CHAPTER 9

AIRCRAFT GENERATORS AND MOTORS

D. C. GENERATORS

Energy for the operation of most electrical equipment in an airplane depends upon the electrical energy supplied by a generator. A generator is any machine which converts mechanical energy into electrical energy by electromagnetic induction. A generator designed to produce alternating-current energy is called an a.c. generator, or alternator; a generator which produces direct-current energy is called a d.c. generator. Both types operate by inducing an a.c. voltage in coils by varying the amount and direction of the magnetic flux cutting through the coils.

For airplanes equipped with direct-current electrical systems, the d.c. generator is the regular source of electrical energy. One or more d.c. generators, driven by the engine, supply electrical energy for the operation of all units in the electrical system, as well as energy for charging the battery. The number of generators used is determined by the power requirement of a particular airplane. In most cases, only one generator is driven by each engine, but in some large airplanes, two generators are driven by a single engine. Aircraft equipped with alternating-current systems use electrical energy supplied by a.c. generators, also called alternators.

Theory of Operation

In the study of alternating current, basic generator principles were introduced to explain the generation of an a.c. voltage by a coil rotating in a magnetic field. Since this is the basis for all generator operation, it is necessary to review the principles of generation of electrical energy.

When lines of magnetic force are cut by a conductor passing through them, voltage is induced in the conductor. The strength of the induced voltage is dependent upon the speed of the conductor and the strength of the magnetic field. If the ends of the conductor are connected to form a complete circuit, a current is induced in the conductor. The conductor and the magnetic field make up an elementary generator. This simple generator is illustrated in figure 9–1, together with the components of an external generator circuit which collect and use the energy produced by the simple generator. The loop of wire (A and B of figure 9–1) is arranged to rotate in a magnetic field. When the plane of the loop of wire is parallel to the magnetic lines of force, the voltage induced in the loop causes a current to flow in the direction indicated by the arrows in figure 9–1. The voltage induced at this position is maximum, since the wires are cutting the lines of force at right angles and are thus cutting more lines of force per second than in any other position relative to the magnetic field.

As the loop approaches the vertical position shown in figure 9–2, the induced voltage decreases because both sides of the loop (A and B) are approximately parallel to the lines of force and

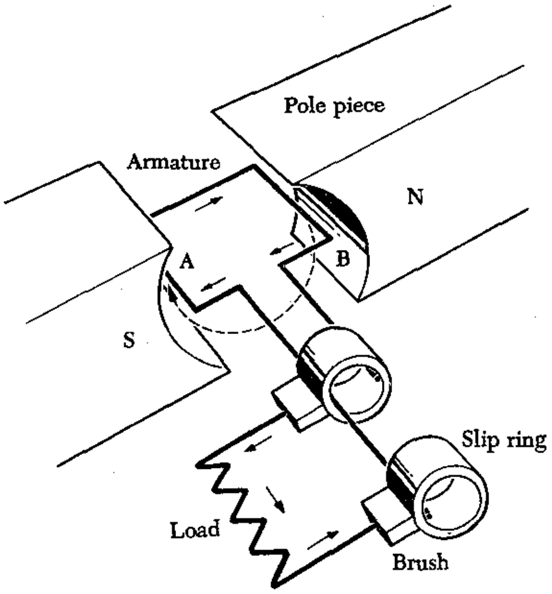


FIGURE 9–1. Inducing maximum voltage in an elementary generator.

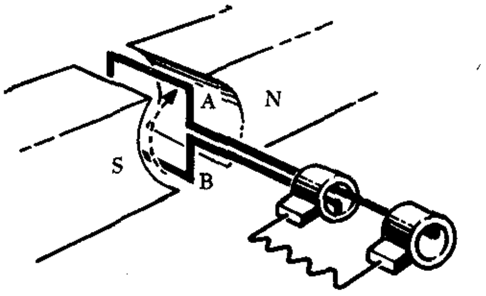


FIGURE 9–2. Inducing minimum voltage in an elementary generator.

the rate of cutting is reduced. When the loop is vertical, no lines of force are cut since the wires are momentarily traveling parallel to the magnetic lines of force, and there is no induced voltage. As the rotation of the loop continues, the number of lines of force cut increases until the loop has rotated an additional 90° to a horizontal plane. As shown in figure 9–3, the number of lines of force cut and the induced voltage once again are maximum. The direction of cutting, however, is in the opposite direction to that occurring in figures 9–1 and 9–2, so the direction (polarity) of the induced voltage is reversed.

As rotation of the loop continues, the number of lines of force having been cut again decreases, and the induced voltage becomes zero at the position shown in figure 9–4, since the wires A and B are again parallel to the magnetic lines of force.

If the voltage induced throughout the entire 360° of rotation is plotted, the curve shown in figure 9–5 results. This voltage is called an alternating voltage because of its reversal from positive to negative values—first in one direction and then in the other.

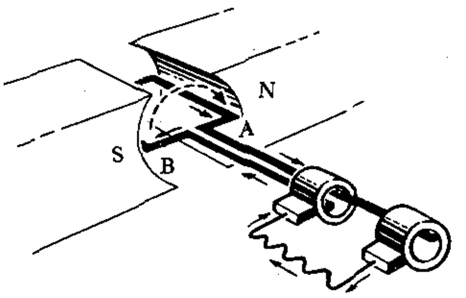


FIGURE 9–3. Inducing maximum voltage in the opposite direction.

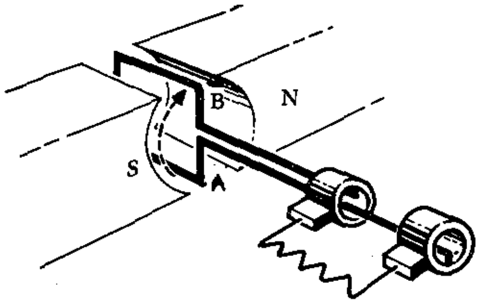


FIGURE 9–4. Inducing a minimum voltage in the opposite direction.

To use the voltage generated in the loop for producing a current flow in an external circuit, some means must be provided to connect the loop of wire in series with the external circuit. Such an electrical connection can be effected by opening the loop of wire and connecting its two ends to two metal rings, called slip rings, against which two metal or carbon brushes ride. The brushes are connected to the external circuit.

By replacing the slip rings of the basic a.c. generator with two half-cylinders, called a commutator, a basic d.c. generator (figure 9–6), is obtained. In this illustration the black side of the coil is connected to the black segment and the white side of the coil to the white segment. The segments are insulated from each other. The two stationary brushes are placed on opposite sides of the commutator and are so mounted that each brush contacts each segment of the commutator as the latter revolves simultaneously with the loop. The rotating parts of a d.c. generator (coil and commutator) are called an armature.

The generation of an e.m.f. by the loop rotating in the magnetic field is the same for both a.c. and d.c. generators, but the action of the commutator produces a d.c. voltage. This generation of a d.c. voltage is described as follows for the various

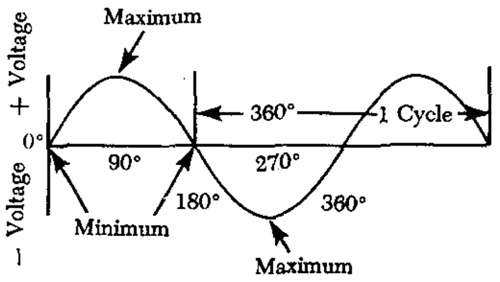


FIGURE 9–5. Output of an elementary generator.

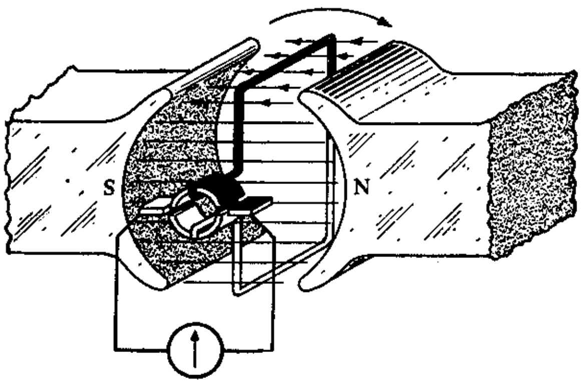


FIGURE 9–6. Basic d.c. generator.

positions of the loop rotating in a magnetic field, with reference to figure 9–7.

The loop in position A of figure 9–7 is rotating clockwise, but no lines of force are cut by the coil sides and no e.m.f. is generated. The black brush is shown coming into contact with the black segment of the commutator, and the white brush is just coming into contact with the white segment.

In position B of figure 9–7, the flux is being cut at a maximum rate and the induced e.m.f. is maximum. At this time, the black brush is contacting the black segment and the white brush is contacting the white segment. The deflection of the meter is toward the right, indicating the polarity of the output voltage.

At position C of figure 9–7, the loop has completed 180° of rotation. Again, no flux lines are being cut and the output voltage is zero. The important condition to observe at position C is the action of the segments and brushes. The black brush at the 180° angle is contacting both black and white segments on one side of the commutator, and the white brush is contacting both segments on the other side of the commutator. After the loop rotates slightly past the 180° point, the black brush is contacting only the white segment and the white brush is contacting only the black segment.

Because of this switching of commutator elements, the black brush is always in contact with the coil side moving downward, and the white brush is always in contact with the coil side moving upward. Though the current actually reverses its direction in the loop in exactly the same way as in the a.c. generator, commutator action causes the current to flow always in the same direction through the external circuit or meter.

A graph of one cycle of operation is shown in figure 9–7. The generation of the e.m.f. for positions A, B, and C is the same as for the basic a.c. generator, but at position D, commutator

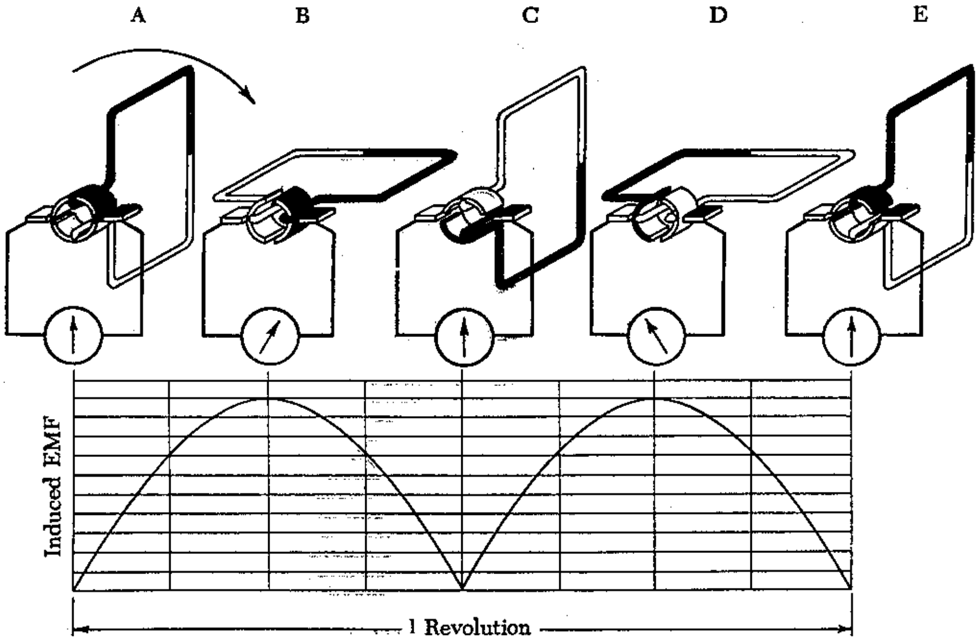


FIGURE 9–7. Operation of a basic d.c. generator.

action reverses the current in the external circuit, and the second half-cycle has the same waveform as the first half-cycle. The process of commutation is sometimes called rectification, since rectification is the converting of an a.c. voltage to a d.c. voltage.

At the instant that each brush is contacting two segments on the commutator (positions A, C, and E in figure 9–7), a direct short circuit is produced. If an e.m.f. were generated in the loop at this time, a high current would flow in the circuit, causing an arc and thus damaging the commutator. For this reason, the brushes must be placed in the exact position where the short will occur when the generated e.m.f. is zero. This position is called the neutral plane.

The voltage generated by the basic d.c. generator in figure 9–7 varies from zero to its maximum value twice for each revolution of the loop. This variation of d.c. voltage is called "ripple," and may be reduced by using more loops, or coils, as shown in A of figure 9–8. As the number of loops is increased, the variation between maximum and minimum values of voltage is reduced (B of figure 9–8), and the output voltage of the generator approaches a steady d.c. value. In A of figure 9–8 the number of commutator segments is increased in direct proportion to the number of loops; that is, there are two segments for one loop, four segments for two loops, and eight segments for four loops.

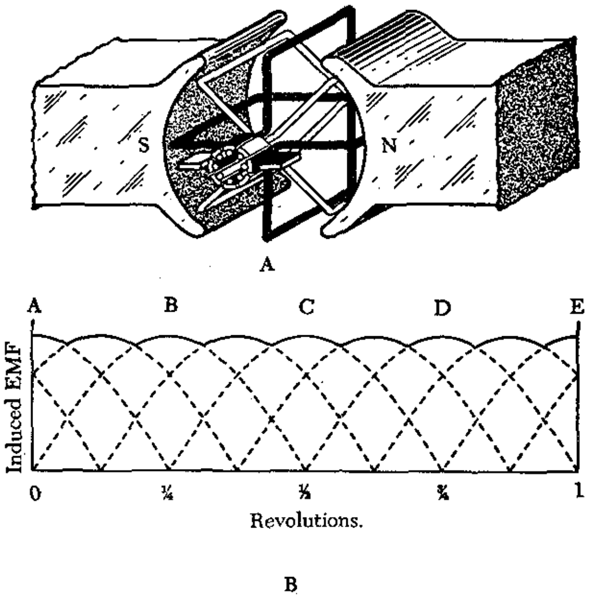


FIGURE 9–8. Increasing the number of coils reduces the ripple in the voltage.

The voltage induced in a single-turn loop is small. Increasing the number of loops does not increase the maximum value of generated voltage, but increasing the number of turns in each loop will increase this value. Within narrow limits, the output voltage of a d.c. generator is determined by the product of the number of turns per loop, the total flux per pair of poles in the machine, and the speed of rotation of the armature.

An a.c. generator, or alternator, and a d.c. generator are identical as far as the method of generating voltage in the rotating loop is concerned. However, if the current is taken from the loop by slip rings, it is an alternating current, and the generator is called an a.c. generator, or alternator. If the current is collected by a commutator, it is direct current, and the generator is called a d.c. generator.

Construction Features of D. C. Generators

Generators used on aircraft may differ somewhat in design, since they are made by various manufacturers. All, however, are of the same general construction and operate similarly. The major parts, or assemblies, of a d.c. generator are a field frame (or yoke), a rotating armature, and a brush assembly. The parts of a typical aircraft generator are shown in figure 9–9.

Field Frame

The field frame is also called the yoke, which is the foundation or frame for the generator. The frame has two functions: It completes the magnetic circuit between the poles and acts as a mechanical support for the other parts of the generator. In A of figure 9–10, the frame for a two-pole generator is shown in a cross-sectional view. A four-pole generator frame is shown in B of figure 9–10.

In small generators, the frame is made of one piece of iron, but in larger generators, it is usually made up of two parts bolted together. The frame has high magnetic properties and, together with the pole pieces, forms the major part of the magnetic circuit.The field poles, shown in figure 9–10, are bolted to the inside of the frame and form a core on which the field coil windings are mounted. The poles are usually laminated to reduce eddy

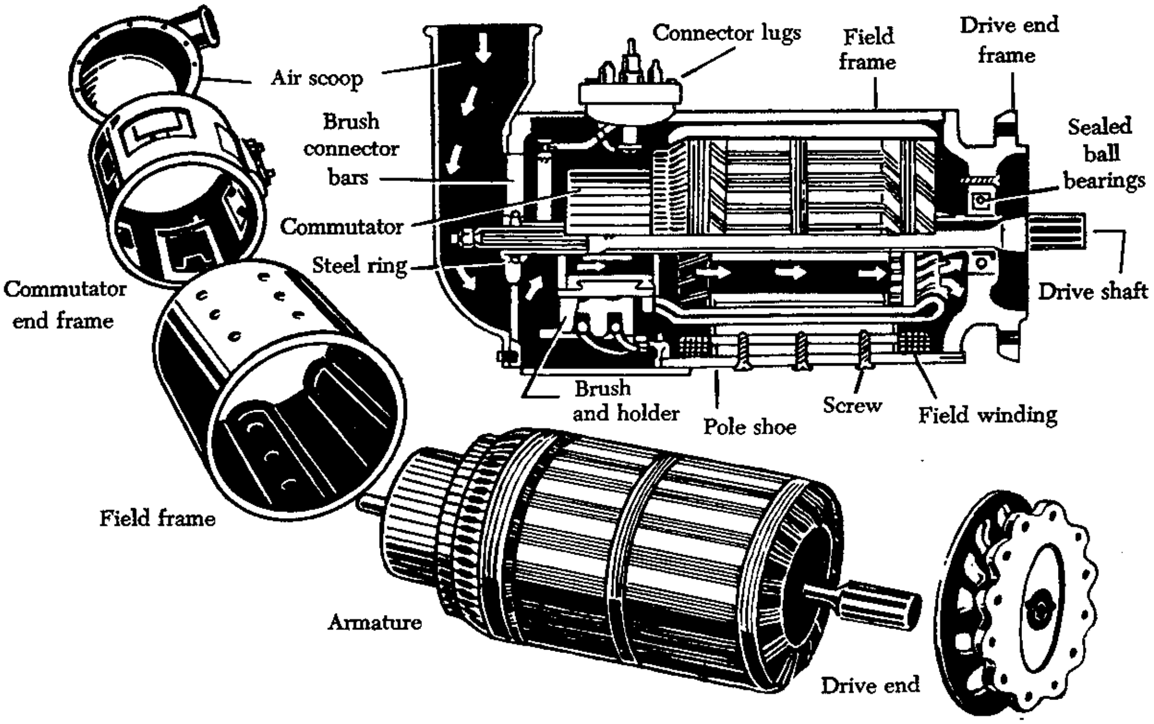


FIGURE 9–9. Typical 24-volt aircraft generator.

current losses and serve the same purpose as the iron core of an electromagnet; that is, they concentrate the lines of force produced by the field coils. The entire frame including field poles, is made from high-quality magnetic iron or sheet steel.

