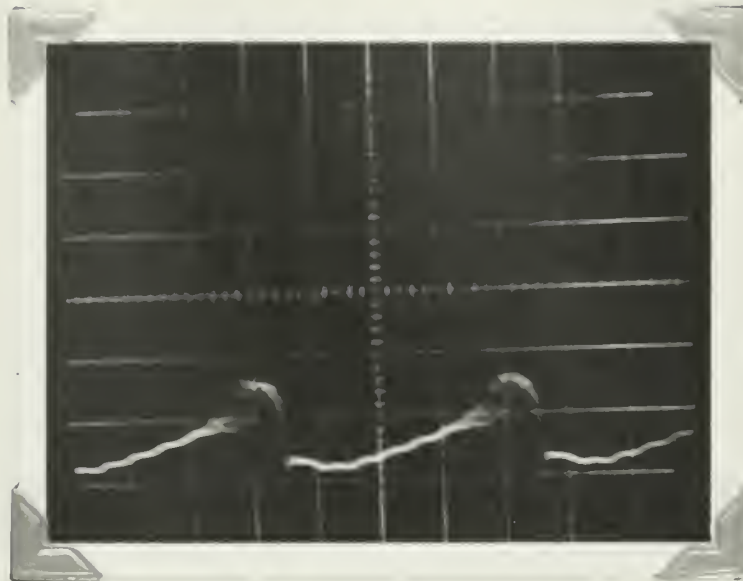
FIGURE 12   FIRST STAGE TRANSISTOR OUTPUT
             Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

FIGURE 13   SECOND STAGE TRANSISTOR OUTPUT
             Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

FIGURE 14   THIRD STAGE TRANSISTOR OUTPUT
               Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

FIGURE 15   FOURTH STAGE TRANSISTOR OUTPUT
               Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm
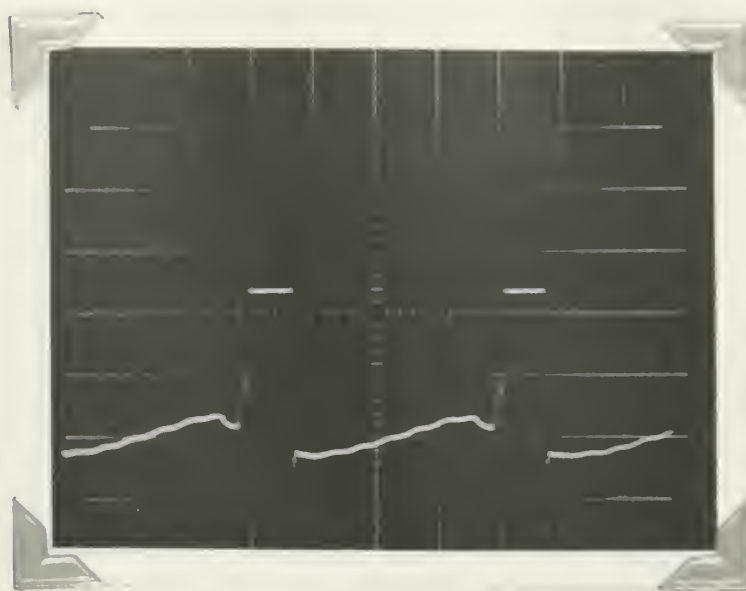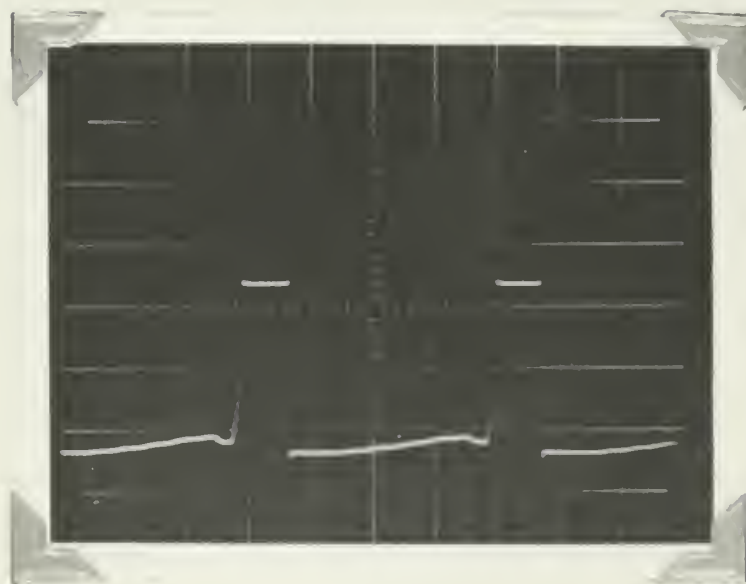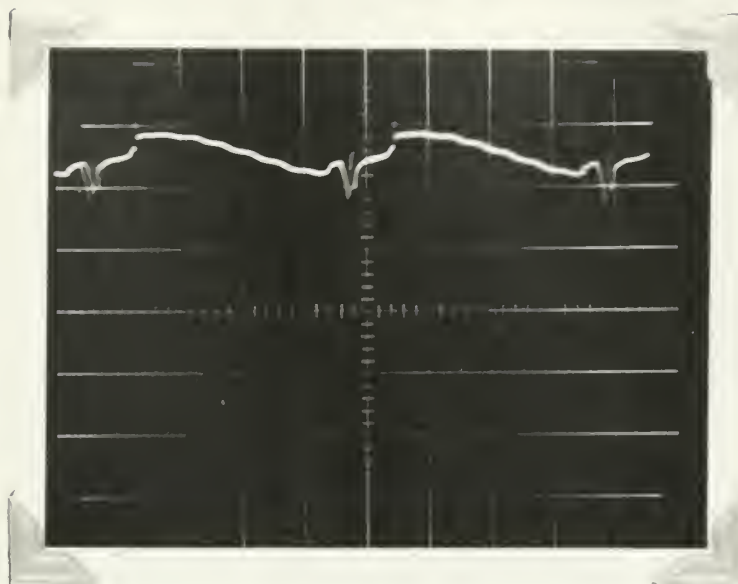
FIGURE 16   RECTIFIED OUTPUT OF TRANSFORMER SECONDARY (S-2)
              Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm
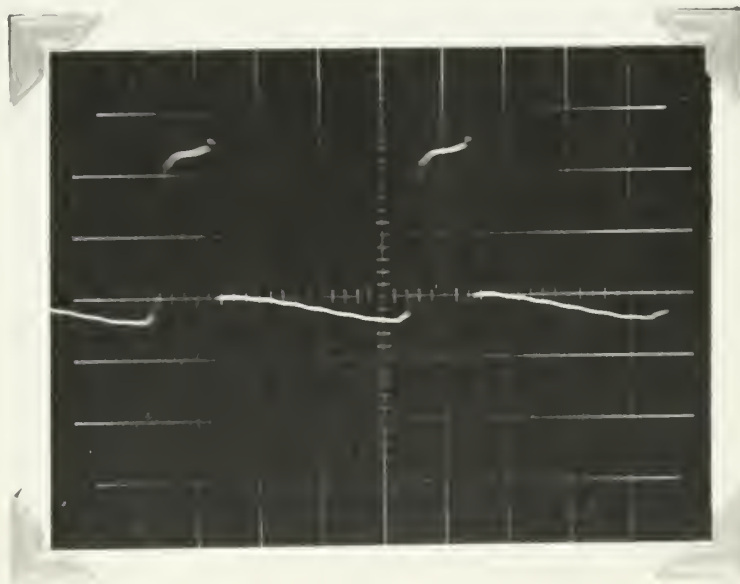
FIGURE 17   REGULATOR OUTPUT TO GENERATOR EXCITER
              Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

voltage, some external means must be used to get the generator started.

Referring to Figure 8, this is accomplished by the field flashing circuit. To start the generator, the prime mover is brought up to speed and an external d.c. supply is applied to the field flashing circuit at terminals K (+) and C(-). This provides the generator excitation.

When the generator is in the vicinity of its rated operating voltage, the relay (K-1) activates and opens the contacts in the field flashing circuit and allows the regulator output to be applied to the generator exciter. The external d.c. supply may then be disconnected from the generator and the regulator is in full operation.

E.   The Regulator Output.

The output of the regulator is a series of pulses at a frequency of 2400 cycles per second. This frequency comes from the three phase, 400 cycle, rectified input to the detector. The three phase, 400 cycle signal has 1200 peak values per second. When this three phase signal is full wave rectified, the numbers of peaks is doubled to 2400 per sec. Each peak input to the detector circuit represents a minimum of detector output. Since these minimums are repeated 2400 times per second, the regulator pulse output frequency is 2400 cycles per second.

The output pulse is a nearly rectangular pulse of constant amplitude whose width is dependent on the output of the detector circuit, which is dependent on the generator line voltage. The base line of these pulses is at ground or zero d.c. potential. The pulses, therefore, give rise to some time average, direct current. As the width of the pulses is varied, the d.c. value of the pulses is varied.

Figures 18 and 19 are photographs of the oscilloscope presentation of

21

two regulator outputs for different generator terminal voltages. Figure 18 shows the regulator output for a 113 volt, line to neutral voltage and Figure 19 shows the output for a 116 volt line to neutral generator voltage. It should be noted that the amplitude of the pulses is the same, but the width of the pulses are not. The 113 volt pulse is wider than the 116 volt pulse. These two figures show the capacity of the regulator for manufacturing a D. C. level which varies inversely with the generator terminal voltage.

Because the regulator amplifier unit is made up of transistors, there is a very narrow generator voltage band through which the regulator will function linearly. The experimentally found range of linear voltage operation was from 110 volts, RMS, line to neutral to 118 volts, R.M.S., line to neutral. Within this range, the load pulses as shown in Figures 18 and 19 were obtained. Throughout this range, the load pulses had the same general shape, differing only in the pulse widths.

When the generator line voltage went over 118 volts, line to neutral, however, a new output picture was obtained. At this high level, there is very little output from the detector circuit. This small output does not overdrive any of the transistor amplifier stages and the output of the regulator has a very low d.c. level. This point was called regulator "cutoff", as the voltage was increased even further, there was very little change in the regulator output.

When the generator line voltage went below 110 volts, line to neutral, a second entirely different picture was obtained. At this level, the detector circuit output is so high that the entire saw tooth output wave is at a positive potential. With the entire wave positive, there are no

FIGURE 18   REGULATOR OUTPUT AT 113 volts-rms
             Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

FIGURE 19   REGULATOR OUTPUT AT 116 volts-rms
             Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm
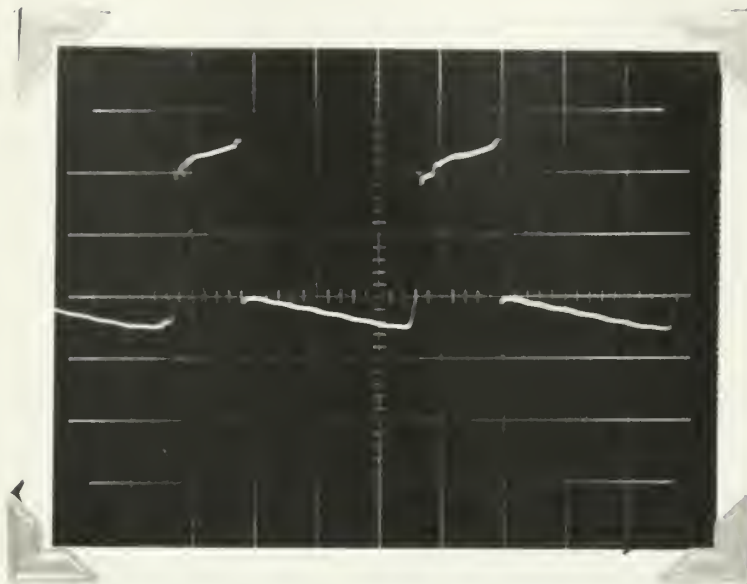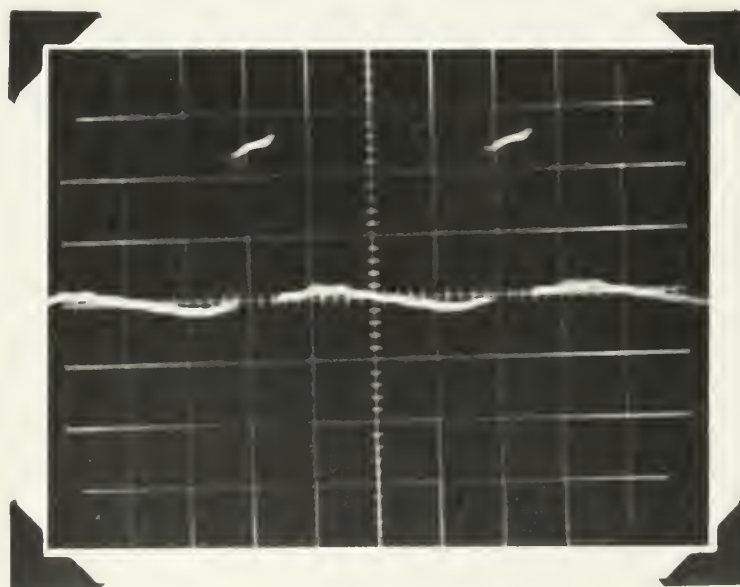
output pulses. Rather, the transistors are continuously overdriven causing a continuous d. c. level output with an amplitude determined by the operating limits of the fourth stage transistor amplifier. This position is known as the "saturation level" of the regulator. As the generator line voltage was decreased even further, there was no appreciable change in the regulator output. Figure 20 is an oscilloscope picture of the regulator output at "cut-off" and Figure 21 is a picture of the regulator output at the "saturation level".

The narrow operation limits of the regulator output do not adversely affect the regulator's operation at any voltage level. Normally, there will not be large terminal voltage variations with changes of generator loads. If, however, something should happen and the generator voltage should either drop below the "saturation level" or rise above the "cut-off" level, the regulator will either put out its maximum or minimum signal, depending on which is required, to return the generator to its correct line voltage.

The regulator is also quite sensitive to the magnitude and type of load to which its output signal is being sent. The 20B63 is designed to excite only certain generators whose exciter fields have approximately the same impedance. Experimental testing has shown this exciter impedance to be of the Resistance-inductance type with the resistance equal to 5.3 ohms and the inductance equal to .114 henries. All photographs of regulator outputs in this chapter were shown with the regulator output attached to a dummy load of approximately these values.

If however, the load resistance is either increased or decreased, severe output distortion takes place. Further, as the resistance is increased the output signal is rapidly reduced becoming zero when the load
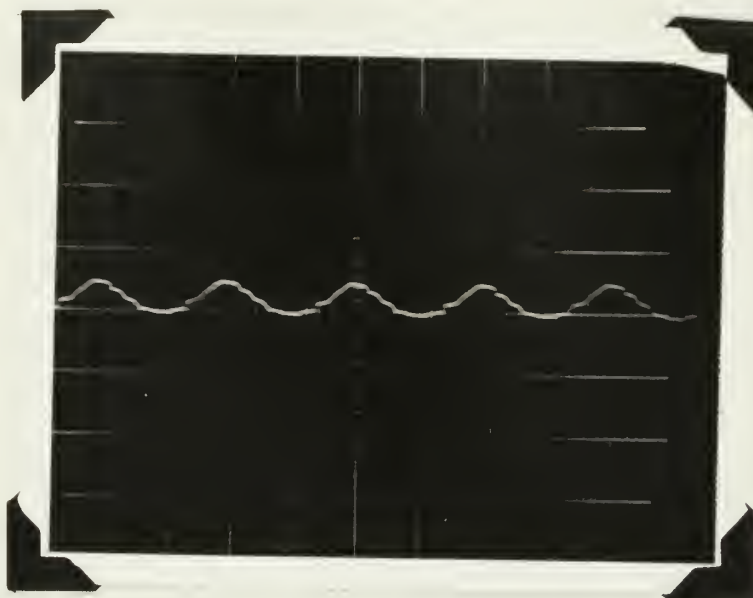
FIGURE 20   REGULATOR OUTPUT SHOWING CUT-OFF
              Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm
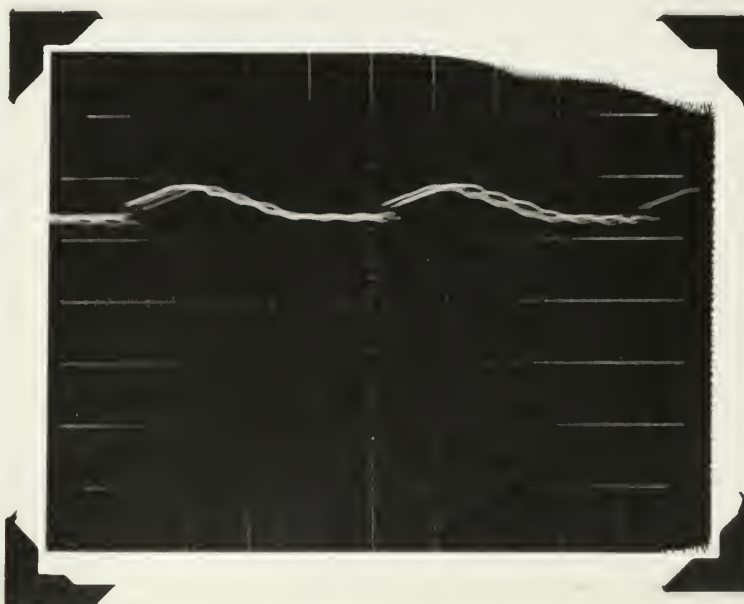
FIGURE 21   REGULATOR OUTPUT SHOWING SATURATION
              Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

resistance is 30 ohms.

The regulator output wave shape is also sensitive to the ratio of resistance to inductance in the load circuit. Under the normal load, the inductance acts as an energy storage device which serves to preserve the rectangular voltage pulse shape and to act as a current damping device so that the load current is a straight line, d.c. signal.

If the inductance is removed from the load, the regulator cannot maintain the square wave pulses across the remaining pure resistive load. Rather, the leading edges of the pulses are curved showing the high speed load transient. The current will of course have the same shape as the voltage for a pure resistive load.

Figures 22 and 23 are shown to indicate the regulator outputs for varying loads. Figure 22 shows the output to a nearly pure resistive load. This may be compared with Figure 23 which shows the output for the normal R-L load condition.
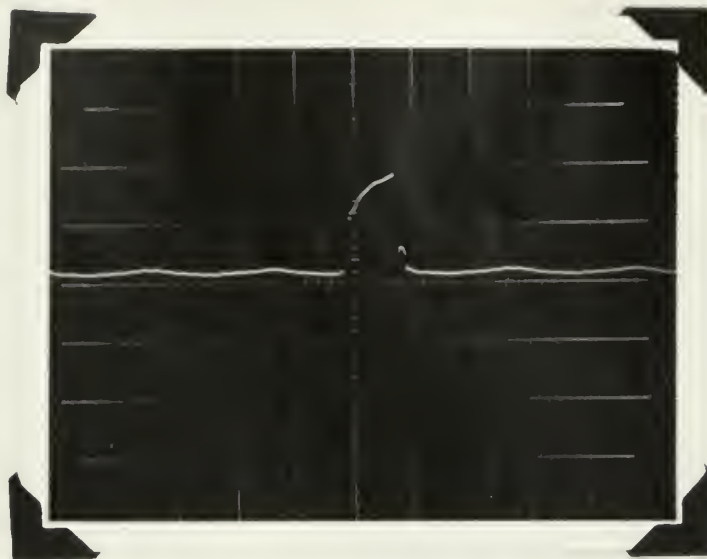
FIGURE 22   REGULATOR OUTPUT TO RESISTIVE LOAD
              Scale: Vert. 10 volts/cm , Hor. 200 microsec/cm
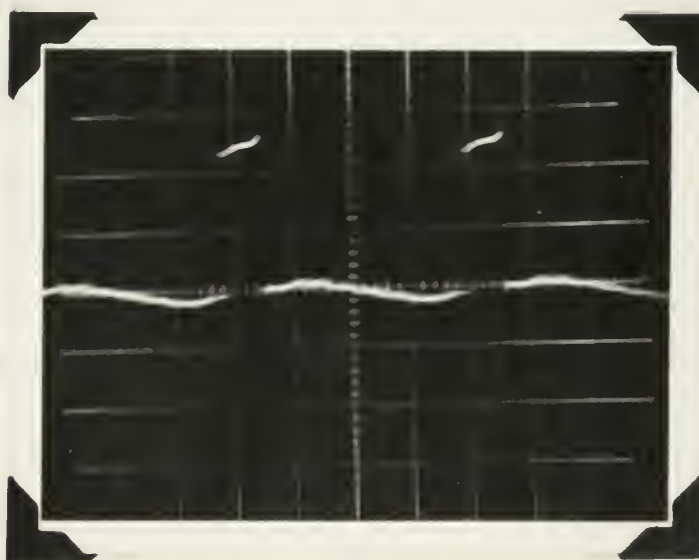
FIGURE 23   REGULATOR OUTPUT TO RESISTIVE/INDUCTIVE LOAD
              Scale: Vert. 10 volts/cm , Hor. 100 microsec/cm

CHAPTER III

ACCESSORY EQUIPMENT

This chapter is devoted to the familiarization of the reader with some of the major experimental tools used in this analysis. As will be seen in the subsequent chapters several unusual and sometimes devious schemes were needed to produce useable results. It is acknowledged that methods and equipments superior for the purposes at hand are known. However, the experimental work undertaken used only those tools readily available in the laboratory and those which could be manufactured easily. No effort is made at this time to fit these devices into their respective experimental procedures, but merely to present their construction and operation where necessary for clarity in the following chapters.

A. Generator and Generator Drive Unit.

Upon undertaking this thesis project, it became immediately apparent that a 400 cycle per second voltage source was needed. Fortunately a Bendix generator type 28E20 was obtained without undue complications. This generator is compatible for operation with the type 20B63-1-A voltage regulator also manufactured by the Bendix corporation. The following general facts about the generator were known.

> Cylindrical rotor
>
> 8000 rpm, 6 pole, 400 cps
>
> 3 phase air cooled
>
> Integrally mounted exciter

The problem of obtaining a drive of 8000 rpm was solved by using an existing laboratory arrangement that had seen use in previous experiments.

Figure 24 shows the arrangement of components.

In the lower right side of the picture is the drive motor which was a three phase 220/440 volt induction motor of 7.5 horsepower rating. This motor operated at about 3485 rpm under the loading conditions. The shaft of the induction motor was directly connected to the input of a variable speed gear box. The handle in the center of Figure 24 was available for adjusting the output speed of the gear box. A considerable speed range was available with this unit which encompassed the desired speed. A belt drive connected the output of the gear box with the input to the generator. The generator is shown in Figure 24 with a portion of its cover removed to alleviate heating problems. The bare panel in the background of this figure contained output terminals for the generator and circuit breaker for load application.

B. Induction Regulators.

Due to some of the procedures used, voltage drops in the line or in other test equipment caused the input voltage to the regulator being tested to drop to an unacceptable low value. In addition it was desired to operate the regulator with various input (steady-state) levels without resetting the internal regulator potentiometer (R-10). Since it was desirable to regulate the only 400 cycle supply available, namely the Bendix generator in order to maintain a constant test voltage, it was decided to use some sort of line transformation to adjust the base voltage. Three induction regulators were obtained and placed in the line as shown schemitically in Figure 25.

