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A 3-PHASE, 1.5-MW, ELECTRONIC LINE REGULATOR FOR THE BERKELEY 88-INCH CYCLOTRON

Berkeley, California

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Bob H. Smith and Everett L. Harris, Jr.

August 12, 1965

A 3-Phase, 1.5 MW, Electronic Line Regulator for the Berkeley 88-Inch Cyclotron*

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ABSTRACT

Six hundred power transistors on water-cooled heatsinks are connected in a Kerns actuator circuit to modulate the power line feeding the Berkeley 88-in. cyclotron. The regulator senses the rectified three-phase line voltage and attenuates the frequency components between 0.001 and 200 Hz to 0.03% of the average value. Elimination of these components from the main power line removes the need for expensive wide-band regulators for each of the many critical high-power loads in the building. The paper discusses the design considerations and construction techniques of this regulator.

thermal effects. Thus a wide-band line regulator permits a very significant simplification of the regulating equipment throughout the plant. It refines industrial-grade power to research-grade power.

The 88-Inch Cyclotron went into operation in January 1962, and like other sector-focussed cyclotrons subsequently built throughout the country, has proved itself to be an extremely versatile precision tool for nuclear research. During the Cyclotron's initial period of operation, the Bevatron was shut down, undergoing a conversion to produce higher beam currents. When the Bevatron returned to operation, it put severe perturbations on the power line. Many regulators associated with the 88-Inch Cyclotron plant did not have sufficient bandwidth to attenuate these perturbations, and the precision work underway at the Cyclotron could not be continued.

As an interim solution to the power problem, the power line feeding the Cyclotron was transferred to the main Campus in Berkeley which was supplied from a different part of the power company network than that feeding the Laboratory. Thus it was possible to continue the research program at the 88-Inch Cyclotron and also the high-energy physics program at the Bevatron. We realized at the time that something would have to be done to allow the Cyclotron to return to the Laboratory power lines. It became apparent that either we had to develop an electronic line regulator with sufficient loop gain in the 1- to 10-Hz region to provide the research-grade power required, or else we had to increase the bandwidth of a good fraction of the regulators throughout the plant. Because so many of the loads consist of short-time-constant, low-voltage, high-current magnets, the latter solution was not appealing. It would have meant the installation of tens of thousands of transistors in transistor-bank type regulators.

The former solution, that of removing the perturbations from the incoming power lines, required a regulator that would pass the entire ac current for critical loads of the 88-Inch Cyclotron. The regulator would have to reduce perturbations approaching 1% of the power-line voltage to a few hundredths of a percent. This could be accomplished with a transistor bank of approximately 600 transistors. The relative simplicity (with the resulting increased reliability) of this approach led to the decision to develop the line regulator.

DESCRIPTION OF THE REGULATOR

The regulator consists of a sensing device, a regulator amplifier, and an actuating device (Fig. 1). The sensing device consists essentially of an instrumentation-type, three-phase, bridge rectifier to determine the average line voltage. The regulator amplifier provides gain and contains the necessary compensation for stability of the feedback loop. The actuating device consists of a transistor-bank type of Kerns' actuator.[1]

The Sensing Chassis

The input signal from the 480-V, three-phase power line is introduced into a bank of instrumentation transformers connected in a delta-delta configuration. This bank serves the dual purpose of providing electrical isolation from the power line and transforming the 480-V to 120 V for electrical safety. The transformers were built specifically for this application. Wound on a toroidal core, they contain Faraday shields between the primary and secondary windings, and each transformer is mounted in four mu-metal shields to prevent introduction of error signals from stray magnetic fields.

The transformer secondaries are connected to a three-phase bridge rectifier. This arrangement was selected because it simulates the critical loads used throughout the building (Fig. 2). Because of the imperfect waveform of the

power line, the output of the sensing chassis does not exactly simulate the output of a three-phase magnetic amplifier, but the difference is insignificant. Additionally, there is a difference between the average three-phase-rectified voltage of the sensing chassis and the average of three single-phase rectified voltages because of the imperfect waveform of the heavily mag-amp and SCR loaded power line.

The rectifier is resistively loaded by R1 in order to insure that we measure the true three-phase average value. The 360-Hz null network is included to make the regulator insensitive to the 360-Hz rectifier ripple. This signal contains no information, and if not eliminated, would waste a substantial proportion of the transistor bank range.

