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Ferd Voelker and George Farly

August 19, 1963

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Lawrence Radiation Laboratory
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ABSTRACT

This paper describes the conversion of a 12-phase high-powered mercury rectifier to supply energy to a pulsed load. Newly developed hard-tube switches and a shunted RC network are used in combination with the rectifier to replace the existing pulse-line energy storage and the associated charging system. The switch tubes will also serve as a regulating means to reduce ripple voltage during the pulse.

Pulse durations of 2.5 to 5 milliseconds are contemplated. The load will require 250 amperes at 25 to 30 kV during the pulse. The pulse repetition rate will probably be 40 per second, as this avoids unsymmetrical magnetization of the rectifier transformers. A low-powered test model has been used to confirm the design parameters.

A POWER SUPPLY FOR A 7.5-MW PULSED LOAD*

Ferd Voelker and George Farly

Lawrence Radiation Laboratory
University of California
Berkeley, California

August 19, 1963

Design of Power Supply

We want to describe in this paper what we are doing to upgrade the dc power supply for our linear accelerator. A number of things have influenced the final design of the power supply system, and in order to make them clear, we have shown in Fig. 1 what we call a logic-arrow diagram. In this diagram the arrow leaving a circle depends on all the arrows entering that circle. Starting with the left side of the diagram at circle 1, we see two inputs. The first represents the fact that pulse lines had been designed and were available, and that kenotron power supplies were also available, both of these for the cost of transportation and minor modifications. The second and controlling consideration was that we had a very tight budget to work within. Our original design used these components, and with some additional transformer cooling we were able to achieve a 3% duty cycle.

Very early in the life of this accelerator there was an increasing need for more beam as the simpler experiments were completed and more sophisticated ones were planned. By pushing the design limits somewhat on the electrical parts of the machine we could have handled a 4.5% duty cycle. However, we were limited to 3% because the tank was convection-cooled. The mechanical design was therefore modified by the addition of water cooling to the tank to handle an 18% duty cycle, which was the maximum anticipated at that time.

In 1960 money was budgeted to double the number of pulse lines and rectifiers so as to bring the duty cycle to 9%. The rf amplifiers were designed around amplifier tubes that were available and had an inherent capacity for 67% duty cycle, and the cooling was already capable of 18% duty cycle. As we began to study the power supply it appeared as if this would again be the limiting factor unless we could significantly increase its capacity.

At about this time we found that a 10-megawatt rectifier and some large transformers at Livermore were going to be declared surplus. The availability of this rectifier at a low cost made it possible for us to greatly increase the power supply rating. We also became aware of recent development of several types of large vacuum tubes that were suitable as switches. Westinghouse and Machlett have tubes that switch several hundred amperes at 50 to 75 kV. With these large tubes we can use hard-tube modulators, which allows us to eliminate much of the energy storage in the pulse lines. Since energy storage is a large part of the cost of the system, and since our budget was set up to only double the duty cycle, we must minimize energy storage and still minimize the perturbations in the line voltage.

The dc power required by the rf amplifiers is 6 MW during the time the accelerator is on. An additional 1.5 MW will be consumed in the modulators because we intend

to use them as electronic regulators to remove the ripple and to flatten the pulse. With the modulators we can have an arbitrary pulse length, so we will start with a short pulse length and gradually increase it as various components of the machine are modified to handle the increasing duty cycle.

We intend to take the dc power out of the rectifier on a 30-kV dc bus, and to tie hard-tube modulators between the bus and each of the rf amplifiers. Figure 2 is a schematic of the power supply. More will be said about the capacitor and damping resistor later. We will also use the modulators to disconnect dc power in the event of a fault in the rf system, which is a frequent occurrence.

For a number of reasons we are planning to start with 40 pps and 4.5-msec pulse length. The load as reflected on the power system corresponds to a pulsed single-phase load with some distortion of the wave shape every third half-cycle.

To better understand the effects of this type of operation we designed and built a model of the system. (The second part of this paper is an account of the model study.) One of the first things the model showed us was that at the beginning of each pulse the voltage on the load would rise at a rate limited by the leakage reactance of the transformers. When we turned off the modulators, there was an enormous voltage kick due to the energy stored in the inductive impedance of the power supply. We found on the model that we could control both these phenomena by shunting a capacitor and a series damping resistor across the dc bus. The model also showed us what to expect for regulation under load, and gave us an idea of the amount of control necessary in the hard-tube modulators to achieve good electronic regulation.

We have now fixed the design of the power supply, and we are planning to begin construction as soon as the building is completed. We have also completed design and construction of a prototype modulator shown in Fig. 3, and have begun tests on it. Our next step will be to construct the final modulators and combine the power supply system. The system will be debugged on a 1-MW water-cooled dummy load.

Experimental Tests on Model

The scale for the model was chosen so that impedances and frequency were at full scale, whereas rectifier voltages and currents were about 1/300 actual value. We built two low-reactance three-phase transformers with delta-delta and delta-wye windings. The total reactance was adjusted by adding series inductors to the secondary. The six inductors were set equal in value through adjustment of the air gaps. The rectifier ignitrons were simulated by miniature silicon rectifiers; this was adequate because we do not propose to use phase control. The apparatus was mounted on a plywood board with the wiring accessible so that meters and oscilloscopes could be connected at convenient points. The hard-tube modulator was simulated by a mercury relay driven by an audio oscillator.

In order to establish the modulator parameters we observed the waveforms of the pulse voltage, and selected values of R and C to approximate a flat-top pulse (see Figs. 4 and 5).

Effect of Pulse Rate

By varying the frequency of the audio oscillator we observed the effect of adjusting the pulse rate. We chose a pulse rate of 40 per second because it does not cause unsymmetrical magnetizing currents in the transformers, and because its beat rate

with 60 cps is above the frequency that causes the most troublesome voltage perturbation. The harmonics that cause perturbation are particularly evident at the ac input to a rectifier bridge. In Fig. 6 the notches show the duration of commutation overlap.

At 40 pps the transformer secondary currents alternate in polarity for each successive pulse. The power system loading is a single-phase load modulated at 20 cps. The distribution of the single-phase component in the power lines depends upon the pulse timing. In Fig. 7 multiple exposures show the precession of phase when the pulse rate is not exactly 2/3 of the line frequency. This precession may be used to equalize the average power loss in the rectifier tubes and transformers.

The rectifier output current is indicated in Fig. 8. Note that it does not follow the load voltage. Figure 9 shows how the capacitor and rectifier currents combine to produce a uniform output pulse.

Rectifier Regulation Characteristic

Numerous references show the regulation of six-phase bridge rectifiers, with and without load inductance. 1,2,3 The experimental twelve-phase model was tested; its regulation characteristic, uncorrected for losses, resembles the six-phase inductive case. Two effects contribute. (a) Each rectifier acts as series inductance to its partner. (b) When the overlap angle of series rectifiers exceeds the ripple angle, the common source impedance causes additional phase shifts which reduce the output voltage.

In our model there is an appreciable effect, due to the three-phase source impedance, which causes the transformer primary voltage to be a function of load. The regulation characteristic of the model exhibits 11% droop at full load.

Conclusions

The model has enabled us to confirm design factors for the full-scale power supply. It also revealed effects we had not anticipated. We have decided to extend use of the model to other programs by adding controlled rectifier elements. We can then study combinations of rectifiers and inverters that are applicable to other laboratory problems.

Appendix - Supplementary Information Gained From Model

We get interesting effect when two rectifier bridges are added in series. The commutation of each bridge may be altered by the presence of the other bridge. Figures 10, 11, and 12 show this effect.

The usefulness of damping networks to reduce transients is illustrated in Figs. 13 and 14.

Additional useful information obtained through use of the model is indicated in Figs. 15, 16, and 17.

When two six-phase bridges are connected in parallel instead of in series, the total load current may commutate between the bridges (see Fig. 18). An interphase inductor restores the normal conduction period to 120 degrees in each bridge.

*Work done under the auspices of the U. S. Atomic Energy Commission.

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2. Extended Regulation Curves for Six-Phase Double-Way and Double-Wye Rectifiers, I. K. Dortort. A.I.E.E. T.P. 53-36.

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FIGURE LEGENDS

Fig. 1. Logic-arrow diagram.

Fig. 2. Schematic representation of system. Twelve-phase series bridge ignitron rectifier. Anode power supply for Hilac.

Fig. 3. Prototype of hard-tube modulator.

Fig. 4. Rectifier voltage at 40 pps. R = 28 ohms, C = 50 μf.

Fig. 5. Rectifier voltage at 40 pps. R = 68 ohms, C = 50 μf.

Fig. 6. Line-to-line voltage at one rectifier bridge.

Fig. 7. Transformer secondary current. Multiple exposure to show change in phase when pulse timing is varied.