In an induction regulator the mutual coupling between the coils can be varied mechanically, thus the output voltage of this device can be raised or lowered with respect to the input voltage. As can be seen from
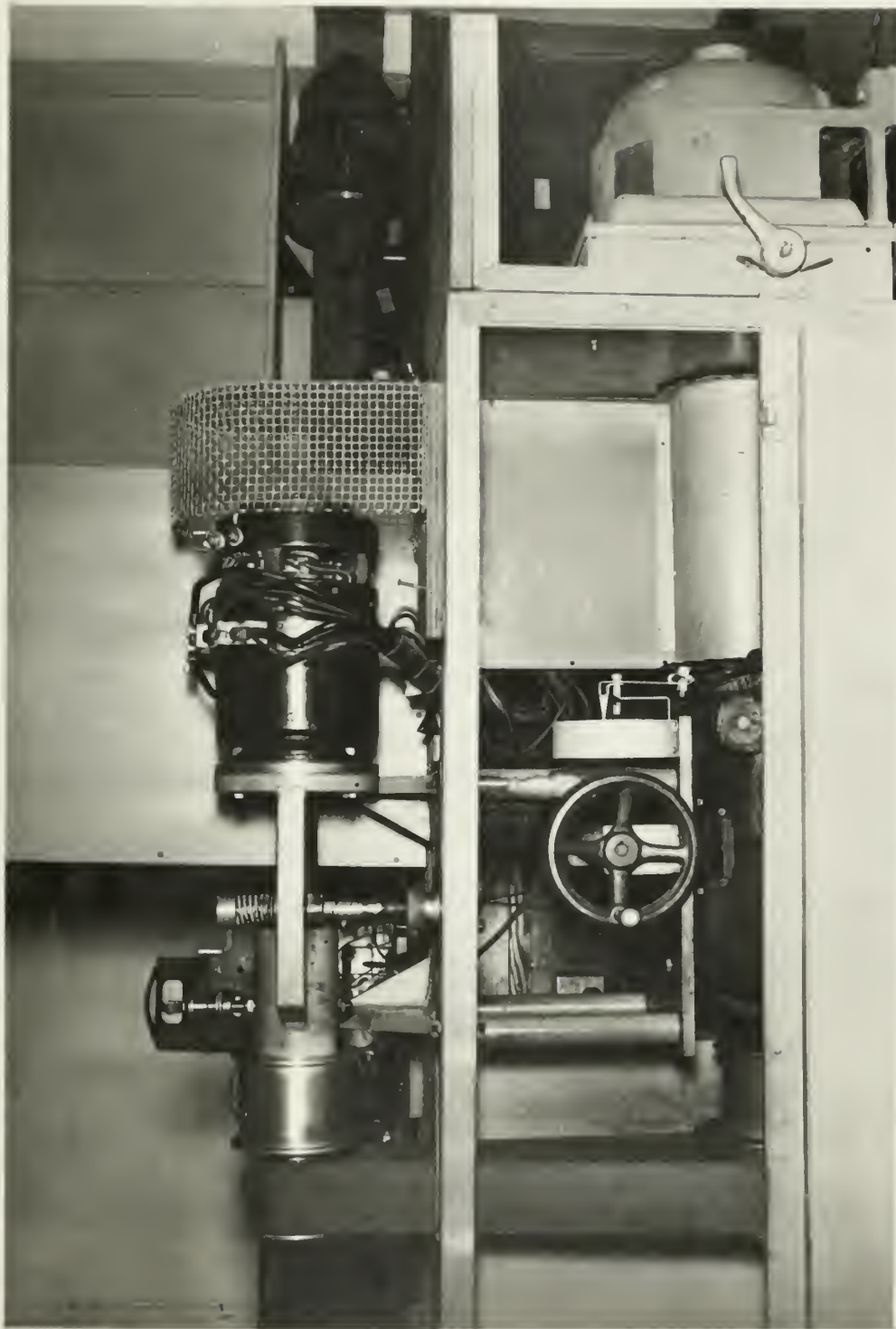
FIGURE 24   PHOTOGRAPH OF GENERATOR/DRIVE ASSEMBLY

the schematic diagram, the regulator arrangement used is equivalent to a Y-Y transformer bank with the neutrals solidly connected but not grounded.

Some difficulty was encountered in this setup. Originally, the "neutral" of the regulator bank was grounded. However, this arrangement caused the output signal of the induction regulator to be non-sinusoidal in nature and to have varying magnitudes between different phases and ground. When the ground was removed, normal sinusoidal waveforms were experienced. This arrangement of the induction regulators allowed the voltage magnitude to be varied to the desired operating point.

C. The Amplidyne.

The amplidyne generator used in this series of experiments was a General Electric model 5AM73AB52. The unit was arranged for laboratory work with external connection points for all windings.

The schematic of the mode of connection for the amplidyne used is shown in Figure 26. With this arrangement it is possible to excite the control fields with separate signals to obtain a desired output characteristic with a signal or signals applied to the control windings, a speed voltage is produced across the brushes qq due to the signal produced flux. Since brushes qq are shorted through the quadrature axis series winding, large currents may flow in this connection for rather small amounts of signal current. The quadrature axis current produces cross-magnetizing armature reaction and the armature reaction flux is stationary in space and centered in the quadrature axis of the machine. This flux gives rise to a speed voltage across brushes dd which supply the load. The direct axis compensating winding compensates for the armature reaction mmf created by the load current and prevents cancellation of the control field mmf and

31

subsequent collapse of the machine fluxes and voltages. The quadrature

axis series field serves to reinforce the flux created by the quadrature

axis current.

The ampidyne generator gives a relatively high power amplification.

In addition it affords a method of combining the effects of several

different signals applied to individual control fields.

D. The Scotch Yoke.

In various operations in the experimental procedures developed, it

became necessary to amplitude modulate a 400 cps, three phase voltage.

Several methods were attempted to accomplish this end. Varying degrees

of success were obtained.

The most successful method was mechanically modulating the output of

the generator. To accomplish this a sinusoidally varying resistance was

required in each phase. Additionally, the resistance in each phase had to

be the same at each instance of time. Therefore, a "Scotch Yoke" was built.

Figure 27 shows a rudimentary scotch yoke.

The input to this system is a constant speed torque applied to fly-

wheel A. Pin B, attached to flywheel fits into the groove in the yoke C.

As the pin rotates at constant speed, the rotational motion is converted

to translation motion of the constrained yoke. If the arm of the yoke is

meshed to the gear D, gear D will rotate and reverse direction once every

half cycle of the flywheel. By varying the radial position of pin B on

wheel A, the magnitude of swing of gear D is changed. By varying the speed

of rotation of the input shaft, the frequency of the swing of gear D is

varied.

Thus, if the moveable arm of a potentiometer were attached to the shaft

E, the instantaneous ohmic value of the potentiometer would follow a sinu-

soidal variation.

LINE
INPUT

LINE
OUTPUT

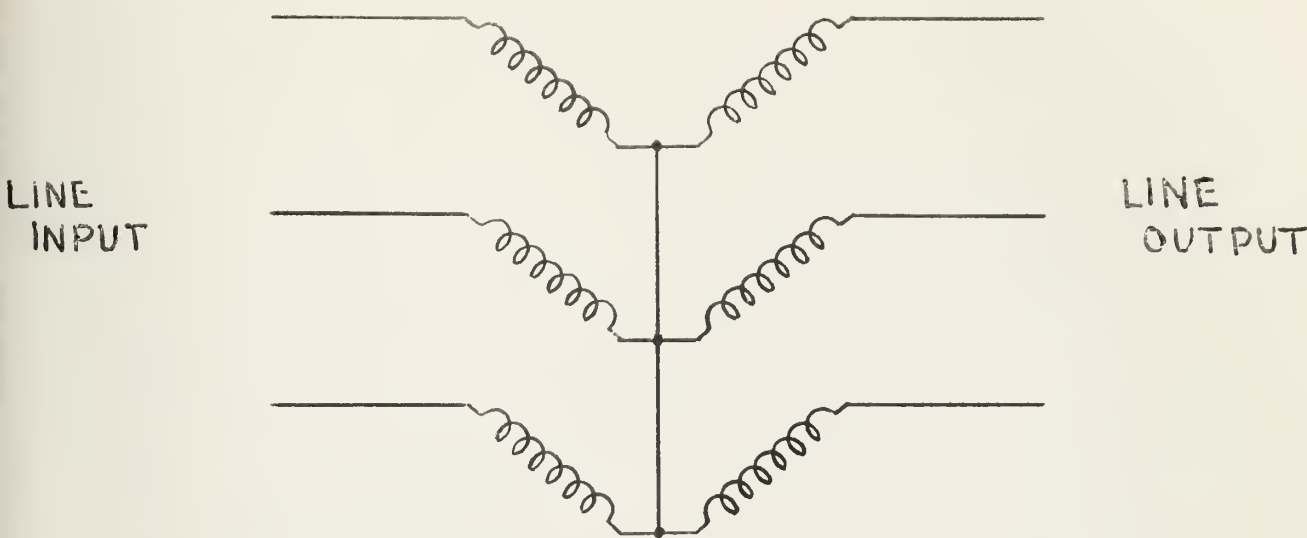FIGURE 25   SCHEMATIC OF INDUCTION
REGULATORS

LOAD

CONTROL FIELDS

QUADRATURE AXIS
SERIES FIELD

q

d   d
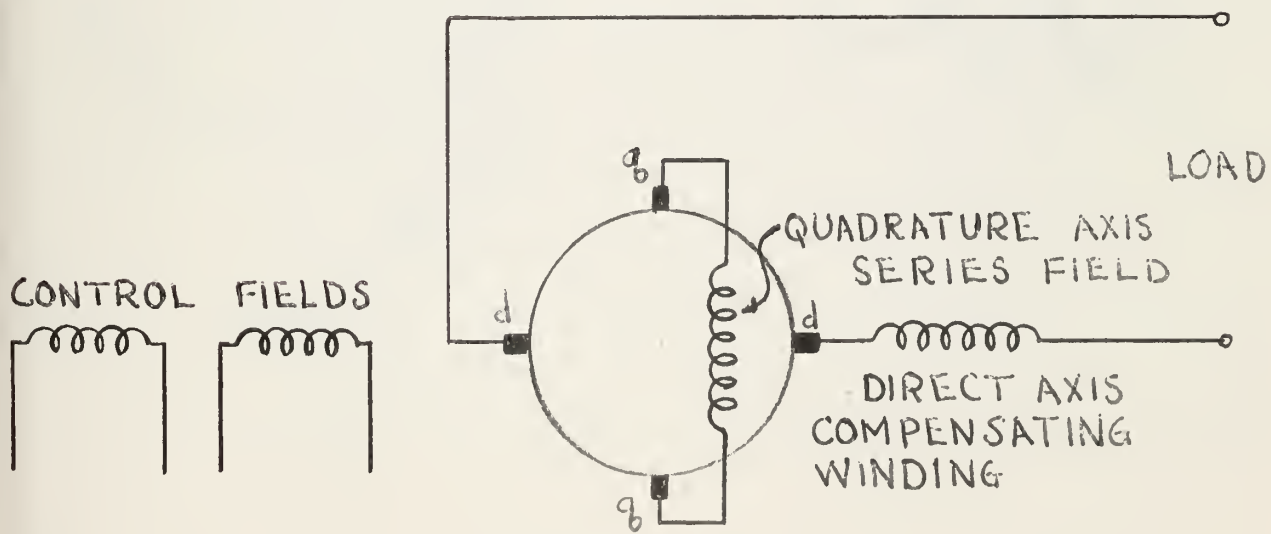
q

DIRECT AXIS
COMPENSATING
WINDING

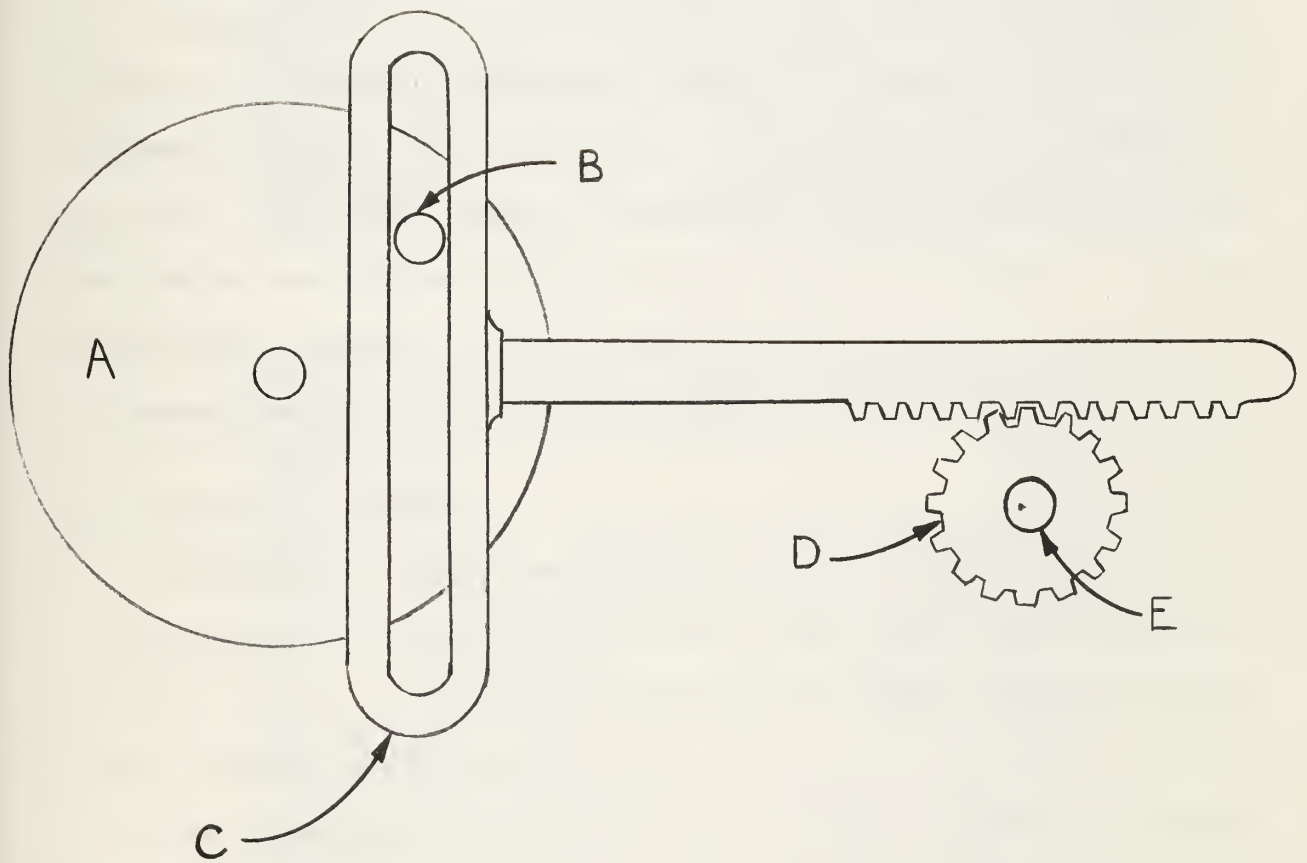FIGURE 26   SCHEMATIC OF AMPLIDYNE

33

FIGURE 27   SCHEMATIC OF SCOTCH YOKE

34

The scotch yoke built for this experiment was made from an X-Y plotter assembly out of a Navy Mark 1-A computer. The arrangement, as shown in Figure 28, allowed adjustment of magnitude of swing during operation. The mechanism was powered by a 1/8 horsepower d-c shunt motor, hence continual speed adjustment was available with field and armature rheostats. Three sturdy potentiometers were connected in tandem on the output shaft. One thousand ohm potentiometers were used snice they were the only appropriately constructed ones that were available.

The major drawback to the scotch yoke system lay in the mechanical limits to the frequency attainable. Due to the loading upon the d-c motor, including friction of the moving parts, the minimum frequency obtained was 1cps. In the upper range of frequencies, a limit was enforced by the gear ratios available and by the ability of the potentiometers to maintain good contact. It was found that this scotch yoke performed very well up to frequencies of 25 to 30 cycles per second.

E. Additional Equipment.

In addition to the aforementioned equipments several other major units were used. A Bendix type 20B36-3/A, serial RX1, Voltage Regulator which was rated at 115/200 volts, 380/420 cps was used in several arrangements to control the generator.

A motor generator set was also used. The unit consisted of a General Electric, D-C drive motor and a General Electric 60 cps A-C generator. This generator was part of a large installation with the purpose of generation of harmonic voltages. Consequently, it was well compensated to give a good sinusoidal output. These two pieces of equipment were mounted together and used to produce a sinusoidal voltage of varying frequency by varying
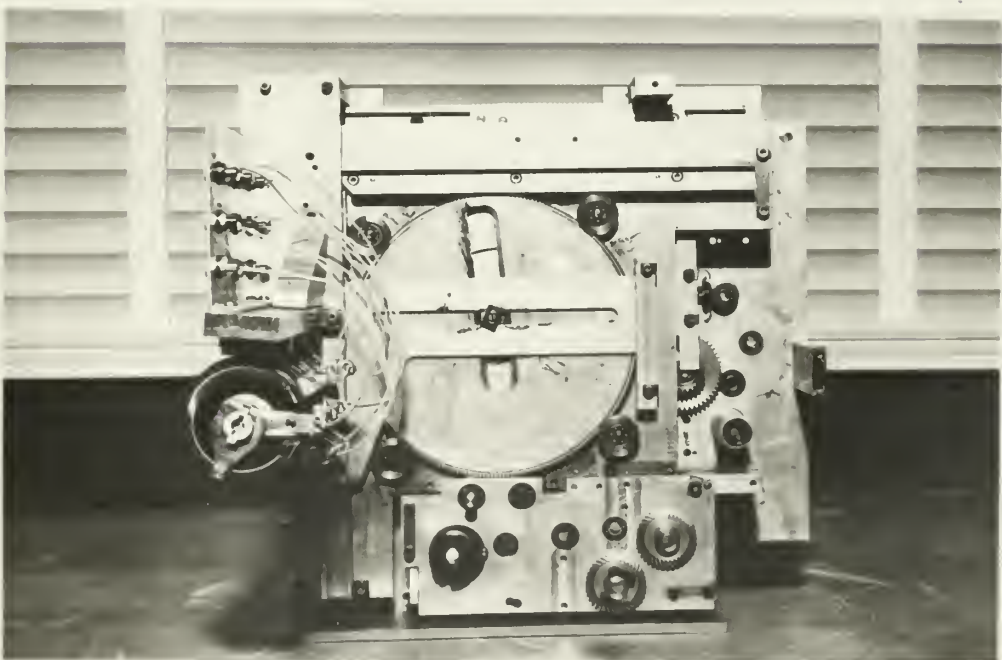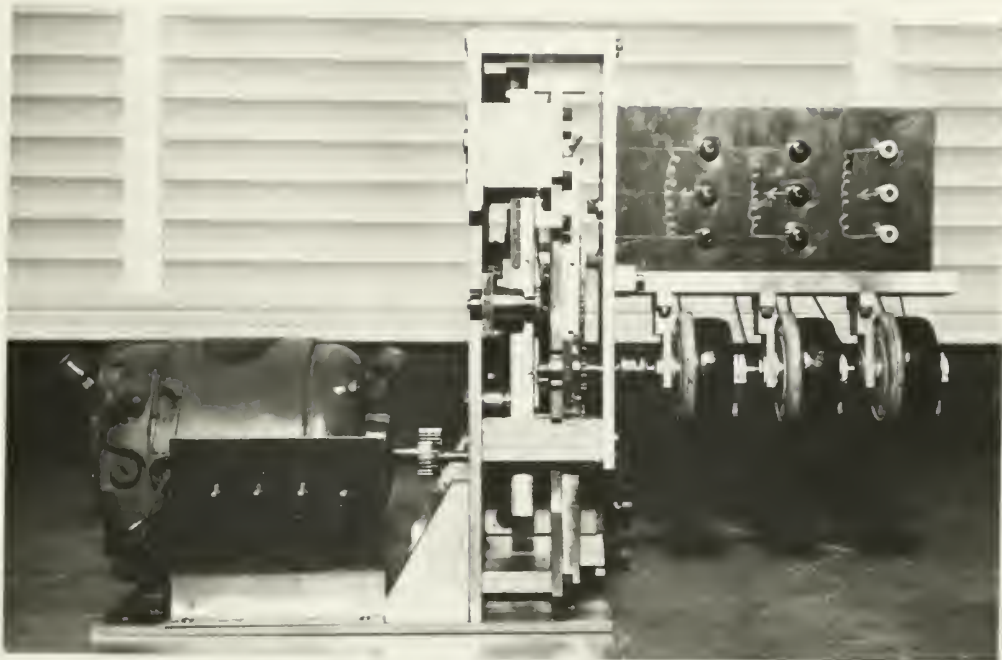
35

FIGURE 28   TWO VIEWS OF SCOTCH YOKE ASSEMBLY

the speed of the D-C drive motor. The three phase windings of the generator had external connections.

A listing of all equipment used in the experimental procedures presented herein, including test equipment, may be found in Appendix I.

CHAPTER IV

REGULATOR TESTS

The research for this thesis was begun with no descriptive regulator
information available other than the regulator circuit diagram (Figure 8).
The known Navy and industrial sources were checked for further data on this
device, but none was available.

It was possible, however, to make the following initial presumptions
and observations; first, because of the transistorized amplifier stages,
the regulator was believed to react extremely rapidly to changes in
generator terminal voltage. Second, the input to the regulator was a
three phase, 400 cycle, 115 volt linc to neutral source which was WYE con-
nected with a solidly grounded neutral. The output was a series of square
wave pulses at a frequency of 2400 cycles second with some time average value.
Finally, to operate correctly, the regulator had to incorporate a 180
degree phase shift. That is, for a voltage rise to the regulator input,
there had to be a decrease in the output, and for a decreased input there
had to be an increased output.

An inspection of the internal circuitry of the regulator seemed to
indicate that the research could best be conducted by considering it as a
non-linear, servo component. It was therefore, necessary to design and
conduct a series of transient and frequency response tests on the regulator.
From these tests, it was anticipated that a describing function could be
obtained to define the regulator. It is the purpose of this chapter to
discuss the procedures and results of these tests.

In order for the transient and frequency response tests to have
significance; it was necessary to consider the variations of only one of

the three phase line to neutral inputs versus the variations in the
direct current output signal. In other words, while all three phases
of the input were varied in equal amounts, only one of the phases was
considered in the test computations and also only the variations in d.c.
output level were considered and not the actual output pulses.

A. The Transient Response Tests.

Basically, a transient response test consists of instantaneously
changing the input to a component and observing the output response of the
component due to the input step. From the output transient shape, a
great deal of information about the component can be obtained.

The system generator (discussed in Chapter III) was used as the in-
put to the regulator. A dummy load of 5.8 ohms resistance and a .110
henries inductance in series was used as the output. These values very
closely approximated the generator exciter field values which were the
normal regulator load.

Several different methods were used in the transient testing of the
regulator. A first attempt was made as follows: The generator was ex-
cited for 116 volts, rms, line to neutral at no load. The three phase,
four wire output was then sent to the regulator and through a load breaker
to three large WYE connected load bank resistors. It was thought that by
turning the load bank switch on and off a step variation of generator
terminal voltage would be obtained and the transient d.c. variat on of the
regulator could be read out on a pen recorder.

Several tests at various resistance loads were taken and the data
was analyzed. It was found that the time constant (the time for the out-
put to reach 63.6% of the new steady state value) was considerably larger
than had been anticipated by preliminary research. It was therefore felt
that the test circuitry was in error.

A re examination of the resistive load banks readily pointed out the source of error. These load banks had a small inductance in them and so were not purely resistive. It was this resistance -- inductance load which was causing the large time constant which showed up as the regulator output.

