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VOLUME III

CHAPTER IV

MAGNET REGULATORS

by

Kenneth Macleish

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by K. MacLeish

4.01 Introduction.

For operation of the calutron at maximum efficiency, it is essential that the correct relationship between accelerating voltage and magnetic field strength be maintained to a high degree of accuracy. A fluctuating magnetic field can be tolerated if each high-voltage supply is equipped with a device (such as the "beam sniffer" described elsewhere in this volume) which will continuously vary the accelerating voltage in such a way as to hold the beam focused on the collector. In practice, however, it has been found desirable to provide regulating equipment designed to keep the variations in magnetic field as small as possible, preferably less than one part in 5,000. Since the reluctance of the magnetic flux path does not vary appreciably with time, a steady magnetic field is obtained if the current supplied to the exciting coils of the magnet is held constant. The problem of magnetic field regulation thus reduces to that of providing a suitable constant-current supply.

From the point of view of current control, a calutron magnet is simply a large iron-core inductor possessing a high ratio of inductance to d.c. resistance. Since most of the magnetic reluctance is due to the air gaps, the magnetic field varies almost linearly with the current in the coils. Various electrical properties of typical prototype and plant magnets are given in Table I. The time-constant values, which are the times required for the magnet coil current to rise to 63 percent of its final value after voltage is applied, are of importance in determining the stability of the current-regulating system.

Excitation power is supplied by a conventional motor-driven d.c. generator, or in some cases by two or more generators in series or parallel. Some early consideration was given to the possibility of using polyphase mercury-arc rectifiers instead of rotating machines, but limited time schedules and the availability of suitable motor-generator sets dictated the use of the latter in all installations.

If a fixed voltage were applied to the field circuit of the generator, the magnet current would be subject to fluctuations of several per cent arising from such factors as the change of magnet and generator winding resistances with temperature. The regulator system operates by continuously measuring the magnet current and automatically adjusting the generator field excitation as required to hold a constant load current.

TABLE I

Magnet	XA	Alpha I	Beta
Operating current (amperes)	820	7500	4100
Operating voltage (volts)	250	610	305
Power consumption (kilowatts)	205	4580	1250
Inductance (henries)	2.4	1.13	1.35
d.c. resistance (ohms)	0.30	0.081	0.075
Time constant (inductance/resistance)	8 sec.	14 sec.	18 sec.

4.02 ~~4.2~~ Basic Principles.

Although differing widely in circuit details, all of the commonly

used systems of magnet current regulation are represented in principle by the diagram of Figure 4.1. The current to be regulated passes through a "shunt" connected in series with the magnet windings. This is simply a resistor designed to have a constant resistance under load; usually an ordinary ammeter shunt of appropriate current rating is used. The voltage drop in the shunt is compared by series opposition with a reference voltage which can be adjusted to an arbitrary constant value. The algebraic sum of the shunt voltage and the reference voltage appears across the input terminals, A and B, of a high-gain voltage amplifier. The output of the voltage amplifier controls a power amplifier of sufficient capacity to provide excitation for the shunt field of the main generator. The polarity of the connections is such that an increase in magnet current (and hence in the voltage across the shunt) causes a reduction in the generator field excitation.

It is readily apparent that this type of circuit tends to hold the magnet current at a value such that the shunt voltage is, on the average, nearly equal to the reference voltage. Because of time lags in the response of the various circuit elements, however, a sudden disturbance occurring anywhere in the system will cause the magnet current to differ transiently from the equilibrium value. Following a disturbance such as a sudden change in line voltage, the current goes through a series of damped oscillations before returning to the regulated value. The speed with which the oscillations are damped out governs the precision with which the current can be held constant over short periods of time. The long-period stability of the average current, on the other hand, depends on the ability of the regulator system to counteract the effects of slow changes, such as variations in the resistance of the magnet windings with temperature or drift in the characteristics of the regulator amplifiers themselves.

