SECTION 5

VOLTAGE-REGULATOR CIRCUITS

PART A. ELECTRON-TUBE CIRCUITS

GAS-TUBE REGULATOR.

APPLICATION.

The gas-tube regulator circuit is used in certain electronic equipment power-supply circuits to obtain nearly constant output voltage(s).

CHARACTERISTICS.

Regulated output voltage to load is nearly constant; voltage drop across regulator tube remains nearly constant for considerable range of tube currents.

Voltage-divider principle employed, using fixed resistance and variable resistance (gaseous regulator tube) in series; regulated load is taken from across regulator tube.

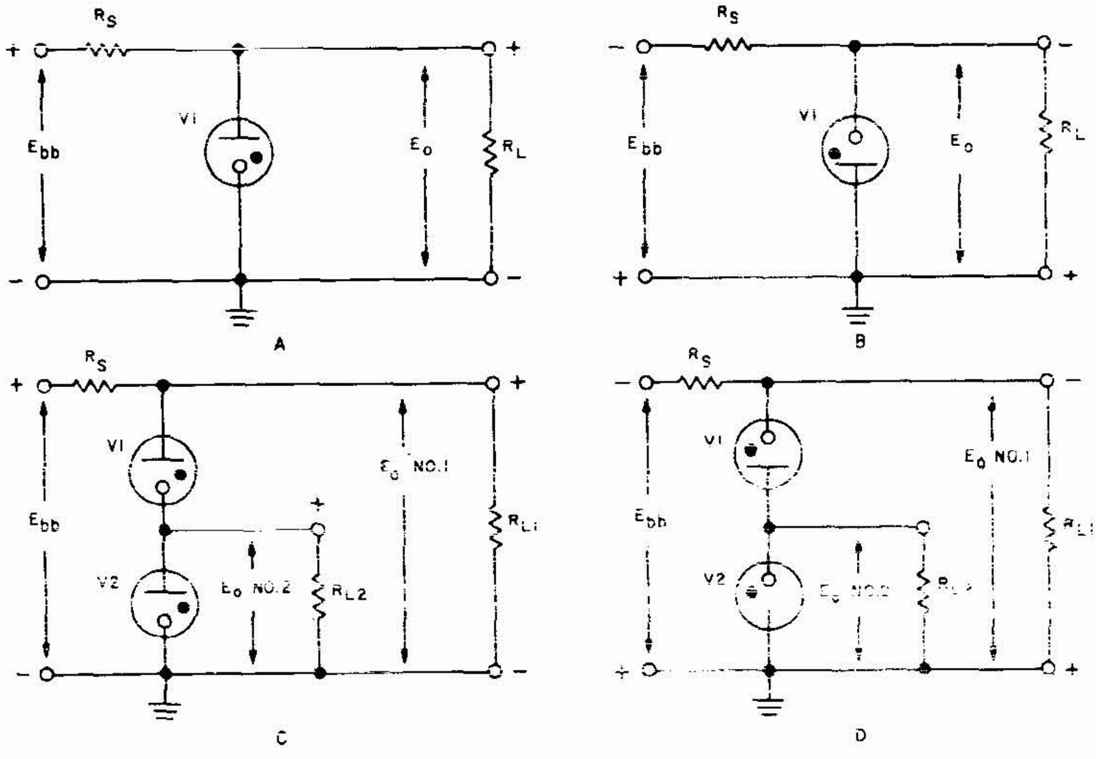
Variation in basic circuit permits positive (plate and screen) or *negative (bias) supply voltages to be regulated.*

CIRCUIT ANALYSIS.

General. The gas-tube regulator is one of the simplest types of voltage regulators. The regulator circuit consists of a fixed resistor in series with a cold-cathode, gas-filled regulator tube. The regulated output voltage is developed across the regulator tube; therefore, it is across this tube that the load is connected.

The regulator circuit develops a definite output voltage which is dependent upon the type of gas tube used in the circuit, provided that the variation in load current is within the operating range of the tube type employed. Gas tubes are rated according to the voltage appearing across the tube during normal operation and according to the maximum permissible current through the tube. Typical approximate operating voltage ratings for cold-cathode gas-filled tubes are 75, 90, 105, and 150 volts d-c; typical maximum current ratings are 30, 40, and 50 milliamperes.

Circuit Operation. *In the accompanying circuit schematic,* parts A and B illustrate a gas tube used in a basic voltage regulator circuit. Resistor R_s is the series resistor; electron tube V1 is the gas-filled regulator tube. The circuit given in part A provides regulation of a positive input voltage, while the circuit given in part B provides regulation of a negative input voltage. Several regulator tubes may be connected in a series combination, if desired, to obtain a higher regulated output voltage. In the accompanying circuit schematic, parts C and D illustrate two regulator tubes in series. The circuit given in part C provides regulation *of a positive input voltage,* while the circuit given in part D provides regulation of a negative input voltage. Intermediate regulated voltages can be obtained from the junction



Gas-Tube Regulator Circuits

of the regulator tubes in the latter two circuits (or from the junction of any series combination of regulator tubes), provided that the current drain of the associated load is kept low.

The cold-cathode gas-filled regulator tube is a two-electrode tube with a cathode and plate. The evacuated tube contains a small amount of gas, such as neon, which is sealed inside the tube. When sufficient voltage is applied to the tube, ionization of the gas molecules occurs and is responsible for the current passing through the tube during operation. If a gas tube is connected directly across a source of voltage which is high enough to ionize the gas, the current will immediately increase to such proportions that the tube may be damaged. The use of a series resistance is essential, therefore, to limit the current through the tube.

There are two separate voltages to be considered in discussing the conditions under which the regulator tube will ionize and operate; these voltages are the breakdown, or firing, voltage and the operating voltage. The breakdown (or firing) voltage is that voltage at which the gas becomes ionized and begins to pass current. Below this starting voltage the gas will not ionize and current will not pass through the tube. The operating voltage is the voltage at which the tube will remain ionized after having started. There is a considerable difference between the supply voltage and the voltage at which the regulator operates. [illegible] difference is compensated for by the series resistor, which also serves to stabilize the load. [illegible] value of the series resistor depends upon the [illegible] d-c voltage input to the regulator circuit, the re[illegible] d-c output voltage, and the combined currents of the regulator tube and the load. The resistor is generally chosen to be of sufficient resistance to limit the current through the regulator tube to a value which is always less than the rated maximum operating current. The current through the regulator tube at the instant of ionization and before the load current has risen to its normal value may initially exceed the maximum value; however, as soon as the load current rises to its normal value, the regulator tube current drops to a value which is within operating limits because of the series resistance in the circuit.

The ionization of the gas within the tube changes, depending upon the applied voltage; as a result, the internal resistance of the regulator tube changes. When the applied voltage increases, the ionization of the gas increases to lower the tube resistance, and a larger current is passed. Conversely, when the applied voltage decreases, the ionization of the gas decreases to increase the tube resistance, and a smaller current is passed.

From the accompanying circuit schematic, note that the load current and the regulator tube current both pass through the series resistor, R_s. If the d-c input voltage to the regulator circuit drops, the voltage across the regulator tube also drops momentarily, at which time the gas within the tube deionizes slightly and less current passes through the regulator tube. Therefore, the current through the series resistor decreases by the amount of the decrease in the regulator tube. Since the current through the series resistor decreases, the voltage drop across the resistor also decreases, and the output voltage delivered to the load increases to return to its original value. In a similar manner, if the input voltage to the regulator circuit increases, the voltage across the regulator also increases momentarily, at which time the gas within the tube is further ionized and more current passes through the regulator tube. Thus, the current through the series resistor is increased. Since the current through the series resistor increases, the voltage drop across the resistor also increases, and the output voltage delivered to the load decreases to return to its original value. When the value of the series resistance is the correct value for the load to be regulated, the output voltage is held nearly constant by the action of the regulator tube. As just described, this action depends upon the fact that changes in the ionization of the gas within the tube varies the amount of current that the tube conducts.

The discussion above assumed that a change occurred in the d-c input voltage applied to the regulator circuit. However, the regulator circuit also compensates for changes occurring in the load current. If the load current should increase, the voltage drop across the series resistor, R_s, will immediately increase. As a result, the voltage across the regulator tube decreases momentarily, at which time the gas within the tube deionizes slightly and less current passes through the regulator tube. Therefore, the current through the series resistor decreases by the amount of the decrease in the regulator tube. Since the current through the series resistor decreases, the voltage drop across the resistor also decreases, and the output voltage delivered to the load increases, returning to its original value. In a similar manner, if the load current should decrease, the voltage drop across the series resistor will immediately decrease. As a result, the voltage across the regulator tube increases momentarily, at which time the gas within the tube is further ionized and more current passes through the regulator tube. Thus, the current through the series resistor is increased. Since the current through the series resistor increases, the voltage drop across the resistor also increases, and the output voltage delivered to the load decreases, returning to its original value. From the discussion given here, it is seen that the output voltage is held nearly constant by action of the regulator tube when changes occur in the load current.

The d-c input voltage required to cause ionization of the regulator tube when the circuit is first energized is approximately 30 percent greater than the operating voltage specified for the regulator tube. The output voltage of the regulator circuit quickly drops to the operating value of the regulator tube as soon as the tube ionizes and begins to conduct, causing a voltage drop to appear across the series resistance, R_s. In order to obtain stable operation, the regulator tube must be operated so that it is ionized at all times, and its operating current must fall within specified maximum and minimum current ratings. If, for some reason, the operating current exceeds the specified maximum current rating or if the voltage across the tube is excessive, the tube will become highly ionized, will lose its ability to regulate, and may be permanently damaged. Conversely, if the operating current drops below the specified minimum current rating (approximately 5 milliamperes), the tube will become deionized and will no longer regulate the output.

Also, if the voltage across the regulator tube drops below the specified operating voltage to a value which is approximately 70 percent of the breakdown (or firing) voltage, the tube will become deionized.

The value of the series resistor, R_s, can be approximated using the following formula:

$$R_s = \frac{E_{bb} - E_o}{(I_p + I_{load})}$$

where:

E_{bb} = unregulated d-c input (supply) voltage
E_o = regulated output voltage (to load)
I_p = regulator-tube current
I_{load} = load current

When operation of the regulator tube is desired at the mid-point of its rated current range, the value of tube current used in the above formula is given as:

$$I_p = \frac{I_{max} + I_{min}}{2}$$

where:

I_{max} = rated maximum tube current
I_{min} = rated minimum tube current

In applications where a regulated voltage greater than the voltage rating of a single regulator tube is required, several regulator tubes may be connected in series to obtain regulation of the desired voltage. Furthermore, if the current drain of the load is kept low, an intermediate regulated voltage can be obtained at the junction of any two regulator tubes of the series. Parts C and D of the accompanying circuit schematic illustrate two regulator tubes connected in series. This circuit configuration permits a lower regulated voltage (E_o No. 2) to be taken from the d-c supply. Note that the current through regulator tube V2 and the load current of the lower regulated voltage (E_o No. 2) must pass through regulator tube V1; therefore, the load current of the lower voltage must be relatively small to prevent the combined currents from exceeding the maximum current rating of regulator tube V1.

FAILURE ANALYSIS.

General. Initially, some indication of the trouble associated with a gas-tube regulator circuit can be obtained by visual inspection to determine the presence of the characteristic glow from the ionized gas within the tube. When current through the tube is near its maximum rating, the tube is highly ionized; when the current is near its minimum rating, the tube is lightly ionized; therefore, the intensity of the gaseous discharge within the tube is an indication of tube conduction. If the tube is not ionized, however, this does not necessarily mean that the tube is defective, since the same indication (lack of characteristic glow) may possibly occur if the series resistor (R_s) increases in value if the d-c input voltage (E_{bb}) is below normal, or if the load current is excessive. It is therefore necessary to make d-c voltage measurements at the input and output terminals of the voltage regulator circuit to determine whether the fault lies within the regulator circuit or whether it is external to the regulator circuit.

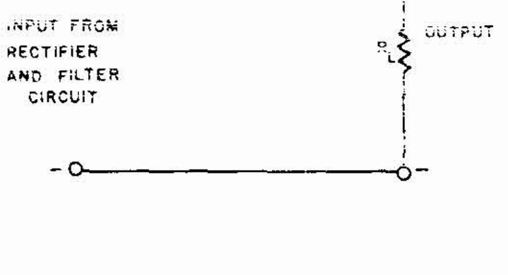
The value of the series resistor, R_s, can be checked by ohmmeter measurements to determine whether any change in resistance has occurred. If the maximum current rating of the regulator tube is exceeded for a considerable length of time, the tube may be damaged and lose its regulation characteristics; therefore, the regulator tube itself can be suspected as a possible source of trouble. Furthermore, a regulator tube which is subjected to a very strong r-f field may be unable to regulate while the field is present, because the r-f field may ionize the gas within the tube independent of the normal d-c conduction current.

ELECTRONIC REGULATOR.

General. Most electronic equipment can operate satisfactorily with a certain amount of variation in the supply voltage without affecting equipment perfomance. However, the operation of certain circuits is very sensitive to slight changes in supply voltage; thus, the use of a voltage regulator is required.

An electronic voltage regulator is a device connected in the output of a power supply to maintain the output voltage at a specified value. The regulator circuit reacts automatically within its design limits to compensate for any change in the output voltage, due either to a change in the supply voltage or to a change in the load current. This regulating action can be described as a form of negative feedback.

The electronic voltage regulator can be compared to a variable resistance, R_S, in series with the load resistance, R_L, and the output of the rectifier and filter circuit. Such a circuit is shown in the accompanying illustration. Variable resistance R_S and load resistance R_L form a voltage divider. If the supply viltage increases, resistance R_S is increased, causing a greater drop across it and thus maintaining a constant voltage across the load. On the other hand, if the supply voltage decreases, resistance R_S is decreased, again maintaining a constant voltage across the load. Similar variations in R_S occur for any variations in the load. If the load resistance increases, with a decrease in load current, R_S is made smaller; thus the voltage dropped across it is less, and the voltage across the load is maintained constant. With a decrease in the load resistance and a corresponding increase in the load current, the resistance of R_S is made larger, causing a greater drop across it; again the constant voltage across the load is maintained.



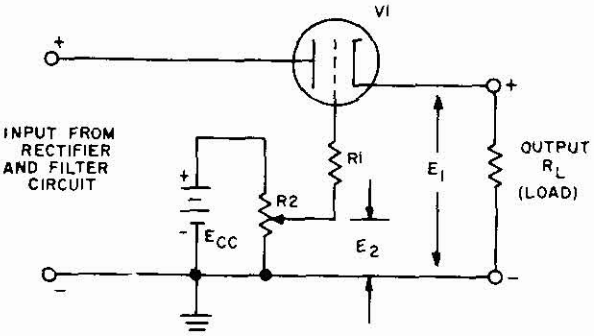
Simple Voltage-Regulator Circuit

Thus, it is seen that the voltage regulator is essentially a voltage-divider circuit, with the voltage drop across the series resistor absorbing any changes in the supply voltage or the load current, so that the voltage across the load is held constant.

In the simple voltage-regulator circuit illustrated above, it is assumed that variable resistance R_S is varied manually to keep the voltage across the load constant. In an actual regulated power supply, the control action required to vary the series resistance, and, consequently, to produce a corresponding variable voltage drop, is completely automatic. This basic principle of voltage regulation is used in the electron-tube, d-c voltage regulators to be described in this section of the handbook.

An electron tube may be considered as a variable resistance. When the tube is conducting, its effective resistance is the plate-to-cathode voltage divided by the plate current. This calculated value of resistance is called the **d-c plate resistance,** or R_p, of the tube. For a given applied plate voltage, the value of R_p depends on the current through the tube, which, in turn, depends on the grid bias of the tube. Therefore, varying the grid bias applied to the tube controls the amount of current through the tube and causes the d-c plate resistance, R_p, to vary accordingly.

The accompanying illustration shows a triode used as a variable resistance in a simple voltage-regulator circuit.

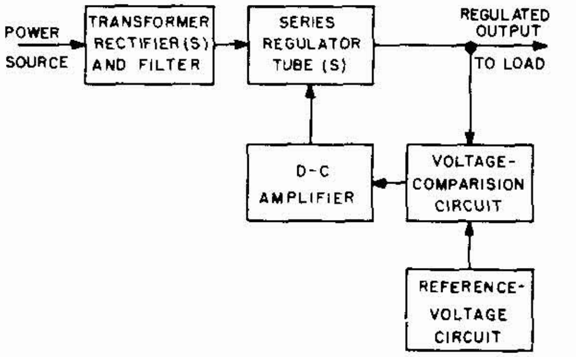


Simple Voltage-Regulator Circuit Using Triode Electron Tube

The d-c plate resistance, R_p, of the series regulator tube, V1, is established by the grid bias of the tube. The actual grid bias, e_g, is the grid-to-cathode voltage; it equals E2 - E1. Potentiometer R2 is placed across E_{cc} to provide a variable source of grid voltage. It is adjusted until the grid bias is the value that will allow V1 to conduct the exact value of load current required to produce the desired value of voltage E1 across load resistance R_L. Thus, adjustment of the bias alters the R_p of V1 to control the current through the tube, the voltage drop across the tube, and, therefore, the voltage across the load. Consider the condition where voltage E1 tries to increase, due either to an increase in the supply voltage, or to an increase in the load resistance. As E1 goes more positive, e_g is made more negative ($e_g = E_2 - E_1$), the conduction of the tube is reduced, the voltage drop across the tube is increased, and the voltage across the load is kept constant. Conversely, if voltage E1 tends to decrease, due either to a decrease in the supply voltage or to a decrease in the load resistance, e_g becomes less negative. This causes an increase in the conductivity of the tube, a decrease in its R_p, a corresponding decrease in the voltage drop across the tube; again the voltage across the load is maintained constant. In a properly designed regulator circuit, the voltage change which occurs across the series regulator tube is approximately equal to the voltage change which appears across the combined resistance of the regulator tube and the load; thus the voltage across the load remains constant.

Since the series regulator may not be sufficiently sensitive to small voltage changes, the output voltage of the simple voltage regulator may not be held absolutely constant. Therefore, where the regulation must be held to a small percentage, additional amplification must be used to increase the sensitivity of the regulator circuit.

Regulated Power Supplies. A complete regulated power supply consists of a power source, a transformer, rectifier, and filter circuit, and a d-c regulator circuit. The d-c regulator circuit may, in turn, be subdivided into four parts: series regulator electron tube(s), d-c amplifier, voltage-comparison circuit, and reference-voltage circuit. The d-c amplifier, the voltage-comparison circuit, and the reference-voltage circuit are considered as one complete functional circuit, generally referred to as the **regulator-amplifier** circuit of the electronic voltage-regulated power supply. The design of the regulator-amplifier circuit depends primarily upon the degree of voltage regulation desired, and is relatively independent of the load current to be supplied. The majority of regulated power supplies which are used to provide plate and screen potentials for electronic equipments provide an output voltage of 150, 250, or 300 volts, dc, with either a positive-output or a negative-output polarity. A typical electronic voltage-regulated power supply is shown in the accompanying block diagram.



Block Diagram of Electronic Voltage-Regulated Power Supply

The series regulator tube, sometimes called the series control tube, used in the electronic voltage regulator is generally one of three possible circuit configurations: a triode-connected beam power tube, such as the type 6L6 or 6Y6; a low-mu, high-conduction triode tube, such as the type 6AS7 or 6080; or a beam power tube, such as the type 6L6, operated with a separate screen supply. The first two configurations mentioned are in common use. The third configuration has the disadvantage of requiring a separate power supply for the screen potential; for this reason its use is somewhat limited.

The triode-connected beam power tube used as a series regulator tube has higher gain characteristics and provides a greater useful percentage of rated capacity than do the other circuit configurations; in addition, the triode-connected beam power tube requires a lower plate-voltage swing of the associated d-c amplifier. The low-mu, high-conduction triode offers the advantage of a low d-c plate resistance; the low-mu triode is frequently used where minimum power loss in the regulator circuit is an important consideration. The beam power tube operated with a separate screen supply has the advantages of a high gain characteristic, a low plate resistance, and a generally higher plate dissipation than the first two configurations mentioned above, but it does have a disadvantage in that a separate screen-voltage supply is required.

Regulator-amplifier circuits generally fall into one of several circuit configurations: single pentode, twin-triode cascode, twin-triode cascade, twin-triode and pentode with balanced input, and pentode and twin-triode with balanced output. For each of these regulator-amplifier circuit configurations, there are basic circuit variations which result in different reference-voltage polarities, different connection points for the amplifier plate-load resistor (s), various methods used to obtain voltage comparison, and in the case of a pentode d-c amplifier, various connection points for the screen-dropping resistor. These and other typical circuit variations will be discussed in connection with the various types of electronic voltage-regulator circuits described in this section of the handbook.

D-C REGULATOR USING PENTODE AMPLIFIER.

APPLICATION.

The d-c regulator with series tube, pentode amplifier, and gas-tube voltage reference is used in certain electronic equipment power-supply circuits to obtain nearly constant output voltage(s).

CHARACTERISTICS.

Regulated output voltage to load is nearly constant, even though changes in input voltage or changes in load current occur.

Voltage-divider principle employed, using variable resistance (electron tube) in series with load resistance; series electron tube may be a triode, a triode-connected pentode or a pentode with separate screen voltage supply.

Uses pentode amplifier circuit to control series electron tube.

Uses gas-tube regulator circuit as reference-voltage source.

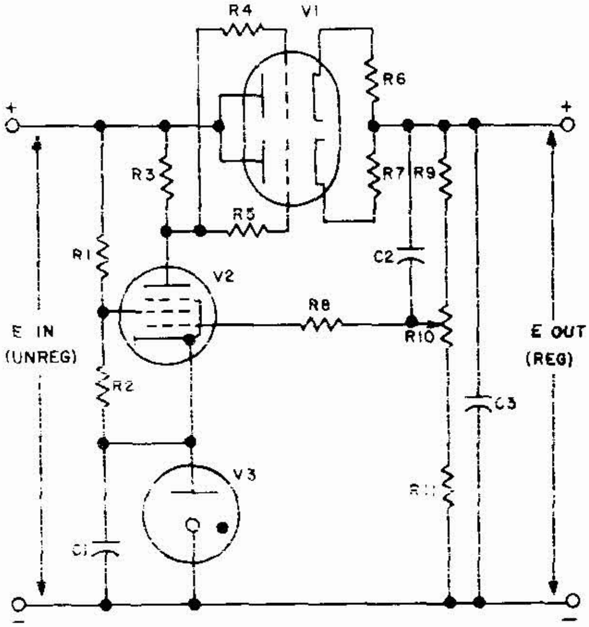
Variation in basic circuit permits positive (plate and screen) or negative (bias) supply voltages to be regulated.

CIRCUIT ANALYSIS.

General. The d-c regulator with triode series tube, single-pentode amplifier, and gas-tube voltage reference is capable of providing very stable output-voltage regulation. The high amplification obtained from the pentode amplifier stage enables the circuit to have good sensitivity to small output-voltage variations. In this type of voltage regulator, regulation is accomplished by allowing the cathode-to-plate resistance of an electron tube, in series with the output of a power supply, to function as a variable resistance, and thus provide the voltage drop necessary to compensate for any change in output voltage. Voltage regulation which is better than 1 percent can be obtained with this type of regulator, depending upon circuit design.

Typical regulated output voltages obtained with this regulator circuit are 150, 250, and 300 volts, dc.

Circuit Operation. A typical voltage regulator circuit using a pentode amplifier and gas-tube voltage reference is illustrated in the accompanying circuit schematic. Electron tube V1 is a twin triode used as the series regulator tube; V2 is a pentode used as a d-c amplifier; V3 is a cold-cathode, gas-filled regulator tube used to provide a reference voltage for operation of the regulator-amplifier circuit. Resistors R1 and R2 are voltage-dropping resistors connected in series with regulator tube V3 across the input circuit. In addition, they function as a voltage divider to provide d-c potential for the screen grid of V2. C1, connected in parallel with regulator tube V3, is a bypass capacitor which provides a low-impedance path at the power-supply ripple frequency (usually 120 cps), to reduce the possibility of degeneration in the cathode circuit of V2.



Typical Voltage Regulator Circuit Using Pentode Amplifier and Gas-Tube Voltage Reference

The value of capacitor C1 is usually a compromise between a value which offers low impedance to the power-supply ripple frequency (usually 120 cycles) and a value which is not so large as to affect normal operation of the regulator tube, V3. Capacitor C2 couples the full value of ripple voltage from the output of the regulator circuit; if C2 were not used, only a portion of the ripple voltage would be applied to the grid of V2, as determined by the voltage-divider action of R9, R10, and R11. The value of this capacitor is chosen to be just large enough to provide satisfactory ripple suppression. If the value of C2 is made too large, the response time of the regulator circuit to normal d-c output-voltage variations will be affected; a value of from 0.01 to 0.1 μf is typical in most regulator-amplifier circuits. Capacitor C3 is connected across the output terminals to lower the output impedance of the regulator circuit; the value of this capacitor depends upon circuit design, but is usually 2 μf or larger. Resistor R3 is the plate-load resistor for the pentode amplifier, V2. Resistors R4 and R5, in the grid circuits of V1, are parasitic oscillation suppressors; they are of equal value, generally between 270 and 1000 ohms. Resistors R6 and R7, in the cathode circuits of V1, are included for the purpose of equalizing the current flow in the parallel triode sections; these equalizing resistors are of equal value, generally between 10 and 47 ohms, depending upon circuit design. Resistor R8, in the control-grid circuit of V2, is a parasitic oscillation suppressor. Resistors R9, R10, and R11 form a voltage divider across the output of the regulator circuit, and are in parallel with the resistance of the load; resistor R10 is adjustable, and is used to set the output voltage to the desired value the circuit is to maintain.