A second method of evaluating the transient response was attempted. This time the load banks were removed and only the regulator was used as the generator load. Between the regulator and the generator, a slide wire rheostat, of essentially pure resistance, was placed in each line of the generator output. A three phase shorting switch was placed across the three rheostats. It was felt that as the shorting switch was opened and closed a series of step voltage variations could be imposed upon the regulator input. Several tests were made using this method and once again an inordinately long time constant was obtained. Besides the long time constant, the general shape of the transient output seemed peculiar. That is, it was nearly linear instead of being the usual exponential shape.

Once again the theory of the circuitry was examined. This time it was found that the faulty time constant was due to an improper usage of the regulator as the only generator load. Since the output of the regulator is dependent on the generator terminal voltage, the amount of current drawn into the regulator is dependent on the regulator terminal voltage.

When the regulator was tested using this method, the load current input variation to the regulator became apparent. As the shorting switch across the series resistors was opened, an instantaneous reduction in the regulator input voltage occurred. The regulator reacted by increasing its

40

power output as expected. This however meant that the regulator drew more current from the generator and therefore, the voltage drop across the resistors was increased and the voltage drop at the terminals of the regulators was further increased causing it to supply more power output. This meant an even larger current drop in and a correspondingly increased voltage drop at the regulator. Eventually, the system stabilized itself, but the transient data obtained was clearly not representative of the regulator transient.

The problems involved in the previous testing methods were easily eliminated by using the test circuit arrangement shown in the circuit diagram in Figure (29).

This arrangement is basically the same as described above, except that slide wire rheostats of essentially pure resistance were connected in WYE to furnish a relatively high current load. With this large current through the lines a relatively small resistance was used to obtain the correct magnitude of regulator step input variations. The problem of load current variations due to the regulator was made insignificant because of the much larger current drawn by the resistive load.

Additional accessory equipment was also added to improve the transient results. As shown in Figure (29), a second transitorized regulator was obtained and incorporated in the test circuit to stabilize the generator output, which was seen to drift slightly when the stabilizing regulator was not used.

The stabilizing regulator was a slightly different type than the regulator being tested. Consequently, it stabilized the generator output voltage at a level about 3 volts rms below that at which the test regulator was set to operate. Three WYE connected induction regulators were
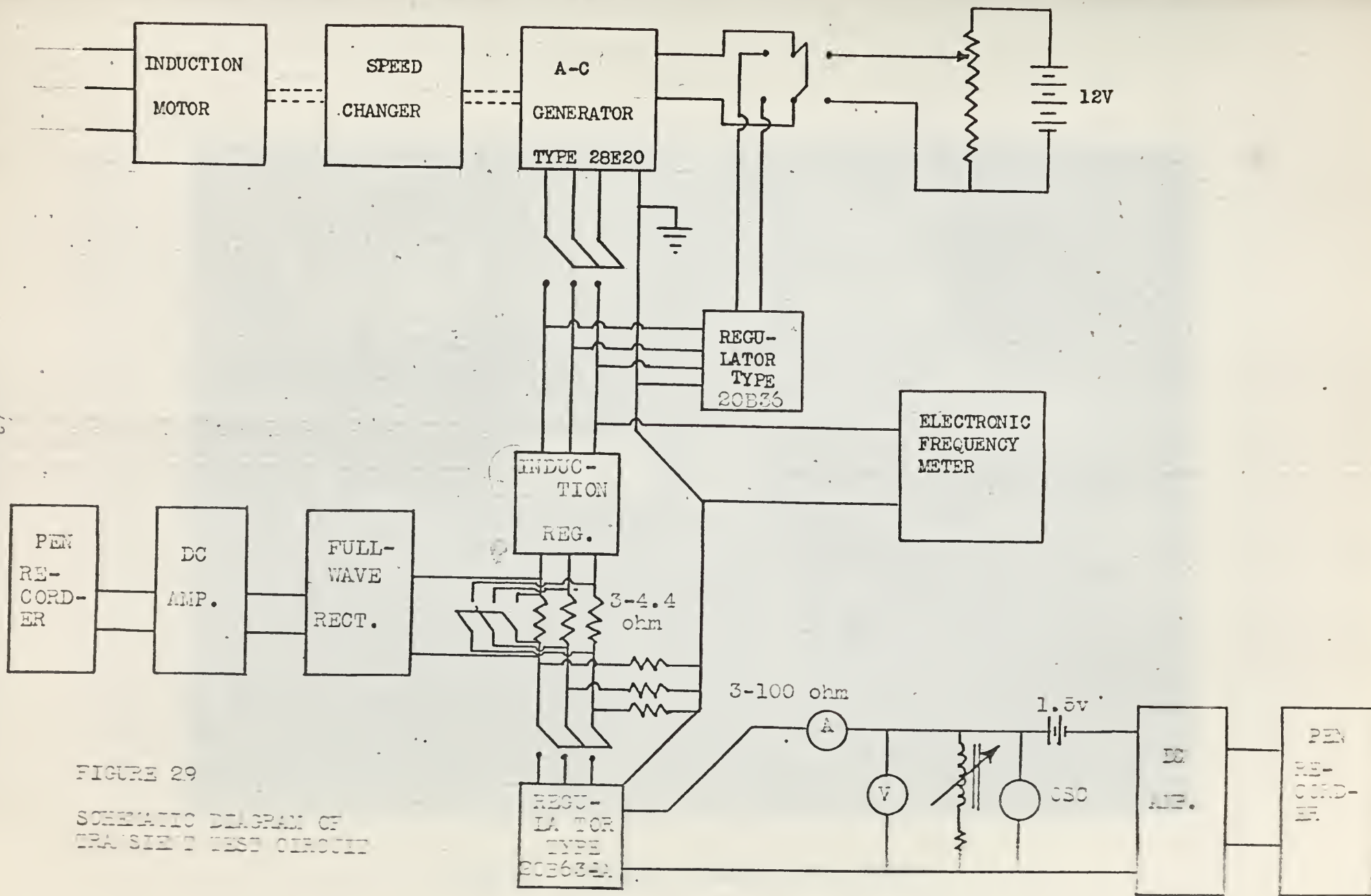
41

FIGURE 29

SCHEMATIC DIAGRAM OF
TRANSIENT TEST CIRCUIT

FIGURE 30   PHOTOGRAPH OF TRANSIENT TEST EQUIPMENT

needed therefore, to raise the voltage to the test regulator to its correct value. A photograph of the complete test arrangement is shown in Figure (30).

A series of transient tests were made using this circuit. By varying the ohmic value of the series rheostats, it was possible to obtain steps of various magnitudes. The steps were taken in small increments around the 116 volt operating point from saturation to cut off voltage.

The results of the tests were printed out on a high speed Edin Pen recorder (500 mm/second). When these tests were analyzed, it was noted that the transients appeared to have the correct shape, but that the amplitudes of the steady state responses to the various steps appeared to be too small.

The tests were re-run using meters to check the initial and final steady state values and it was found that the pen recorder readings were indeed in error.

The reason for this error was believed to be that the 2400 cycle per second pulses going into the Brush amplifier were attenuated by the amplifier, because of their high frequency. They were then sent to the recorder which read out the d.c. value of the attenuated signal rather than the true d.c. value.

It was noted, however, that the time scale remained true and also the amount of attenuation in the Brush amplifier remained constant as long as the amplifier scale setting was unchanged. With this knowledge it was possible to evaluate the transient responses test from the recorder tapes, using the value of gain obtained from the meter readings.

The first evaluation made was for the time constant of the regulator. Figure (31) shows a table of values of time constants for various step sizes around the 116 volt operating point.

STEP DOWN	INPUT STEP	STEP UP
SECONDS	VOLTS-RMS	SECONDS
.0032	.6	.0020
.0036	1.2	.0020
.0035	1.6	.0022
.0030	2.0	.0020
.0040	2.5	.0018
.0036	3.0	.0022
.0040	3.5	.0020
.0036	AVERAGE	.0020

FIGURE 31   TIME CONSTANT TABLE

As was expected, the regulator response was extremely fast.
What was not expected was that the time constant would be independent of
the amplitude of the step. That is, be the same for any size step input
in the linear region of the regulator.

Even more surprising was the fact that the regulator showed two time
constants, one for an input step down and another for an input step up.
These results were at first believed to be in error. It was felt that some
other component of the circuit, such as a switch, was changing the regula-
tor time constants. As a check, all of the components were reversed so
that what was formerly a step up would be a step down and vice-versa. A
new set of tests was made and the results were the same, proving that the
regulator definitely had two different time constants and that the time
constant for an input step down was almost twice as long as that for an
input step up. No attempt was made to explain this phenomenon at this
point. A discussion of the causes may be found in the conclusions sec-
tion of this paper.

Figure (32-a) is a table showing the voltage gains obtained in the
various transient step tests. While there is minor variance between each
gain, it is felt that this was due to inexact meter reading and that the
gain is a constant and equal to .315 volts, d.c. out/volt, a.c. Pk in.

The transient tapes showed that the regulator reacted as an undamped
system. Figures 32-b and 32-c are tables of overshoot analysis. Figure
32-b shows the amount of maximum overshoot as a percentage of steady state
output variation. Figure 32-c shows the time to reach maximum overshoot.

While there are minor variations from step to step, there are no
definite trends either up or down. The variations are therefore felt to
be slight inaccuracies in the readings and the respective evaluations are

GAIN TABLE

Input Step Volts Peak	Output Step D. C. Average	Gain V out/ V in
0.85	0.25	.295
1.70	0.55	.325
2.26	0.70	.31
2.82	0.82	.32
3.54	1.15	.325
4.24	1.32	.310
4.92	1.58	.315
		AVG. .315

% OVERSHOOT TABLE

Input Step Volts Peak	% Overshoot (Step Up)	% Overshoot (Step down)
0.85	45.0%	28.6%
1.70	49.0%	29.1%
2.26	47.6%	27.7%
2.82	41.5%	27.2%
3.54	42.0%	30.0%
4.24	45.8%	29.1%
4.92	45.2%	26.5%
	AVG. 45.1%	AVG. 28.3%

TIME TO PEAK OVERSHOOT

Input Step Volts Peak	Time to Peak Overshoot (seconds) (Step up)	Time to Peak Overshoot (seconds) (Step Down)
0.85	.005	.008
1.70	.005	.008
2.26	.005	.008
2.82	.004	.009
3.54	.005	.009
4.24	.005	.009
4.92	.005	.009
	AVG. .005	AVG. .0085

FIGURE 32   TABULATION OF TRANSIENT TEST
RESULTS

believed to be constants at the average value.

Both tables clearly show that there are two different criteria involved, depending on whether the step is up or down. It can be seen that the step up is much more underdamped and much faster than the step down. It is also noted that a ratio of; time constants, percent overshoot and time to maximum overshoot between the step up and the step down is essentially a constant.
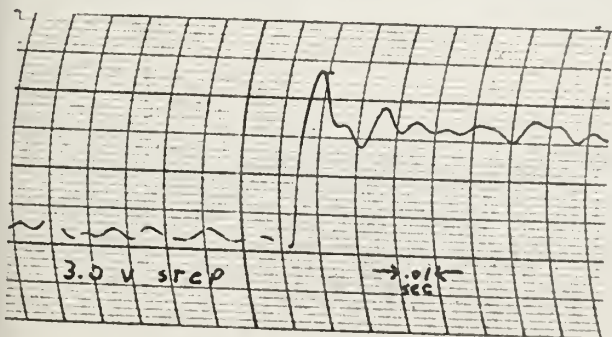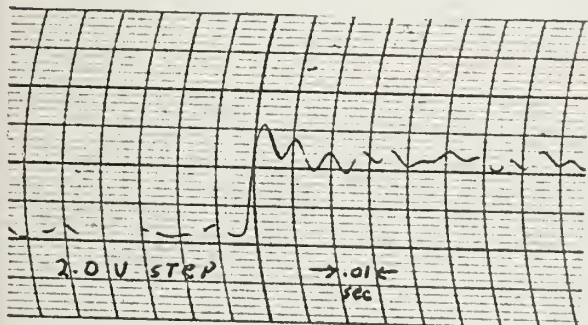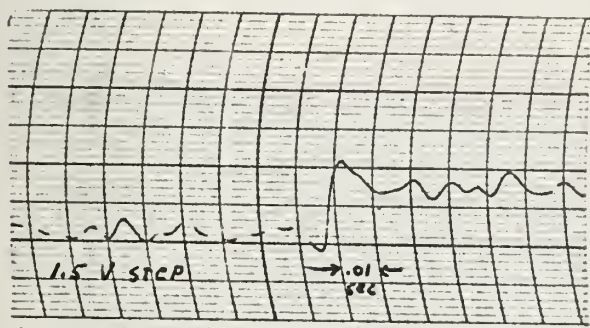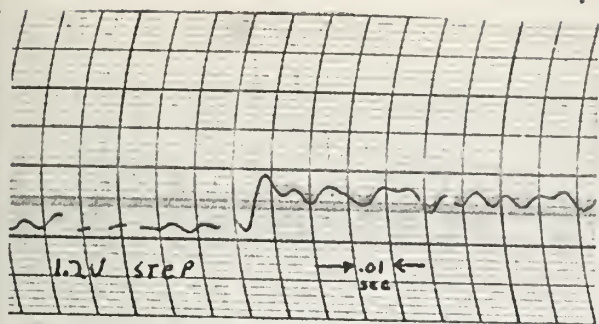
Figures 33 and 34 are sample tapes of the transient tests. All tapes were run at 500 mm/second. Figure 33 shows the response to steps up and down in the linear region. They clearly show the system underdamping and the variations between the response for steps up or down.

The tapes also show a very high noise level. It was this noise level that made it difficult to get an accurate analysis of the transient data. This noise is some function of the generator input and is believed to have its origin in the commutator bars of the generator exciter. Several attempts were made to remove this noise signal, but none were successful.

Figure 34 shows sample tapes of the transient response when the regulator is driven to "cut-off" and "saturation". All of the data previously mentioned was pertinent only to the linear region.

The phenomena of saturation and cut-off were discussed in Chapter II. The tapes of Figure 34 show some of the characteristics of these limiting cases. It is evident that in coming out of either saturation or cut-off to some linear voltage, a good transient wave shape is obtained. These wave shapes are in agreement with the linear transients. When, however, the step was made from the linear region to saturation, an entirely different situation occurred. The transient waves contain dips and level spots and in general a variety of unpredictable shapes. Further, when the
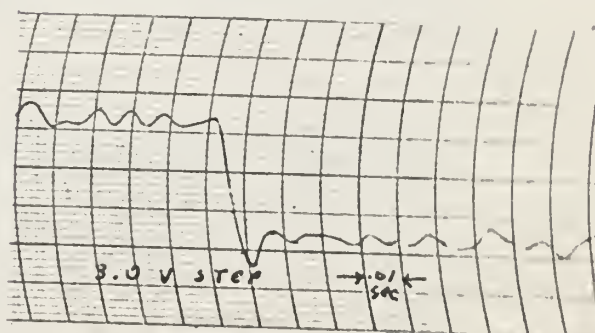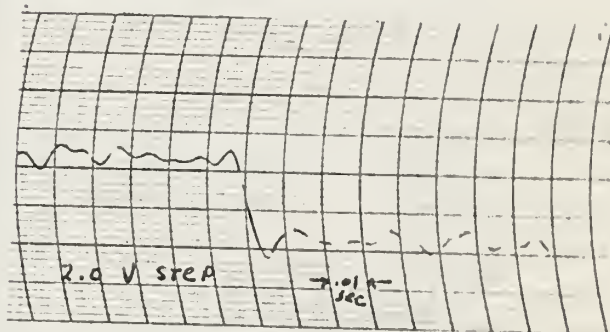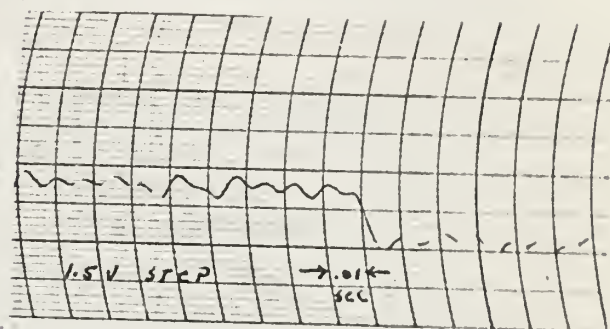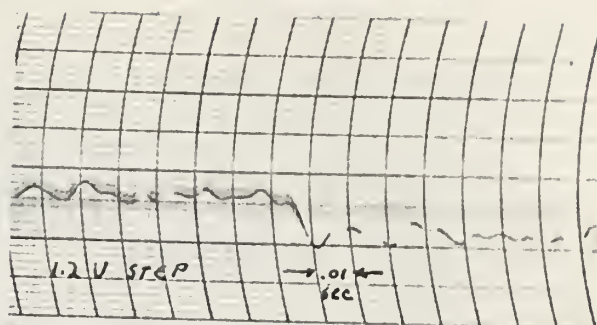
FIGURE 33   TRANSIENT TAPES FOR LINEAR OPERATION

8 VOLT STEP DOWN
INTO SATURATION

→.01←
sec

21-30   BRUSH INSTRUMENTS   DIVISION OF CLEVITE CORPORATION   CLE

8 VOLT STEP UP
OUT OF SATURATION

→.01←
sec

4 VOLT STEP UP
INTO CUT-OFF

→.01←
sec

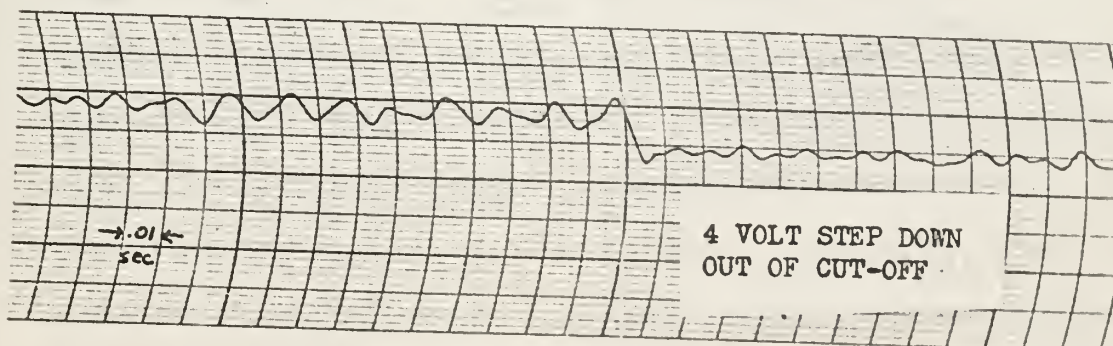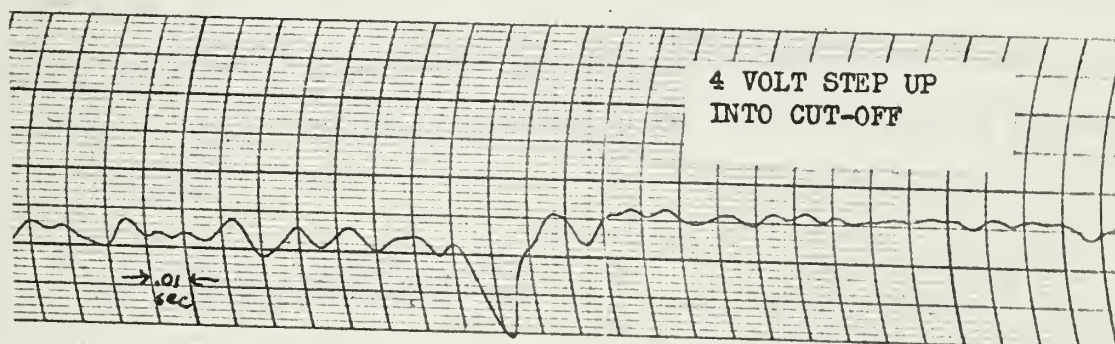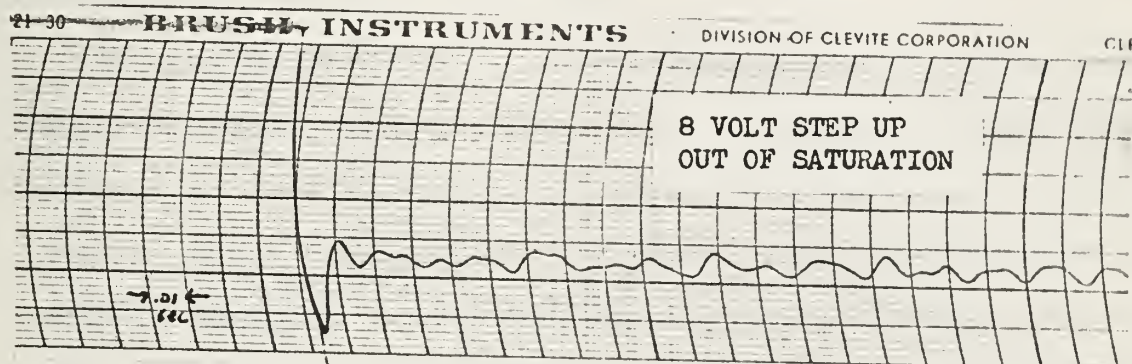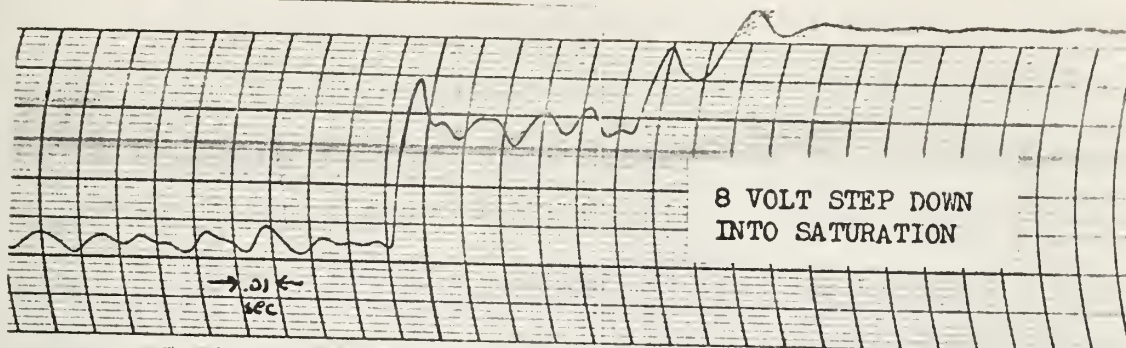4 VOLT STEP DOWN
OUT OF CUT-OFF

→.01←
sec

FIGURE 34   TRANSIENT TAPES FOR SATURATION AND CUT-OFF

same step was taken into saturation several times, no two transient wave shapes were alike. The most important variations however, were in the time constant evaluation in driving to the saturation limit. It was noted on the tapes that the regulator drives to some level and then remains there for an indefinite period of time and then drives on to a higher saturation level. This irregularity is believed to have its basis in the thermal properties of the transistors and thermistor of the regulator. It is important because of the very long apparent time constant required to drive the regulator to complete saturation.

Considering these factors, the following conclusions can be stated about the limiting regions. First, gain has little significance because no matter how big a step input, the output is the same if the regulator is driven to either "saturation" or "cut-off". Second, any step which is of sufficient magnitude to drive the regulator to its saturation limit, evidences a relatively long time constant in driving to complete saturation. This long time constant, which is a function of the thermal properties of the regulators components, was not analyzed because it was seen to vary slightly in its transient curve when repetitive steps of the same magnitude were applied.

B. The Frequency Response Tests.

A second major method of servo analysis testing is the frequency response test. This is a steady state component analysis. It is accomplished by applying a constant amplitude sinusoidal signal, which is varied through a range of frequencies, to the input of the component being tested. For each input frequency, the magnitude and phase shift of the output sine wave is read out. The frequency response furnishes information on the transfer function of the component. Or, if the component is

51

non-linear, the frequency response test can furnish a linear approximation of the component known as the describing function.