A practical d.c. generator uses electromagnets instead of permanent magnets. To produce a magnetic field of the necessary strength with permanent magnets would greatly increase the physical size of the generator.

The field coils are made up of many turns of insulated wire and are usually wound on a form which fits over the iron core of the pole to which it is securely fastened (figure 9–11). The exciting current, which is used to produce the magnetic field and which flows through the field coils, is obtained from an external source or from the generated d.c. of the machine. No electrical connection exists between the windings of the field coils and the pole pieces.

Most field coils are connected in such a manner that the poles show alternate polarity. Since there is always one north pole for each south pole, there must always be an even number of poles in any generator.

Note that the pole pieces in figure 9–10 project from the frame. Because air offers a great amount of reluctance to the magnetic field, this design reduces the length of the air gap between the poles and the rotating armature and increases the efficiency of the generator. When the pole pieces are made to project as shown in figure 9–10, they are called salient poles.

Armature

The armature assembly consists of armature coils wound on an iron core, a commutator, and associated mechanical parts. Mounted on a shaft, it rotates through the magnetic field produced by the field coils. The core of the armature acts as an iron conductor in the magnetic field and, for this reason, is laminated to prevent the circulation of eddy currents.

There are two general kinds of armatures: the ring and the drum. Figure 9–12 shows a ring-type armature made up of an iron core, an eight-section winding, and an eight-segment commutator. This kind of armature is rarely used; most generators use the drum-type armature.

A drum-type armature (figure 9–13) has coils placed in slots in the core, but there is no electrical connection between the coils and core. The use of slots increases the mechanical safety of the armature. Usually, the coils are held in place in the slots by means of wooden or fiber wedges. The connections of the individual coils, called coil ends, are brought out to individual segments on the commutator.

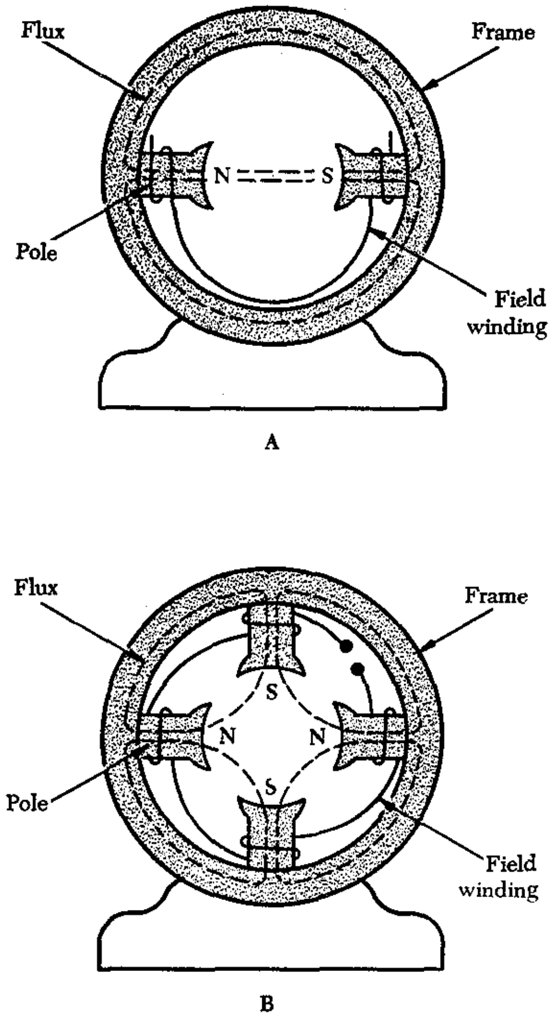


FIGURE 9–10. A two-pole and a four-pole frame assembly.

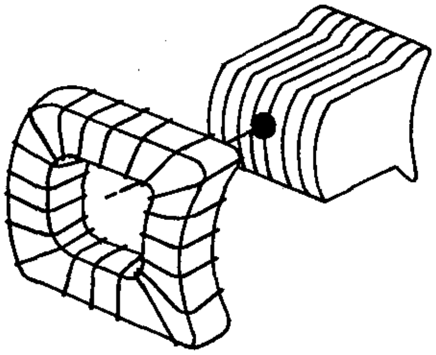


FIGURE 9–11. A field coil removed from a field pole.

Commutators

Figure 9–14 shows a cross-sectional view of a typical commutator. The commutator is located at the end of an armature and consists of wedge-shaped segments of hard-drawn copper, insulated from each other by thin sheets of mica. The segments are held in place by steel V-rings or clamping flanges fitted with bolts. Rings of mica insulate the segments from the flanges. The raised portion of each segment is called a riser, and the leads from the armature coils are soldered to the risers. When the segments have no risers, the leads are soldered to short slits in the ends of the segments.

The brushes ride on the surface of the commutator, forming the electrical contact between the armature coils and the external circuit. A flexible, braided-copper conductor, commonly called a pigtail, connects each brush to the external circuit. The brushes, usually made of high-grade carbon and held in place by brush holders insulated from the frame, are free to slide up and down in their holders in order to follow any irregularities in the surface of the commutator. The brushes are usually adjustable so that the pressure of the brushes on the commutator can be varied and the position of the brushes with respect to the segments can be adjusted.

The constant making and breaking of connections to the coils in which a voltage is being

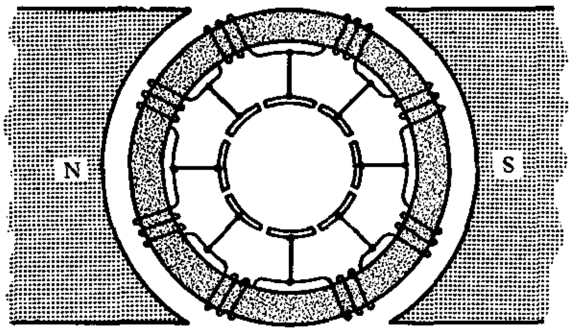


FIGURE 9–12. An eight-section, ring-type armature.

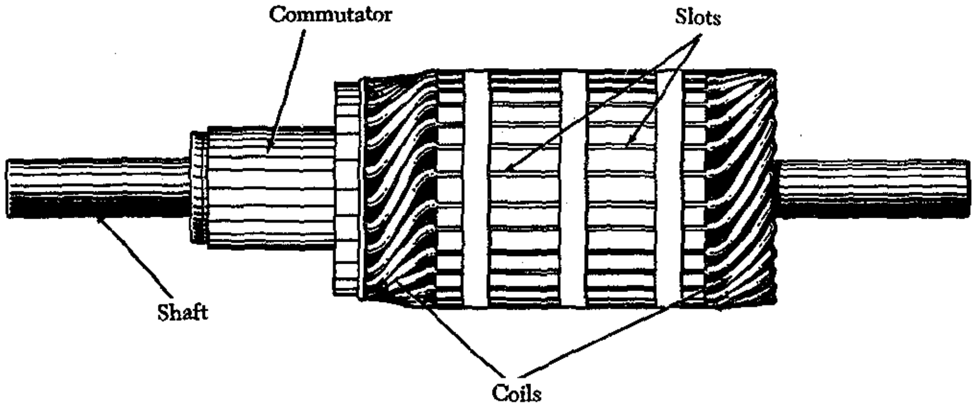


FIGURE 9–13. A drum-type armature.

induced necessitates the use of material for brushes which has a definite contact resistance. Also, this material must be such that the friction between the commutator and the brush is low, to prevent excessive wear. For these reasons, the material commonly used for brushes is high-grade carbon. The carbon must be soft enough to prevent undue wear of the commutator and yet hard enough to provide reasonable brush life. Since the contact resistance of carbon is fairly high, the brush must be quite large to provide a large area of contact. The commutator surface is highly polished to reduce friction as much as possible. Oil or grease must never be used on a commutator, and extreme care must be used when cleaning it to avoid marring or scratching the surface.

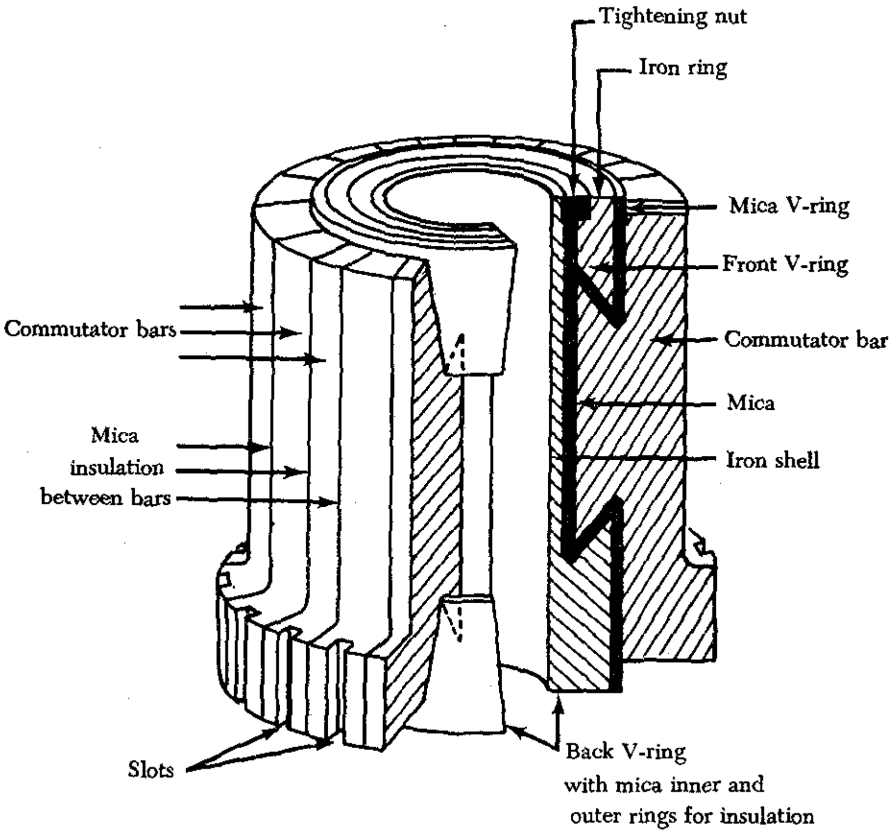


FIGURE 9–14. Commutator with portion removed to show construction.

TYPES OF D. C. GENERATORS

There are three types of d.c. generators: series-wound, shunt-wound, and shunt-series or compound wound. The difference in type depends on the relationship of the field winding to the external circuit.

Series-Wound D. C. Generators

The field winding of a series generator is connected in series with the external circuit, called the load (figure 9–15). The field coils are composed of a few turns of large wire; the magnetic field strength depends more on the current flow rather than the number of turns in the coil. Series generators have very poor voltage regulation under changing load, since the greater the current through the field coils to the external circuit, the greater the induced e.m.f. and the greater the terminal or output voltage. Therefore, when the load is increased, the voltage increases; likewise, when the load is decreased, the voltage decreases. The output voltage of a series-wound generator may be controlled by a rheostat in parallel with the field windings, as shown in A of figure 9–15. Since the series-wound generator has such poor regulation, it is never employed as an airplane generator. Generators in airplanes have field windings which are connected either in shunt or in compound.

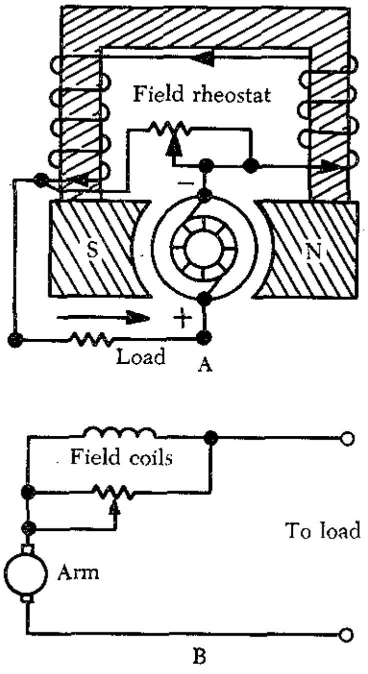


Figure 9–15. Diagram and schematic of a series-wound generator.

Shunt-Wound D. C. Generators

A generator having a field winding connected in parallel with the external circuit is called a shunt generator, as shown in A and B of figure 9–16. The field coils of a shunt generator contain many turns of small wire; the magnetic strength is derived from the large number of turns rather than the current strength through the coils. If a constant voltage is desired, the shunt-wound generator is not suitable for rapidly fluctuating loads. Any increase in load causes a decrease in the terminal or output voltage, and any decrease in load causes an increase in terminal voltage; since the armature and the load are connected in series, all current flowing in the external circuit passes through the armature winding. Because of the resistance in the armature winding, there is a voltage drop (*IR* drop = current × resistance). As the load increases, the armature current increases and the IR drop in the armature increases. The voltage delivered to the terminals is the difference between the induced voltage and the voltage drop; therefore, there is a decrease in terminal voltage. This decrease in voltage causes a decrease in field strength, because the current in the field coils decreases in proportion to the decrease in terminal voltage; with a weaker field, the voltage is further decreased.

When the load decreases, the output voltage increases accordingly, and a larger current flows in the windings. This action is cumulative, so the output voltage continues to rise to a point called field saturation, after which there is no further increase in output voltage.

The terminal voltage of a shunt generator can be controlled by means of a rheostat inserted in series with the field windings as shown in A of figure 9–16. As the resistance is increased, the field current is reduced; consequently, the generated voltage is reduced also. For a given setting of the field rheostat, the terminal voltage at the armature brushes will be approximately equal to the generated voltage minus the *IR* drop produced by the load current in the armature; thus, the voltage at the terminals of the generator will drop as the load is applied. Certain voltage-sensitive devices are available which automatically adjust the field rheostat to compensate for variations in

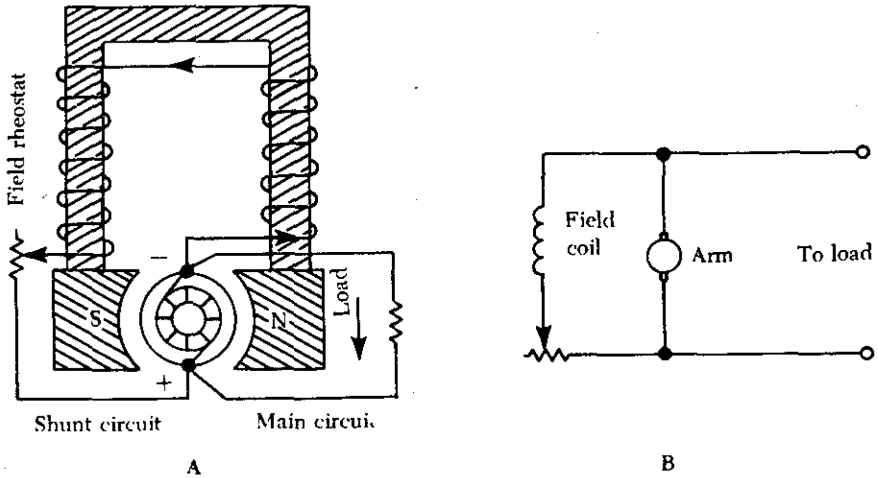


FIGURE 9–16. Shunt-wound generator.

load. When these devices are used, the terminal voltage remains essentially constant.

Compound-Wound D. C. Generators

A compound-wound generator combines a series winding and a shunt winding in such a way that the characteristics of each are used to advantage. The series field coils are made of a relatively small number of turns of large copper conductor, either circular or rectangular in cross section, and are connected in series with the armature circuit. These coils are mounted on the same poles on which the shunt field coils are mounted and, therefore, contribute a magnetomotive force which influences the main field flux of the generator. A diagrammatic and a schematic illustration of a compound-wound generator is shown in A and B of figure 9–17.

If the ampere-turns of the series field act in the same direction as those of the shunt field, the combined magnetomotive force is equal to the sum of the series and shunt field components. Load is added to a compound generator in the same manner in which load is added to a shunt generator, by increasing the number of parallel paths across the generator terminals. Thus, the decrease in total load resistance with added load is accompanied by an increase in armature-circuit and series-field circuit current.