Electron tubes V1 and V2 are indirectly heated, cathode-type tubes; V1 normally has a high heater-to-cathode voltage rating, while V2 has a heater-to-cathode voltage rating which is typical for receiving-type tubes. Because of the heater-to-cathode breakdown voltage limitations imposed by the tubes themselves, it is usually necessary to isolate the filament circuits from each other and to supply the filament (heater) voltages from independent sources.

When the unregulated voltage, E_{in}, is first applied to the input of the regulator circuit, voltage is applied to regulator tube V3 through resistors R1 and R2, in series; V3 ionizes and begins to conduct, thus establishing a reference voltage at the cathode of V2. The action which occurs is the same as that previously described under **Gas-Tube Regulator Circuit,** in Section 5, Part A, of the handbook. The voltage divider formed by resistors R1 and R2 establishes the voltage applied to the screen grid of V2. Regardless of the value of d-c voltage applied to the input of the regulator circuit, the voltage at the cathode of V2 will be held constant by the action of V3 for use as a reference voltage; however, the voltage at the screen grid of V2 is subject to change if the input voltage changes. This screen-circuit configuration increases the gain of the amplifier stage and also the regulator-amplifier sensitivity to either input or output voltage changes.

As previously mentioned, this regulator circuit is based upon the voltage-divider principle of using a variable resistance in the form of electron tube V1 in series with the load resistance. The regulated output voltage, e_{out}, appears across the voltage divider formed by series resistors R9, R10, and R11, which are connected across the output of the regulator circuit and in parallel with the load. The total resistance of these series resistors in parallel with the load resistance constitutes one part of the resistance in the series voltage-divider arrangement, which includes the variable cathode-to-plate resistance of V1; the currents which pass through the parallel branches (series resistors and load resistance) combine, and this total current passes through the series regulator tube, V1. When the cathode-to-plate resistance of V1 is controlled to vary the voltage drop across V1, the output voltage developed across the load can be regulated and maintained at a constant value.

The voltage appearing at the plate of V2 is dropped from the input to the regulator circuit through plate-load resistor R3 and is applied to the control grids of V1. The amount of current through R3 and the resulting value of voltage at the plate of V2 are determined by the bias on the control grid of V2. The voltage applied to the grid of V2 is obtained from the voltage divider circuit composed of R9, R10, and R11; the exact value of voltage applied to the grid of V2 is determined by the setting of R10. Since the potential at the cathode of V2 is maintained at a constant positive value by the action of regulator tube V3, adjustable resistor R10 is set to the point where the bias applied to the grid of V2 permits a predetermined value of current to be drawn by V2. When V2 is conducting, the voltage drop through plate-load resistor R3 develops a voltage at the grid of V1 which is less than either the plate or cathode voltage of V1; the difference in voltage between the cathode of V1 and the plate of V2 is the operating bias for V1. Thus, the setting of resistor R10 determines the current through V2, establishes the bias for V1, and initially determines the effective internal resistance of V1 to obtain the desired output voltage from the regulator circuit.

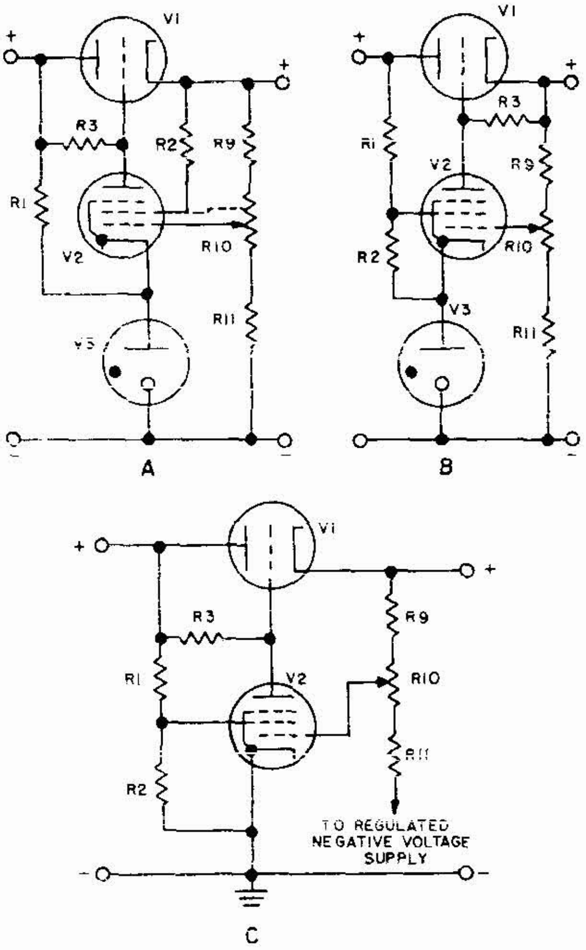
Assume that the regulated output voltage, E_{out}, attempts to increase, either because of an increase in the input voltage to the regulator circuit or because of a decrease in the load current. Through the voltage-divider action of resistors R9, R10, and R11, a slightly higher positive voltage now appears across R10 and R11. This results in an increase in the positive voltage applied to the grid of V2 and a corresponding decrease in the bias voltage between the cathode and grid. (The cathode voltage of V2 remains constant because of the action of regulator tube V3.) As a result of the decreased bias, V2 now conducts more current, and this additional current flow through plate-load resistor R3 results in a greater voltage drop across R3; thus, the voltage at the plate of V2 decreases and causes the difference in voltage between the cathode of V1 and the plate of V2 to increase. This difference in voltage between the cathode of V1 and the plate of V2 is the operating bias for V1; thus, as a result of this voltage increase, the effective internal resistance of V1 increases. When the internal resistance of V1 increases, less load current flows through V1, the voltage drop across V1 increases, and the output voltage of the regulator circuit decreases to its original value.

An action similar to that just described occurs when the regulated output voltage, E_{out}, attempts to decrease. Through the voltage-divider action of resistors R9, R10, and R11, the bias voltage between the cathode and grid of V2 is increased, since a slightly lower positive potential now exists across R10 and R11. As a result of the increased bias, V2 now conducts less current, and this decreased current flow through plate-load resistor R3 causes a smaller voltage drop to occur across R3; thus, the voltage at the plate of V2 increases and causes the difference in voltage between the cathode of V1 and the plate of V2 to decrease. This difference in voltage between the cathode of V1 and the plate of V2 is the operating bias for V1; thus, as a result of this voltage decrease, the effective internal resistance of V1 decreases. When the internal resistance of V1 decreases, more load current flows through V1, the voltage drop across V1 decreases, and the output voltage of the regulator circuit increases to its original value.

The actions described in the preceding paragraphs are practically instantaneous; consequently, the output voltage (E_{out}) remains practically constant. Since all of the load current must pass through the series regulator tube, V1, the tube(s) must be capable of passing considerable current. In some circuit applications where the load current requirements exceed the capabilities of a single tube, two or more identical tubes are connected in parallel (as the sections of twin-triode V1 have been paralleled) in order to obtain suitable regulation characteristics and current-handling capability.

The output of the regulator circuit is coupled to the grid of the pentode amplifier tube, V2, through coupling capacitor C2. Any ripple component present in the output voltage is amplified by V2, and, since the circuit is basically a negative feedback circuit, the ripple component is suppressed. Also, since the screen-grid voltage for V2 is obtained from the unregulated input voltage to the regulator circuit, the sensitivity of the amplifier to voltage changes is increased. As a result, the regulator circuit is sensitive to any voltage changes and is very effective in removing any fundamental ripple-frequency component which is present in the unregulated voltage supplied to the input of the regulator circuit.

As previously mentioned in this section, there are several circuit variations possible for the series regulator tube, V1. These variations in the series regulator circuit include the use of a triode (a twin-triode is shown in the schematic), a triode-connected pentode, and a pentode with separate screen-voltage supply. Also, there are several variations in the regulator-amplifier circuit which are commonly employed in electronic regulators. For example, the screen-grid voltage for V2 may be obtained through a separate screen dropping resistor from the cathode circuit of V1, or from a tap placed on the bleeder resistance formed by resistors R9, R10, and R11; this is shown in part A of the accompanying illustration. In some cases the screen voltage is obtained from a separate regulated-voltage source. Another circuit variation, shown in part B of the illustration, is connection of the plate-load resistor, R3, to the cathode circuit of V1 instead of to the plate circuit (as shown in the schematic); in this case, the voltage drop developed across plate-load resistor R3 is the bias voltage for V1. Still another circuit variation is obtaining the voltage for operation of regulator tube V3 through a separate series resistor connected to the cathode circuit of V1. An alternative method of obtaining the reference voltage (See part C) is to ground the cathode of V2 and connect resistor R11 of the voltage divider (R9, R10, and R11) to a regulated negative-voltage source. Although there are many minor variations in the regulator-amplifier circuit configuration, the function of the regulator circuit remains the same, that is, to supply a regulated output voltage to the load which is independent of variations in input voltage or changes in load current.



Typical Regulator-Amplifier Circuits (Showing Variations)

FAILURE ANALYSIS.

General. The voltage-regulator circuit includes several parts which are rather critical and directly affect operation of the regulator circuit. For this reason, resistors R9, R10, and R11, and perhaps resistors R1 and R2, are normally close-tolerance resistors with good temperature stability characteristics. If for any reason these particular resistors should change in value, the operation of the circuit will be impaired.

Since the regulator circuit attemps to hold the output voltage constant, it is usually good practice to determine whether the load current is within tolerance before suspecting trouble within the regulator circuit. A load-current measurement may be made by inserting a milliammeter (having a suitable range) in series with the output of the regulator circuit. Also, a voltage measurement should be made at the input to the regulator circuit to determine whether the unregulated voltage output from the power supply (and filter circuit) is within tolerance.

No Output. In the voltage-regulator circuit using a pentode amplifier, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage applied to series regulator tube V1, the lack of applied d-c voltage (from the associated power supply and filter circuit), or a shorted load circuit (including output capacitor C3).

A visual check of the glass-envelope series-regulator tube, V1, should be made to determine whether the filament(s) is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of voltage at the tube socket should be determined by measurement.

The d-c voltage applied to the regulator circuit should be measured at the input (plate of V1) to determine whether it is present and of the correct value, since the lack of input voltage from the associated power supply and filter circuit causes a lack of output voltage.

With the d-c voltage removed from the input to the circuit, resistance measurements can be made across the load (resistors R9, R10, and R11) to determine whether the load circuit, including capacitor C3, is shorted. (The resistance measured across the load circuit will normally measure something less than the total value of series resistors R9, R10, and R11, depending upon the load circuit design.)

High Output. The high-output condition is usually caused by a decrease in operating bias for the series regulator tube, V1, which, in turn, causes the tube to decrease its internal resistance and permits the regulator output voltage to rise above normal; therefore, any defects in the regulator-amplifier circuit which can cause a decrease in the operating bias for V1 are to be suspected.

Voltage measurements should be made at the socket of V1 to determine whether bias (cathode-to-grid) is present. The series regulator tube, V1, may be checked by substitution of a known good tube to determine whether the tube is defective (grid-to-cathode short, etc).

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for operation of the regulator-amplifier circuit, should be made to determine whether the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage is above normal, the tube may be defective; a tube known to be good may be substituted to check for proper operation of the circuit. If the voltage measured across V3 is below normal, it is likely that resistor R1 or R2 is open or possibly the d-c amplifier tube, V2, is not conducting.

A visual check of amplifier tube V2 should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of voltage at the tube socket should be determined by measurement. The grid voltage applied to V2 should be measured to determine whether the tube is improperly biased and causing the operating bias on V1 to decrease. Assuming that V3 is conducting normally to provide a reference voltage, if the voltage at the grid of V2 is below normal, is is possible that resistors R9 and R11 have changed in value or that resistor R10 is not set properly; however, if no voltage is present at the grid of V2, the tube will be biased to cutoff and V1 will conduct heavily as a result of decreased operating bias. In this case, it is likely that either resistor R9 or a portion of R10 (connected to R9) is open. If amplifier tube V2 has low emission, the voltage drop across plate-load resistor R3 will be below normal; therefore, a known good tube should be substituted and operation of the circuit observed to determine whether V2 is the cause of the trouble.

Low Output. The low-output condition is usually caused by an increase in operating bias for the series regulator tube, V1, which, in turn, causes the tube to increase its internal resistanc[illegible] and permits the regulator output voltage to fall below nor[illegible] therefore, any defects in the regulator-amplifier circuit w[illegible] can cause an increase in the operating bias for V1 are [illegible] be suspected.

In the twin-triode series regulator tube, trouble in one section (such as low cathode emission or an open tube element) will cause a reduction in output. The tube may be checked by substitution of a known good tube to determine whether the tube is defective. Voltage measurements should be made at the socket of V1 to determine whether the bias (cathode-to-grid) is excessive. The equalizing resistors, R6 and R7, in the cathode circuits of V1 should be measured to determine that neither one is open, that they have not increased in value, and that they are of equal resistance.

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for operation of the regulator-amplifier circuit, should be made to determine that the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage measured across V3 is below normal, or if no voltage is present, it is likely that capacitor C1 is either leaky or shorted.

The grid voltage applied to V2 should be measured to determine whether the tube is improperly biased, thus causing the operating bias on V1 to increase. Assuming that V3 is conducting normally to provide a reference voltage, if the voltage at the grid of V2 is above normal, it is possible that resistors R9 and R11 have changed in value or that resistor R10 is not set properly; however, if a high voltage is present at the grid of V2, the tube will conduct heavily and V1 will conduct less as a result of an increase in operating bias. In this case, it is likely that coupling capacitor C2 is either leaky or shorted, or that either resistor R11 or a portion of R10 (connected to R11) is open. Also, if amplifier tube V2 is shorted and conducting heavily, the voltage drop across plate-load resistor R3 will be excessive; therefore, a known good tube should be substituted and operation of the circuit observed to determine whether V2 is the cause of trouble.

As mentioned previously, excessive load current can cause the output voltage to be low, especially if the load current exceeds the maximum rating of series regulator tube V1 (resulting in excessive voltage drop across V1) or if the load current exceeds the rating of the power supply (resulting in a decrease in the applied voltage). For these reasons, output capacitor C3 should be checked to determine whether it is satisfactory; a leaky output capacitor could result in reduced output voltage, although the regulator amplifier circuit may be functioning normally but is unable to compensate for the decrease in output.

Poor Regulation Characteristics. Voltage instability, slow response, etc, are frequently caused by weak or unbalanced triode sections in series regulator V1, unbalanced cathode resistors R6 and R7, or a defective d-c amplifier, V2. The gain of the d-c amplifier stage is determined primarily by amplifier tube V2 and its applied voltages; therefore, the condition of V2 and its applied voltages are important factors governing satisfactory operation of the regulator circuit.

D-C REGULATOR USING CASCODE TWIN-TRIODE AMPLIFIER.

APPLICATION.

The d-c regulator using a cascode twin-triode amplifier is employed in certain electronic equipment power supply circuits to obtain nearly constant output voltage (or voltages) despite variations of input voltage or output load current.

CHARACTERISTICS.

Regulated output voltage to load is nearly constant, even though changes in input voltage or changes in load current occur.

Voltage-divider principle employed, using variable resistance (electron tube) in series with load resistance; series electron tube may be a triode, a triode-connected pentode, or a pentode with separate screen-voltage supply.

Uses cascode twin-triode d-c amplifier circuit to control series electron tube.

Uses gas-tube regulator circuit as reference-voltage source.

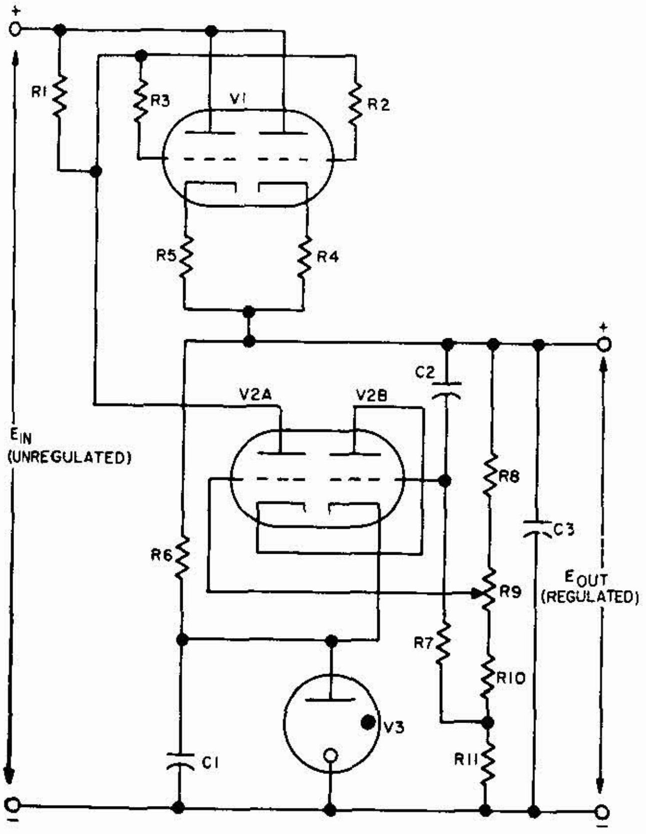
Variation in basic circuit permits positive (plate and screen) or negative (bias) supply voltage to be regulated.

CIRCUIT ANALYSIS.

General. The d-c regulator with twin-triode series regulator tube, *cascode twin-triode amplifier,* and gas-filled voltage reference tube is capable of providing very stable output voltage regulation. The term "regulation" as used here means the maintenance of a nearly constant output voltage despite changes in the input voltage or the load current. The variation in output voltage that normally result from component aging, changes in operational environment, etc, are usually considered in the design of the circuit, and are compensated for by using close-tolerance (on the order of 1, 2, or 5 percent) components whose values do no deviate from the nominal by more than the strict limits specified.

In this type of voltage regulator, regulation is accomplished by allowing the cathode-to-plate conduction resistance of an electron tube, in series with the output of a power supply, to function as a variable resistance, and thus provide the voltage drop necessary to compensate for any change in output voltage. That is, the change in output voltage is compared and amplified in the regulator-amplifier circuit, and applied as a bias voltage to the grid of the series regulator tube, thereby varying the conduction resistance of this tube. The varying conduction resistance of the regulator tube, in turn, varies the load current drawn by the series circuit and the voltage drop across the regulator tube; in so doing, the regulator tube absorbs the change in the output voltage. Voltage regulation of approximately 1 percent can be obtained with this type of electronic d-c regulator, depending on the circuit design.

Circuit Operation. A typical d-c regulator using a cascode twin-triode amplifier is illustrated in the accompanying circuit schematic. Electron tube V1 is a *parallel-connected twin-triode* used as the series regulator tube. (In applications where the current drain exceeds the current-handling capability of a single series regulator tube, two or more tubes of the same type may be connected in parallel.) Electron tube V2 is another twin-triode, in a cascode d-c amplifier circuit configuration, used as the regulator amplifier. Tube V3 is a cold-cathode, gas-filled tube used to provide a reference voltage for operation of the regulator-amplifier circuit. The use of the gas-filled regulator tube in this application is satisfactory as a reliable reference since there are no excessive currents in that branch of the circuit. Electron tubes V1 and V2 are indirectly heated, cathode-type tubes; V1 normally has a high heater-to-cathode voltage rating, while V2 has a heater-to-cathode voltage rating which is typical for receiving-type tubes. Because of the heater-to-cathode breakdown voltage limitations imposed by the tubes themselves, it is usually necessary to isolate the filament circuits from each other and to supply the filament (heater) voltages from independent sources.



D-C Regulator Using Cascode Twin-Triode Amplifier

Resistors R2 and R3, in the grid circuits of V1, are parasitic oscillation suppressors; they are of equal value, generally between 270 and 1000 ohms. Resistors R4 and R5, in the cathode circuits of V1, are included for the purpose of equalizing the current flow in the parallel-connected triode sections; these resistors are of equal value, generally between 10 and 47 ohms, depending upon the circuit design. Resistor R6, connected in series with reference tube V3 across the output circuit, serves to apply the full output voltage of the regulator to V3, to ensure a satisfactory striking potential and also to act as a current-limiting resistor once the tube is ionized. Capacitor C1, connected in parallel with reference tube V3, is a bypass capacitor which provides a low-impedance path at the power-supply ripple frequency (usually 120 cps), to reduce the possibility of degeneration in the cathode circuit of V2B. The value of capacitor C1 is usually a compromise between a value which offers low impedance to the power-supply ripple frequency and a value which is not so large as to affect the normal operation of the reference tube, V3.

Capacitor C2 couples the full value of ripple voltage from the output of the regulator circuit to the grid of V2B; if capacitor C2 were not used, only a portion of the ripple voltage would be applied to the grid of C2B, as determined by the voltage-divider action of R8, R9, R10, and R11. The value of capacitor C2 is chosen so that it is just large enough to provide satisfactory ripple suppression. If the value of capacitor C2 were made too large, the response time of the regulator circuit to normal d-c output-voltage variations would be affected; a value of from 0.01 to 0.1 microfarad is typical in most regulator-amplifier circuits. Capacitor C3 is connected across the output terminals to lower the output impedance of the regulator circuit; the value of this capacitor depends upon the circuit design, but is usually 2 microfarads or larger. Resistors R8, R9, R10, and R11 form a voltage divider across the output of the regulator circuit, and are in parallel with the resistance of the load. Resistor R9 is adjustable, and is used to set the output voltage to the desired value the circuit is to maintain.

The cascode configuration of the regulator-amplifer circuit, V2, can be considered as two triode amplifiers directly connected (direct-coupled) in series. The action of this circuit is similar to that of a pentode in that the isolating effect of the screen grid on the plate is achieved, with the advantage that no screen-voltage supply is required. The cascode circuit is used when the gain required of the regulator amplifier is too high for a single triode, yet it is desired to eliminate the pentode screen-voltage supply. However, in order to achieve adequate gain, the cascode circuit requires a large-value plate-load resistor (R1, on the order of 2.2 megohms); this requirement causes the frequency response to be reduced and thereby restricts the area of application of the circuit. The effects of poor frequency response can be reduced somewhat by using a relatively large-value capacitor (about 5 microfarads) for C3.

The two triodes of the cascode twin-triode regulator amplifier are the input section, which is the right-hand tube (V2B), and the output section, which is the left-hand tube (V2A). The cathode of the input section is at a positive potential determined by the reference tube, V3. The control grid of the input section is returned through resistor R7 to the voltage divider at the junction of resistors R10 and R11. The voltage at the top of resistor R11 is slightly less positive than the operating potential of reference tube V3; hence, a bias voltage of only a few volts is established between the control grid and cathode of V2B. The plate of V2B is directly connected to the cathode of the output section, V2A. The control grid of V2A is returned to the wiper arm of voltage-divider variable resistor R9. The value of grid voltage of V2A, as determined by the setting of resistor R9, is of sufficient amplitude to keep the grid of V2B from drawing appreciable grid current.

The operating range of V2A plate voltage, which is applied through plate-load resistor R1, is far enough above its grid voltage so that the current in the grid circuit of V2A does not approach or become comparable with the V2A plate current.

As previously mentioned, the operation of this regulator circuit is based upon the voltage-divider principle of using a variable resistance in the form of electron tube V1 in series with the load resistance. The regulated ouput voltage, E_{out}, appears across the voltage divider formed by resistors R8, R9, R10, and R11, which are connected across the output of the regulator circuit and in parallel with the load. The total resistance of these voltage-divider resistors in parallel with the load resistance constitutes one part of the resistance in the regulator series voltage-divider arrangement, which includes the variable cathode-to-plate resistance of series regulator tube V1. The currents which pass through the parallel branches (voltage-divider resistors and load resistance) combine, and this total current passes through series regulator tube V1. When the cathode-to-plate reference of V1 is controlled to vary the voltage drop across this tube, the output voltage developed across the load can be regulated and maintained at a constant value.

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In order to understand how the d-c regulator circuit operates under varying-load conditions, it is necessary to examine first the static voltage distribution under normal-load conditions. The cathode of series regulator tube V1 is held positive with respect to ground by the output voltage, E_{out}, while the grid is held somewhat less positive by the action of regulator amplifier V2. The difference between these two voltages is the bias voltage for V1, which is at the proper value for series regulator tube V1 to have the required amount of cathode-to-plate resistance to produce the correct output voltage. The output voltage is applied to reference tube V3 through resistor R6, causing V3 to ionize and conduct, thereby establishing a reference voltage at the cathode of the input section, V2B, of the cascode regulator amplifier. (The action of the gas-filled reference tube, V3, is the same as that previously described under Gas-Tube Regulator Circuit earlier in Section 5 of this Handbook.) Regardless of the value of d-c voltage applied to the input, E_{in}, of the regulator circuit, the voltage at the cathode of V2B will be held constant (by the action of V3) for use as a reference voltage.