Fig. 8. Rectifier voltage and current at 40 pps.

Fig. 9. Combination of currents.

Fig. 10. Rectifier output voltage and mid-tap voltage with inductive load.

Fig. 11. Rectifier output voltage and mid-tap voltage with non-inductive load.

Fig. 12. Illustrating mid-tap voltage at 40 pps.

Fig. 13. Rectifier ac voltage showing commutation transients.

Fig. 14. Portion of rectifier ac voltage with and without commutation damping.

Fig. 15. Addition of transformer primary currents.

Fig. 16. Transformer secondary voltage on each side of commutating inductance.

Fig. 17. Current and rate of change of current at rectifier input.

Fig. 18. Secondary currents with and without inductance between parallel bridges.

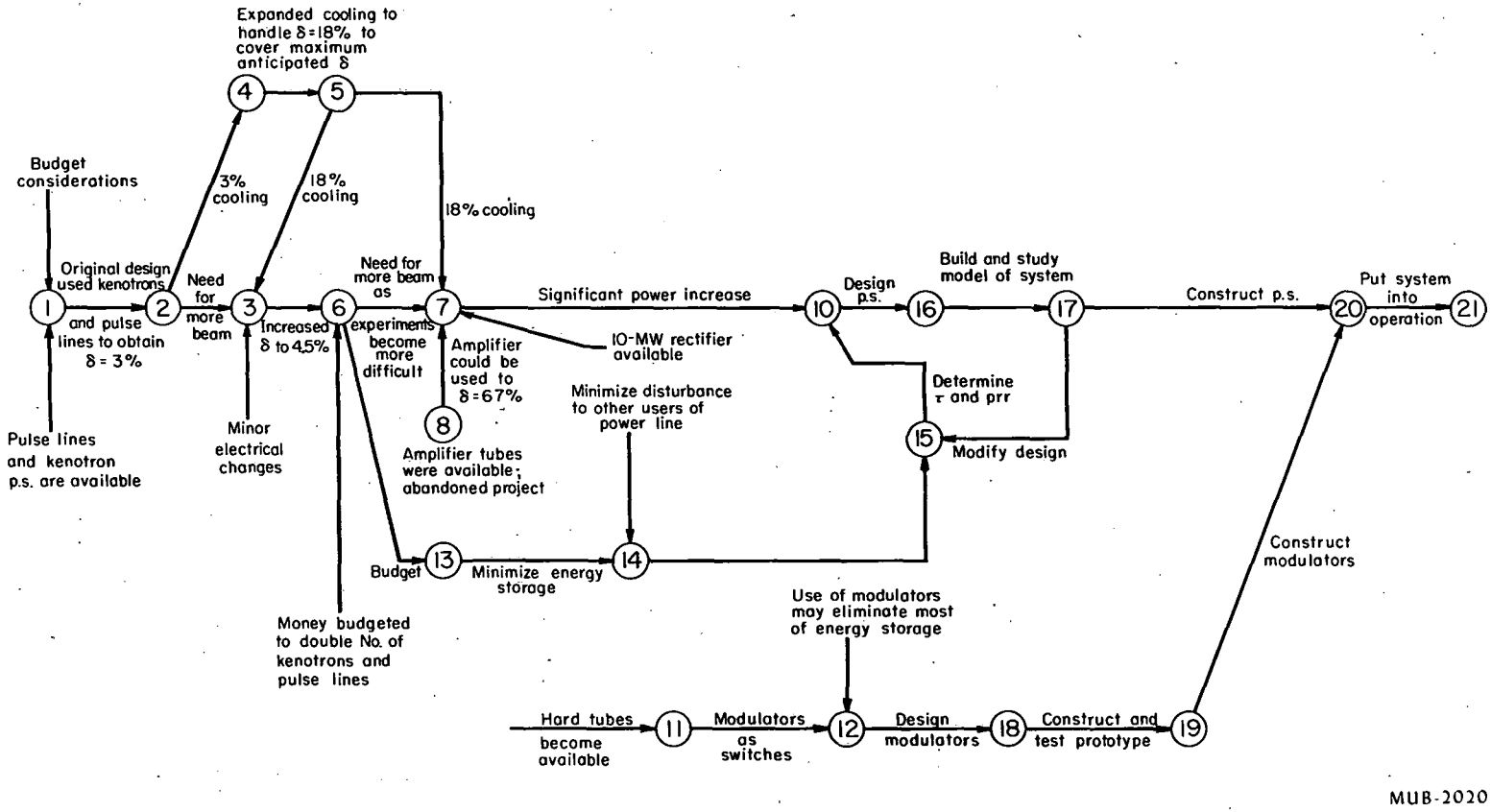

Fig. 1

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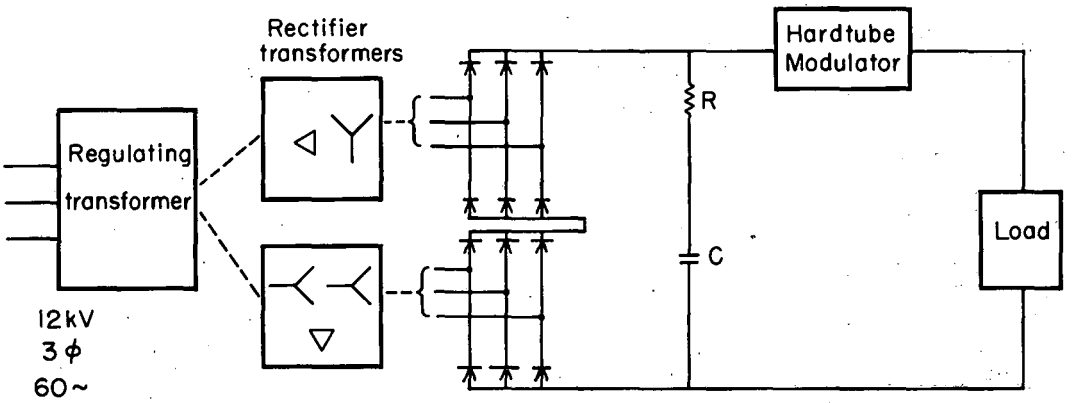