To obtain a series of frequency response tests on the voltage regulator, it was necessary to modulate the 400 cycle/second, three phase input voltage with a variable low frequency singal. As with the transient response tests, the problem, at first glance, seeme trivial. As the evaluation progressed, however, various difficulties presented themselves so that several methods were attempted before a satisfactory evaluation could be made. A brief discussion of the unsuccessful methods of frequency response testing follows.

A modulation frequency range of from 0.5 to 100 cycles/second and modulation amplitude range of from 0.5 to 7.0 volts peak was considered adequate. It was felt that the easiest way to accomplish this would be to use an amplified function generator to modulate the exciter field input of the main generator which would in turn produce a modulated three phase, 400 cycle output.

The circuit was set up and the modulated generator output was applied to the regulator. For any given modulation frequency, the input to the regulator appeared to be a very good sinusoidal approximation. In attempting to run the tests, however, it was found that there were variations in the generator output voltage because of either generator drift or a d.c. field drift. This meant that it was impossible to maintain a constant basic generator output operating point. Since the regulator was extremely sensitive to generator voltage variations, these minute deviations of the generator rms voltage caused the regulator output signal to lose its significance for frequency response analysis.

To eliminate the generator terminal voltage variations, it was necessary to use a second voltage regulator to stabilize the generator output.

This meant that it was no longer possible to apply the modulation signal to the generator exciter field. It was therefore, necessary to modulate the voltage signal between the generator and the voltage regulator being tested.

The first attempt to accomplish this modulation consisted of connecting the three phase generator output in series with the output of a three phase rotating sine wave generator whose output frequency could be varied by varying the speed of its prime mover rotation. It was felt that the electro-motive force generated by the three phase sine wave generator could be used to modulate the 400 cycle input to the regulator. When this system was tested, however, it was found that the generator did not modulate as expected. Rather, several undesireable frequencies were produced and the idea was discarded.

A second attempt to solve this problem was made using electronic circuitry. Three 6L6 power vacuum pentode tubes were connected together as triodes with their cathodes common. The common cathode was then biased to about -200 volts d.c. and connected to the netural wire of the generator output. The grids of the three tubes were also tied together and then biased negatively with respect to the cathode. The plates of the respective tubes were then connected to each of three phases of the generator output.

By placing a sine wave generator in the common grid circuit it was possible to have the tubes draw sinusoidal current from the lines whose frequency was dependent on the frequency of the sine wave generator in the grid circuit. Then, by placing a resistance in series in each of the lines at the output of the generator, the variable current drawn by the tubes would cause a sinusoidal voltage drop in the resistors and the net results would be a modulation of the voltage input to the voltage regulator being tested.

53

This method worked satisfactorily for very small modulation signals. Unfortunately, it was impossible to enlarge the magnitude of the modulation signals by either increasing the number of vacuum tubes or enlarging the series resistances in the lines.

The reason that additional vacuum tubes could not be paralleled into the circuit was that the 400 cycle line (plate) voltage varied over a range of 325 volts peak to peak. This large voltage variation meant that the tubes were driven to their extreme limits of linear operation and to obtain a satisfactory sinusoidal current variation, grid current had to be drawn some time in the cycle. These very tight tolerances made it impossible to satisfactorily parallel any appreciable number of tubes into the circuit.

It was found that when the line resistance was increased to larger values, the voltage regulator went into an unstable condition. The reason for this was that it was necessary to adjust the generator terminal voltage to allow for the voltage drop through the resistors and then leave the correct voltage at the terminals of the test regulator. The current drawn by the regulator was dependent on the input voltage to the regulator. Therefore, if too high a voltage were set at the generator terminals the regulator would draw little current and there would be only a small voltage drop across the series resistors and the regulator would drive to "cutoff". If, on the other hand, the generator terminal voltage were set lower and the regulator placed in the circuit, a much larger current would be drawn by the regulator causing a larger voltage drop across the resistors and the regulator would drive to "saturation."

It was experimentally found that a value of 10 ohms series resistance in each line was the maximum that could be used and still maintain the

54

stability of the regulator. Since this was insufficient to give a satis-
factory amplitude of modulation the vacuum tube circuitry was discarded.

Several attempts were then made to modulate the neutral wire of the
generator output. Since little current was drawn in the neutral line,
it was felt that it should be possible to vary the neutral wire sinusoidal-
ly with respect to ground thus modulating the input to the regulator. This
method was also unsuccessful because the impedance of the test circuit to
low frequency signals was very low and the modulation could not be sustain-
ed without large current variations.

Finally, it was decided to use the scotch yoke described in Chapter II,
to modulate the signal. Figure 35 is a circuit diagram showing the complete
test circuit employing the scotch yoke. The 400 cycle signal modulation
was accomplished by the sinusoidal modulating current drawn by the vary-
ing resistors in the scotch yoke. This current causes a sinusoidal volt-
age drop across the three small line resistors and thus a modulated signal
was obtained for the input to the test regulator. A photograph of the
test set up was taken and is shown as Figure 36.

Using this test circuit, families of frequency response tests were
taken in the frequency range from .5 cps to 30.0 cps. A series of tests
was made at each different magnitude of modulation from 0.5 volts peak to
peak to 10.0 volts peak to peak. A complete family of tests was made at
every integreal rms voltage input from regulator "saturation" to regulator
"cut-off".

The frequency response evaluations were read out on a high speed Brush
recorder. Two channels were used, one for regulator input and one for
regulator output. Upon completion of the tests, the data was evaluated
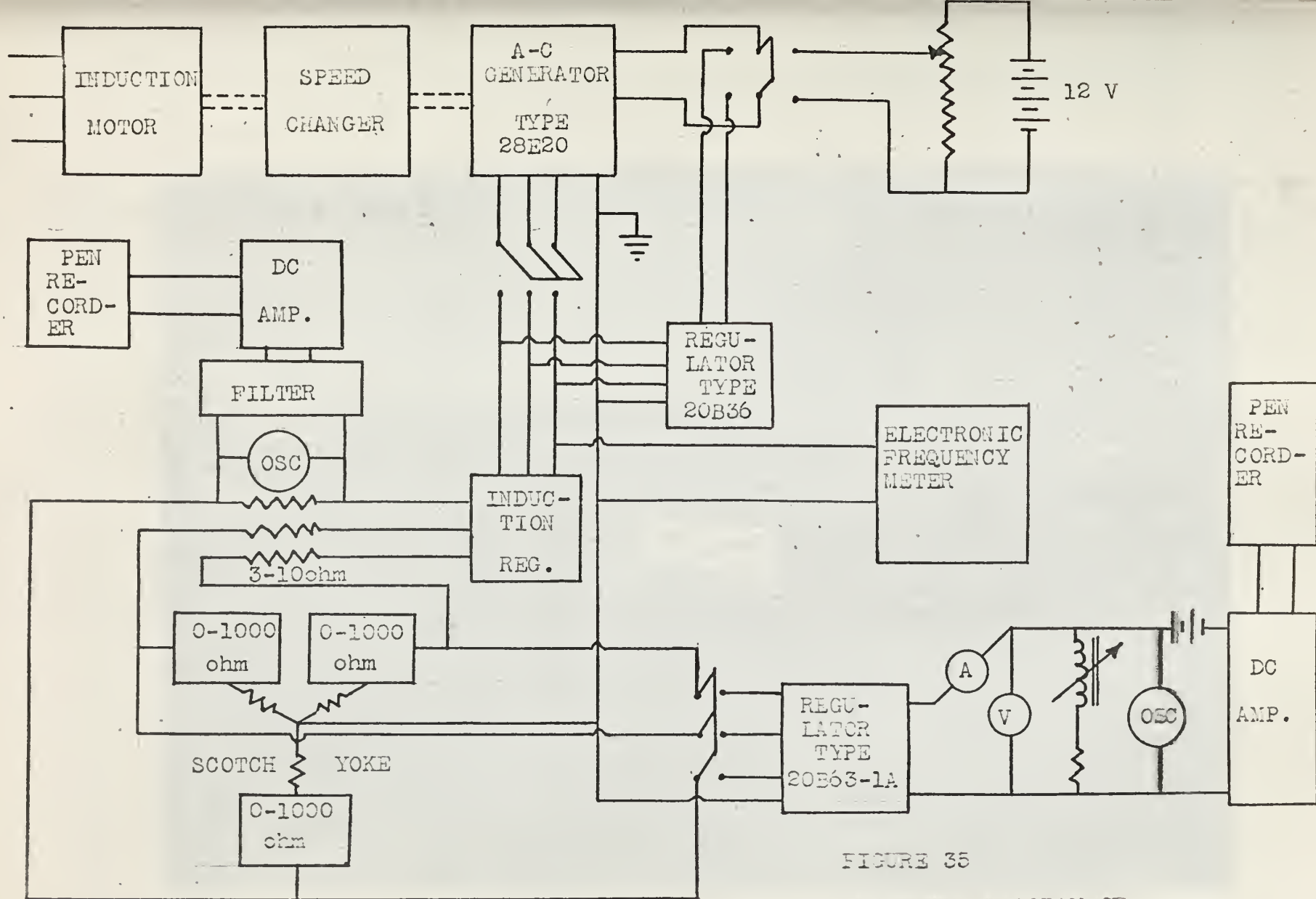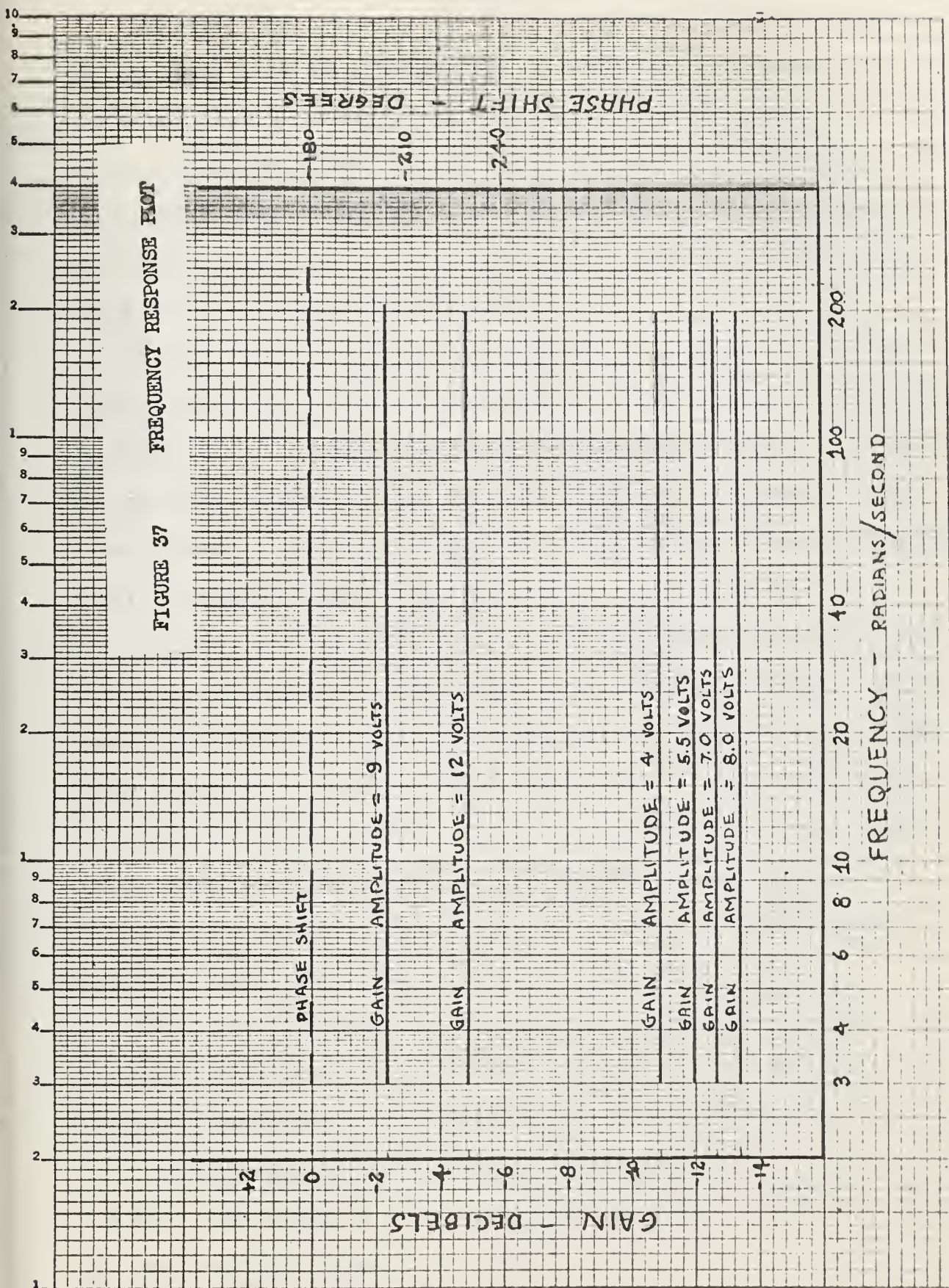and put on a Bode diagram which is shown in Figure 37.

55

FIGURE 35

SCHEMATIC DIAGRAM OF
FREQUENCY RESPONSE CIRCUIT

FIGURE 36   PHOTOGRAPH OF FREQUENCY RESPONSE EQUIPMENT

FIGURE 37   FREQUENCY RESPONSE PLOT

58

The first point which is immediately apparent in the Bode diagram

is that there is no break in gain nor any variation in the phase shift

out to the limits of measurement; which was 200 radians/second. In view

of the time constants shown in the transients section of this chapter, this

result is not surprising. Since the time constant is the reciprocal of

the break frequency, it was not expected that a definite frequency break

would occur below 300 radians per second.

A second point of interest, was that there was no variation in the

gain of the frequency response regardless of the magnitude of the modulat-

ing signal or of the 400 cycle voltage input operating point, as long as

the operating point was within the linear range of the regulator. This

constant gain in the linear range is also verified by the transient response

tests shown earlier in the chapter.

Figure 38 shows an experimental curve of the variation in d. c. regula-

tor output voltage for various 3 phase, 400 cycle input voltages. The re-

gulator linear region is that portion of the curve from 154 volts to 167

volts E in. The regulator operating point of 163.5 Volts (116 $\sqrt{2}$ rms)

is located in this region, but not at the midpoint of the range. Rather,

it is located well down toward the cut-off limit of 167.5 volts. At

slightly under 154 volts input, the output voltage runs out at a very

high gain to the saturation voltage of 14.8 volts d.c.

This curve shows the reasons for the gain variations shown on the Bode

diagram. As expected, when the gain was increased beyond the linear range,

the first non-linearity became apparent. This non-linearity was a wave

distortion and gain reduction because of the cut-off limit. As the modulat-

ing signal was increased further, the gain was further reduced and the out-

put wave even more clipped by cut-off.

59

FIGURE 38   REGULATOR CHARACTERISTIC CURVE

E_{IN} IN VOLTS PEAK (RMS$\sqrt{2}$)
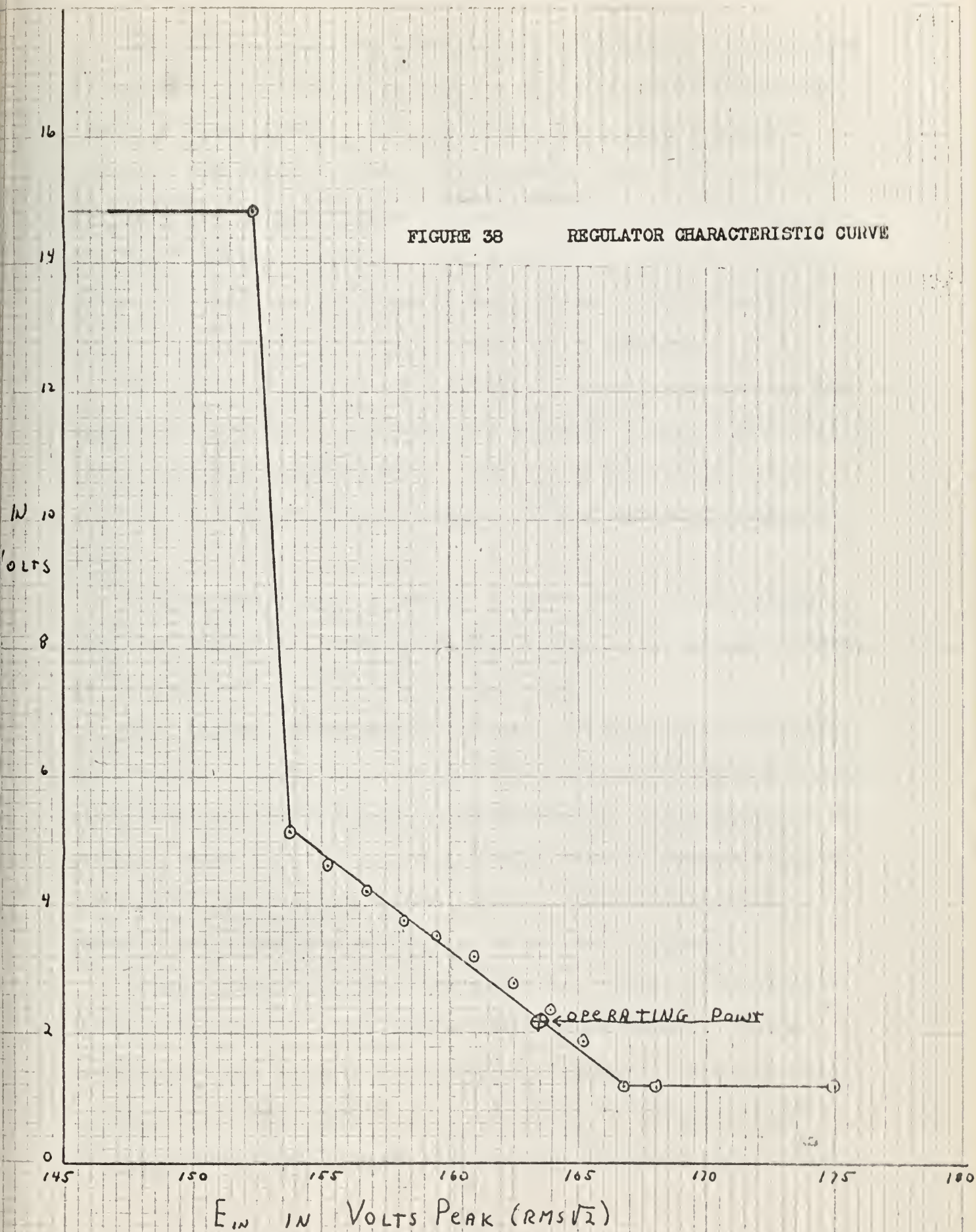
Eventually, a modulating signal of large enough magnitude was applied to reach both saturation and cut-off. At this time, the saturation non-linearity became apparent. This was evidenced by a sharp increase in gain and a pronounced increase in the saturation side of the output wave. The reason for the gain increase was the very high slope of the line from the linear region to saturation. As the modulating signal was increased beyond this point, the gain began to fall off slowly again because both "saturation" and "cut-off" were the limits of the regulator.

The effects of saturation and cut-off are readily seen from the Bode diagram of Figure 37. It can further be seen that the only effect of these limiting cases is a gain variation. That is, all phase shifts for any magnitude of modulating signal remained at 180° throughout the frequency range.

From the Bode diagram, therefore, it would appear that the voltage regulator responds as a degenerative gain feedback, the magnitude of whose gain is dependent on the terminal voltage variation.

This, however, is not exactly the case. The reason for this was that the mechanical limitations of the scotch yoke made it impossible to increase the modulation frequency beyond 200 radions/second. It was known from the transient response data that there definitely was a measureable regulator time constant and therefore a break frequency. This indicates that the regulator was not quite a pure gain as it appeared in Figure 37.

Further, evidence of the two response times previously discussed in the transients section of the chapter again became apparent This was verified by noting that for low modulating frequencies, the output of the regulator was a pure sinusoid. As the frequency was increased, however, the output wave gradually became more distorted because it took the output

61

wave progressively longer to get to its positive peak than it did to get to its negative peak. This phenomenon became more apparent as the frequency was increased toward the break frequency of the slower time constant.

Figures 39, 40, 41 and 42 are Brush recorder tapes, for a 116V line to neutral base operating point, showing the various output wave distortions for various magnitudes of sine wave modulation. As was true with the transient tests, the Brush recorder severly attenuated the input and output signals. Oscilloscopes and meters were therefore used to assure a constant amplitude input and to verify gain evaluations. All the recorder tapes also show large noise levels which are believed to be a function of the generator exciter commutator.

The series of tapes in Figures 39 and 40 show two different magnitudes of modulation in the linear range. The only non-linearity appearing in these tapes is the gradual deviation from a sine wave with increasing frequency because of the two component time constants. To allow more tapes to be shown on the same page, no samples of the input wave are shown in the figures. Therefore, no indication of phase shift phenomena can be observed. A careful study of all tapes was made, however, and on no run was there the slightest indication of any phase shift other than 180 degrees.

Figure 41 shows a series of tapes whose modulation magnitude was sufficient to drive the regulator to "cut-off" but not to saturation. All tapes show the pronounced clipping of the cut-off region and also, to a lesser extent, the distortion of the two time constants was once again apparent.

In Figure 42 a large amplitude modulating signal was used and the regulator was driven to both saturation and cut-off. Lines have been drawn through the zero point of these tapes to indicate the very large

62

output voltage of the regulator when it is driven to saturation. This large saturation voltage partially obscured the cut-off and time constant distortion of these waves, but careful scrutiny of the tapes will show that they are still there.

Several frequency response tests were taken with a small resistance inserted into the dummy load and the output read across this resistance. This effectively gave a response of d.c. current out versus voltage in. These current responses were much like the voltage tapes with the exception that they showed a break frequency which corresponded to the L/R time constant of the dummy load indicating that the regulator output current was dependent on the regulator load.

In summation it may be said that the frequency response verified the transient response data indicating two time constants. Furhter, the frequency response indicated several non-linearities in the regulator gain because of the saturation and cut-off limits. If a plot of this describing function were made on a Nichols Chart, it would appear as a straight line of gain variation on the 180 degree axis. The effect of the two time constants on this describing function plot can not be predicted because of the lack of sufficient data in the high frequency range.