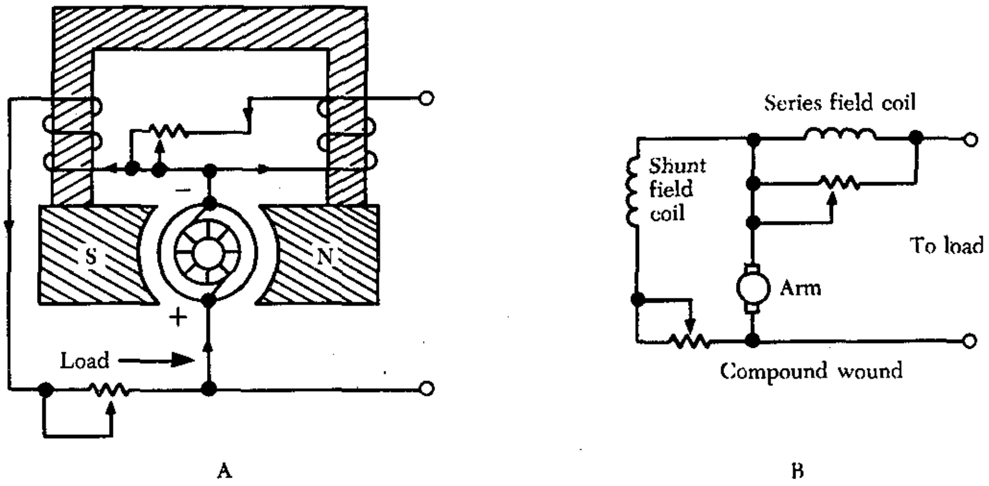


FIGURE 9–17. Compound-wound generator.

The effect of the additive series field is that of increased field flux with increased load. The extent of the increased field flux depends on the degree of saturation of the field as determined by the shunt field current. Thus, the terminal voltage of the generator may increase or decrease with load, depending on the influence of the series field coils. This influence is referred to as the degree of compounding.

A flat-compound generator is one in which the no-load and full-load voltages have the same value; whereas an under-compound generator has a full-load voltage less than the no-load value, and an over-compound generator has a full-load voltage which is higher than the no-load value. Changes in terminal voltage with increasing load depends upon the degree of compounding.

If the series field aids the shunt field, the generator is said to be cumulative-compounded (B of figure 9–17).

If the series field opposes the shunt field, the machine is said to be differentially compounded, or is called a differential generator.

Compound generators are usually designed to be overcompounded. This feature permits varied degrees of compounding by connecting a variable shunt across the series field. Such a shunt is sometimes called a diverter. Compound generators are used where voltage regulation is of prime importance.

Differential generators have somewhat the same characteristics as series generators in that they are essentially constant-current generators. However, they generate rated voltage at no load, the voltage dropping materially as the load current increases. Constant-current generators are ideally suited as power sources for electric arc welders and are used almost universally in electric arc welding.

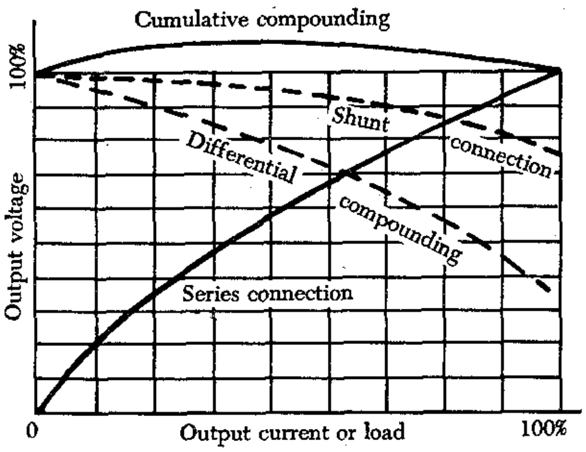


FIGURE 9–18. Generator characteristics.

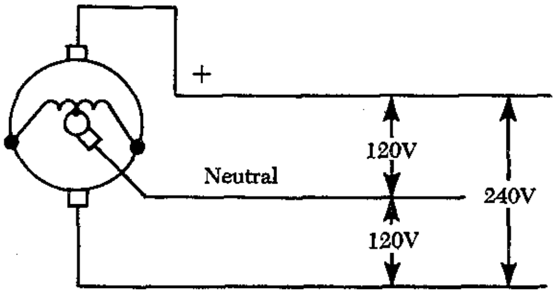


FIGURE 9–19. Three-wire generator.

If the shunt field of a compound generator is connected across both the armature and the series field, it is known as a long-shunt connection, but if the shunt field is connected across the armature alone, it is called a short-shunt connection. These connections produce essentially the same generator characteristics.

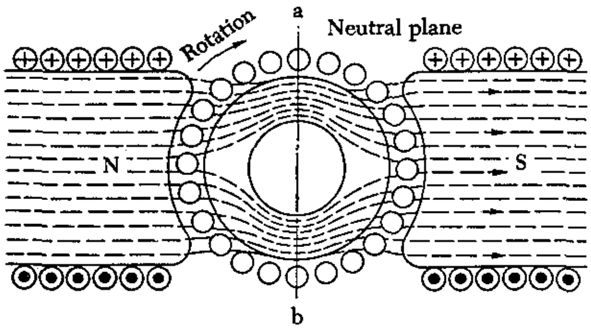
A summary of the characteristics of the various types of generators discussed is shown graphically in figure 9–18.

Three-Wire Generators

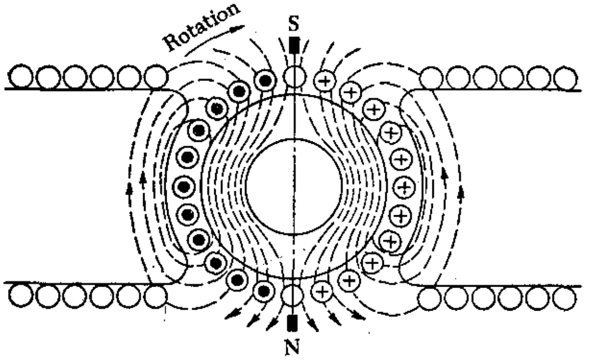
Some d.c. generators, called three-wire generators, are designed to deliver 240 volts, or 120 volts from either side of a neutral wire (figure 9–19). This is accomplished by connecting a reactance coil to opposite sides of the commutator, with the neutral connected to the midpoint of the reactance coil. Such a reactance coil acts as a low-loss voltage divider. If resistors were used, the IR loss would be prohibitive unless the two loads were perfectly matched. The coil is built into some generators as part of the armature, with the midpoint connected to a single slip ring which the neutral contacts by means of a brush. In other generators, the two connections to the commutator are connected, in turn, to two slip rings, and the reactor is located outside the generator. In either case, the load unbalance on either side of the neutral must not be more than 25 percent of the rated current output of the generator. The three-wire generator permits simultaneous operation of 120-volt lighting circuits and 240-volt motors from the same generator.

Armature Reaction

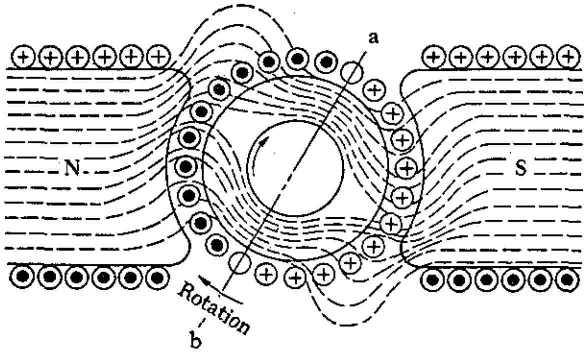
Current flowing through the armature sets up electromagnetic fields in the windings. These new fields tend to distort or bend the magnetic flux between the poles of the generator from a straight line path. Since armature current increases with load, the distortion becomes greater with an increase in load. This distortion of the magnetic field is called armature reaction and is illustrated in figure 9–20.



A Field excited, armature unexcited



B Armature excited, field unexcited



C Both field and armature excited

FIGURE 9–20. Armature reaction.

Armature windings of a generator are spaced in such a way that, during rotation of the armature, there are certain positions when the brushes contact two adjacent segments, thereby shorting the armature windings to these segments. Usually, when the magnetic field is not distorted, there is no voltage being induced in the shorted windings, and, therefore, no harmful results occur from the shorting of the windings. However, when the field is distorted, a voltage is induced in these shorted windings and sparking takes place between the brushes and the commutator segments. Consequently, the commutator becomes pitted, the wear on the brushes becomes excessive, and the output of the generator is reduced. To correct this condition, the brushes are set so that the plane of the coils which are shorted by the brushes is perpendicular to the distorted magnetic field, which is accomplished by moving the brushes forward in the direction of rotation. This operation is called shifting the brushes to the neutral plane, or plane of commutation. The neutral plane is the position where the plane of the two opposite coils is perpendicular to the magnetic field in the generator. On a few generators, the brushes can be shifted manually ahead of the normal neutral plane to the neutral plane caused by field distortion. On nonadjustable brush generators, the manufacturer sets the brushes for minimum sparking.

Interpoles may be used to counteract some of the effects of field distortion, since shifting the brushes is inconvenient and unsatisfactory, especially when the speed and load of the generator are changing constantly. An interpole is a pole placed between the main poles of a generator. For example, a four-pole generator has four interpoles, which are north and south poles, alternately, as are the main poles. A four-pole generator with interpoles is shown in figure 9–21.

An interpole has the same polarity as the next main pole in the direction of rotation. The magnetic flux produced by an interpole causes the current in the armature to change direction as an armature winding passes under it. This cancels the electromagnetic fields about the armature windings. The magnetic strength of the interpoles varies with the load on the generator; and since field distortion varies with the load, the magnetic field of the interpoles counteracts the effects of the field set up around the armature windings

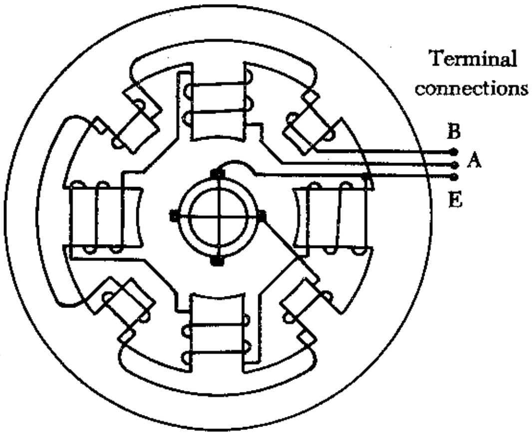


FIGURE 9–21. Generator with interpoles.

and minimizes field distortion. Thus, the interpole tends to keep the neutral plane in the same position for all loads on the generator; therefore, field distortion is reduced by the interpoles, and the efficiency, output, and service life of the brushes are improved.

Generator Ratings

A generator is rated in power output. Since a generator is designed to operate at a specified voltage, the rating usually is given as the number of amperes the generator can safely supply at its rated voltage.

Generator rating and performance data are stamped on the name plate attached to the generator. When replacing a generator, it is important to choose one of the proper rating.

The rotation of generators is termed either clockwise or counterclockwise, as viewed from the driven end. Usually, the direction of rotation is stamped on the data plate. If no direction is stamped on the plate, the rotation may be marked by an arrow on the cover plate of the brush housing. It is important that a generator with the correct direction of rotation be used; otherwise the voltage will be reversed.

The speed of an aircraft engine varies from idle r.p.m. to takeoff r.p.m.; however, during the major portion of a flight, it is at a constant cruising speed. The generator drive is usually geared to revolve the generator between 1⅛ and 1½ times the engine crankshaft speed. Most aircraft generators have a speed at which they begin to produce their normal voltage. Termed the "coming-in" speed, it is usually about 1,500 r.p.m.

Generator Terminals

On most large 24-volt generators, electrical connections are made to terminals marked B, A, and E. (See figure 9–22.) The positive armature lead in the generator connects to the B terminal. The negative armature lead connects to the E terminal. The positive end of the shunt field winding connects to terminal A, and the opposite end connects to the negative terminal brush. Terminal A receives current from the negative generator brush through the shunt field winding. This current passes through the voltage regulator and back to the armature through the positive brush. Load current, which leaves the armature through the negative brushes, comes out of the E lead and passes through the load before returning to the armature through the positive brushes.

REGULATION OF GENERATOR VOLTAGE

Efficient operation of electrical equipment in an airplane depends on a constant voltage supply from the generator. Among the factors which determine the voltage output of a generator, only one, the strength of the field current, can be conveniently controlled. To illustrate this control, refer to the diagram in figure 9–22, showing a simple generator with a rheostat in the field circuit. If the rheostat is set to increase the resistance in the field circuit, less current flows through the field winding and the strength of the magnetic field in which the armature rotates decreases. Consequently, the voltage output of the generator decreases. If the resistance in the field

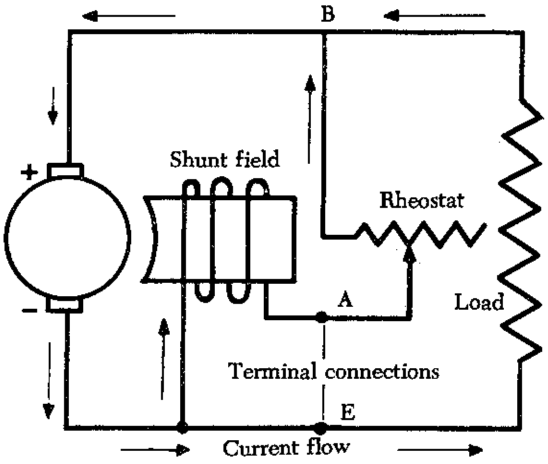


FIGURE 9–22. Regulation of generator voltage by field rheostat.

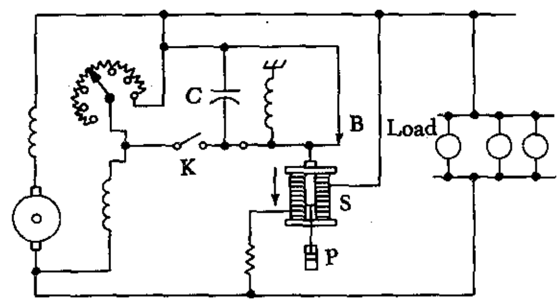


FIGURE 9–23. Vibrating-type voltage regulator.

circuit is decreased with the rheostat, more current flows through the field windings, the magnetic field becomes stronger, and the generator produces a greater voltage.

With the generator running at normal speed and switch K open (figure 9–23), the field rheostat is adjusted so that the terminal voltage is about 60 percent of normal. Solenoid S is weak and contact B is held closed by the spring. When K is closed, a short circuit is placed across the field rheostat. This action causes the field current to increase and the terminal voltage to rise.

When the terminal voltage rises above a certain critical value, the solenoid downward pull exceeds the spring tension and contact B opens, thus reinserting the field rheostat in the field circuit and reducing the field current and terminal voltage.

When the terminal voltage falls below a certain critical voltage, the solenoid armature contact B is closed again by the spring, the field rheostat is now shorted, and the terminal voltage starts to rise. The cycle repeats with a rapid, continuous action. Thus, an average voltage is maintained with or without load change.

The dashpot P provides smoother operation by acting as a damper to prevent hunting. The capacitor C across contact B eliminates sparking. Added load causes the field rheostat to be shorted for a longer period of time and, thus, the solenoid armature vibrates more slowly. If the load is reduced and the terminal voltage rises, the armature vibrates more rapidly and the regulator holds the terminal voltage to a steady value for any change in load, from no load to full load, on the generator.

Vibrating-type regulators cannot be used with generators which require a high field current, since the contacts will pit or burn. Heavy-duty generator systems require a different type of regulator, such as the carbon-pile voltage regulator.

Carbon-Pile Voltage Regulator

The carbon-pile voltage regulator depends on the resistance of a number of carbon disks arranged in a pile or stack. The resistance of the carbon stack varies inversely with the pressure applied. When the stack is compressed under appreciable pressure, the resistance in the stack is less. When the pressure is reduced, the resistance of the carbon stack increases, because there is more air space between the disks, and air has high resistance. Pressure on the carbon pile depends upon two opposing forces: a spring and an electromagnet. The spring compresses the carbon pile, and the electromagnet exerts a pull which de-

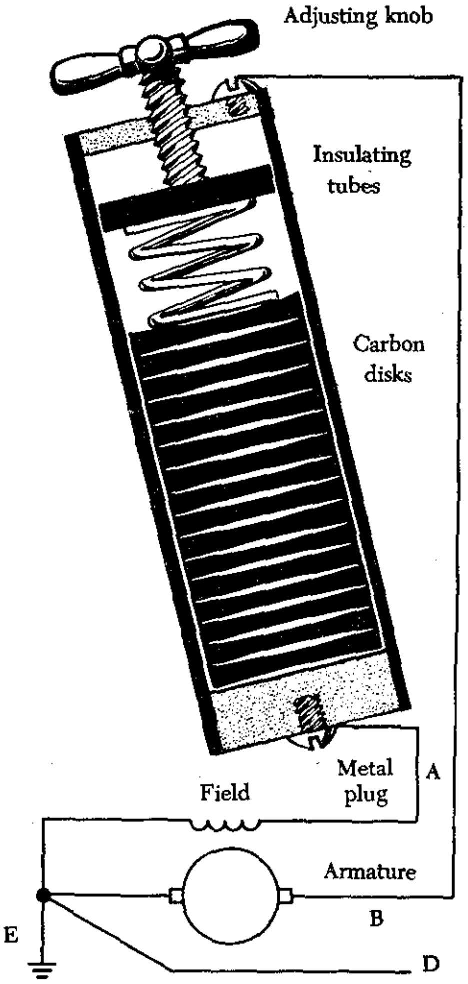


FIGURE 9–24. Illustrating the controlling effect of a carbon-pile voltage regulator.