The Regulator Amplifier

The regulator amplifier, Fig. 3, is a three-stage, vacuum-tube-type amplifier with differential input. We found that it was necessary to regulate the filament voltages, and a Sola filament transformer is used for this purpose. The B-supply voltages are regulated also. The amplifier has a maximum voltage gain of about 1000. Compensation for the feedback loop is achieved by means of R1, C1, C2, and the effective resistance of R3, R10, and R6. These are discussed under the section on feedback analysis.

The Kerns Actuator

At maximum load, the incoming 480-V power line has a line current of 1800 A. We decided to make the control range of the Kerns actuator approximately 5% of the line voltage or 24 V (Figs. 1, 4). Thus, per leg, transformer T1 must be capable of 15 V and 90 kVA. With a unity turns ratio for transformer T1, the rectifier must be capable of producing an average current of 4.5 kA at a maximum voltage of 20 V. We built the rectifier with 24 International Rectifier 70U50's and 70U50R's, all mounted on water-cooled heatsinks.

Transistor-bank heatsinks are an expensive item requiring considerable engineering. Because we had a complete set of drawings and experience with the heatsinks and transistors of Ref. 2, we decided to duplicate these units. Each tray contains 63 Minneapolis-Honeywell DA3F3 transistors which, at 20 V, operate satsifactorily with a dissipation of 150 W per transistor (Fig. 5). At this rating, 600 transistors are required for the final bank to dissipate 90 kW. Ten trays of transistors are used, but one of the trays (the driver tray) has 25 of the transistors connected as a driver amplifier, which in turn is driven by three emitter-follower stages (Fig. 5). Also, the driver stage includes an 18-V Zener clamp to protect the transistor bank from over-voltage transients. Figure 4 is a photograph of the Kerns actuator showing details of construction.

The input stage of the transistor bank also includes a 22-V Zener clamp to prevent accidentally overdriving the input transistor.

Analysis of the Feedback System

If we assume that the driving-source impedance of the sensing chassis is low compared to R1, the combination R1 and C1 produces a pole at 934 mHz. For the equivalent resistance of R2, R6 and R10, we obtain a value of 638 kΩ, which, when combined with C2, produces a zero at zero frequency and a pole at 250 mHz. Thus if we neglect the effect of the null network in the sensor chassis, the transfer function of the regulator has a zero at zero frequency, a pole at 250 mHz, a second pole at 934 mHz and no other poles up to the kilocycle region, which is beyond the range of interest. If the loop gain is 200 at 500 mHz, unity gain will occur at 200 Hz and at 1.2 mHz. Clearly this system is stable and possesses sufficient phase margin to accommodate the 360-Hz null network.

PERFORMANCE OF THE REGULATOR

A pair of depressed-zero voltmeters were built to monitor the power lines before and after the regulator. Each voltmeter consists of a three-phase instrumentation-type rectifier (similar to that used in the sensing chassis) and a sharp-cutoff filter. Both metering and oscilloscope types of outputs are provided. Figure 6 is a typical pair of oscillograms taken from these two voltmeter circuits. The vertical scale is 0.1% per large division, whereas the horizontal scale is 1 sec per large division. The incoming line perturbations, which typically amount to about 0.5%, are reduced to about 0.03% by the regulator, as shown in Fig. 6. The lower frequency components of the perturbations are reduced to less than 0.03%.

With the installation of the regulator, the 88-Inch Cyclotron was transferred back to the Radiation Laboratory power line and the experimental program has continued, undisturbed by the Bevatron operation.

ACKNOWLEDGMENT

The authors would like to express their appreciation for the contributions of the other members of the electronics team. W. L. Dexter and H. H. Warnock did the systems engineering. The equipment was installed by the Cyclotron's installation and electrical crews under the direction of M. J. Enos and K. N. Jaeckel, respectively. J. P. Burke and the Cyclotron's electronic maintenance crew checked out the system, and D. R. Struthers, P. E. Frazier, and G. Gerding contributed to the preliminary research and development work.

FOOTNOTES AND REFERENCES

*This work was done under the auspices of the U. S. Atomic Energy Commission.

†Present address: Alpha Scientific Laboratories, Berkeley, California.

