SUPERREGULATED POWER SUPPLIES

Grid-controlled thyratron rectifiers in preregulator work with servo-stabilized d-c amplifier in superregulator to provide 300 volts at 20 amperes with required 0.001-percent regulation for mathematical operations in 4,000-tube analog-digital computer. Other equally stable plate and bias supplies with high current output are also described

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THE FIVE power supplies described here are believed particularly interesting because of the high degree to which some of them are regulated, the means for regulation and the unusually high current ratings for what might be considered receiving tube service. All give 0.001 percent regulation as required for plate and bias voltages in the d-c amplifiers used as integrators, differentiators, multipliers and for other purposes in the Project Typhoon analog-digital type computer recently built for the U. S. Navy. The plate supplies give + 300 and − 300 volts at 20 amperes, while the bias supplies give + 75 and − 75 volts at 6 amperes and − 500 volts at 3 amperes.

In general the genesis of each plate-bias supply is the same. As shown in Fig. 1, power is metered through the power rack to transformers, fed to the rectifiers—preregulators in the case of the − 500, − 300 and + 300 volt supplies—thence to the superregulators and on through delay-operated starting-current limiters to the distribution point. The design of each, too, is similar. For simplicity the operation of one of them, the + 300-volt supply, will be explained and subsequently the important differences between it and the other supplies will be described.

The full regulation of the + 300 volt supply is obtained in two stages. In the first, called the preregulator stage, a moderate degree of regulation is obtained by using grid control on the thyratron rectifier tubes. The output voltage from this stage is purposely made 50 volts higher so that this additional voltage may be fed to a second stage of regulation called a superregulator.

+350 Volt Preregulator

Referring to the circuit of the + 350 volt preregulator in Fig. 2, leg voltages *A-N*, *B-N* and *C-N* of a three-phase 395-volt power line are applied to the plates of the type 105 thyratrons V_4, V_5 and V_6 respectively. Disregarding the controlling bias on these thyratrons for the moment, the rectified output is fed to the filter network where the voltage to ground at the arm of the voltage divider and that obtained across the 0D3 tube may be adjusted to substantially the same value or as desired. Any variation in the set potential difference between these two points and ground may be considered to be the error voltages.

Any difference, however, in potential between these two points is fed through appropriate gain control networks to the d-c/a-c converters B_1, B_2 and B_3 where alternating voltages essentially of square wave form may be generated across the secondaries of transformers T_1, T_2 and T_3, the amplitude

