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TM-758
2231.000

A RIPPLE REDUCTION MODULE FOR TRANSREX POWER SUPPLIES

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INTRODUCTION

The twelve phase, 0.5 MW Transrex power supplies normally have substantial subharmonic ripple in their output at various output levels. The lowest frequency subharmonics (60, 120, 180 Hz) are the biggest problems for magnet loads since these frequencies generate proportionally the largest current and field ripple in the magnets. Subharmonic ripple is typically caused by reference timing errors, firing circuit imbalance, line imbalance, transformer imbalance, and hard-fire circuit delay errors. In the Transrex supplies most of the problem is related to the firing circuits. A new Transrex firing circuit which is described in TM-755 removes most of the subharmonic ripple problem. For very critical applications where still lower subharmonic ripple is required, a module called the Ripple Reduction Module (R^2 Module) has been designed which further reduces the 60, 120 and 180 Hz ripple in the Transrex output. The R^2 module can be used either with the new firing circuits or with the older, original Transrex firing circuits. Performance improvements for both cases are described later in this paper.

OPERATION

The R² module is a negative voltage-feedback module which senses subharmonic ripple in a power supply output and feeds a signal directly into the power supplies' firing circuits to reduce the ripple at the output. In a sense the module acts like an active power filter within the power supply itself. The filter's ability to reduce ripple is primarily limited by the power supplies' firing circuits and converter frequency characteristic.

To understand how the R² modules works, one must begin by looking at the Transrex voltage regulator shown in Fig. 1. This Meson Lab voltage regulator has R47 and R48 changed to 68K to provide higher common mode rejection and R32 changed to 49.9K so that the loop gain is not changed. (Changing R32 does change the frequency response of the low pass filter, IC6, somewhat.) Otherwise, the regulator is the same as all other Transrex voltage regulators.

Each amplifier or section in the regulator can be represented in block diagram form as part of the overall system shown in Fig. 2a. The voltage error amplifier, IC1, is designated A1; the output transistor amplifier which is comprised of the circuitry from the output of IC4 to the emitter of Q3, is designated A2; the 12 firing circuits and AC to DC power convertor is labeled A3; the bus voltage divider and differential amplifier IC4 is called A4; the low pass filter, IC6, is labeled A5; and the 720 Hz band stop filter, IC5, is called A6. Most power supply subharmonic ripple is caused by the firing circuits and line or transformer imbalance. For the purpose of analysis, the subharmonic ripple is

shown added to the converter output as shown in Fig. 2a. A somewhat simplified form of the conventional Transrex regulator is shown in Fig. 2b. In order to reduce the output ripple of the power supply, the R^2 module (A_7 in Fig. 2c) is added which feeds a signal from the power supply output back to the firing circuit input. The function of the R^2 module becomes clearer by moving the feedback summing point to the output of the firing circuit and converter (Fig. 2d). In analyzing the ripple attenuation of the system, the program input can be assumed to be a constant and not related to the output voltage ripple at the frequencies of interest. Then for AC signal analysis, the block diagram can be redrawn as shown in Fig. 2e. The Transrex firing circuits have an inverting signal characteristic. By assuming the circuits are non-inverting and moving, the negative characteristic to the feedback summing mode, as shown in Fig. 2f, a simple negative feedback loop is formed for acting upon the input ripple signal. The voltage regulator amplifier (A_1) (A_2) (A_4) (A_5) (A_6) and the firing circuits/converter form one feedback path, designated $H_1(s)$ and the R^2 module and the firing circuits/converter form a parallel feedback path designated $H_2(s)$, Ripple attenuation is given by the following equation

$$\frac{V_O(s)}{V_R(s)} = \frac{1}{1 + [H_1(s) + H_2(s)]} \quad (1)$$

Both the $H_1(s)$ and $H_2(s)$ feedback paths act to reduce output ripple. First $H_1(s)$ is examined to understand why $H_2(s)$ is required. It is assumed that the Transrex is operating as a 100V power supply and that there are no additional voltage dividers in front of the divider associated with A_4 . (As a 200V or 400V power

supply, an additional voltage divider is normally used before A4 and the firing circuit/converter gain is higher but the overall gain is the same. If the power supply is tapped for lower voltage operations, the firing circuit/converter gain is lower and the overall gain is lower.) Using a Transrex regulator module, the frequency response of each of the amplifiers in Fig. 2a was measured except for A3. Each of these amplifiers' response is plotted in Fig. 3. Whenever simple breakpoints could be used to characterize the amplifiers, straight line approximations are plotted. The gain characteristic of A3 was assumed to be flat for the frequencies of interest. The firing circuit/converter characteristic, A3, is discussed in more detail later. It should be pointed out, however, that while the firing circuit/converter gain is approximately constant (about 20) at DC, the gain is dependent on the firing angle and falls off quickly at small firing angles.

By combining all of the individual amplifier responses, the total gain $H_1(j\omega)$ can be plotted as also shown in Fig. 3. Note that the 0db point or unity gain crossover is at 5.5 Hz. From the corner frequencies, the total loop phase shift is found to be -102° , providing a phase margin of 78° . From equation 1 it is now seen that $H_1(s)$ can only attenuate ripple if it is below 5.5 Hz. At 60 Hz, $H_1(j\omega)$ loop gain is -16 db, no attenuation of 60 Hz ripple is possible. Thus the conventional Transrex voltage regulator is ineffective for reducing subharmonic ripple.

The function of the R^2 module is to provide feedback gain at the subharmonic frequencies of concern and at the same time not to change the transient response characteristics of the voltage

regulator with which all regular users are familiar. To understand the R^2 module, it is first desirable to try to evaluate the frequency characteristic of the firing circuits and converter so that all phase shifts can be considered in a stability analysis. Figure 4 shows the Transrex firing circuit and AC/DC converter connections. The circuit output can only be changed in discreet steps. When an SCR is fired, the converter output voltage takes on an average value which cannot be changed until the next SCR in the firing sequence is turned on. If the firing circuit input is changing during this time, the output voltage will respond by taking on a new average value when the next SCR is fired. Parrish and McVey¹ presents a model which compares the discrete action of firing the converter SCR's to a sampler and a zero-order hold circuit typically found in sample data systems. (See Figs. 4b and 4c.) The sampler is represented by a switch and the zero-order hold circuit by a capacitor. When the switch is closed for an instant, the output capacitor takes on the value of the input signal and holds that value until the switch is closed again at a later time. Groenenboom² has extended this approach to higher phase number converters. The transfer function for the sampler and zero-order hold circuit is given by Eqs. 2 and 3.^{1,2}

$$|G(j\omega)| = \frac{\sin \frac{\omega T}{2}}{\frac{\omega T}{2}} \quad (2)$$

$$\phi(\omega) = -\frac{\omega T}{2} \quad \text{radians} \quad (3)$$

where T = sampling interval and $\pi \geq \frac{\omega T}{2} \geq 0$. Evaluation of these equations show that the phase shift looks like a transport lag equal

to half the hold time, and that the gain at low frequencies is approximately equal to unity. The gain and phase characteristics for a 12-phase 60 Hz power supply have been calculated from Eqs. 2 and 3 and are plotted in Fig. 5. There are two assumptions which the SCR converter must meet in order to be represented by Eqs. 2 and 3. First, the system band width must be small compared to the sampling frequency. Since some low pass filtering is always present, this is not usually a problem. And second, any changes in the conduction period should be small.

An attempt was made to verify the phase shift that could be expected using Eq. 3. A small 12 phase power supply with a star connected transformer and 12 Transrex power supply firing circuits were used for the test. A resistive load was used so that phase overlap would not be a factor and no interphase transformers were present. The firing circuits were driven with a 120 Hz input signal and from Eq. 3 one would expect a -30° phase shift in the output. The results of the test was that no such phase shift was present. Closer inspection finds that the second assumption, that the conduction period is nearly constant has been violated. The variation in conduction time is clearly shown in Fig. 6. By using ramp generators and comparators in the firing circuits, the firing angle is allowed to change up to the instant when an SCR is finally fired. Thus the sampling frequency is frequency modulated by the firing circuit input signal. The modulation is in such a way that the output tends to follow the input without a phase shift. In a test driving the firing circuit input with frequencies from 10 to 240 Hz, no phase shift greater than the measurement errors was found. It is felt that these results

were obtained because the firing circuits are not frequency limited. If the firing circuits were operated in such a way that the SCR firing angle was set at the instant when $\alpha = 0$ (delay angle = 0) and then the SCR was fired after the appropriate delay, a phase shift similar to that given by the Eq. 3 could then be expected.

It has been shown that these firing circuits do not exhibit a frequency dependence at the frequencies of interest. However, it has been observed that a frequency dependent phase shift can take place in the power output section. In one test on the 6SASAI power supply with magnet load, the firing circuits input was driven at 60, 120, and 180 Hz. Phase shifts of approximately -12° , -24° , and -36° respectively, were observed in the power supply output waveform with respect to the input. These phase shifts are thought to be due to phase overlap and the interphase transformer action of the power supply. No attempt is made at this time to further study these phase shifts. Although it would be interesting to analyze these phase shifts further, it is considered to be sufficient at this time to recognize that the phase shifts do exist and to make some allowance for them in the following analysis.

Now look at the response of $H_2(s)$ in Fig. 2f. To reduce the subharmonics in the power supply output, it is necessary for the R^2 module to provide as much gain at as many subharmonic frequencies as possible and still maintain overall system stability. Another requirement which was placed on the R^2 module was that the addition of the module have a minimum effect upon the transient response of the voltage regulator. The approach taken with the R^2 module is to use parallel tuned circuits to sense as many of the subharmonics as possible and to feed a bucking signal into the

power supplies' firing circuits. After studying the phase characteristic for the firing circuits and converter, it was apparent that both 60 and 120 Hz and perhaps 180 Hz ripple could be attenuated by this technique. Tuned circuits similar to those used in the main ring active filter³ electronics were designed and are shown in the R² module schematic diagram, Fig. 7. The input to the module, pins p and n, is connected to a 0 to 100V power supply output signal. (Do not use a 0-200V or 0-400V signal since the overall loop gain is too high.) After the input signal is attenuated and passed through a differential amplifier, it is sent to the tuned circuits. Precision components are used to set the resonant frequency of each of the 60, 120 and 180 Hz tuned circuits. Variable resistor R17, R26, and R45 are used to set the Q or gain of each of the tuned circuits. The tuned circuit gains are set so that the "gain" of the R² module from input to output is -6 db at the resonant frequency points. The gain of the module is 50% of the peak gain at approximately 60 \pm 2 Hz, 120 \pm 4 Hz, and 180 \pm 6 Hz. Integrated circuit U5, is used to sum the tuned circuit outputs and to add them to the voltage regulator output which is brought in on pin H. The summed signal on pin M is sent to the input of all 12 firing circuits.