1. Q. A. Kerns, Rectifier System, U. S. Patent No. 2,579,235 (December 8, 1951).
2. B. H. Smith, J. R. Atwood, and D. N. Lyon "Current Regulator for a 10,000 Amp. dc 7.5-Megawatt Magnet Power Supply" Rev. Sci. Inst. 35, 340 (1964).

Fig. 1. Simplified system schematic.

Fig. 2. Schematic diagram of the sensing chassis.

Fig. 3. Schematic diagram of the regulator amplifier.

Fig. 4. Transistor bank and rectifier.

Fig. 5. Schematic diagram of the transistor bank showing (a) the driver tray and (b) a typical final-amplifier tray.

Fig. 6. Input and output line perturbations. The upper trace is the incoming line voltage; the lower trace is the regulated line. The vertical scale is 0.1% per large division, and the horizontal scale is 1 second per large division. The regulator reduces the perturbations from 0.5 to 0.03%.

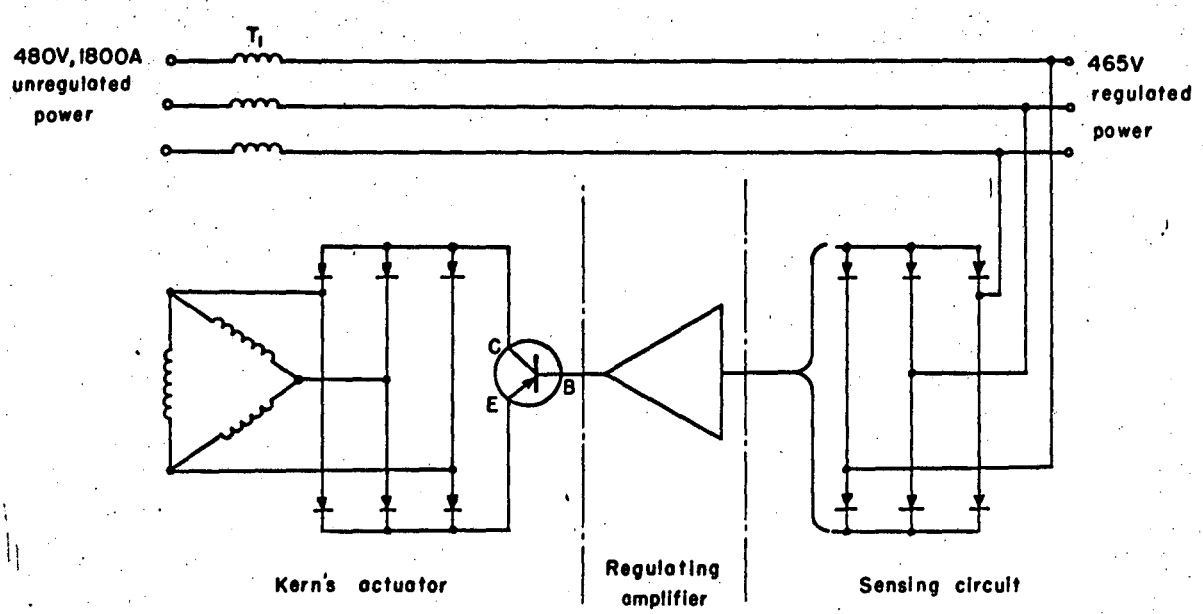

480V, 1800A
unregulated
power
T_1
465V
regulated
power
C
E
B
Kern's actuator
Regulating
amplifier
Sensing circuit
MUB-7570