12 ϕ Series Bridge Ignitron Rectifier

MU-31503

Fig. 2

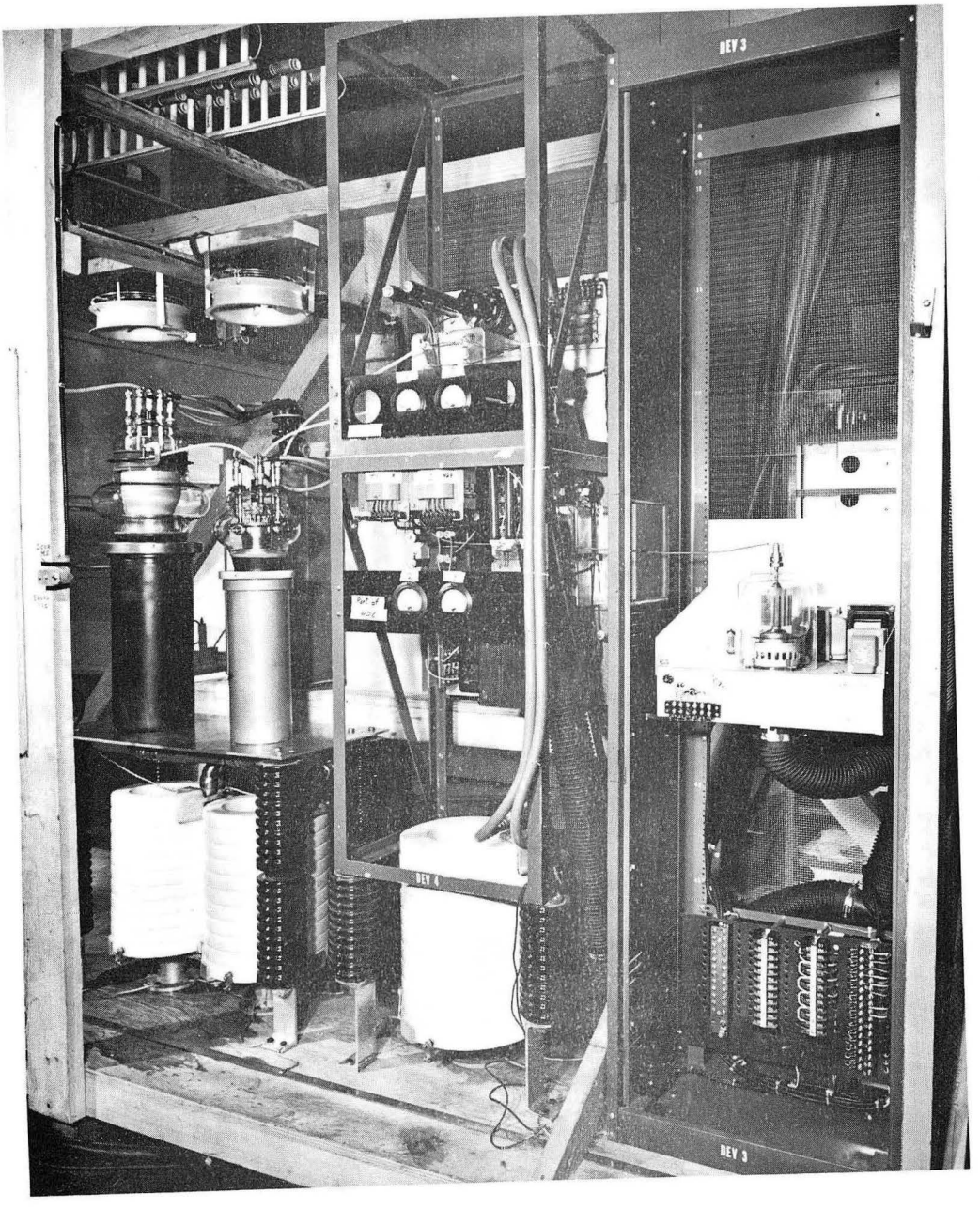

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Fig. 3

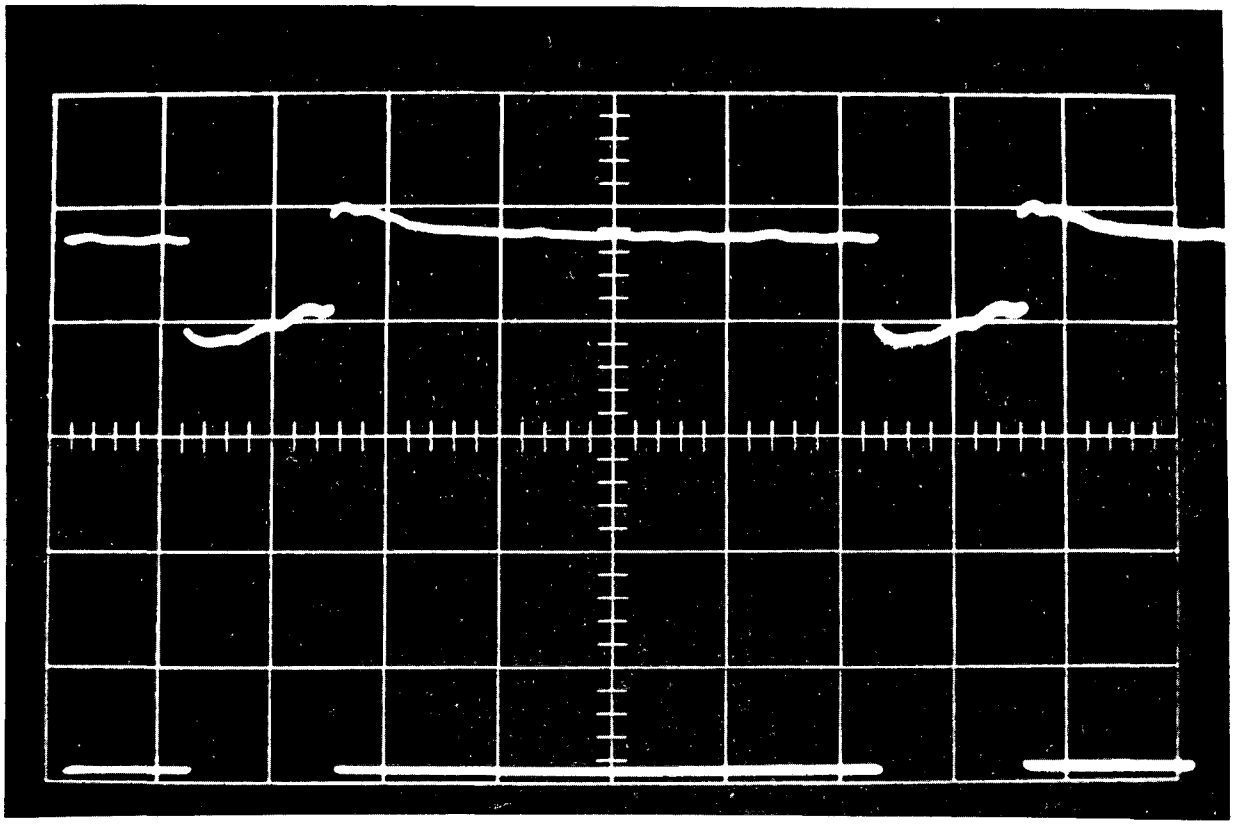

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Fig. 4

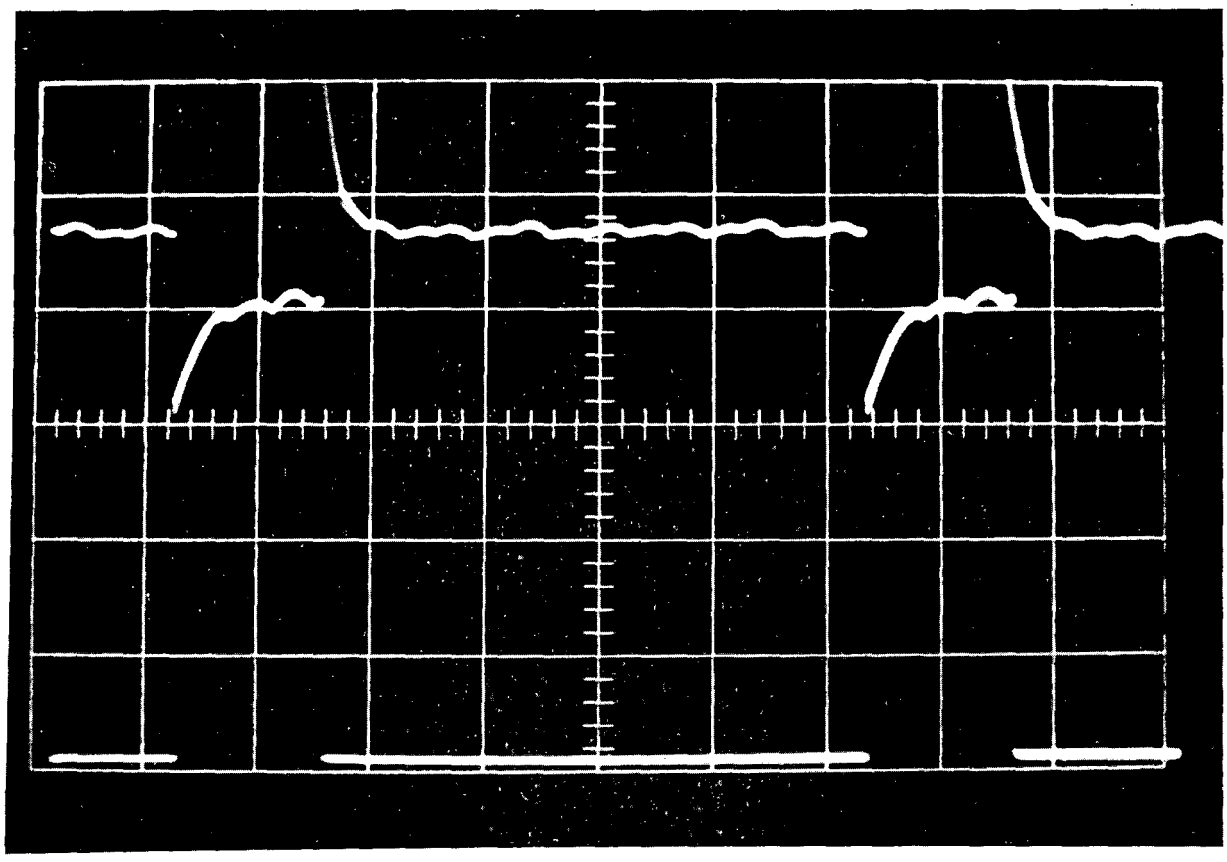

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Fig. 5

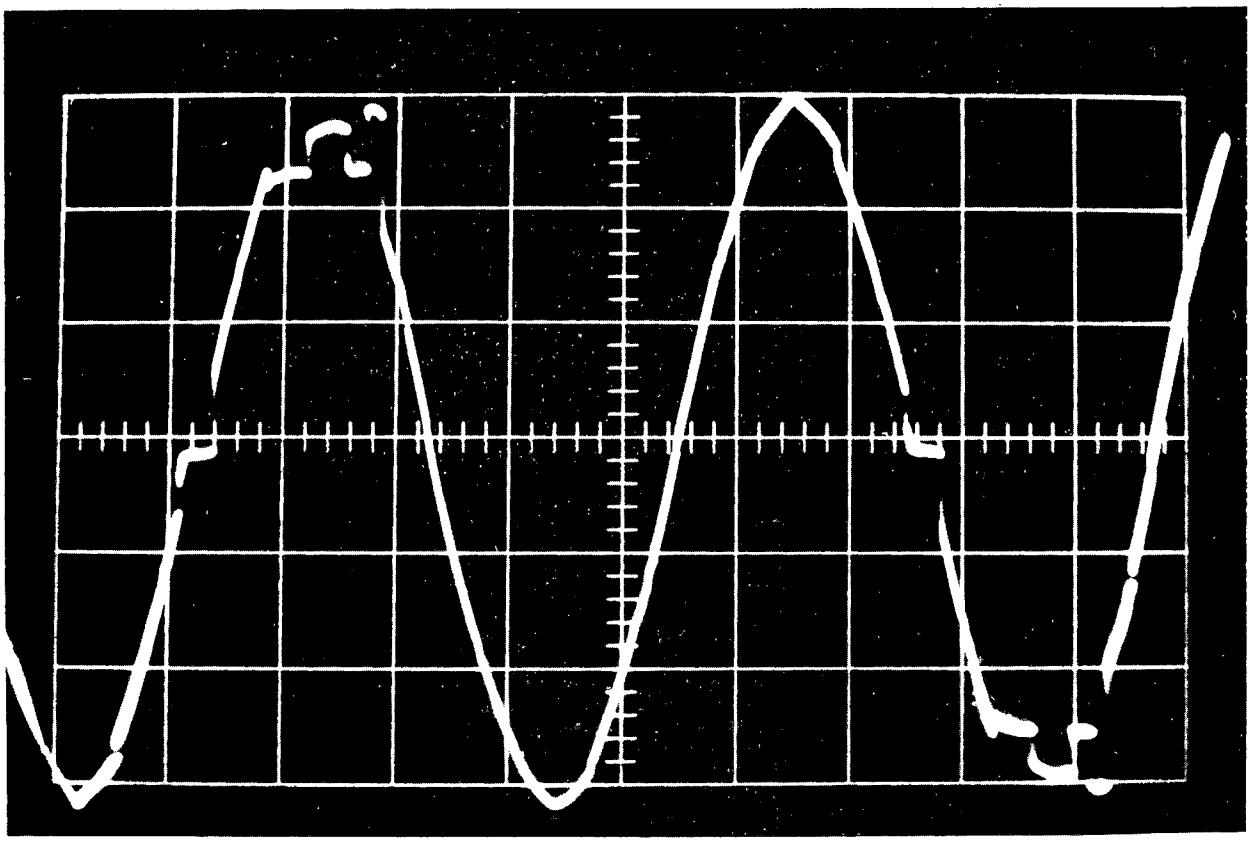