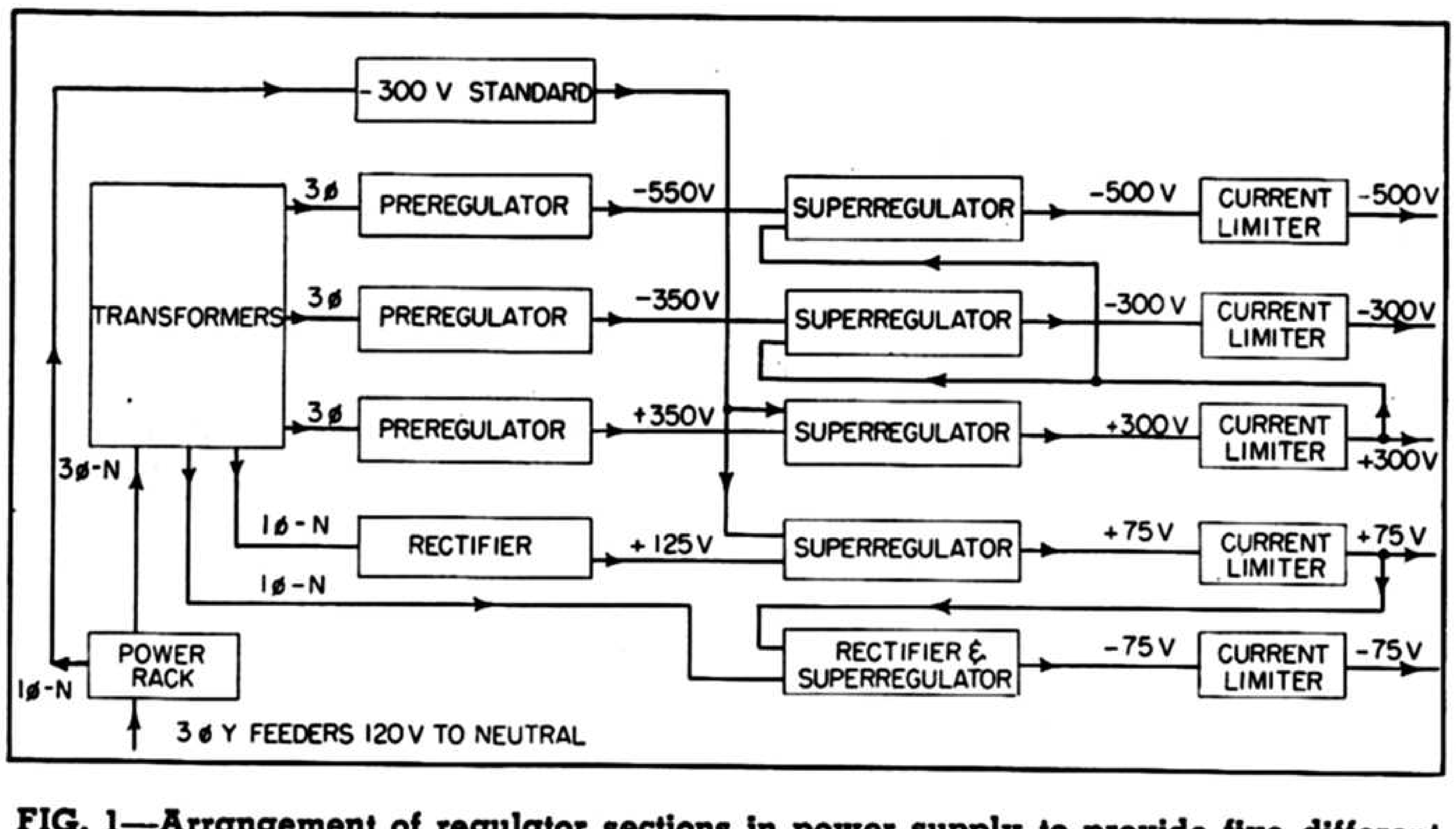


FIG. 1—Arrangement of regulator sections in power supply to provide five different highly regulated plate and bias voltages for Project Typhoon guided-missile computer

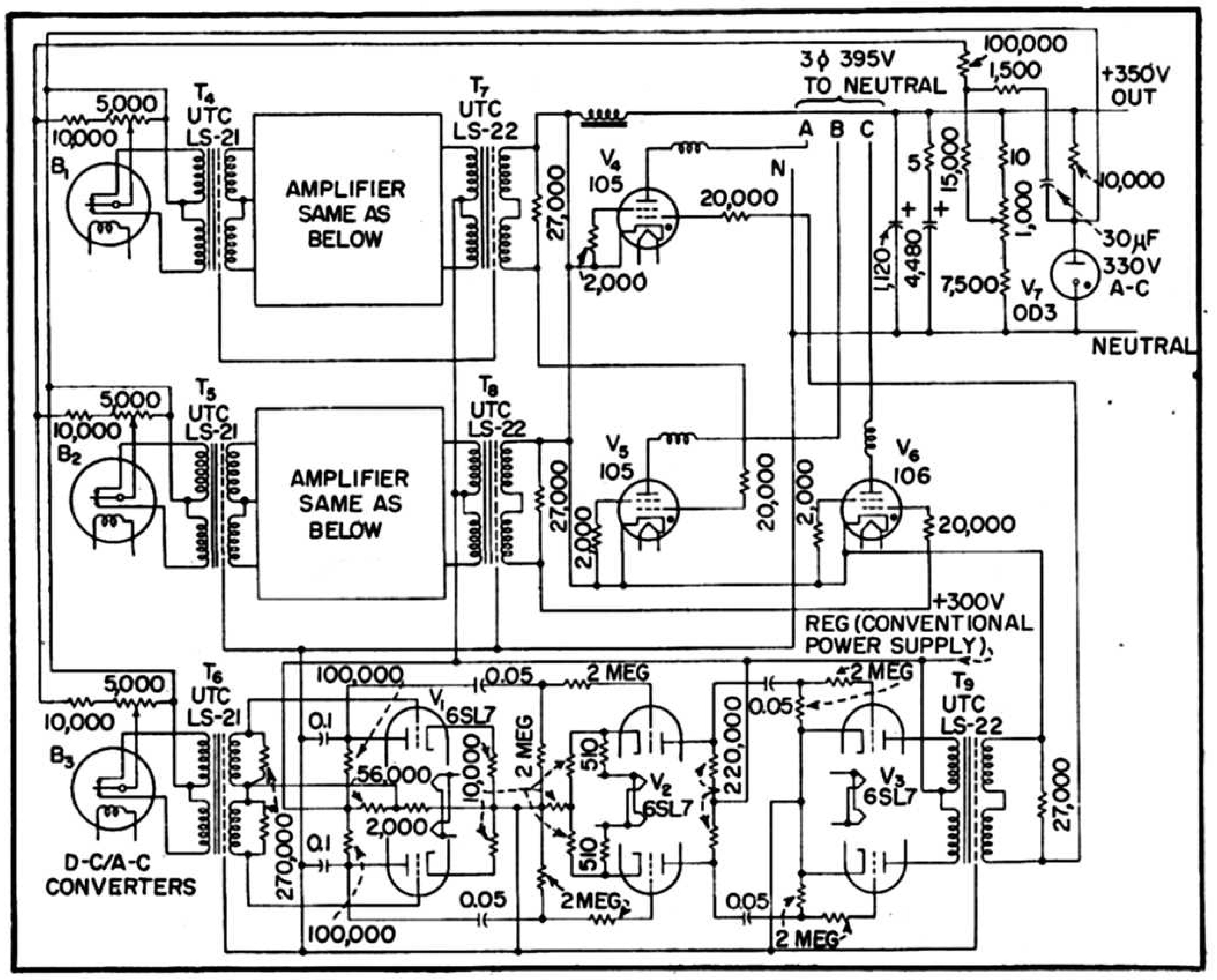


FIG. 2—Circuit of 350-volt preregulator used in the 500-volt bias supply and the two 300-volt plate supplies

being proportional to the difference voltage.