Fig. 1

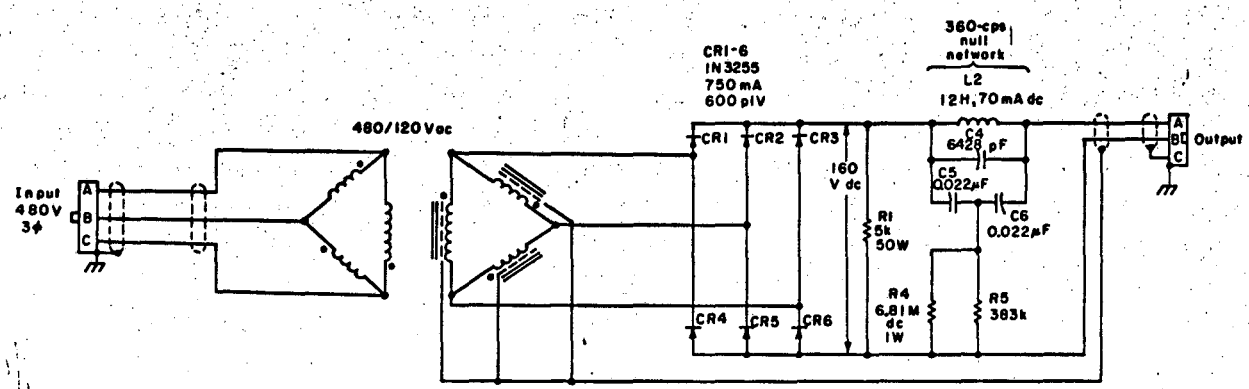

Input
480V
3φ
A
B
C
480/120Vac
CR1-6
1N3255
750mA
600pIV
CR1
CR2
CR3
CR4
CR5
CR6
160
V dc
R1
5k
50W
360-cps
null
network
L2