Analysis of the short and long period behavior of the system is most easily carried out by applying the theory of feedback amplifiers. The generator is regarded as an amplifying element having a certain voltage gain (change in armature voltage divided by change in field voltage), and the magnet windings and shunt in series are regarded as a voltage divider by which a fraction of the generator output is fed back to the input terminals of the sequence of amplifiers. The system is characterized by a "loop gain" which is the product of the voltage gains in the voltage amplifier, power amplifier, generator, and voltage divider. The gain in the voltage divider is of course less than unity, being the ratio of the resistance of the shunt to the total series impedance of the shunt and the magnet windings. The loop gain has its maximum value at zero frequency; that is, at frequencies so low that attenuation by the reactances in the system is negligible. At higher frequencies the loop gain falls off with increasing frequency. Application of feedback amplifier theory shows that the long-period stability of the current is related to the loop gain at zero frequency, while the response of the current to transient disturbances depends on the manner in which the loop gain varies with frequency. By analyzing the problem from this standpoint, it is possible to derive two simple rules on which the design of a regulating system can be based.

The long-period stability may be obtained by the following rule, which applies when the zero-frequency loop gain is large compared to unity: <u>changes of current that occur with feedback are equal to the changes that would occur without feedback, divided by the loop gain at zero frequency</u>. In applying this rule, the phrase "without feedback" means with the feedback loop open; that is, with the connection from

point A (Figure 4-1) to the shunt removed and a steady voltage of appropriate magnitude connected between points A and B. For example, suppose that the natural stability of the amplifiers, generator, and magnet are such that over a given period of time, with the feedback loop open, the current would drift by five per cent. To reduce the drift to 0.02 per cent will then require a zero-frequency loop gain of 250. Since one of the factors in the loop gain is the ratio of the resistance of the shunt to that of the magnet windings, and since this ratio is usually of the order of 10^{-4}, the voltage gain from the input of the voltage amplifier to the armature terminals of the generator must be about 2,500,000. Thus, with the feedback loop open, changing the voltage between A and B by 10 microvolts causes the generator armature voltage to change by 25 volts. The attainment of reasonable stability in a direct-current amplifier having this much gain is one of the problems of magnet current regulator design.

To estimate the transient response and short-period stability of the system, it is necessary to consider the behavior of the loop gain at frequencies other than zero. In a magnet regulator system, it is convenient to express the variation of gain with frequency in terms of the time constants of the various elements of the loop. The longest time constants are usually those of the magnet, the generator, and the power amplifier. If all other time constants are negligible in comparison with these three, the following rule applies: <u>for rapid damping of transient oscillations, the loop gain at zero frequency must be less than the ratio of the largest to the smallest time constant.</u> The presence of additional time constants in the loop will further limit the loop gain that can be used. With a given combination of three or more simple time constants, it is always possible for the system to exhibit

spontaneous oscillations of large amplitude if the loop gain is made sufficiently high.

In order to use the high loop gain required for long-period stability and at the same time avoid oscillation or poor transient response, an attempt is made to select in accordance with the above rule. The time constants of the generator and of the magnet are generally not at the disposal of the regulator designer. Hence it is desirable that the voltage and power amplifiers be made as fast-acting as possible. If, however, the power amplifier is a rotating machine of several kilowatts capacity, as is often the case, its time constant may be so large that the loop gain permitted by the above rule is not sufficient to provide the desired long-period stability. In such cases it is possible to increase the permissible loop gain through the use of a damping circuit which improves the transient response by effectively modifying the frequency characteristic of the magnet-shunt combination. Various methods of damping will be described in connection with the regulator circuits with which they have been employed.

4.03 ~~4.6~~ Survey of Regulator Types.

The various regulating circuits that have been used with calutron magnets all follow the basic scheme of Figure 4.1 ~~1~~, but differ in the details of the voltage amplifier, power amplifier, reference voltage source, and damping circuits. For purposes of comparison, a brief survey of the salient features of several regulator types is given here, arranged in historical sequence. The details of particular installations are described in the next section.

1. Early galvanometer-type regulator. The first regulator used with the calutron process was an adaptation of a circuit that had

served for several years for regulation of the current of a cyclotron magnet. This regulator was used with the 184-inch Berkeley magnet at the start of operations. The input stage of the voltage amplifier employed a suspension-type galvanometer, deflections of which were translated into voltage changes by means of a photo-electric coupling system. Further amplification was provided by a direct-coupled d.c. amplifier. The power amplifier was a six kilowatt self-excited d.c. generator controlled by vacuum tubes in series with the shunt field. The main generator was a 350-kilowatt compound-wound machine with the series field disconnected. Reference voltage was furnished by a 1-1/2 volt dry cell and a resistance network. Transient damping was derived principally from the voltage induced by change of magnetic flux in a loop of wire encircling one leg of the magnet yoke.