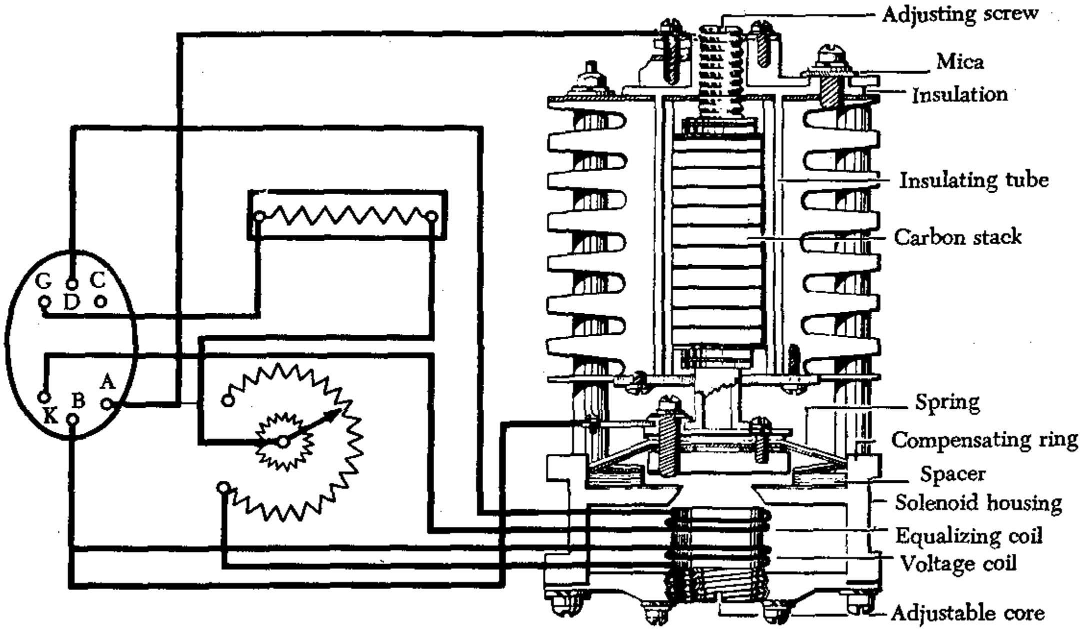


FIGURE 9–25. A 24-volt voltage regulator showing internal circuits.

creases the pressure. The coil of the electromagnet, as represented in the diagram in figure 9–24, is connected across the generator terminal B and through a rheostat (adjustable knob) and resistor (carbon disks) to ground.

When the generator voltage varies, the pull of the electromagnet varies. If the generator voltage rises above a specific amount, the pull of the electromagnet increases, decreasing the pressure exerted on the carbon pile and increasing its resistance. Since this resistance is in series with the field, less current flows through the field winding, there is a corresponding decrease in field strength, and the generator voltage drops. On the other hand, if the generator output drops below the specified value, the pull of the electromagnet is decreased and the carbon pile places less resistance in the field winding circuit. In addition, the field strength increases and the generator output increases. A small rheostat provides a means of adjusting the current flow through the electromagnet coil. Figure 9–25 shows a typical 24-volt voltage regulator with its internal circuits.

Three-Unit Regulators

Many light aircraft employ a three-unit regulator for their generator systems. This type of regulator includes a current limiter and a reverse-current cutout in addition to a voltage regulator.

The action of the voltage regulator unit is similar to the vibrating-type regulator described earlier. The second of the three units is a current regulator to limit the output current of the generator. The third unit is a reverse-current cutout that disconnects the battery from the generator. If the battery is not disconnected, it will discharge through the generator armature when the generator voltage falls below that of the

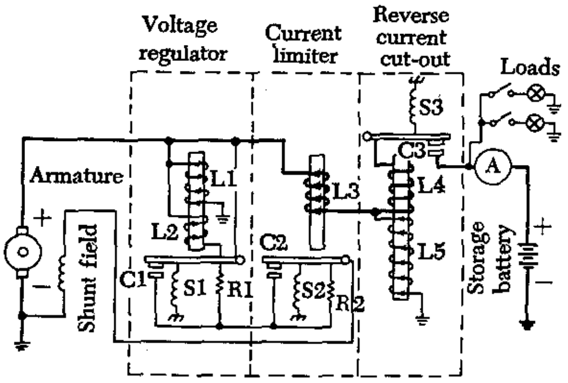


FIGURE 9–26. Three-unit regulator for variable-speed generators.

battery, thus driving the generator as a motor. This action is called "motoring" the generator and, unless it is prevented, it will discharge the battery in a short time.

The operation of a three-unit regulator is described in the following paragraphs. (Refer to figure 9–26.)

The action of vibrating contact C1 in the voltage regulator unit causes an intermittent short circuit between points R1 and L2. When the generator is not operating, spring S1 holds C1 closed; C2 is also closed by S2. The shunt field is connected directly across the armature.

When the generator is started, its terminal voltage will rise as the generator comes up to speed, and the armature will supply the field with current through closed contacts C2 and C1.

As the terminal voltage rises, the current flow through L1 increases and the iron core becomes more strongly magnetized. At a certain speed and voltage, when the magnetic attraction on the movable arm becomes strong enough to overcome the tension of spring S1, contact points C1 are separated. The field current now flows through R1 and L2. Because resistance is added to the field circuit, the field is momentarily weakened and the rise in terminal voltage is checked. Also, since the L2 winding is opposed to the L1 winding, the magnetic pull of L1 against S1 is partially neutralized, and spring S1 closes contact C1. Therefore, R1 and L2 are again shorted out of the circuit, and the field current again increases; the output voltage increases, and C1 is opened because of the action of L1. The cycle is rapid and occurs many times per second. The terminal voltage of the generator varies slightly, but rapidly, above and below an average value determined by the tension of spring S1, which may be adjusted.

The purpose of the vibrator-type current limiter is to limit the output current of the generator automatically to its maximum rated value in order to protect the generator. As shown in figure 9–26, L3 is in series with the main line and load. Thus, the amount of current flowing in the line determines when C2 will be opened and R2 placed in series with the generator field. By contrast, the voltage regulator is actuated by line voltage, whereas the current limiter is actuated by line current. Spring S2 holds contact C2 closed until the current through the main line and L3 exceeds a certain value, as determined by the tension of spring S2, and causes C2 to be opened. The increase in current is due to an increase in load. This action inserts R2 into the field circuit of the generator and decreases the field current and the generated voltage. When the generated voltage is decreased, the generator current is reduced. The core of L3 is partly demagnetized and the spring closes the contact points. This causes the generator voltage and current to rise until the current reaches a value sufficient to start the cycle again. A certain minimum value of load current is necessary to cause the current limiter to vibrate.

The purpose of the reverse-current cutout relay is to automatically disconnect the battery from the generator when the generator voltage is less than the battery voltage. If this device were not used in the generator circuit, the battery would discharge through the generator. This would tend to make the generator operate as a motor, but because the generator is coupled to the engine, it could not rotate such a heavy load. Under this condition, the generator windings may be severely damaged by excessive current.

There are two windings, L4 and L5, on the soft-iron core. The current winding, L4, consisting of a few turns of heavy wire, is in series with the line and carries the entire line current. The voltage winding, L5, consisting of a large number of turns of fine wire, is shunted across the generator terminals.

When the generator is not operating, the contacts, C3 are held open by the spring S3. As the generator voltage builds up, L5 magnetizes the iron core. When the current (as a result of the generated voltage) produces sufficient magnetism in the iron core, contact C3 is closed, as shown. The battery then receives a charging current. The coil spring, S3, is so adjusted that the voltage winding will not close the contact points until the voltage of the generator is in excess of the normal voltage of the battery. The charging current passing through L4 aids the current in L5 to hold the contacts tightly closed. Unlike C1 and C2, contact C3 does not vibrate. When the generator slows down or, for any other cause, the generator voltage decreases to a certain value below that of the battery, the current reverses through L4 and the ampere-turns of L4 oppose those of L5. Thus, a momentary discharge current from the battery reduces the magnetism of the core and C3 is opened, preventing the battery from discharging into the generator and motoring it. C3 will not close again until the generator terminal voltage

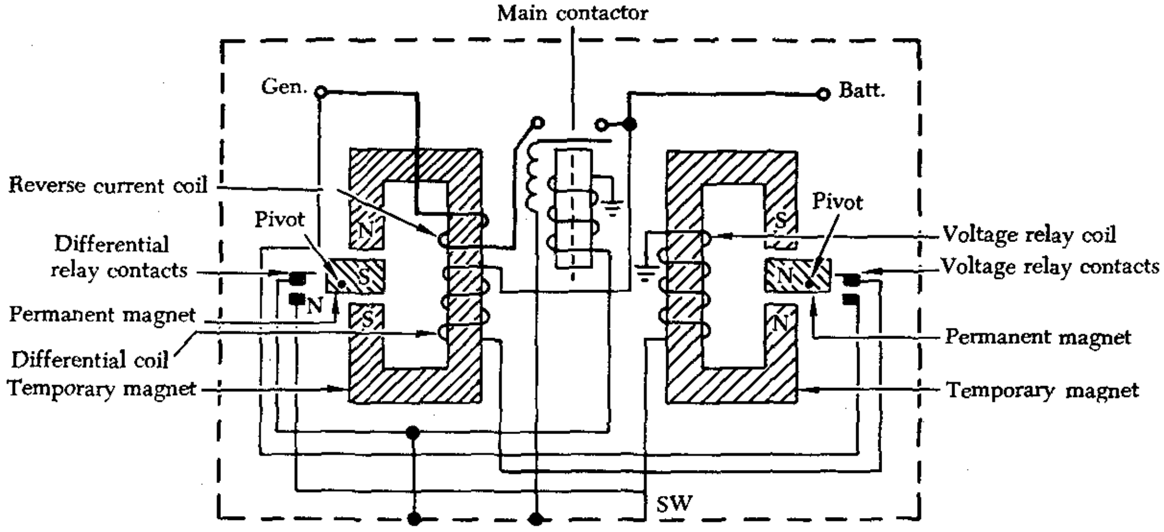


FIGURE 9–27. Differential generator control relay.

exceeds that of the battery by a predetermined value.

DIFFERENTIAL RELAY SWITCH

Aircraft electrical systems normally use some type of reverse-current relay switch, which acts not only as a reverse-current relay cutout but also serves as a remote-control switch by which the generator can be disconnected from the electrical system at any time. One type of reverse-current relay switch operates on the voltage level of the generator, but the type most commonly used on large aircraft is the differential relay switch, which is controlled by the difference in voltage between the battery bus and the generator.

The differential type relay switch connects the generator to the main bus bar in the electrical system when the generator voltage output exceeds the bus voltage by 0.35 to 0.65 volt. It disconnects the generator when a nominal reverse current flows from the bus to the generator. The differential relays on all the generators of a multiengine aircraft do not close when the electrical load is light. For example, in an aircraft having a load of 50 amperes, only two or three relays may close. If a heavy load is applied, the equalizing circuit will lower the voltage of the generators already on the bus and, at the same time, raise the voltage of the remaining generators, allowing their relays to close. If the generators have been paralleled properly, all the relays stay closed until the generator control switch is turned off or until the engine speed falls below the minimum needed to maintain generator output voltage.

The differential generator control relay shown in the illustration in figure 9–27 is made up of two relays and a coil-operated contactor. One relay is the voltage relay and the other is the differential relay. Both relays include permanent magnets, which pivot between the pole pieces of temporary magnets wound with relay coils. Voltages of one polarity set up fields about the temporary magnets with polarities which cause the permanent magnet to move in the direction necessary to close the relay contacts; voltages of the opposite polarity establish fields that cause the relay contacts to open. The differential relay has two coils wound on the same core. The coil-operated contactor, called the main contactor, consists of movable contacts that are operated by a coil with a movable iron core.

Closing the generator switch on the control panel connects the generator output to the voltage relay coil. When generator voltage reaches 22 volts, current flows through the coil and closes the contacts of the voltage relay. This action completes a circuit from the generator to the battery through the differential coil. When the generator voltage exceeds the bus voltage by 0.35 volt, current will flow through the differential coil, the differential relay contact will close and, thus, complete the main contractor coil circuit. The contacts of the main contactor close and connect the generator to the bus.

When the generator voltage drops below the bus (or battery) voltage, a reverse current weakens the magnetic field about the temporary magnet of the differential relay. The weakened field permits a spring to open the differential relay contacts, breaking the circuit to the coil of the main contactor relay, opening its contacts, and disconnecting the generator from the bus.

The generator-battery circuit may also be broken by opening the cockpit control switch, which opens the contacts of the voltage relay, causing the differential relay coil to be deenergized.

Overvoltage and Field Control Relays

Two other items used with generator control circuits are the overvoltage control and the field control relay.

As its name implies, the overvoltage control protects the system when excessive voltage exists. The overvoltage relay is closed when the generator output reaches 32 volts and completes a circuit to the trip coil of the field control relay. The closing of the field control relay trip circuit opens the shunt field circuit and completes it through a resistor, causing generator voltage to drop; also, the generator switch circuit and the equalizer circuit (multiengine aircraft) are opened. An indicator light circuit is completed, warning that an overvoltage condition exists. A "reset" position of the cockpit switch is used to complete a reset coil circuit in the field control relay, returning the relay to its normal position.

PARALLELING GENERATORS

When two or more generators are operated at the same time to supply power for a load, they are operated in parallel; that is, each supplies a proportional part of the ampere-load. Successful multigenerator operation requires that each generator share the load equally, since a very small increase in the voltage output of one generator will result in that generator's supplying the greater part of the power needed by the load.

The power supplied by a generator for a load is often referred to as ampere-load. Although power is actually measured in watts—the product of voltage and current—the term "ampere-load" is applicable because the voltage output of a generator is considered constant; therefore, the power is directly proportional to the ampere output of the generator.

Negative Lead Paralleling

To distribute the load equally among generators operated in parallel, a special coil is wound on the same core as the voltage coil of the voltage regulator. This is part of the equalizing system shown in figure 9–28. A calibrated resistor is located in the lead from the generator negative terminal E to ground. The value of the resistance in this lead is such that when the generator is operating at full current output, there is a 0.5-volt drop across the resistor. This resistor may be a special resistor; it may be a ground lead long enough to have the required resistance, or a series winding of the generator.

The equalizing system depends upon the voltage drop in the individual calibrated resistors. If all generators are supplying the same current, the voltage drop in all ground leads is the same. If the current supplied by the generators is unequal, there is a greater voltage drop in the ground lead of the generator supplying more current. Thus, when the No. 1 generator is supplying 150 amperes and the No. 2 generator is supplying 300 amperes, the voltage drop in the negative lead of the No. 1 generator is 0.25 volt and that in the negative lead of the No. 2 generator is 0.5 volt. This means that point E of the No. 1 generator is at a lower voltage than point E of the No. 2 generator, and current will flow in the equalizing circuit from E of the No. 2 generator to E of the No. 1 generator. The equalizing coil will aid the voltage coil in voltage regulator No. 2 and oppose the voltage coil in regulator No. 1. In this way, the voltage of generator No. 2 will be lowered and that of the other will be increased.

Positive Lead Paralleling

The diagram in figure 9–29 shows two generators carrying a total load of 300 amperes. If the generators were sharing this load equally, the ammeters would each indicate 150 amperes. The generators would be "paralleled" and no current would flow in the equalizing coils between the K and D terminals on the regulators. Note, however, that the ammeter for the No. 1 generator indicates only 100 amperes, but the ammeter for the No. 2 generator indicates 200 amperes. This is an unbalanced load and causes current to flow through the equalizing circuit (dotted lines) in the direction indicated by the arrows. The reason is as follows: With 200 amperes of current flowing through the No. 2 equalizing resistor (from Ohm's law, $E =$

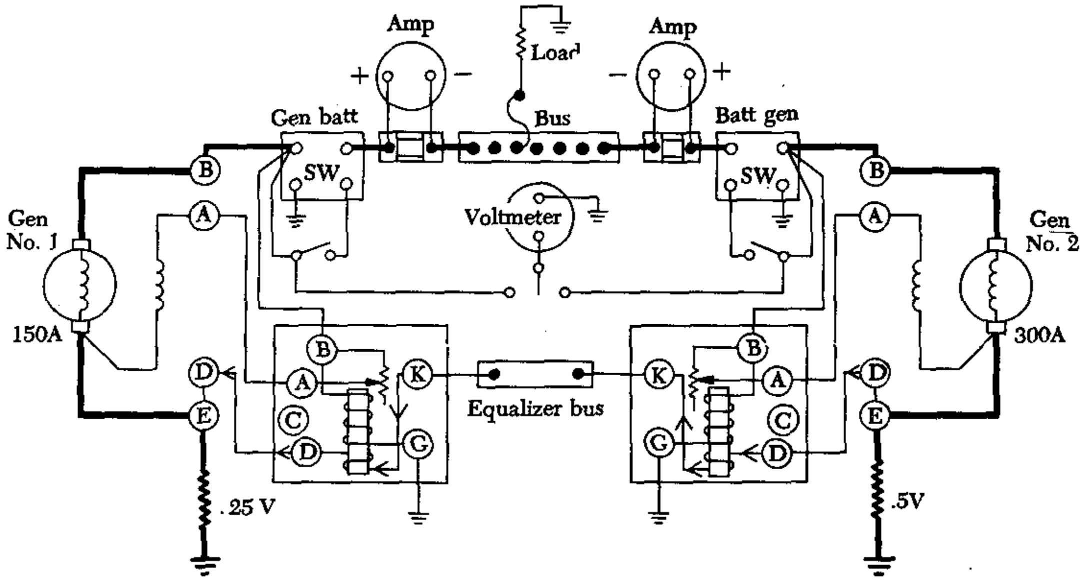


FIGURE 9–28. Generator equalizer circuits.