No attempt was made to get an analytic expression for this describing function, because along with the other regulator non-linearities, the regulator is disymmetrical about the zero point of the voltage characteristic curve. This disymmetry gives rise to a very complicated analytic equation for the regulator describing function and hence the derivation was not considered useful.

f = 4 cps
.2 volt / line

f = 8 cps
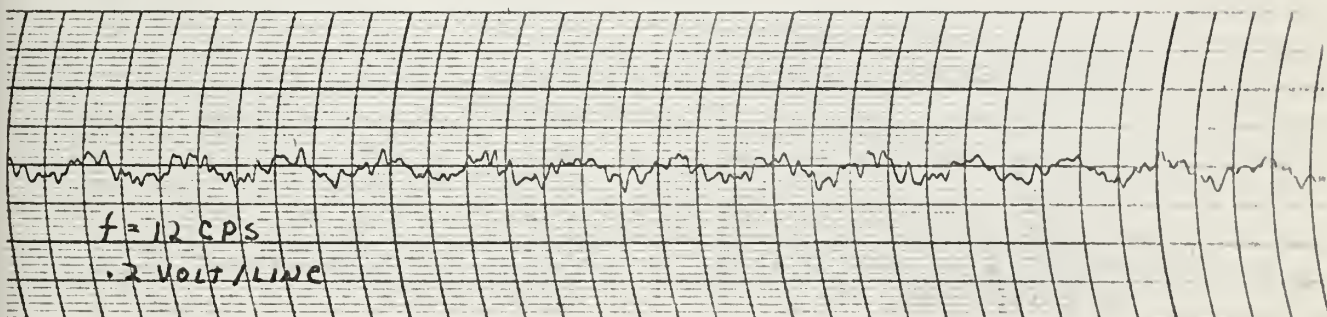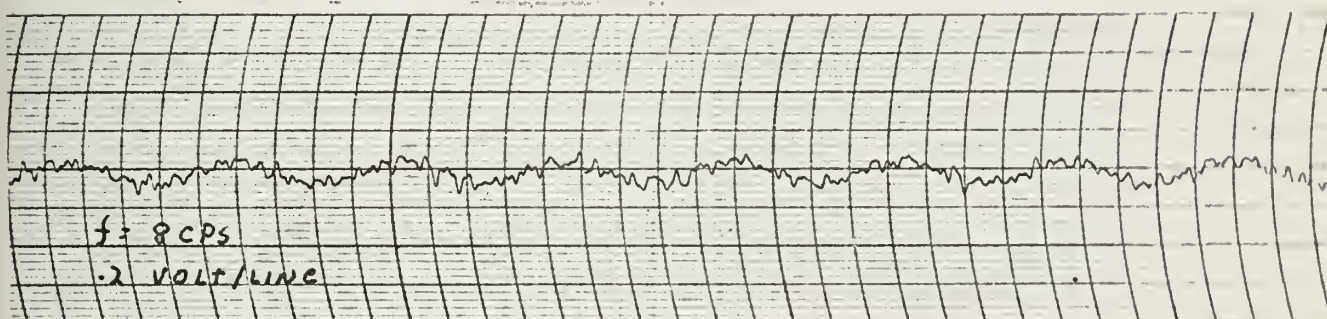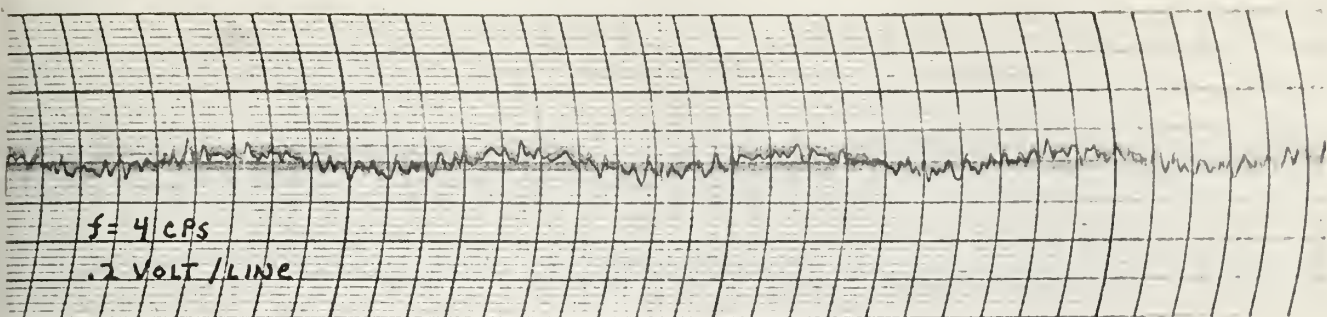.2 volt / line

f = 12 cps
.2 volt / line

f = 17 cps
.2 volt / line
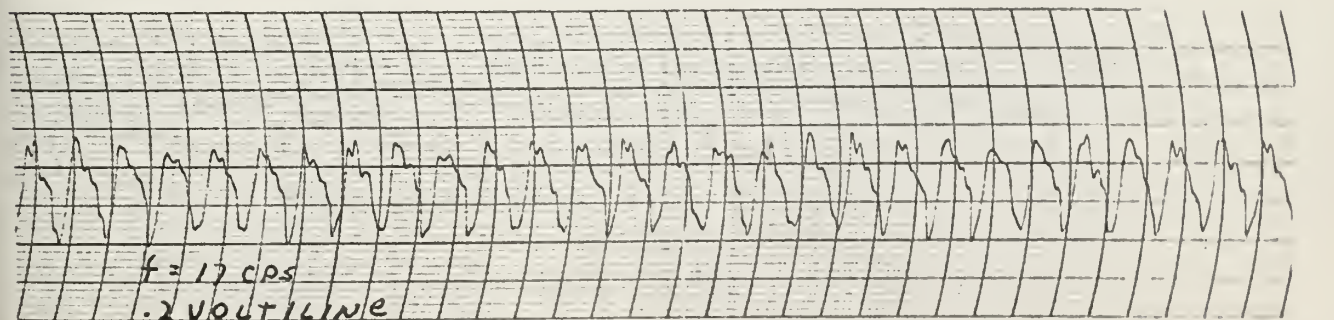
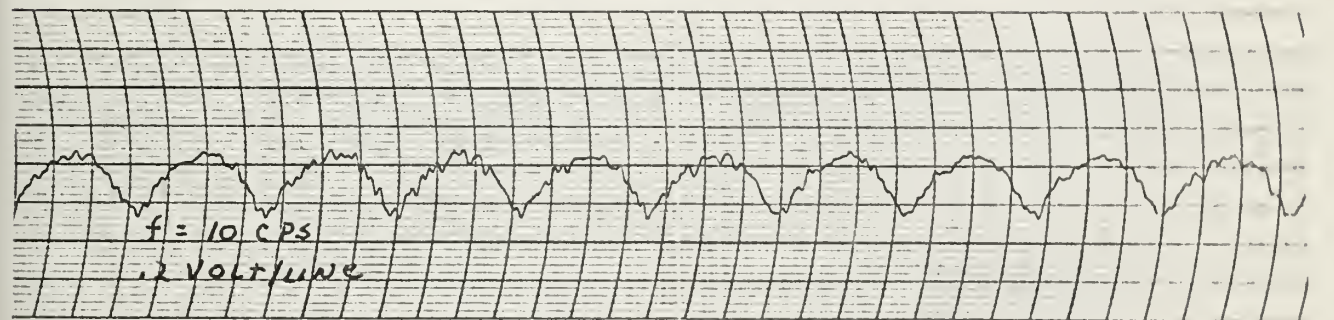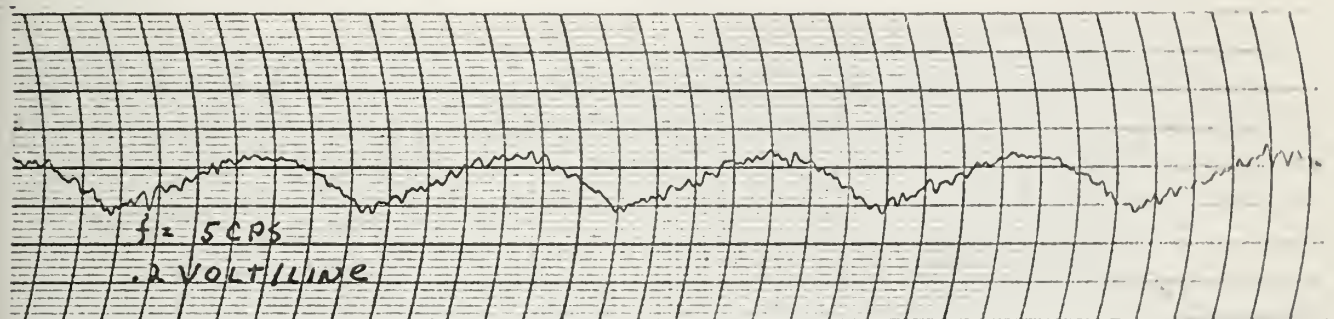FIGURE 39   FREQUENCY RESPONSE TAPES -- .6 Volts Modulation
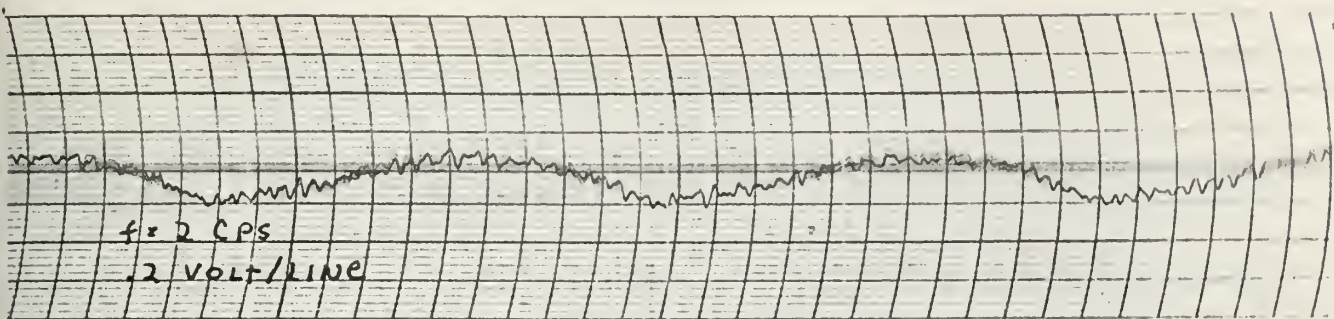
64

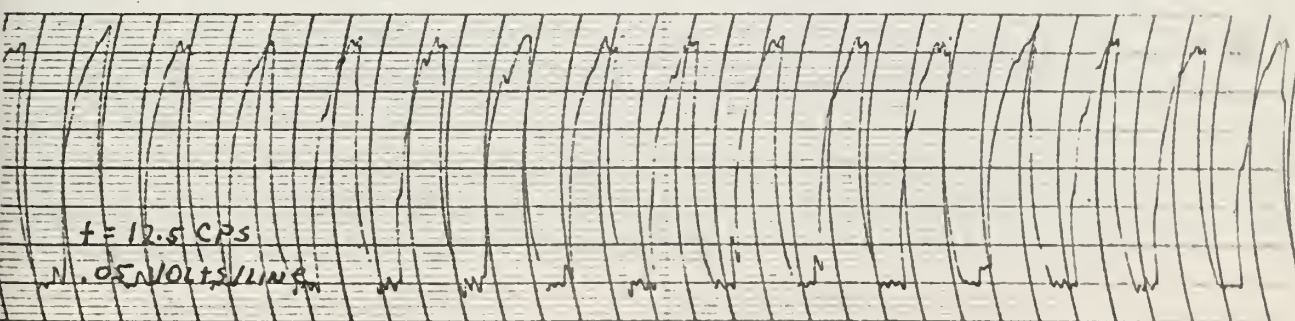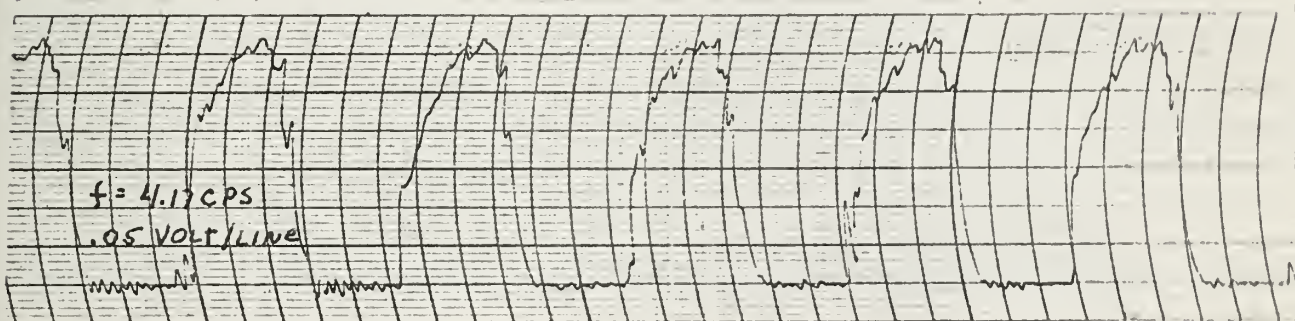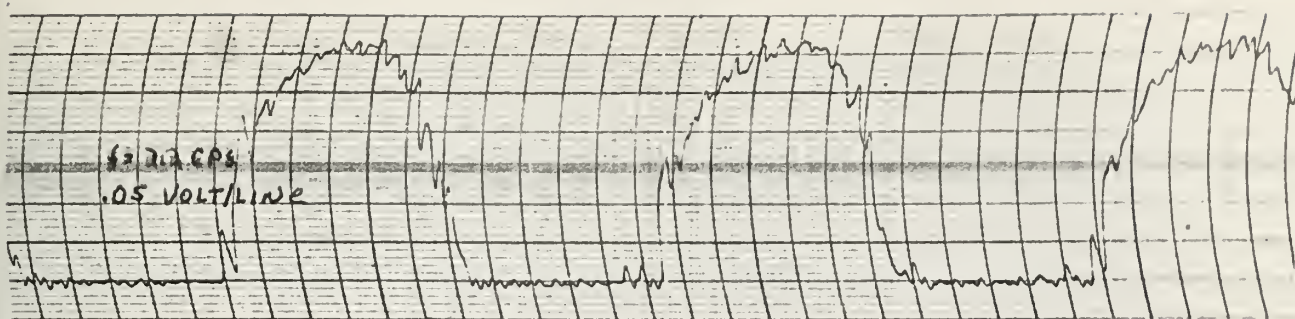FIGURE 40   FREQUENCY RESPONSE TAPES --   2 Volts Modulation

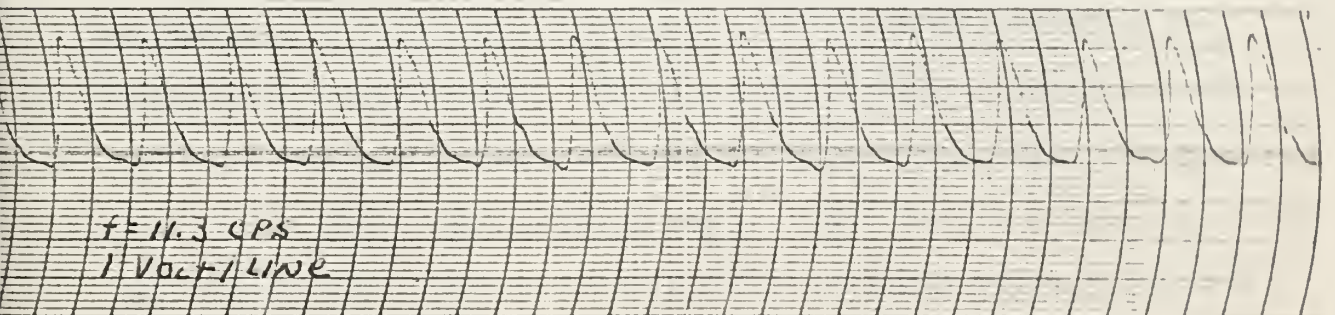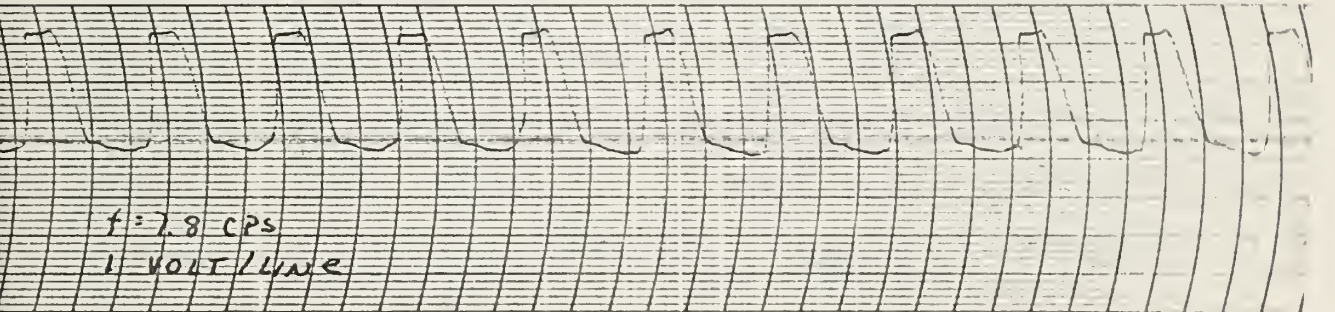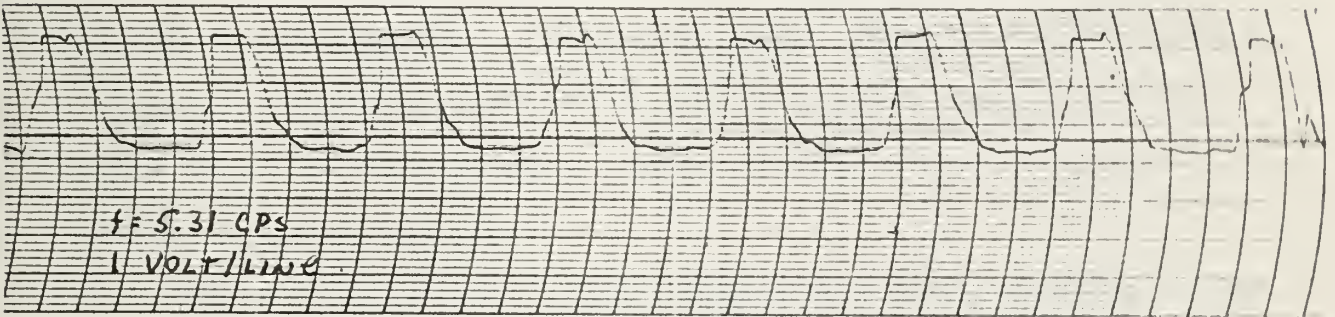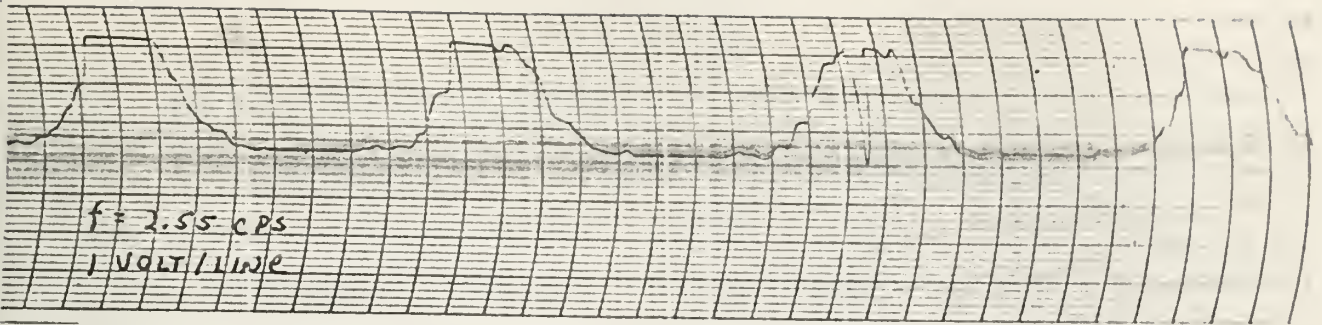FIGURE 41   FREQUENCY RESPONSE TAPES -- 4 Volts Modulation

FIGURE 42   FREQUENCY RESPONSE TAPES -- 10 Volts Modulation

CHAPTER V

SYSTEM TESTS

A.   System Definition and Regulation Performance

Thus far the analysis as described in previous chapters has been confined to testing of individual components. But, a feedback control system, the aspect considered in this paper, may be defined as a control system in which the difference between a reference input and some function of the controlled variable is used to supply an actuating signal to the control elements. It logically follows that the progression of experiments should now include the regulator in its rightful position with respect to the alternator. Hence, the closed loop system is now to be defined and analyzed.

Figure 43 illustrates in block diagram form, the closed loop system used. Several deviations from normal feedback control system definitions were required in this system. The speed of the generator was considered to be constant in all cases except where the contrary is noted. The reference input to the system was the potentiometer setting (R-10, Figure 8). However, since this reference was a constant for normal operation of this system, varying this input in the testing would have had little physical significance to the system performance.

As seen previously, the regulator operates as a pure gain over a considerable bandwidth when operated within the linear portion of the voltage gain characteristic. The closed loop analysis, with the generator being considered linear over the narrow operating range, was expected to follow linear control system theory. With the aid of the closed loop analysis the system performance was investigated and more specific considerations of regulator performance were made.
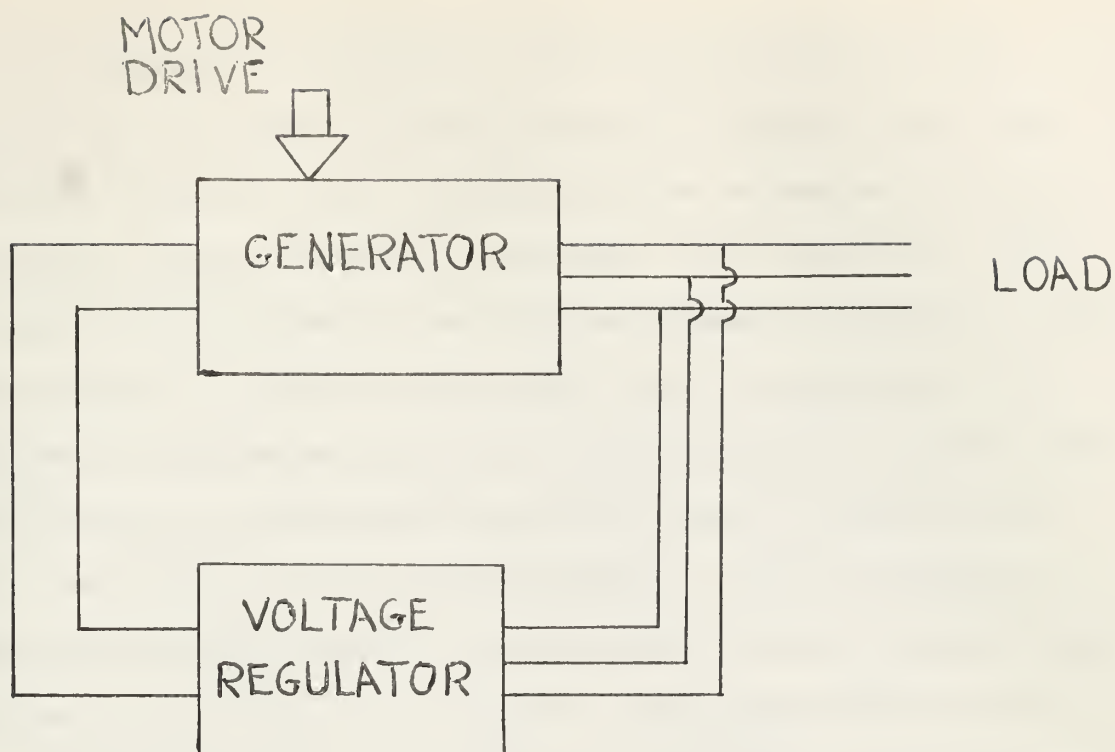
68