2. Converter-type regulators. This type was developed at the Radiation Laboratory to overcome some of the troubles of the earlier regulator by elimination of the galvanometer. It was used first with the 37-inch magnet and subsequently with the 184-inch, XA, and XC magnets. In the voltage amplifier, the signal was first converted to an alternating voltage by a mechanically vibrating converter. After amplification by an a.c. amplifier, the signal was converted back to d.c. through the action of a grid-controlled rectifier. The power amplifier was usually a self-excited generator controlled by vacuum tubes in series with the shunt field, although in some instances the exciter generator was omitted and the control tubes were placed directly in the field circuit of the main generator. In the XA and XC installations, transient damping was obtained by means of a current transformer which furnished a signal proportional to the rate of change of magnet current. No damping was needed with the 37-inch and 184-inch magnets, since these magnets,

being designed for economy of power, had very large time constants. Reference voltage was again derived form a 1-1/2 volt dry cell.

3. General Electric regulators. The regulators for the plant magnets at Oak Ridge were furnished by the General Electric Company. In these regulators the voltage amplifier utilized a galvanometer-photocell arrangement similar in principle to the one mentioned above, except that provision was made for neutralizing the restoring torque of the galvanometer suspension by means of a small permanent magnet mounted on the moving element. For power amplification the regulator used a phase-controlled thyratron rectifier feeding the shunt field winding of an exciter generator. Stability against oscillation was obtained by purposely making the time constant of the galvanometer very large compared to that of the magnet. Since the current-measuring circuit could not detect rapid changes, a direct feedback was provided from the main generator armature to the photocell amplifier for the purpose of holding the generator voltage constant over short periods. The reference voltage was originally furnished by a second galvanometer-photocell circuit controlled by a standard cell; this arrangement was subsequently replaced by a dry-cell circuit similar to that of the preceding regulators.

4. Amplidyne-type regulators. A regulator system using an amplidyne generator was developed by the Tennessee Eastman Corporation as a possible replacement for the galvanometer-type regulators in the Oak Ridge plant. Regulators of this type were installed in the XAX and XBX pilot plant units and on one Beta refining plant magnet. The voltage amplifier was similar to that used in the converter-type regulators. For power amplification, advantage was taken of the low excitation

power and high speed of response inherent in the amplidyne type of generator. No damping circuit was needed in the XBX installation owing to the fast response of the two kilowatt amplidyne exciter. The slower response of the 15-kilowatt machine used with the Beta magnet necessitated the use of damping in that installation. The damping circuit took the form of a resistance-capacitance network for feeding rapid changes in magnet voltage directly to the voltage amplifier.

4.04

4.4 Circuit Details.

As examples of the various regulator types outlined above, three typical installations will now be described in some detail. The General Electric regulators used in the Oak Ridge plant are covered in detail elsewhere and will not be further described here.

1. Galvanometer-type regulator; 184-inch magnet. The complete circuit diagram of this installation is given in Figure 4.2. The reference voltage, derived from dry cell B1, appears between the sliding contacts of potentiometers R2 and R6. Motion of the coarse current control R2 varies the reference voltage over a range from zero to about 70 millivolts, and the fine current control R1 provides an additional variation of about 2.5 per cent. In series with the reference voltage and the galvanometer coil are potentiometers R1 and R16, which inject adjustable damping voltages into the input circuit. The damping voltage across R1 comes from a single turn of wire surrounding one leg of the magnet yoke and is proportional to the time derivative of the magnetic flux. The effect of this damping voltage is similar to an "anticipation" of changes in magnet current, for, when the current starts to change for any reason, the voltage induced in the pick-up loop affects the galvanometer before the total change in shunt voltage becomes appreciable. The damping

voltage fed in from T1 and R16 is proportional to the rate of change of exciter field current. The effect of this second feedback is difficult to analyze, and it was of doubtful value in actual operation.