If, further, each converter is operated on a different phase of the plate 3-phase supply, at reduced voltage, the difference voltage may be made to change the firing time of all three thyratrons, the error voltage itself changing the firing time to hold the difference initially set. The method of control for one thyratron only will be described since the principle is the same for each.

There is an amplifier associated with each converter and its corresponding thyratron. The amplifier associated with the converter operated from phase *C* controls the grid potential of thyratron V_4, whose plate potential is supplied by phase *A*. The nature of this control for V_4 is shown in Fig. 3. Independent of any difference voltage fed into the input, there is introduced into the cathode circuits of V_2 an alternating voltage *a* from phase *C* which produces a square-wave voltage *a′* at the secondary of T_9. A voltage of approximately 0.165 volt rms between each cathode and ground produces a peak-to-peak square-wave voltage of 146 volts across the 27,000-ohm resistor when there is no thyratron conducting. This voltage will be in phase with phase *C* for this amplifier.

The input stage of the amplifier integrates any square-wave voltage supplied by the converter, making it essentially a symmetrical sawtooth voltage. This voltage, now shifted in phase approximately 90 degrees with respect to phase *C*, is introduced in the grid circuit of V_2 between ground and the voltage-limiting two-megohm grid resistor. The magnitude and polarity of the input difference voltage determine the amount of phase shift in the square-wave output voltage produced by the cathode-introduced a-c voltage alone, as indicated in Fig. 3. As an example, if square-wave voltage *b* represents a positive difference voltage relative to phase-*C* voltage *a*, voltage *b′* indicates the resulting integration of this voltage. The algebraic sum of voltages *b′* and *a* then produces the square-wave output voltage *b″*, the zero crossover points being to the right on the figure, causing conduction later in thyratron V_4 at point *m* rather than at point *l* with no difference voltage. Similarly, a negative difference voltage will cause earlier firing of V_4. In general, except for the phase-*A* plate voltage and the square-wave output voltages *a′*, *b″* and *c″*, the amplitudes shown are greatly exaggerated as regulating correction will be made on a particular thyratron every single-phase cycle. However, actually the slider on the 1,000-ohm potentiometer is set to give the difference voltage necessary to regulate at the desired output voltage. Any error voltage shifts the phase to regulate at this point.

In operation under a load of about four amperes, 350-volt d-c output is obtained when V_4 or any other thyratron is triggered at about 100 degrees. The firing point shifts to the left as the load is increased. At the load of four amperes a shift to the left of about 10 degrees occurs for an increase in regulated output voltage from 350 to 365 volts. The firing point approaches full conduction, with plate at cathode potential, near full load.

Phase shifting is employed on the primaries of T_2 and T_3 in Fig. 2 to obtain exact 120-degree displacement between the a-c drive voltages supplied to the converters. Transformer differences with converter and filament load caused as much as 5-degree phase shift. The transformers were selected so that resistance and capacitance could be used on two of them.

Series resistor-capacitor combinations in the output-input circuits were somewhat arbitrarily selected to stabilize the amplifier feedback