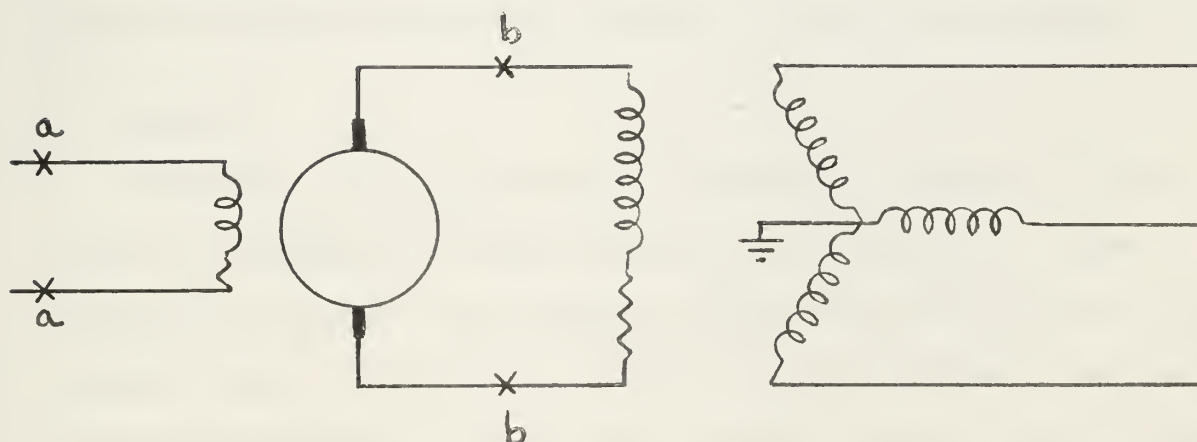FIGURE 43   SYSTEM BLOCK DIAGRAM

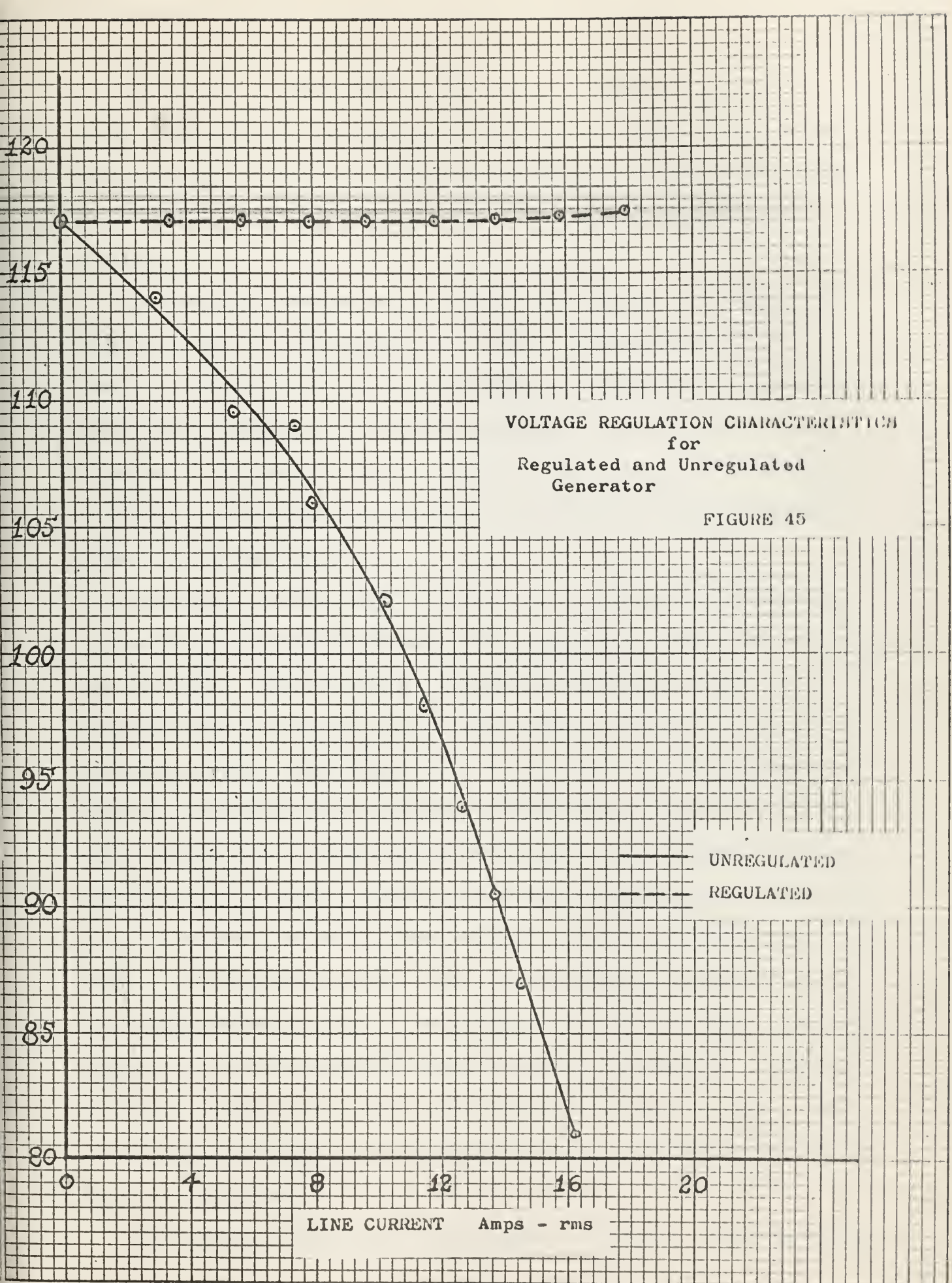FIGURE 44   GENERATOR TESTING POINTS

The true test of a regulating scheme is its performance in its designed function, namely regulating a generator terminal voltage over a variation of loads. Hence, diverging from the servomechanism concept, a regulation curve was obtained. A variable, unity power factor load was imposed upon the generator both with and without the regulator in place. Figure 45 shows the graphical test results. Due to overloading of the prime mover arrangement, no data could be obtainted at greater than half load. This limitation also necessitated running this test in a manner to add load to the generator in its unloaded condition. This was contrary to normal machine testing procedures, however, this procedure was satisfactory to illustrate the effect of the regulator. The results obtained did indicate the effectiveness of the regulator in its steady state performance.

While running these tests the variable speed drive was constantly adjusted to maintain the output frequency (and hence the generator speed), at 400 cycles per second. Thus the operational environment of a "stiff" drive was maintained. Also, a constant field voltage was maintained for the unregulated test.

It can be noted from the characteristics of Figure 45 that the regulator performs well within its rated $\pm$ 2% regulation tolerance.

B. Generator.

In order to close the system and to predict the results, it was necessary to determine a transfer function for the generator. Experimentally this was done with frequency response tests and internal circuit transient tests. In theory, the complexity of the synchronous machine and its transient behavior was prohibitive. In this respect, very little was known about the generator, its windings and structural details. The testing

70

VOLTAGE REGULATION CHARACTERISTICS
for
Regulated and Unregulated
Generator

FIGURE 45

UNREGULATED
REGULATED

LINE CURRENT   Amps - rms

71

K·E   10 x 10

assumed a constant speed source. Due to lack of specific information

about the generator a mathematical approach to the transfer function was

not attempted. It was felt that the experimentally determined data would

be more useful since analysis of the generator was not of primary im-

portance.

An additional problem in this phase of testing was the integrally

mounted exciter with the generator. Clearly, representation of the

machine by a semi-equivalent circuit diagram was desirable. However, for

the answers required, it was deemed unnecessary to go this deeply into

synchronous machine circuitry and theory of performance. As illustrated

in Figure 44, the machine was broken into two sections for the transient

tests at points aa and bb.

The exciter was investigated first. A d-c voltage was impressed at

aa, and with appropriate metering of the voltage and current, the resistance

was determined. Next, 6) cps a-c voltage was applied at aa and the im-

pedance of the circuit was found. These tests were made with the machine

rotating at rated speed of 8000 rpm. By the simple relationship between

impedance, resistance and reactance, it was determined that the circuit

had a resistance of 5.3 ohms and an inductance of .114 henries. The time

constant of this circuit, defined as the ratio of inductance to resistance,

was .022 seconds. To verify these results, a series of dynamic tests were

taken. In the dynamic tests, a step of d-c voltage was applied at aa and

the voltage variation at bb was recorded on a pen type recorder. The result-

ing tapes showed an overdamped system with a time constant of .02 seconds.

This time constant agrees with that obtained in the previous test. Addi-

tional tests run with d-c meters in both test points showed a unity voltage

gain for the exciter.

The generator proper was tested somewhat similarily. Applying both a-c

and d-c voltages at bb produced information to give the resistance and inductance of the circuit as in the previous case. These values were found to be a resistance of .5 ohms and an inductance of .00944 henries. The time constant produced by this combination is .0189 seconds. To determine the gain of the generator, a d-c voltage was impressed at bb sufficient in magnitude to produce voltage of 115 volts, rms line to neutral, at the output of the generator. The input voltage was determined by metering while the output was read, peak to peak, on an oscilloscope. The input voltage was varied in small amounts to give a range of output voltages about the designed operating point. The voltage gain of each setting was determined by a simple ratio of peak voltage over d-c voltage, and then all the runs were averaged to obtain a constant gain figure for this narrow operating range. This gain was determined to be 63.4. The difference in voltage gains in the range of output voltages of 110 to 118 volts rms, line to neutral, was only .2; hence, it was felt that the gain taken, and taken as linear over the range in question, was a reasonable approximation.

Having determined the gain and time constants for each section of the generator, verification of the generator characteristics was done with a frequency response for the complete unit. Figure 46 shows the equipment and its arrangement for the frequency response testing.

Due to the power requirements of the exciter and the fact that it required a d-c level, some difficulties were encountered. It would have been a simple matter to superimpose an a-c signal upon the d c level if a suitable sine wave generator had been available that is, a sine wave generator with sufficient power output. Since such equipment was not available, it was necessary to interject an amplidyne generator to amplify and combine the input signals. A minor problem encountered in this arrangement was the

12 VDC

74

AMPLIDYNE GENERATOR

GENERATOR

FUNCTION GENERATOR

OSCILLOSCOPE

OSCILLOSCOPE
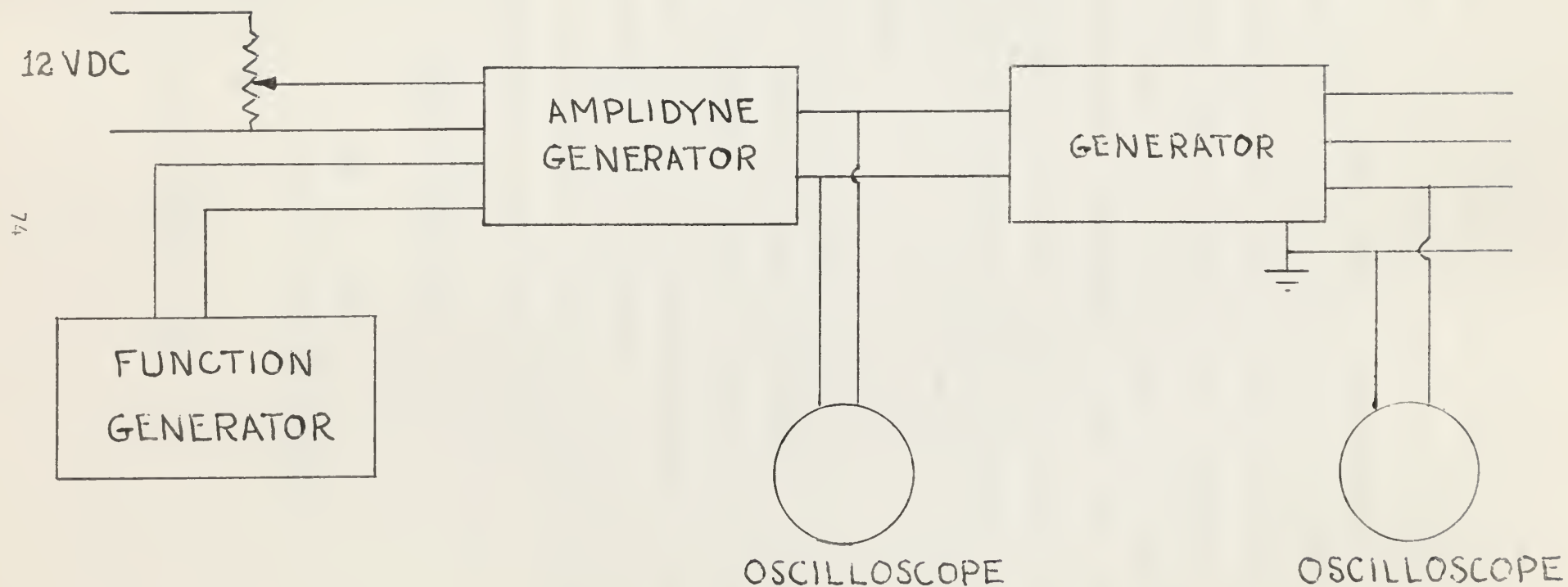
SCHEMATIC DIAGRAM OF GENERATOR FREQUENCY RESPONSE CIRCUIT
FIGURE 46

brush noise of the amplidyne generator. To effectively circumvent this problem, a calibration curve was made and used to control the input to the exciter. Thus knowing the input sine wave magnitude and having the ability to maintain it constant, the output modulation magnitude was read from the oscilloscope. Phase shift was unattainable due to the amplidyne noise. Figure 47 shows the results of the frequency response test plotted in the normal Bode diagram form of gain in decibels versus frequency in radians per second. The asymptotes, shown as dashed lines, were obtained from the previous tests and show that the experimental accuracy of the frequency response corroborated the transient tests. The initial gain of the response was 36.8 db which corresponded to a 63.4 voltage gain. The Bode diagram of Figure 47 was an average of several responses taken at different input magnitudes.

The Bode diagram shows a second order transfer function for the generator as was predicted. The actual response approaches a 12 db per octive slope at the higher frequencies. Using the frequency response for verification and the transient data for actual break frequencies, it was possible to write the transfer function for the generator. The break frequency in radians per second is the reciprocal of the time constant in seconds. The linear transfer function thus obtained was of the form:

$$G = \frac{K_a}{(s\tau_1 + 1)(s\tau_2 + 1)}$$

where,

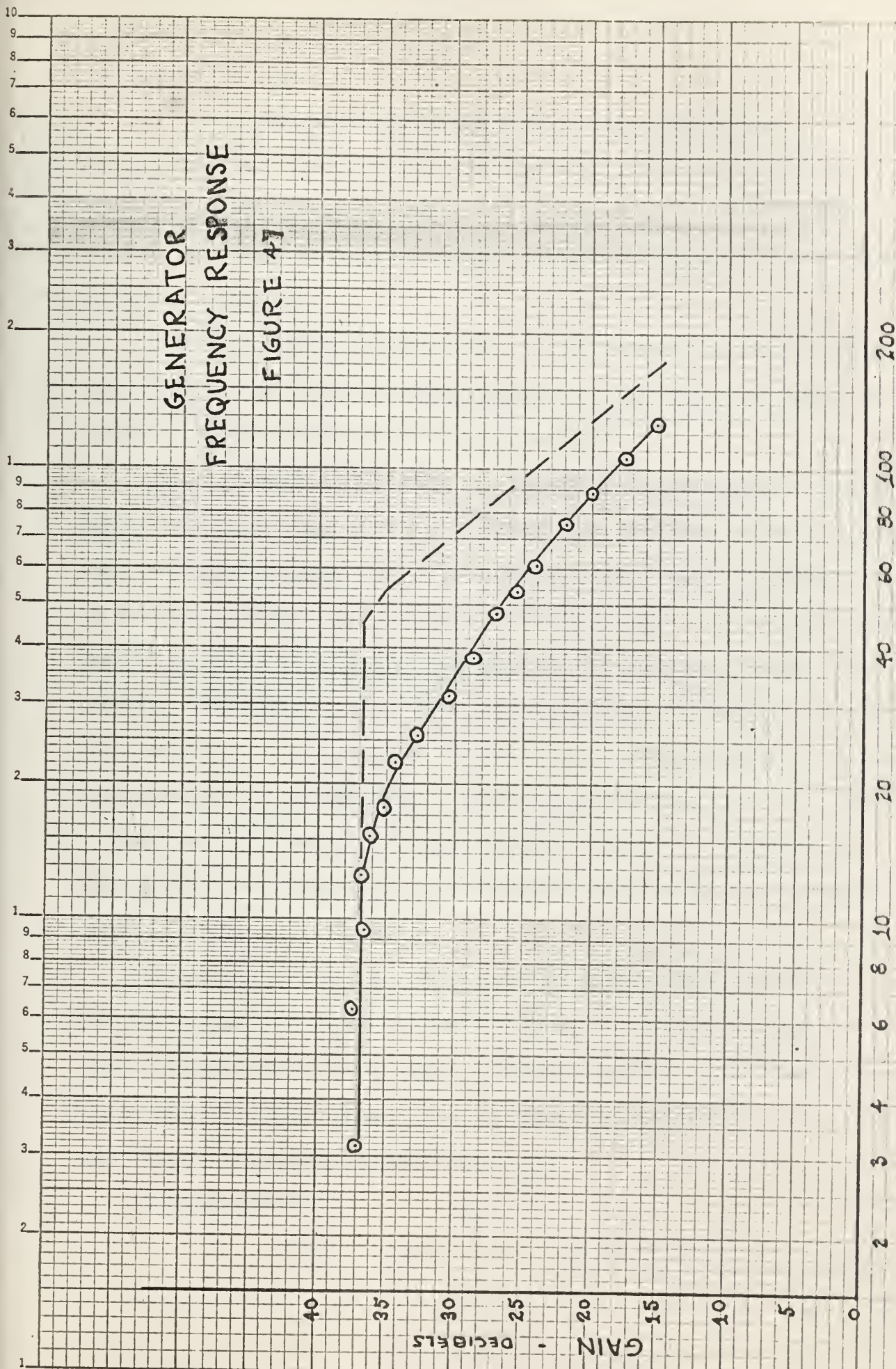$$K_a = \text{gain}$$
$$\tau_1 \text{ and } \tau_2 \text{ are time constants}$$

Substituting values obtained gives

$$G = \frac{63.4}{(s.019 + 1)(s.022 + 1)}$$

75

GENERATOR
FREQUENCY RESPONSE

FIGURE 47

GAIN - DECIBELS

FREQUENCY - RADIANS/SECOND

C. System Function.

At this point, having developed the "linear" transfer function for the generator and a function for the regulator in the previous chapter, a system characteristic function could be determined. A relationship between the change of system terminal voltage with respect to load current and time was desired.

In order to proceed analytically, it was necessary to define, more specifically, the system parameters involved. Thus Figure 48 shows the system in detail with corresponding definitions.

Since, as shown earlier, the non-linearity of the regulators was essentially a gain change that was dependent upon the input magnitude, and that the 180 degree phase shift was constant, the system as shown in Figure 48 held for all magnitudes of terminal voltage change. For magnitudes of change sufficient to drive the regulator out of its linear region, the term G_{reg} would have a value other than as defined in Figure 48 and would be a variable. The development done and included herein was for the linear system where G_{reg} was constant. However, qualitatively from the function as developed, the operation in the non-linear regions of operation for the regulator were predicted by appropriately considering the increase or decrease of G_{reg}.

The expression for $V_o(t)$ indicates that a step change in the load current would produce a damped sinusoidal change in terminal voltage with a final constant value only slightly different from zero. The time constant of the damped sinusoid showed that the decay was very rapid, even though the initial displacement approximated $I_a r_a$.

In the expression,

$$\Delta V_c = -I_a r_a \left[1 - \frac{13.5}{(s \cdot 0.1? \ldots \ldots 1) \ldots 3.3?} \right]$$

77
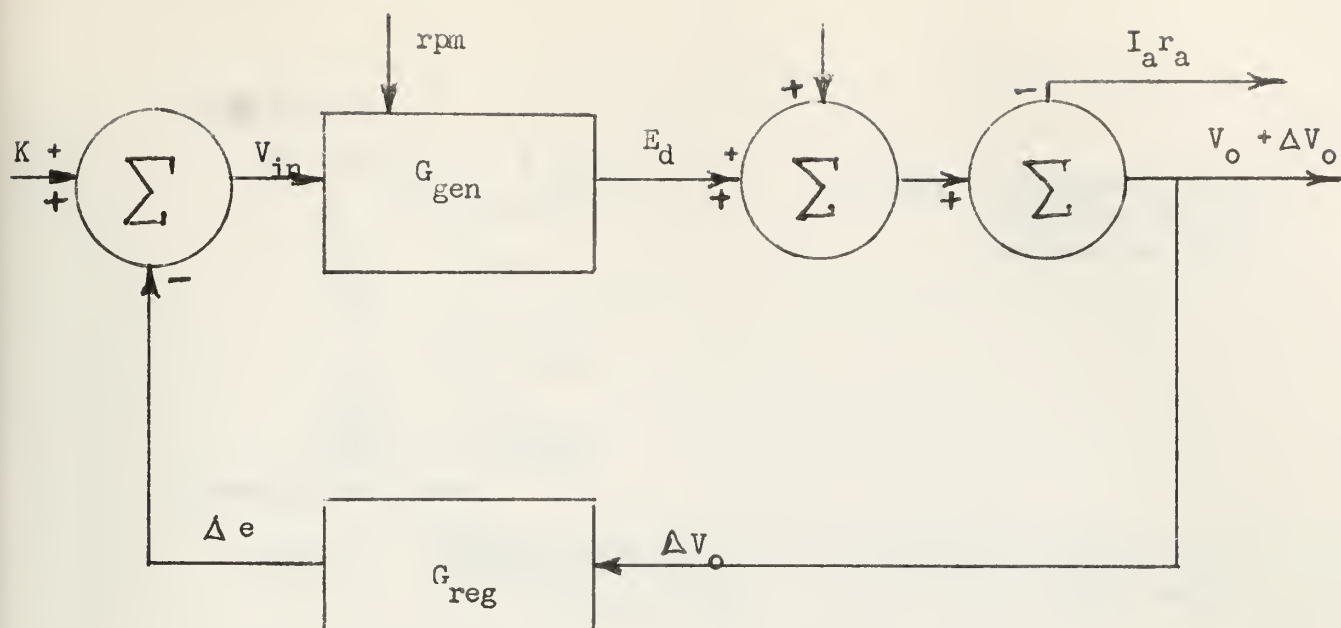
Definitions:

K ≡ Constant regulator output to give V_o 116 volts; K 2.46 volts

$\triangle$ e ≡ ± variance of regulator output with respect to K

V_{in} ≡ Input to generator exciter

E_d ≡ Generator developed voltage less residual

E_r ≡ Residual voltage output of generator

I_a ≡ Armature current

r_a ≡ Armature resistance

V_o ≡ Normal output voltage   116 volts rms

$\triangle V_o$ ≡ ± change in V_o from 116n volts

$$G_{gen} = \frac{63.4}{(s.0189 + 1)(s.022 + 1)}$$

$$G_{reg} = .315 \quad \text{for "linear" region of operation}$$

$$E_r = 8 \text{ volts}$$

FIGURE 48   SYSTEM BLOCK DIAGRAM

Relationships:

$$V_c + \Delta V_o = E - I_a r_a$$
$$E = E_d + E_r$$
$$\frac{E_d}{V_{IN}} \cdot G_{gen}$$

$$V_{IN} = K + \Delta e$$
$$\frac{\Delta e}{\Delta V_o} = -G_{reg}$$

Note: All quantities are functions of the LaPlace variable s.

Substituting gives,

$$\Delta V_o = \frac{K G_{gen} + E_r - V_6}{1 + G_{gen} G_{reg}} - I_a r_a \left[\frac{1}{1 + G_{gen} G_{reg}} \right]$$

For inputs of sufficiently small magnitude and relatively slow frequencies which would maintain a "linear" system, the first term of the above equation is approximately zero.