Overall system stability and ripple reduction can be studied by first plotting the frequency response of the R² module. Figure 8 shows the gain and phase relationship for a 3 peak R² module. By superimposing the firing circuit/converter characteristic on these plots it is apparent that the gain of H₂(s) at the resonant peaks is about + 20 db which results in a theoretical ripple reduction at 60, 120 and 180 Hz of a factor of 10. Furthermore it is seen that

the unity gain point of $H_2(j\omega)$ is at 250 Hz and the associated phase margin at this point is $+43^\circ$. When this feedback arrangement was tested, ripple at the 3 resonant peaks was always reduced although not always by the theoretical amount. At one point in the power supply output range a small amount 360 Hz ripple was observed. Presence of the R^2 module seemed to enhance the 360 Hz ripple which was present by a small amount. The increase was not significant. However, by eliminating the 180 Hz circuit, the effect disappeared. Figure 9 shows the response curves for an R^2 module with resonant peaks at 60 and 120 Hz. Again the firing circuits and converter characteristic has been added to derive $H_2(j\omega)$. The unity gain crossover point is now at 155 Hz and the associated phase margin is found to be $+68^\circ$. If it is desired to eliminate the 180 Hz circuit, simply remove R35. Alternatively, the space on the printed circuit board could conceivably be used to eliminate some other low frequency harmonic present in the power supply output.

INSTALLATION AND USE

A Ripple Reduction Module can be installed in a 0.5 MW Transrex power supply with a minimum amount of power supply re-wiring. Figure 10a shows a typical supply without an R^2 module. Note that slot #3 is not used except for a jumper between pins S and P. Also ± 15 volt power is already available in slot 3. Remove the jumper module and insert an R^2 module in its place as shown in Fig. 10b. (The R^2 module already has an S-P jumper wire in it.) The inputs, n and p, can be taken from pins M and L of the regulator module. Instead of the regulator output, pin S, going to pin P of the 4

firing circuit modules, it is brought to pin N of the R^2 module. The R^2 module output signal, pin M. is then connected to pin P of the firing circuits. Thus the R^2 module tuned circuit feedback signal is connected in parallel with the voltage regulator feedback signal.

Examination of Fig. 7 reveals several other features of the R^2 module. One is a front panel switch which allows the user to disconnect the R^2 module feedback circuits. With the R^2 module "OFF", the control system is the same as if the R^2 module was never installed. Another is the 3 front panel BNC's labeled 60 Hz, 120 Hz, and 180 Hz which allows the user to monitor the subharmonics in the power supply output at all times. By using the "ON-OFF" switch and the 3 front panel BNC's the user can immediately see the effect of the R^2 module feedback paths on the power supply subharmonics. The third feature is a front panel BNC power supply voltage monitor which does not require a differential input scope for monitoring and which is well protected from the bus voltage. And finally, a rear panel switch has been added which allows the user to "open-loop" the power supply. In the open loop mode, a front panel pot allows the user to provide an independent variable voltage (0 to 13.5V) to the firing circuit inputs. Thus the so-called "open loop box" which is required to tune up the original Transrex firing circuits is always available in the Transrex supply.

PERFORMANCE

About 10 ramped and non-ramped Transrex 0.5 MW power supplies in the Meson Lab are presently using R^2 modules to minimize magnet field ripple in critical applications. Performance of these

modules has been quite satisfactory. Figure 11 shows the results of a series of tests performed with original Transrex firing circuits and new Transrex firing circuits⁴ using a Ripple Reduction Module with 60, 120 and 180 Hz tuned circuits. (The Transrex circuits were tuned to provide a balanced output at 60VDC). The tests were run on the Meson Lab 6SASAI power supply (100V max) with a typical bend magnet load. First look at the 3 left-hand photos for the original Transrex firing circuits. The 3 photos are for operation at an output voltage of 10, 50 and 100 volts. Each photo shows magnet field ripple and power supply output voltage with the R² module "OFF" and then with it "ON". In the 10V photo, the top trace is the magnet field ripple at 6 Gauss/division with the R² module "OFF". There is a very obvious 60 Hz ripple present. The second trace shows the power supply output voltage at 50 volts/division. The power supply balance is so poor that 2 of the SCR's are not being fired at all. In the third trace, the R² module has been turned "ON" and the field ripple has been noticeably improved. The last trace shows that with the R² module "ON" the output voltage balance is much better although one of SCR's is still not being fired. Similar although less dramatic improvements can be seen in the 50 and 100V photos. The effect of the R² module being "ON" is to tend to correct the firing circuit imbalance. Performance improvements in these cases are limited to some extent by the firing circuits. The Transrex firing circuits have been found to have abrupt changes in the output timing pulses when the input is slowly changed. Also at low outputs, the imbalance is often so poor that several SCR's may not be firing. With these non-linearities in the system, the R² module cannot remove ripple as

effectively as it should. The new firing circuits designed for the Transrex supplies have a much cleaner transfer characteristic.

The three right-hand photos in Fig. 11 show the Transrex performance at 10, 50 and 100V with new firing circuits. In each photo the top trace shows the magnet field ripple with the R² module "OFF". Note that in all cases, the subharmonic ripple is already less than that found with Transrex firing circuits and the R² module "ON". For all practical purposes subharmonic ripple is eliminated and only 720 Hz remains.

There are two factors which limit the R² modules' ripple reduction ability regardless of which type of firing circuit is used. The first is that the firing circuit gain varies with the power supply output voltage and to some extent with the load. As long as the maximum gain is considered for stability purposes, the main problem is at low output levels where the firing circuit gain is low and consequently the ripple reduction capability is at a minimum. Second, tapping a power supply to provide less than a 100V maximum output, effectively reduces the firing circuits gain and the ripple attenuation ability of the module. Best overall power supply performance is achieved when the New Transrex Firing Circuits are used along with the R² module.

In transient tests on a Meson Lab power supply with and without an R² module, no difference in power supply response to step inputs was observed. This is attributed to the very narrow bandwidth of the R² module. Performance tests with the R² module have been run on a Transrex power supply in the current and voltage modes with equivalent results.

CONCLUSION

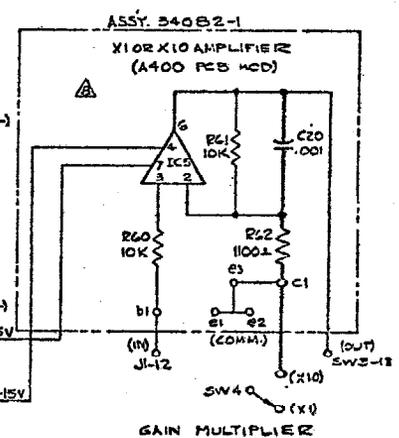
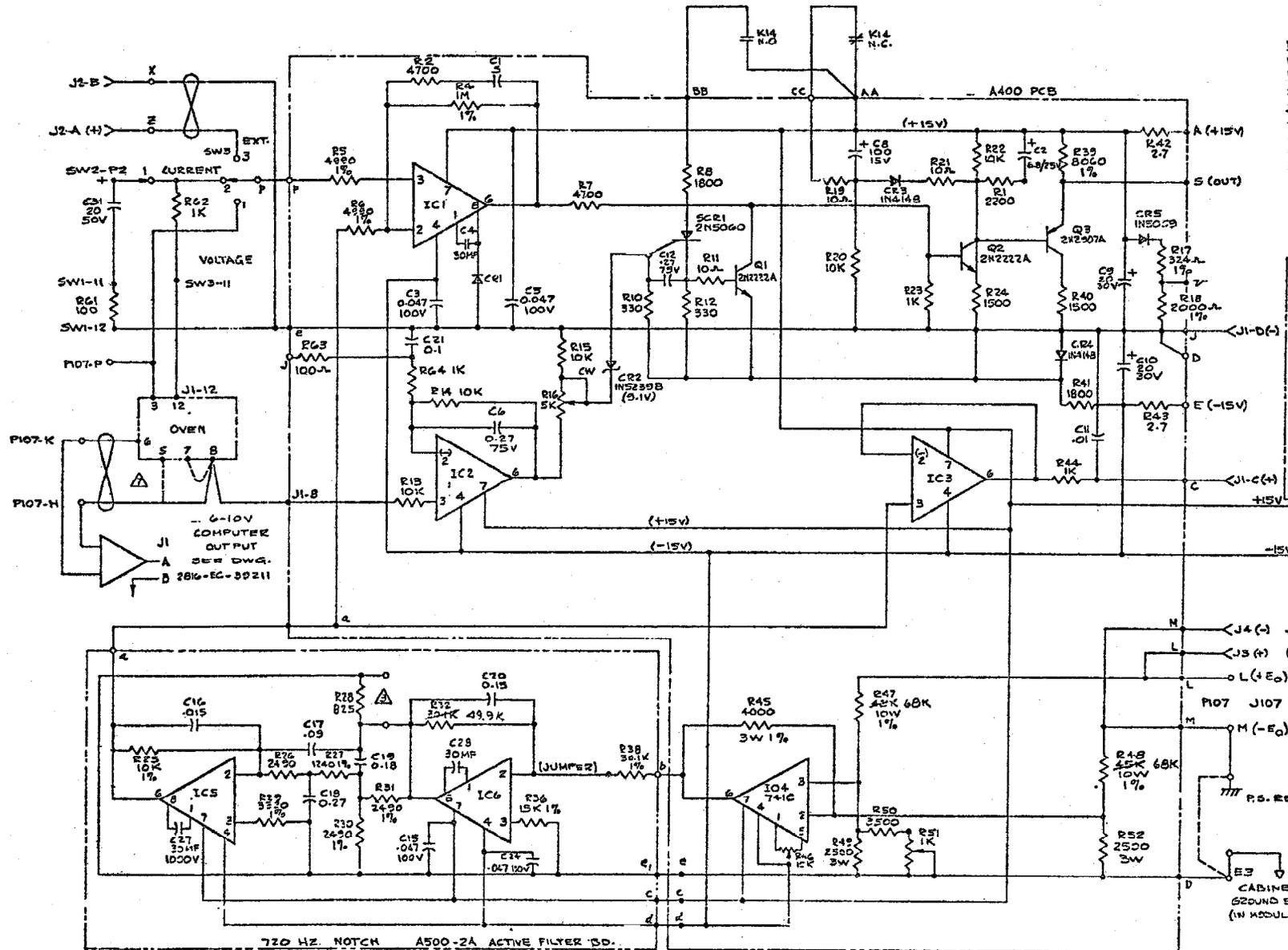
The ripple reduction technique described in this paper has been designed for an used with the Transrex 0.5 MW power supplies. However, the approach can be applied to most types of AC/DC converter power supplies that have a limited voltage loop bandwidth. The main consideration in applying the technique is that the firing circuits not be frequency limited. Some attempt has been made to show how to handle the characteristics of other types of firing circuits. Using the design described herein along with Transrex firing circuits a maximum ripple attenuation factor of about 10 has been achieved.