Cascode regulator-amplifier V2, in essence a two-stage series-connected triode amplifier, uses the plate load of the input section, V2B, as the cathode input impedance of the output section, V2A. Thus, the signal to the input stage is applied between the control grid and ground, while the output of this same stage is the input to the direct-coupled output stage, and is applied between the cathode and ground. The output section, V2A, has a fixed voltage on its grid, obtained from adjustable resistor R9 of the voltage-divider network. This bias voltage limits the excursions of the V2A cathode voltage, which is also the plate voltage of the input section, V2B. The grid voltage for V2B is obtained from voltage-divider resistor R11. Since the potential at the cathode of V2B is maintained at a constant positive value by the action of reference tube V3, the bias on V2B and V2A, as determined by voltage-divider resistors R11 and R9, respectively, is such that it permits a pre-determined value of current to be drawn by V2. The plate voltage of V2A is obtained from the unregulated input, E_{in}, and applied to the regulator amplifier through plate-load resistor R1. When V2 is conducting, the voltage drop across plate-load resistor R1 develops a voltage at the plate of V2A; this voltage is coupled to the grids of V1. The voltage at the grids of V1 is less than the voltage at the cathodes of V1; hence, the operating bias for V1 is established. The setting of resistor R9, therefore, determines the current through V2A, establishes the bias for V1, and initially determines the effective internal resistance of V1 to obtain the desired output voltage, E_{out}, from the regulator circuit.

Assume, now, that the regulated output voltage, E_{out}, attempts to increase, either because of an increase in the input voltage, E_{in}, to the regulator circuit or because of a decrease in the load current. Through the voltage-divider action of resistors R8, R9, R10, and R11, a slightly higher positive voltage now appears across resistors R9, R10, and R11. This results in an increase in the positive voltage applied to the grids of V2A and V2B, and a corresponding decrease in the bias voltage of this stage. (The cathode voltage of V2B remains constant because of the action of reference tube V3.) As a result of the decreased bias, V2 now conducts more current, and this additional current flow through plate-load resistor R1 results in a greater voltage drop across resistor R1. Thus, the voltage at the plate of V2A, which is coupled to the grids of V1, decreases and causes the difference in voltage between the grids and cathodes of V1 to increase. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. As a result of the bias voltage increase, the effective internal resistance of V1 increases. When the internal resistance of V1 increases, less load current flows through V1, the voltage drop across V1 increases, and the output voltage, E_{out}, of the regulator circuit decreases to its original value.

An action similar to that just described occurs when the regulated output voltage, E_{out}, attempts to decrease. Through the voltage-divider action of resistors R8, R9, R10, and R11, the bias voltage on the grids of V2A and V2B is increased, since a slightly lower positive potential now exists across resistors R9, R10, and R11. As a result of the increased bias, V2 now conducts less current, and this decreased current flow through plate-load resistor R1 causes a smaller voltage drop to occur across resistor R1. Thus, the voltage at the plate of V2A (and the grids of V1) increases and causes the difference in voltage between the grids and cathodes of V1 to decrease. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. As a result of the bias voltage decrease, the effective internal resistance of V1 decreases. When the internal resistance of V1 decreases, more load current flows through V1, the voltage drop across V1 decreases, and the output voltage of the regulator circuit increases to its original value.

The actions described in the preceding paragraphs are practically instantaneous; consequently, the output voltage, E_{out}, remains practically constant. Since all of the load current must pass through the series control tube, V1, the tube must be capable of passing considerable current. In some circuit applications where the load current requirements exceed the capabilities of a single tube, two or more identical tubes are connected in parallel (as the sections of twin-triode V1 have been paralleled) in order to obtain suitable regulation characteristics and current handling capability.

The output of the regulator circuit is coupled to the grid of the input section of the cascode twin-triode regulator-amplifier tube, V2B, through coupling capacitor C2. Any ripple component present in the output voltage is amplified in the regulator amplifier, and, since the circuit is basically a negative-feedback circuit, the ripple component is suppressed. As a result, the regulator circuit is sensitive to any voltage changes and is very effective in removing any fundamental ripple-frequency component which is present in the regulated voltage output. Although there are many minor variations in the regulator-amplifier circuit configuration, the function of the regulator circuit remains the same, that is, to supply a regulated output voltage to the load which is independent of variations in input voltage or changes in load current.

FAILURE ANALYSIS.

General. The d-c regulator using a cascode twin-triode amplifier includes several components which are rather critical and directly affect the operation of the regulator circuit. For this reason, voltage-divider resistors R8, R9, and R10, and R11, as well as resistor R6 are normally close-tolerance (on the order of 1, 2, or 5 percent) resistors with good temperature stability characteristics. The operation of the circuit will be impaired if these resistors should change in value for any reason. Since the regulator circuit attempts to hold the output voltage constant, it is usually good practice to determine whether the load current is within tolerance before suspecting trouble within the regulator circuit proper. A load-current measurement may be made by inserting a milliammeter (having a suitable range) in series with the output of the regulator circuit. Also, a voltage measurement should be made at the input to the regulator circuit to determine whether the unregulated voltage output from the power supply (and filter circuit) is within tolerance.

No Output. In the d-c regulator using a cascode twin-triode amplifier, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage applied to series regulator tube V1, the lack of applied d-c voltage (from the associated power supply and filter circuit), or a short-circuited load (including output capacitor C3). A visual check of the glass-envelope series regulator tube, V1, should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The d-c voltage applied to the regulator circuit should be measured at the input (plate of V1) to determine whether it is present and of the correct value, since the lack of input voltage from the associated power supply and filter circuit will cause a lack of output voltage. With the d-c voltage removed from the input to the circuit, resistance measurements can be made across the load (voltage-divider resistors R8, R9, R10, and R11) to determine whether the load circuit, including capacitor C3, is shorted. (The resistance measured across the load circuit will normally measure something less than the total value of series-connected resistors R8, R9, R10, and R11, depending upon the load circuit design.)

High Output. The high-output condition is usually caused by a decrease in operating bias for the series regulator tube, V1, which, in turn, causes the tube to decrease its internal resistance and permits the regulator output voltage to rise above normal. Therefore, any defects in the electronic regulator circuit which can cause a decrease in the operating bias for V1 should be suspected. Voltage measurements should be made at the socket of V1 to determine whether bias (cathode-to-grid) voltage is present. The series regulator tube, V1, may be checked by substitution of a tube known to be good to determine whether the tube is defective (grid-to-cathode short, etc).

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for the operation of the cascode twin-triode amplifier circuit, should be made to determine whether the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage is above normal, the tube may be defective; a tube known to be good may be substituted to check for proper operation of the reference-voltage circuit. If the voltage measured across V3 is below normal, it is likely that resistor R6 is open, or possibly the cascode regulator-amplifier stage, V2, is not conducting.

A visual check of regulator-amplifier tube V2 should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The bias voltages applied to V2 should be measured to determine whether the tube is improperly biased, causing the operating bias on V1 to decrease. Assuming that V3 is conducting normally to provide a reference voltage, if the voltages at the grids of V2 are below normal, and thus cause an increase in V2 bias, it is possible that voltage-divider resistor R8, R10, or R11 has changed in value; in addition, an improper setting of variable-resistor R9 will affect the bias voltage at the grid of V2A. However, if no voltage whatsoever is present at the grids of V2, the tube will be biased to cutoff and V1 will conduct heavily as a result of the decreased operating bias. In this case, it is likely that resistor R8, R9, or R10 is open. If regulator-amplifier tube V2 has low emission, the voltage drop across plate-load resistor R1 will be below normal; therefore, a tube known to be good should be substituted and operation of the circuit observed to determine whether tube V2 is the cause of the trouble.

Low Output. The low-output condition of the regulator is usually caused by an increase in operating bias *for the* series regulator tube, V1, which, in turn, causes the tube *to increase its internal resistance* and permits the regulator output voltage to fall below normal. Therefore, any defects in the electronic regulator circuit which can cause an increase in the operating bias for V1 should be suspected. Trouble in one section of V1 (such as low cathode emission or an open tube element) will cause a reduction in the output. The tube may be checked by *substitution of a tube known to be good to determine* whether the tube is defective. Voltage measurements should be made at the socket of V1 to determine whether the bias (cathode-to-grid) voltage is excessive. The equalizing resistors, R4 and R5, in the cathode circuits of V1 should be measured to determine that neither one is open, that they have not increased in value, and that they are of equal resistance.

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for operation of the cascode twin-triode regulator-amplifier circuit, V2, should be made to determine that the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage measured across V3 is below normal, or if no voltage is present, it is likely that capacitor C1 is either leaky or shorted.

The bias voltages applied to V2 should be measured to determine whether the tube is improperly biased, causing the operating bias on V1 to increase. Assuming that V3 is conducting normally to provide a reference voltage, if the voltages at the grids of V2 are above normal, it is possible that voltage-divider resistor R8, R10, or R11 has changed in value; in addition, an improper *setting of variable resistor* R9 will affect the bias voltage at the grid of V2A. However, if a high voltage is present at the grids of V2, the tube will conduct heavily and V1 will conduct less as a result of an increase in operating bias. In this case, it is likely that coupling capacitor C2 is either leaky or shorted, or that resistor R11 is open. Also, if regulator-amplifier tube V2 is shorted and conducting heavily, the voltage drop across plate-load resistor R1 will be excessive; therefore, a tube *known to be good should be substituted and operation of the* circuit observed to determine whether tube V2 is the cause of the trouble.

As mentioned previously, excessive load current can cause the output voltage to be low, especially if the load current exceeds the maximum rating of series regulator tube V1 (resulting in excessive voltage drop across V1) or if the load current *exceeds the rating of the power supply* (resulting in a decrease in the applied voltage). For these reasons, output capacitor C3 should be checked to determine whether it is satisfactory. A leaky output capacitor could result in reduced output voltage, although the regulator-amplifier circuit (V2) may be functioning normal but unable to compensate for the decrease in output.

Poor Regulation Characteristics. Voltage instability, slow response, etc, are frequently caused by weak or *unbalanced triode sections in series regulator tube* V1, unbalanced cathode resistors R4 and R5, or a defective *regulator-amplifier* V2. The gain of the regulator-amplifier stage is determined primarily by tube V2 and its applied voltages; therefore, the condition of V2 and its applied voltages are important factors governing satisfactory operation of the regulator circuit.

D-C REGULATOR USING CASCADE TWIN-TRIODE AMPLIFIER.

APPLICATION.

The d-c regulator using a cascade twin-triode amplifier is employed in certain electronic equipment power supply circuits to obtain nearly constant output voltage *(or voltages) despite variations* of input voltage or output load current.

CHARACTERISTICS.

Regulated output voltage to load is nearly constant, even though changes in input voltage or load current occur.

Voltage divider principle employed, using variable resistance (*electron tube*) *in series with load resistance;* series electron tube may be a triode, a triode-connected *pentode*, or a pentode with a separate screen-voltage supply.

Uses cascade twin-triode d-c amplifier circuit to control series electron tube.

Uses gas-tube regulator circuit as reference-voltage source.

Variation in basic circuit permits positive (plate or *screen*) or *negative (bias)* supply voltages to be regulated.

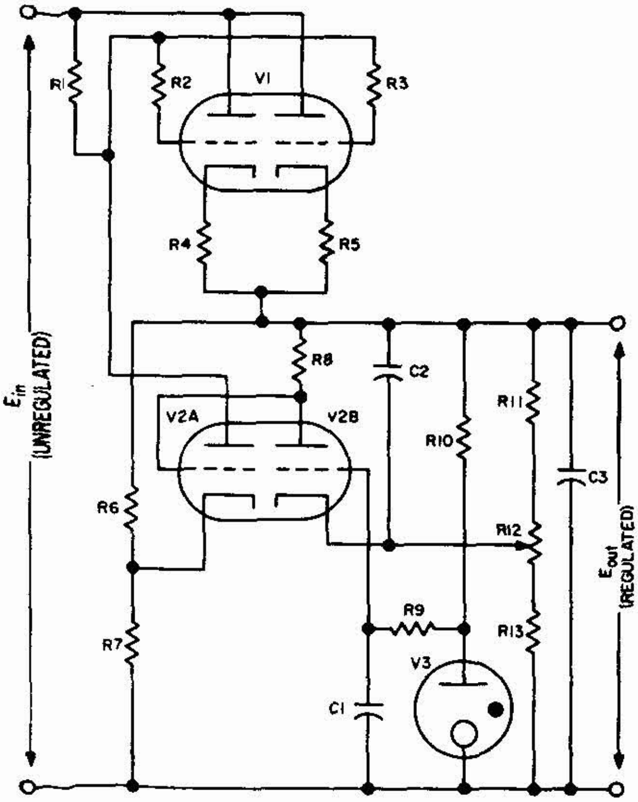
CIRCUIT ANALYSIS.

General. The d-c regulator with twin-triode series regulator tube, cascade twin-triode amplifier, and gas-filled voltage reference tube is capable of providing very stable output voltage regulation. In this discussion the term "regulation" means *the maintenance of a nearly constant* output voltage, regardless of changes in the input voltage or the load current. The variations in output voltage that normally result from component aging, changes in operational environment, etc, are usually considered in the design of the circuit, and are compensated for by using close-tolerance (on the order of 1, 2, or 5 percent) components whose values *do not deviate from the nominal by more than* the strict limits specified.

In this type of voltage regulator, regulation is accomplished by allowing the cathode-to-plate conduction resistance of an electron tube, in series with the output of a power supply, to function as a variable resistance, and thus provide the voltage drop necessary to compensate for any change in output voltage. That is, the change in output voltage is compared and amplified in the cascade twin-triode *amplifier circuit, and applied as a bias voltage to the* grid of the series regulator tube, thereby varying the conduction resistance of this tube. The varying conduction resistance of the regulator tube, in turn, varies the load current drawn by the series circuit and the voltage drop across the series regulator tube; in so doing, the series regulator tube absorbs the change in the output voltage. Voltage regulation on the order of 1 percent can be obtained with this type of d-c regulator, depending on the circuit design.

Circuit Operation. A typical d-c regulator circuit using a cascade twin-triode amplifier is illustrated in the accompanying circuit schematic. Electron tube V1 is a parallel-connected twin triode used as the series regulator tube. (In applications where the current drain exceeds the current-handling capability of a single series regulator tube, two or more tubes of the same type may be connected in parallel.) Electron tube V2 is another twin triode, in a cascade d-c amplifier circuit configuration, used as the regulator amplifier. Tube V3 is a cold-cathode, gas-filled regulator tube used to provide a reference voltage for operation of the regulator-amplifier circuit. The use of the gas-filled regulator tube in this application is satisfactory as a reliable reference since there are no excessive currents in that branch of the circuit. Electron tubes V1 and V2 are indirectly heated, cathode-type tubes; V1 normally has a high heater-to-cathode voltage rating, while VZ has a heater-to-cathode voltage rating which is typical for receiving-type tubes. Because of the heater-to-cathode breakdown voltage limitations imposed by the tubes themselves, it is usually necessary to isolate the filament circuits from each other and to supply the filament (heater) voltages from independent sources.

Resistors R2 and R3, in the grid circuits of V1, are parasitic oscillation suppressors; they are of equal value, generally between 270 and 1000 ohms. Resistors R4 and R5, in the cathode circuits of V1, are included for the purpose of equalizing the current flow in the parallel-connected triode sections; these resistors are of equal value, generally between 10 and 47 ohms, depending upon the circuit design. Resistor R10, connected in series with reference tube V3 across the output circuit, serves to apply the full output voltage of the regulator to V3, to ensure a satisfactory striking potential and also to act as a current-limiting resistor once the tube is ionized. The choise of current is a compromise between shortened tube life at high currents and higher noise level at low currents. Resistor R9 returns the grid of V2B to the positive reference voltage; also, resistor R9, in conjunction with capacitor C1, forms a series R-C filter across V3 to suppress the transient noise generated by the gas tube and thereby prevent these undesirable signals from appearing on the grid of V2B. The value of capacitor C1 is usually a compromise between a value which offers low impedance to the transient noise and a valve which is not so large as to affect the normal operation of reference tube V3.



D-C Regulator Using Cascade Twin-Triode Amplifier

Capacitor C2 couples the full valve of the power supply ripple voltage (usually 120 cps) appearing in the output of the regulator to the cathode of V2B. If capacitor C2 were not used, only a portion of the ripple voltage would be applied to the cathode of V2B, as determined by the voltage-divider action of resistors R11, R12, and R13. The value of capacitor C2 is chosen so that it is just large enough to provide satisfactory ripple suppression. If the value of capacitor C2 were made too large, the response time of the regulator circuit to normal d-c output voltage variations would be affected; a value of from 0.01 to 0.1 microfarad is typical in most regulator-amplifier circuits, although values to 2 microfarads may occasionally be used. Capacitor C3 is connected across the output terminals to lower the output impedance of the regulator circuit; the value of this capacitor depends upon the circuit design, but is usually 2 microfarads or larger. Resistors R11, R12, and R13 form a voltage divider across the output of the regulator circuit, and are in parallel with the resistance of the load. Resistor R12 is adjustable, and is used to set the output voltage to the desired value that the circuit is to maintain.

The cascade configuration of the regulator-amplifier circuit, V2, can be considered as two triode amplifiers that use direct coupling. In a direct-coupled (d-c) amplifier, operating plate voltage and current are usually established by the circuit design, and the grid bias is then adjusted to compensate for tube tolerance. Since, in order to function, the plate of a tube must have a positive voltage with respect to its cathode, and the grid of the next tube must have a negative voltage with respect to its cathode, the voltage-divider arrangements indicated in the diagram are required to obtain the necessary operating voltages for the cascade twin-triode direct-coupled amplifier, V2.

The two triodes of the cascade twin-triode amplifier are the input stage, which is the right-hand tube (V2B), and the output stage, which is the left-hand tube (V2A). The control grid of the input stage is at a positive potential determined by the reference tube, V3. The cathode of the input stage is returned to the wiper arm of voltage-divider variable resistor R12. *The cathode voltage of V2B, as determined* by the setting of resistor R12, is slightly more positive than the operating potential of reference tube V3; hence, a bias voltage of only a few volts is established between the control grid and cathode of V2B. Resistor R8 is the plate-load *resistor for the input stage,* V2B; since direct coupling is used from the plate of V2B to the grid of V2A, resistor R8 also serves as the grid-return resistor for the control grid circuit of the output stage, V2A. Thus, the plate voltage of V2B is also the grid voltage of V2A. The cathode of V2A is returned to the junction of resistors R6 and R7, which form a voltage divider across the regulator output, E_{out}. The V2A cathode voltage, which is the voltage developed across resistor R7, is slightly more positive than the voltage at the grid of V2A; hence, a bias voltage of only a few volts is established between the control grid and cathode of V2A. Plate voltage for V2A is obtained from the unregulated voltage input, E_{in}, through plate-load resistor R1.

As previously mentioned, the operation of this regulator circuit is based upon the voltage-divider principle of using a variable resistance in the form of electron tube V1 in series with the load resistance. The regulated output voltage, E_{out}, appears across the voltage dividers formed by resistors R11, R12, and R13, and resistors R6 and R7, which are connected across the output of the regulator circuit and in parallel with the load. The total resistance of these voltage-divider resistors in parallel with the load resistance constitutes one part of the resistance in the *regulator series voltage-divider arrangement, which includes* the variable cathode-to-plate resistance of series regulator tube V1. The currents which pass through the parallel branches (voltage-divider resistors and load resistance) combine, and this total current passes through series regulator tube V1. *When the cathode-to-plate resistance of* V1 is controlled to vary the voltage drop across this tube, the output voltage developed across the load can be regulated and maintained at a constant value.

In order to understand how the d-c regulator circuit *operates under varying-load conditions,* it is necessary to examine first the static voltage distribution under normal-load conditions. The cathode of series regulator tube V1 is held positive with respect to ground by the output voltage, E_{out}, while the grid is held somewhat less positive *by the action of regulator amplifier V2.* The difference between these two voltages is the bias voltage for V1, which is at the proper value for series regulator tube V1 to have the required amount of cathode-to-plate resistance to produce the correct output voltage. The output voltage is applied to reference tube V3 through resistor R10, causing V3 to ionize and conduct, thereby establishing a reference voltage at the grid of the input stage, V2B, of the cascade regulator amplifier. (The action of the gas-filled reference tube, V3, is the same as that previously described under Gas-Tube Regulator Circuit earlier in Section 5 of this Handbook.) Regardless of the value of the d-c voltage applied to the input, E_{in}, of the regulator circuit, the voltage at the grid of V2B will be held constant (by the action of V3) for use as a reference voltage.

Cascade regulator amplifier V2, in essence a two-stage series-connected triode amplifier, uses the plate load of the input stage, V2B, as the gride input impedance of the output stage, V2A. Thus, *the signal to the input stage is* applied between the cathode and ground; the output of this same stage, which is developed across resistor R8, is the input to the direct-coupled output stage, and is applied between the control grid and ground. The grid of V2B is *connected through resistor* R9 to the positive reference voltage established by V3, and the cathode of the same tube is at a potential slightly more positive than the reference voltage, since it is returned to the wiper arm of voltage-divider variable resistor R12; this arrangement establishes *the operating bias for* V2B. The plate of V2B is connected to the full voltage of the regulated output through resistor R8; because the plate of V2B is more positive than its cathode, and the proper bias is established, tube V2B conducts. When V2B plate current flows through resistor R8, a voltage is dropped across this resistor; this voltage is also the grid voltage of V2A, and is at a relatively high value.

A two-stage direct-coupled amplifier is usually designed so that approximately one-half of the available voltage of the regulated output, E_{out}, is used for the input stage. The plate of the output stage, V2A, of the two-stage configuration is connected through a suitable load resistor to the most positive point of the available voltage, which, in this regulator circuit, is through resistor R1 to the unregulated input, E_{in}. The cathode of the output stage, V2A, must be connected to a positive voltage point suitable for providing the proper biasing voltage and the proper plate-operating voltage. *This point is determined by the proper selection* of voltage-divider resistors R6 and R7 so that the voltage developed across resistor R7, which is the cathode-bias voltage of V2A, is slightly more positive than the voltage at the grid (which is determined by the voltage drop across resistor R8).

Although the cascade twin-triode regulator-amplifier circuit is a rather complex resistance network which must be adjusted carefully to obtain the proper plate, grid, and cathode voltages for both stages, it provides a rather high *gain and good frequency response; therefore,* it serves very well as the d-c amplifier in an electronic voltage regulator. That is, when regulator amplifier V2 is conducting, the voltage drop across V2A plate-load resistor R1 provides a voltage for the grids of series regulator tube V1; this voltage is less than either the plate or cathode voltage of V1. The difference in voltage between the cathode and grid of V1 is the operating bias for V1. Thus, the setting of resistor R12 determines the current through V2B, which, in turn, determines the bias of V2A. This bias controls the conduction of V2A hence the voltage drop across resistor R1, which establishes the bias for V1. It is this bias level that initially determines the effective internal resistance of V1 to obtain the desired output voltage, E_{out}, from the regulator circuit.

Assume, now, that the regulated output voltage, E_{out}, attempts to decrease, either because of a decrease in the input voltage to the regulator circuit or because of an increase in the load current. Through the voltage-divider action of resistors R11, R12, and R13, a slightly lower positive voltage now appears across R12, and R13. This results in a decrease in the positive voltage applied to the cathode of V2B and a corresponding decrease in the bias voltage between this cathode and the grid of V2B. (The grid voltage of V2B remains constant because of the action of reference tube V3.) As a result of the decreased bias, V2B now conducts more current, and this additional current flow through plate-load resistor R8 results in a greater voltage drop across R8; thus, the voltage at the plate of V2B decreases. Since the voltage at the plate of V2B is also the grid voltage of V2A, the bias on V2A now increases; this results from the fact that a negative-going grid signal in conjunction with a fixed voltage on the cathode causes the difference in potential between these two electrodes to become greater. The increased bias of V2A reduces the conduction through this tube and causes a decrease of plate current through plate-load resistor R1, thereby producing a smaller voltage drop across this resistor to cause a rise in V2A plate voltage. This positive-going voltage at the plate of V2A is coupled to the grids of V1 and causes the difference in potential between the grids and cathodes of V1 to decrease. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. Thus, as a result of this bias voltage decrease, the effective internal resistance of V1 decreases. When the internal resistance of V1 decreases, more load current flows through V1, the voltage drop across V1 decreases, and the output voltage of the regulator circuit increases to its original value.

An action similar to that just described occurs when the regulated output voltage, E_{out}, attempts to increase. Through the voltage-divider action of resistors R11, R12, and R13, the bias voltage between the cathode and grid of V2B is increased, since a slightly higher positive potential now exists across R12 and R13. As a result of the increased bias, V2B now conducts less current, and this decreased current flow through plate-load resistor R8 causes a smaller voltage drop to occur across R8; thus, the voltage at the plate of V2B increases, and this positive-going voltage causes the bias of V2A to decrease. With a decreased bias, V2A conducts more heavily and the increased plate current through plate-load resistor R1 produces a negative-going voltage at the plate of V2A. This negative-going signal is coupled to the grids of V1, causing the difference in potential between the grids and cathodes of V1 to increase. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. Thus, as a result of this bias voltage increase, the effective internal resistance of V1 increases. When the internal resistance of V1 increases, less load current flows through V1, the voltage drop across V1 increases, and the output voltage of the regulator circuit decreases to its original value.