The position of the galvanometer armature controls the grid voltage of tube V1 through an optical coupling arrangement. A diaphragm near the light source is imaged on a type 920 twin photocell by reflection from a concave mirror attached to the armature of the galvanometer. As the armature turns, the image moves off one cathode of the photocell and on to the other. The potential of the grid of V1 depends on the fraction of the total light falling on each photocell cathode and therefore varies as the galvanometer armature turns. Changes in the grid voltage of V1 are amplified in V1 and V2 and fed to the grids of eight type 48 tubes, V3 to V10, connected in parallel. For simplicity, only one of the eight tubes is shown in Figure 4.2.

The six kilowatt exciter generator is operated self-excited, and the variable plate resistance of tubes V3 to V10 controls the exciter output in the same manner as a field rheostat. A resistor, R17, in series with the exciter field absorbs some of the voltage in the field circuit and reduces the required power dissipation at the plates of the control tubes. The purpose of capacitor C1, paralleling the control tubes, is to absorb any voltage surges arising in the highly inductive exciter field due to sudden changes in the grid voltage of the control tubes.

When operating properly, this regulator held the magnet current constant to about one part in 1,000 over periods of six hours. Most of the operational troubles were associated with the galvanometer system, the principal troubles being as follows:

a. Sticking of galvanometer armature. - To prevent over-travel of the light spot past the "turn-on" photocell element and consequent

loss of control, it was necessary to limit the possible angular displacement of the armature. An adjustable stop was provided for this purpose. In spite of careful design of the stop (a ground tungsten point bearing against a polished glass surface) the armature would occasionally stick against the stop while the magnet current was being adjusted. The current would then rise to the maximum value permitted by the circuit, and control could be regained only by physically jarring the galvanometer.

b. ~~2.~~ Difficulty of maintenance. - Breakage of the galvanometer suspension and burn-out of the light source were frequent occurrences. Readjustment of the mechanical zero of the galvanometer, a delicate operation, was required periodically.

c. ~~3.~~ Susceptibility to vibration. - In spite of shock mounting, building vibrations and even loud noises would cause sufficient vibration of the galvanometer armature to affect the magnet current appreciably.

d. ~~4.~~ Slow response. - The inertia of the armature acted as a time constant in the voltage amplifier circuit, seriously limiting the loop gain that could be used without oscillation.

Because of these difficulties, the use of galvanometers in calutron magnet current regulators was abandoned at the Radiation Laboratory in favor of the converter type of circuit.

2. Converter-type regulator; XA magnet. Figure ~~3~~ 4.3 is an elementary circuit diagram of this installation. The 350-kilowatt main generator and six-kilowatt exciter were the same machines that had formerly been used with the 184-inch magnet, which was then excited by a smaller machine.

A signal of about 30 millivolts is obtained from the shunt in series with the grounded negative current bus. The reference voltage is provided

by dry cell B2 and resistors R2 to R6 in a circuit similar to that used with the galvanometer-type regulator. A damping transformer, T1, feeds in a voltage proportional to the rate of change of magnet current. Although the damping ~~action~~ so obtained is equivalent to that of the pick-up loop of Figure ~~2~~ 4.2, the current transformer is preferable here because the signal from it is less susceptible to interference from stray alternating fields. Nevertheless, a filter composed of R1 and C1 is necessary to prevent 60-cycle voltages induced in T1 from affecting the voltage amplifier. Dry cell B1 furnishes a polarizing voltage for the electrolytic capacitor C1. Transformer T1 is somewhat similar in construction to a bushing-type current transformer; it consists of a laminated iron core surrounding the current bus and wound with a few turns of No. 12 wire. An air gap in the core prevents saturation of the iron. The length of the air gap and the number of secondary turns are selected so that the mutual inductance between the current bus and the secondary winding is about five microhenries; that is, a current change of one ampere per second produces a secondary voltage of about five microvolts. Potentiometer R2 controls the degree of damping.

The converter and step-up transformer T2 convert the difference signal appearing between points A and B to a 60-cycle square wave. The signal is applied between the primary center-tap of T2 and the moving contact of the converter. The moving contact, vibrated at line frequency by a small a.c. electromagnet, touches the fixed contacts alternately and thus connects the input signal alternately across the two halves of the primary of T2. The resulting voltage induced in the secondary of T2 is a 60-cycle square wave whose amplitude is proportional to the d.c. input voltage. The step-up ratio of transformer T2 is about

eight to one. The converter and transformer are the same type used in continuous-balance potentiometers manufactured by the Brown Instrument Company.