REFERENCES

1. E.A. Parrish, E.S. McVey, "A Theoretical Model for Single-Phase Silicon Controlled Rectifier Systems", IEEE Transactions on Automatic Control, Vol. AC-12, pp 577-579, Oct. 1967.
2. M. Groenenboom, "The Evolution of Firing Circuits for Static Converters," Hazemeyer Holecotechniek '72/1.
3. R.J. Yarema, "Quadrupole Power Supply Active Ripple Filters," January 1973, Fermilab TM-407.
4. R.J. Yarema, "New Firing Circuits for Transrex Power Supplies," November 1977, Fermilab TM-755.

REVISIONS			
SYM	DESCRIPTION	DRAWN	DATE
D	REDRAWN DESIGNED		10-1-74

- NOTES:
 UNLESS SHOWN OTHERWISE:
 1. RESISTORS - 1/2 W 5%
 2. CAPACITORS - MF
 3. Δ SELECT-IN-TEST
 4. 1% RESISTOR - ENGOC
 5. CAP. SYMBOL ∇ CURVE SIDE IS BLACK BAND
 6. ∇ SELECT TO SET E_0 MAX.
 7. Δ JUMPERS FOR RESISTIVE LOAD.



J4 (-) TOTAL VOLTAGE OUTPUT (0-300V).
 J3 (+) 1/4" SPACED JACKS ON MOD-7.
 L (+E₀)
 M (-E₀)

REV. NO.	PART NO.	DESCRIPTION	QTY
PARTS LIST			
UNLESS OTHERWISE SPECIFIED: DESIGNATOR: PCB, ENCL, ETC.			
FUNCTIONAL DIMENSIONS: ANGLES: DRAWN: []			
MATERIAL: FINISH: []			
1. SHARP ALL SHARP EDGES: APPROVED: []			
2. DO NOT SCALE DIMS: ESTD: []			
3. DIMENSIONS IN ACCORD WITH UNLESS NOTED: []			
4. MAX. ALL MACHINED SURFACES: []			
NATIONAL ACCELERATOR LABORATORY U.S. ATOMIC ENERGY COMMISSION			
MESON LABORATORY TRANSFER MATH POWER SUPPLY VOLTAGE CONTROL (A500) PARTS LIST			

FIGURE 1

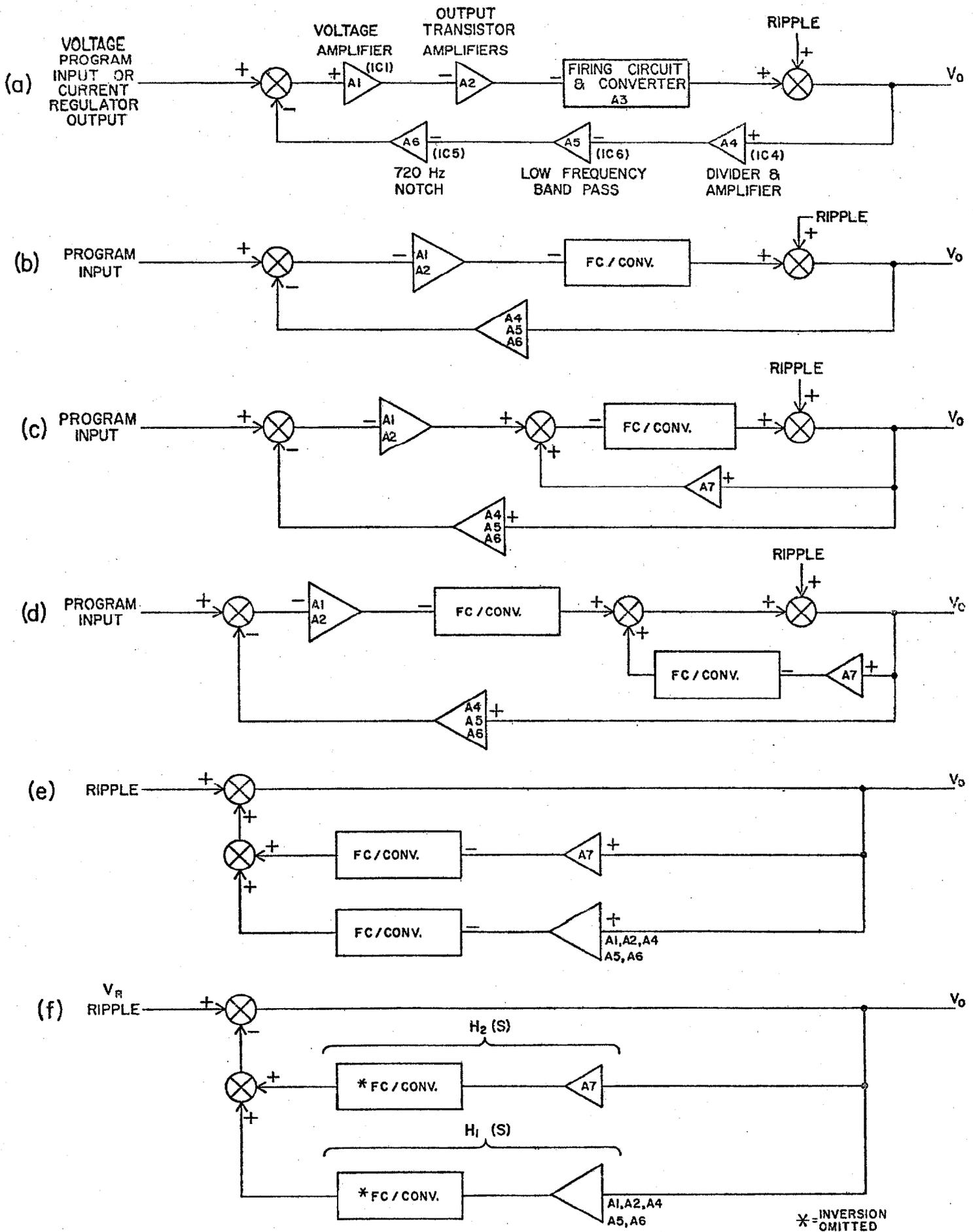
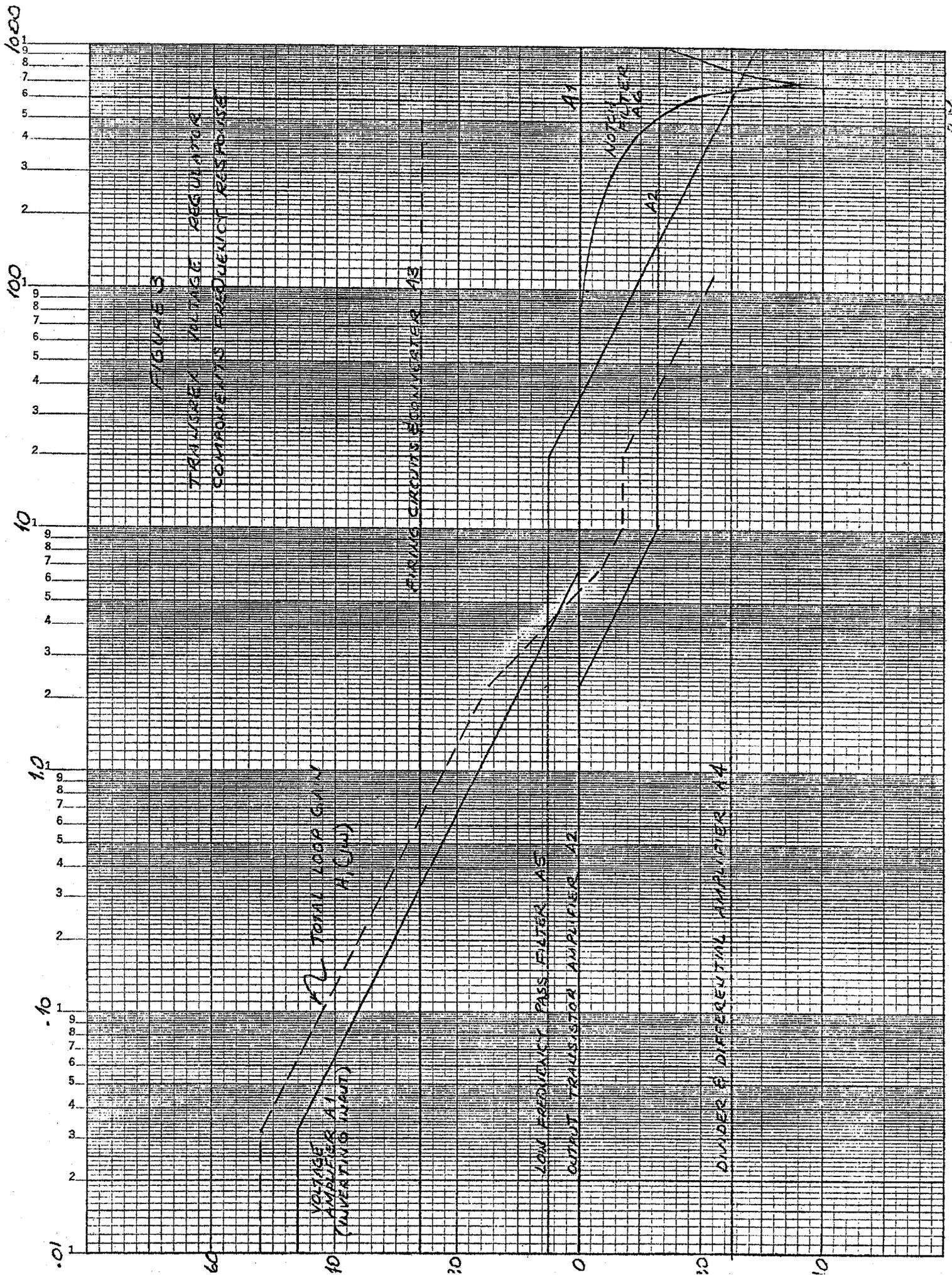