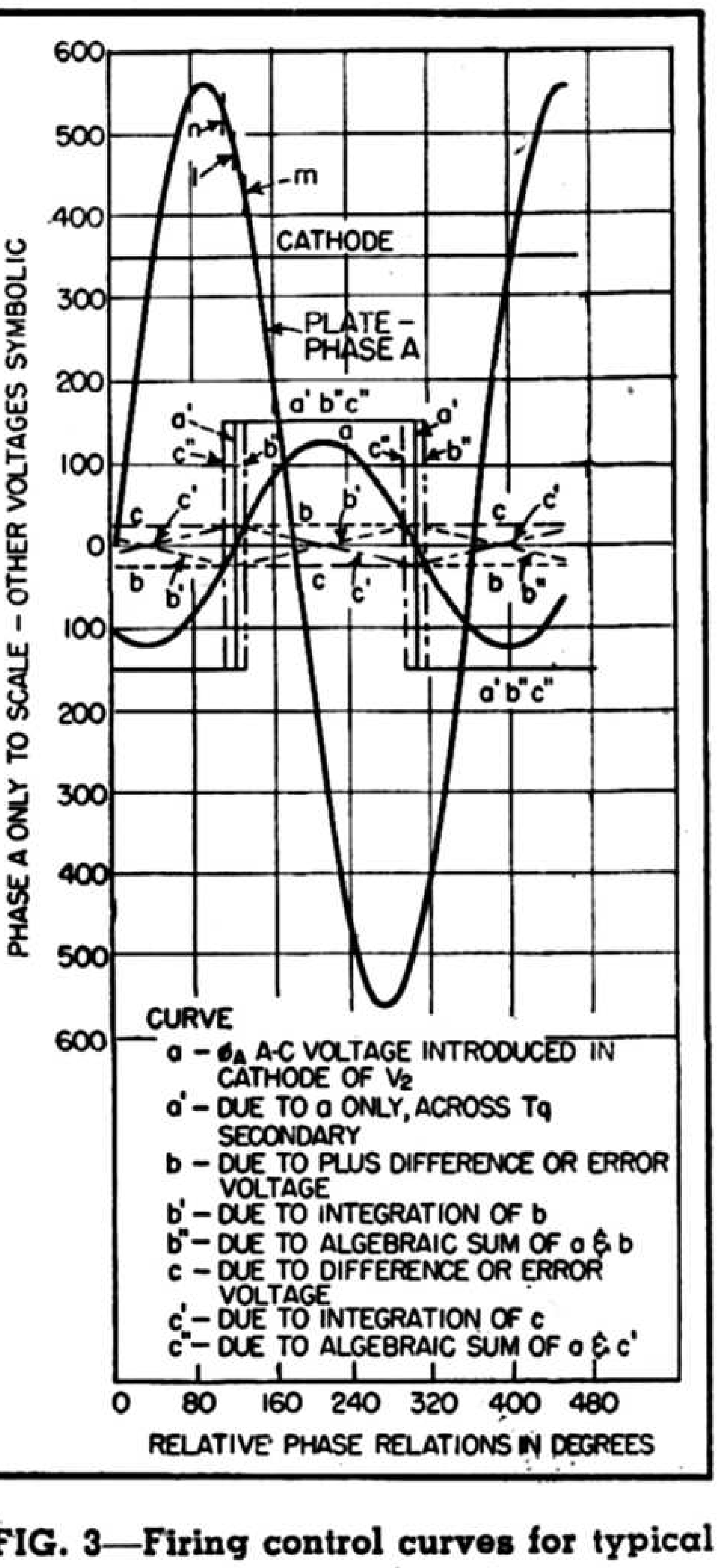
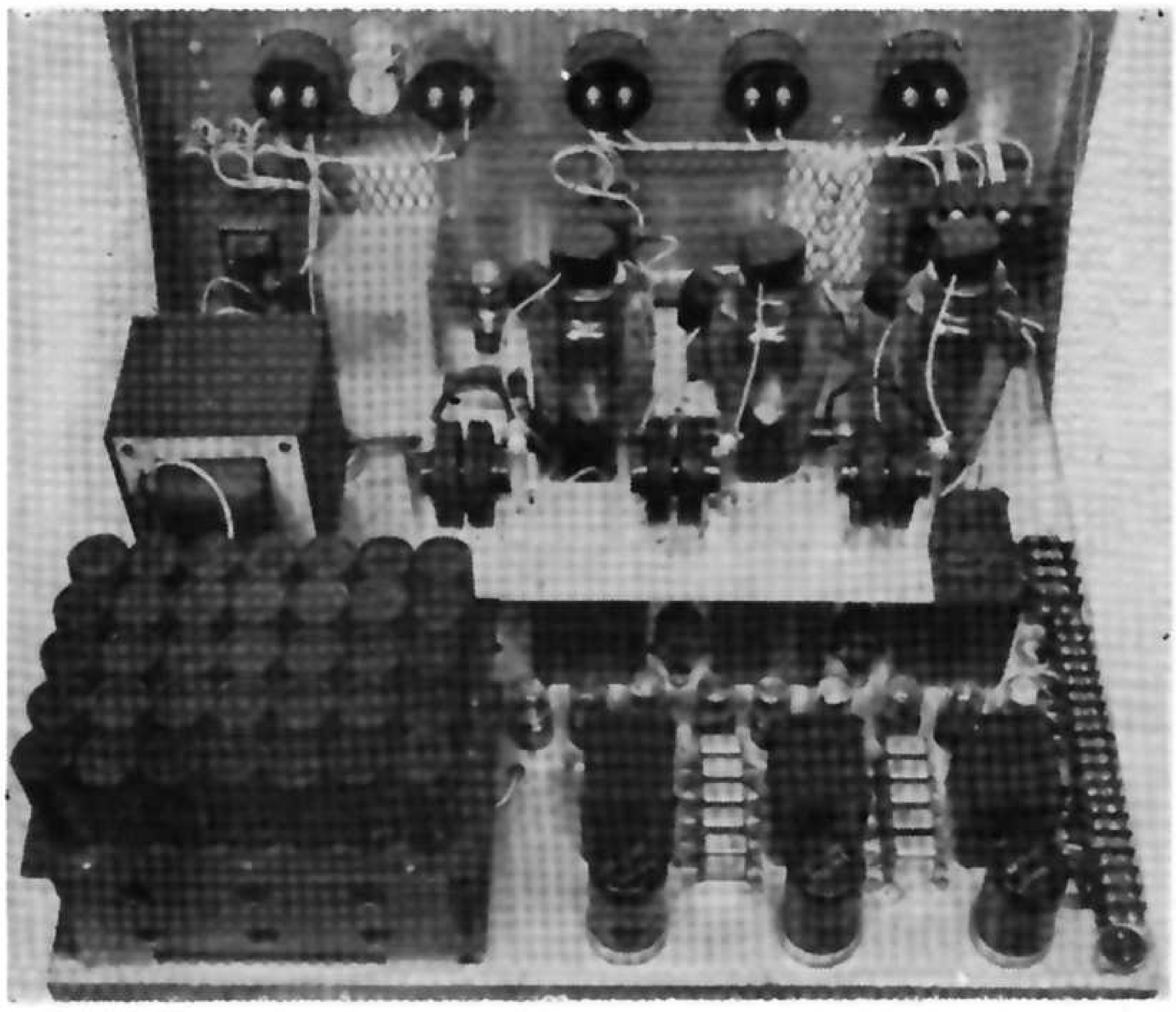