Tubes V1 and V2 and associated circuit elements form a two-stage a.c. amplifier of conventional design. Negative feedback from the plate circuit of V2 to the cathode of V1 stabilizes the gain, which is about 560 for the two stages. The amplified signal is fed to tube V3 through a linear potentiometer R14, whose function is to control the gain of the amplifier and hence the overall loop gain of the system. The first half of tube V3 provides a further voltage gain of about 45, and the second half operates as a phase inverter by amplifying a small fraction of the plate signal of the first half of the tube. The a.c. voltages at the plates of V3 are equal in magnitude but 180 degrees out of phase with each other.

Tube V4 and transformer T3 are connected in a grid-controlled full-wave rectifier circuit. The d.c. voltage output of this circuit is controlled by the amplitude of the a.c. signals from the preceding stage. If the voltage on each grid of V4 is in phase with the voltage supplied by T3 to the corresponding plate, the tube passes current and a rectified voltage appears across capacitor C16. If, on the other hand, the grid voltages of V4 are 180 degrees out of phase with the corresponding plate voltages and are sufficiently large, V4 does not pass current on either half-cycle and the rectified voltage across C16 is zero. Either of these two conditions may prevail, depending on the polarity of the d.c. input signal applied between points A and B; for a reversal in the polarity of this signal is equivalent to a 180-degree phase change

in the a.c. signal passing through the amplifier. The polarity of the voltage between A and B depends in turn on whether the voltage across the shunt is greater or less than the reference voltage. If the shunt voltage is within a few microvolts of the reference voltage, a partial throttling of the rectifier occurs. In this range, the output of the rectifier is a smoothly varying function of the shunt voltage, and the entire circuit up to C16 acts as a high-gain d.c. amplifier. The response characteristic at zero frequency with R14 at maximum gain setting is plotted in Figure 4.4. The maximum slope of the curve corresponds to a voltage gain of 2.5×10^6 between the shunt and capacitor C16.

The rectified voltage from V4 is reduced by a factor of two by resistors R27 and R28 and applied to the grids of four paralleled 6Y6G beam tubes, V5 to V8, only one of which is shown in the diagram. The voltage reduction is used in order to make the maximum voltage from V4 just sufficient to cut off the 6Y6G tubes, thus causing the normal operating point of the voltage amplifier to lie on the steep part of the curve of Figure 4.4. Filter capacitors C16 and C17 serve to remove some of the 120-cycle ripple from the voltage applied to the grids of the 6Y6G tubes. This filter determines the overall frequency response of the amplifier, and the attenuation introduced by it has a small but nevertheless undesirable effect on the transient response of the regulator system. Small resistors in the grid, plate, and screen leads of each of the 6Y6G tubes are required for suppression of high-frequency parasitic oscillations. The four tubes, capable of passing 0.5 ampere, control the output of the six-kilowatt self-excited generator by acting as a variable resistance in series with the generator field. The overall loop gain of the system, with R14 at maximum setting, is about 800.

By comparison with earlier regulators, the performance and reliability of the converter-type regulator were very gratifying. In the XA installation

the current was constant to one part in 6,000 over twenty-minute periods and one part in 3,000 over six-hour periods. The converter gave absolutely trouble-free operation and was highly insensitive to external vibration. The chief limitation on the amounts of gain and damping that could be used was set by distortion of the wave form in the amplifier due to hum pick-up in the low-level circuits. Noise arising from stray magnetic fluxes linking the input circuit had to be minimized by tightly twisting the wires and enclosing the long leads from the shunt and damping transformer in steel conduit. Care was required in the physical layout of the reference voltage circuit to avoid drift due to temperature inequalities. The stability of the dry cell used in the reference voltage circuit is discussed below in connection with the amplidyne-type regulator.

