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TRANSISTOR REGULATORS FOR 5-AMPERE CURRENTS

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ABSTRACT

A simple and efficient transistor regulator is described which is designed to maintain a constant direct current of the order of 5 amperes, at potentials up to 130 volts, in an electromagnet used with travelling-wave amplifiers. Current regulation against load variations is improved by a factor of 170 over that of the unregulated supply, and the regulation against line variations by a factor of 50. The ripple output of the rectifier supply is reduced by 34 db. The transistors are fully protected against overload or short-circuit.

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TRANSISTOR REGULATORS FOR 5-AMPERE CURRENTS

- J.K. Pulfer and D.W.R. McKinley -

INTRODUCTION

Some microwave oscillators and amplifiers of the travelling-wave type require stable magnetic focussing fields of 1000-2000 gauss across a gap of 10-20 inches. A source of constant direct current, in the range 1-5 amperes, is needed to energize the focussing electromagnet, at potentials up to 130 volts. Fluctuations of the magnet current, such as a superimposed ripple, can cause undesirable frequency modulation effects in the oscillator. Regulation of the solenoid current is necessary, therefore, both to stabilize the average current, and, even more important when a 60-cycle rectifier power supply is used, to reduce the ripple voltage to an acceptable level.

Carbon pile regulators, although bulky and sometimes temperamental in adjustment, could be used to regulate the average current satisfactorily, but their action is not fast enough to provide adequate ripple filtering. A number of high-current vacuum tubes could be employed in parallel in a current regulator that would also be a good filter. However, the large internal voltage drop that is inherent in vacuum tubes would cause an excessive wastage of power, entirely apart from the cathode heater requirements. A fast-acting magnetic amplifier and saturable reactor might provide an acceptable solution, but this avenue was not explored exhaustively, since the availability of a suitable power transistor has made possible the design of simple, compact, and efficient regulators that meet the requirements very satisfactorily.

TRANSISTOR CURRENT REGULATORS

The type 2N173 PNP transistor is rated at 55 watts dissipation and a maximum collector current of 12 amperes. Thus, at 5 amperes a maximum potential drop of 11 volts across the transistor is permissible. The transistor will function satisfactorily with emitter-collector potentials as low as 0.5 volts.

The basic current regulator circuit is shown in Fig. 1. With a collector current of 5 amperes (which is also the load current) the transistor base will be at a potential of about -0.6 volts with respect to the emitter, and the base current will be about 100 ma. This base bias is the differential voltage between the reference battery voltage and the IR drop across the series resistor, R. If the resistance of the output load were to increase, the current through R would decrease; hence the base bias would become more negative, causing the internal resistance of the transistor to fall, and tending to raise the load current to its former value.

The battery in Fig. 1 may be replaced by some other low impedance voltage source. In the practical circuit of the first experimental type of transistor regu-