The actions described in the preceding paragraphs are practically instantaneous; consequently, the output voltage, E_{out}, remains practically constant. Since all the load current must pass through the series regulator tube, V1, the tube must be capable of passing considerable current. In some circuit applications where the load current requirements exceed the capabilities of a single tube, two or more identical tubes are connected in parallel (as the sections of twin-triode V1 have been paralleled) in order to obtain suitable regulation characteristics and current-handling capability.

The output of the regulator circuit is coupled to the cathode of the input stage of the cascade twin-triode amplifier tube, V2, through coupling capacitor C2. Any ripple component present in the output voltage is amplified by V2, and, since the circuit is basically a negative feedback circuit, the ripple component is suppressed. As a result, the regulator circuit is sensitive to any voltage changes and is very effective in removing any fundamental ripple-frequency component which is present in the regulated voltage output. Although there are many minor variations in the regulator-amplifier circuit configuration, the function of the regulator circuit remains the same, that is, to supply a regulated output voltage to the load which is independent of variations in input voltage or changes in load current.

FAILURE ANALYSIS.

General. The d-c regulator using a cascade twin-triode amplifier includes several components which are rather critical and affect the operation of the regulator circuit. For this reason, voltage-divider resistors R11, R12, and R13, as well as resistors R6 and R7 are normally close-tolerance (on the order of 1, 2, or 5 percent) resistors with good temperature stability characteristics. If for any reason these particular resistors should change in value, the operation of the circuit will be impaired. Since the regulator circuit attempts to hold the output voltage constant, it is usually good practice to determine whether the load current is within tolerance before suspecting trouble within the regulator circuit proper. A load-current measurement may be made by inserting a milliammeter (having a suitable range) in series with the output of the regulator circuit. Also, a voltage measurement should be made at the input to the regulator circuit to determine whether the unregulated voltage output from the power supply (and filter circuit) is within tolerance.

No Output. In the d-c regulator using a cascade twin-triode amplifier, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage applied to series regulator tube V1, the lack of applied d-c voltage (from the associated power supply and filter circuit), or a shorted load circuit (including output capacitor C3.) A visual check of the glass-envelope series regulator tube, V1, should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The d-c voltage applied to the regulator circuit should be measured at the input (plate of V1) to determine whether it is present and of the correct value, since the lack of input voltage from the associated power supply and filter circuit will cause a lack of output voltage. With the d-c voltage removed from the input to the circuit, resistance measurements can be made across the load (voltage-divider resistors R11, R12, and R13, or resistors R6 and R7) to determine whether the load circuit, including capacitor C3, is shorted. (The resistance measured across the load circuit will normally measure something less than the total value of series-connected resistors R11, R12, and R13, or the total value of series-connected resistors R6 and R7, depending upon the load circuit design.)

High Output. The high-output condition is usually caused by a decrease in operating bias for the series regulator tube, V1, which, in turn, causes the tube to decrease its internal resistance and permits the regulator output voltage to rise above normal. Therefore, any defects in the electronic regulator circuit which can cause a decrease in the operating bias for V1 should be suspected. Voltage measurements should be made at the socket of V1 to determine whether bias (cathode-to-grid) voltage is present. The series regulator tube, V1, may be checked by substitution of a tube known to be good to determine whether the tube is defective (grid-to-cathode short, etc).

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for operation of the cascade twin-triode regulator-amplifier circuit, should be made to determine whether the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage is above normal, the tube may be defective; a tube known to be good may be substituted to check for proper operation of the reference-voltage circuit. If the voltage measured across V3 is below normal, it is likely that resistor R10 is open.

A visual check of regulator-amplifier tube V2 should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The bias voltages applied to V2 should be measured to determine whether the tube is improperly biased, causing the operating bias on V1 to decrease. Assuming that V3 is conducting normally to provide a reference voltage, if the voltage at the cathode of V2B is below normal, it is possible that voltage-divider resistor R11 or R13 has changed in value or that variable-resistor R12 is not set properly. If the voltage at the cathode of V2A is above normal, it is possible that voltage-divider resistor R6 or R7 has changed in value. However, if no voltage whatsoever is present at the cathode of V2B and a high voltage is present at the cathode of V2A, tube V2A will be biased to cutoff and V1 will conduct heavily as a result of decreased operating bias. In this case, it is likely that resistor R11, the portion of variable-resistor R12 connected to R11, or resistor R7 is open to drive V2A into cutoff. If regulator-amplifier tube V2 has low emission, the voltage drop across plate-load resistors R1 and R8 will be below normal; therefore, a tube known to be good should be substituted and operation of the circuit observed to determine whether tube V2 is the cause of the trouble.

Low Output. The low-output condition is usually caused by an increase in operating bias for the series regulator tube, V1, which, in turn, causes the tube to increase its internal resistance and permits the regulator output voltage to fall below normal. Therefore, any defects in the electronic regulator circuit which can cause an increase in the operating bias for V1 should be suspected. Trouble in one section of V1 (such as low cathode emission or an open tube element) will cause a reduction in output. The tube may be checked by substitution of a tube known to be good to determine whether the tube is defective. Voltage measurements should be made at the socket of V1 to determine whether the bias (cathode-to-grid) voltage is excessive. The equalizing resistors, R4 and R5, in the cathode circuits of V1 should be measured to determine that neither one is open, that they have not increased in value, and that they are of equal resistance.

A visual check of the gas-filled regulator tube, V3, which provides a reference voltage for operation of the cascade twin-triode regulator-amplifier circuit, should be made to determine that the tube is conducting. A voltage measurement made between the plate and cathode of V3 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage measured across V3 is below normal, or if no voltage is present, it is likely that capacitor C1 is either leaky or shorted.

The bias voltages applied to V2 should be measured to determine whether the tube is improperly biased, causing the operating bias on V1 to increase. Assuming that V3 is conducting normally to provide a reference voltage, if the voltage at the cathode of V2B is above normal, it is possible that voltage divider resistor R11 or R13 has changed in value or that variable-resistor R12 is not set properly. If the voltage at the cathode of V2A is below normal, it is possible that voltage-divider resistor R6 or R7 has changed in value. However, if a high voltage is present at the cathode of V2B and no voltage whatsoever is present at the cathode of V2A, tube V2A will conduct heavily and V1 will conduct less as a result of increased operating bias. In this case, it is likely that coupling capacitor C2 is either leaky or shorted, or that resistor R13, the portion of variable-resistor R12 connected to R13, or resistor R6 is open to cause V2A to conduct heavily. If regulator-amplifier tube V2 is shorted and conducting heavily, the voltage drop across plate-load resistor R1 will be excessive; therefore, a tube known to be good should be substituted and operation of the circuit observed to determine whether V2 is the cause of the trouble.

As mentioned previously, excessive load current can cause the output voltage to be low, especially if the load current exceeds the maximum rating of series regulator tube V1 (resulting in excessive voltage drop across V1) or if the load current exceeds the rating of the power supply (resulting in a decrease in the applied voltage). For these reasons, output capacitor C3 should be checked to determine whether it is satisfactory; a leaky output capacitor could result in reduced output voltage, although the regulator-amplifier circuit (V2) may be functioning normally but unable to compensate for the decrease in output.

Poor Regulation Characteristics. Voltage instability, slow response, etc, are frequently caused by weak or unbalanced triode sections in series regulator tube V1, unbalanced cathode resistors R4 and R5, or a defective regulator-amplifier tube, V2. The gain of the regulator-amplifier stage is determined primarily by tube V2 and its applied voltages; therefore, the condition of V2 and its applied voltages are important factors governing satisfactory operation of the regulator circuit.

D-C REGULATOR USING TWIN-TRIODE AND PENTODE (BALANCED INPUT).

APPLICATION.

The d-c regulator using a twin-triode amplifier and a pentode amplifier is employed in certain electronic equipment power-supply circuits to obtain nearly constant output voltage or voltages despite variations in input voltage or load current.

CHARACTERISTICS.

Regulated output voltage to load is nearly constant, even though changes in input voltage or load current occur.

Voltage-divider principle employed, using variable resistance (electronic tube) in series with load resistance; series electron tube may be a triode, a triode-connected pentode, or a pentode with separate screen-voltage supply.

Uses twin-triode differential amplifier and pentode amplifier circuit to control the series electron tube; the pentode amplifier uses a separate external screen-voltage supply.

Uses gas-tube regulator circuits as reference-voltage sources; the gas tubes are fed from an external regulated negative-voltage supply.

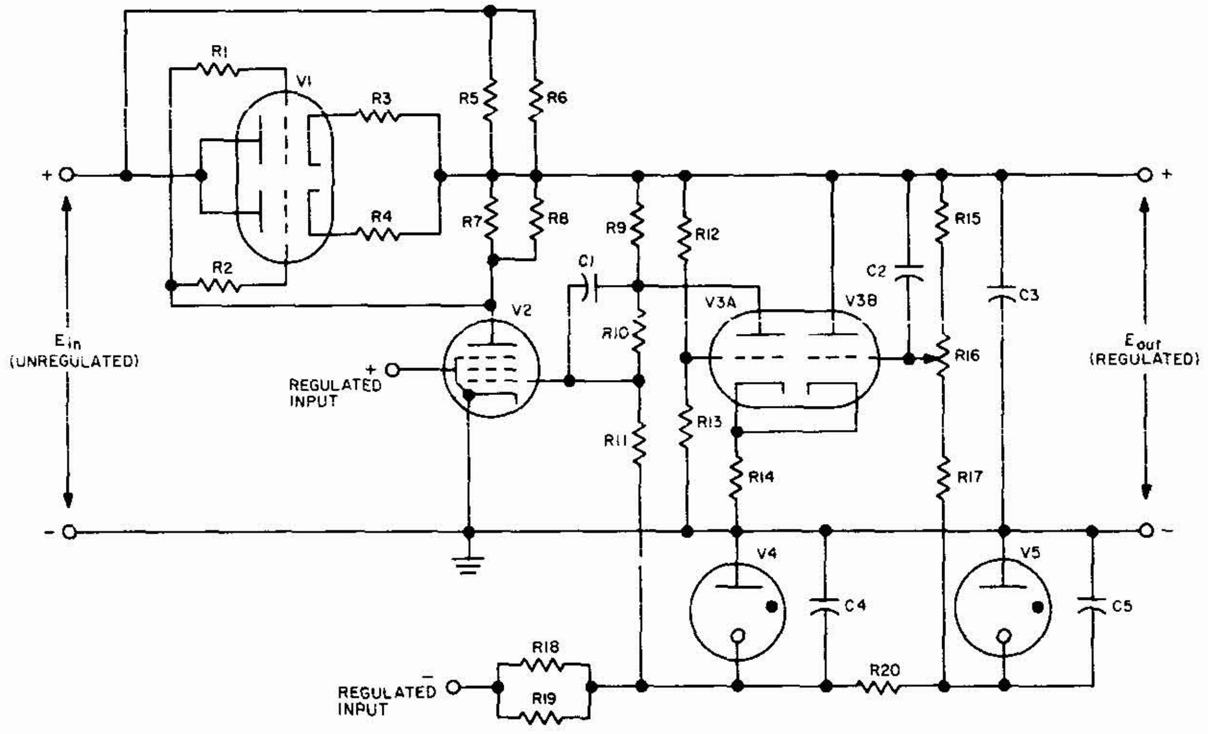
Variation in basic circuit permits positive (plate and screen) or negative (bias) supply voltages to be regulated.

CIRCUIT ANALYSIS.

General. The d-c regulator using a twin-triode differential amplifier and pentode amplifier is capable of providing very stable output voltage regulation. In this discussion the term "regulation" means the maintenance of a nearly constant output voltage regardless of changes in the input voltage or the load current. The variations in output voltage that normally result from component aging, changes in operational environment, etc, are usually considered in the design of the circuit, and are compensated for by using close-tolerance (on the order of 1, 2, or 5 percent) components whose values do not deviate from the nominal by more than the strict limits specified.

In this type of voltage regulator, regulation is accomplished by allowing the cathode-to-plate conduction resistance of an electron tube, in series with the output of a power supply, to fuction as a variable resistance, and thus provide the voltage drop necessary to compensate for any change in output voltage. That is, the change in output voltage is compared and amplified in the twin-triode and pentode regulator-amplifier circuit, and applied as a bias voltage to the grid of the series regulator tube, thereby varying the conduction resistance of this tube. The varying conduction resistance of the regulator tube, in turn, varies the load current drawn by the series circuit and the voltage drop across the series regulator tube; in so doing, the series regulator tube absorbs the change in the output voltage. Voltage regulation on the order of 1 percent can be obtained with this type of voltage regulator, depending on the circuit design.

Circuit Operation. A typical d-c regulator circuit using a twin-triode differential amplifier and pentode amplifier is illustrated in the accompanying circuit schematic. Electron tube, V1 is a parallel-connected twin-triode used as the series regulator tube. (In applications where the current drain exceeds the current-handling capability of a single series regulator tube, two or more tubes of the same type may be connected in parallel.) Electron tube V2 is a high-gain pentode, and electron tube V3 is a high-gain twin-triode; V3 functions as a cathode-coupled differential amplifier and is the input stage of the regulator-amplifier circuit, whereas pentode amplifier V2 is the output stage of the same circuit. The high amplification obtained from differential amplifier V3 and pentode amplifier V2 enables the circuit to have good sensitivity to small-voltage variations. Tubes V4 and V5 are cold-cathode, gas filled tubes used to provide reference voltages for operation of the regulator-amplifier circuit. The use of the gas-filled regulator tubes in this application is satisfactory as reliable references since there are no excessive currents in those branches of the circuit. Electron tubes V1, V2, and V3 are indirectly heated, cathode-type tubes; V1 normally has a high heater-to-cathode voltage rating, while V2 and V3 have a heater-to-cathode voltage rating which is typical for receiving-type tubes. Because of the heater-to-cathode breakdown voltage limitations imposed by the tubes themselves, it is usually necessary to isolate the filament circuits from each other and to supply the filament (heater) voltages from independent sources.



D-C Regulator Using Twin-Triode and Pentode (Balanced Input)

Resistors R1 and R2, in the grid circuits of V1, are parasitic oscillation suppressors; they are of equal value, generally between 270 and 1000 ohms. Resistors R3 and R4, in the cathode circuits of V1, are included for the purpose of equalizing the current flow of the parallel-connected triode sections; these resistors are of equal value, generally between 10 and 47 ohms, depending upon circuit design. Resistors R5 and R6 are connected in parallel with series regulator tube V1 to reduce its plate dissipation. The value of these resistors is selected so that their current flow under all operating conditions is less than the minimum load current; this will ensure a current flow through series regulator tube V1 and thereby permit the regulator to function.

Gas-filled regulator tubes V4 and V5 provide reference voltage for the grid circuits of V2 and V3B, respectively. Parallel-connected resistors R18 and R19 apply to the cathode of V4 a negative potential which is sufficiently high to ensure satisfactory ionization; these resistors also limit the current through V4 once the gas in the tube is ionized. Because tube V5 provides a reference voltage less negative than of V4, its cathode potential is accordingly made less negative by the voltage drop across resistor R20, which also serves as a current limiting resistor once tube V5 is ionized. In a typical d-c regulator circuit, V4 may be a type OA2 gas tube to provide a reference voltage of -150 volts, and V5 may be a type 5651 gas tube to provide a reference voltage in the range of -82 to -92 volts. By supplying the reference tubes from an external regulator negative-voltage source rather than connecting the tubes in the cathode circuit of the regulator-amplifier stages (as is done in some d-c regulator circuits), several advantages are obtained. First, the cathodes of the regulator-amplifier stages are at ground rather than at a high positive potential, thereby allowing a larger plate swing of the stages; second, the reference tube is in a grid circuit rather than in a cathode circuit, and thus operates under constant-current conditions; and third, the regulator-amplifier stage gain is greater with this connection because cathode degeneration caused by gas-tube impedance is not present. The choice current for the respective gas-filled tubes, as determined by resistors R18, R19, and R20, is a compromise between shortened tube life at high currents and higher noise level at low currents. Capacitors C4 and C5, connected across V4 and V5, respectively, are bypass capacitors to supress the transient noise generated by the gas tubes. The value of these capacitors is usually the largest value recommended by the tube manufacturer.

The regulator-amplifier circuit consists of cathode-coupled differential amplifier V3, used as a balanced input stage, cascaded with pentode amplifier V2, used as a single ended output stage. The left-hand section of the differential amplifier, V3A, functions as a triode amplifier, and the right-hand section, V3B, functions as a cathode follower. The balanced-input configuration of twin-triode V3 reduces the effects of tube aging and heater voltage variations.

If an input signal is applied to the grid of the cathode follower and the output signal is taken from the plate of the triode amplifier, the cathode-coupled differential amplifier will have a high input impedance and provide high amplification without signal inversion between the input and output. Resistors R15, R16, and R17 form a voltage divider across the regulator output and the regulated negative input to gas-filled reference tube V5. This voltage divider provides the operating bias for the grid of V3B; the value of bias voltage is selected by setting variable resistor R16. Resistor R14 is the common cathode resistor that provides the cathode coupling from cathode follower V3B to triode amplifier V3A. Resistors R12 and R13 also form a voltage divider, but this one is across the regulator output and ground. The voltage developed across resistor R13 provides the operating bias for the grid of triode amplifier V3A. Plate voltage for V3A is obtained from the regulator output through resistor R9; this resistor, along with resistors R10 and R11, is in a voltage divider across the regulator output and the regulated negative input to gas-filled reference tube V4.

In addition to providing the plate voltage for V3A, voltage divider R9, R10, and R11 provides the operating bias for the grid of output pentode amplifier V2; this bias voltage is obtained from the junction of resistors R10 and R11. Resistors R10 provides direct coupling from the plate of V3A to the grid of V2. The R-C combination of resistor R10 and capacitor C1 is a phase-lead network in the coupling circuit; the purpose of this network is to provide stabilization and thereby prevent oscillation within the regulator amplifier. The suppressor grid of pentode V2 is connected internally to the cathode, and the cathode is returned directly to ground. The pentode screen grid receives its operating voltage from an external regulated positive-voltage source. Plate voltage for output pentode amplifier V2 is obtained from the regulator output through parallel-connected, equal-value resistors R7 and R8; this arrangement lowers the effective plate-load resistance, but permits the pentode to handle higher plate currents. The decreased plate-load resistance improves the frequency response of the circuit.

Capacitor C2 couples the full value of the power-supply ripple voltage (usually 120 cps) appearing in the output of the regulator to the grid of V3B. If capacitor C2 were not used, a portion of the ripple voltage would be applied to the grid of V3B, as determined by the voltage-divider action of resistors R15, R16, and R17. The value of capacitor C2 is chosen so that it is just large enough to provide satisfactory ripple suppression. If the value of capacitor C2 were made too large, the response time of the regulator circuit to normal d-c output-voltage variations would be affected; a value of from 0.01 to 0.1 microfarad is typical in most regulator-amplifier circuits, although values up to 2 microfarad may occasionally be used. Capacitor C3 is connected across the output terminals to lower the output impedance of the regulator circuit; the value of this capacitor depends upon the circuit design, ranging from 0.5 microfarad to 2 microfarads. The voltage dividers formed by the series-connected combinations of resistors R9, R10, and R11, resistors R12 and R13, and resistors R15, R16, and R17 are all across the output of the regulator circuit and are thereby in parallel with the load. Any resistance measurement across the output must take into consideration these parallel circuits. Voltage-divider resistor R16, in the grid circuit of V3B, is adjustable and is used to set the output voltage to the desired value that the circuit is to maintain.

The cathode-coupled differential amplifier configuration of V3 provides a single-ended output signal having high amplification but no signal inversion from input to output. The single-ended output makes the circuit sensitive to power-supply voltage changes, and the common-cathode arrangement causes the cathodes to mutually offset the drift due to heater-voltage variations. The gain of the differential amplifier is a combination of the gains of the cathode-follower section, V3B, and the triode-amplifier section, V3A. The output impedance of the cathode follower acts as an impedance in series with the cathode input to the triode amplifier. To avoid an excessively large bias produced by a large-value cathode resistor (R14), the cathods of the differential amplifier are returned to ground and the grids are returned to the regulator output. The sum of the plate currents of V3A and V3B is equal to the current through cathode resistor R14. This value of current is essentially constant; that is, an increase in cathode follower V3B plate current causes an almost equal decrease in triode amplifier V3A plate current. In this manner the current through resistor R14 is kept essentially constant.

As previously mentioned, the operation of this regulator circuit is based upon the voltage-divider principle of using a variable resistance in the form of electron tube V1 in series with the load resistance. The regulated output voltage, E_{out}, appears across the voltage dividers (previously pointed out) which are in parallel with the load. The total resistance of these voltage-divider resistors in parallel with the load resistance constitutes one part of the resistance in the regulator series voltage-divider arrangement, which includes the variable cathode-to-plate resistance of series regulator tube V1. The currents which pass through the parallel branches (voltage-divider resistors and load resistance) combine, and this total current passes through series regulator tube V1 (and parallel-connected resistors R5 and R6). When the cathode-to-plate resistance of V1 is controlled to vary the voltage drop across this tube, the output voltage developed across the load can be regulated and maintained at a constant value.

In order to understand how the d-c regulator circuit operates under varying-load conditions, it is necessary to examine first the static voltage distribution under normal-load conditions. The cathode of series regulator tube V1 is held positive with respect to ground by the output voltage, E_{out}, while the grid is held somewhat less positive by the action of the regulator amplifier (pentode amplifier V2 and differential amplifier V3). The difference between these two voltages is the bias voltage for V1, which is at the proper value for series regulator tube V1 to have the required cathode-to-plate resistance to produce the correct output voltage.

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A negative voltage is fed from an external regulated source to the cathode of reference tube V4 through parallel-*connected resistors* R18 *and* R19, and to the cathode of reference tube V5 through resistor R20. Since the plate of each reference tube is at ground potential, the negative voltage at the cathode causes the gas to ionize and the tube to conduct. In this manner negative reference voltage are established for the voltage dividers feeding *the grid of pentode* amplifier V2 and the grid of the cathode-follower section, V3B, of the differential amplifier. (The action of the gas-filled reference tubes is the same as that previously described, under Gas-Tube Regulator Circuit, in Section 5 of this Handbook.) Regardless of the value of d-c voltage applied to the input, E_{in}, of the regulator circuit, the negative-voltage references in the grid circuits of V2 and V3B will be held constant by the action of V4 and V5, respectively.

The regulator-amplifier circuit, which consists of pentode amplifier V2 and cathode-coupled differential amplifier V3, uses the cathode load impedance of cathode follower V3B as the cathode input impedance of triode amplifier V3A. Thus, the signal of the cathode follower is applied between *the control grid and ground,* while the output of this same stage is the input to the triode amplifier, and is applied between the cathode and ground. The grid voltage for the cathode follower is determined by the setting of voltage-divider resistor R16. The triode amplifier has a fixed voltage on its grid, obtained from *the junction of voltage-divider* resistors R12 and R13. The plate voltage of V3A and V3B is obtained from the regulated output, E_{out}; the plate of V3B is returned directly to the regulator output, whereas the plate of V3A is returned to this potential through plate-load resistor R9, which is part of the voltage-divider network consisting of resistors R9, R10, and R11. Thus, the *operating potentials at the electrodes of V3A and V3B* are such that, under normal-load conditions, they permit a predetermined value of current to be drawn by V3 and develop an output signal across plate-load resistor R9.

The output signal of V3A developed across resistor R9 is direct-coupled through resistor R10 to the grid of pentode amplifier V2. This signal, then, acts to control the conduction *through* V2. *When V2 is conducting,* the current through parallel-coducted plate-load resistors R7 and R8 develops a voltage at the plate of V2; this voltage is coupled to the grids of V1. The voltage at the grids of V1 is less than the voltage at the cathodes of this tube; hence, the normal-load operating bias for V1 is established. *The setting of variable* resistor R16, therefore, determines the current through V3, *which, in turn,* controls the current through V2 and thereby establishes the bias for V1. This bias voltage of V1 initially determines the effective normal-load internal resistance of V1 to obtain the desired output voltage, E_{out}, from the regulator circuit.

Assume, now, *that the regulated output voltage,* E_{out}, attempts to increase, either because of an increase in the input voltage, E_{in}, to the regulator circuit or because of a decrease in the load current. Through the voltage-divider action of resistors R15, R16, and R17, a slightly higher positive voltage now appears across resistors R16 and R17. This results in an increase in the voltage applied to the *grid of V3B, and a corresponding decrease in the bias of this* E_{out}, *remains practically constant.* Since most of the load current must pass through series regulator tube V1, the tube stage. As a result of the decreased bias, V3B now conducts more current, and this additional current flow through cathode-load resistor R14 results in a greater voltage drop across this resistor. *The voltage at the cathode of V3, in* going more positive, increases the bias on V3A and thereby reduces conduction through this stage. The reduced plate current of V3A causes a smaller voltage drop across a plate-load resistor R9, which, in effect, is a positive-going signal at the plate of V3A. The differential amplifier, therefore, amplifies but does not invert the positive-going signal applied to the grid of V3B.