I × *R*), there will be a 0.5 volt drop in voltage across the No. 2 resistor. Since there are only 100 amperes flowing through the No. 1 equalizing resistor, there will be a one-fourth volt drop across that resistor, and a difference in voltage of one-fourth volt will exist between the two resistors. Since current flows from a high pressure (potential) to a lower pressure and from negative to positive, it will be in the direction indicated by the arrows. When the load is equal, there will not be a difference in voltage betweeen the two resistors.

The current can be traced through the equalizing circuit and through the voltage regulator coils to show the effect on the electromagnets. With the current in the direction shown, the equalizing coil and voltage coil of the No. 1 voltage regulator set up magnetic fields opposing each other, thus weakening the electromagnet of the No. 1 voltage regulator. This allows the spring to compress the carbon disks, decreasing their resistance and allowing more current to flow in the field circuit of the No. 1 generator. As a result, the voltage output of that generator increases, but at the same time, the current through the equalizing coil and voltage coil of No. 2 voltage regulator sets up magnetic fields that aid each other, thus increasing the strength of that electromagnet. This decreases the spring pressure on the carbon disks, increasing their resistance and allowing less current to flow in the field circuit of the No. 2 generator. As a result, the voltage output of this generator will decrease. With the voltage output of the No. 1 generator increased, the voltage drop across No. 1 equalizing resistor increases; and with a decrease in voltage output of the No. 2 generator, the voltage drop across the No. 2 equalizing resistor decreases. When the voltage output of the two generators is equal, the voltage drop across the equalizing resistors will also be equal. No current will flow in the equalizing circuit, the load will be balanced, and the ammeters will read approximately the same. The generators are then paralleled.

The purpose of the equalizing circuit is to help the voltage regulators automatically by lowering the voltage of the high generator and raising the voltage of the low generator, so that the total will be shared equally by the generators.

D. C. GENERATOR MAINTENANCE

Inspection

The following information about the inspection and maintenance of d.c. generator systems is general in nature because of the large number of differing aircraft generator systems. These procedures are for familiarization only. Always follow the applicable manufacturer's instructions for a given generator system.

In general, the inspection of the generator in-

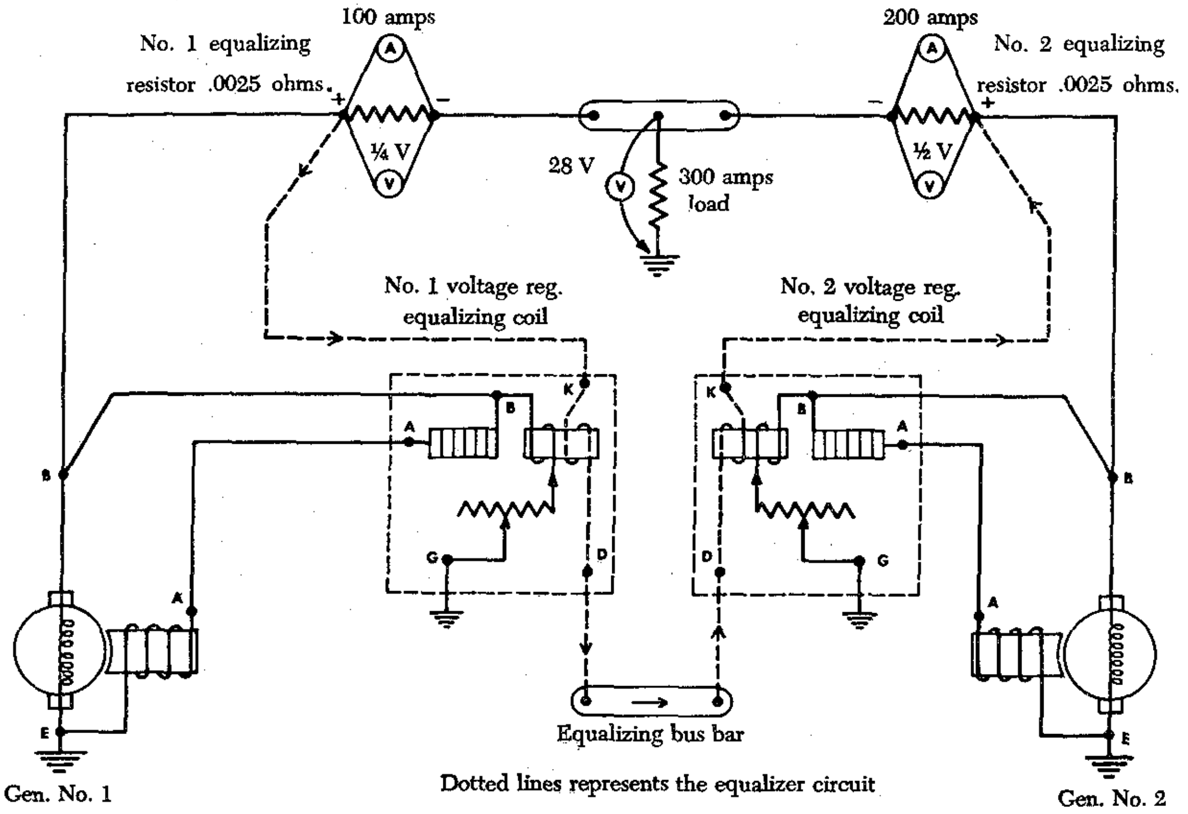


FIGURE 9–29. Generator and equalizer circuits.

stalled in the aircraft should include the following items:

1. Security of generator mounting.
2. Condition of electrical connections.
3. Dirt and oil in the generator. If oil is present, check engine oil seal. Blow out dirt with compressed air.
4. Condition of generator brushes.
5. Generator operation.
6. Voltage regulator operation.

A detailed discussion of items 4, 5, and 6 is presented in the following paragraphs.

Condition of Generator Brushes

Sparking of brushes quickly reduces the effective brush area in contact with the commutator bars. The degree of such sparking should be determined. Excessive wear warrants a detailed inspection.

The following information pertains to brush seating, brush pressure, high-mica condition, and brush wear.

Manufacturers usually recommend the following procedures to seat brushes which do not make good contact with slip rings or commutators.

The brush should be lifted sufficiently to permit the insertion of a strip of No. 000, or finer, sandpaper under the brush, rough side out (figure 9–30). Pull sandpaper in the direction of armature rotation, being careful to keep the ends of the sandpaper as close to the slip ring or commutator surface as possible in order to avoid rounding the edges of the brush. When pulling the sandpaper back to the starting point, the brush should be raised so it does not ride on the sandpaper. The brush should be sanded only in the direction of rotation.

After the generator has run for a short period, brushes should be inspected to make sure that pieces of sand have not become embedded in the brush and are collecting copper.

Under no circumstances should emery cloth or similar abrasives be used for seating brushes

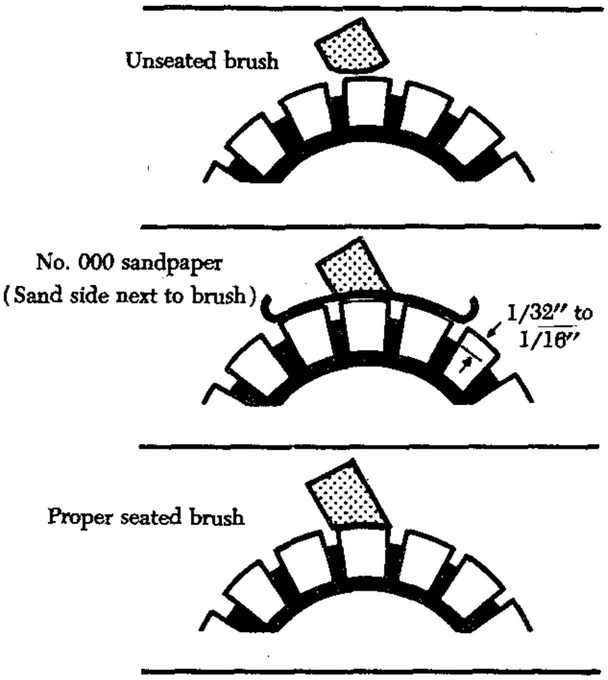


FIGURE 9–30. Seating brushes with sandpaper.

(or smoothing commutators), since they contain conductive materials which will cause arcing between brushes and commutator bars.

Excessive pressure will cause rapid wear of brushes. Too little pressure, however, will allow "bouncing" of the brushes, resulting in burned and pitted surfaces.

A carbon, graphite, or light metalized brush should exert a pressure of 1½ to 2½ p.s.i. on the commutator. The pressure recommended by the manufacturer should be checked by the use of a spring scale graduated in ounces. Brush spring tension is usually adjusted between 32 to 36 ounces; however, the tension may differ slightly for each specific generator.

When a spring scale is used, the measurement of the pressure which a brush exerts on the commutator is read directly on the scale. The scale is applied at the point of contact between the spring arm and the top of the brush, with the brush installed in the guide. The scale is drawn up until the arm just lifts off the brush surface. At this instant, the force on the scale should be read.

Flexible low-resistance pigtails are provided on most heavy-current-carrying brushes, and their connections should be securely made and checked at frequent intervals. The pigtails should never be permitted to alter or restrict the free motion of the brush.

The purpose of the pigtail is to conduct the current, rather than subjecting the brush spring to currents which would alter its spring action by overheating. The pigtails also eliminate any possible sparking to the brush guides caused by the movement of the brushes within the holder, thus minimizing side wear of the brush.

Carbon dust resulting from brush sanding should be thoroughly cleaned from all parts of the generators after a sanding operation. Such carbon dust has been the cause of several serious fires as well as costly damage to the generator.

Operation over extended periods of time often results in the mica insulation between commutator bars protruding above the surface of the bars. This condition is called "high mica" and interferes with the contact of the brushes to the commutator.

Whenever this condition exists, or if the armature has been turned on a lathe, carefully undercut the mica insulation to a depth equal to the width of the mica, or approximately 0.020 inch.

Each brush should be a specified length to work properly. If a brush is too short, the contact it makes with the commutator will be faulty, which can also reduce the spring force holding the brush in place. Most manufacturers specify the amount of wear permissible from a new brush length. When a brush has worn to the minimum length permissible, it must be replaced.

Some special generator brushes should not be replaced because of a slight grooving on the face of the brush. These grooves are normal and will appear in a.c. and d.c. generator brushes which are installed in some models of aircraft generators. These brushes have two cores made of a harder material with a higher expansion rate than the material used in the main body of the brush. Usually, the main body of the brush face rides on the commutator. However, at certain temperatures, the cores extend and wear through any film on the commutator.

Generator Operation

If there is no generator output, follow a systematic troubleshooting procedure to locate the malfunction. The following method is an example. Although this method may be acceptable for most 28-volt, twin-engine or four-engine d.c. generator systems using carbon-pile voltage regulators, the applicable manufacturer's procedures should be followed in all cases.

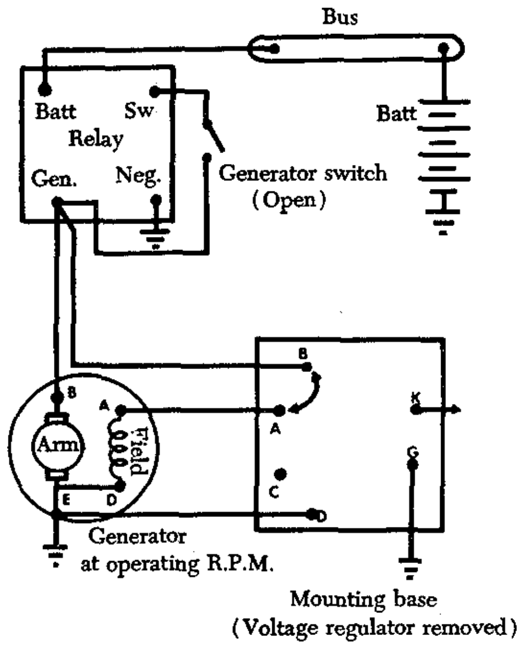


FIGURE 9–31. Checking generator by shorting terminals A and B.

If the generator is not producing voltage, remove the voltage regulator and, with the engine running at approximately 1,800 r.p.m., short circuit terminals A and B at the subbase of the regulator as shown in the diagram of figure 9–31. If this test shows excessive voltage, the generator is not at fault, but the trouble lies in the voltage regulator. If the test fails to produce voltage, the generator field may have lost its residual magnetism.

To restore residual magnetism, flash the generator field by removing the regulator and connect terminal A of the voltage regulator base to the battery at a junction box or a bus bar as indicated by the dotted line in the diagram of figure 9–32, while running the engine at cruising r.p.m. If there is still no voltage, check the leads for continuity shorts and grounds. If the generator is located where the brushes and commutator can be inspected, check each for proper condition as prescribed in the applicable manufacturer's procedures. If necessary, replace the brushes and clean the commutator. If the generator is located so that it cannot be serviced in the airplane, remove it and make the inspection.

VOLTAGE REGULATOR OPERATION

To inspect the voltage regulator, remove it from the subbase and clean all the terminals and contact surfaces. Examine the base or housing for cracks. Check all connections for security. Remember that the voltage regulator is a precision instrument and cannot withstand rough treatment. Handle it with care. To adjust a voltage regulator, a precision portable voltmeter is required. This, too, must be handled with care, since it will not maintain accuracy under conditions of mishandling, vibration, or shock.

Detailed procedures for adjusting voltage regulators are given in applicable manufacturer's instructions. The following procedures are guidelines for adjusting the carbon-pile voltage regulator in a multiengine 28-volt d.c. electrical system:

1. Start and warm up all engines which have installed generators.
2. Turn all generator switches to the "off" position.
3. Connect a precision voltmeter from the B terminal of one voltage regulator to a good ground.

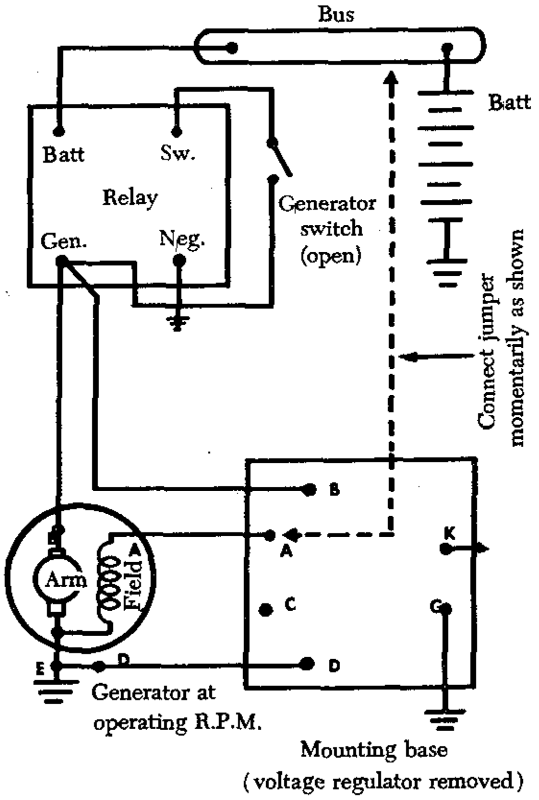


FIGURE 9–32. A method of flashing generator field.

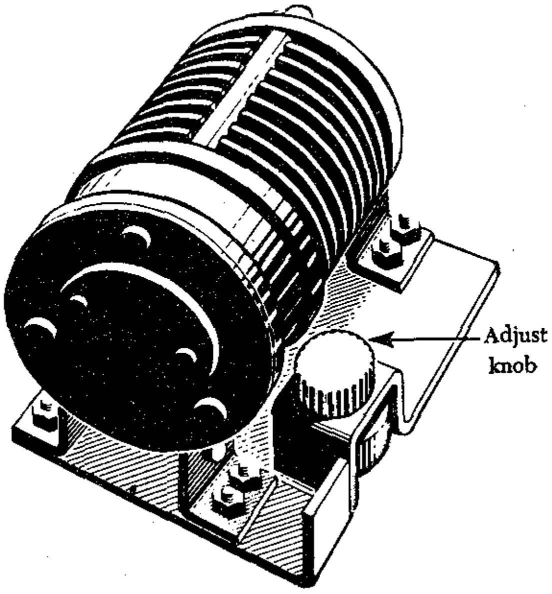


FIGURE 9–33. Adjustment knob on carbon-pile voltage regulator.