FIGURE 2 - TRANSREX VOLTAGE REGULATOR
BLOCK DIAGRAM



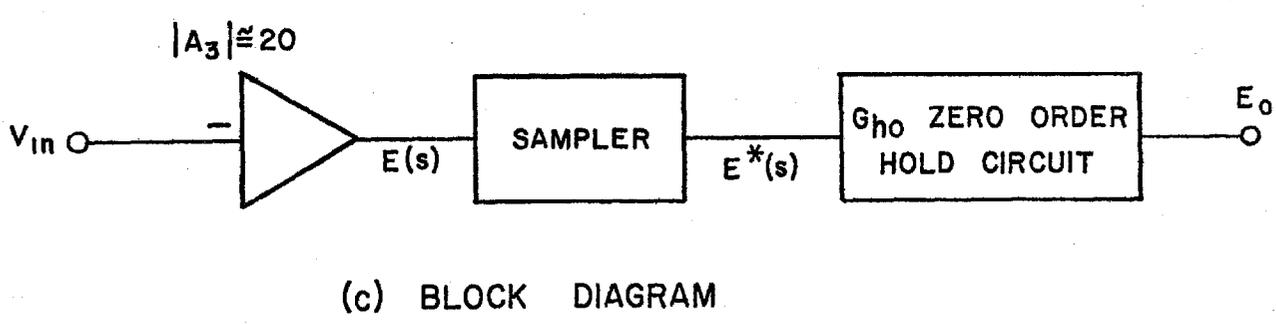
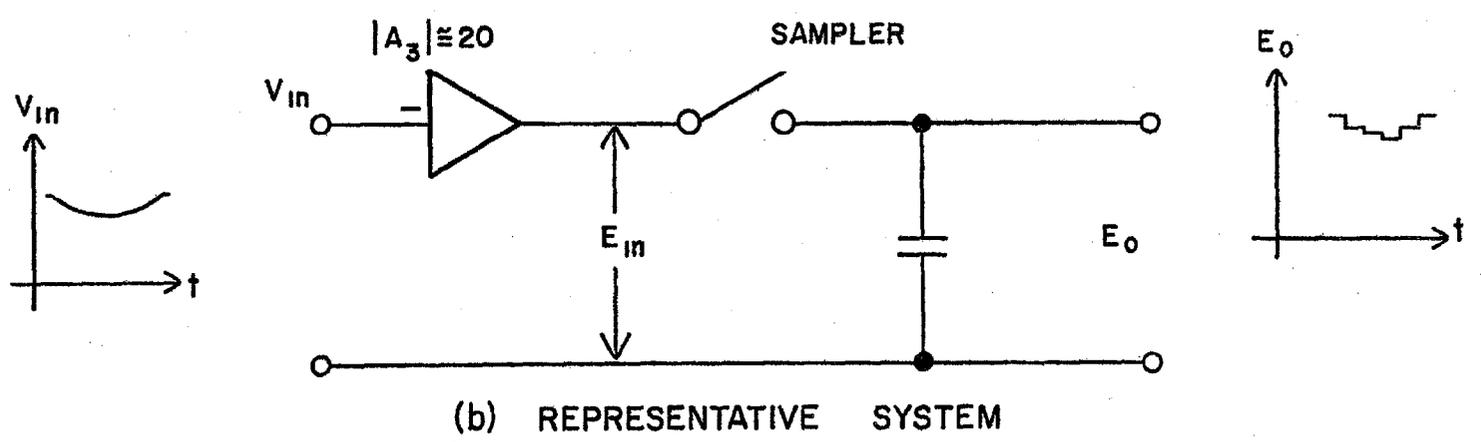
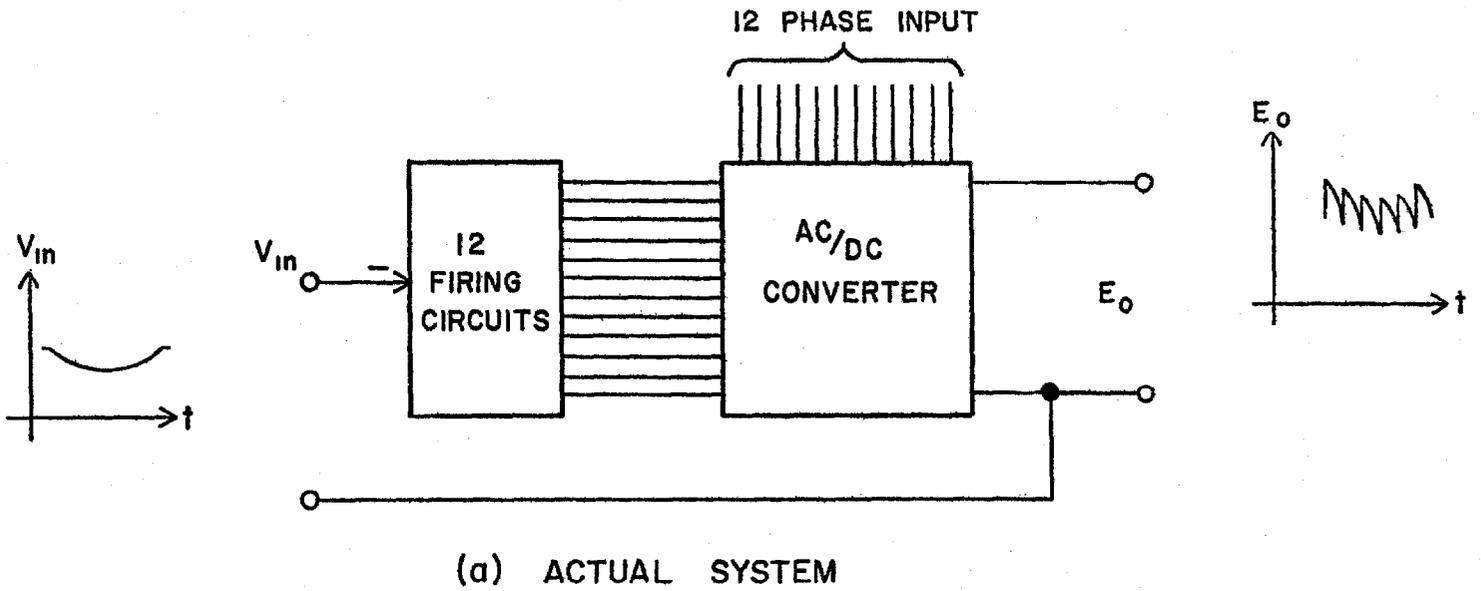
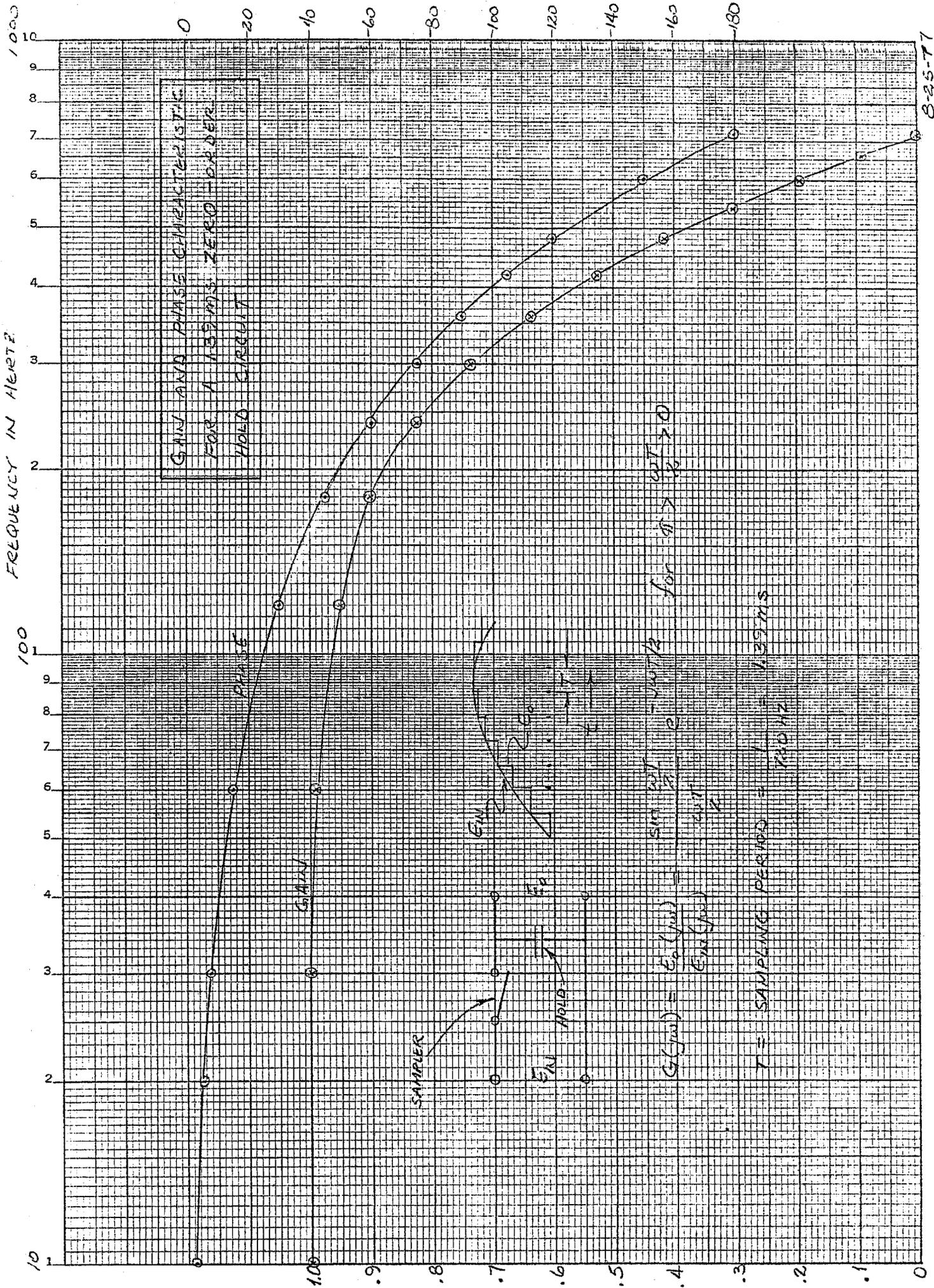