3. Amplidyne-type regulator; Beta magnet. Development of the amplidyne-type regulator by the Tennessee Eastman Corporation was prompted by persistent difficulties with the galvanometer-type regulators in the plant. Previous experience with converter-type regulators at the Radiation Laboratory suggested that the same principles could be applied to the regulation of the large calutron magnets at the Oak Ridge plant. Two new factors entered into the design. First, the magnet windings were operated ungrounded to minimize the destructive effects of accidental grounds within the coil structure. Hence the control shunt could not be kept at ground potential as before, and the input circuit of the regulator had to operate at a potential that not only differed from ground by as much as several hundred volts d.c. but also varied up and down with respect to ground at the 2000-cycle commutating frequency of the main generators. Second, conventional d.c. exciter generators large enough to supply field excitation for the main generators had a time constant that was too large in comparison with that of the magnet for satisfactory

precision control. The amplidyne-type of generator, characterized by high speed of response and low control power, was therefore selected for power amplification.

Figure 4.5 shows the circuit of the Beta installation. The total input signal to the voltage amplifier is the sum of the shunt voltage, the reference voltage, and a damping voltage appearing across R3. The damping action of the circuit composed of R1, R2, R3, C2, and C3 is similar in principle to that of the other damping circuits described previously, but in this case the signal that "anticipated" a change in magnet current is derived from a change in the voltage across the magnet coils, rather than from the rate of change of current or of magnetic flux. Any rapid change in generator voltage is transmitted through the large capacitor C2 and appears across the series combination of R1, R2, and R3. A small fraction of the total voltage change is fed from R3 to the amplifier input circuit, where it produces the same effect as a change in magnet current. C3 is a by-pass or filter capacitor which prevents the high-frequency generator commutator ripple (usually about 20 volts peak to peak) from reaching R3 and interfering with the normal action of the voltage amplifier.

The reference voltage is produced by current from an Eveready No. 742 dry cell, B1, flowing through two resistors, R4 and R5, each of which can be varied in ten steps. The two resistors have dials calibrated respectively in hundreds and in thousands of amperes of magnet current. A fine current control, R8, providing a stepless variation of about five per cent, is used for small current adjustments and to compensate occasionally for slow drift in the voltage of B1. To determine the way in which the voltage of B1 varies as the cell ages, a series of tests was made with several cells. It was found that the cell voltage

decreased with time at a rate depending on the current drain. The voltage dropped off most rapidly when the cell was new. The stability of a new cell could be improved by " seasoning" the cell before installation. For the seasoning operation, the cell was subjected to a relatively heavy current drain (five milliamperes) until its voltage had dropped to about 1.44 volts. This initial drop took place over a period of about six weeks. The current load was then reduced to the normal value of 0.5 milliampere required by the circuit of Figure 5. After about two weeks at this load, the cell was placed in operation, its voltage then being about 1.46 volts. Over the succeeding twelve months, the voltage decreased at an average rate of about 0.3 per cent per month. A curve of voltage versus time for a typical cell, covering a period of 463 days, is shown in Figure 6. In addition to falling off with time, the cell voltage was subject to temperary fluctuations due to changes in ambient temperature. The temperature coefficient seemed to vary from cell to cell, but an average value was in the neighborhood of 0.02 per cent per degree Centigrade.

Since the operation of the voltage amplifier circuit is similar to that already outlined for the converter-type regulator, only the main points of difference will be mentioned here.

The feedback over the first two amplifier stages is from the cathode of the second stage to the grid return of the first stage. This arrangement permits by-passing the cathode resistor of V1 and eliminates some undesirable hum that was produced in the circuit of Figure 3 by 60-cycle voltage pick-up from the heater of V1.

Capacitor C1 connected between the control shunt and ground causes most of the generator commutator ripple to appear on the negative current bus. Nevertheless, owing to distributed capacitance to ground in the magnet coils, an appreciable ripple voltage also exists between the

control shunt and ground. It is necessary for the regulator to amplify a difference signal whose magnitude is of the order of microvolts in the presence of a 2000 cycle voltage that may be several volts. For this reason, a shielding system is provided which surrounds the low-level parts of the circuit. Both the shield and the "ground" bus of the amplifier are connected to earth ground through high resistances R39 and R40 to the positive current bus through a large capacitor C21. Hence the entire amplifier and shield are carried up and down with respect to ground at commutator-ripple frequency, and the low-level parts inside the shield are unaware of the existence of the ripple voltage. If the shield were omitted or connected directly to earth ground, the interference in the amplifier from commutator-ripple would be several hundred times as strong as the control signal being amplified. The reference circuit, damping network, converter, and input transformer are at the same d.c. potential as the positive current bus, but blocking capacitors C4, C5, and C21 allow the remainder of the electronic circuit to operate at ground d.c. potential while at the same time carrying the commutator-ripple voltage.