4. Increase the engine speed of the generator being checked to normal cruising r.p.m. Operate remaining engines at idling speed.
5. Adjust the regulator until the voltmeter reads exactly 28 volts. (The location of the adjustment knob on a carbon-pile voltage regulator is shown in figure 9–33.)
6. Repeat this procedure to adjust all voltage regulators.
7. Increase the speed of all engines to normal cruising r.p.m.
8. Close all generator switches.
9. Apply a load equivalent to approximately one-half full load rating of one generator when checking a two-generator system or a load comparable to the rating of one generator when checking a system that has more than two generators.
10. Observe the ammeters or load meters. The difference between the highest and lowest generator current should not exceed the value listed in the manufacturer's maintenance instructions.
11. If the generators are not dividing the load equally (unparalled), first lower the voltage of the highest generator and slightly raise the voltage of the lowest generator by adjusting the corresponding voltage regulators. When the generators have been adjusted to share the load equally, they are in "parallel."
12. After all adjustments have been made, make a final check of bus voltage from positive bus to ground, with a precision voltmeter. The voltmeter should read 28 volts, (±0.25 volt on most 28-volt systems). If the bus voltage is not within the proper limits, readjust all voltage regulator rheostats and recheck.

When inspecting the generator relay switch, examine the relay for cleanness and security of mounting and see that all electrical connections are tightly fastened. Look for burned or pitted contacts. Never close the relay manually by pressing the contacts together; this might severely damage the relay or cause an injury. Never adjust the differential type relay, since it closes when the generator voltage exceeds the system voltage by a specified value and is not checked to close at any set voltage; however, check it for proper closing by noting the ammeter indication with the battery generator control switches turned on while running the engines. It is sometimes necessary to put a slight load on the system before the ammeter will show a positive indication when the engine is run up to cruising speed. If the ammeter does not indicate, the relay is probably defective; therefore, remove it and replace it with a new relay. Check the reverse-current relay for proper opening value. If the relay fails to close when the engine speed is increased or fails to disconnect the generator from the bus bar, the relay is defective.

Troubleshooting

If a generator system malfunctions, there are two general possibilities: (1) The generator itself may be at fault (burned out, damaged mechanically, etc.), or (2) that part of the circuit leading to or from the generator may be at fault. Continuity testing refers to checking for the existence of a complete electrical system between two points. The three main types of continuity testers are:

1. The portable dry cell tester, having a buzzer or a 3-volt lamp to indicate the completed circuit, is used to test circuits with the main circuit power off.

2. An ordinary lamp bulb (24-volt type), with one lead from the center lamp contact and one ground lead attached to the lamp housing, can be used to test circuits with the main circuit power on.
3. A precision voltmeter is used to test circuits with the main circuit power on by placing the positive lead on the circuit point and the negative lead on any convenient ground.

Tests should be made at each terminal of the circuit. Between the last point at which voltage is indicated and the first point at which zero voltage is indicated, there is an open circuit or a voltage drop caused by unit operation or short to ground. If the same voltage reading is obtained on the negative terminal of a unit as was obtained on the positive terminal, an open ground is indicated. If a small voltage reading is obtained on the negative terminal of the unit, a high resistance is indicated between the unit and ground.

The following troubleshooting chart outlines the most commonly encountered malfunctions, a list of probable causes to isolate the malfunction, and the proper corrective action to be taken. This chart is a general guide for troubleshooting a twin-engine d.c. generator system, which utilizes carbon-pile voltage regulators.

TROUBLE	ISOLATION PROCEDURE	CORRECTION
No voltage indication on any one generator.	Check for defective generator switch or field switch.	Replace generator switch or field switch.
	Determine if generator polarity is reversed.	Flash generator field.
	Check for open, shorted, or grounded wiring.	Replace defective wiring.
	Check for defective generator.	Replace generator.
Low voltage on any one generator.	Check voltage regulator adjustment.	Adjust voltage regulator.
	Check for defective voltage regulator.	Replace voltage regulator.
	Check for defective wiring.	Replace defective wiring.
	Check for defective generator.	Replace generator.
Generator cuts out.	Check for defective reverse-current cutout relay.	Replace reverse-current cutout relay.
	Check for defective overvoltage relay.	Replace overvoltage relay.
	Check for defective field control relay.	Replace field control relay.
	Check for defective voltage regulator.	Replace voltage regulator.
	Check for defective wiring.	Replace defective wiring.
Voltage unsteady for any one generator.	Check for defective wiring.	Replace defective wiring.
	Check for defective generator.	Replace generator.
	Check wear of generator bearings.	Replace generator.
No load indication on any one generator. Voltage is normal.	Check for defective reverse-current cutout relay.	Replace reverse-current cutout relay.
	Check for defective generator switch.	Replace generator switch.
	Check for defective wiring.	Replace defective wiring.

TROUBLE	ISOLATION PROCEDURE	CORRECTION
Low d.c. bus voltage.	Check improper voltage regulator adjustment.	Adjust voltage regulator.
	Check for defective reverse-current cutout relays.	Replace reverse-current cutout relays.
Voltage high on any one generator.	Check for improper voltage regulator adjustment.	Adjust voltage regulator.
	Check for defective voltage regulator.	Replace voltage regulator.
	Determine if generator field lead A is shorted to positive.	Replace shorted wiring or repair connections.
Generator fails to build up more than approximately 2 volts.	Check voltage regulator or base. Take precision voltmeter reading between A terminal and ground. No voltage reading indicates trouble in either regulator or base. Reading of about 2 volts indicates regulator and base are OK.	Check regulator contacts where they rest on the silver contact bar. Any signs of burning at this point is cause for replacement of regulator.
	Check for defective generator. Low ohmmeter reading indicates current is good and trouble must be within the generator.	Disconnect generator plug. Place one lead of ohmmeter on A terminal and the other lead on E terminal. High reading indicates that the generator field is open. Replace generator.
Instrument panel voltmeter reading of excessive voltage.	Check for short across A and B terminal of voltage regulator.	If shorted, change voltage regulator.
	Check voltage regulator control.	Replace voltage regulator.
Instrument panel voltmeter reading of zero volts.	Check for defective voltmeter circuit.	Place positive lead of voltmeter on positive terminal of instrument panel voltmeter and negative lead to ground. Reading should be 27.5 volts. If not, lead from regulator to instrument is defective. Replace or correct lead. Place positive lead of voltmeter on negative terminal of instrument panel voltmeter and negative lead to ground. If voltmeter reading is zero, instrument panel voltmeter is defective. Replace voltmeter.
	Check for broken B or E lead. Remove voltage regulator and take ohmmeter reading between B contact finger of regulator	High resistance most likely is caused by oil, dirt, or burning at connector plug or commutator. Replace generator.

TROUBLE	ISOLATION PROCEDURE	CORRECTION
	base and ground. Low reading indicates circuit is OK. High reading indicates that a high resistance is the trouble.	
	Check for loss of residual magnetism.	Place flasher switch in ON position momentarily. Do not hold. *NOTE:* If flasher switch is held ON rather than switched momentarily, damage may be done to generator field coils.
Voltage does not build up properly when field is flashed.	Check for open field. Disconnect generator connector and take ohmmeter reading between A and E terminals of generator connectors. High reading indicates field circuit is open.	Check and repair lead or connectors.
	Check for grounded field. Take ohmmeter reading between A terminal of generator and generator housing. Low reading indicates field is grounded.	Insulation on field winding is broken. Replace generator.
	Check for open armature. Remove generator cover and inspect commutator. If solder is melted and has been thrown off, then armature is open (caused by generator overheating).	Replace generator.

ALTERNATORS

An electrical generator is a machine which converts mechanical energy into electrical energy by electromagnetic induction. A generator which produces alternating current is referred to as an a.c. generator and, through combination of the words "alternating" and "generator," the word "alternator" has come into widespread use. In some areas, the word "alternator" is applied only to small a.c. generators. This text treats the two terms synonymously and uses the term "alternator" to distinguish between a.c. and d.c. generators.

The major difference between an alternator and a d.c. generator is the method of connection to the external circuit; that is, the alternator is connected to the external circuit by slip rings, but the d.c. generator is connected by a commutator.

Types of Alternators

Alternators are classified in several ways in order to distinguish properly the various types. One means of classification is by the type of excitation system used. In alternators used on aircraft, excitation can be affected by one of the following methods:

1. A direct-connected, direct-current generator. This system consists of a d.c. generator fixed on the same shaft with the a.c. generator. A variation of this system is a type of alternator which uses d.c. from the battery for excitation, after which the alternator is self-excited.
2. By transformation and rectification from the a.c. system. This method depends on residual magnetism for initial a.c. voltage buildup,

after which the field is supplied with rectified voltage from the a.c. generator.

3. Integrated brushless type. This arrangement has a direct-current generator on the same shaft with an alternating-current generator. The excitation circuit is completed through silicon rectifiers rather than a commutator and brushes. The rectifiers are mounted on the generator shaft and their output is fed directly to the alternating-current generator's main rotating field.

Another method of classification is by the number of phases of output voltage. Alternating-current generators may be single-phase, two-phase, three-phase, or even six-phase and more. In the electrical systems of aircraft, the three-phase alternator is by far the most common.

Still another means of classification is by the type of stator and rotor used. From this standpoint, there are two types of alternators: the revolving-armature type and the revolving-field type. The revolving-armature alternator is similar in construction to the d.c. generator, in that the armature rotates through a stationary magnetic field. The revolving-armature alternator is found only in alternators of low power rating and generally is not used. In the d.c. generator, the e.m.f. generated in the armature windings is converted into a unidirectional voltage (d.c.) by means of the commutator. In the revolving-armature type of alternator, the generated a.c. voltage is applied unchanged to the load by means of slip rings and brushes.

The revolving-field type of alternator (figure 9–34) has a stationary armature winding (stator) and a rotating-field winding (rotor). The advantage of having a stationary armature winding is that the armature can be connected directly to the load without having sliding contacts in the load circuit. A rotating armature would require slip rings and brushes to conduct the load current from the armature to the external circuit. Slip rings have a relatively short service life and arc-over is a continual hazard; therefore, high-voltage alternators are usually of the stationary-armature, rotating-field type. The voltage and current supplied to the rotating field are relatively small, and slip rings and brushes for this circuit are adequate. The direct connection to the armature circuit makes possible the use of large cross-section conductors, adequately insulated for high voltage.

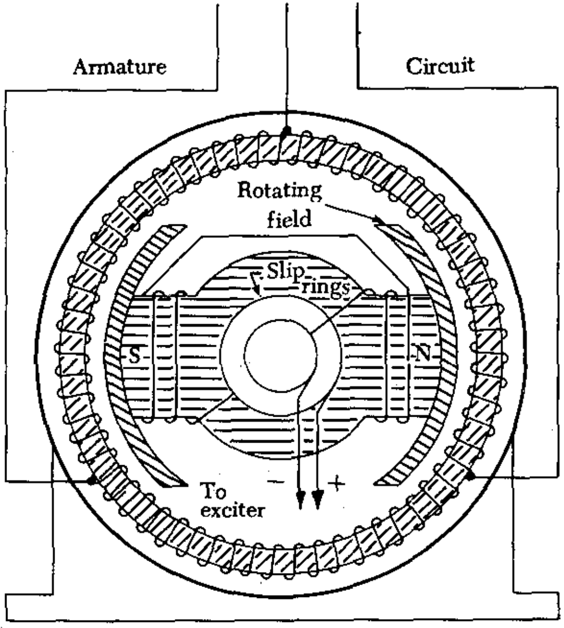


FIGURE 9–34. Alternator with stationary armature and rotating field.

Since the rotating-field alternator is used almost universally in aircraft systems, this type will be explained in detail, as a single-phase, two-phase, and three-phase alternator.

Single-Phase Alternator

Since the e.m.f. induced in the armature of a generator is alternating, the same sort of winding can be used on an alternator as on a d.c. generator. This type of alternator is known as a single-phase alternator, but since the power delivered by a single-phase circuit is pulsating, this type of circuit is objectionable in many applications.

A single-phase alternator has a stator made up of a number of windings in series, forming a single circuit in which an output voltage is generated. Figure 9–35 illustrates a schematic diagram of a single-phase alternator having four poles. The stator has four polar groups evenly spaced around the stator frame. The rotor has four poles, with adjacent poles of opposite polarity. As the rotor revolves, a.c. voltages are induced in the stator windings. Since one rotor pole is in the same position relative to a stator winding as any other rotor pole, all stator polar groups are cut by equal numbers of magnetic lines of force at any time. As a result, the voltages induced in all the windings have the same amplitude, or value, at

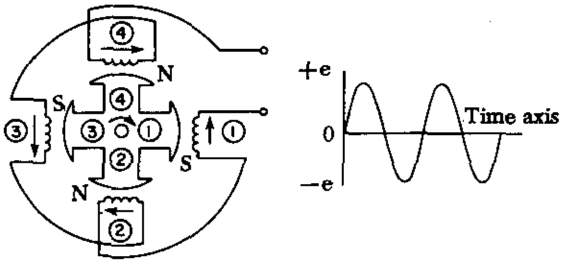


FIGURE 9–35. Single-phase alternator.

any given instant. The four stator windings are connected to each other so that the a.c. voltages are in phase, or "series adding." Assume that rotor pole 1, a south pole, induces a voltage in the direction indicated by the arrow in stator winding 1. Since rotor pole 2 is a north pole, it will induce a voltage in the opposite direction in stator coil 2 with respect to that in coil 1.

For the two induced voltages to be in series addition, the two coils are connected as shown in the diagram. Applying the same reasoning, the voltage induced in stator coil 3 (clockwise rotation of the field) is the same direction (counterclockwise) as the voltage induced in coil 1. Similarly, the direction of the voltage induced in winding 4 is opposite to the direction of the voltage induced in coil 1. All four stator coil groups are connected in series so that the voltages induced in each winding add to give a total voltage that is four times the voltage in any one winding.

Two-Phase Alternator

Two-phase alternators have two or more single-phase windings spaced symmetrically around the stator. In a two-phase alternator there are two single-phase windings spaced physically so that the a.c. voltage induced in one is 90° out of phase with the voltage induced in the other. The windings are electrically separate from each other. When one winding is being cut by maximum flux, the other is being cut by no flux. This condition establishes a 90° relation between the two phases.

Three-Phase Alternator

A three-phase, or polyphase circuit, is used in most aircraft alternators, instead of a single or two-phase alternator. The three-phase alternator has three single-phase windings spaced so that the voltage induced in each winding is 120° out of phase with the voltages in the other two windings. A schematic diagram of a three-phase stator showing all the coils becomes complex and difficult to see what is actually happening.

A simplified schematic diagram, showing each of three phases, is illustrated in figure 9–36. The rotor is omitted for simplicity. The waveforms of voltage are shown to the right of the schematic. The three voltages are 120° apart and are similar to the voltages which would be generated by three single-phase alternators whose voltages are out of phase by angles of 120°. The three phases are independent of each other.

Rather than have six leads from the three-phase alternator, one of the leads from each phase may be connected to form a common junction. The stator is then called wye- or star-connected. The common lead may or may not be brought out of the alternator. If it is brought out, it is called the neutral lead. The simplified schematic (A of figure 9–37) shows a wye-connected stator with the common lead not brought out. Each load is connected across two phases in series. Thus, R_{AB} is connected across phases A and B in series; R_{AC} is connected across phases A and C in series; and R_{BC} is connected across phases B and C in series. Therefore, the voltage across each load is larger than the voltage across a single phase. The total voltage, or line voltage, across any two phases is the vector sum of the individual phase voltages. For balanced conditions, the line voltage is 1.73 times the phase voltage. Since there is only one path for current in a line wire and the phase to which it is connected, the line current is equal to the phase current.

A three-phase stator can also be connected so that the phases are connected end-to-end as shown in B of figure 9–37. This arrangement is called a delta connection. In a delta connection, the voltages are equal to the phase voltages; the line currents are equal to the vector sum of the

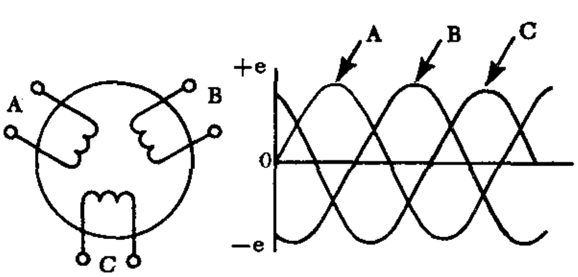
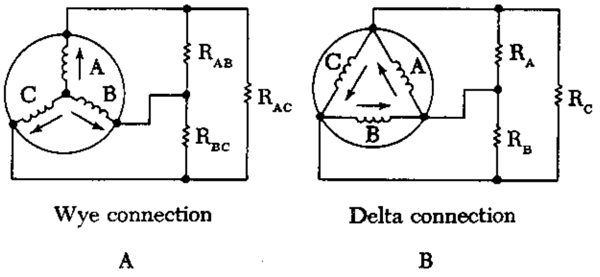


FIGURE 9–36. Simplified schematic of three-phase alternator with output waveforms.



Wye connection

A

Delta connection

B

FIGURE 9–37. Wye- and delta-connected alternators.

phase currents; and the line current is equal to 1.73 times the phase current, when the loads are balanced.

For equal loads (equal kw. output), the delta connection supplies increased line current at a value of line voltage equal to phase voltage, and the wye connection supplies increased line voltage at a value of line current equal to phase current.