FIGURE 4 - SMALL SIGNAL REPRESENTATION OF FIRING CIRCUITS AND CONVERTER



B-25-T7
RJY

FIGURE 5

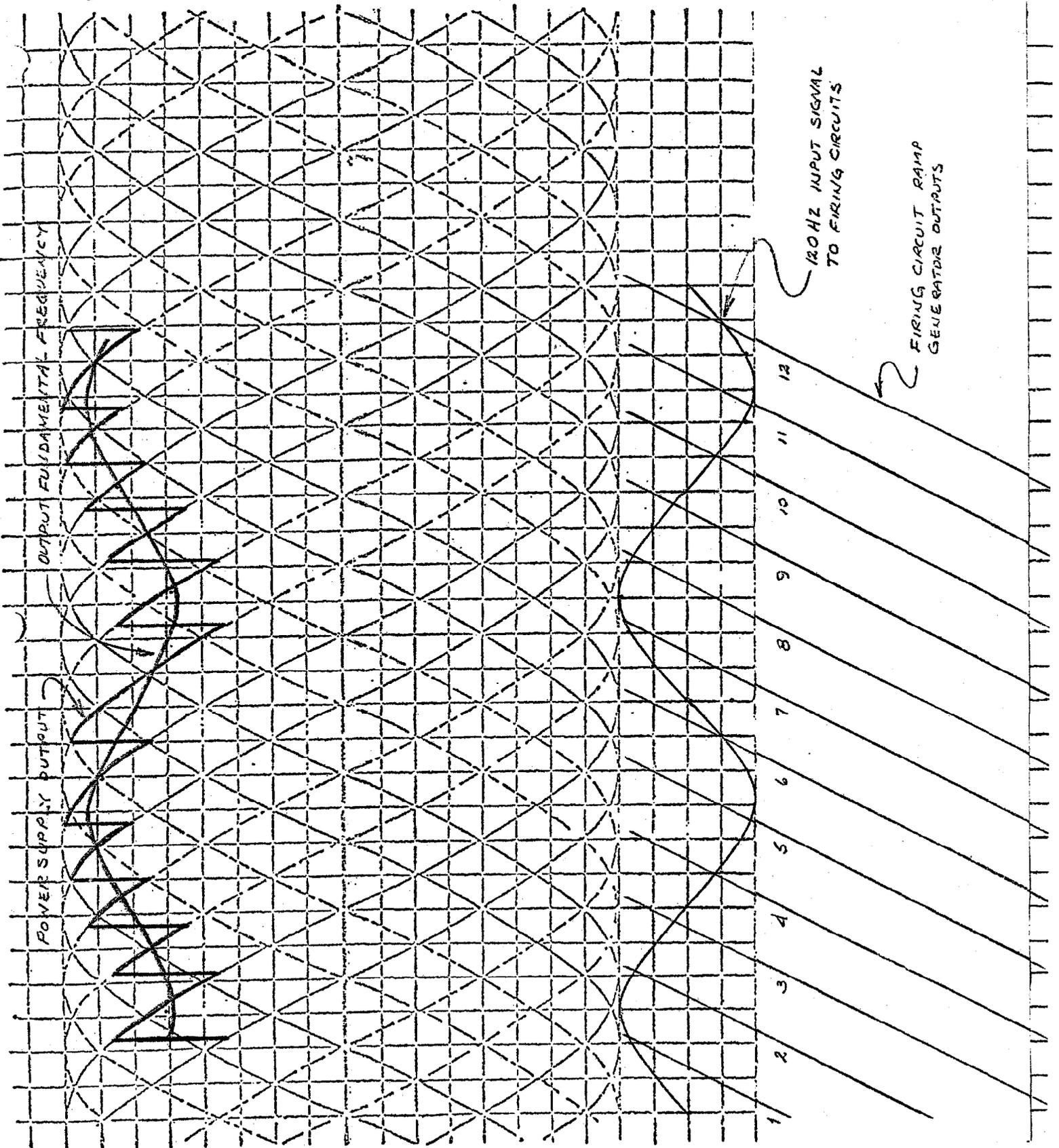


Figure. 6
Twelve-Phase Power Supply Operation With 120 Hz Firing
Firing Circuit Input Drive