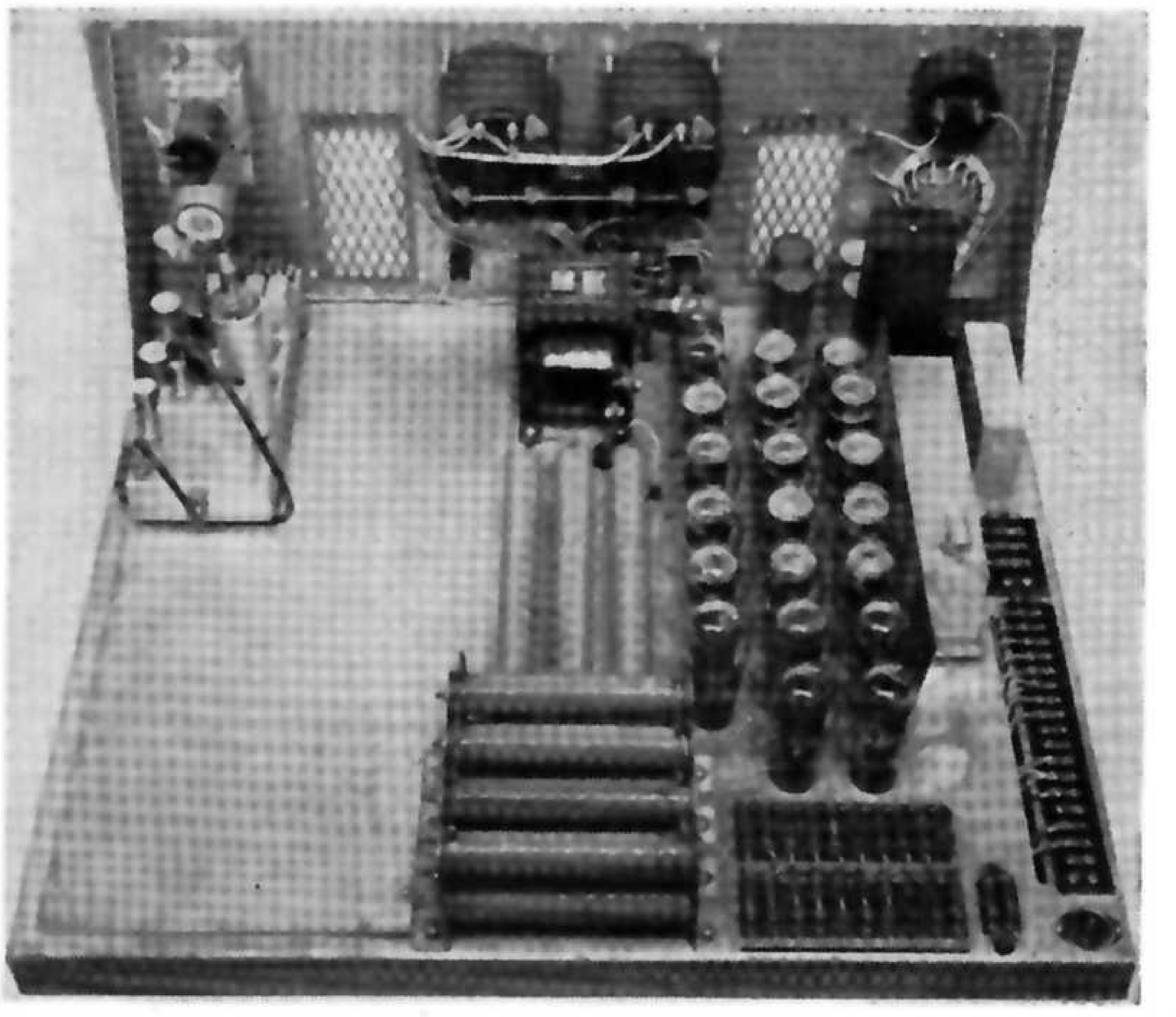