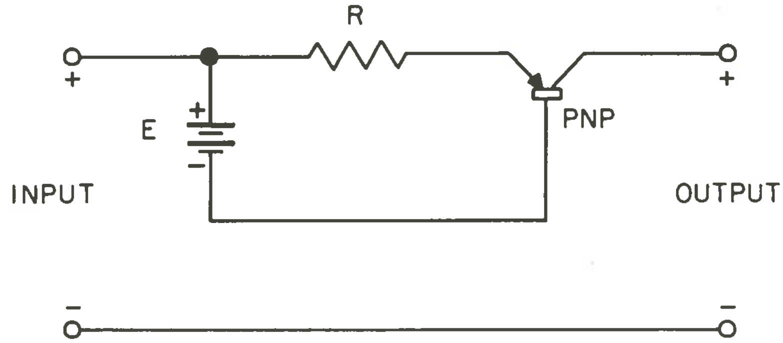

FIG. 1. BASIC CIRCUIT OF CURRENT REGULATOR

lator (see Fig. 2) a Zener diode, D_1, has been used, which acts as a voltage reference supply of about 20 volts, with an internal impedance of about 7 ohms. Better control may be achieved by increasing the reference voltage, that is, by selecting a Zener diode with a higher breakdown voltage, or by using several in series. This means, though, that more power will be wasted in the series resistor. The 20-volt Zener diode is considered to be a reasonable compromise. The type SV-918 diode is quite capable of directly supplying the required variations in base current of T_1, which are of the order of several milliamperes. However, it will do so at the expense of some deterioration in regulation owing to its internal resistance, and it is better to include at least one, and preferably two current-amplifying PNP transistors, shown in Fig. 2 as T_2 and T_3. The overall current gain of these two transistors is over 1000, so that the Zener diode current is subject to variations of only a few microamperes in its normal current of 25 ma. Since the diode D_1, is on the input side of the regulator it is reasonably free from the effect of load fluctuations, but its potential will change slightly with input voltage variations. To minimize this effect another Zener diode of higher striking voltage could be used in cascade, prior to D_1, to provide a better constant voltage source for D_1.

A second current-regulating circuit was developed, as shown in Fig. 3, which has improved characteristics. The series resistance, across which the control voltage is developed for comparison with the reference voltage provided by D_1, is now placed on the load side of the regulator. An increase in load resistance, i.e., a decrease in load current, results in a positive increase in the base bias of T_3, which is already positive with respect to the emitter. By using an NPN transistor for T_3, this voltage change is converted to a negative current change at the base of T_2, which, in turn, increases the negative bias on T_1 and lowers its resistance to allow more current to flow. At first sight it might appear that putting the Zener diode, D_1, on the load side of the regulating transistor would adversely affect its constant voltage properties. Actually, the effect can be self-compensating. For example, suppose that the voltage across the load rises as the load resistance increases. The voltage across D_1 will rise slightly too, but this increment is added to the positive-going error voltage developed across the series resistors, and therefore the transistors will tend to conduct more heavily than