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Fig. 6

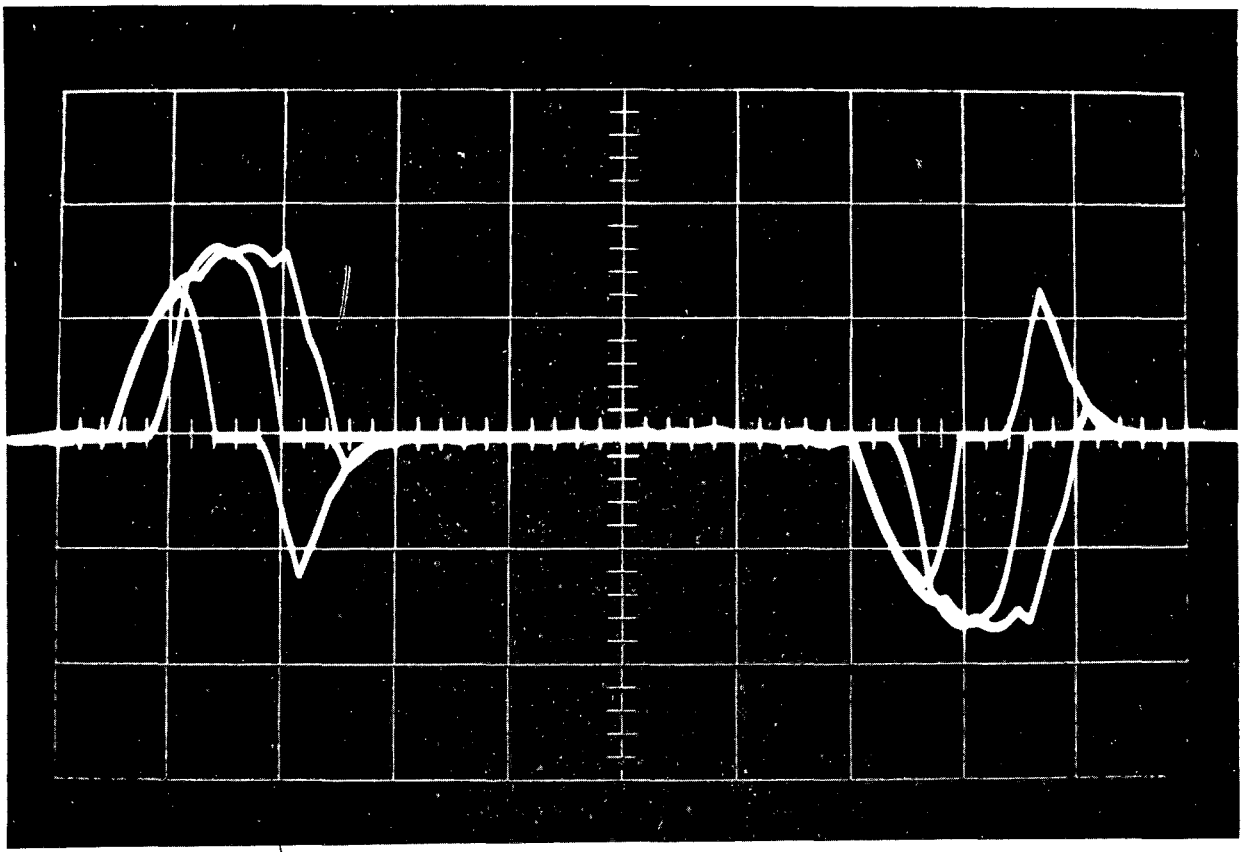

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Fig. 7

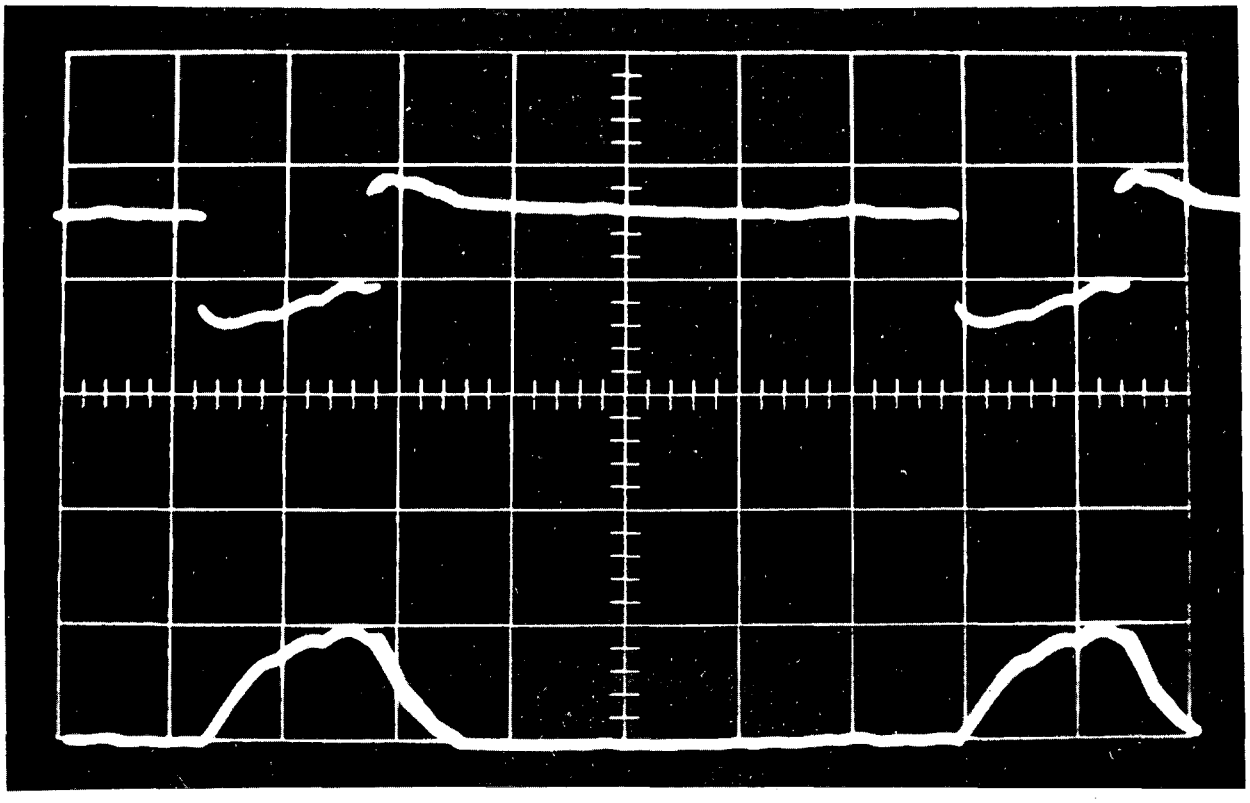

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Fig. 8

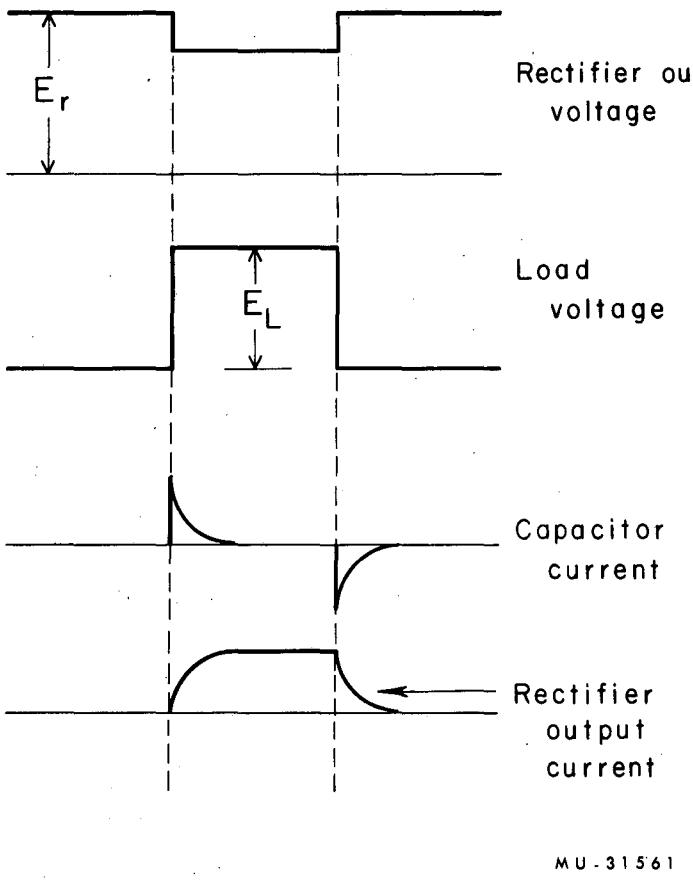
E_r
Rectifier output voltage
E_L
Load voltage
Capacitor current
Rectifier output current
MU-31561