The positive-going signal at the plate of V3A is direct-coupled through resistor R10 to the grid of pentode amplifier V2, where it reduces the bias and causes an increase in the conduction of this stage. When the conduction of V2 is increased, the additional plate current through plate-load resistors R7 and R8 produces a greater voltage drop across *these resistors,* and thereby develops a negative-going signal at the plate of V2. This negative-going signal is coupled to the grids of V1, where it causes the difference in voltage between the grids and cathodes of V1 to increase. The difference in voltage between the grids and cathodes of V1 is the operating bias for V1. *As a result of the bias voltage* increase, the effective internal resistance of V1 increases. When the internal resistance of V1 increases, less load current flows through V1, the voltage drop across V1 increases, and the output voltage E_{out}, of the regulator circuit decreases to its original value.

An action similar to that just described occurs when the *regulated output voltage,* E_{out}, *attempts to decrease.* Through the voltage-divider action of resistors R15, R16, and R17, the bias voltage on the grid of V3B is increased, since a slightly lower positive potential now exists across resistors R16 and R17. As a result of the increased bias, V3B now conducts less than current, and the decreased current flow through cathode-load resistor R14 causes a smal*ler voltage drop to occur across* this resistor. The voltage at the cathode of V3, in going negative, decreases the bias on V3A and thereby increases conduction through this stage. The increased plate current of V3A causes a greater voltage drop across plate-load resistor R9, which, in effect, is a negative-going signal at the plate of V3A. *This negative-*going signal is direct-coupled through resistor R10 to the grid of pentode amplifier V2, where it increases the bias and causes a decrease in the conduction of V2. When V2 conduction decreases, less plate current flows through plate-load resistors R7 and R8, thereby producing a smaller voltage drop across these resistors. Thus, the voltage at *the plate of V2 (and the grids of V1) increases and causes* the difference in voltage between the grids and cathodes of V1 to decrease. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. As a result of the bias voltage decrease, the effective internal resistance of V1 decreases. When the internal resistance of V1 decreases, more load current flows through V1, the voltage drop across V1 decreases, and the output voltage of the regulator circuit increases to its original value.

The actions described in the preceding paragraphs are practically instantaneous; consequently, the output voltage, the correct value, since the lack of input voltage from the associated power supply and filter circuit will cause a lack of output voltage. With the d-c voltage removed from the in- must be capable of passing considerable current. In some circuit applications where the load current requirements exceed the capabilities of a single tube, two or more identical tubes are connected in parallel (as the sections of twin-triode V1 have been paralleled) in order to obtain suitable regulation characteristics and current-handling capability. Also, in order to reduce the plate dissipation of series regulator tube V1, resistors can be connected in parallel with the tube (as resistors R5 and R6 have been connected in this regulator circuit).

The output of the regulator circuit is coupled to the grid of the cathode-follower section, V3B, of the differential amplifier through coupling capacitor C2. Any ripple component present in the output voltage is amplified in the regulator amplifier, and, since the circuit is basically a negative-feedback circuit, the ripple component is suppressed. As a result, the regulator circuit is sensitive to any voltage changes and is very effective in removing any fundamental ripple-frequency component which is present in the regulated voltage output. Although there are many variations in the regulator-amplifier circuit configuration, the function of the regulator circuit remains the same, that is, to supply a regulated output voltage to the load which is independent of variations in input voltage or changes in load current.

FAILURE ANALYSIS.

General. The d-c regulator using a twin-triode and pentode regulator amplifier includes several components which are rather critical and thus directly affect the operation of the regulator circuit. For this reason, the resistors in the regulator-amplifier circuit are normally close-tolerance (on the order of 1, 2, or 5 percent) resistors with good temperature-stability characteristics. The operation of the circuit will be impaired if these resistors should change in value for any reason. Since the regulator circuit attempts to hold the output voltage constant, it is usually good practice to determine whether the load current is within tolerance before suspecting trouble within the regulator circuit proper. A load-current measurement may be made by inserting a milliammeter (having a suitable range) in series with the output of the regulator circuit. Also, a voltage measurement should be made at the input to the regulator circuit to determine whether the unregulated voltage output from the power supply (and filter circuit) is within tolerance.

No Output. In this d-c regulator circuit, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage applied to series regulator tube V1, the lack of applied d-c voltage (from the associated power supply and filter circuit), or a short-circuited load (including output capacitor C3). A visual check of the glass-envelope series regulator tube, V1, should be made to determine whether the filament is lit; if the filament is not lit, it may be open or the filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The d-c voltage applied to the regulator circuit should be measured at the input (plate of V1) to determine whether it is present and of tion of resistor R16 is open to cut off V3B, or that resistor R13 is open to cause the heavy conduction of V3A.

If pentode amplifier V2 has low emission, the voltage drop across plate-load resistors R7 and R8 will be below put to the circuit, resistance measurements can be made across the load to determine whether the load circuit, including capacitor C3, is shorted. (The resistance measured across the load circuit will normally be something less than the total value of the voltage-divider resistors, depending upon the load circuit design.)

High Output. The high-output condition is usually caused by a decrease in operating bias for the series regulator tube, V1, which, in turn, causes the tube to decrease its internal resistance and permit the regulator output voltage to rise above normal. Therefore, any defects in the electronic regulator circuit which can cause a decrease in the operating bias for V1 should be suspected. Voltage measurements should be made at the socket of V1 to determine whether bias (cathode-to-grid) voltage is present. The series regulator tube, V1, may be checked by substitution of a tube known to be good to determine whether the tube is defective (grid-to-cathode short, etc).

A visual check of gas-filled regulator tube V5, which provides a reference voltage for the operation of the cathode-follower section (V3B) of the differential amplifier circuit, should be made to determine whether the tube is conducting. A voltage measurement made between the cathode and plate of V5 will determine whether sufficient negative voltage is present at the tube to cause conduction. If the voltage is more negative than normal, the tube may be defective; a tube known to be good may be substituted to check for proper operation of the V5 reference-voltage circuit. If the voltage measured across V5 is less negative than normal, it is likely that resistor R20 has changed in value.

A visual check of regulator-amplifier tubes V2 and V3 should be made to determine whether their filaments are lit; if the filaments are not lit, they may be open or the filament voltage may not be applied. The tube filaments should be checked for continuity; also, the presence of filament voltage at the tube sockets should be determined by measurement.

The bias voltages applied to V2 and V3 should be measured to determine whether these tubes are improperly biased, causing the operating bias on V1 to decrease. Assuming that V4 and V5 are conducting normally to provide the proper reference voltages, if the voltage at the grid of V2 or V3B is below normal, there will be an increase in the bias on the respective tube. In this case it is possible that resistor R9, R10, or R11 has changed in value to increase the bias of V2, or that resistor R15 or R16 has changed in value to increase the bias of V3B; in addition, an improper setting of variable resistor R16 will affect the bias voltage at the grid of V3B. A high output from the regulator also will result when the voltage at the grid of V3A is above normal, and thereby cause a bias decrease on this stage; a change in the value of resistor R12 or R13 will produce this effect. If V2 or V3B is biased to cutoff, or if V3A is conducting heavily as a result of a high positive voltage at its grid, V1 will be made to conduct heavily as a result of a decreased operating bias. In this case, it is likely that resistor R9 or R10 is open to cut off V2, that resistor R15 or the top porhigh positive voltage will be placed on the grid of V3B if the bottom portion of resistor R16 or resistor R17 is open, or if capacitor C2 is leaky or shorted. A bias sufficient to cut off V3A will result if resistor R12 is open; also, an open cathode resistor, R14, in the differential amplifier will cut off V3A.

normal; therefore, the bias of V1 will be decreased and a high output from the regulator will result. Under this circumstance, a tube known to be good should be substituted at V2 and operation of the circuit observed to determine whether tube V2 is the cause of the trouble.

Low Output. The low-output condition of the regulator is usually caused by an increase in operating bias for the series regulator tube, V1, which, in turn, causes the tube to increase its internal resistance and permit the regulator output voltage to fall below normal. Therefore, any defects in the electronic regulator circuit which can cause an increase in the operating bias for V1 should be suspected. Trouble in one section of V1 (such as low cathode emission or an open tube element) will cause a reduction in the output. The tube may be checked by substitution of a tube known to be good to determine whether the tube is defective. Voltage measurements should be made at the socket of V1 to determine whether the bias (cathode-to-grid) voltage is excessive. The equalizing resistors, R3 and R4, in the cathode circuits of V1 should be measured to determine that neither one is open, that they have not increased in value, and that they are of equal resistance.

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A visual check of gas-filled regulator tube V4, which provides a reference voltage for the operation of pentode amplifier V2, should be made to determine that the tube is conducting. A voltage measurement made between the cathode and plate of V4 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage is more negative than normal, the tube may be defective; a tube known to be good may be susbtituted to check for proper operation of the V4 reference voltage circuit. If the voltage measured across V4 is less negative than normal, it is likely that resistor R18 or R19 is open, thereby providing a voltage which is not sufficiently negative to cause gas tube V4 to ionize.

The bias voltages applied to V2 and V3 should be measured to determine whether these tubes are improperly biased, causing the operating bias on V1 to increase. Assuming that V4 and V5 are conducting normally to provide the reference voltages, if the voltage at the grid of V2 or V3B is above normal, there will be a decrease in the bias on the respective tube. In this case, it is possible that resistor R9, R10, or R11 has changed in value to decrease the bias of V2, or that resistor R15 or R16 has changed in value to decrease the bias of V3B; in addition, an improper setting of variable resistor R16 will affect the bias voltage at the grid of V3B. A low output from the regulator also will result when the voltage at the grid of V3A is below normal, and thereby cause a bias increase on this stage; a change in the value of resistor R12 or R13 will produce this effect. If V2 or V3B is biased by a high positive voltage on its grid so that either tube conducts heavily, or if V3A is biased to cutoff, V1 will be made to conduct less as a result of an increased operating bias. In this case, it is likely that resistor R11 is open or capacitor C1 is leaky or shorted, thus placing a high positive voltage on the grid of V2. A It is possible for the symptom of a high positive voltage at the grid of V2 or V3B to be caused by a defect in the voltage reference circuits. For example, if capacitor C4 or C5 (paralleling reference tubes V4 and V5, respectively) is leaky or shorted, the grids of pentode amplifier V2 and cathode follower V3B will be returned to ground instead of to their respective negative voltage reference. As a result, the voltage distribution across the respective voltage dividers will be such that the voltage at the grid of V2 or V3B is made more positive. Separately, the voltage at the grid of V2 will be more positive if reference tube V4 is defective, and a similar condition will be noted for the grid of V3B if resistor R20 is open. The result of each of the foregoing defects will be an increase in the bias on series regulator tube V1, and a decrease in the regulator output voltage.

If plate-load resistor R7 or R8 (for pentode amplifier V2) is open, the bias voltage applied to the grids of V1 will be made larger, causing a decrease in the regulator output. Also, if tube V2 is shorted and conducting heavily, the voltage drop across plate-load resistors R7 and R8 will be excessive; therefore, a tube known to be good should be substituted and operation of the circuit observed to determined whether tube V2 is the cause of the trouble. If differential amplifier tube V3 has low emission, the voltage drop across its plate-load resistor (R9) will be below normal; therefore, the bias of V2 will be decreased, and in turn, cause an increase in the bias of V1 and a decrease in the output of the regulator. A tube known to be good should be substituted at V3, and operation of the circuit observed to determine whether tube V3 is the cause of the trouble.

As mentioned previously, excessive load current can cause the output voltage to be low, especially if the load current exceeds the maximum rating of series regulator tube V1 (resulting in excessive voltage drop across V1) or if the load current exceeds the rating of the power supply (resulting in a decrease in the applied voltage). For these reasons, output capacitor C3 should be checked to determine whether it is satisfactory. A leaky output capacitor could result in reduced output voltage, although the regulator-amplifier circuit (V2 and V3) may be functioning normally but still be unable to compensate for the decrease in output.

Poor Regulation Characteristics. Voltage instability, slow response, etc, are frequently caused by weak or unbalanced triode sections in series regulator tube V1, unbalanced cathode resistors R3 and R4, or defective regulator amplifier tubes V2 and V3. The gain of the regulator-amplifier stage is determined primarily by tubes V2 and V3 and their applied voltages; therefore, the condition of V2 and V3 and the applied voltages are important factors governing satisfactory operation of the regulator circuit.

D-C REGULATOR USING PENTODE AND TWIN-TRIODE (BALANCED OUTPUT).

APPLICATION.

The d-c regulator using a pentode amplifier and a twin-triode amplifier is employed in certain electronic equipment power supply circuits to obtain nearly constant output voltage (or voltages) despite variations of input voltage or load current.

CHARACTERISTICS.

Regulated output voltage to load is nearly constant, even though changes in input voltage or load current occur.

Voltage-divider principle employed, using variable resistance (electron tube) in series with load resistance; series electron tube may be a triode, a triode-connected pentode, or a pentode with separate screen-voltage supply.

Uses pentode amplifier and twin-triode differential amplifier to control the series electron tube.

Uses gas-tube regulator circuits as reference-voltage sources.

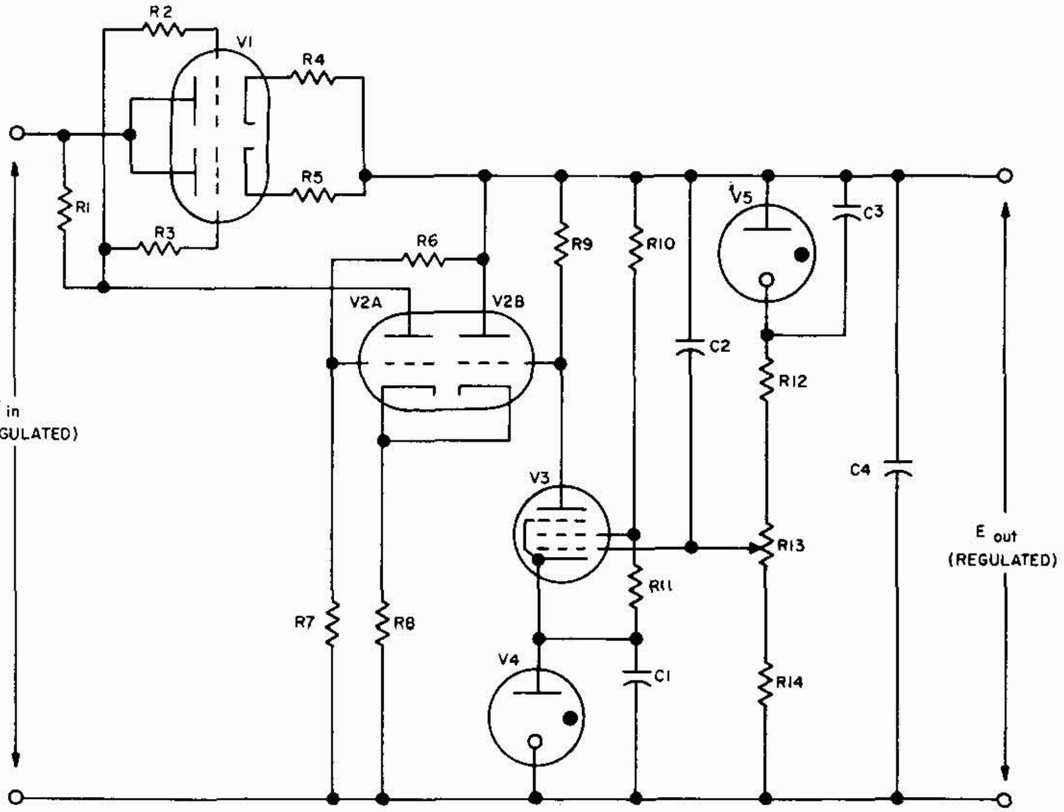
Variation in basic circuit permits positive (plate and screen) or negative (bias) supply voltages to be regulated.

CIRCUIT ANALYSIS.

General. The d-c regulator using a pentode amplifier and a twin-triode differential amplifier is capable of providing very stable output voltage regulation. In this discussion the term "regulation" means the maintenance of a nearly constant output voltage, regardless of changes in the input voltage or the load current. The variations in output voltage that normally result from component aging, changes in operational environment, etc, are usually considered in the design of the circuit, and are compensated for by using close-tolerance (on the order of 1, 2, or 5 percent) components whose values do not deviate from the nominal by more than the strict limits specified.

In this type of voltage regulator, regulation is accomplished by allowing the cathode-to-plate conduction resistance of an electron tube, in series with the output of a power supply, to function as a variable resistance, and thus provide the voltage drop necessary to compensate for any change in output voltage. That is, the change in output voltage is compared and amplified in the pentode and twin-triode regulator-amplifier circuit, and applied as a bias voltage to the grid of the series regulator tube, thereby varying the conduction resistance of this tube. The varying conduction resistance of the regulator tube, in turn, varies the load current drawn by the series circuit and the voltage drop across the series regulator tube; in so doing, the series regulator tube absorbs the change in the output voltage. Voltage regulation of approximately 1 percent can be otained with this type of electronic d-c regulator, depending on the circuit design.

Circuit Operation. A typical d-c regulator circuit using a pentode amplifier and twin-triode differential amplifier is illustrated in the accompanying circuit schematic Electron tube V1 is a parallel-connected twin-triode used as the series regulator tube. (In applications where the current drain exceeds the current-handling capability of a single series regulator tube, two or more tubes of the same type may be connected in parallel.) Electron tube V2 is another twin-triode, and is used as a cathode-coupled differential amplifier stage. Electron tube V3 is a high-gain pentode amplifier. Together, tubes V2 and V3 function as the regulator-amplifier circuit; pentode V3 is the input stage, and twin-triode V2 is the output stage. Tubes V4 and V5 are cold-cathode, gas-filled tubes used to provide



D-C Regulator Using Pentode and Twin-Triode (Balanced Output) reference voltages for operation of the regulator-amplifier circuit. The gas-filled regulator tubes in this application are satisfactory as reliable references since there are no excessive currents in those branches of the circuit. Electron tubes V1, V2, and V3 are indirectly heated, cathode-type tubes; V1 normally has a high heater-to-cathode voltage rating, while V2 and V3 have a heater-to-cathode voltage rating which is typical for receiving-type tubes. Because of the heater-to-cathode breakdown voltage limitations imposed by the tubes themselves, it is usually necessary to isolate the filament circuits from each other and to supply the filament (heater) voltages from independent sources.

Resistors R2 and R3, in the grid circuits of series regulator tube V1, are parasitic oscillation suppressors; they are of equal value, generally between 270 and 1000 ohms. Resistors R4 and R5, in the cathode circuits of V1, are included for the purpose of equalizing the current flow in the parallel-connected triode sections; these resistors are of equal value, generally between 10 and 47 ohms, depending upon the circuit design.

The regulator-amplifier circuit consists of pentode amplifier V3, used as a single-ended input stage, cascaded with cathode-coupled differential amplifier V2, used as a balanced output stage. The left-hand section of the differential amplifier, V2A, functions as a triode amplifier, and the right-hand section, V2B, functions as a cathode follower. The balanced configuration of twin-triode V2 reduces the effects of tube aging and heater voltage variations. If an input signal is applied to the grid of the cathode follower and the output signal is taken from the plate of the triode amplifier, the cathode-coupled differential amplifier will have a high input impedance and provide high amplification without signal inversion between the input and the output. Resistor R1, connected to the source of unregulated input voltage, E_{in}, provides plate voltage for triode amplifier V2A. Control grid voltage for this same stage is obtained from voltage-divider resistors R6 and R7, connected across the regulated output voltage, E_{out}. Resistor R8 is a common resistor for triode amplifier V2A and cathode follower V2B.

Gas-filled regulator tubes V4 and V5 furnish reference voltages for pentode amplifier V3; V4 is in the cathode circuit, and V5 is in the control grid circuit. Resistors R10 and R11, connected in series with reference tube V4 across the output circuit, serve to apply the full output voltage of the regulator to V4, to ensure a satisfactory striking potential and also to act as current-limiting resistors once the tube is ionized. In addition, resistors R10 and R11 function as a voltage divider to provide the d-c operating potential for the screen grid of pentode amplifier V3. Plate voltage for the pentode amplifier is furnished by the regulated output through plate-load resistor R9. Capacitor C1, connected in parallel with reference tube V4, is a bypass capacitor which provides a low-impedance path at the power-supply ripple frequency (usually 120 cps), to reduce the possibility of degeneration in the cathode circuit of V3. The value of capacitor C1 is usually a compromise between a value which offers low impedance to the power-supply ripple frequency and a value which is not so large as to affect the normal operation of the reference tube, V4.

Gas tube V5 is in series with voltage-divider resistors R12, R13, and R14 across the regulated output, E_{out}. Because this arrangement permits a larger percentage of the output-voltage variations to be coupled to the control grid of the pentode amplifier, the over-all gain of the regulator amplifier is made greater. In some d-c regulators, two or more gas tubes may be used in series with the voltage-divider resistors. The number and type of gas tubes used in this manner depends upon the voltage drop required between the output and the grid of pentode amplifier V3; it is usually desirable that the largest portion of the required voltage drop be obtained across the gas tube(s). With a gas tube placed in a grid circuit, such as V5 is in this d-c regulator, an additional advantage is realized in that there is a constant current through the gas tube, and its dynamic resistance is of little consequence. Therefore, the gas tube is selected solely on the merits of its ability to regulate at the same voltage each time the power supply (equipment) is turned on and the degree to which the voltage is regulated at a constant value so long as the equipment is in operation. Capacitor C3, connected in parallel with V5, is used to suppress the transient noise generated by the gas tube, and thereby prevent these undesirable signals from appearing on the grid of pentode amplifier V3. The value of capacitor C3, which is usually the largest value recommended by the tube manufacturer, is a compromise between a value which eliminates the transient noise and a value which is not so large as to affect the normal operation of reference tube V5.

Capacitor C2 couples the full value of ripple voltage from the output of the regulator circuit to the grid of V3; if capacitor C2 were not used, only a portion of the ripple voltage would be applied to the grid of V3, as determined by the action of V5 and voltage-divider resistors R12, R13, and R14. The value of capacitor C2 is chosen so that it is just large enough to provide satisfactory ripple suppression. If the value of capacitor C2 were made too large, the response time of the regulator circuit to normal d-c output-voltage variations would be affected; a value of from 0.01 to 0.1 microfarad is typical in most regulator-amplifier circuits. Capacitor C4 is connected across the output terminals to lower the output impedance of the regulator circuit; the value of this capacitor depends upon the circuit design, but is usually 2 microfarads or larger. Resistors R12, R13, and R14, which form a voltage divider in series with reference tube V5 across the output of the regulator circuit, are in parallel with the resistance of the load. Resistor R13 is adjustable, and is used to set the output voltage to the desired value the circuit is to maintain.

The cathode-coupled differential amplifier configuration of V2 provides a single-ended output signal having high amplification but no signal inversion from input to output. The single-ended output makes the circuit sensitive to power-supply voltage changes, and the common cathode arrangement causes the cathodes to mutually offset the drift due to heater-voltage variations. The gain of the differential amplifier is a combination of the gains of the cathode follower section, V2B, and the triode-amplifier section, V2A. The output impedance of the cathode follower acts as an impedance in series with the cathode input to the triode amplifier. The sum of the plate currents of V2A and V2B is equal to the current through cathode resistor R8. This value of current is essentially constant; that is, an increase in the plate current of cathode follower V2B causes an almost equal decrease in the plate current of triode amplifier V2A. In this manner, the current through resistor R8 is kept essentially constant.

As previously mentioned, the operation of this regulator circuit is based upon the voltage-divider principle of using a variable resistance in the form of electron tube V1 in series with the load resistance. The regulated output voltage, E_{out}, appears across the voltage dividers formed by gas tube V5 and resistors R12, R13, and R14, and resistors R6 and R7, which are connected across the output of the regulator circuit and in parallel with the load. The total resistance of these voltage-divider resistors in parallel with the load resistance constitutes one part of the resistance in the regulator series voltage-divider arrangement, which includes the variable cathode-to-plate resistance of series regulator tube V1. The currents which pass through the parallel branches (voltage-divider resistors and load resistance) combine, and this total current passes through series regulator tube V1. When the cathode-to-plate resistance of V1 is controlled to vary the voltage drop across this tube, the output voltage developed across the load can be regulated and maintained at a constant value.