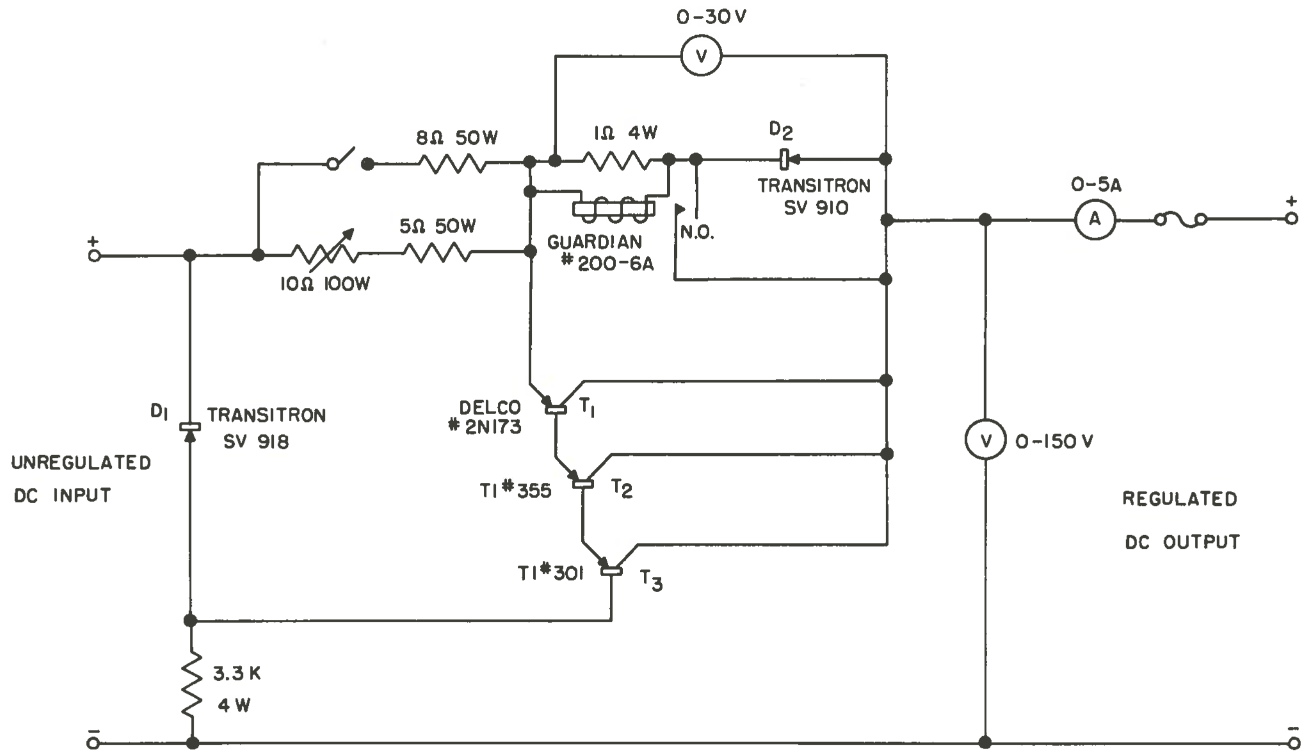

FIG. 2. CIRCUIT DIAGRAM OF FIRST EXPERIMENTAL TRANSISTOR CURRENT REGULATOR

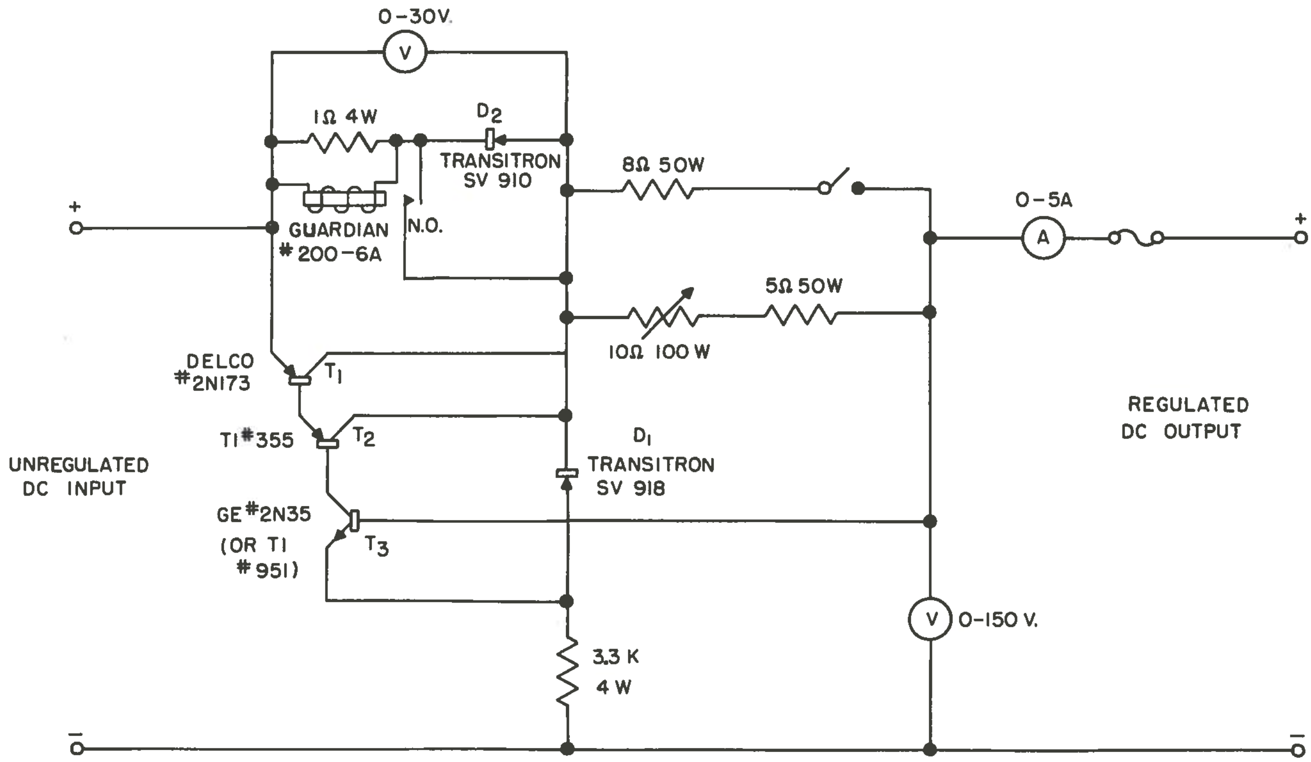

FIG. 3. CIRCUIT DIAGRAM OF SECOND TRANSISTOR CURRENT REGULATOR

if an absolutely constant voltage reference were used. It is quite possible to overcompensate in this manner and to make the conductance of the regulator negative over a small range, i.e., to have the load current increase with increasing load resistance. In the interests of stability, though, the internal conductance of the regulator should be positive over the desired working range.

PROTECTION OF TRANSISTORS AGAINST OVERLOADS AND SHORT CIRCUITS

The transistors must be protected against both over-dissipation and over-voltage. An overload relay, set at 7 amperes, is included in the rectifier power supply (see Fig. 4), and this provides adequate protection against a slow overload, but no available relay or fuse will operate fast enough to prevent the transistors from being destroyed when a short circuit is applied to the output terminals. In attempting to maintain a current of 5 amperes through the short circuit the regulator develops about 100 volts across the transistors. The combined effects of over-voltage and localized over-dissipation in the transistors can burn them out in a millisecond. To solve this problem a 10-volt Zener diode, D_2 (see Figs. 2 and 3), is connected across the transistor from emitter to collector. Its resistance will be very high for potentials less than 10 volts and very low for higher potentials; hence the