Fig. 9

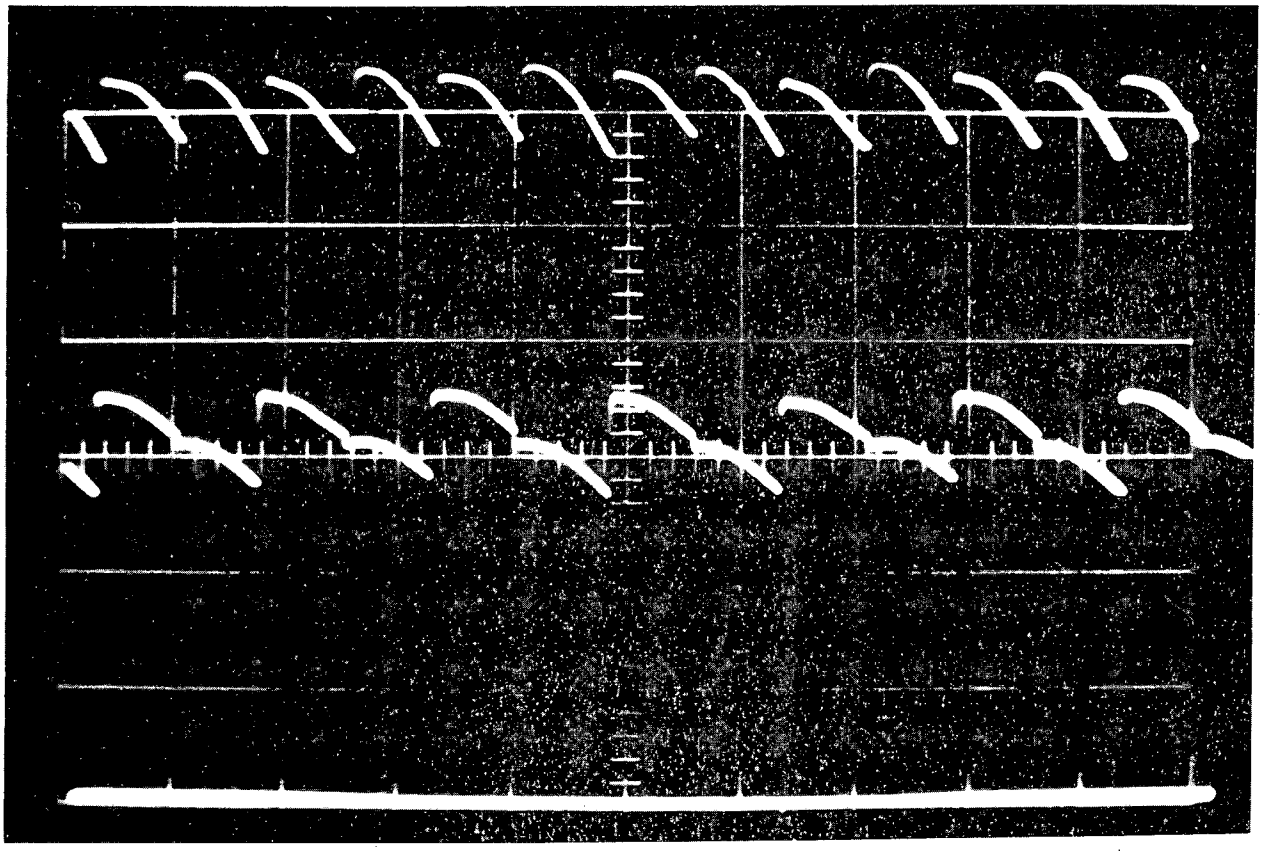

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Fig. 10

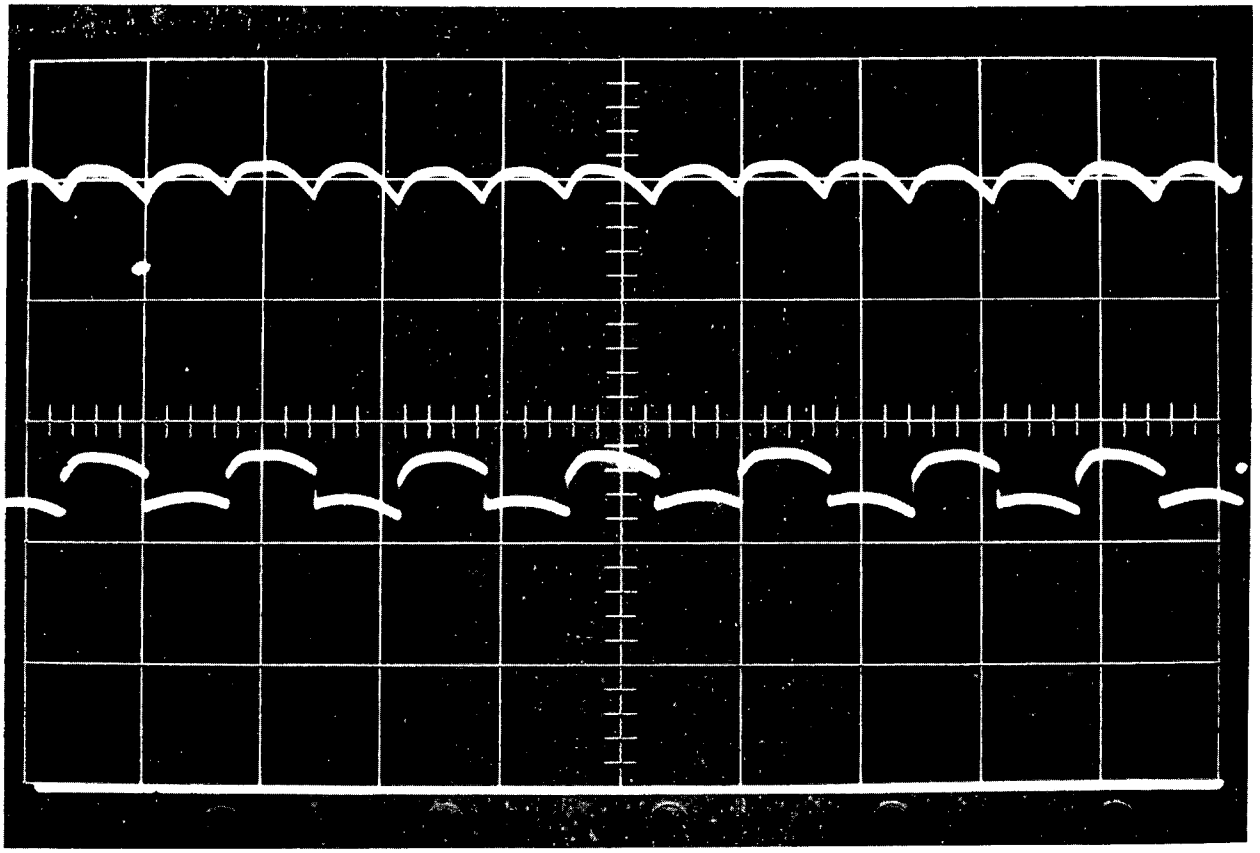

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Fig. 11

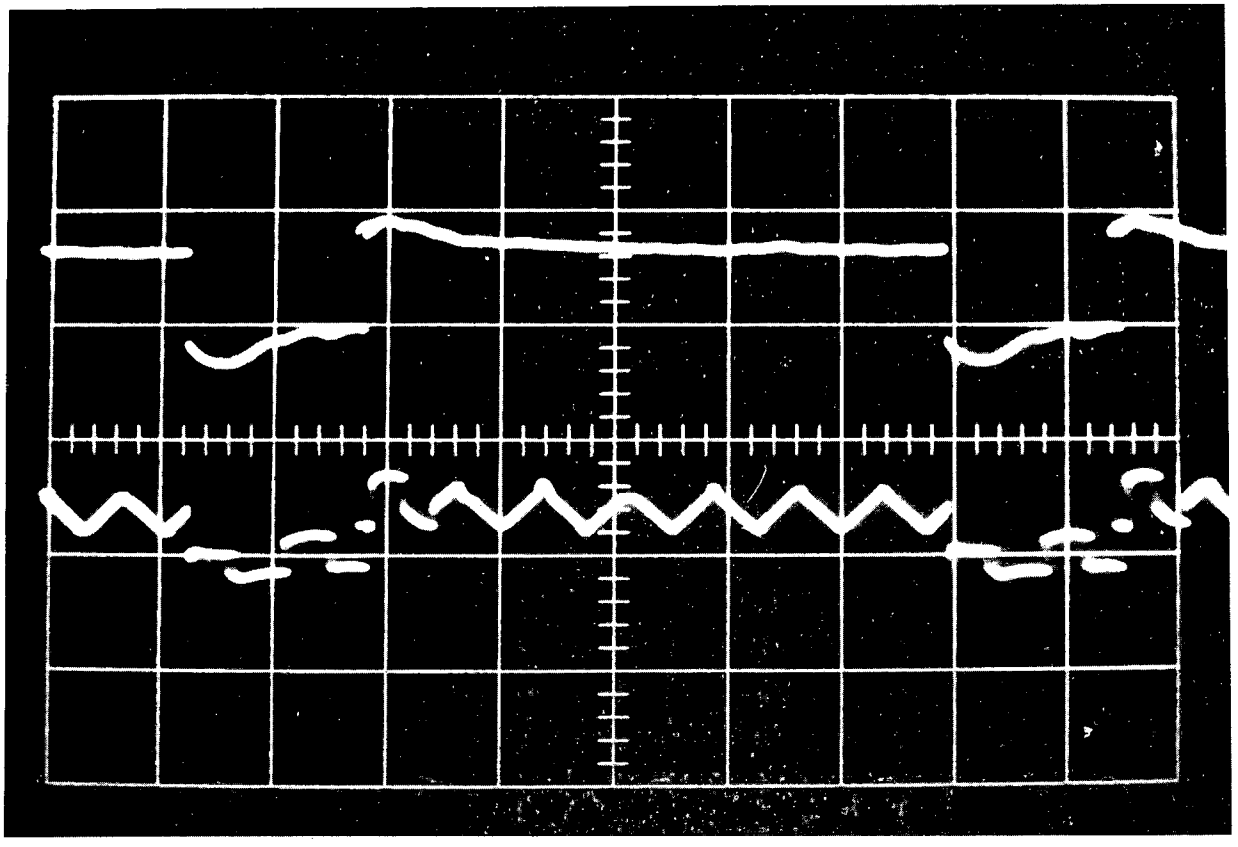