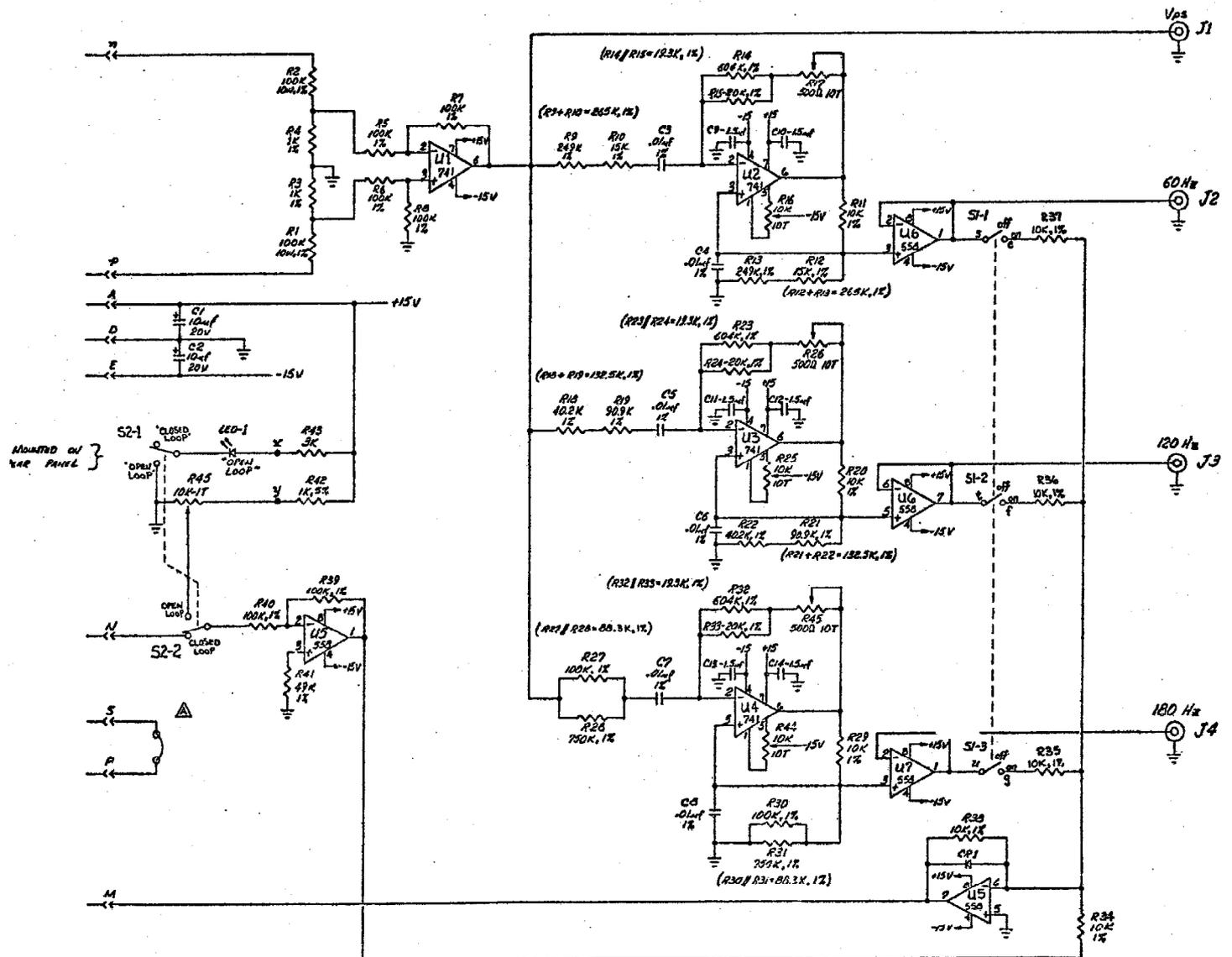


FIGURE 7

REV.	DESCRIPTION	DRAWN	DATE
A	ADDED JUMPER FROM S TO P	A. CADELLA	12-21-77

REV.	DESCRIPTION	DRAWN	DATE
33	U1-U4	GEN. GRANOVSK	12-21-77
32	PAT. R430-R439	RAYTHEON	70-2400-E
31	GUIDE SCHEMATS - SUP. INC.	20L-28-1	2
30	GUIDE PWS - SUP. INC.	20E-54-1	2
29	MODULE 4000 - SUP. INC.	20E-54-2	1
28	AND INC. 20L-25A-3		1
27	SMALL SUPPLY FOR SUP. INC.	PAGE 37E-1	1
26	C3-C6	0.01uF 1% 10V ANTIMONY CAP. P-DUKE	6
25	R41	49K 1% M.F. RV55C	1
24	S2	3PDT TOGGLE SWITCH ALCO	1
23	S1	3PDT TOGGLE SWITCH ALCO	1
22	LED-1	LIGHT EMITTING DIODE HP 5002-4403	1
21	C81	DIODE HYDRIN 100V PV SIL.	1
20	C9-C14	15uF @ 50V CERAMIC	6
19	C1, C2	10uF @ 20V 10% TANTALUM	2
18	R45	10K 1% TRIM POT. RW CERMET	1
17	R43	3K 5% 1/4W CARBON	1
16	R42	1K 5% 1/4W CARBON	1
15	R28, R31	700K 1% M.F. RV55C	2
14	R19, R21	90.5K 1% M.F. RV55C	2
13	R18, R22	402K 1% METAL FILM RV55C	2
12	R17, R24, R48	500K T.T. TRIM POT. CERMET	3
11	R16, R25, R44	10K T.T. TRIM POT. CERMET	3
10	R15, R24, R33	20K 1% M.F. RV55C	3
9	R14, R23, R32	604K 1% M.F. RV55C	3
8	R32, R34, R35	10K 1% M.F. RV55C	3
7	R9, R13	249K 1% M.F. RV55C	2
6	R10, R12	15K 1% M.F. RV55C	2
5	R4, R5, R27, R30	100K 1% M.F. RV55C	3
4	R3, R4	1K 1% M.F. RV55C	2
3	R1, R2	100K 10W 1% DUAL RS-10	2
2	U5, U6, U7	7255E DUAL G.R. OP-AMP	3
1	U1-U4	72741 GENERAL PURPOSE OP-AMP	4

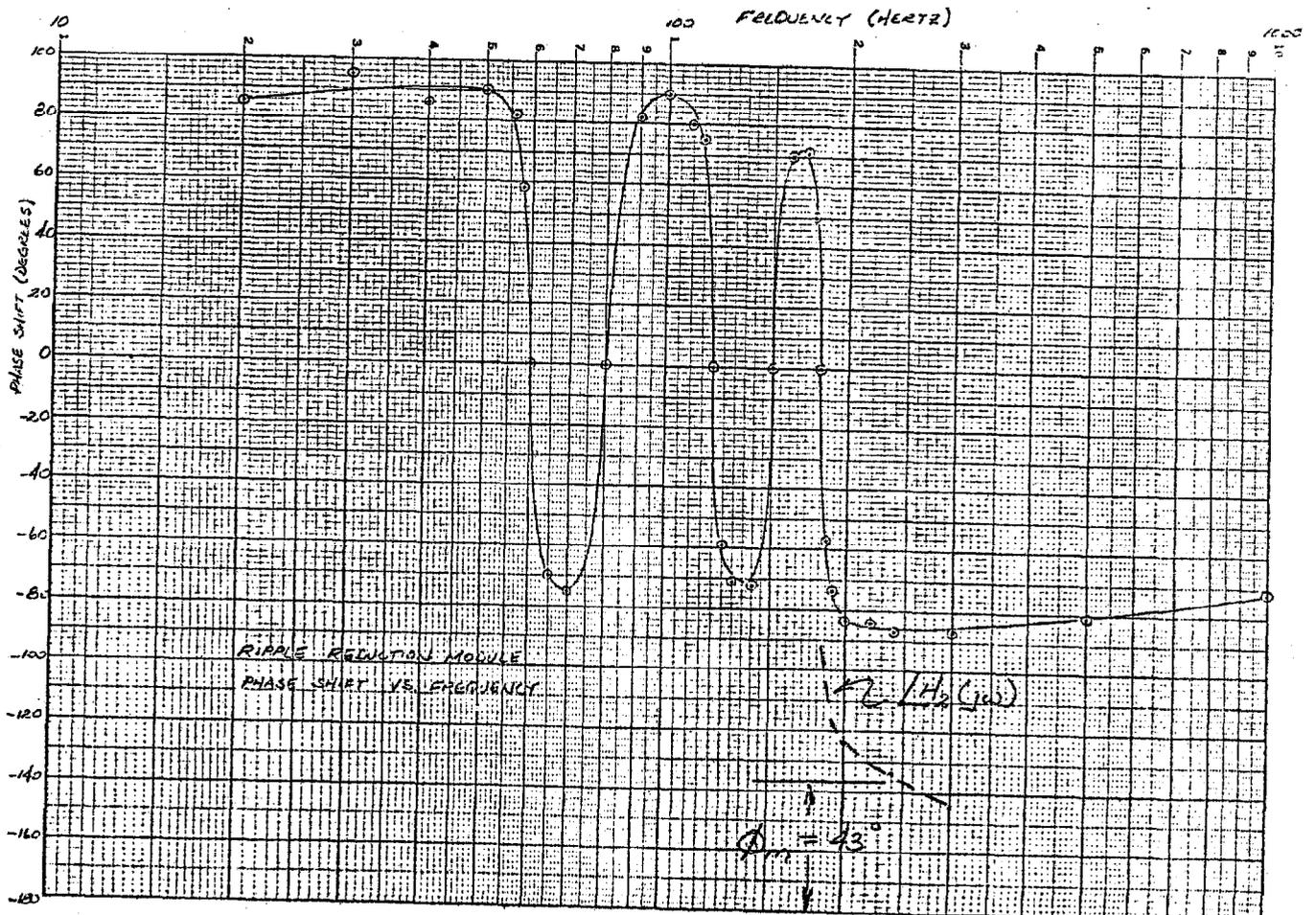
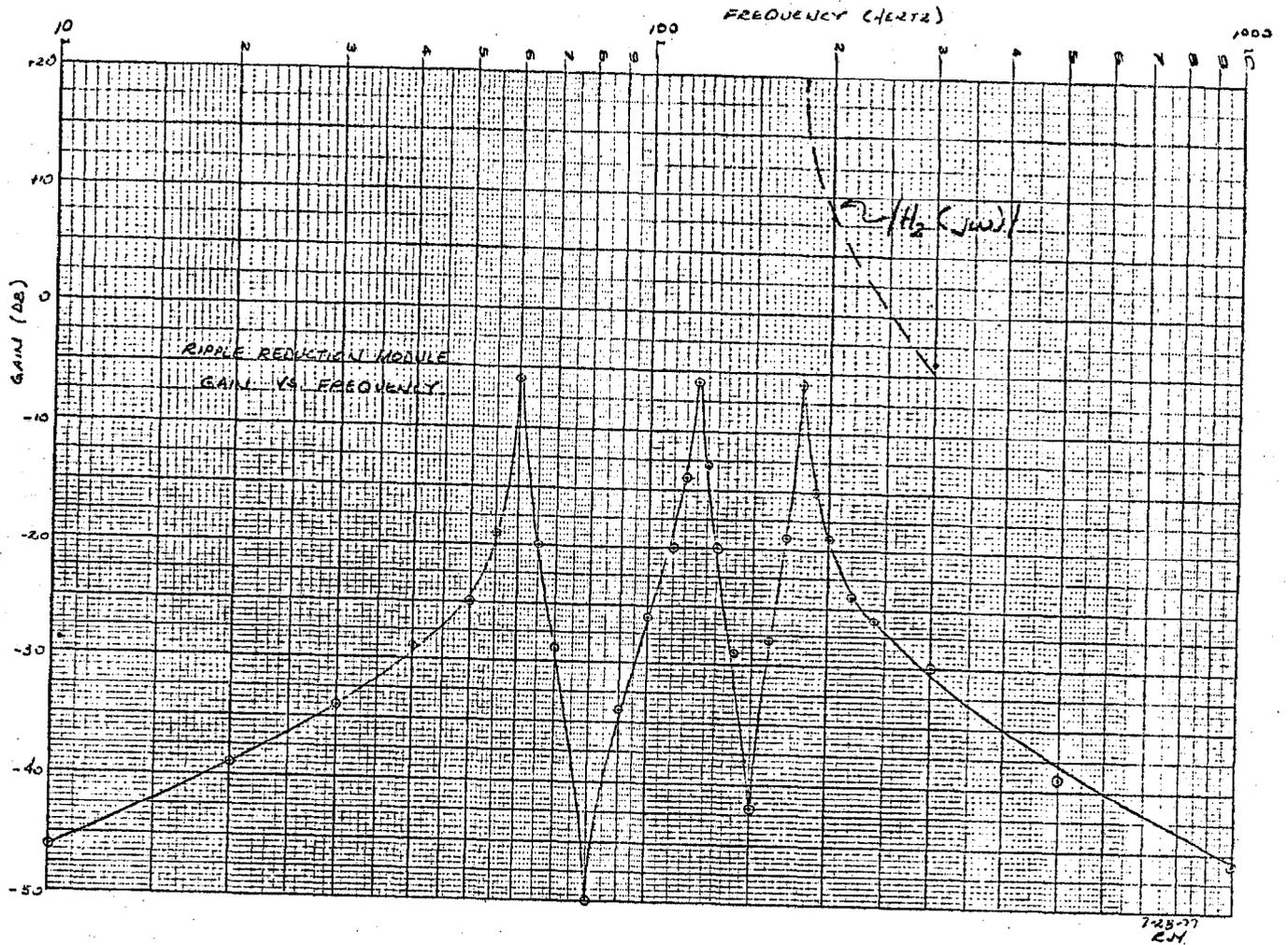
REV.	DESCRIPTION	DRAWN	DATE
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PARTS LIST
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 ACTIONS (DIMENSIONS) ANGLES
 1 1 1 1
 1. BREAK ALL SHARP EDGES
 1/16 MAX.
 2. DO NOT SCALE DIMS.
 3. DIMENSIONS IN ACCORD
 WITH AND 244.6 STD.
 ✓ MAX. ALL MACHINING
 SURFACES

MATERIAL:

FERMIL NATIONAL ACCELERATOR LABORATORY
 ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
 RESEARCH SERVICES
 TRANSFER POWER SUPPLY
 RARE PRODUCTION MODULE

SCALE: 1/8" = 1" DRAWING NUMBER: 22310-ED-46543 REV.