diode will come into action as a low shunt resistance whenever the transistor potential approaches 10 volts, but it will have negligible effect at lower potentials. The Zener diode appears to be able to conduct relatively high currents without damage for a longer time than the transistor, but it cannot be relied on to by-pass all the excess current. Consequently the diode, D_2, has been connected in series with a relay, which is shunted by a 1-ohm resistor. This relay operates with 1 volt and 0.5 ampere d-c. When the potential across the transistor reaches 10 volts and the diode strikes, the relay closes and short-circuits the diode, thus limiting the potential across T_1 to the IR drop in the 1-ohm resistor. The relay operates within 15 to 20 milliseconds which is fast enough to protect the diode even if a short circuit is applied to the output terminals, and, in turn, the resistor protects the transistors until the main overload relay (or a fuse) can open the circuit.

PERFORMANCE CHARACTERISTICS

A conventional rectifier supply (see Fig. 4) was used to furnish the d-c supply to the transistor regulators. The inherent current regulation of this supply alone is shown as Curve (b) in Fig. 5, and can be expressed as a conductance of about 85 millimhos. For comparison, one can say that the poorest current regulator is a theoretically constant voltage supply, with infinite conductance, indicated by the vertical straight line (a), Fig. 5, and the best one is a theoretically constant current supply with zero conductance, as illustrated by the horizontal line (e).