12H, 70mA dc
C4
6428 pF
C5
0.022μF
C6
0.022μF
R4
6.81M
dc
1W
R5
383k
Output
A
B
C
MUB-7572

Fig. 2

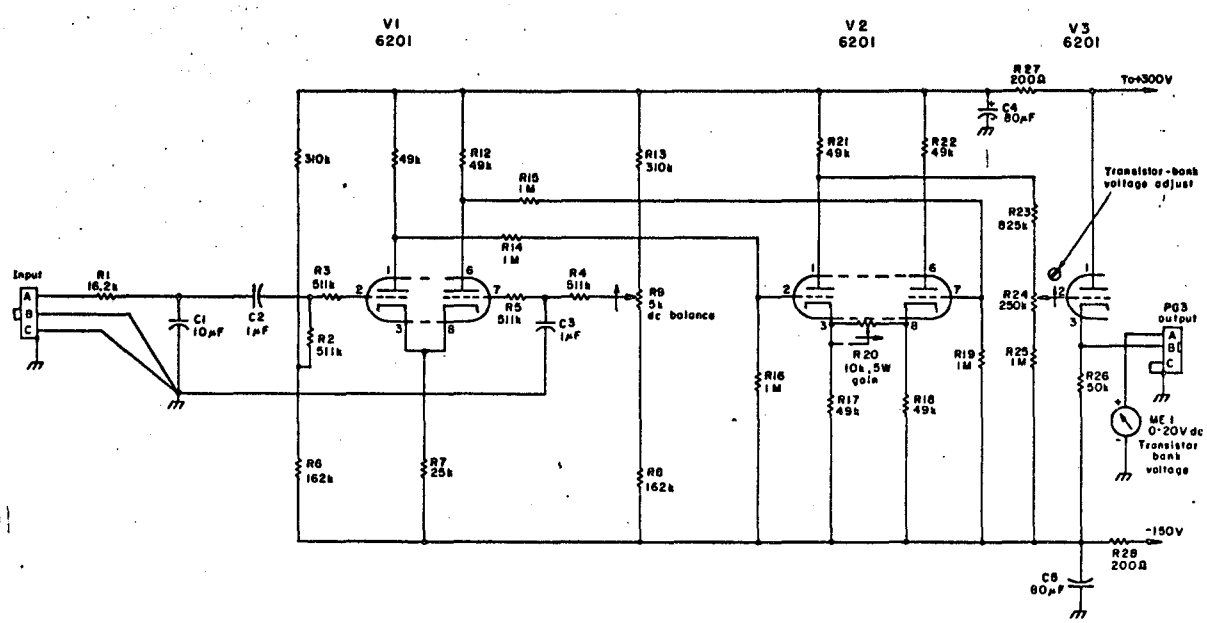
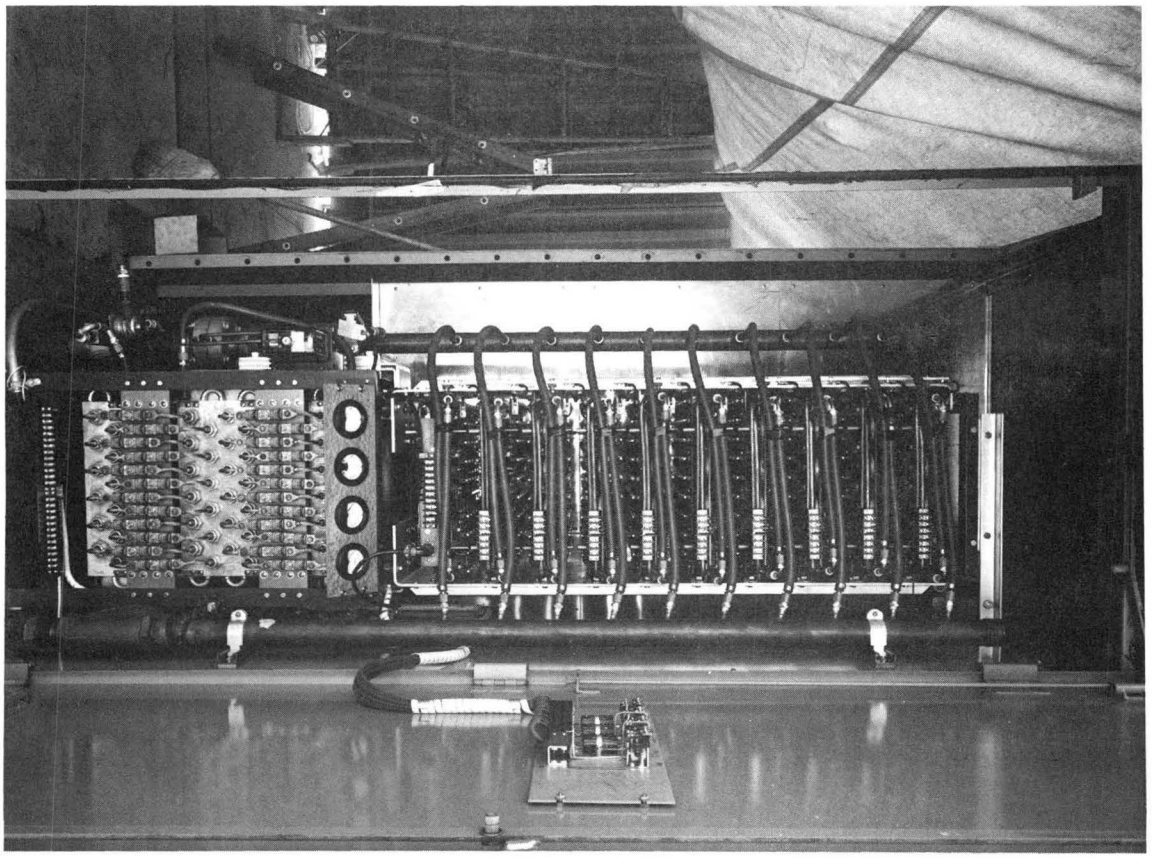