FIG. 3—Firing control curves for typical thyratron in preregulator



Typical preregulator chassis, showing the three Brown converters in right foreground, three groups of three 6SL7 amplifier tubes behind, and the three type 105 thyratrons. Bank of electrolytics at left provide 1,120 μf and 4,480 μf across 350-volt output. Hum level (rms) ranges from 220 mv for +125 v and —125 v units to 440 mv for +350 units



Typical superregulator chassis, showing 20 paralleled 6AS7 tubes. Servo system is at left. Hum level (rms) is 0.25 mv for —500, —300 and +300 units, 0.3 mv for ±75 and 0.6 mv for —75 units. Maximum offset voltage in percent ranges from 0.00027 to 0.05 for different combinations of units, between each nominal voltage and its reference

loop. One combination is of relatively high capacitance and low resistance, and the other of relatively high resistance and low capacitance. The former was used to suppress a tendency toward a low-frequency oscillation and the latter for a high-frequency oscillation.

The local + 300 volt regulated power supply shown on Fig. 2 is used to supply plate power to all of the amplifiers of all of the preregulators.

+300 Volt Superregulator

The superregulator circuit in Fig. 4 consists primarily of a stabilized d-c amplifier of the current-summing type wherein one of the voltages fed to the summing resistors is obtained from a standard reference voltage of − 300 volts and the other is obtained from the point of distribution of the + 300 volt output of the superregulator. The voltage supplied to the + 300 superregulator is + 350 volts in order to allow 50 volts for further regulation. This 50-volt drop is maintained across the 20 6AS7-G tubes used for regulating, hence their plates are operating at + 350 volts. The + 300 volt output voltage appears across the cathodes of these tubes. Thus, any deviation in output voltage from the value of + 300 volts at the distribution point, in operating to change the potential of the first grid at the d-c amplifier input, changes the grid voltages of the 6AS7-G tubes to increase or decrease the plate voltage drop across these tubes in the direction to correct for the deviation.

It will be noted that enough 6AS7-G tubes to carry the total rated output current are not provided. With a plate voltage of 50 volts, one 6AS7-G will carry approximately 0.5 ampere but for possible variations of total current in the solution of problems, it was decided to limit the current generally to 0.25 ampere per tube. Also, it was decided to try regulating with 25 percent of the total current for each superregulator. This fixed the number of tubes at 20 for the + 300 (and − 300) volt supplies.

For d-c continuity and complete stability, a local minimum load is kept on the output of the superregulator at the chassis if no other load is drawn. When the load is greater than that permissible through the 6AS7-G regulator tubes, resistance shunts are provided to bypass the excess. Each of the eight shunts consists of 25 ohms to provide a shunt of 2 amperes.

The switch that inserts one of these removes the local load so that a reduction in 6AS7-G current of 4 amperes is obtained. Thus for a tested rated current of 20 amperes, all shunts were used; no local load was connected and the 6AS7-G mean current was 4 amperes. No greater load than about 15 amperes has been demanded in the computer up to the present, however.

To observe the individual behavior of each of the 6AS7-G tubes, a small resistor is inserted in series with each tube and switching of a voltmeter is arranged so that the voltage across each resistor may be read individually.

D-C Amplifiers

All of the d-c amplifiers require three B supply voltages, + 75, + 300 and − 500 volts. With the 3-gang switch shown at the lower left of Fig. 4, these voltages may be obtained from the superregulators themselves, from an auxiliary supply or from the + 300 and − 500 volt preregulators and the + 75 rectifier. Normal operation may be obtained using the first two sources, but use of the last is limited only for test. The use of the auxiliary supply allows independent operation of either the + 300 or the + 75 volt supply since each uses the − 300 volt standard for reference. The other supplies require the first two for reference and may then be turned on together or separately.

The auxiliary supply serves no other purpose and will not be described further other than to men-