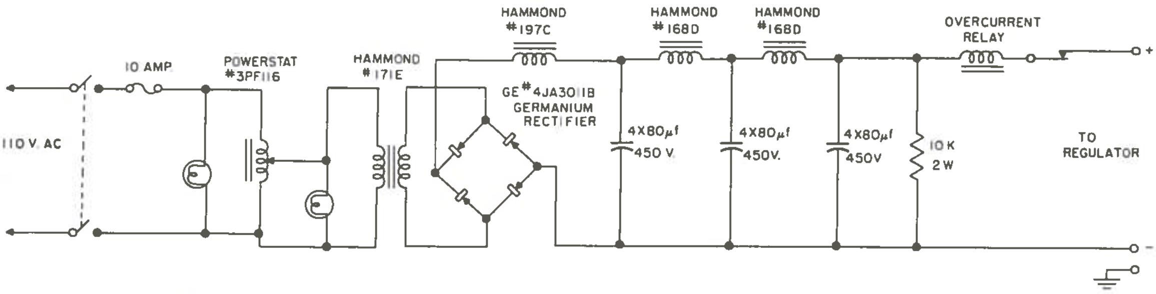

FIG. 4. CIRCUIT DIAGRAM OF FULL-WAVE BRIDGE RECTIFIER SUPPLY AND FILTER

Curve (c) of Fig. 5 shows the regulating characteristics of the first transistor circuit of Fig. 2. Over a small range, 2 or 3 volts, the internal conductance is 5 millimhos, which is a factor of 17 better than that of the unregulated supply. Curve (d) of Fig. 5, applies to the second transistor circuit of Fig. 3. Over a somewhat larger working range, 7 or 8 volts, the effective conductance of the second regulator is about 0.5 millimhos, or a factor of 170 better than that of the unregulated supply. These figures apply to load variations. The regulation against input variations is somewhat poorer; for either of the regulated supplies the factor is about 50.

The filtering properties of the second regulator circuit are shown in Fig. 6, where Curve (a) is the peak-to-peak value of the ripple voltage at the input of the regulator, plotted as a function of the current in an 18-ohm load, and Curve (b) shows the improvement achieved at the output of the regulator. The ripple suppression ratio is about 50 : 1 in voltage, or 34 db, for load currents in the neighbourhood of 5 amperes. The ripple suppression factor of the first regulator (not shown) is 34 db also, despite the poorer gross regulation against load changes of the circuit of Fig. 2. At low load currents, 1 ampere or less, the peak-to-peak ripple is about 5 millivolts. It should be mentioned that the data for Fig. 6 were obtained while maintaining a 5-volt drop across the type 2N173 transistor, by suitable adjustment of the input voltage level. Obviously, the transistor cannot accommodate a current variation of 1-5 amperes, over a range of 20-100 volts, without manual control of the input voltage. For automatic operation the parameters are pre-set to the middle of the desired working region and, for a 5-ampere load current, the range of permissible variation is then given by the appropriate curve in Fig. 5. A smaller load current will allow more latitude in voltage variation, of course.

In Fig. 7, output ripple voltage is plotted as a function of voltage drop across T_1 for constant collector current of 5 amperes. Although the transistor will regulate the gross current quite satisfactorily with an emitter-collector potential as low as 0.5 volts, it is clear that ripple suppression does not become fully effective