Equalizing capacitors C12 and C13 are used in the phase-inverter stage for the purpose of flattening the tops of the square waves presented to the grids of V4. Their action is to emphasize the low-frequency components of the carrier signal in comparison with the higher frequencies and thus to compensate for the low-frequency attenuation introduced by coupling capacitors C4, C5, C9, C11, C14, and C15. Omission of C12 and C13 causes the carrier wave to have a sloping top.

The grid-controlled rectifier stage of Figure ~~3~~ 4.3 is replaced by a full-wave synchronous rectifier, V4, which rectifies the carrier signal directly. The grids of V4 are ~~dirven~~ driven by 60-cycle voltage from transformer T2 in synchronism with the vibration of the converter contacts. The

relative polarities of the supply connections to the converter coil and to the primary of T2 are such that V4 rectifies the signal only when point A in the input circuit is positive with respect to point B. A small phase lag that exists between the motion of the converter contacts and the voltage from T2 is compensated by the networks R29 - C16 and R31 - C17 in the grid circuits of V4.

Because of the low control field power requirement of the 15-kilowatt amplidyne generator, a single 6AG7 tube, V5, suffices for control. Discharge tube V6 protects V5 from inductive voltage surges arising from abrupt changes in the amplidyne field current. The amplidyne is provided with two separate control fields. The current in the No. 1 field comes from the amplifier power supply and passes through the plate circuit of V5. The No. 2 field is connected across the amplidyne output terminals and produces a control flux that opposes the flux from the No. 1 field. The resulting negative feedback within the machine makes the control characteristic practically linear, at the expense of an easily afforded reduction in the overall power gain. The static control characteristics of the amplidyne with and without the feedback connection are plotted in Figure ~~7~~ 4.7. The high dynamic plate resistance of the pentode tube V5 and the negative feedback from the second control field both improve the speed of response of the amplidyne. Controlled in this manner, the machine has an effective time constant of 0.13 second, compared with about 0.4 second for a conventional generator of comparable power rating.

To insure continuity of operation and facilitate maintenance, two duplicate regulating channels are provided, only one of which is shown in Figure ~~5~~ 4.5. A standby regulator and amplidyne are thus kept in readiness for operation in the event of circuit failure. While one regulator is controlling the magnet current, the standby regulator is left connected

to the control shunt and serves to monitor the operation of the controlling regulator. This is effected by adjusting the current control knobs on the standby regulator to bring the reading of its output milliammeter, M1, to approximately mid-scale. The standby regulator then acts as a stable high-gain amplifier, and minute fluctuations in the magnet current are registered on meter M1. The sensitivity is such that each scale division of M1 corresponds to a change in magnet current of one part in 10,000. Use of the standby regulator for monitoring in this fashion also yields a continuous indication of the readiness of the standby regulator to take over control of the current. Control is switched from one regulator to the other by means of transfer relays in the No. 1 field circuits of the amplidynes, the relays being so arranged that either regulator can be used with either amplidyne. Selection of the amplidyne to be used is accomplished with a switch in the main generator field circuit. The magnet must be de-energized while changing amplidynes, but the transfer from one regulator to the other can be made without appreciably disturbing the magnet current.

Figure 4.8 is a 2-1/2-hour record of the Beta magnet current controlled by this type of regulator, operating with a loop gain of 500. The record was made by a recording milliammeter connected in series with the output meter of the standby regulator. The indicated stability of the current is of the order of one part in 10,000. This record is typical of the short-period behavior of the regulator. Over longer periods a drift occurred, owing chiefly to slow changes in the reference voltage. Slow drift, however, was of minor importance in calutron operation, since other considerations necessitated periodic readjustment of the accelerating voltage of each calutron unit. Of much greater importance was the ability of this type of regulator to operate continuously for periods as long as nine months without maintenance attention.

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