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Fig. 12

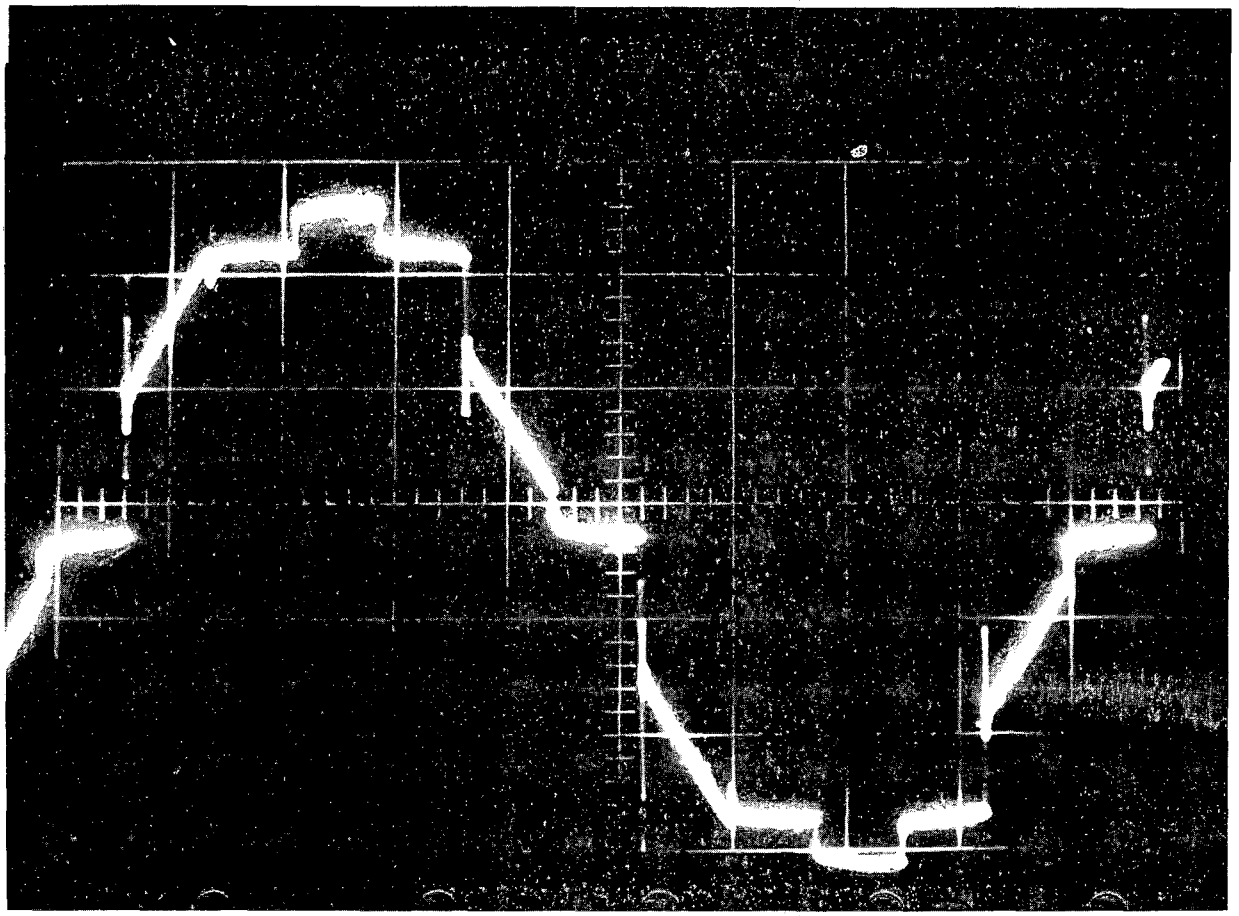

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Fig. 13

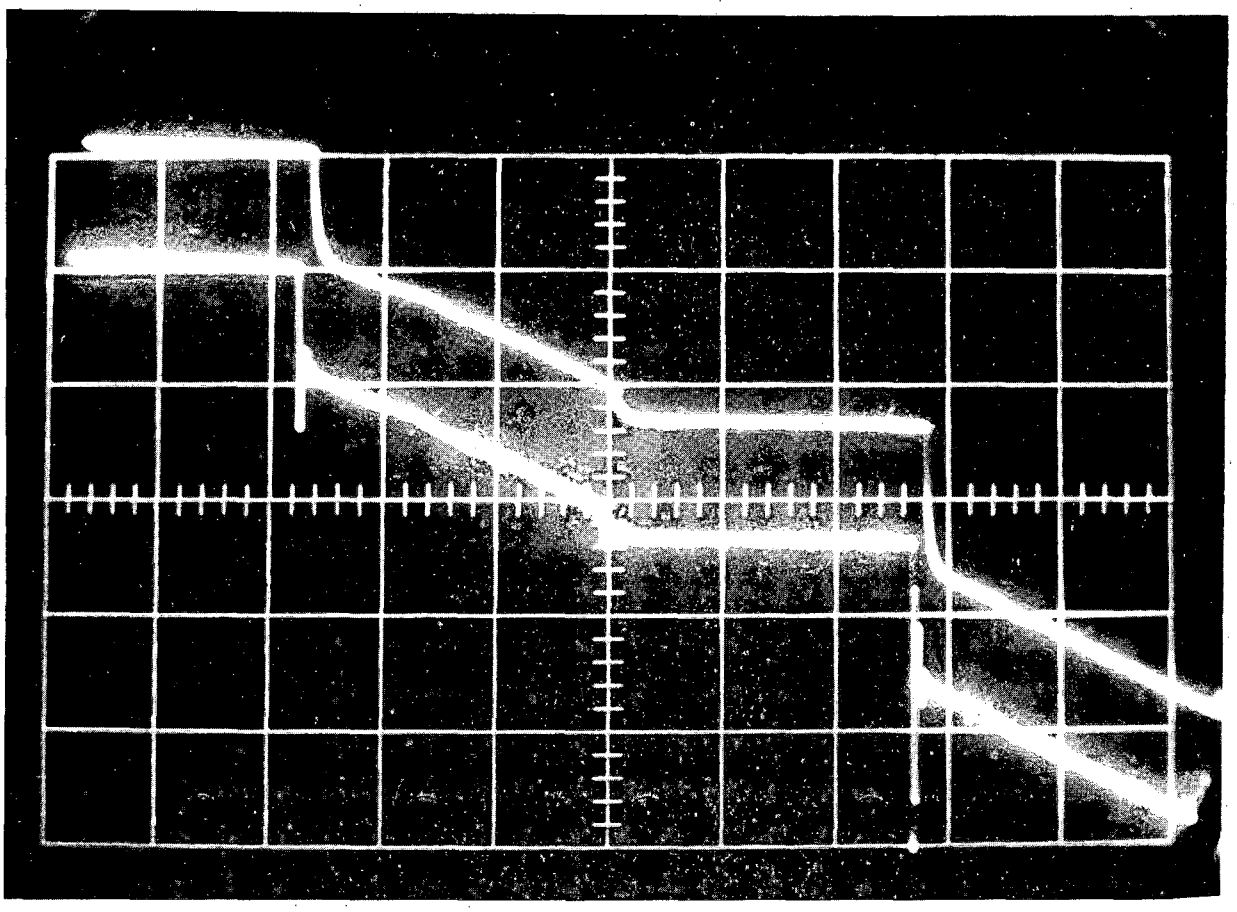

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Fig. 14