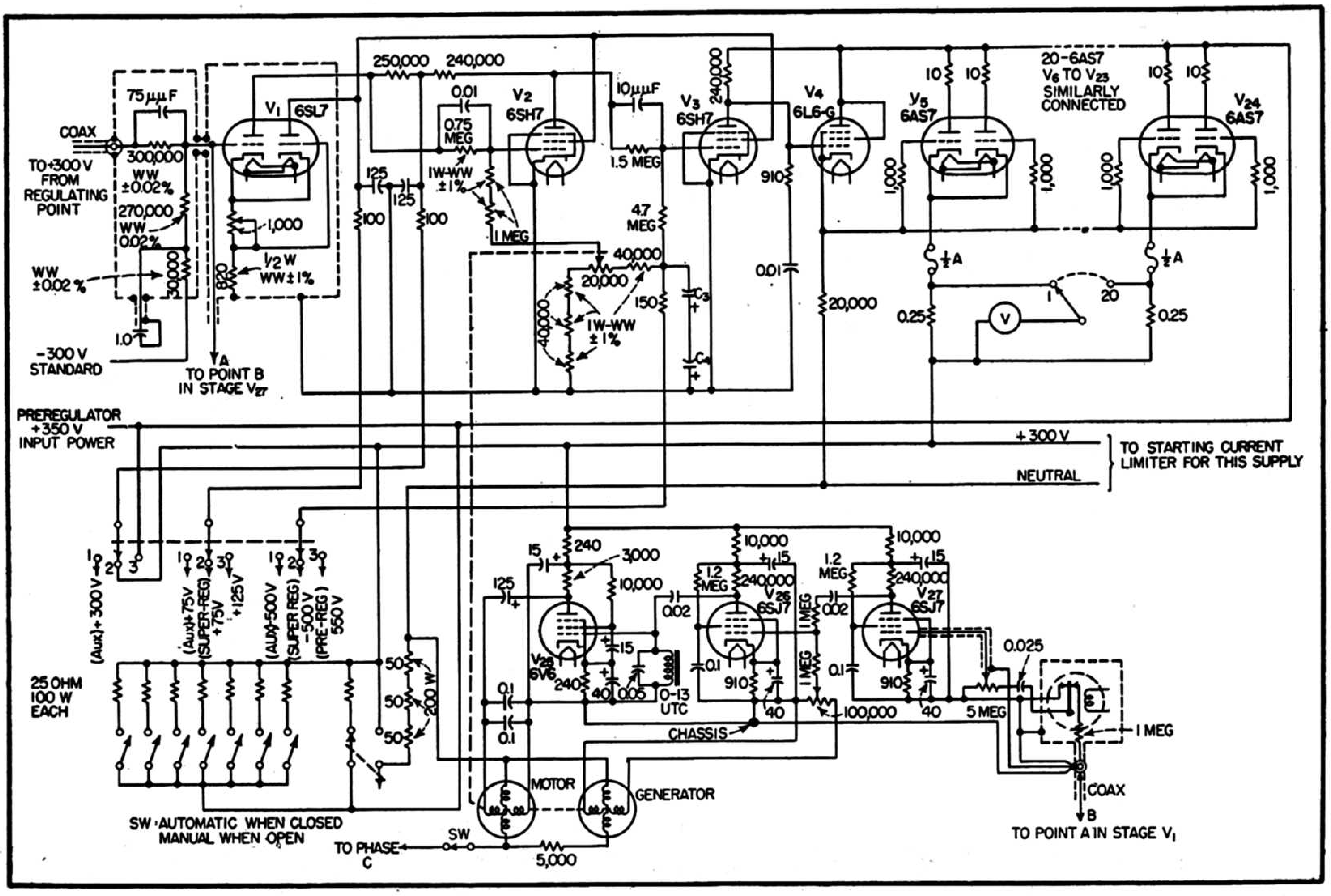


FIG. 4—Circuit of 300-volt superregulator. Voltage drop across 20 paralleled 6AS7 double-triodes is controlled by d-c amplifier and motor-generator servo system to drop exactly 50 volts of the 350-volt input power from preregulator even though load current varies from zero to 20 amperes

tion that it is a regulated supply referenced to a glow tube with a hum level of the order of 100 millivolts for the − 500 volt supply and proportionately less for the other supplies.

Zero d-c amplifier difference current between that caused by the standard voltage across the resistance string associated with it and that caused by the regulating superregulator voltage across the resistance chain associated with it is obtained only if the resistances have the same resistance per volt. These resistors are therefore as accurate and free from temperature drift as could be secured. In the case of the + 75 and − 75 volt superregulators, small padding resistors were inserted for additional adjustment.

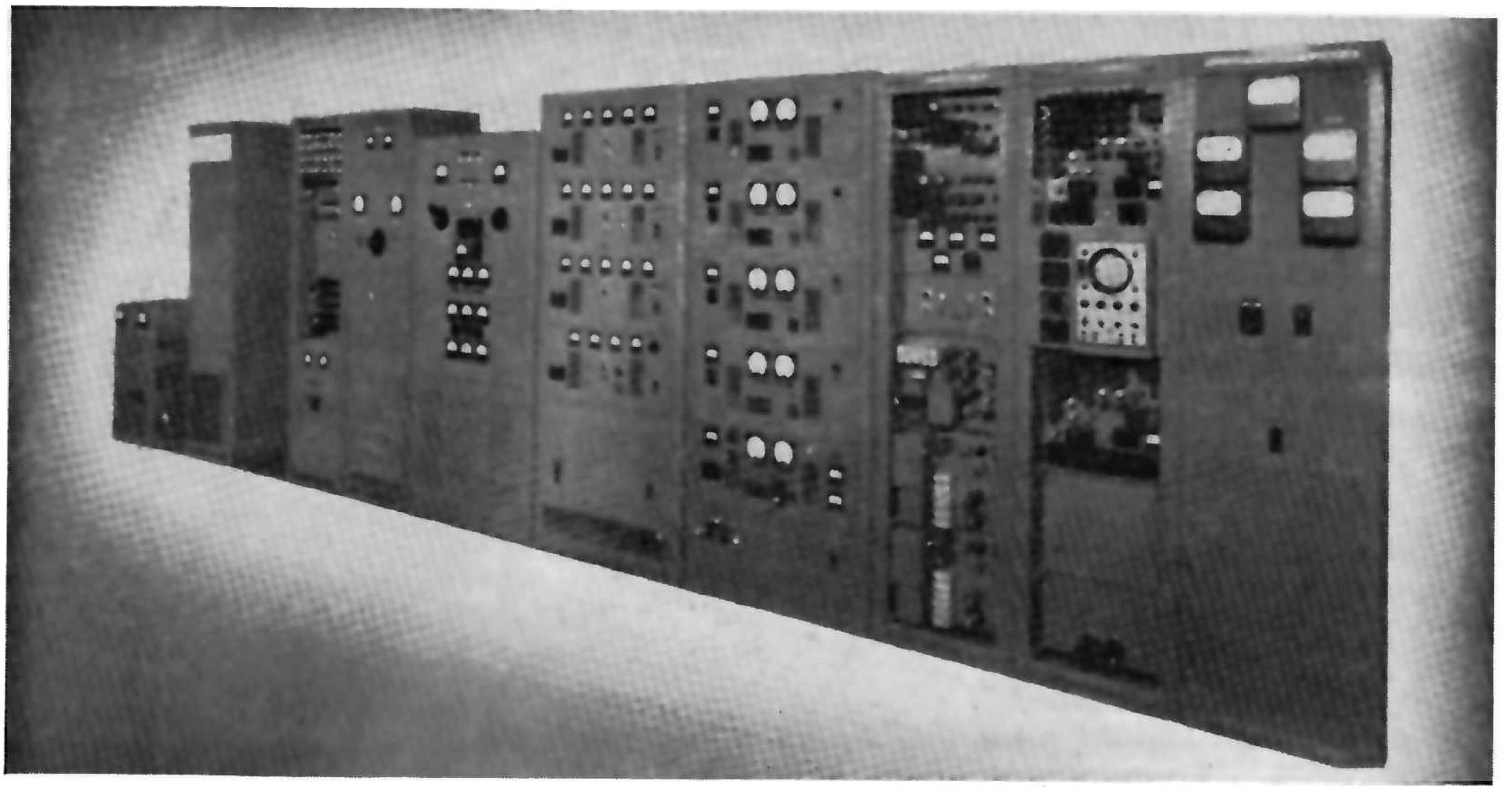
To prevent ground currents from affecting the regulating voltage fed to the amplifier, the ground connections of the later higher-current less-sensitive stages are not returned through the ground regulating lead (shield). The shield box containing the summing resistors and that containing the input tube are connected to the ground shield, as is the low side of the 1-μf filter capacitor used across the first resistor of the resistance for each standard voltage to filter any possible hum or extraneous voltage from it.