V1
6201
V2
6201
V3
6201
R27
200Ω
To+300V
C4
80μF
310k
49k
R12
49k
R15
1M
R13
310k
R21
49k
R22
49k
Transistor-bank
voltage adjust
R23
825k
R14
1M
Input
R1
16.2k
R3
511k
R4
511k
R9
5k
dc balance
R24
250k
PG3
output
C1
10μF
C2
1μF
R2
511k
R5
511k
C3
1μF
R20
10k, 5W
gain
R19
1M
R25
1M
R26
50k
R16
1M
R17
49k
R18
49k
ME 1
0-20V dc
Transistor
bank
voltage
R6
162k
R7
25k
R8
162k
-150V
R28
200Ω
C6
80μF
MUB-7573

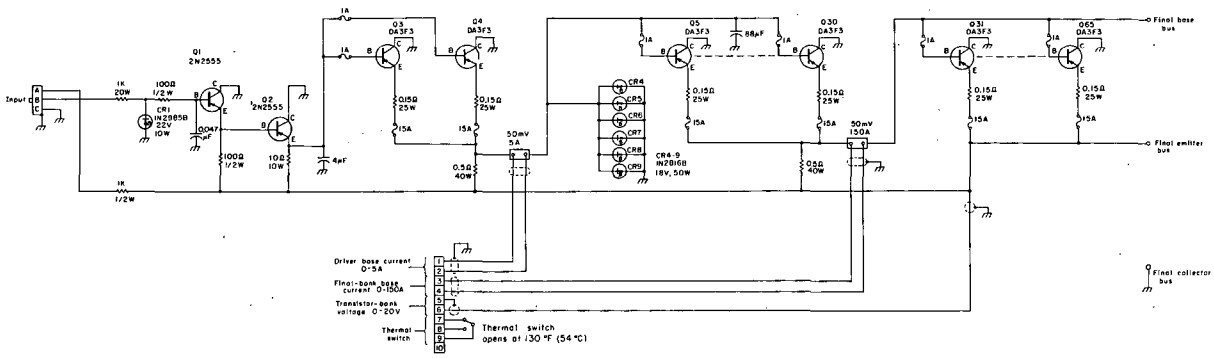
Fig. 3



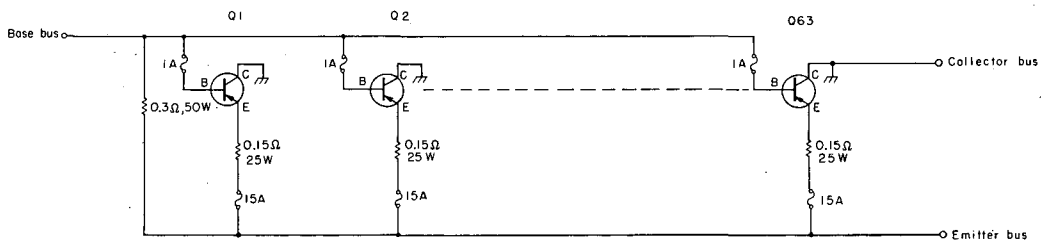
ZN-5188

Fig. 4

(a)



(b)

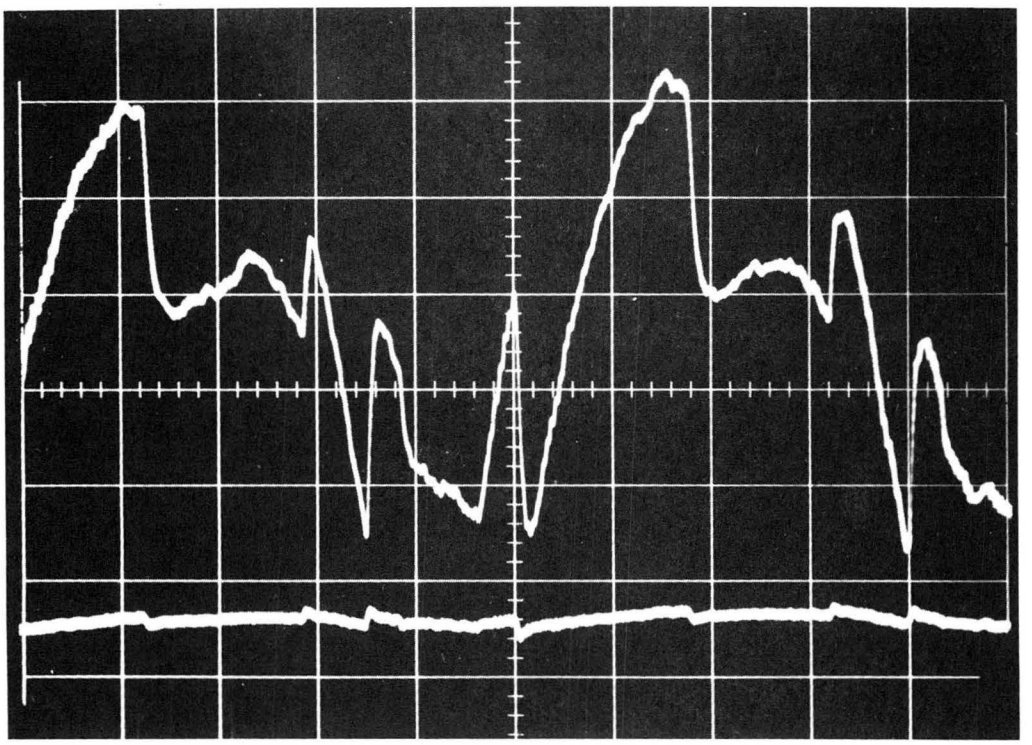


Notes:

1. All transistors are Minneapolis Honeywell DA3F3 and are mounted to heat sink.
2. Resistors are water cooled by heat sink.

MUB-8123

Fig. 5



ZN-5173

Fig. 6

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