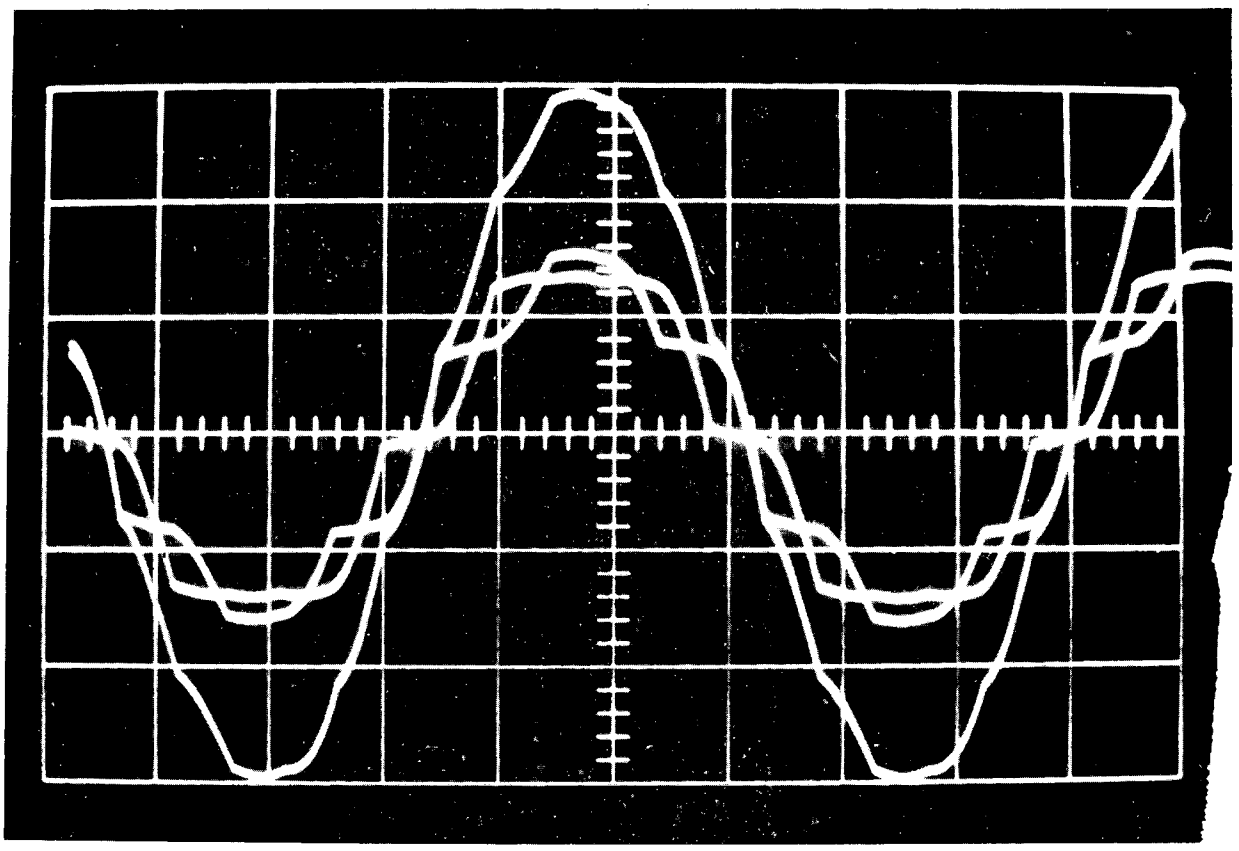

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Fig. 15

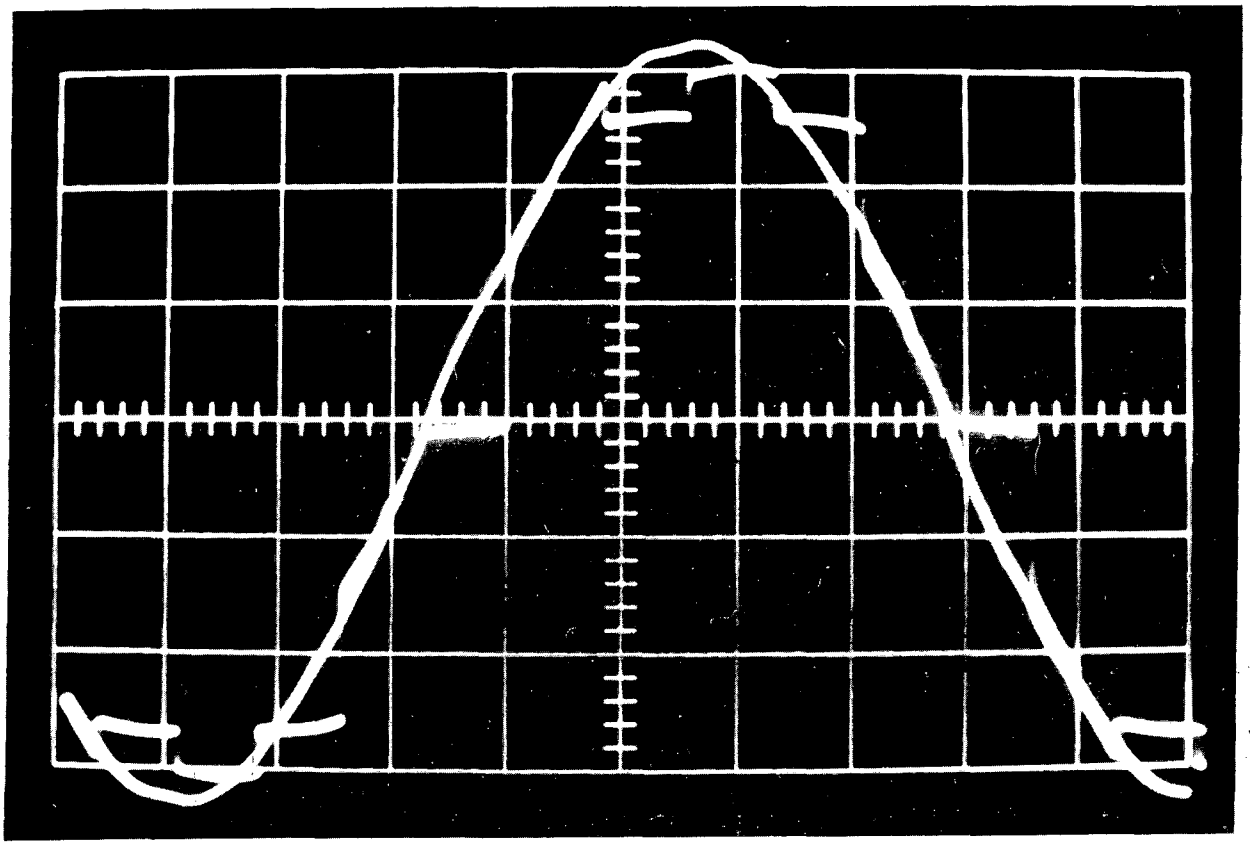

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Fig. 16