In order to understand how the d-c regulator circuit operates under varying-load conditions, it is necessary to examine first the static voltage distribution under normal-load conditions. The cathode of series regulator tube V1 is held positive with respect to ground by the output voltage, E_{out}, while the grid is held somewhat less positive by the action of the regulator-amplifier circuit. The difference between these two voltages is the bias voltage for V1, which is at the proper value for series regulator tube V1 to have the required amount of cathode-to-plate resistance to produce the correct output voltage. The output voltage is applied to reference tube V4 through resistors R10 and R11, causing V4 to ionize and conduct, thereby establishing a reference voltage at the cathode of pentode amplifier V3. In a like manner, gas tube V5 also ionizes and conducts to produce a constant voltage drop in the voltage-divider circuit consisting of that tube as well as resistors R12, R13, and R14. (The action of the gas-filled reference tubes, V4 and V5, is the same as that previously described under Gas-Tube Regulator Circuit earlier in Section 5 of this Handbook.) Regardless of the value of the d-c voltage applied to the input, E_{in}, of the regulator circuit, the voltage at the cathode of V3 will be held constant (by the action of V4) for use as a reference voltage. Likewise, the voltage at the top of resistor R12 will be held constant by the action of gas tube V5.

The input to the regulator-amplifier circuit, as determined by the setting of resistor R13, is applied to the grid of pentode amplifier V3. The output signal of this stage, developed across plate-load resistor R9, is direct-coupled to the grid of V2B-the cathode follower input section of cathode-coupled differential amplifier V2. The cathode load impedance of cathode follower V2B is used as the cathode input impedance of triode amplifier V2A. Thus, the signal to the cathode follower is applied between the control grid and ground, while the output of this same stage is the input to the triode amplifier, and is applied between the cathode and ground. The grid voltage for the cathode follower is determined by the voltage drop across the pentode plate-load resistor, R9. The triode amplifier, V2A, has a fixed voltage on its grid, obtained from the junction of voltage-divider resistors R6 and R7. The plate voltage of V2A is obtained from the unregulated input, E_{in}, through plate-load resistor R1; the plate of V2B is returned directly to the regulator output. Thus, the operating potentials at the electrodes of V2A and V2B are such that, under normal-load conditions, they permit a predetermined value of current to be drawn by V2 and develop an output signal across plate-load resistor R1.

The output signal of V2A developed across resistor R1 is direct-coupled through resistors R2 and R3 to the grids of series regulator tube V1. This signal, then, acts to control the conduction through V1. That is, when differential amplifier V2 is conducting, the voltage drop across V2A plate-load resistor R1 provides a voltage for the grids of series regulator tube V1; this voltage is less than either the plate or cathode voltage of V1. The difference in voltage between the cathodes and grids of V1 is the operating bias for V1. Thus, the setting of resistor R13 determines the current through V3, which, in turn, determines the conduction of V2, and thus the voltage drop across resistor R1, which establishes the bias for V1. It is this bias level that initially determines the effective internal resistance of V1 to obtain the desired output voltage, E_{out}, from the regulator circuit.

Assume, now, that the regulated output voltage, E_{out}, attempts to decrease, either because of a decrease in the input voltage to the regulator circuit or because of an increase in the load current. Through the voltage-divider action of resistors R12, R13, and R14, a slightly lower positive voltage now appears across R13 and R14. This results in a decrease in the positive voltage applied to the grid of pentode amplifier V3 and a corresponding increase in the bias voltage between the cathode and the grid of V3. (The cathode voltage of V3 remains constant because of the action of reference tube V4.) As a result of the increased bias, V3 now conducts less current, and this reduced current flow through plateload resistor R9 results in a smaller voltage drop across R9; thus, the voltage at the plate of V3 increases. Since the voltage at the plate of V3 is also the grid voltage of cathode follower V2B, the bias on V2B now decreases. As a result of the decreased bias, V2B conducts more current, and this additional current flow through cathode-load resistor R8 results in a greater voltage drop across this resistor. The voltage at the cathode of V2, in going more positive, increases the bias on triode amplifier V2A, and thereby reduces conduction through this stage. The reduced plate current of V2A causes a smaller voltage drop across plate-load resistor R1, which, in effect, is a positive-going signal at the plate of V2A. The differential amplifier, therefore, amplifies but does not invert the positive-going signal applied to the grid of V2B. The positive-going voltage at the plate of V2A is coupled to the grids of V1 and causes the difference in potential between the grids and cathodes of V1 to decrease. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. Thus, as a result of this bias voltage decrease, the effective internal resistance of V1 decreases. When the internal resistance of V1 decreases, more load current flows through V1, the voltage drop across V1 decreases, and the output voltage of the regulator circuit increases to its original value.

An action similar to that just described occurs when the regulated output voltage, E_{out}, attempts to increase. Through the voltage-divider action of resistors R12, R13, and R14, the bias voltage between the cathode and grid of V3 is decreased, since a slightly higher positive potential now exists across R13 and R14. As a result of the decreased bias, V3 now conducts more current, and this increased current flow through plate-load resistor R9 causes a larger voltage drop to occur across R9; thus, the voltage at the plate of V3 decreases, and this negative-going voltage causes the bias of V2B to increase. As a result of the increased bias, V2B now conducts less current, and the decreased current flow through cathode-load resistor R8 causes a smaller voltage drop to occur across this resistor. The voltage at the cathode of V2, in going negative, decreases the bias on triode amplifier V2A, and thereby increases the conduction through this stage. The increased plate current of V2A causes a greater voltage drop across plate-load resistor R1, which, in effect, is a negative going voltage at the plate of V2A. This negative-going signal is coupled to the grids of V1, causing the difference in potential between the grids and cathodes of V1 to increase. This difference in voltage between the grids and cathodes of V1 is the operating bias for V1. Thus, as a result of this bias voltage increase, the effective internal resistance of V1 increases. When the internal resistance of V1 increases less load current flows through V1, the voltage drop across V1 increases, and the output voltage of the regulator circuit decreases to its original value.

The actions described in the preceding paragraphs are practically instantaneous; consequently, the output voltage, E_{out}, remains practically constant. Since all the load current must pass through the series regulator tube, V1, the tube must be capable of passing considerable current. In some circuit applications where the load current requirements exceed the capabilities of a single tube, two or more identical tubes are connected in parallel (as the sections of twin-triode V1 have been paralleled) in order to obtain suitable regulation characteristics and current-handling capability.

The output of the regulator circuit is coupled to the grid of pentode amplifier V3 through coupling capacitor C2. Any ripple component present in the output voltage is amplified in the regulator amplifier, and, since the circuit is basically a negative-feedback circuit, the ripple component is suppressed. As a result, the d-c regulator circuit is sensitive to any voltage changes and is very effective in removing any fundamental ripple-frequency component which is present in the regulated voltage output. Although there are many variations in the regulator-amplifier circuit configuration, the function of the d-c regulator circuit remains the same, that is, to supply a regulated output voltage to the load which is independent of variations in the input voltage or changes in the load current.

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FAILURE ANALYSIS.

General. The d-c regulator using a pentode and a twin-triode regulator amplifier includes several components which are rather critical and directly affect the operation of the regulator circuit. For this reason, the resistors in the regulator-amplifier circuit are normally close-tolerance (on the order of 1, 2, or 5 percent) resistors with good temperature stability characteristics. The operation of the circuit will be impaired if these resistors should change in value for any reason. Since the regulator circuit attempts to hold the output voltage constant, it is usually good practice to determine whether the load current is within tolerance before suspecting trouble within the regulator circuit proper. A load-current measurement may be made by inserting a milliammeter (having a suitable range) in series with the output of the regulator circuit. Also, a voltage measurement should be made at the input to the regulator circuit to determine whether the unregulated voltage output from the power supply (and filter circuit) is within tolerance.

No Output. In this d-c regulator circuit, the no-output condition is likely to be limited to one of the following possible causes: the lack of filament voltage applied to series regulator tube V1, the lack of applied d-c voltage (from the associated power supply and filter circuit), or a short-circuited load (including output capacitor C3). A visual check of the glass-envelope series regulator tube, V1, should be made to determine whether the filament is lit; if the filament is not lit, it may be open or filament voltage may not be applied. The tube filament should be checked for continuity; also, the presence of filament voltage at the tube socket should be determined by measurement. The d-c voltage applied to the regulator circuit should be measured at the input (plate of V1) to determine whether it is present and of the correct value, since the lack of input voltage from the associated power supply and filter circuit will cause a lack of output voltage. With the d-c voltage removed from the input to the circuit, resistance measurements can be made across the load to determine whether the load circuit, including capacitor C3, is shorted. (The resistance measured across the load circuit will normally measure something less than the total value of the voltage-divider resistors, depending upon the load circuit design.)

High Output. The high-output condition is usually caused by a decrease in operating bias for the series regulator tube, V1, which, in turn, causes the tube to decrease its internal resistance and permits the regulator output voltage to rise above normal. Therefore, any defects in the electronic regulator circuit which can cause a decrease in the operating bias for V1 should be suspected. Voltage measurements should be made at the socket of V1 to determine whether bias (cathode-to-grid) voltage is present. The series regulator tube, V1, may be checked by substitution of a tube known to be good to determine whether the tube is defective (grid-to-cathode short, etc).

A visual check of the gas-filled regulator tubes, V4 and V5, which provide the reference voltages for the operation of pentode amplifier V3, should be made to determine whether the tubes are conducting. A voltage measurement made between the plate and cathode of V4 or V5 will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage is above normal, the tube may be defective; a tube known to be good may be substituted to check for proper operation of the respective reference-voltage circuit. If the voltage measured across V4 is below normal, it is likely that resistor R10 or R11 is open. A below-normal voltage measurement across V5 will indicate that resistor R12, R13, or R14 is probably open.

A visual check of regulator-amplifier tubes V2 and V3 should be made to determine whether their filaments are lit; if the filaments are not lit, they may be open or the filament voltage may not be applied. The tube filaments should be checked for continuity; also, the presence of filament voltage at the tube sockets should be determined by measurement.

The bias voltages applied to V2 and V3 should be measured to determine whether these tubes are improperly biased, causing the operating bias on V1 to decrease. Assuming that V4 and V5 are conducting normally to provide the proper reference voltages, if the voltage at the grid of V2A or V3 is below normal, there will be an increase in the bias on the respective tube. In this case it is possible that resistor R6 or R7 has changed in value to increase the bias of V2A, or that resistor R12, R13, or R14 has changed in value to increase the bias of V3; in addition, an improper setting of variable resistor R13 will affect the bias voltage at the grid of V3. If V2A or V3 is biased to cutoff, V1 will be made to conduct heavily as a result of the decreased operating bias. In this case, it is likely that resistor R6 is open to cut off V2A, or that resistor R12 or the top portion of resistor R13 is open to cut off V3.

A high output from the regulator will also result when the voltage at the grid of V2B is above normal, thereby causing a bias decrease on this stage. This condition will result when pentode amplifier V3 is in cutoff because of a floating control grid or open cathode circuit. In the case of a floating control grid, it is likely that the bottom portion of resistor R13 or resistor R14 is open; and open cathode circuit of tube V3 will result if resistor R10 or R11 is open.

If the differential amplifier tube, V2, has low emission, the voltage drop across V2A plate-load resistor R1 will be below normal; therefore, the bias of V1 will be decreased and a high output from the regulator will result. Under this condition, a tube known to be good should be substituted for V2 and the operation of the circuit observed to determine whether tube V2 is the cause of the trouble. An open cathode resistor, R8, will produce the same effects as a defective differential amplifier tube.

Low Output. The low-output condition of the regulator is usually caused by an increase in operating bias for the series regulator tube, V1, which, in turn, causes the tube to increase its internal resistance and permits the regulator output voltage to fall below normal. Therefore, any defects in the electronic regulator circuit which can cause an increase in the operating bias for V1 should be suspected. Trouble in one section of V1 (such as low cathode emission or an open tube element) will cause a reduction in the output. The tube may be checked by substitution of a tube known to be good to determine whether the tube is defective. Voltage measurements should be made at the socket of V1 to determine whether the bias (cathode-to-grid) voltage is excessive. The equalizing resistors, R4 and R5, in the cathode circuits of V1 should be measured to determine that neither one is open, that they have not increased in value, and that they are of equal resistance.

A visual check of the gas-filled regulator tubes, V4 and V5, which provide the reference voltages for the operation of the pentode amplifier circuit, should be made to determine that the tube is conducting. A voltage measurement made between the plate and cathode of V4, and also between the plate and cathode of V5, will determine whether sufficient voltage is present at the tube to cause conduction. If the voltage measured across V4 is below normal, or if no voltage is present, it is likely that capacitor C1 is either leaky or shorted. A below-normal voltage measurement across V5 will indicate that capacitor C2 or C3 is probably either leaky or shorted.

The bias voltages applied to V2 and V3 should be measured to determine whether these tubes are improperly biased, causing the operating bias on V1 to increase. Assuming that V4 and V5 are conducting normally to provide the reference voltages, if the voltage at the grid of V2A or V3 is above normal, there will be a decrease in the bias on the respective tube. In this case, it is possible that resistor R6 or R7 has changed in value to decrease the bias of V2A, or that resistor R12, R13, or R14 has changed in value to decrease the bias of V3; in addition, an improper setting of variable resistor R13 will affect the bias voltage at the grid of V3. If V2A or V3 is biased by a high positive voltage on its grid so that either tube conducts heavily, V1 will be made to conduct less as a result of an increased operating bias. In this case, it is likely that capacitor C2 is leaky or shorted, thus placing a high positive voltage on the grid of V3. A high positive voltage will be placed on the grid of V2A if resistor R7 is open.

If plate-load resistor R1 (for differential amplifier V2) is open, the bias voltage applied to the grids of V1 will be made larger, causing a decrease in the regulator output. Also, if tube V2 is shorted and conducting heavily, the voltage drop across plate-load resistor R1 will be excessive; therefore, a tube known to be good should be substituted and the operation of the circuit observed to determine whether tube V2 is the cause of the trouble. If pentode amplifier tube V3 has high emission, the voltage drop across its plate-load resistor, R9, will be above normal; therefore, the bias of V2B will be increased, thus causing an increase in the bias of V1 and a decrease in the output of the regulator. A tube known to be good should be substituted for V3, and the operation of the circuit observed to determine whether tube V3 is the cause of the trouble. If resistor R9 is open, the cathode follower (V2B) control grid will be floating; this will cause the cathode follower to cut off. As a result, the regulator output will decrease.

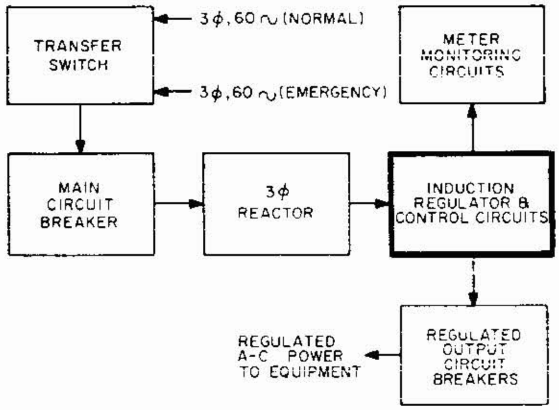
As mentioned previously, excessive load current can cause the output voltage to be low, especially if the load current exceeds the maximum rating of series regulator tube V1 (resulting in excessive voltage drop across V1) or if the load current exceeds the rating of the power supply (resulting in a decrease in the applied voltage). For these reasons, output capacitor C4 should be checked to determine whether it is satisfactory. A leaky output capacitor could result in reduced output voltage, although the regulator-amplifier circuit (V2 and V3) may be functioning normally but still be unable to compensate for the decrease in output.

Poor Regulation Characteristics. Voltage instability, slow response, etc, are frequently caused by weak or unbalanced triode sections in series regulator tube V1, unbalanced cathode resistors R4 and R5, or defective regulator amplifier tubes V2 and V3. The gain of the regulator-amplifier stage is determined primarily by tubes V2 and V3 and their applied voltages; therefore, the condition of V2 and V3 and the applied voltages are important factors governing satisfactory operation of the regulator circuit.

ELECTROMAGNETIC REGULATORS.

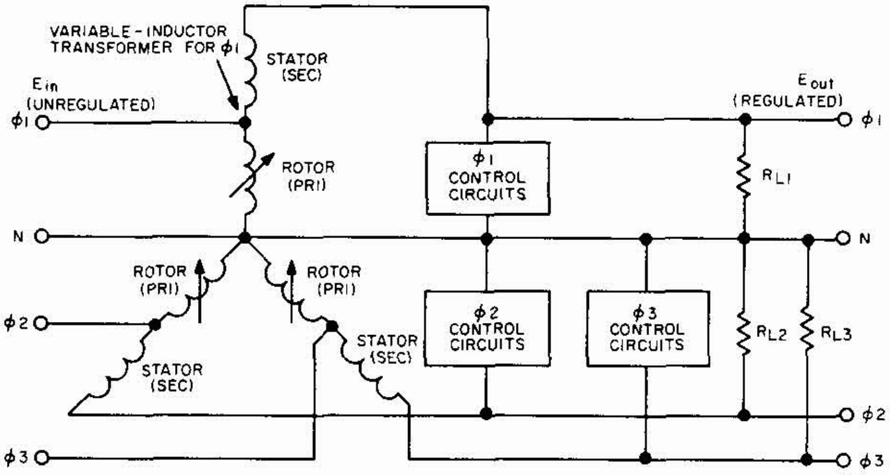
General. Electromagnetic regulators are automatic devices which are magnetic rather than electronic or mechanical in nature. These regulators are of two basic types: the induction regulator, which employs a variable-inductor transformer, and the saturable-core-reactor regulator An application of the induction regulator is its use in an a-c power regulator and distribution system wherein the unregulated power from the generating source is converted into a form required by the electronic systems or equipment at a particular facility or installation. The saturable-core-reactor regulator is used in such applications as the regulation of the a-c voltage input to an electronic equipment or the equipment's power supply, or the regulation of the d-c voltage output from the power supply in a given electronic equipment. Each of the two types of electromagnetic regulators will be discussed in the following paragraphs.

Induction Regulator. An example of an induction regulator used in an a-c regulation and distribution system is illustrated in the accompanying block diagram . The input power (in this case, three-phase, 60-cps ac) is applied through a transfer switch that automatically connects to an emergency power source when the normal source voltage between any phase and the neutral line falls below a predetermined level. When the normal source voltage returns to the proper level, the transfer switch again connects to the normal source.
After passing through the transfer switch, the input power is applied through the system main circuit breaker to a three-phase reactor. The purpose of the three-phase reactor is to limit any short-circuit currents within the system to a preselected value of the regulator full-load current for any one phase. The reactor opposes large, rapid changes of current until a circuit breaker trips and opens the circuit; in this manner the system is protected and the effects of short circuits are localized. The output from the three-phase reactor is applied to the induction regulator and its associated control circuits. The regulated a-c output is then fed through a circuit-breaker panel to the applicable equipment. Voltage and current meters monitor the load voltages and currents at the output of the induction regulator.



A-C Regulation and Distribution System Using Induction Regulator

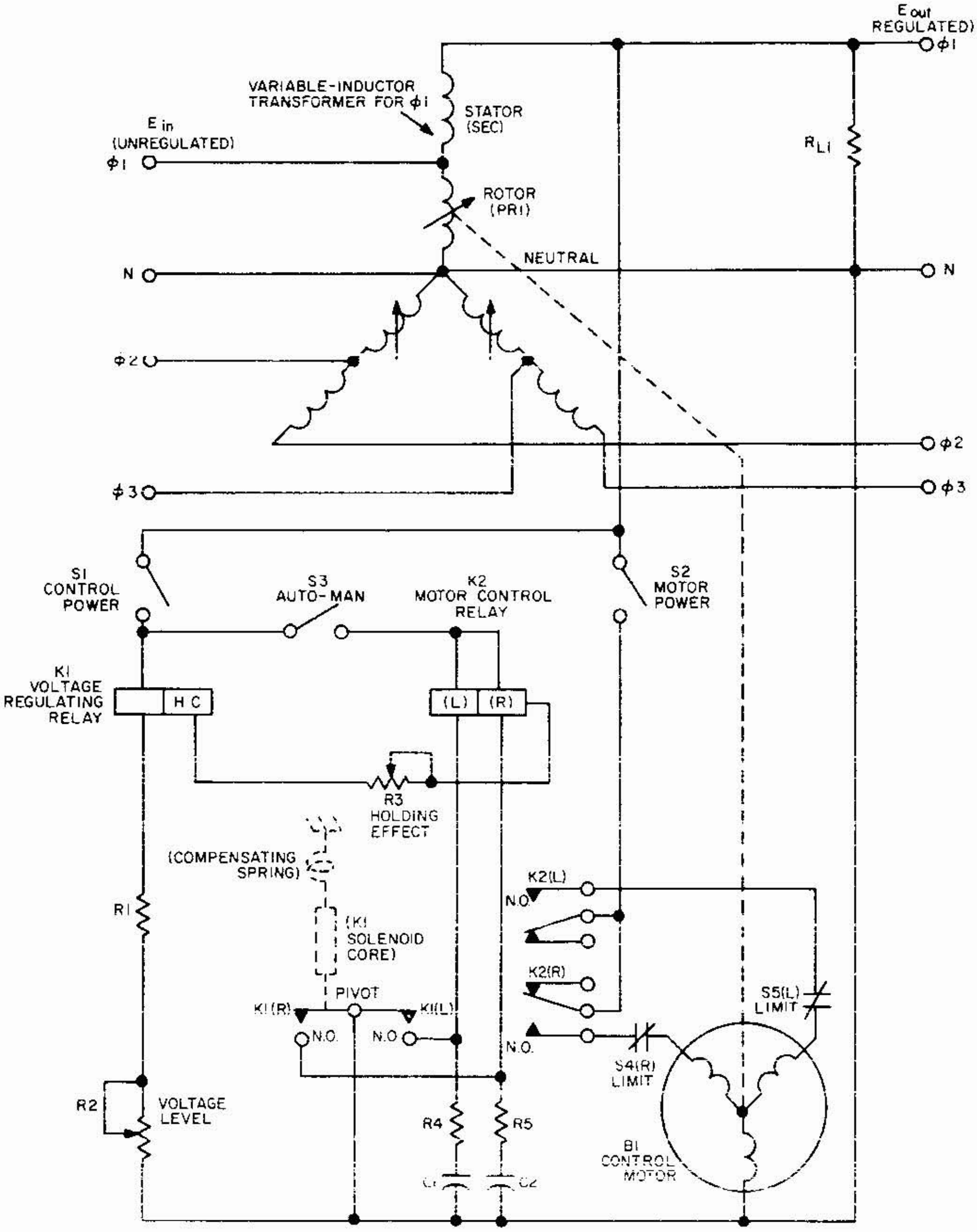
A simplified diagram of a three-phase induction regulator and its control circuits is given in the accompanying figure. The voltage-regulating component of this regulator is a variable-inductor transformer which is split into a rotating section and a stationary section. The rotating section, or rotor, for each phase is connected across the input line; hence, it is in parallel with the load (R_L) for that phase. The stationary section, or stator, for each is connected in series with the input line; hence, it is in series with the load for that phase. A variation in the output (load) voltage is obtained by rotating the rotor inside the stator to change their flux linkage in both magnitude and direction. Thus, depending upon their relative angular positions, the rotor induces in the stator a voltage that either aids or opposes the line voltage. When the stator voltage aids the rotor voltage, the load voltage is greater than the input voltage. That is, the load voltage will be maximum when both the flux linkage between rotor and stator and the voltage induced in the stator are maximum and the stator voltage is in phase with the rotor voltage. When the rotor is turned 180 degrees, both the flux linkage between rotor and stator and the voltage induced in the stator will again be maximum, but the voltage induced in the stator will be out of phase with the rotor voltage. Hence, at this time the stator voltage opposes the rotor voltage and the load voltage is minimum. For relative angular positions of rotor and stator between the extremes noted, the load voltage likewise will be a value between the maximum and minimum extremes.



Three-Phase Induction Regulator, Simplified Diagram

The rotation of the rotor is accomplished by a reversible motor, which, in turn, is controlled by the action of two relays; this arrangement is illustrated schematically in the accompanying diagram. In a typical application of an induction regulator, a variable-inductor transformer and its associated control circuits are placed in each phase line of the distribution system. In this case, however, only the control circuits for phase 1 will be analyzed; the phase 2 and phase 3 control circuits are identical to those of phase 1, and thus will not be considered in this discussion. The output voltage of the selected-phase variable-inductor transformer is sensed by a voltage-regulating relay, K1, which causes a motor-control relay, K2, to operate a reversible motor. The motor, B1, drives the rotor of the applicable variable-inductor transformer in the direction necessary to compensate for the output-voltage variation.

The sensing element of voltage-regulating relay K1 is an iron-core solenoid, which is suspended on a compensating spring. (The solenoid core and compensating spring are shown dotted in the illustration.) The solenoid current is made proportional to the output voltage by inserting limiting resistors R1 and R2 in series with the solenoid coil. In this manner, the solenoid current is maintained constant for a given voltage, and yet it can still change with the voltage to be regulated. A holding coil is wound in the opposite direction over the solenoid coil of K1; the holding coil, HC, is excited through the tapped sections of the K2 motor-control relay coils. The purpose of the holding coil is twofold: to modify the "pull" of the K1 solenoid, and to hold the contacts of K1 closed until the control motor has caused the variable-inductor transformer to correct the output voltage. When voltage-regulating relay K1 is in operation for a normal output voltage, the pull of its solenoid, which varies with the current through the coil, and the tension of the compensating spring are balanced against the weight of the solenoid core. The solenoid core operates a set of single-pole, double-throw contacts mounted on opposite ends of a pivoted beam and separated by equal distances from the stationary contacts; one normally open contact of the set closes when the output voltage increases, and the other normally open contact of the set closes when the output voltage decreases. This action causes voltage-regulating relay K1 to operate motor-control relay K2, which, in turn, causes control motor B1 to turn and thus rotate the rotor of the variable-inductor transformer to correct the output voltage when this voltage is higher or lower than normal. In the accompanying diagram, the symbols (L) and (R) denote the components that produce the action necessary to "lower" and "raise" the output voltage, respectively.