Hence,

$$\Delta V_o = -I_a r_a \left[\frac{1}{1 + G_{gen} G_{reg}} \right]$$

$$\Delta V_o = -I_a r_a \left[\frac{(s.0189 + 1)(s.022 + 1)}{(s.0189 + 1)(s.022 + 1) + 19.95} \right]$$

which rearranges to

$$\Delta V_o = -I_a r_a \left[1 - \frac{19.95}{(s.0189 + 1)(s.022 + 1) + 19.95} \right]$$

Where the load is applied in step fashion, $I_a(s)$ has the form $\frac{I_a}{s}$, giving

$$\Delta V_o = -\frac{I_a r_a}{s} + \frac{19.95 \, I_a r_a}{s \left[s^2 (4.16 \times 10^{-4}) + .0409 s + 20.95 \right]}$$

In standard form is:

$$\Delta V_o = -\frac{I_a r_a}{s} + .952 \, I_a r_a \left[\frac{1}{s \left(\frac{s^2}{(224.5)^2} + \frac{2(.2185)}{224.5} s + 1 \right)} \right]$$

79

where:

$$\zeta = .2185 \qquad (\text{DAMPING RATIO})$$

$$\omega_n = 224.5 \qquad (\text{NATURAL FREQUENCY})$$

The inverse transform is,

$$\Delta V_o(t) = -I_a r_a + .952\, I_a r_a \left[1 + \frac{\epsilon^{-49.1t}}{.9758} \sin\left(224.5(.9758)t - \text{TAN}^{-1}\frac{.9758}{-.2185} \right) \right]$$

$$\Delta V_o(t) = -.048\, I_a r_a + .975\, I_a r_a\, \epsilon^{-49.1t} \sin\left(219t - 102°38' \right)$$

the term in the parentheses, for low frequencies, took the form:

$$1 = \frac{13.95}{20.95} \approx \frac{1}{20.95}$$

This attenuation factor was applied to the armature drop with respect to the terminal voltage. Thus if I_a was changed sinusoidally, at low frequencies, the attenuation prevented significant terminal voltage variations. Even higher frequencies were attenuated by a large, but decreasing value. The attenuation factor was evident in several system tests, and predicted a good performance for the system.

D. System Dynamic Testing.

It was desired to investigate the system response to step application of different power factor loads to determine the effect of the power factor upon response. Two loadings were chosen; unity and .75 power factor. The diagram of Figure 49 represents the equipment configuration for both sets of tests. The procedure is evident from the equipment used. A load of the specified power factor was switched on or off the system. The recording oscilloscope was triggered electrically by the switch which had a mechanical time advance incorporated in order to obtain the full response. Photographs were obtained with a Pollaroid camera mounted upon the oscilloscope. Satisfactory pictures were obtained using an open shutter; therefore, the camera did not have to be synchronized to the switch.

The procedures involved in this test presented no great difficulty. However, due to the laboratory set-up one unrealistic condition did exist. The induction motor used to drive the generator was rated at only 7-1/2 horse power and the generator drew over 13 horsepower at full load. Hence, full load conditions could not generally be tested. And, with any significant loading, there was a definite speed reduction by the motor. The speed changes were not determined explicitly, but the electronic frequency meter

81
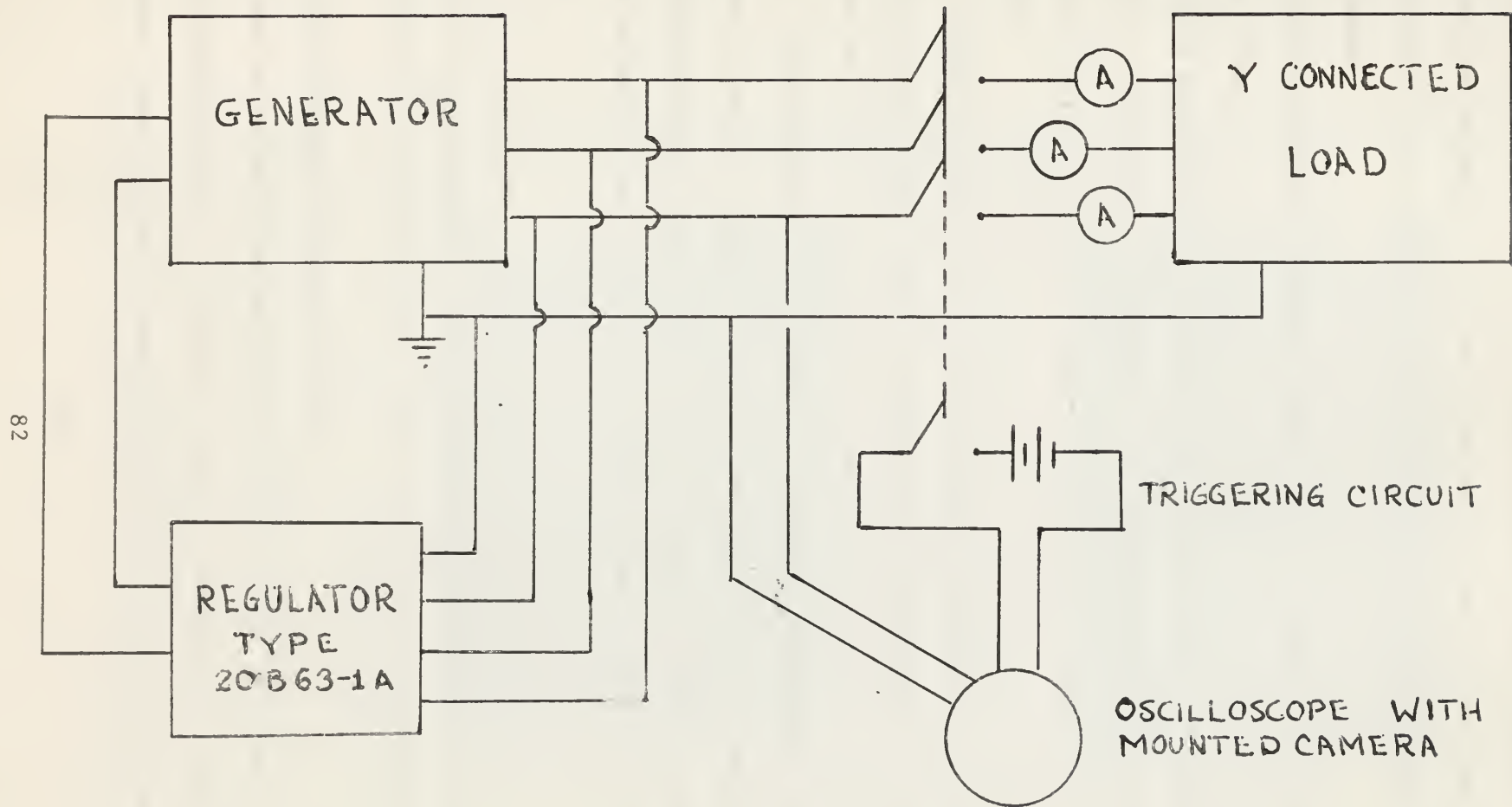
SCHEMATIC DIAGRAM OF SYSTEM TRANSIENT TEST CIRCUIT
FIGURE 49

was used on the output of the generator to indicate speed changes through
frequency variations. To protect the regulator, load variations which
dropped the frequency below 380 cycles per second were not sustained.
Variations of this magnitude were observed with loading at about 16 amperes
per phase.

Figures 50 and 51 show photographs of the system terminal voltage
taken during this test for both power factor conditions. As could be
seen from the photographs, the accuracy of the transient response data was
limited, in the high slope regions, to the time displacement of the peaks
of the 400 cycle per second voltage. However, the results were very satis-
factory.

Figures 52, 53, 54, and 55 are transient responses for the system for
load application and removal for both power factor conditions. That the
system reacted as a damped sinusoid, as predicted earlier, was quite evi-
dent. Also evident was the effect of a lagging power factor load. In
Figures 54 and 55, the overshoots and settling times were much greater than
for the unity power factor case. In all cases, the effect of prime mover
speed variations was evident in the final values to which the system set-
tled.

The correlation of these results with the system function as developed
previously was attempted. Though exact correlation was not obtained, the
correlation was considered good within the limits of experimental accuracy.

E. System Frequency Response Testing.

Having completed the series of transient tests, frequency response
tests were undertaken. In order to conduct these tests, a controlled
frequency signal of desired magnitude had to be imposed upon the system.
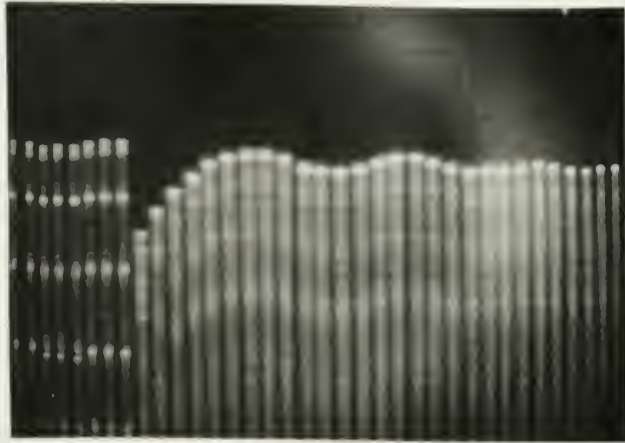
A.   Load Application   Phase Current = 15.5 amps
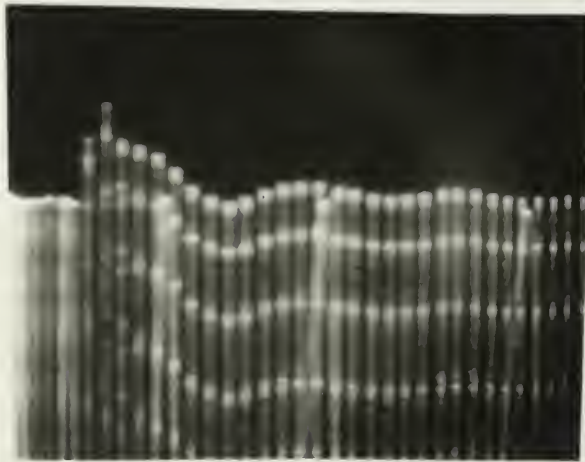
B.   Load Removal   Phase Current = 15.5 amps

PHOTOGRAPHS OF SYSTEM TRANSIENT RESPONSE

Power Factor = 1

FIGURE 50

A.   Load Application   Phase Current = 14.1 amps

B.   Load Removal   Phase Current = 14.1 amps

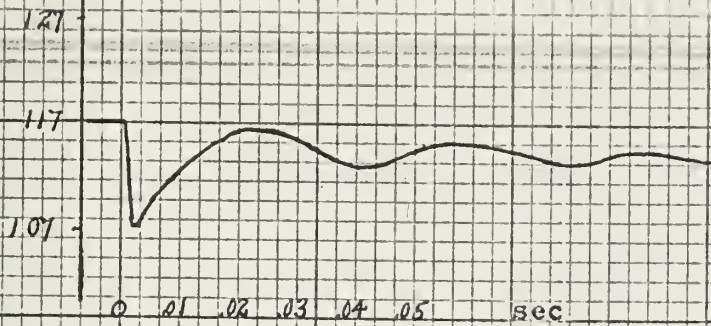PHOTOGRAPHS OF SYSTEM TRANSIENT RESPONSE

Power Factor = .75

FIGURE 51

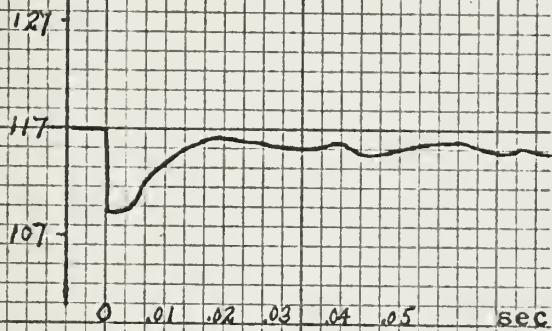SYSTEM TRANSIENT RESPONSE
LOAD APPLICATION
Power Factor = 1

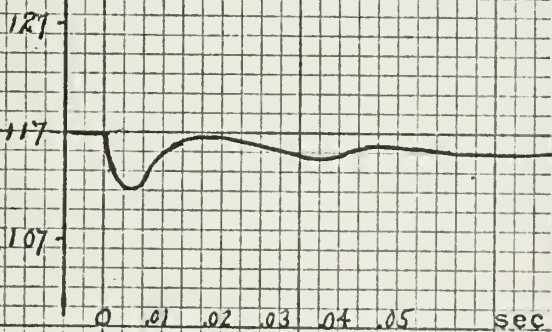Phase Current = 20 amps
% Rated Load = 100

Phase Current = 19.5 amps
% Rated Load = 67.3

Phase Current = 15.5 amps
% Rated Load = 53.5

Phase Current = 7.5 amps
% Rated Load = 25.8

FIGURE 52

SYSTEM TRANSIENT RESPONSE
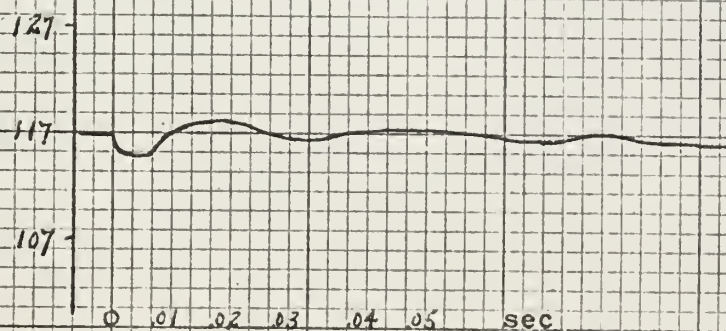LOAD REMOVAL
Power Factor = 1

Phase Current = 18.5 amps
% Rated Load = 63.8

Phase Current = 15.5 amps
% Rated Load = 53.5

Phase Current = 7.5 amps
% Rated load = 25.0

FIGURE 53

SYSTEM TRANSIENT RESPONSE
LOAD APPLICATION
Power Factor = .75

Phase Current = 22 amps
% Rated Load = 70

Phase Current = 14.1 amps
% Rated Load = 44.7

Phase Current = 7.5 amps
% Rated Load = 23.8

FIGURE 54

88

SYSTEM TRANSIENT RESPONSE
LOAD REMOVAL.
Power Factor = .75

Phase Current = 22 amps
% Rated Load = 75.0

Phase Current = 14.1 amps
% Rated Load = 48.7

Phase Current = 7.5 amps
% Rated Load = 25.0

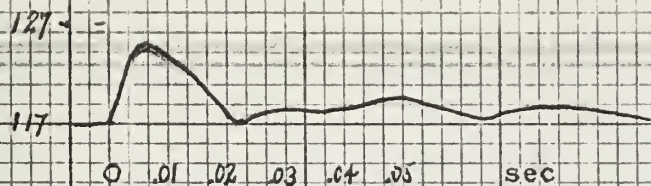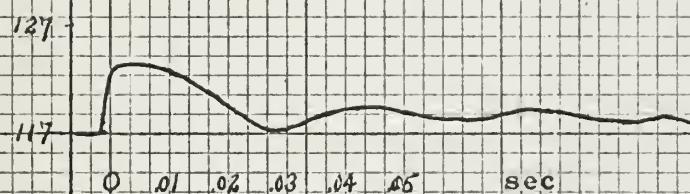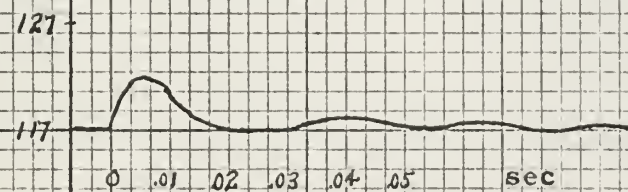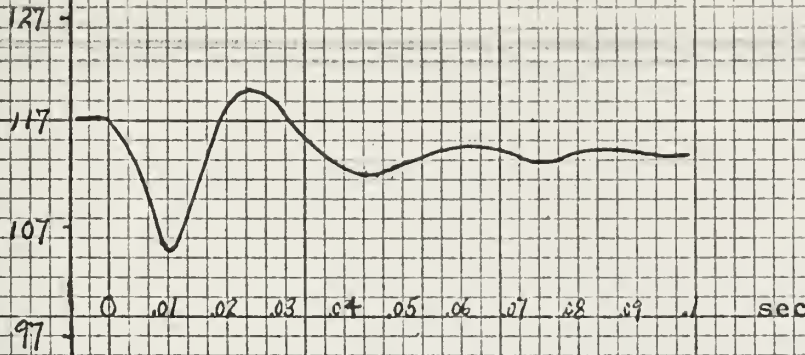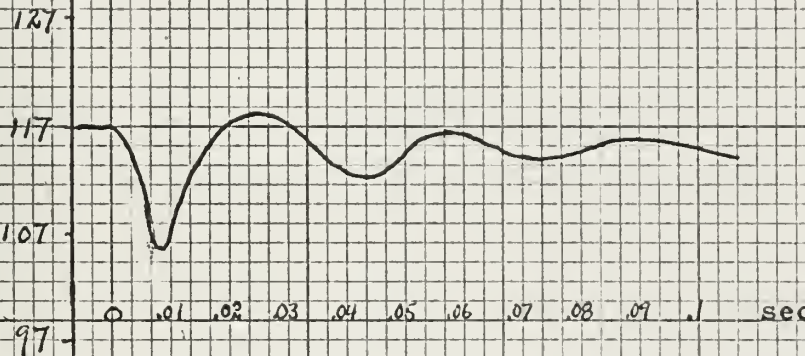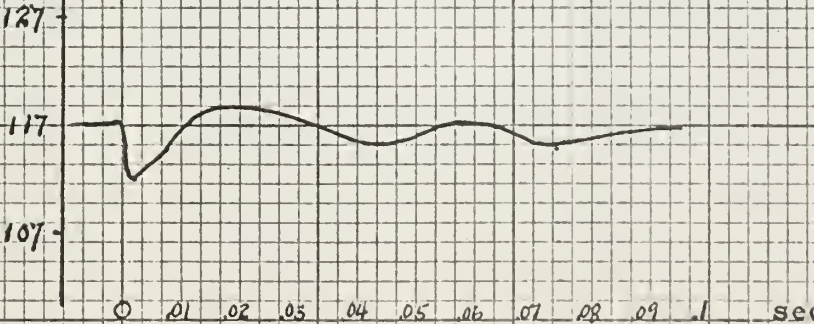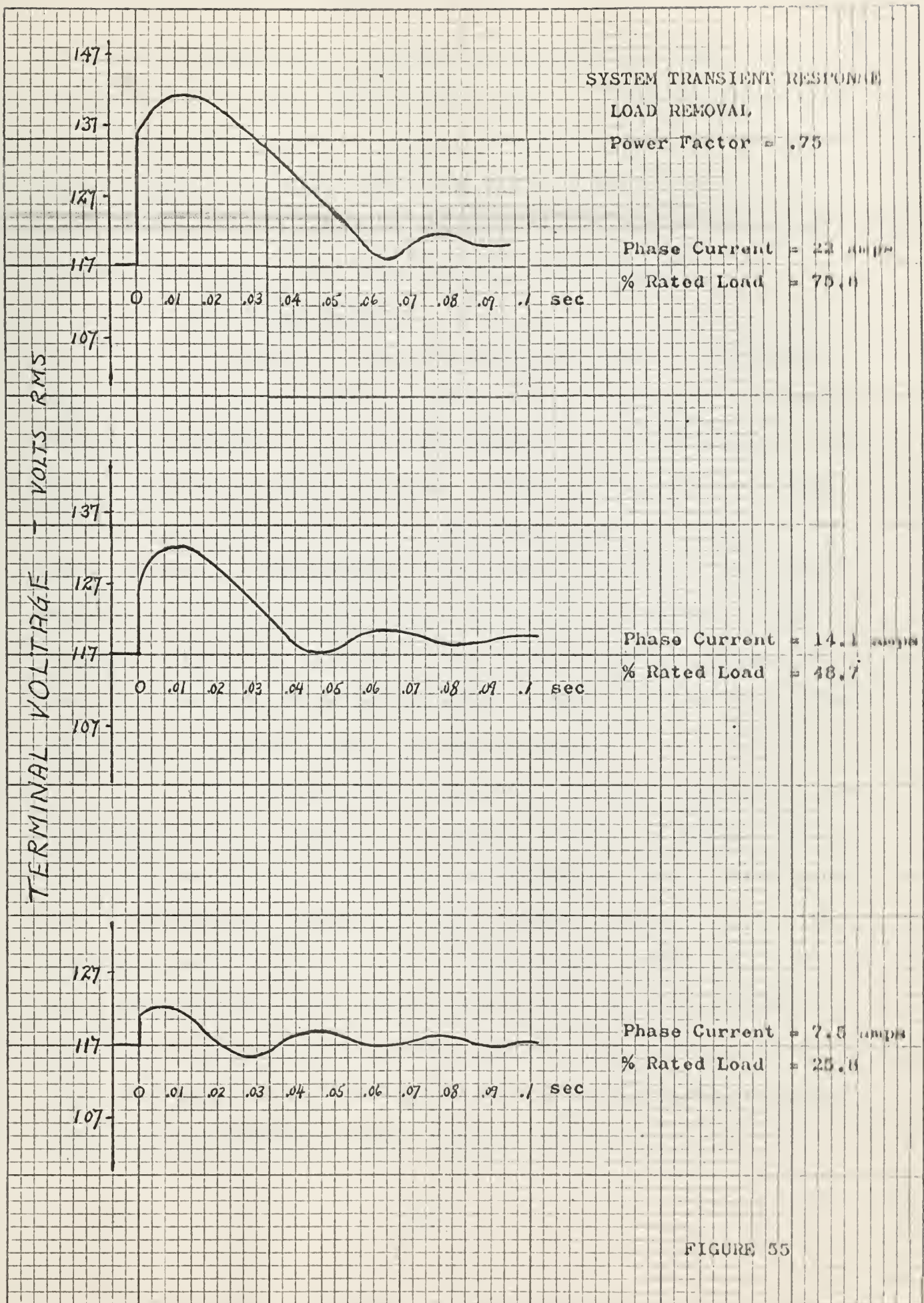FIGURE 55

Two points of interest were considered for injection of a signal. First, the system load was varied sinusoidally to obtain a sinusoidal variation in the generator output current. Second, a sinusoidal signal was superimposed upon the input to the exciter field (the output of the regulator). It was anticipated that both these testing procedures would provide interesting and correlating data, either quantitatively or qualitatively.

    1.   Load Variance Tests.

In order to obtain a sinusoidal variation of the generator output current, it was necessary to obtain a load configuration that could be varied sinusoidally. It was finally decided to use an arrangement similar to that used in the regulator testing. In that previous test, the scotch yoke was used to sinusoidally vary a resistance through the control of the moving contact of a potentiometer. It was anticipated that a load current variation of at least 5 amperes peak to peak would be necessary in order to attain a significant variation in the generator terminal voltage. As mentioned before, the potentiometers used with the scotch yoke had a current limitation of .3 amperes, hence, they were unsuitable.

The limited torque transmitting capability of the scotch yoke also required careful selection of a load to be driven. A General Electric Diactor Voltage Regulator was obtained and dismantled, and the carbon piles of this regulator were connected through linkages to the scotch yoke. The carbon piles were connected in a three phase Y and a current limiting re-sistor of 15 ohms was placed in each phase. This arrangement provided a satisfactory sinusoidal load variation. The sine wave consisted of dis-crete steps; however, by careful adjustment of the pressure applied to the carbon piles the waveform averaged to a good sine wave.

At this point, the load was applied to the system. The terminal voltage of the generator was observed with an oscilloscope. The magnitude of the current variation was set to 8 amperes peak to peak and the frequency range was run up to 20 cycles per second. No terminal voltage variation could be observed.

An example of this result is seen in Figure 56a, b & c. Figure 56a shows the unregulated generator terminal voltage with a load current variation from 6 to 12 amperes at a frequency of 8-1/2 cycles per second. Figure 56b shows the generator terminal voltage of the regulated system with no load variation. While, Figure 56c shows the regulated generator terminal voltage with the same loading as imposed in Figure 56a.