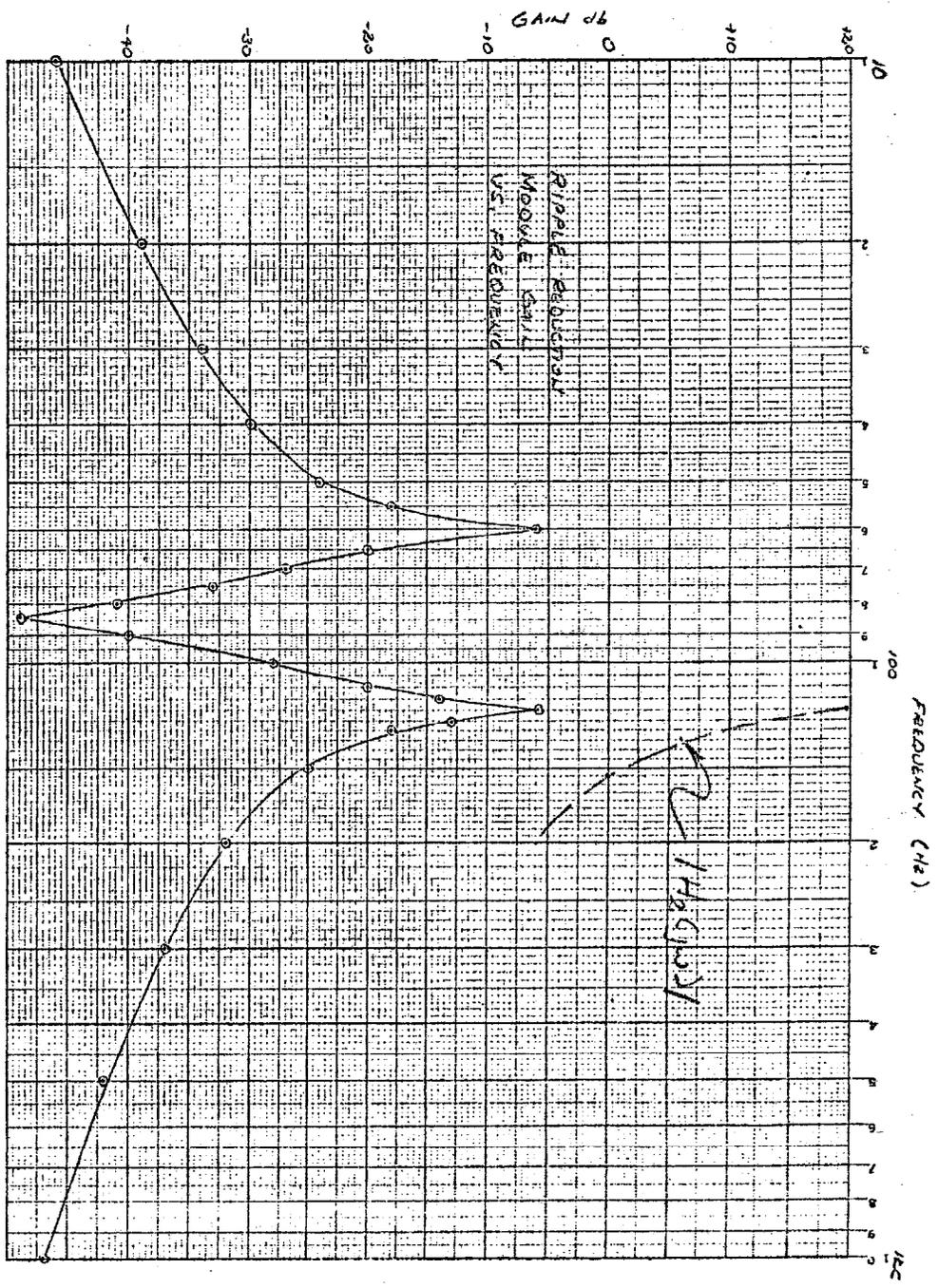
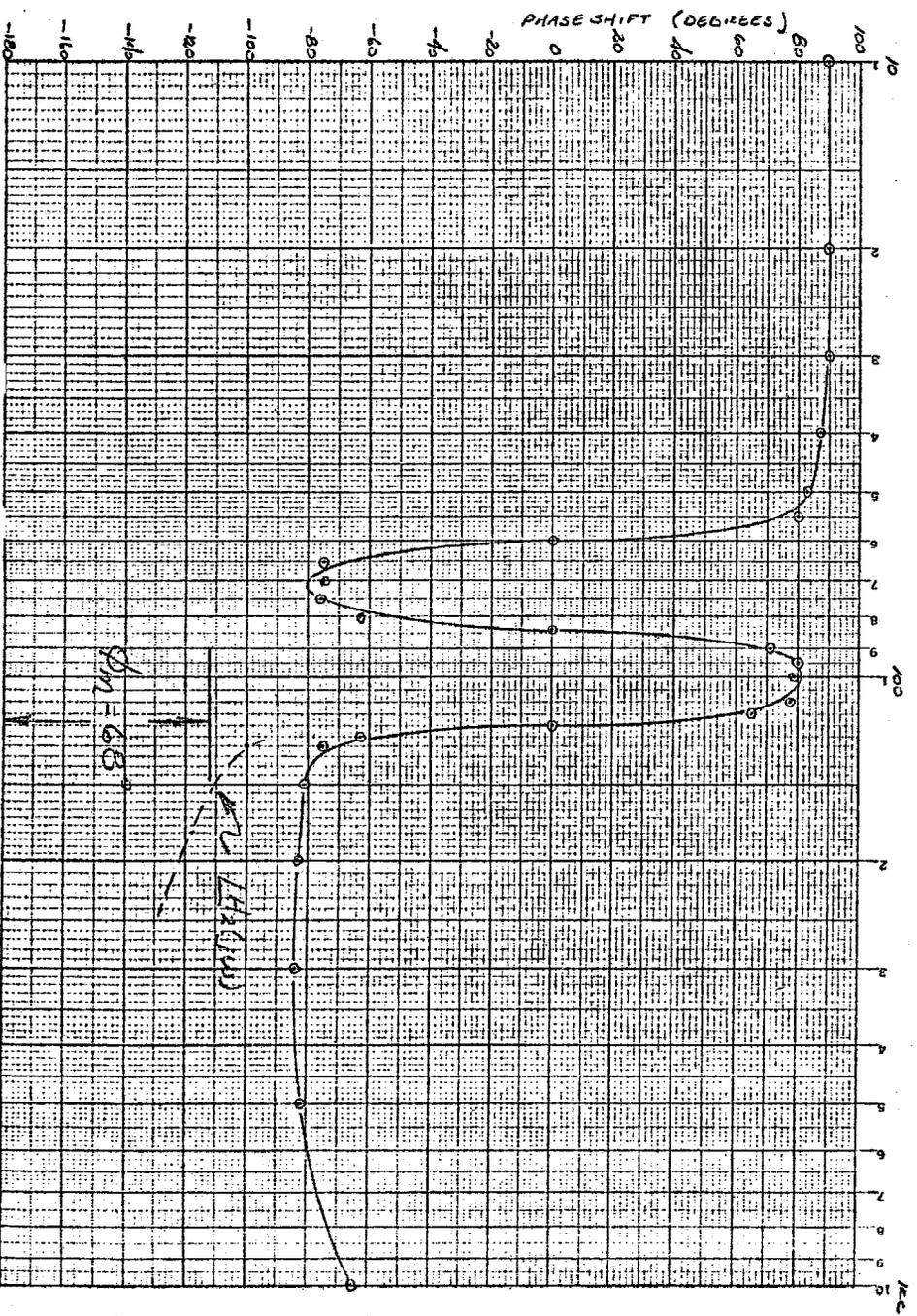
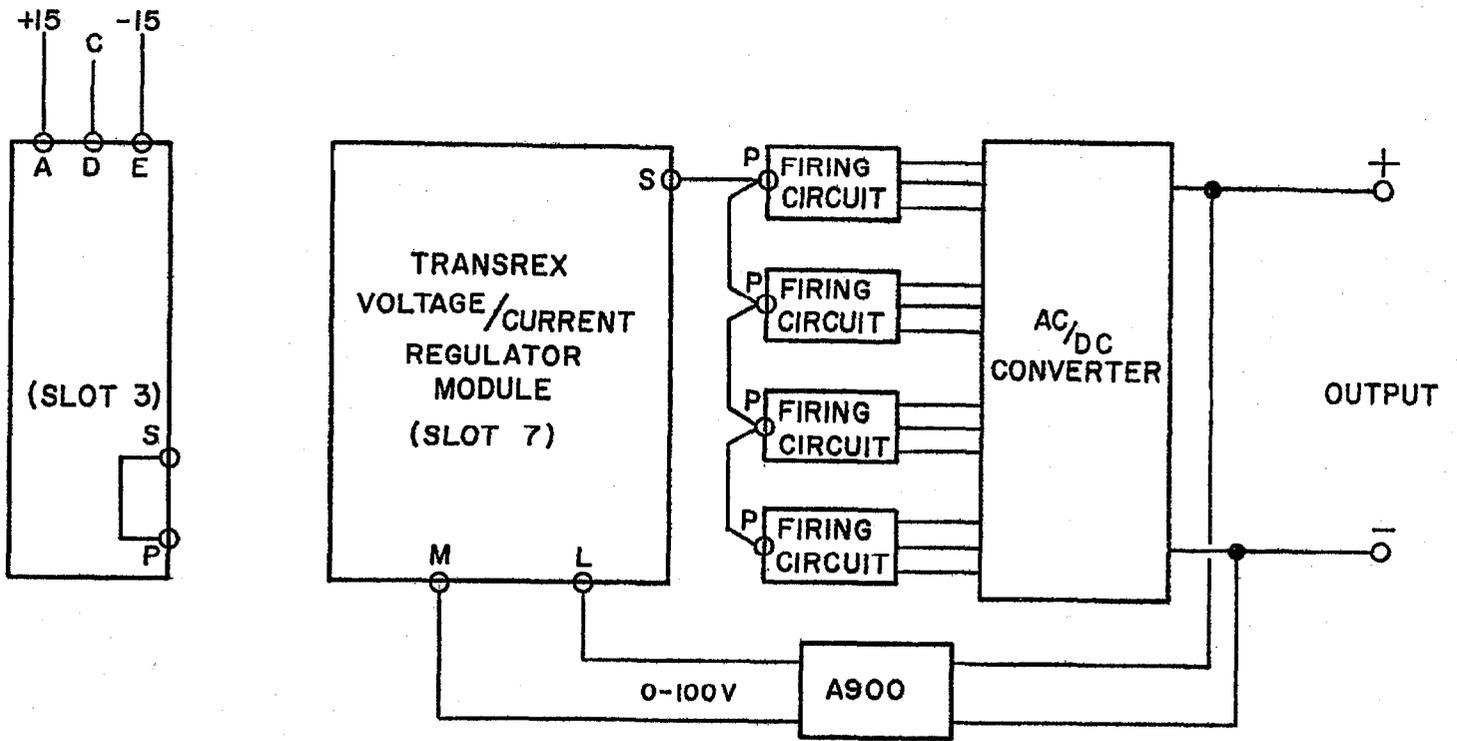
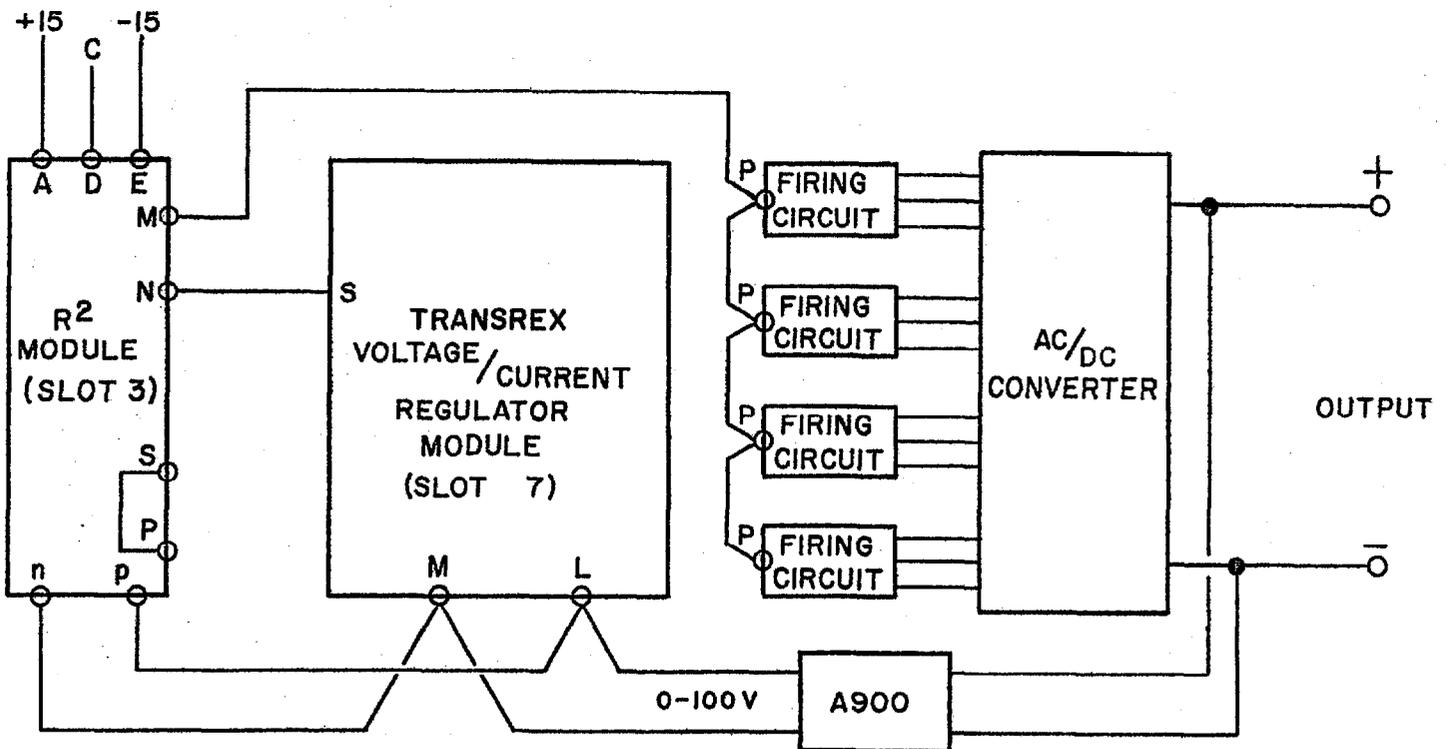