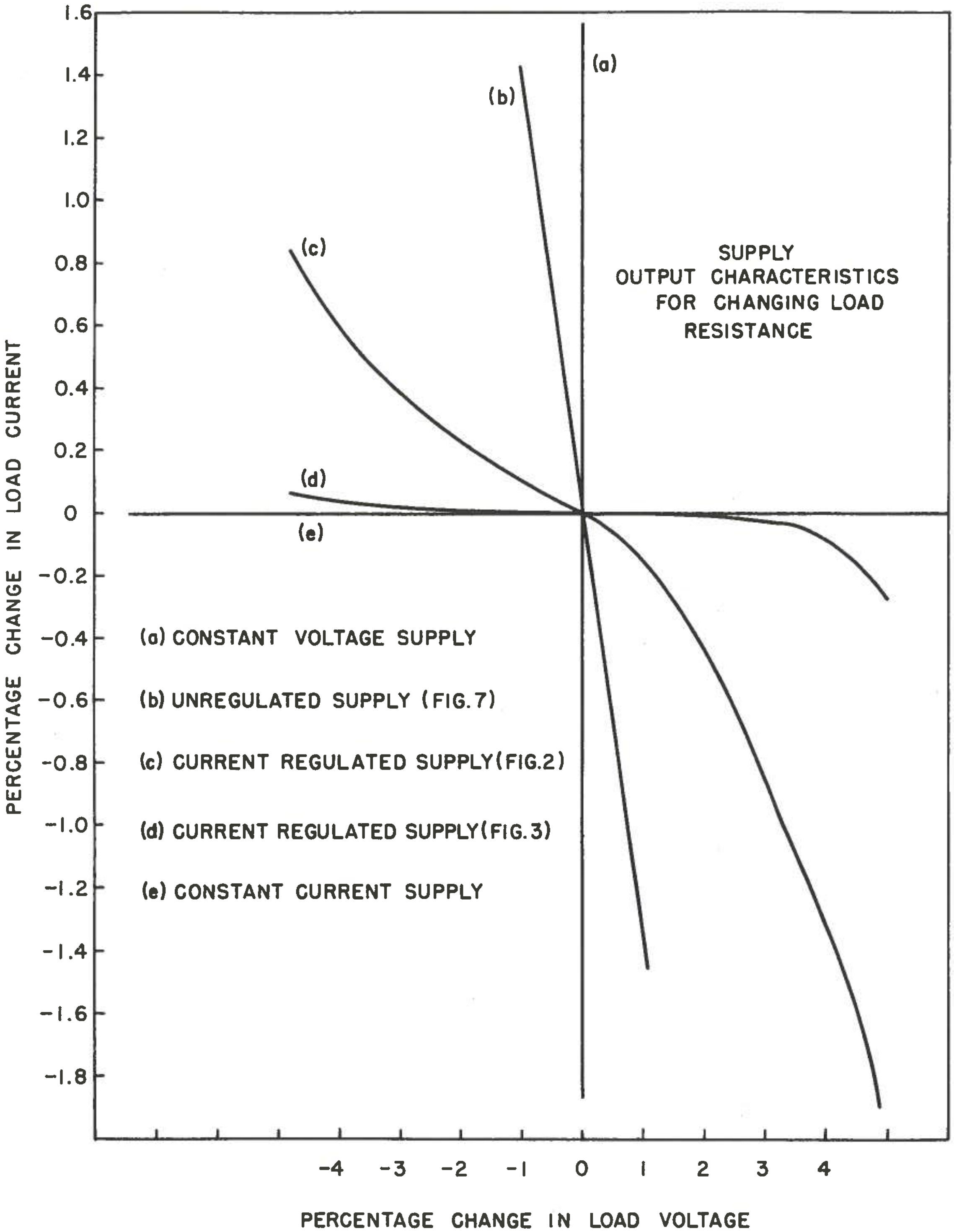

FIG. 5. CURRENT REGULATION AGAINST VARIATION OF LOAD RESISTANCE, EXPRESSED IN TERMS OF PERCENTAGE OF CURRENT CHANGE VERSUS PERCENTAGE OF VOLTAGE CHANGE DEVELOPED ACROSS A VARIABLE LOAD (MEAN CURRENT LEVEL IS 5 AMPERES)