Alternator-Rectifier Unit

A type of alternator used in the electrical system of many aircraft weighing less than 12,500 pounds is shown in figure 9–38. This type of power source is sometimes called a d.c. generator, since it is used in d.c. systems. Although its output is a d.c. voltage, it is an alternator-rectifier unit.

This type of alternator-rectifier is a self-excited unit but does not contain a permanent magnet. The excitation for starting is obtained from the battery, and immediately after starting, the unit is self-exciting. Cooling air for the alternator is conducted into the unit by a blast air tube on the air inlet cover (figure 9–38).

The alternator is directly coupled to the aircraft engine by means of a flexible drive coupling. The d.c. output voltage may be regulated by a carbon pile voltage regulator. The output of the alternator portion of the unit is three-phase alternating current, derived from a three-phase, delta-connected system incorporating a three-phase, full-wave bridge rectifier (figure 9–39).

This unit operates in a speed range from 2,100 to 9,000 r.p.m., with a d.c. output voltage of 26–29 volts and 125 amperes.

BRUSHLESS ALTERNATOR

One generator now in use is the brushless type. It is more efficient because there are no brushes to wear down or to arc at high altitudes.

This generator consists of a pilot exciter, an exciter, and the main generator system. The necessity for brushes has been eliminated by utilizing an integral exciter with a rotating armature that has its a.c. output rectified for the main a.c. field, which is also of the rotating type. A brushless alternator is illustrated in figure 9–40.

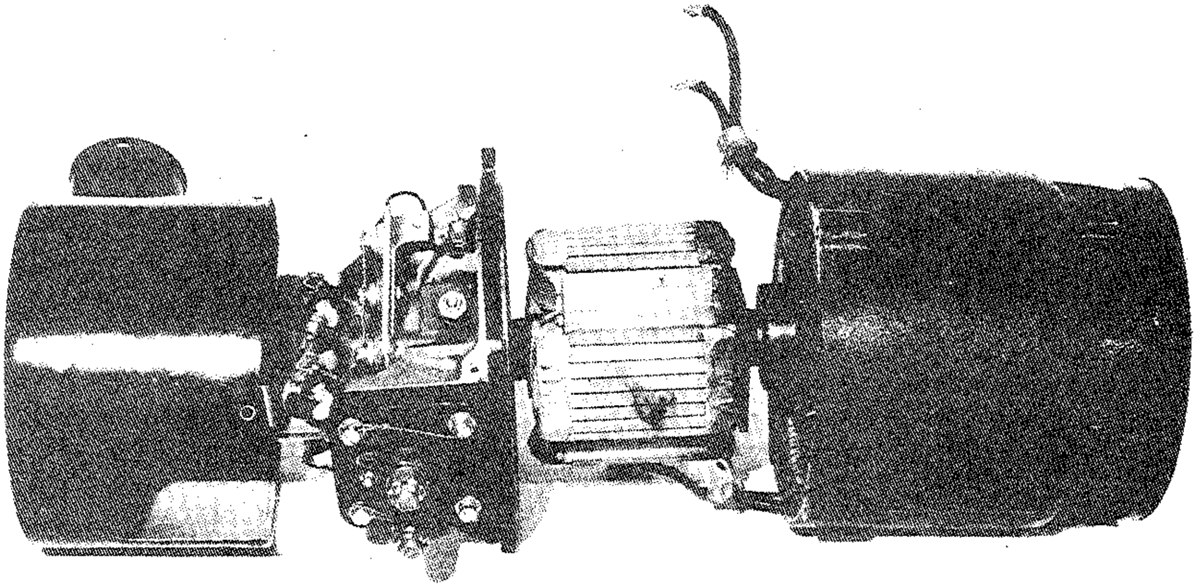


FIGURE 9–38. Exploded view of alternator-rectifier.

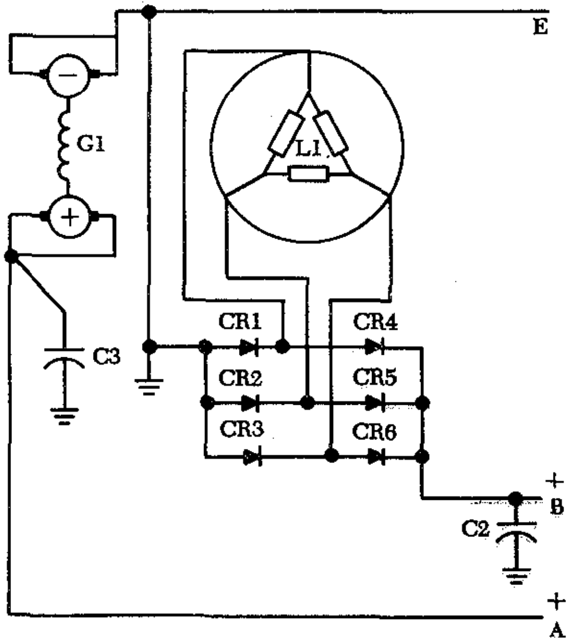


FIGURE 9–39. Wiring diagram of alternator-rectifier unit.

The pilot exciter is an 8-pole, 8,000 r.p.m., 533 c.p.s., a.c. generator. The pilot exciter field is mounted on the main generator rotor shaft and is connected in series with the main generator field (figure 9–40). The pilot exciter armature is mounted on the main generator stator. The a.c. output of the pilot exciter is supplied to the voltage regulator, where it is rectified and controlled, and is then impressed on the exciter field winding to furnish excitation for the generator.

The exciter is a small a.c. generator with its field mounted on the main generator stator and its 3-phase armature mounted on the generator rotor shaft. Included in the exciter field are permanent magnets mounted on the main generator stator between the exciter poles.

The exciter field resistance is temperature compensated by a thermistor. This aids regulation by keeping a nearly constant resistance at the regulator output terminals. The exciter output is rectified and impressed on the main generator field and the pilot exciter field. The exciter stator has a stabilizing field, which is used to improve stability and to prevent voltage regulator overcorrections for changes in generator output voltage.

The a.c. generator shown in figure 9–40 is a 6-pole, 8,000 r.p.m. unit having a rating of 31.5 kilovolt amperes (KVA), 115/200 volts, 400 c.p.s. This generator is 3-phase, 4-wire, wye-connected with grounded neutrals. By using an integral a.c. exciter the necessity for brushes within the generator has been eliminated. The a.c. output of the rotating exciter armature is fed directly into the 3-phase, full-wave, rectifier bridge located inside the rotor shaft, which uses high-temperature silicon rectifiers. The d.c. output from the rectifier bridge is fed to the main a.c. generator rotating field.

Voltage regulation is accomplished by varying the strength of the a.c. exciter stationary fields. Polarity reversals of the a.c. generator are eliminated and radio noise is minimized by the absence of the brushes. Any existing radio noise is further reduced by a noise filter mounted on the alternator.

The rotating pole structure of the generator is laminated from steel punchings, containing all six poles and a connecting hub section. This provides optimum magnetic and mechanical properties.

Some alternators are cooled by circulating oil through steel tubes. The oil used for cooling is supplied from the constant-speed drive assembly. Oil flow between the constant-speed drive and the generator is made possible by ports located in the flange connecting the generator and drive assemblies.

Voltage is built up by using permanent magnet interpoles in the exciter stator. The permanent magnets assure a voltage buildup, precluding the necessity of field flashing. The rotor of the alternator may be removed without causing loss of the alternator's residual magnetism.

COMBINED A.C. AND D.C. ELECTRICAL SYSTEMS

Many aircraft, especially aircraft of more than 12,500 pounds, employ both a d.c. and an a.c. electrical system. Often the d.c. system is the basic electrical system and consists of paralleled d.c. generators with output of, for example, 300 amperes each.

The a.c. system on such aircraft may include both a fixed frequency and a variable frequency system. The fixed frequency system may consist of three or four inverters and associated controls, protective, and indicating components to provide single-phase, a.c. power for frequency sensitive a.c. equipment. The variable frequency system may consist of two or more engine-driven alternators, with associated control, protective, and indicating components, to provide three-phase, a.c. power for such purposes as resistive heating on propellers, engine ducts, and windshields.

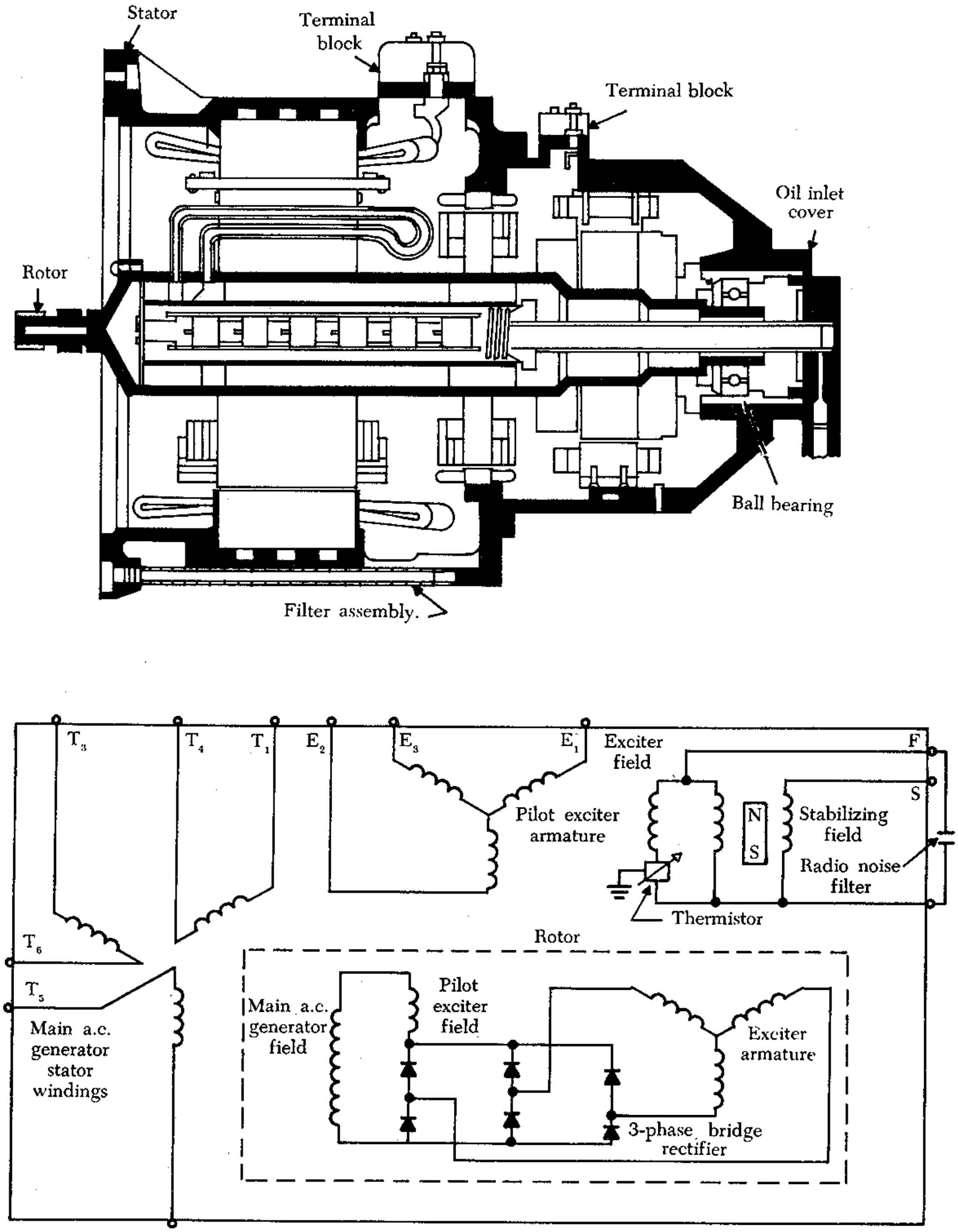


FIGURE 9–40. A typical brushless alternator.

Such combined d.c. and a.c. electrical systems normally include an auxiliary source of d.c. power to back up the main system. This generator is often driven by a separate gasoline or turbine-powered unit.

Alternator Rating

The maximum current that can be supplied by an alternator depends upon the maximum heating loss (I^2R power loss) that can be sustained in the armature and the maximum heating loss that can be sustained in the field. The armature current of an alternator varies with the load. This action is similar to that of d.c. generators. In a.c. generators, however, lagging power factor loads tend to demagnetize the field of an alternator and terminal voltage is maintained only by increasing d.c. field current. For this reason, alternating current generators are usually rated according to KVA, power factor, phases, voltage, and frequency. One generator, for example, may be rated at 40 KVA, 208 volts, 400 cycles, three-phase, at 75 percent power factor. The KVA indicate the apparent power. This is the KVA output, or the relationship between the current and voltage at which the generator is intended to operate.

The power factor is the expression of the ratio between the apparent power (volt-amperes) and the true or effective power (watts). The number of phases is the number of independent voltages generated. Three-phase generators generate three voltages 120 electrical degrees apart.

Alternator Frequency

The frequency of the alternator voltage depends upon the speed of rotation of the rotor and the number of poles. The faster the speed, the higher the frequency will be; the lower the speed, the lower the frequency becomes. The more poles on the rotor, the higher the frequency will be for a given speed. When a rotor has rotated through an angle so that two adjacent rotor poles (a north and a south pole) have passed one winding, the voltage induced in that winding will have varied through one complete cycle. For a given frequency, the greater the number of pairs of poles, the lower the speed of rotation will be. A two-pole alternator rotates at twice the speed of a four-pole alternator for the same frequency of generated voltage. The frequency of the alternator in c.p.s. is related to the number of poles and the speed, as expressed by the equation

$$F = \frac{P}{2} \times \frac{N}{60} = \frac{PN}{120},$$

where P is the number of poles and N the speed in r.p.m. For example, a two-pole, 3,600-r.p.m. alternator has a frequency of $\frac{2 \times 3{,}600}{120} = 60$ c.p.s.; a four-pole, 1,800-r.p.m. alternator has the same frequency; a six-pole, 500-r.p.m. alternator has a frequency of $\frac{6 \times 500}{120} = 25$ c.p.s.; and a 12-pole, 4,000-r.p.m. alternator has a frequency of $\frac{12 \times 4{,}000}{120} = 400$ c.p.s.

VOLTAGE REGULATION OF ALTERNATORS

The problem of voltage regulation in an a.c. system does not differ basically from that in a d.c. system. In each case the function of the regulator system is to control voltage, maintain a balance of circulating current throughout the system, and eliminate sudden changes in voltage (anti-hunting) when a load is applied to the system. However, there is one important difference between the regulator system of d.c. generators and alternators operated in a parallel configuration. The load carried by any particular d.c. generator in either a two- or four-generator system depends on its voltage as compared with the bus voltage, while the division of load between alternators depends upon the adjustments of their speed governors, which are controlled by the frequency and droop circuits.

When a.c. generators are operated in parallel, frequency and voltage must both be equal. Where a synchronizing force is required to equalize only the voltage beween d.c. generators, synchronizing forces are required to equalize both voltage and speed (frequency) between a.c. generators. On a comparative basis, the synchronizing forces for a.c. generators are much greater than for d.c. generators. When a.c. generators are of sufficient size and are operating at unequal frequencies and terminal voltages, serious damage may result if they are suddenly connected to each other through a common bus. To avoid this, the generators must be synchronized as closely as possible before connecting them together.

The output voltage of an alternator is best controlled by regulating the voltage output of the d.c. exciter, which supplies current to the alternator rotor field. This is accomplished as shown in figure 9–41, by a carbon-pile regulator of a 28-volt system connected in the field circuit of the exciter. The carbon-pile regulator controls the exciter field current and thus regulates the exciter output voltage applied to the alternator field. The only difference between the d.c. system

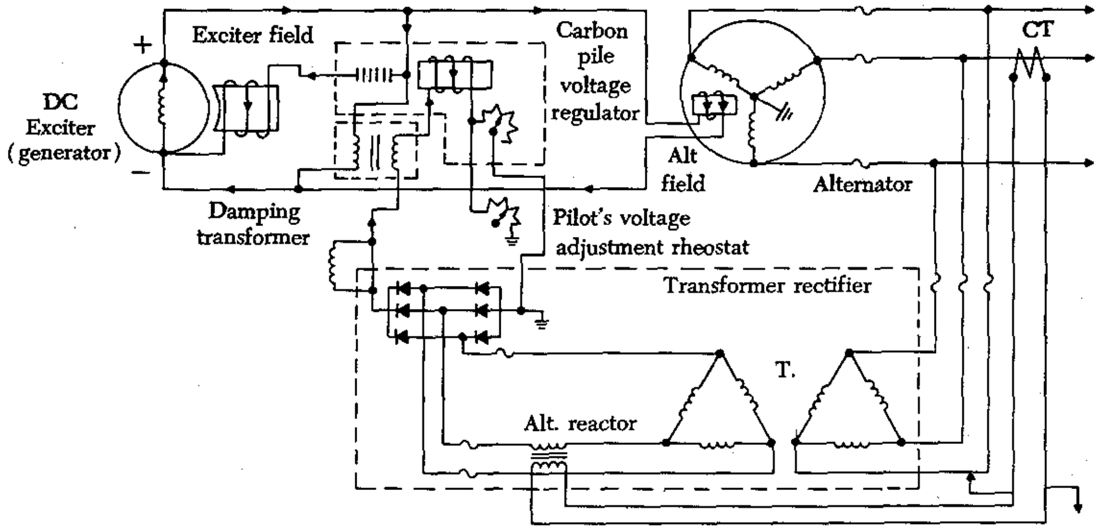


FIGURE 9–41. Carbon-pile voltage regulator for an alternator.

and the a.c. system is that the voltage coil receives its voltage from the alternator line instead of the d.c. generator. In this arrangement, a three-phase, step-down transformer connected to the alternator voltage supplies power to a three-phase, full-wave rectifier. The 28-volt, d.c. output of the rectifier is then applied to the voltage coil of the carbon-pile regulator. Changes in alternator voltage are transferred through the transformer rectifier unit to the voltage coil of the regulator and vary the pressure on the carbon disks. This controls the exciter field current and the exciter output voltage. The exciter voltage anti-hunting or damping transformer is similar to those in d.c. systems and performs the same function.