FIGURE 9 - RIPPLE RESONANCE MODE GAIN VS. FREQUENCY

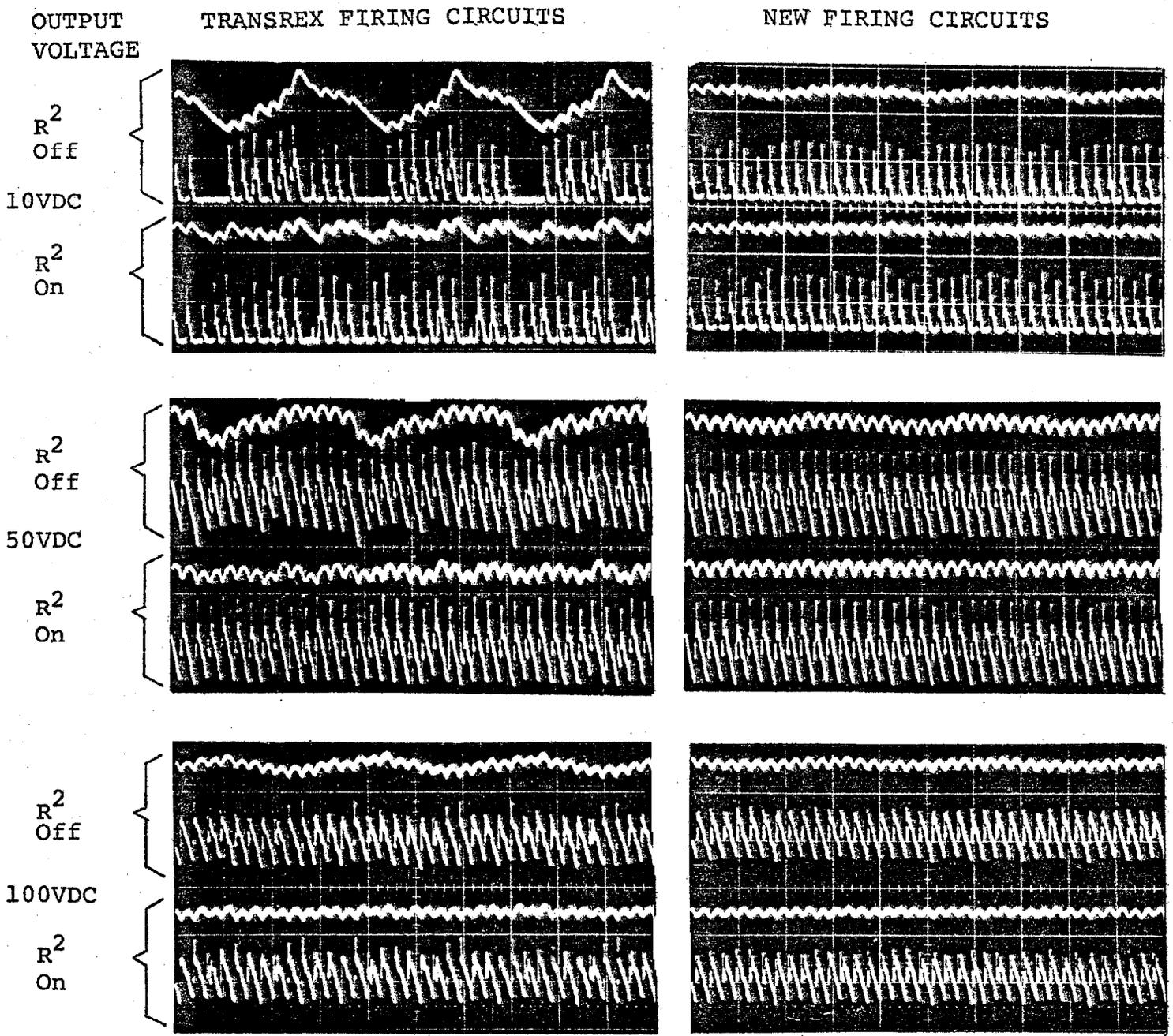


(a) BEFORE R² MODULE INSTALLATION



(b) AFTER R² MODULE INSTALLATION

FIGURE 10 — RIPPLE REDUCTION MODULE INSTALLATION



- NOTES: 1) Photos taken on 6SASAI power supply with bend magnet load
 2) Transrex firing circuits balanced at 60VDC.

3) All Photos

Trace 1: R^2 Off - Field Ripple - 6 G/Div.
 Trace 2: R^2 Off - Output Voltage Ripple - 50V/Div.
 Trace 3: R^2 On - Field Ripple - 6 G/Div.
 Trace 4: R^2 On - Output Voltage Ripple - 50V/Div.

Figure 11: Ripple Reduction Module Performance with Original Transrex Firing Circuits and New Firing Circuits