Servo System

The servo amplifier stabilizer serves the same purpose as the a-c amplifier in the Goldberg stabilizing amplifier, and permits convenient manual zero output setting if desired. The correcting voltage is introduced in the grid circuit of the second d-c amplifier tube by motor drive (automatic) of the potentiometer arm or by manual operation if the motor is not supplied with a-c on its field coils. The sensitivity is such that approximately 50 microvolts will initiate movement.

In the case of the servo units for the +75 and −75 volt superregulators, however, the sensitivity has been increased by increasing the gain of the amplifier to the point where about 7 microvolts input will initiate control. The voltage across the rotor of the motor may be either polarity depending on the d-c offset at the input of the d-c amplifier. This causes the motor to move in the right direction to correct for the offset. In addition, the motor drives a generator, the output voltage of which is in phase with the driving voltage on the motor. A portion of this voltage is introduced in the second stage of the servo amplifier to prevent too-violent motor movement and hunting.

As a part of the regulating network, large values of capacitors are connected across the outputs of the superregulators. The initial starting currents of these capacitors would open the circuit breakers if starting protection were not provided. This protection is provided by seven relays that operate in quick succession to short out current-limiting resistors, leaving no resistance in series at the final step.



Complete power supply system for the 4,000-tube computer is a research engineer's dream, filling an entire room and providing plate voltages that stay constant within 0.001 percent. The ten racks are, from left to right: servo power; filament filter; odd-frequency power; relay power; filament power; preregulators and rectifiers; superregulators; auxiliary and plotting-board power; calibrator and scope; incoming three-phase power panel

For the +300 volt and +75 volt superregulators, a −300 volt standard supply was built. In essence this is a well regulated supply developed by F. F. Shoup, the output voltage of which is referenced ultimately to an unsaturated standard cell. For continuous reference a Mallory mercury cell is used.

For the −300 and −500 volt supplies, the output of the +300 volt superregulator is used for reference. For the −75 volt supply, the reference is the +75 volt unit.

Calibrator Unit

Developed by F. F. Shoup, the calibrator unit allows the hum of all important voltage outputs to be measured directly on a commercial cathode-ray oscilloscope. Of even greater importance, it permits a comparison of any voltage output from the superregulators, auxiliary voltage supply or plotting voltage supply with an appropriate reference. The maximum sensitivity of the voltage comparison is 125 microvolts per inch and of the hum 12.5 millivolts per inch.

General Characteristics

Because of the lower voltages and lower loads required, preregulators were not used for the +75 and −75 volt supplies. A conventional single-phase full-wave rectifier using type 6B gas-filled rectifiers was used.

Since the highest negative voltage of each negative-voltage supply is connected to the cathodes of the 6AS7 regulating tubes, it was necessary to supply bias to these tubes by means of a floating bias supply. This was generated by an r-f oscillator whose rectified isolated-from-ground output was controlled by the input of the d-c amplifier. Essentially, all d-c amplifiers are otherwise the same.

The ratio of the voltage change obtained across the load terminals to the a-c load applied is called the dynamic impedance. For frequencies throughout the audio range the dynamic impedance for all plate-bias supplies may conservatively be stated to be less than 0.1 milliohm for peak currents not exceeding the mean value of current carried by the regulator tubes. At zero frequency or for changes in d-c load the dynamic impedance is less than 5 micro-ohms for changes again within the currents carried by the regulator tubes.

The important offset as regards computer operation is that between the −75 and +75 voltage supplies. For these supplies small trimming resistors were placed in series with the d-c amplifier summing resistors for further adjustment. This could have been done also for the other supplies but was not considered necessary.

Changes in offset are principally due to temperature changes. This is particularly true for the substandard mercury cell and the standard cell. Actually the offset attributed to the mercury cell is believed due to the standard cell; however, this latter cell is taken as the absolute reference. In its final placement the whole supply will be in an air-conditioned room so that the temperature factor will be minimized.

The hum output has short spikes of relatively high amplitude and very short duration which, while not apparently interfering with computer operation, are still undesirable.

Very few power supply tube failures have been experienced. These have averaged less than one per month of operation. However, it has been the practice to change thyratron and other heavy current tubes every 1,000 hours.