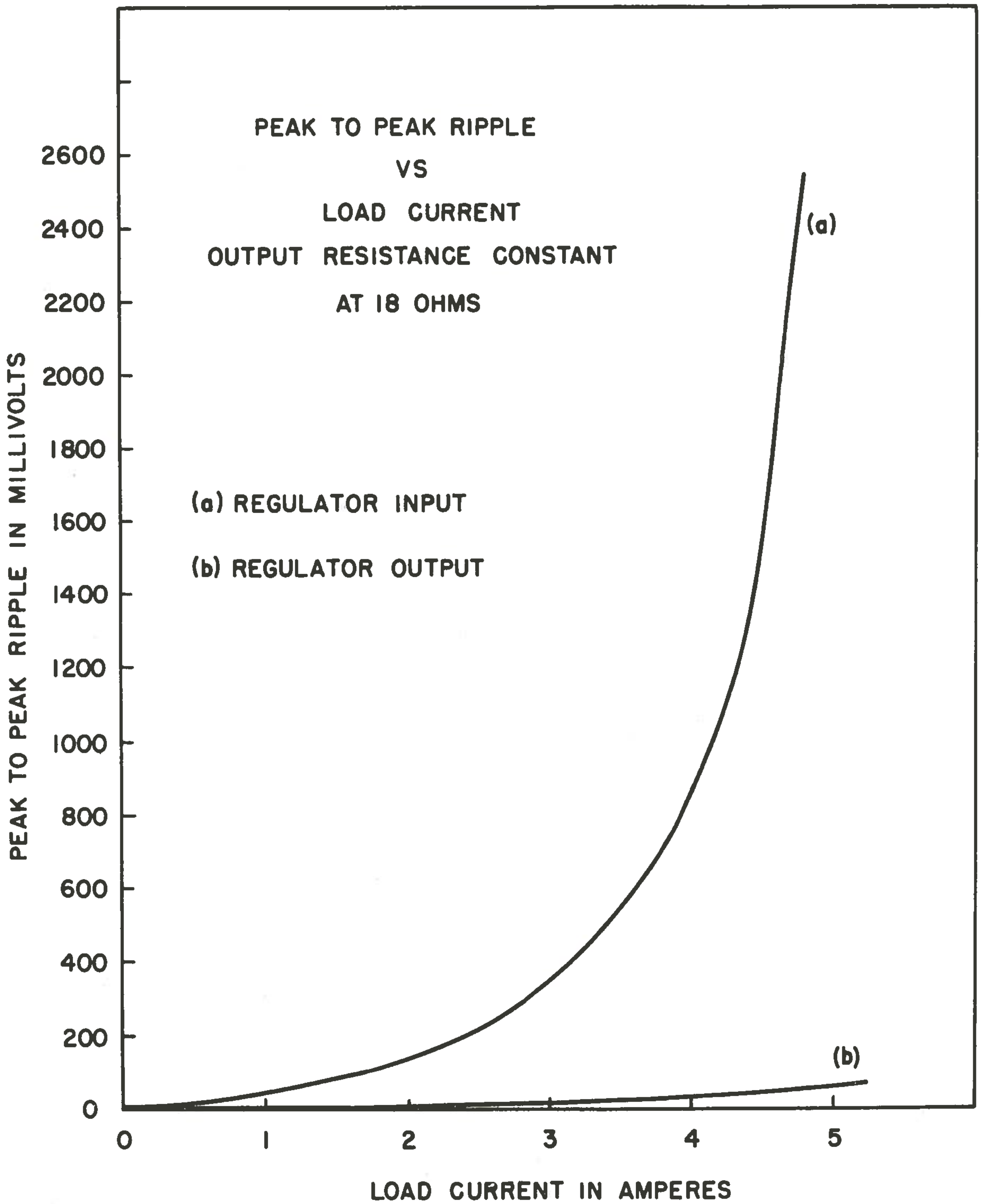

FIG. 6. RIPPLE VOLTAGE AS A FUNCTION OF LOAD CURRENT MEASURED BEFORE AND AFTER THE REGULATOR

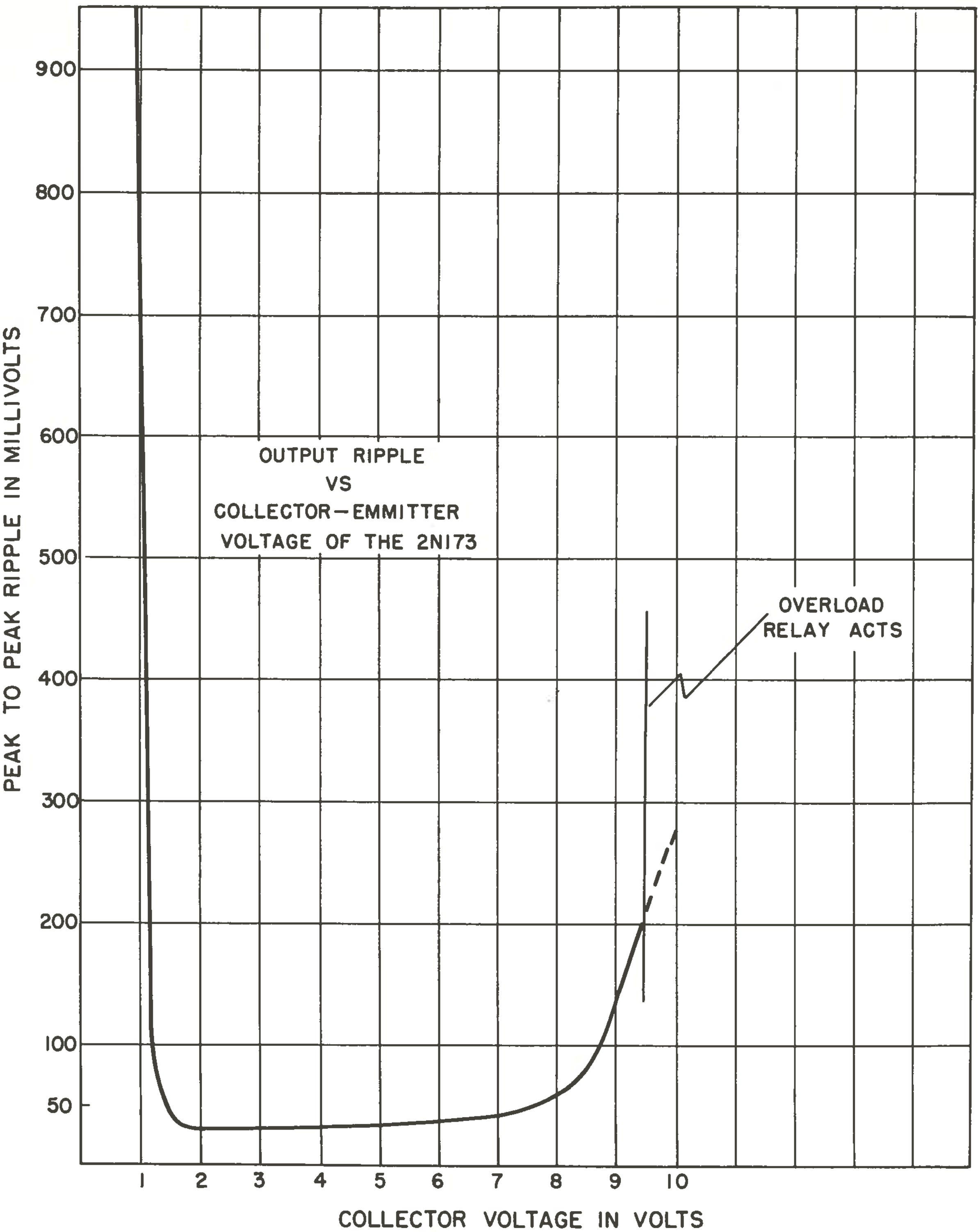

FIG. 7. OUTPUT RIPPLE VOLTAGE AS A FUNCTION OF THE VOLTAGE DROP ACROSS THE TYPE 2N173 TRANSISTOR (MEAN CURRENT LEVEL IS 5 AMPERES)

until the potential approaches 2 volts. This is simply because the input ripple amplitude is 2 volts or more, which overrides the transistor on peaks of the ripple cycle: better primary filtering would help here. The slight increase in ripple just beyond the 8-volt mark in Fig. 7 is due to current beginning to flow in the protective diode, D_2 . At 9.5 volts, enough current is flowing through D_2 to operate the relay.

In Fig. 3, the NPN transistor T_3 may be either a type 2N35 (germanium) or a 951 (silicon), but the silicon transistor is much more satisfactory when the regulator is operated at load currents of less than 1 ampere. This is because the collector cutoff current (I_{CO}) of the type 2N35 is considerably higher than that of the type 951, with the result that the type 2N35 cannot control T_1 (working through T_2) for collector current in T_1 of much less than 1 ampere. At higher current levels this is no problem and either type of transistor is acceptable.

The upper limit of the range of line or load voltage variations that can be accommodated by the regulator is determined by the least of the maximum collector-to-emitter voltage ratings of the three transistors. Within this limit, which in this case is 35 volts for the type 355 transistor, the working range of input or output voltage variations may be found by dividing the rated dissipation of the type 2N173 transistor by the desired load current, and then subtracting the full-load ripple voltage of the unregulated power supply. Two or more type 2N173 transistors may be operated in parallel to increase either the current-carrying capacity or the voltage range. Small series resistors in the emitter leads, of the order of 0.1 to 0.2 ohms, should suffice to ensure equal division of the currents, if the individual transistor characteristics should differ widely. One type 355 transistor should be capable of driving up to five type 2N173 transistors, and a single type 951 transistor will, in turn, supply the base current required by the type 355 under these conditions.