Higher current variations were attempted, however, loading of the prime mover for the experimental set-up occured with the high currents. Even under these conditions the sinusoidal variation could not be observed.

The qualitative results of this test indicated very good performance by the regulator. That is, the regulation is sufficiently fast to obscure a 30 cycle per second oscillation in the load. However, no quantitative analysis could be made from this test, since no data could be obtained.

The explanation for the behavior of this system could be seen from the analytic approach to the system. As mentioned before, the armature voltage drop was attenuated by a factor of 20 with respect to the terminal voltage variation at low frequencies. The terminal voltage variation was present; however, due to this attenuation factor it was reduced in magnitude below the noise level of the system.
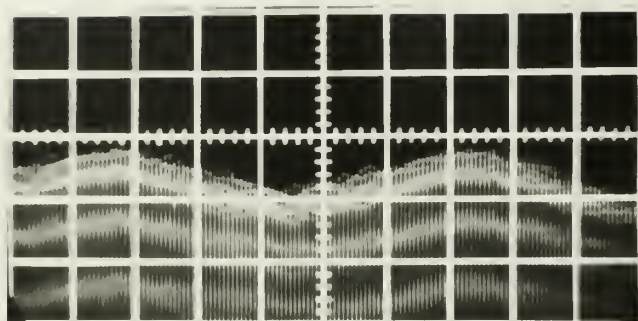
A. Generator Terminal Voltage   No Regulation
   Load Current Variation = 6 amps at 8½ cps
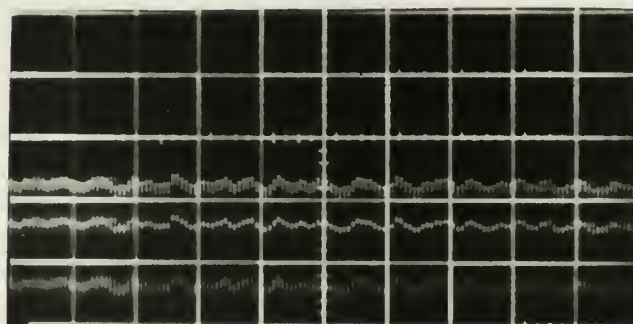
B. Generator Terminal Voltage   With Regulation
   Unloaded
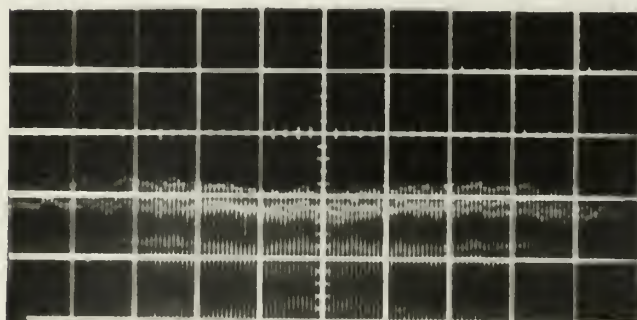
C. Generator Terminal Voltage   With Regulation
   Load Current Variation = 6 amps at 8½ cps

FIGURE 56   PHOTOGRAPHS OF LOAD VARYING TEST RESULTS

The frequency of load variations attainable was limited, as with the regulator tests, to the mechanical limitations of the scotch yoke which was 30 cycles per second. With frequencies in the range of 40 cycles per second, it was felt that the attenuation factor would have been reduced to an extent where the terminal voltage variations would increase. The final tests on the system substantiated this theory.

2. Field Modulation.

Modulation of the exciter field presented several problems. Since, as shown previously, the regulator was load sensitive it was necessary to insert a minimum of change to the regulator output so that the regulator would perform correctly. Additionally, a high frequency, moderately powerful modulation source was needed.

In an attempt to prevent increase of the resistance load on the regulator, a transformer was used with the secondary in series with the field of the exciter and the primary to a function generator. This system, though feasible and productive, had insufficient power to produce a reasonably large magnitude of terminal voltage variation.

An attempt to use the rotating sine wave generator was made. Since the armature coils of this three phase generator were accessable and isolated from one another, it was possible to connect one of the coils in series with the exciter field. The armature coils presented less than .5 ohms to direct current. This system had been attempted previously to modulate a 400 cycle per second signal rather than a direct current signal and the results had been poor. However, this combination of signals worked quite well and this system was powerful enough to give reasonable terminal voltage variations.

By individually adjusting the field current upon the direct
current drive motor and the sine wave generator, the frequency and magnitude,
respectively, of the modulation signal could be adjusted as desired.

Figure 57 is a schematic diagram of the complete test circuit.
In the tests run, modulation amplitude of the system output was maintained
constant for all frequencies for each run. The magnitude of modulation to
the exciter field was altered with the sine wave generator field control
to maintain the output modulation constant. This variable modulation
magnitude was read across the series coil on the pen type recorder. Attempts
to read across the exciter field were made. Due to the changing direct cur-
rent level of the regulator output as combined with the sinusoidal varia-
tions and the effects of a large noise signal superimposed, the data de-
sired could not be obtained from these tapes. Hence, it was necessary to
read the modulation as shown in Figure 57 and then in analyzation of the
data to interject the attenuation factor for this combination to obtain the
true input magnitude.

The data obtained in the above manner was normalized and
adjusted by the attenuation factor and is presented in Figure 58.

The data plotted was very interesting and was predicted from
the previous testing. The system exhibited the characteristics of a second
order system. That is, there was a resonant peaking at the approximate un-
damped natural frequency of the system, which was shown to be about 224
radians per second. In addition, the damping ratio of the system depended
upon the input magnitude of the modulation, the frequency of peaking did
not. The higher magnitudes of modulation presented an interesting gain
phenomena. As the modulation magnitude increased, the regulator was driven
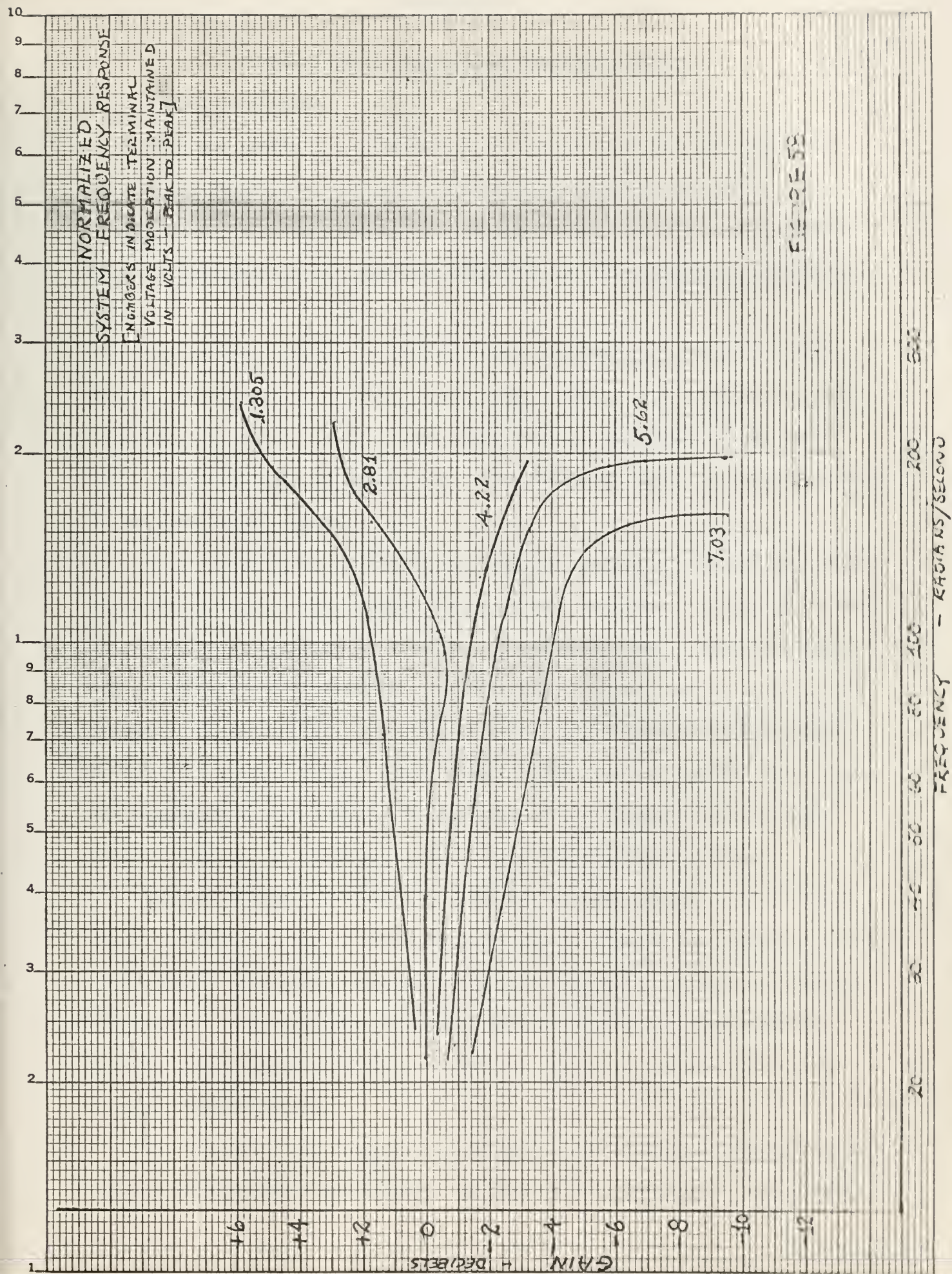into the saturated region (refer to Figure 38) and remained in saturation
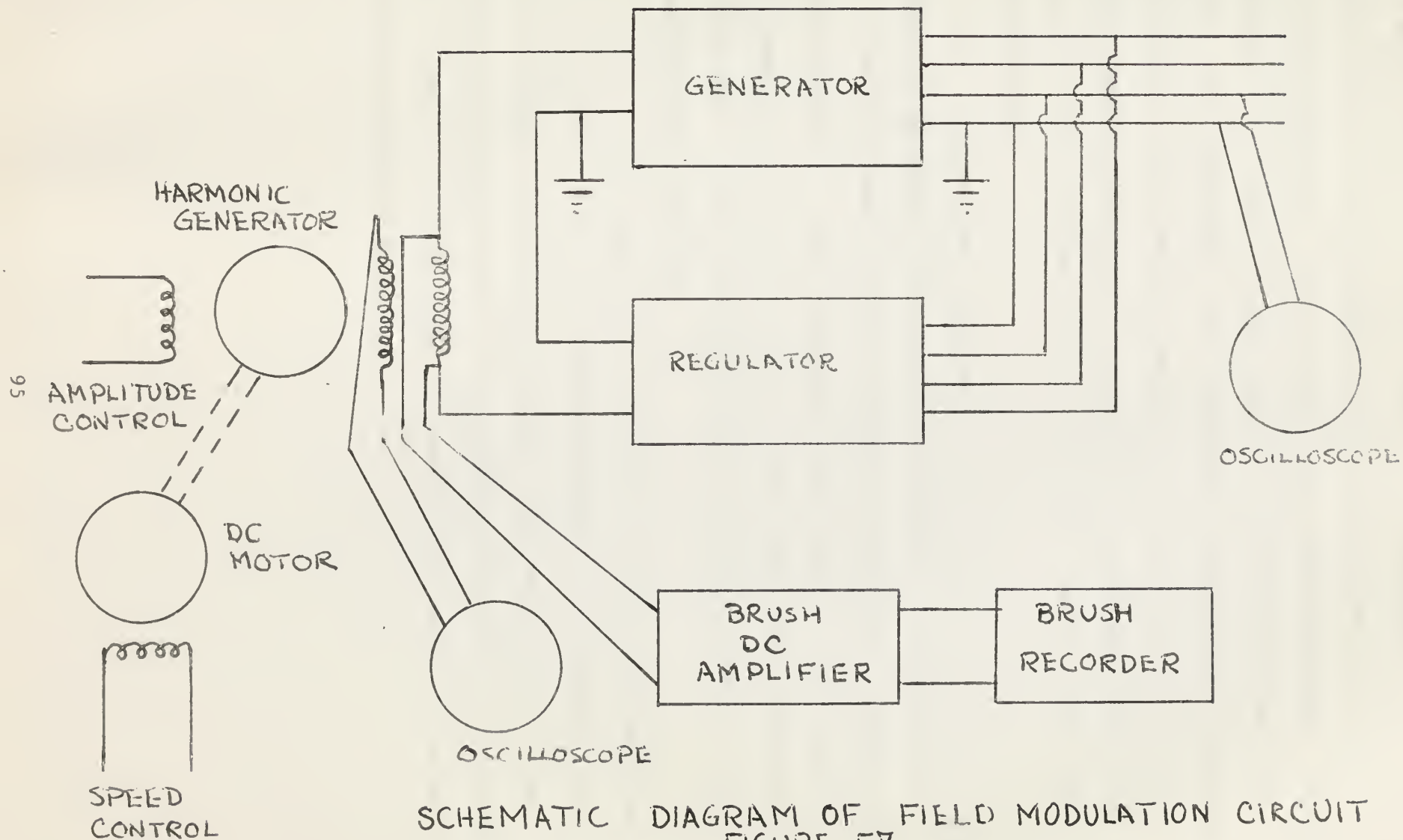
SCHEMATIC DIAGRAM OF FIELD MODULATION CIRCUIT
FIGURE 57

for a greater percentage of time per cycle. Since operation into and out of saturation was shown to be a function of time dependent upon some internal run-away condition, when the regulator was driven into saturation at high frequencies, it did not have time to escape saturation. Hence, the output of the regulator became a high constant and the system reverted to a quasi open loop system. As the magnitude of the modulation increased, the frequency at which the system exhibited this characteristic decreased. At these frequencies the gain of the generator is quite small; hence, the system gain, when the system reverted to this quasi open loop state, dropped off abruptly.

It was deemed inadvisable to proceed with tests in the range of modulation amplitudes that saturated the regulator since the adverse effects of the input signals to the regulator was questionable. Attempts to continue tests with a smaller magnitude of input modulation were thwarted by the magnitude of a 50 cycle per second noise signal that obliterated the useful data. Hence, the analysis made, was made on the basis of the information shown in Figure 58.

It was observed that overlaying of the gain response curves in the region of 100 cycles per second with respect to a fixed point would produce a straight line on the Bode diagram. This was equivalent to saying that the describing function of the regulator would plot on the Nichols Chart as a vertical straight line. This was the same conclusion reached in the regulator testing chapter.

NORMALIZED
SYSTEM FREQUENCY RESPONSE
[Numbers indicate terminal
voltage modulation maintained
in volts — peak to peak]

FIG. 25-58

FREQUENCY — RADIANS/SECOND

DISCUSSION OF RESULTS AND RECOMMENDATIONS

A.   Summary of Results

From the previous test chapters, it may be said that the regulator acts as essentially a pure gain, degenerative feedback component.   Although there are time constants in the regulator, they are so much faster than the generator time constants that they may be considered as insignificant.

The regulator shows two definite time constants and hence two different responses to a variation in voltage; depending on whether the variation is up or down.   Both of these responses are generally of the same type, differing only in magnitudes.   Both responses show the characteristics of an underdamped system.

It may be further said that the limiting regions of cut-off and saturation are of little significance during normal operation.   It was found that it took a load variation of one-third of normal rating to drive the regulator to cut-off and a variation of two-thirds of normal rating to drive the regulator to saturation.   It is not expected that these variations would be found in general usage.   Also, when a large load was applied which drove the regulator to its limits, the reaction of the regulator was so rapid that it remained in these areas for only a brief period of time.

In view of the very fast time constant already present in this regulator, it is felt that it would be difficult to improve the regulator along these lines.   The gain, however, could be increased by using more powerful transistors.   An increased gain would further increase system stability, but the present gain is sufficient for the system to operate well within military specification.

The regulator was subjected to intensive and prolonged testing throughout its voltage range and beyond.   It held up well through all these tests

and is still operational. It must, therefore, be said that the regulator appears to be very durable.

It was also noted that the regulator furnished corrections to variations of a very small percentage of a volt in terminal voltage, indicating a high degree of sensitivity.

When combined with its correct generator, the system demonstrated the characteristics of rapid response and high stability. Step variations of load show a terminal voltage variation indicative of underdamped system.

Load steps were taken from no-load to 75% load and the regulator was capable of rapidly restoring the correct terminal voltage. Prime mover limitations prevented heavier load testing, but it seemed apparent that the regulator would go to the generator load limits and still maintain the correct output voltage.

The system frequency response showed that the system had the characteristics of a second order differential equation with a variable damping ratio which was dependent upon regulator gain.

B. Recommendations for Further Study.

Since only one regulator was tested, it is felt that the results cannot be applied to all of the Bendix Regulators of this type. At least one other regulator should be tested.

The test methods used were all valid, and it is felt that the procedures described in this paper would be adequate for the testing of additional regulators.

The reasons behind the interesting phenomenon of the two regulator responses is not clearly understood. It is believed that further research could be done in this area.

The limiting cases of saturation and cut-off could stand further investigation. Of particular importance is the high power output of complete saturation and the possible injurious affects to the regulator of prolonged operation

in this region. Also, since cut-off adversely affects the gain of the
regulator when high gain is needed most, an investigation of the possibility
of moving the cut-off point further from the operating point would be worth-
while.

Throughout the frequency response tests, a great deal of the most
significant data could not be obtained because of the limitations of the
modulating and metering equipment. In the regulator frequency responses,
it would certainly be worthwhile to design a type of modulator that would
have a range to 100 cycles per second to observe the effects of the regu-
lator break frequencies. In the system frequency testing, the design of a
filter to eliminate the high noise level without significantly changing
the exciter field circuit impedance would be very useful.

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3. Truxal, John G., Control Engineers' Handbook, McGraw-Hill Inc., 1958.

4. Ryder, J. D., Fundamentals of Applied Electronics, Prentice-Hall Inc., 1959.

5. Delfeld, F. D., Murphy, G. J., Analysis of Pulse-Width-Modulated Control Systems, IRE Transactions on Automatic Control, Vol. AC-6, No. 3, September 1961 pp. 283-

6. Bureau of Weapons, Navy Department, NAVWEPS 03-5AA-95, Handbook/ Overhaul Instructions, Voltage Regulator Type 20B63-1-A(1-B, 2-A, 2-B) December 1961.

7. Meints, A. L., Voltage Variations in Aircraft Alternating Current Electric Systems, Unpublished.

8. Krausz, Alfred, Kahle, H. A., Voltage Regulation in Modern Aircraft Electronic Power Systems, Applications and Industry, July 1960.

9. Heinzman, G., Operation of the Type 20B63 Voltage Regulator, Engineering Department of the Bendix Aviation Corporation, August 1959.

10. Military Specification: Electric Power, Alfoat Antishore for Support of Aircraft and Airborne Equipment, Required Characteristics of General Specification for., Mil-I-6181.

11. Thayler, George J., Pastel, Marvin P., Analysis and Design of Nonlinear Feedback Control Systems, McGraw-Hill Inc., 1962.

EQUIPMENT USED

A. Instruments Used in Recording Data.

1. Hewlett-Packard Oscilloscope, Model 120A, Serial Number 1565.

2. Hewlett-Packard Oscilloscope, Model 120A, Serial Number 003-30975.

3. Allen B. Dumont Laboratories Inc. Oscilloscope, Type 304H, Serial
    Number 7865.

4. Hewlett-Packard Oscilloscope Camera, Model 196A, Serial Number
    001-01472. (Polaroid camera).

5. Hewlett-Packard Electronic Frequency Meter, Type 6948, Model 500A,
    Serial Number H1005.

6. Brush Instruments Dual Channel D. C. Amplifier, Model RD-5621-02,
    Serial Number 130.

7. Brush Instruments D. C. Amplifier, Type B1550, Serial Number 550-
    57-1419.

8. Brush Development Co., Oscillograph, Type B1 202, Serial Number
    3850.

9. Krohn-Hite Instrument Co., Derivative-Integral, Servo Design Filter,
    Model 340A, Serial Number 139.

10. Hewlett-Packard R.M.S. Voltmeter (VTVM 0-300 volts), Model 400A,
    Serial Number S1107.

11. Weston Electrical Instrument Corp., AC Voltmeter, Type IS-185,
    Model 433, Serial Number 61019, Frequency 25-2400 cps, Scale 0-150
    volts.

12. Weston Electric Instrument Corp., AC Voltmeter, Model 433, Serial
    Number 94414, Frequency 25-500 cps, Scale 0-150 volts.

13. Westinghouse, DC Voltmeter, Type px5, Serial Number 2320767, Scale 0-5 volts.

14. Westinghouse, DC Ammeter, Style BA-37100-5, Serial Number 2357194, Scale 0-1.5/3/15 amperes.

15. Westinghouse, AC Ammeter, Type PA5, Style 701351, Serial Number 2320665 Frequency   , Scale 0-50 amperes.

16. Westinghouse, AC Ammeter, Type PA5, Style 701351, Serial Number 2320667, Frequency   -   , Scale 0-50 amperes.

17. Westinghouse, AC Ammeter, Type PA5, Style 701351, Serial Number 2320668, Frequency   - , Scale 0-50 amperes.
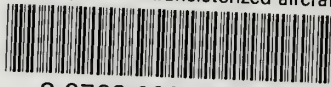
B. Special Equipment.

1.   Bendix Aviation Corporation, AC Generator, Part Number 29E19-31-A, Serial Number R-55M, Rated at: Voltage 120/208 volts, Frequency 400 cps, Speed 8000 rpm, 10 kva, Power Factor .75.

2.   General Electric, Tri Clad Induction Motor, Model 5K254D31, Serial Number KX16968, Rated at: 3 Phase, 7-1/2 Horsepower, 220/440 volts, 20.1/10 amperes, Speed 3465 rpm.

3.   Allis-Chalmers Texrope Vari-Pitch Speed Changer, Unit Number 310, Serial Number 1933.

4.   Bendix Aviation Corporation, Voltage Regulator, Type 20B36-3/A, Serial Number RX1, Rated at: 155/200 volts, 3 Phase, Frequency 380/420 cps.

5.   Marathon Electric Manufacturing Corp., DC Shunt Motor, Type DS, Model Number DL.OM29, Navy Specification 17M17, Serial Number 176013, Rated at: 1/8 Horsepower, 115 volts, 1.3 amperes, Speed 1725 rpm.

103

6. General Electric, Motor Amplidyne, Model 5AM73AB52, Serial Number LY 48005, 3450 rpm Induction Motor, Seperately Excited Generator, Rated Input: 208 volts, 3 Phase, 4.4 amperes, Rated Output. 750 watts, 250 volts.

7. General Electric, Induction Voltage Regulator, Form HK, 24 kva, 60 cps, 1 hour duty, Serial Numbers:7551745, 7571747, 8621623.

8. Superior Electric Co., Powestat, Variable Transformer, Type 9639, Serial Number 916, Rated at: 50/60 cps, 115 volts at 15 amperes.

9. General Electric, A-C Generator, Model 5AB254B, Serial Number 6931040, Rotating Sine Wave Generator rated at: 60 cps, 5 kva, 4.75 kw, .9 power factor, 3600 rpm, 220 volt, 3 phase, field current 13.1 amperes.

10. General Electric, D-C Motor, Type B, Model 5B284A2886, Serial Number 7106193, Rated at: Shunt winding, open duty, 115 volts, 78 amperes.

11. General Electric, Diactor Recgulator, Model 3CDD33BD5, Carbon piles used.

12. General Radio Co., Decade Inductor, Type 1490-A, Serial Number 864.

13. Various resistors and rheostats.