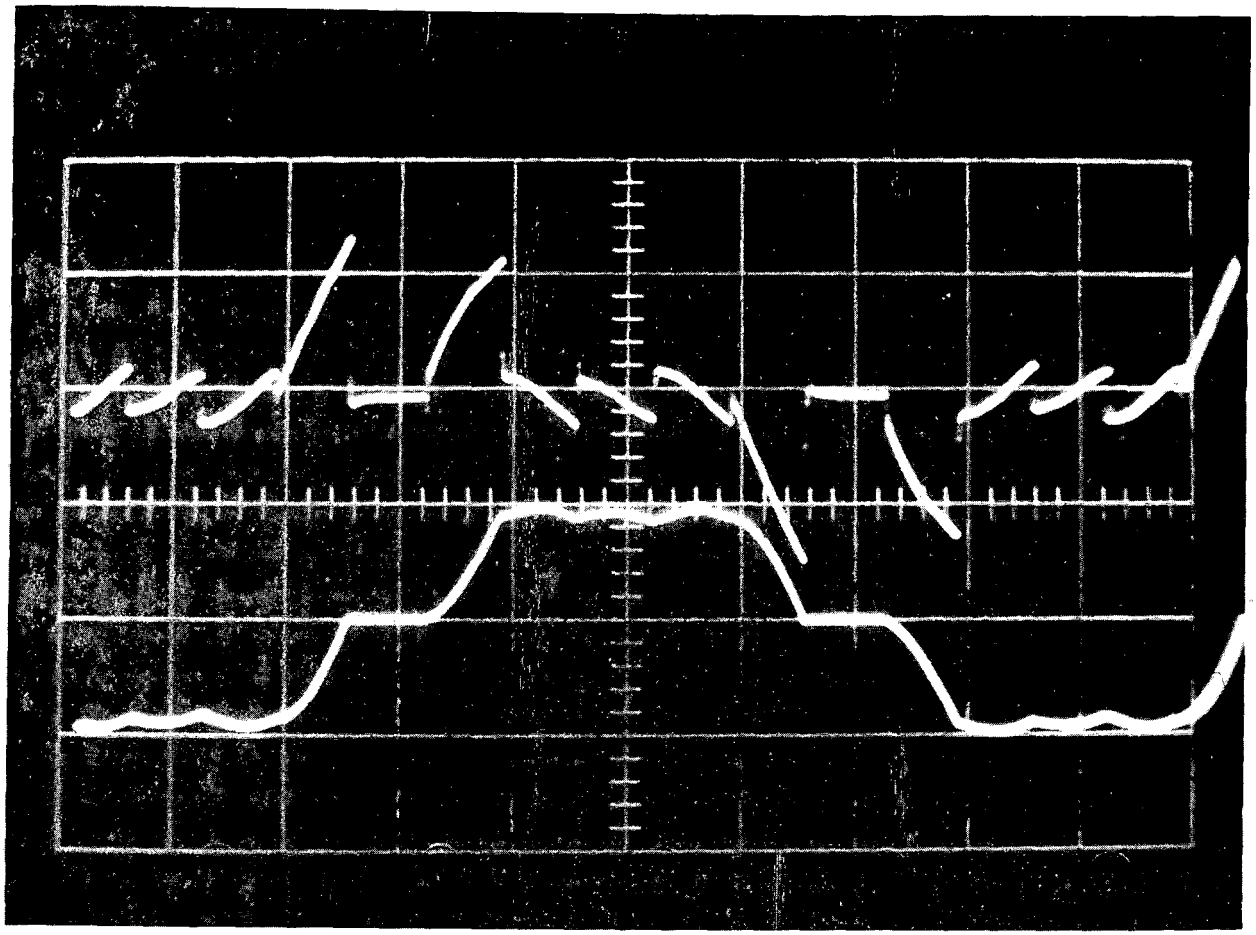

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Fig. 17

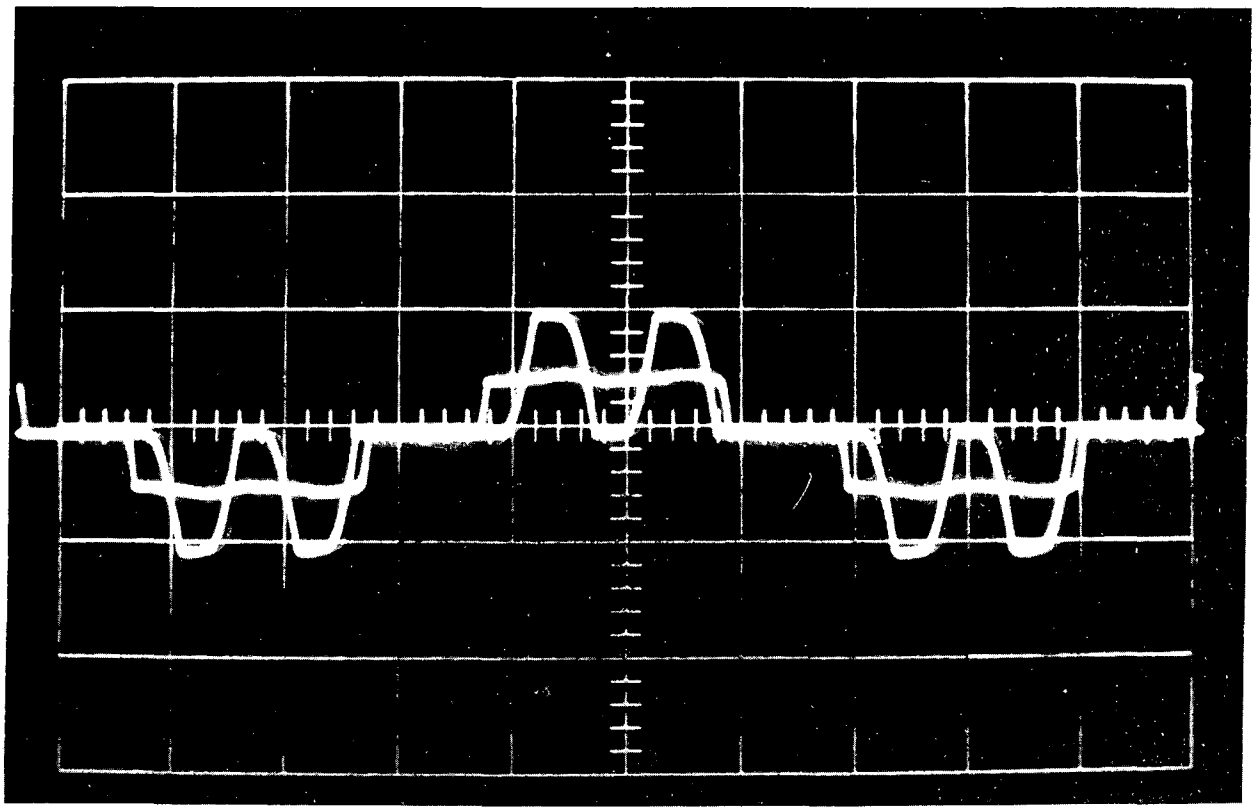

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Fig. 18

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