NOTES:
1 (R)-RAISE
2 (L)-LOWER
3 HC-HOLDING COIL FOR K1
4 N.O.-NORMALLY OPEN CONTACT

Induction Regulator and Control
Circuit for Phase 1

Consider, now, the operation of the induction regulator when the output voltage of phase 1 increases above the level determined by the setting of voltage-level potentiometer R2. To energize the control circuits, including the control motor, control-power switch S1, motor-power switch S2, and auto-manual switch S3 must all be set to the "on" position. Since the output voltage is higher than normal, the control motor must rotate the rotor of the variable-inductor transformer in the direction which will lower the voltage; this is accomplished in the manner described below. The higher-than-normal output voltage of phase 1 causes an increase in the current through the solenoid coil of voltage-regulating relay K1. The stronger magnetic field resulting from the increased current exerts a greater pull and draws the solenoid core farther into the coil, thus relaxing the tension on the compensating spring. When the tension on this spring is relaxed sufficiently, the normally open contacts on the K1 (L) section of the voltage-regulating relay close. When this occurs, the "lower" (L) coil of motor-control relay K2 energizes and closes the normally open (N.O.) contacts on the K2(L) section of this relay. Closing the K2(L) contacts of the motor-control relay applies a voltage to the control motor, B1, thus energizing the motor and causing it to turn to the "lower" direction. The control motor is mechanically coupled to the rotor of the phase 1 variable-inductor transformer. Therefore, when the motor turns, it also turns the rotor of the variable-inductor transformer in the direction which will cause less flux linkage between the rotor (primary) and the stator (secondary). As a result, there will be less voltage induced in the stator; that is, since the stator, or output, voltage varies with the flux linkage between the rotor and the stator, reducing the flux linkage causes a reduction in the output voltage.

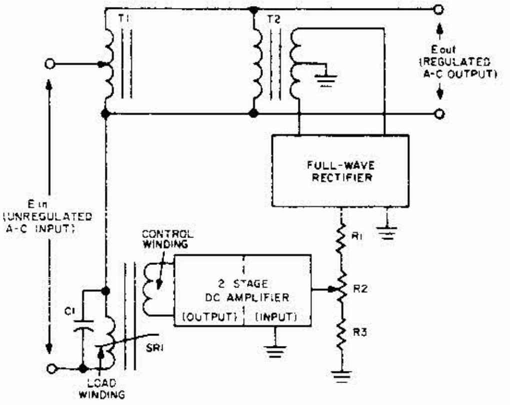
The control motor turns the rotor of the variable-inductor transformer until the output voltage again becomes normal. As this point is approached, the current through the solenoid coil of voltage-regulating relay K1 decreases, since this current is proportional to the output voltage. Thus, at the predetermined level of output voltage, sensed by the current through the coil of K1, the weaker magnetic field resulting from the decreased current exerts a lesser pull on the solenoid core of K1, so that the weight of the core and the tension of the compensating spring are again in balance. When this occurs, the (K1(L) contacts of the voltage-regulating relay open, thereby causing the "lower" (L) coil of K2 to de-energize and, in turn, to open the K2(L) contacts of the motor-control relay. Opening the K2(L) contacts of the motor control relay removes the energizing voltage from control motor B1, and the motor stops turning. When the motor stops turning, the rotor of the variable-inductor transformer also stops turning, and remains stationary at the normal output-voltage level until a further variation from normal occurs.

Assume that the output voltage of phase 1 now decreases below the predetermined level established by the setting of potentiometer R2. Since the output voltage is lower than normal, the control motor must turn the rotor of the variable-inductor transformer in the direction which will raise the voltage; this is accomplished in the manner described below. The lower-than-normal output voltage of phase 1 causes a decrease in the current through the solenoid coil of voltage-regulating relay K1. The weaker magnetic field resulting from the deceased current exerts a lesser pull on the solenoid core and thereby releases the core from the coil; the additional weight of the core now increases the tension on the compensating spring. When the solenoid core is released sufficiently, its weight causes the normally open contacts on the K1(R) section of the voltage-regulating relay to close. When this occurs, the "raise" (R) coil of motor-control relay K2 energizes and closes the normally open (N.O.) contacts on the K2(r) section of this relay Closing the K2(R) contacts of the motor-control relay applies a voltage to the control motor, B1, thus energizing the motor and causing it to turn in the "raise" direction. The control motor is mechanically coupled to the rotor of the phase 1 variable-inductor transformer. Therefore, when the motor turns, it also turns the rotor of the variable-inductor transformer in the direction which will cause more flux linkage between the rotor (primary) and the stator (secondary). As a result, there will be more voltage induced in the stator; that is, since the stator, or output, voltage varies with the flux linkage between the rotor and the stator, increasing the flux linkage causes an increase in the output voltage.

The control motor turns the rotor of the variable-inductor transformer until the output voltage again becomes normal. As this point is approached, the current through the solenoid coil of voltage-regulating relay K1 increases, since this current is proportional to the output voltage. Thus, at the predetermined level of output voltage, as sensed by the current through the coil of K1, the stronger magnetic field resulting from the increased current exerts a greater pull on the solenoid core of K1, so that the weight of the core and the tesnion of the compensating spring are again in balance. When this occurs, the K1(R) contacts of the voltage-regulating relay open, thereby causing the "raise" (R) coil of K2 to de-energize and, in turn, to open the K2(R) contacts of the motor-control relay. Opening the K2(R) contacts of the motor-control relay removes the energizing voltage from control motor B1, and the motor stops turning. When the motor stops turning, the rotor of the variable-inductor transformer also stops turning, and remains stationary at the normal output-voltage level until a further variation from normal occurs.

As previously explained, the voltage-regulating component of the induction regulator is the variable-inductor transformer, and the voltage-sensing element is the voltage-regulating relay, K1. The setting of voltage-level potentiometer R2, which is in series with the coil of relay K1, determines the desired normal-output-voltage level by establishing the initial magnitude of current to determine the amount of pull on the solenoid core of K1 required to just balance the tension of the compensating spring. Thus, the current through the coil of K1 will remain constant as long as the output voltage is normal; when the output voltage changes (increases or decreases), the magnitude of the current will change proportionally and cause the induction regulator to compensate for the change in voltage. By establishing the magnitude of current through the holding coil of relay K1, the setting of holding-effect potentiometer R3 determines the modified pull of the solenoid core and the length of time that the K1 contacts are held closed. In this manner, the holding coil helps the regulator control circuit to rapidly stop the rotor of the variable-inductor transformer when the output voltage reaches the predetermined normal level. The resistor-capacitor networks, R4-C1 and R5-C2, in the "lower" and "raise" sections, respectively, of motor-control relay K2 are used for arc suppression. Switches S4(L) and S5(R) are limiting switches in the "lower" and "raise" power-input lines to the control motor; these switches cut off power to the control motor and thereby prevent mechanical damage by preventing the motor from exceeding the desired maximum rotation in the respective directions.

Saturable-Core-Reactor Regulator. An example of a saturable-core-reactor regulator used in the regulation of an a-c voltage is illustrated in the accompanying simplified diagram. In this application, the saturable-core reactor is used to regulate the a-c voltage applied to an electronic equipment or to the power supply within an equipment. The degree of saturation of the reactor core is controlled by a two-stage d-c amplifier, the bias of which is provided by a full-wave rectifier that receives its input voltage from the regulated output. Before the discussion of the saturable-core reactor regulator is continued, a brief review of the operation of a saturable-core reactor will be presented.



Regulation of A-C Voltage with Saturable-Core Reactor

A saturable-core reactor (or simply "saturable reactor") is a device consisting of one or more coils of wire, or windings, placed on an iron core which has special magnetic properties. Thus, a saturable reactor resembles a transformer in that it has windings on an iron core. However, it differs from a transformer in that the reactor operates in the region of core saturation during part of each a-c input cycle. The basic operating principle of a saturable reactor is self-induction, or that electromagnetic characteristic wherby a counter electromotive force is produced in a winding by a magnetic field which changes with the changes in current through the winding. The magnetic field concentrates in the iron core, and the flux density in the core varies directly with the current through the winding up to the point of core saturation. That is, when the current in a winding is increased from zero, the magnetic field surrounding each turn of the winding expands and cuts the other turns. As a result, a voltage is induced in the winding; this voltage opposes the applied voltage and tends to keep the current in the wire at a low value. While the current through the winding is less than the saturation current, the opposition (inductive reactance) of the winding is high and permits little current to flow. When the current is increased to the point where the core is saturated, the reactance becomes zero because the rate of change of flux density is zero. Thus, when the core becomes saturated, an increase in current in the winding will no longer increase the flux density in the core; at this time, since the reactance is zero, only the d-c resistance of the wire limits the current through the winding. When the current through the winding is decreased from a maximum value, the magnetic field begins to collapse and cut the turns of the winding. Again a voltage is induced in the coil. This voltage is opposite in direction to that which was induced by the rising current and the expanding magnetic field. Consequently, the voltage induced by the collapsing field tends to keep the current in the wire at a high value, even though it is decreasing toward zero.

A practical saturable reactor is different from an ordinary iron-core coil (just described) in that there are two windings associated with the core, as shown by the SR1 component in the accompanying figure. One of the windings is called the control winding, and the other is called the load winding. The control winding is in the plate circuit of the output stage of the two-stage d-c amplifier, and the load winding is in the input circuit of the a-c- voltage applied from the source. Thus, the variation in impedance of the input circuit, of which the saturable reactor load winding is a part, can be used to regulate voltages in a manner similar to the use of the variable resistance characteristic of an electron tube.

The components in the circuit of the accompanying figure may be grouped into three sections: input, rectification, and sensing-control. The input a-c is applied across autotransformer T1, which is in series with the load winding of saturable reactor SR1. Capacitor C1, which is across the load winding, forms a tuned circuit with the load winding. The resonant frequency to which the parallel circuit of capacitor C1 and the load winding is tuned is slightly lower than the input line frequency; that is, it is one the inductive slope of the line frequency impedance curve. This resonant frequency is selected so that the input circuit always appears inductive, even when the input circuit impedance, which includes autotransformer T1, is shifted to increase or decrease the amount of apparent inductance in the circuit. Therefore, the input line voltage will be divided proportionally between autotransformer T1 and saturable reactor SR1, as determined by their impedance ratio.

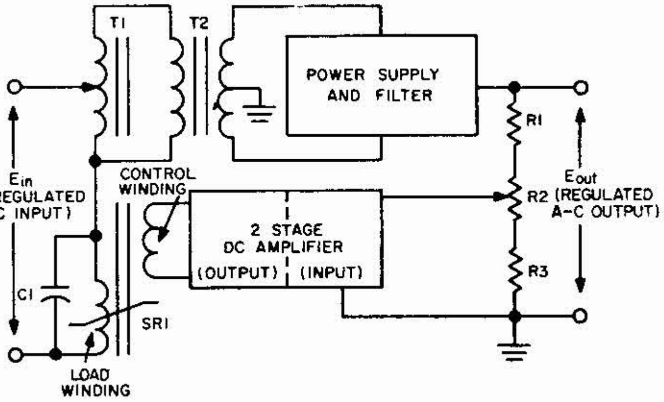
The circuit operates in the manner described below. The unregulated a-c input voltage, Ein, is applied across autotransformer T1 and the load winding of saturable reactor SR1 connected in series. The autotransformer feeds power transformer T2, which is part of a conventional full-wave rectifier circuit. The d-c output of the rectifier is developed across a voltage divider consisting of resistors R1, R2, and R3; the voltage divider provides the bias voltage for the input stage of the two-stage d-c amplifier. The bias voltage, as selected by the setting of variable resistor R2, controls the conduction of the d-c amplifiers, and thereby controls the resultant current through the control winding of saturable reactor SR1. Adjustment of autotransformer T1 and variable resistor R2, therefore, determines the value of the desired a-c output voltage, E_{out}, to be regulated; any variations from the desired value of output voltage will be automatically compensated for by the action of the regulating circuit.

Assume, first, that there is an increase in the a-c output voltage, E_{out}. The increased a-c voltage coupled to the secondary of power transformer T2 results in a greater d-c voltage across the voltage divider in th output of the rectifier. Thus, a higher positive voltage is sensed at the wiper arm of variable resistor R2, thereby causing a decrease in the bias of the input d-c amplifier which. This decrease in bias causes an increase in the conduction of the input d-c amplifier which, in turn develops a bias on the output d-c amplifier and decreases the conduction of the output stage. As a result, the current through the control winding of saturable reactor SR1 is reduced, thereby decreasing the degree of saturation of the reactor core. The saturable reactor now presents a greater impedance to the a-c input voltage, thus permitting a greater voltage to be dropped across the reactor, and, consequently, lowering the voltage applied to autotransformer T1. With less voltage coupled from the autotransformer, the output voltage decreases; thus, the a-c output voltage is returned to the value desired initially.

Consider, now, the analysis of the circuit operation for the condition of a decrease in the a-c output voltage, E_{out}. The decreased a-c voltage coupled to the secondary of power transformer T2 results in a lower d-c voltage across the voltage divider in the output of the rectifier. Thus, a lower positive voltage is sensed at the wiper arm of variable resistor R2, thereby causing an increase in the bias of the input d-c amplifier, This increase in bias cause a decrease in the conduction of the input d-c amplifier, which, in turn, decreases the bias on the output d-c amplifier and increases the conduction of the output stage. As a result, the current through the control winding of saturable reactor SR1 is increased, thereby increasing the degree of saturation of the reactor core. The saturable reactor now presents a lower impedance to the a-c input voltage, thus permitting less voltage to be dropped across the reactor, and, consequently, raising the voltage applied to autotransformer T1. With a greater voltage coupled from the autotransformer, the output voltage increases; thus, the a-c output voltage is returned to the value desired initially.

The circuit will also compensate for variations in the unregulated a-c input voltage, E_{in}. For an increase in the input voltage, the circuit operation is the same as previously described for an increase in the output voltage; also, for a decrease in the input voltage, the circuit operation is the same as previously described for a decrease in the output voltage. Although the configuration of the circuitry of the d-c amplifiers may vary in the regulator circuit, the purpose of this section is always to sense the variation in the voltage coupled to the rectifier, and then to control the degree of core saturation of the saturable reactor to compensate for the variation in voltage.

With slight modifications the saturable-core reactor regulator circuit just described can be used for regulating the d-c voltage output of an equipment's power supply; such a modified circuit is illustrated in the accompanying figure. Note that the fullwave rectifier of the previous circuit is omitted, and the output of the power supply is used in its place to furnish the bias voltage for the input powered supply controls the a-c input voltage to the power supply, to provide regulation. Otherwise, the circuit function and operation in all respects are the same as described previously under this heading.



Regulation of D-C Voltage with Saturable-Core Reactor

PART B. SEMICONDUCTOR CIRCUITS

SEMICONDUCTOR REGULATORS

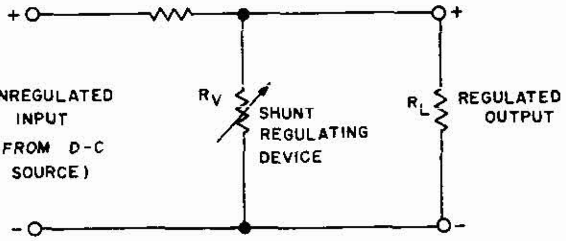
General. The semiconductor voltage regulator performs the same function in a power supply circuit as the electron tube-type regulator.. In the place of tubes, solid state devices are utilized to accomplish regulation. In a manner similar to the electron-tube-type, the semiconductor circuit reacts automatically to compensate for changes in the input voltage and load current and provide a constant output voltage to the load.

Although a variety of circuit arrangements are possible for semiconductor voltage regulators, they are generally of two basic types: the shunt type and series type. Operation of the shunt-type is similar to that of the electron-tube gaseous-type voltage regulator. It is commonly used where input voltage variations are small and the load remains relatively constant. Most applications require the series-type regulator. The series type is a more efficient regulator and is used in power-supply applications where the load resistance and input voltage are large. Variations of the basic series-type semiconductor regulator include the constant-current regulator and the switching regulator. Where a constant current rather than a constant voltage is the primary requirement, the series current regulator is employed. Typical switching-type regulators include the silicon-controlled-rectifier regulator, the transistor-phased-rectifier regulator, and the transistor-chopper regulator.

When good stability is required, and the input voltage and load current are subject to excessive variation, a regulator-amplifier circuit is employed in the shunt- and series-type regulators. Essentially, the regulator-amplifier circuit in semiconductor regulators is a high-gain, direct-coupled amplifier having low noise and good stability characteristics. In direct-coupled amplifiers using semiconductors, drift caused by temperature changes during operation is always a design problem; therefore, a regulator-amplifier circuit using semiconductors is always a more complex circuit than is its electron-tube equivalent. Moreover, the voltage stability of the semiconductor reference-voltage circuit with respect to temperature changes is another important design consideration. As a result of these and other design problems, it is necessary to provide temperature compensation at critical points throughout the circuit in order to obtain the best possible overall performance characteristics for the semiconductor regulator circuit.

Shunt-Type Regulator. The shunt-type regulator, while one of the simplest semiconductor regulators, is usually the least efficient. It may be used to provide a regulated output where the load is relatively constant, the voltage low to medium, and the output current high. The shunt regulator utilizes the voltage-divider principle to obtain regulation of the output voltage.

The accompanying illustration shows the shunt-type regulator reduced to its fundamental form. The fixed resistor, R_S, is in series with the parallel combination of the load resistance, R_L, and the variable resistor, R_v, and forms a voltage divider across the input circuit.



Simple Shunt-Type Voltage-Regulator Circuit

A brief operational description of the basic shunt-type regulator will serve to explain the manner in which regulation of the output voltage is achieved.

All current that flows in the complete circuit passes through the series resistance, R_S. The magnitude of this current, and thus the valve of the voltage drop across R_S, is controlled by variable resistance R_v. The voltage across R_S is equal to the difference between the larger voltage of the d-c source and the output voltage across load resistance R_L. The difference voltage across R_S is varied by action of resistance R_v, as required, to compensate for circuit changes and maintain the output voltage to the load constant at the desired value.

If the input voltage to the regulator circuit decreases, the voltage across load resistance R_L and the variable resistance, R_v, tends to decrease. To counteract this decrease, the resistance of R_v is increased; this reduces the total current flow through R_S and thereby the voltage drop across it. Thus, by decreasing the difference voltage of R_S to compensate for the decrease in the input voltage, the output voltage remains constant at its nominal value. Conversely, if the input voltage increases, the voltage across R_L and R_v tends to increase. To counteract the increase, the resistance of R_v is decreased; this results in more current through R_S and thus an increase in the voltage drop across it. The increase in the difference voltage compensates for the increase in the input voltage, and again, the output voltage remains constant at the regulated value.

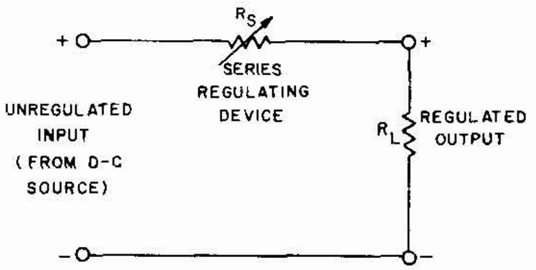
The shunt regulator must be capable of withstanding the entire output voltage of the d-c source; however, it does not have to carry the full load current unless it is required to regulate from the no-load to the full-load condition. Since series dropping resistor R_S, used with the shunt regulator, has relatively high power dissipation, the over-all efficiency of this type of regulator may be less than that of other types. One advantage of the shunt-type regulator is the inherent overload and short-circuit protection offered. This is because the series resistance, R_S, is between the d-c source and the load; thus, a short circuit or overload merely decreases the output voltage drom the regulator circuit. Note that under no-load conditions, however, the shunt regulating device must dissipate the full output; therefore, the shunt-type regulator is most often used in constant-load applications.

From the general discussion given in the preceding paragraphs, it can be seen that the shunt-type voltage regulator is essentially a voltage-divider circuit, with the output voltage produced across the load being held essentially constant, regardless of input voltage or load current variations. The control action required to vary the resistance of R_v, and, consequently, to produce a variable-voltage drop, is completely automatic. This basic principle of voltage regulation is used in the transistorized, shunt-type voltage regulators to be described later in this section of the handbook.

Series-Type Regulator. The series-type regulator, as the name implies, places the regulating device in series with the load; regulation occurs as the result of varying the voltage drop across the series device. The series regulator is preferable for high-voltage and medium-output-current applications where the load may be subject to considerable variation. Most critical semiconductor applications requiring a regulated voltage source utilize the series-type regulator; as a result, there are many regulator circuit configurations. These circuit configurations vary from one application to another, depending upon the regulation required to be maintained over a given temperature range. The series-type regulator employs a regulator-amplifier circuit which has the same basic function as the regulator-amplifier circuit in the electron-tube regulator.

The series-type regulator can be compared to a variable resistance in series with the d-c source and the load, thus forming a voltage divider; the variable-resistance action of the series regulating device maintains the output voltage across the load resistance at a constant value.

A simple series-type voltage-regulator circuit is shown in the accompanying illustration to help explain this principle of voltage regulation.



Simple Series-Type Voltage-Regulator Circuit

The variable resistor, R_S, is in series with the load resistance, R_L; thus, the two resistances in series form a voltage divider across the input voltage. The load current passes through R_S, and causes a voltage drop to occur across it. The voltage drop across R_S depends upon the value of resistance of R_S and the load current through it. Since the input voltage to the regulator circuit is always greater than the desired output voltage, the voltage drop across series resistor R_S is varied to obtain the desired value of output voltage across load resistance R_L.

If the input voltage to the regulator circuit decreases, the voltage across load resistance R_L and variable resistor R_S also decreases; to counteract this voltage decrease, the resistance of variable resistor R_S is decreased so that a smaller voltage drop occurs across R_S, and the voltage across the load resistance returns to its former value. Conversely if the input voltage to the regulator circuit increases, the voltage across load resistance R_L also increases; to counteract this voltage increase, the resistance of R_S is increased so that a larger voltage drop occurs across R_S, and the voltage across the load returns to its former value.

In a practical transistorized series-type regulator, the series regulating device must be capable of carrying the full-load current of the regulator. Regulation is performed by sampling the output voltage taken from a voltage divider and comparing this sample voltage with a reference voltage; any deviation from the desired output voltage when compared with the reference voltage represents an error voltage, which is amplified and used to control the series device. It is interesting to note that a simple shunt-type regulator, using a breakdown (Zener) diode, is frequently employed as the reference-voltage source or as a preregulator in more complex series-type regulators.

From the general discussion given in the preceding paragraphs, it can be seen that the series-type (as well as the shunt-type) voltage regulator is essentially a voltage-divider circuit, with the output voltage produced across the load being held essentially constant, regardless of input voltage or load current variations. The control action required to vary the series regulating device, and, consequently, to produce a corresponding variable-voltage drop, is completely automatic. This basic principle of voltage regulation is used in the transistorized, series-type voltage regulators to be described later in this section of the handbook.

BREAKDOWN DIODE SHUNT-TYPE REGULATOR.

APPLICATION.

The breakdown-diode shunt-type regulator is used as a voltage regulator where the load is relatively constant. This circuit is frequently used in more complex regulator circuits as a reference-voltage source and as a preregulator in transistorized series-type regulators.

CHARACTERISTICS.

Uses a breakdown, or Zener, diode as shunt regulating device.

Regulated output voltage to load is nearly constant, even though changes in input voltage or changes in load current occur.

Voltage-divider principle employed, using fixed resistance and breakdown diode in series; regulated load is taken from across diode.

Variation in basic circuit permits positive or negative voltages to be regulated.

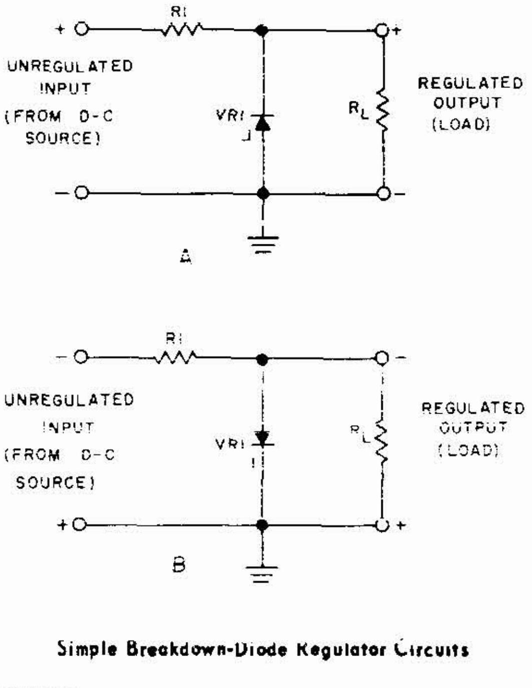
CIRCUIT ANALYSIS.

General. The breakdown-diode regulator is the simplest form of shunt-type regulator. The regulator circuit consists of a fixed resistor in series with a breakdown, or Zener, diode. The regulated output voltage is developed across the diode; therefore, the load is connected across the diode. The regulator circuit develops a definite output voltage which is dependent upon the characteristics of the particular breakdown diode; breakdown diodes are presently available with voltage ratings between 2 and 20 volts, in 5-, 10-, and 20-percent tolerances, and with power dissipation ratings as high as 50 watts.

The breakdown, or Zener, diode is a PN junction which has been modified during its manufacture to produce a specific breakdown voltage level; it operates with a relatively close voltage tolerance over a considerable range of reverse current. The breakdown diode is subject to a variation in resistance with a change in temperature of the diode; a circuit which compensates for this change in resistance is discussed later. The basic theory for the breakdown diode is discussed in Section 3, General Information on Semiconductor Circuits.

Circuit Operation. In the accompanying circuit schematics, parts A and B illustrate a breakdown diode used in a basic voltage-regulator circuit. The two parts are identical in configuration to the electron-tube, gaseous-type voltage regulators discussed earlier in this section of the handbook. Resistor R1 is the series resistor; semiconductor VR1 is a breakdown, or Zener, diode. The circuit in part A provides regulation of a positive input voltage, while the circuit in part B provides regulation of a negative input voltage.

The design of the breakdown-diode regulator differs from that of the gas-tube regulator circuit in that no "firing", or "ionizing", potential must be considered when the value of the series resistance is determined. It is likely that both the input voltage and the load current for the regulator will be subject to variation; therefore, the breakdown-diode regulator is designed to operate within the extremes to be encountered. The series resistor, R1, needs only to stabilize the load; it compensates for any difference between the diode operating voltage and the unregulated input voltage. The value of the series resistor depends upon the combined currents of the breakdown diode and the load. The series resistor is generally chosen with the following factors in mind: the minimum value of input voltage (unregulated), the maximum value of load current, the minimum value of breakdown-diode current, and, knowing the diode characteristics, the value of the highest voltage to be developed across the breakdown diode and its parallel load resistance. Once the value of series resistor R1 is determined, the maximum power dissipation in the diode can be arrived at by considering the maximum value of input voltage (unregulated), the minimum value of load current, and the minimum value of voltage developed across the diode (using the value of series resistance established for R1). In order to obtain stable operation, the breakdown diode must be operated so that its reverse current falls within its minimum and maximum ratings for the specified voltage. It is important to note that under no-load conditions, the breakdown diode must dissipate the full output power; therefore, this regulator circuit is never used in applications where a no-load condition is likely to exist. Instead, the breakdown-diode regulator is most often used in applications where the output voltage is fixed and the load current is relatively constant.

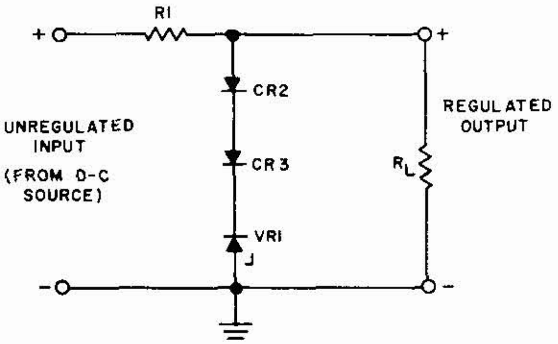


Simple Breakdown-Diode Regulator Circuits

If the input voltage to the regulator circuit decreases, the voltage decrease appears across the breakdown diode, VR1, and immediately the current through the diode decreases; thus, the total current through series resistor R1 decreases, and the voltage drop across R1 decreases proportionately, so that for all practical purposes the output voltage across the load resistance (and breakdown diode) remains the same. Conversely, if the input voltage to the regulator circuit increases, the voltage increase appears across the breakdown diode, and immediately the current through the diode increases; thus, the total current through series resistor R1 increases, and the voltage drop across R1 increases proportionately, so that for all practical purposes the output voltage across the load resistance (and diode) remains the same.

If the current drawn by the load resistance decreases, the total current drawn from the input source does not change; instead, a corresponding increase in current through the breakdown diode occurs and the current drawn from the source remains constant, so that the output voltage across the load resistance (and diode) remains constant. Conversely, if the current drawn by the load resistance increases, the total current drawn from the input source does not change; instead, a corresponding decrease in current through the breakdown diode occurs and the current drawn from the source remains constant, so that the voltage across the load resistance (and diode) remains constant.

Environmental temperature extremes, as well as junction temperature changes, may result in variations of the internal impedance of the breakdown diode, which, in turn, results in changes of the output voltage. Thus, in practical circuits, provisions must be made to compensate for any variation of the impedance of the breakdown diode. The temperature coefficient of resistance of the breakdown diode is normally several times larger than the negative temperature coefficient of resistance of either the forward-biased or reversed-biased junction diode. To obtain a zero coefficient of resistance over a wide range of temperatures, one commonly used method of temperature compensation uses negative-temperature devices, such as forward-biased diodes or thermistors, in series with the breakdown diode. This method is illustrated in the accompanying diagram.



Temperature-Compensated Voltage-Regulator Circuits

The negative temperature coefficient of resistance of diodes CR2 and CR3 in series equals the positive temperature coefficient of resistance of the breakdown diode, VR1. By using forward biasing for diodes CR2 and CR3, the voltage drop across them will be kept to a minimum and, consequently, will have negligible effect on the value of the output voltage.

When the voltage-regulator circuit is temperature-compensated as described above, the total resistance of VR1, CR2, and CR3, in series, remains constant over a wide range of temperatures; the end result is a constant voltage output, even though temperature, applied input voltage, or load current may change during operation.

Silicon breakdown diodes are generally used as the reference-voltage source in the more complex transistorized regulators because the breakdown voltage of a silicon breakdown diode is relatively constant over a wide range of reverse current.

FAILURE ANALYSIS.

General. The shunt-type voltage-regulator circuit should never be operated without a load, since the no-load condition causes the breakdown diode to conduct heavily and it must dissipate power which is normally dissipated by the load resistance. In this case, if the maximum power dissipation or maximum reverse current rating of the breakdown diode is exceeded for any length of time, the diode may be damaged; thus, breakdown diode VR1 may be suspected as a possible source of trouble. Therefore, the load circuit should be carefully checked to determine that a load is presented to the regulator circuit at all times. It is also necessary to make d-c voltage measurements at the input terminals of the regulator circuit to determine whether voltage is applied and whether it is within tolerance.

The operation of the shunt-type regulator is based upon the voltage-divider principle; therefore, voltage measurements made across the output terminals of the regulator circuit and across series resistor R1 (observing correct voltmeter polarity) are necessary to determine whether the output voltage is within tolerance and whether the drop across series resistor R1 is excessive. If the load is shorted, there will be no output from the regulator circuit, and the full output voltage will be measured across series resistor R1. Also, if series resistor R1 should become open, there will be no output from the circuit, and the full output voltage will be measured across the resistor. The value of series resistor R1 can be checked by ohmmeter measurement to determine whether any change in resistance has occurred; disconnect one terminal of R1 from the circuit when making the measurement.

If breakdown diode VR1, or diode CR2 or CR3, should become open, the output voltage will be higher than normal; if breakdown diode VR1 should fail and become shorted, the voltage will be lower than normal, and diodes CR2 and CR3 will become overloaded. If diodes CR2 and CR3 should fail and become shorted, the output voltage will be subject to changes with temperature variations, since the temperature coefficient of resistance for the series diode combination will be changed. In general, if the output voltage is above normal, this is an indication that either an open circuit or an increase in impedance has occurred in the shunt elements VR1, CR2, and CR3) or in the load of the regulator circuit. If the output voltage is below normal, this indicates that either series resistor R1 has increased in value, the input voltage is below normal, or the load current is excessive because of a decrease in load resistance (excessive leakage or shorted components in the load circuit).

PART C. ELECTROMECHANICAL CIRCUITS

ELECTROMECHANICAL REGULATORS.

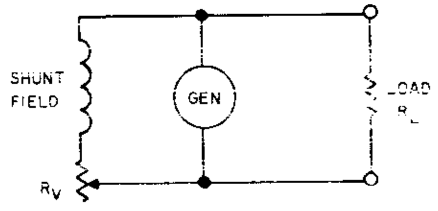
General. Electromechanical regulators are automatic devices which are mechanical rather than electronic in nature and affect the power source itself; these regulators hold the output of a d-c generator, a-c generator (alternator), or other source of primary power at a predetermined value, or vary the output according to a predetermined plan. Because the power source always has some internal resistance or reactance, the output voltage changes when the load is varied; the amount of output-voltage variation depends upon the design of the d-c or a-c generator. In the case of an a-c generator (alternator), the power factor of the load also influences the amount of variation. Under conditions of varying load, some form of voltage regulation is necessary to maintain the output voltage relatively constant; thus, the primary purpose of the regulator is to automatically compensate for any changes in output voltage.

Electromechanical voltage regulators control the generator or alternator output by controlling the current flow through the field (or exciter) winding of the machine. In most cases, control is accomplished by changing the resistance of the field circuit, which controls the field current, thus controlling the output voltage.

The operation of a typical regulation system can be briefly explained as follows: a drop in output voltage sensed by the regulator causes the regulator to increase the field current, and an increase in field current causes a corresponding increase in output voltage to compensate for the original drop in output voltage.

If the output voltage should rise, the regulator decreases the field current, causing a corresponding decrease in output voltage to compensate for the original rise in voltage. Thus, the regulator senses a change in output voltage and compensates for this change by altering the field current accordingly. The major difference between voltage-regulator systems, concerns the method used to control the field current.

The accompanying illustration shows a simplified circuit for controlling the output of a generator.

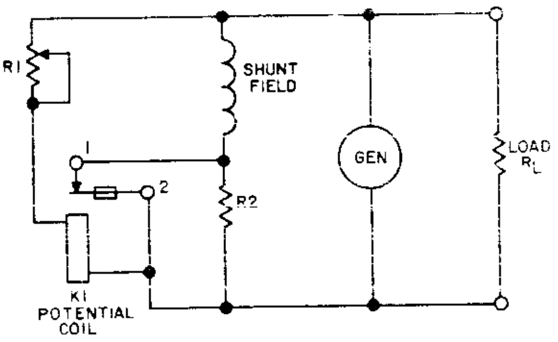


Simplified Circuit for Control of Generator Output

In this simplified circuit, variable resistor R_v is connected in series with the shunt field circuit of the generator. The purpose of this resistor is to control the current flow through the field winding and thus affect the strength of the magnetic flux developed by the field. (As the magnetic flux is either increased or decreased, the output voltage is either raised or lowered.) If the resistance of R_v is increased, less current flows through the shunt field, the magnetic flux developed by the field winding is decreased, and the voltage output developed across load resistance R_L is decreased. Conversely, if the resistance of R_v is decreased, more current flows through the shunt field, the magnetic flux developed by the field winding is increased, and the voltage output developed across load resistance R_L is increased. This principle of output-voltage control was briefly described in connection with rotating electromechanical power sources (generator and inverter), discussed in Section 4, Part C, of this handbook.

There are three common types of electromechanical regulators in general use: the vibrating-contact regulator, the carbon-pile regulator, and the multitapped resistor regulator using a finger-type contactor or similar mechanical device. A brief description of the construction, operation, and application of the three types of voltage regulators is given in the paragraphs which follow.

Vibrating-Contact Regulator. The vibrating-contact regulator is commonly used to control the output of battery-charging generators in automotive, small-boat, and some aircraft applications where the speed of generator rotation varies with engine speed. The vibrating-contact regulator operates on the principle that an intermittent short circuit applied across a resistor which is in series with the shunt field winding causes the output voltage of the generator to fluctuate within narrow voltage limits; such a regulator will maintain an average value of output voltage which is independent of load changes. The accompanying illustration shows a simplified circuit for a vibrating-contact regulator.



Simplified Circuit for Vibrating-Contact Regulator

In this simplified circuit, a vibrating-contact relay, K1, is used as a voltage regulator. Resistor R1 is a voltage-dropping resistor in series with a solenoid, called the **potential coil**, which is part of relay K1. Resistor R2 is in series with the shunt field winding of the generator. The value of resistor R2 is chosen so that if the vibrating contacts of the relay were not in the circuit (held open), the value of output voltage would be approximately 60 percent of the desired value of output voltage when the generator is running at normal speed. If the contacts of the relay are held closed, resistor R2 is shorted by the contacts and maximum current flows through the shunt field winding; thus, the output voltage of the generator is maximum. Thus, it can be seen that in actual practice when the contacts open and close rapidly to intermittently short out resistor R2, the output voltage will reach a value which is greater than 60 percent of the desired value and less than the maximum value. For example, when the output voltage of the generator rises above a critical value, the voltage developed across the potential coil of the relay develops sufficient magnetic flux to attract the armature (or reed), and contacts 1 and 2 of the relay momentarily open to place resistor R2 in series with the shunt field winding. Thus, the current through the field is momentarily reduced and the output voltage of the generator is also momentarily reduced. Then, when the output voltage of the generator drops below a critical value (after the opening of contacts 1 and 2), the voltage developed across the potential coil decreases so that there is no longer sufficient magnetic flux to attract the armature, and contacts 1 and 2 of the relay close to short out resistor R2. Thus, the current through the field winding is maximum and the output voltage of the generator is momentarily increased.

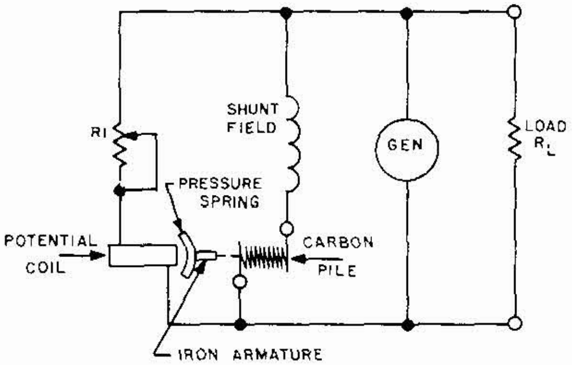
The cycle described above is repeated when the potential coil again develops sufficient magnetic flux to attract the armature and open the contacts of the relay; the action described is rapid, and continues at a rate of approximately 60 to 240 times a second, so that an average voltage is maintained regardless of changes in load. If the load is increased and the output voltage tends to fall, the momentary voltage decrease is reflected by a decrease in voltage applied to the potential coil; thus, the armature vibrates more slowly, permitting an increased average current flow in the field winding. As a result, the output voltage is returned to the normal value. On the other hand, if the load is decreased and the output voltage tends to rise, the momentary voltage increase, when reflected to the potential coil, causes the armature to vibrate more rapidly and thus decrease the average current flow in the field winding. As a result, the output voltage is returned to the normal value.

In a practical application of this type of regulation, means must be provided for adjusting the regulator to obtain the desired value of output voltage. This is accomplished by one or both of the following methods: resistor R1 or resistor R2 is made adjustable to change the value of resistance in the circuit, or the armature (reed) tension is made adjustable to change the amount of magnetic flux required to attract the armature to the solenoid.

The vibrating-contact regulator is sometimes used to control the output of a multiphase a-c generator (alternator). When this is the case, the potential coil receives its operating current from a rectifier connected to one phase of the a-c output, and the regulation action is the same as that described for the d-c generator.

From the brief discussion given here, it can be seen that the vibrating-contact regulator acts as an automatic variable resistance in the field circuit of the generator, to hold the output voltage at a steady value for any change in load which occurs within the no-load to full-load operating conditions of the generator.

Carbon-Pile Regulator. The carbon-pile regulator is commonly used to control the output of generators, alternators, and inverters used in automotive, shipboard, and aircraft applications. The carbon-pile regulator operates on the principle of a variable resistance (in the form of a stack of carbon disks) in series with the shunt field winding, to control the current through the field and thus the output voltage of the generator. The accompanying illustration shows a simplified circuit for a carbon-pile regulator.



Simplified Circuit for Carbon-Pile Regulator

In this simplified circuit, resistor R1 is a voltage-dropping resistor in series with a solenoid (electromagnet), called the **potential coil**; the resistor determines the current flow through the solenoid, and thus affects the magnetic flux developed by the solenoid. A resistance in the form of a stack of carbon disks, called the **pile**, is placed in series with the shunt field winding, to act as a variable resistance which can be controlled automatically. The resistance of the carbon pile depends upon the mechanical pressure applied to the pile by a spring which presses a movable iron armature against the end of the pile. The greater the mechanical pressure applied to compress the carbon disks, the smaller will be the resistance of the pile; if the mechanical pressure is decreased, the resistance of the pile increases. A change in mechanical pressure is accomplished by placement of the solenoid in proximity to the iron armature so that the magnetic flux developed by the solenoid acts to pull (attract) the iron armature away from the carbon pile. In a steady-state condition, the magnetic force attracting the iron armature is opposed by the mechanical force of the spring against the iron armature.

For example, assume that the output voltage of the generator rises above a critical value. The voltage developed across the potential coil increases to develop a stronger magnetic field. Thus, the potential coil offers greater attraction to the iron armature and relieves the mechanical pressure exerted on the carbon disks; as a result, the resistance of the pile increases, the current through the shunt field winding decreases, and the output voltage returns to its former value. Conversely, when the output voltage falls below a critical value, the voltage developed across the potential coil decreases, and the strength of the magnetic field developed by the potential coil also decreases. Thus, the potential coil offers less attraction to the iron armature, and the spring places a greater mechanical pressure on the carbon disks; as a result, the resistance of the pile decreases, the current through the shunt field winding increases, and the output voltage returns to its former value.

The operation of the carbon-pile regulator may be briefly summarized as follows: when the output voltage rises, the spring pressure applied to the carbon pile decreases, *causing an increase in pile resistance and a decrease in* shunt field current; when the output voltage falls, the spring pressure applied to the carbon pile increases, causing decrease *in pile resistance and an increase in shunt* field current. The resultant decrease or increase in shunt field current lowers or raises the generator output, accordingly.

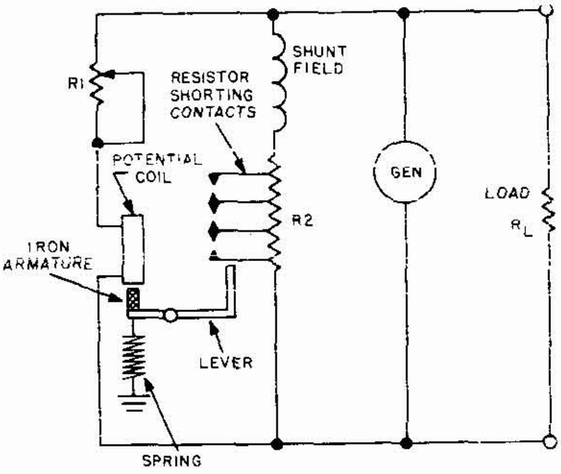
In a practical application of this type of regulator, means must be provided to adjust the regulator in order to obtain the desired value of output voltage. This is normally accomplished by an initial adjustment of the mechanical spring pressure (with resistor R1 set at mid-range), to obtain a steady-state condition whereby the magnetic force and the mechanical force are in balance; minor variations in voltage characteristics during normal operation are compensated for by an adjustment of resistor R1, which controls the current through the potential coil, to set the generator output voltage to the desired value.

The discussion in the preceding paragraphs has been primarily concerned with the operation of the carbon-pile *regulator in conjunction* with a d-c generator; however, this type of regulator can be used equally well in an a-c generating system. In practice, the output voltage of a multi*phase a-c generator (alternator) is controlled* by varying the d-c excitation current applied to the field winding of the machine. In this case, the carbon-pile regulator obtains a d-c voltage for *operation of the potential coil from* a rectifier which is connected to one phase of the a-c output, and the regulation action is the same as that described for the d-c generator.

From the brief discussion given here, it can be seen that the carbon-pile regulator acts as an automatic variable resistance in the field circuit of a d-c generator or in the field (exciter) circuit of an a-c generator (alternator), to hold the output voltage at a specified value of voltage regardless of changes in load.

Multitapped-Resistor Regulator. The multitapped-resistor regulator is commonly used to control the output of generators, alternators, and inverters used in shipboard and shore-based applications. The multitapped-resistor regulator operates on the principle of a stepped, variable resistance connected in series with the generator field winding to control the current through the field, and thus the output of the generator. Basically, the multitapped-resistor regulator consists of a single multitapped resistor (or several resistors connected in series), the terminals of which are either selected or *shorted out automatically to obtain* the desired resistance value. The name given to a particular regulator configuration is derived from the manner in which the over-all series resistance is determined. *For example,* the name **finger-type** regulator, **tilted-plate** regulator, or **rocking-disk** regulator, merely signifies the electromechanical method used to achieve physical contact and thus obtain a variable-resistance action within the regulating device. The accompanying illustration shows a simplified circuit for a typical multitapped-resistor regulator.

In this simplified circuit, resistor R1 is a voltage-dropping resistor in series with a solenoid, called the **potential coil**; the resistor determines the current flow through the solenoid, and thus affects the magnetic flux developed by the solenoid. Resistor R2 is the series resistor in the shunt-field circuit; R2 is a multitapped resistor, with the taps on the resistor connected to leaf springs (fingers) *which* are insulated from each other and are stacked one above the other. Electrical contacts are located at one end of each leaf spring. These contacts are arranged so that *as mechanical pressure* is increased at one end (lower end) of the stack, the number of electrical contacts that close is increased to short out sections of resistor R2. Thus, the greater the *mechanical pressure* applied *to the stack of* leaf springs, the smaller the effective series resistance of R2. If the mechanical pressure is decreased, the effective series resistance of R2 will be increased. A *change in* mechanical pressure is accomplished by placement of the solenoid in proximity to the iron armature, which is spring-loaded and linked mechanically through a lever system to the stack of leaf springs. In a steady-state condition, the magnetic force attracting the iron armature is opposed by the mechanical force of the armature spring pulling against the iron armature, and only a few contacts are closed on the stack of leaf springs to provide some intermediate value of resistance.



Simplified Circuit for Multitapped-Resistor Regulator

When a change in generator output voltage occurs, the voltage developed across the potential coil changes; thus, the magnetic flux developed by the potential coil also changes. As a result, the mechanical force exerted on the *stack of leaf springs* is altered to change the number of contacts which are closed. This, in turn, changes the value of resistance (R2) in series with the shunt field winding and *compensates for the change in output voltage.* For example, assume that the output voltage of the generator rises above the critical value. The voltage developed across the potential coil increases to develop a stronger magnetic field. Thus, the potential coil offers greater attraction to the iron armature and decreases the mechanical pressure exerted on the stack of leaf springs (through the lever system); as a result, the value of resistance (R2) in series with the shunt field winding increases, the current through the shunt field winding decreases, and the output voltage returns to its former value. Conversely, when the output voltage falls below a critical value, the voltage developed across the potential coil decreases, and the strength of the magnetic field developed by the potential coil also decreases. Thus, the potential coil offers less attraction to the iron armature, and the armature spring places a greater mechanical pressure on the stack of leaf springs; as a result, the value of resistance (R2) decreases, the current through the shunt field winding increases, and the output voltage returns to its former value.

In a practical application of the multitapped-resistor regulator, regardless of the mechanical configuration employed to change the value of resistance, means must be provided for adjusting the regulator to the desired value of output voltage. This is normally accomplished by an initial adjustment of the mechanical spring tension which acts upon the armature and lever system (with resistor R1 set at mid-range), to obtain a steady-state condition whereby the magnetic force and the mechanical force are in balance. Minor variations in voltage characteristics during normal operation are compensated for by an adjustment of resistor R1, which controls the current through the potential coil, to set the generator output voltage to the desired value.

The discussion in the preceding paragraphs has been primarily concerned with the operation of the multitapped-resistor regulator in conjunction with a d-c generator; however, this type of regulator is frequently used in an a-c generating system. When the multitapped-resistor regulator is used to control the output of a multiphase a-c generator (alternator), the regulator obtains a d-c voltage for operation of the potential coil from a rectifier connected to one phase of the a-c output voltage, and the regulation action is the same as that described for the d-c generator.

In conclusion, it can be seen that the multitapped-resistor regulator acts as an automatic variable resistance in the field circuit of a d-c generator or in the field (exciter) circuit of an a-c generator (alternator), to hold the output voltage at a specified value of voltage regardless of changes in load.

From the brief descriptions of voltage regulators given in the preceding paragraphs, it can be seen that the vibrating-contact regulator, the carbon-pile regulator, and the multitapped-resistor regulator are merely controlled, automatic variable resistors. The detailed theory of operation and the construction of electromechanical regulators are covered in Navy publications on basic electricity (or in course materials for EM and AE ratings), and, therefore, will not be treated in this handbook. Only the basic principles will be discussed in this section of the handbook, as required, to provide a better understanding of the application and the failure analysis of the electromechanical regulators discussed.