The alternator equalizing circuit is similar to that of the d.c. system in that the regulator is affected when the circulating current supplied by one alternator differs from that supplied by the others.

Alternator Transistorized Regulators

Many aircraft alternator systems use a transistorized voltage regulator to control the alternator output. Before studying this section, a review of transistor principles may be helpful.

A transistorized voltage regulator consists mainly of transistors, diodes, resistors, capacitors, and, usually, a thermistor. In operation, current flows through a diode and transistor path to the generator field. When the proper voltage level is reached, the regulating components cause the transistor to cut off conduction to control the alternator field strength. The regulator operating range is usually adjustable through a narrow range. The thermistor provides temperature compensation for the circuitry. The transistorized voltage regulator shown in figure 9–42 will be referred to in explaining the operation of this type of regulator.

The a.c. output of the generator is fed to the voltage regulator, where it is compared to a reference voltage, and the difference is applied to the control amplifier section of the regulator. If the output is too low, field strength of the a.c. exciter generator is increased by the circuitry in the regulator. If the output is too high, the field strength is reduced.

The power supply for the bridge circuit is CR1, which provides full-wave rectification of the three-phase output from transformer T1. The d.c. output voltages of CR1 are proportional to the average phase voltages. Power is supplied from the negative end of the power supply through point B, R2, point C, zener diode (CR5), point D, and to the parallel hookup of V1 and R1. Takeoff point C of the bridge is located between resistor R2 and the zener diode. In the other leg of the reference bridge, resistors R9, R7, and the temperature-compensating resistor RT1 are connected in series with V1 and R1 through points B, A, and D. The output of this leg of the bridge is at the wiper arm of R7.

As generator voltage changes occur, for example, if the voltage lowers, the voltage across

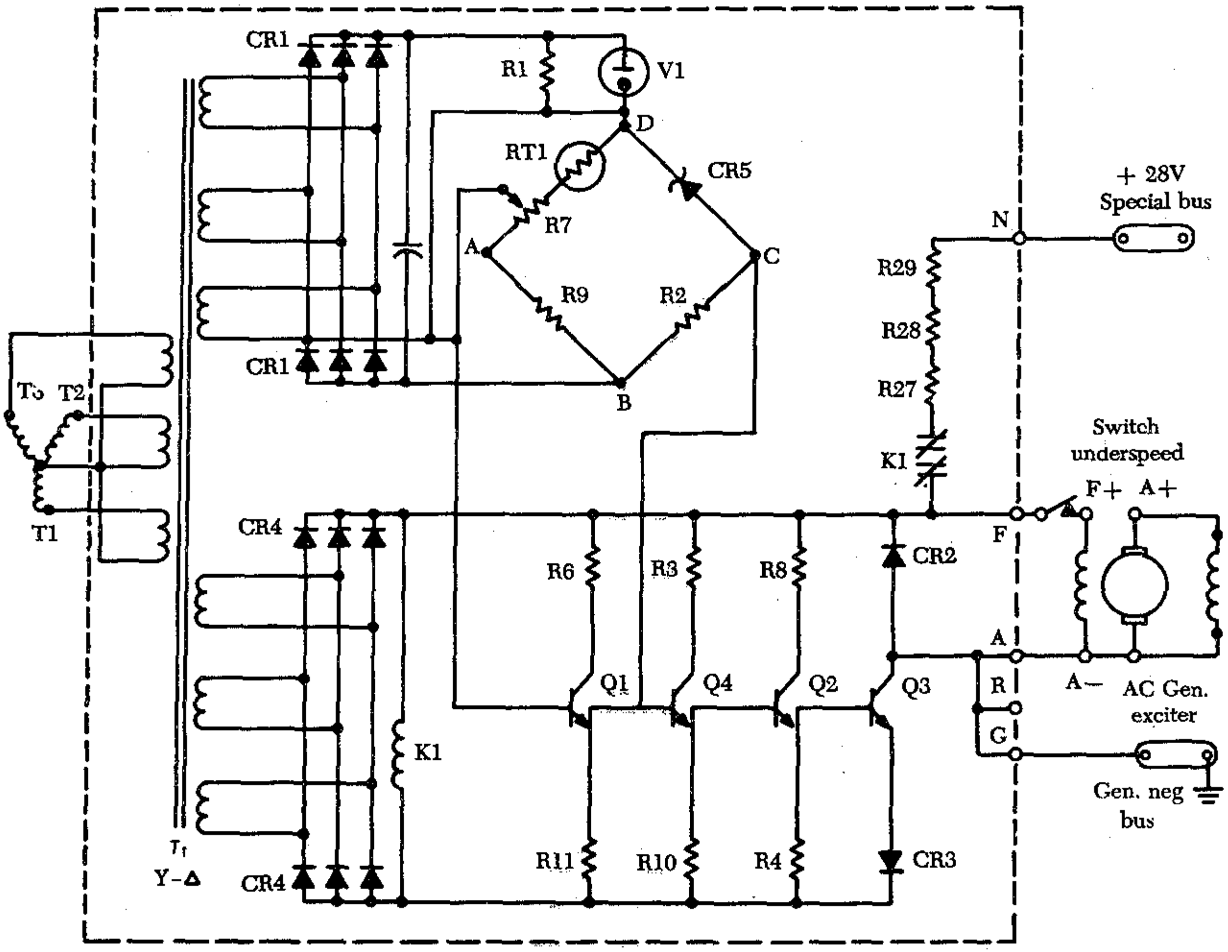


FIGURE 9–42. Transistorized voltage regulator.

R1 and V1 (once V2 starts conducting) will remain constant. The total voltage change will occur across the bridge circuit. Since the voltage across the zener diode remains constant (once it starts conducting), the total voltage change occurring in that leg of the bridge will be across resistor R2. In the other leg of the bridge, the voltage change across the resistors will be proportional to their resistance values. Therefore, the voltage change across R2 will be greater than the voltage change across R9 to wiper arm of R7. If the generator output voltage drops, point C will be negative with respect to the wiper arm of R7. Conversely, if the generator voltage output increases, the polarity of the voltage between the two points will be reversed.

The bridge output, taken between points C and A, is connected between the emitter and the base of transistor Q1. With the generator output voltage low, the voltage from the bridge will be negative to the emitter and positive to the base. This is a forward bias signal to the transistor, and the emitter to collector current will therefore increase. With the increase of current, the voltage across emitter resistor R11 will increase. This, in turn, will apply a positive signal to the base of transistor Q4, increasing its emitter to collector current and increasing the voltage drop across the emitter resistor R10.

This will give a positive bias to the base of Q2, which will increase its emitter to collector current and increase the voltage drop across its emitter resistor R4. This positive signal will control output transistor Q3. The positive signal on the base of Q3 will increase the emitter to collector current.

The control field of the exciter generator is in the collector circuit. Increasing the output of the exciter generator will increase the field strength of the a.c. generator, which will increase the generator output.

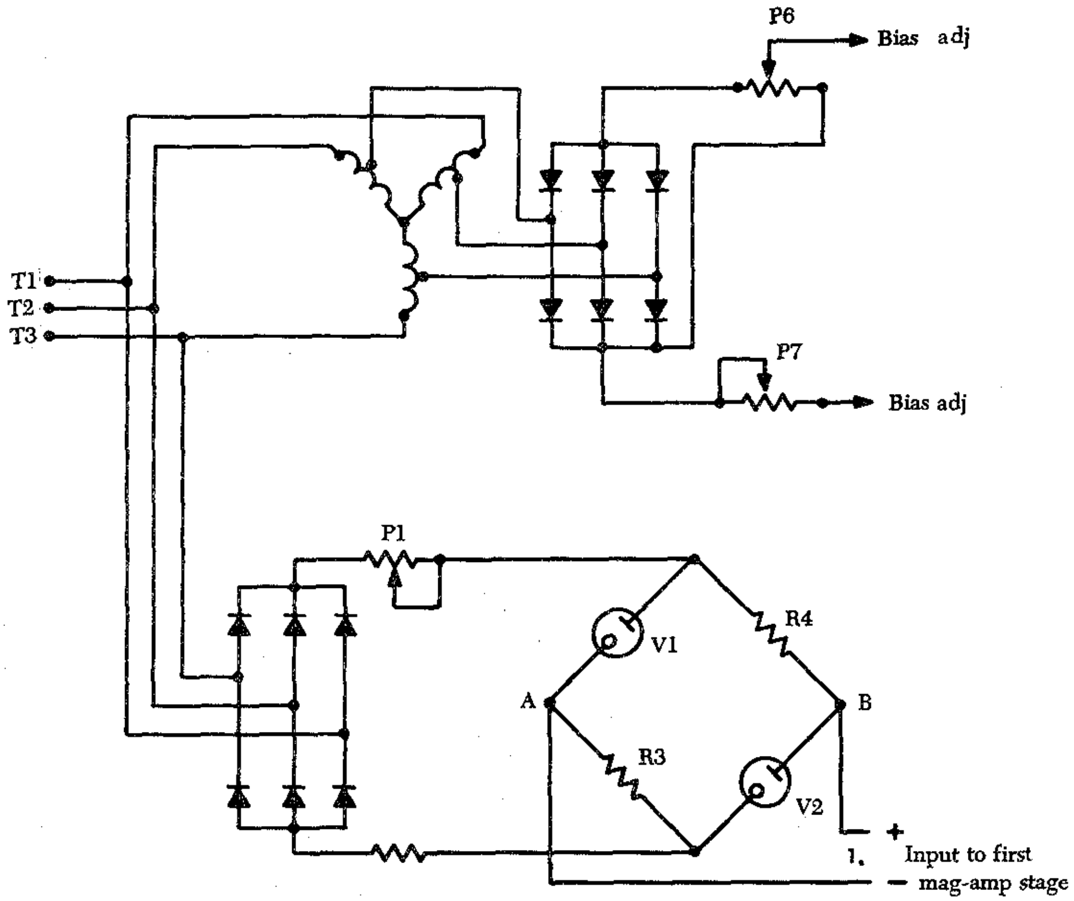


FIGURE 9–43. Voltage reference circuits of a typical magnetic amplifier voltage regulator.

To prevent exciting the generator when the frequency is at a low value, there is an underspeed switch located near the F+ terminal. When the generator reaches a suitable operating frequency, the switch will close and allow the generator to be excited.

Another item of interest is the line containing resistors R27, R28, and R29 in series with the normally closed contacts of the K1 relay. The operating coil of this relay is found in the lower left-hand part of the schematic. Relay K1 is connected across the power supply (CR4) for the transistor amplifier. When the generator is started, electrical energy is supplied from the 28-volt d.c. bus to the exciter generator field, to "flash the field" for initial excitation. When the field of the exciter generator has been energized, the a.c. generator starts to produce, and as it builds up, relay K1 is energized, opening the "field flash" circuit.

Magnetic Amplifier Regulator

Because of their lack of moving parts, this type of voltage regulator is referred to as a static voltage regulator. Some static regulators employ electron tubes or transistors as amplifiers to achieve the necessary high energy gain, but the most commonly used static regulator utilizes a magnetic amplifier.

The magnetic amplifier voltage regulator is somewhat heavier and larger than a carbon-pile regulator of the same rating. Because of the absence of moving parts, regulators of this type do not require shock or vibration mounts.

This regulator consists of a voltage reference circuit, a two-stage magnetic amplifier, and the associated power transformer and rectifier. The reference circuit consists of a three-phase rectifier, a potentiometer (P1), and a bridge circuit made up of two fixed resistors and two glow tubes.

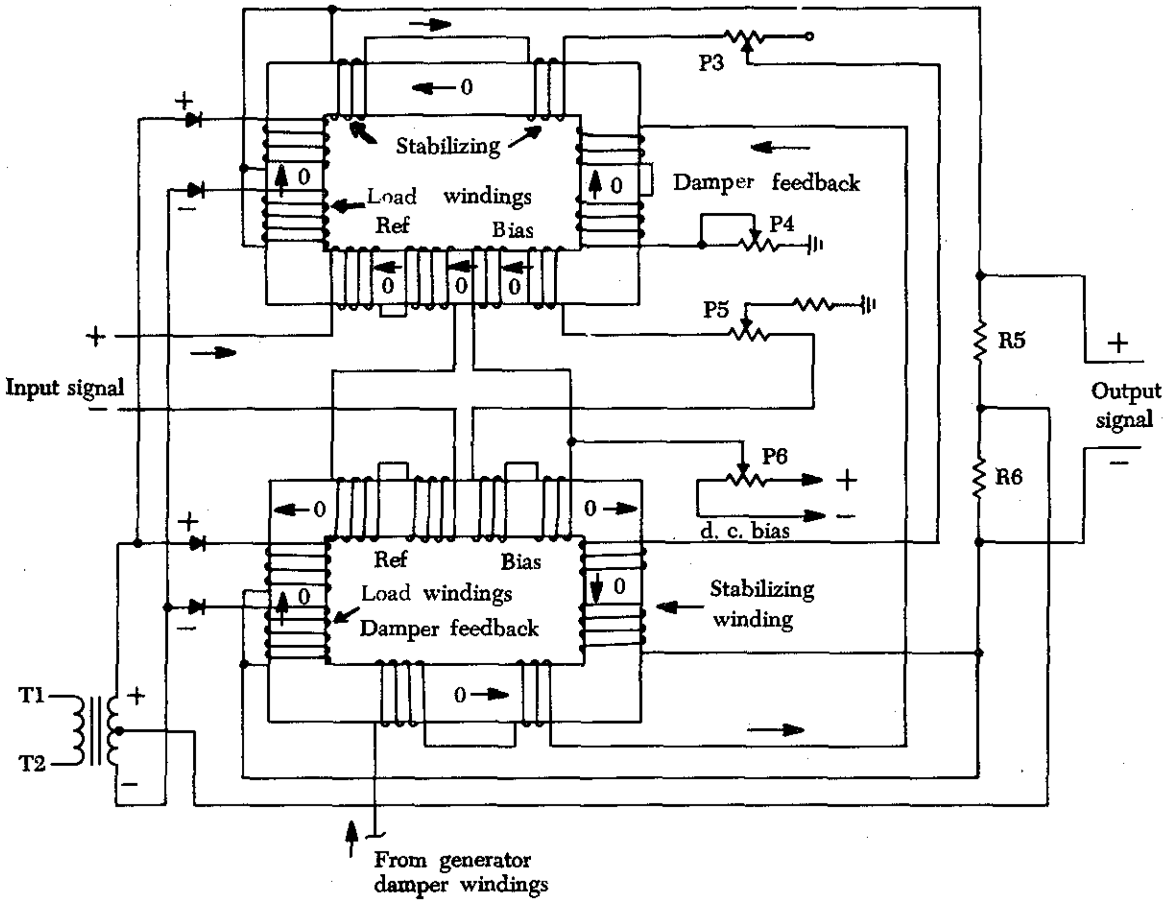


FIGURE 9–44. First stage of a magnetic amplifier voltage regulator.

These units are shown in figure 9–43. Potentiometer P1 is adjusted so that, at rated bus voltage, there is a zero potential difference between points A and B on the bridge circuit. For any other input voltage, the voltage drop across the glow tubes causes a potential to exist between points A and B.

For example, if the generator voltage is low, the current flow through the arms of the bridge will be reduced. The voltage across R4 will be less than the fixed voltage across V1; consequently, point B will be at a higher potential than point A. This gives an error signal used as an input to the first mag-amp (magnetic amplifier) stage. For high input voltages the error signal polarity is reversed.

The second unit in the system is the magnetic amplifier. The circuitry for the first stage of a typical mag-amp voltage regulator is shown in figure 9–44. This unit consists of two reactors, supply voltage transformers and rectifiers, and the following windings: reference, d.c. bias, damper circuit, load circuit, and feedback circuit. The d.c. bias winding fixes the operating level of the reactors and is adjusted by potentiometers P5 and P6.

Potentiometer P6 regulates the magnitude of the bias voltage, and P5 regulates the magnitude of biasing current on each reactor to overcome the slight differences in the two cores and the associated rectifiers. If the bias voltage is properly adjusted and if a zero error signal input exists, the voltages developed across R5 and R6 will be equal and the output will be zero.

The damper circuit is connected into the circuit and is used as a stabilizing winding. Its source of power is the damper winding of the generator. The generator damper winding is energized through transformer action by a changing generator excitation current and is, therefore, proportional to the rate of change of excitation. This current is used as a feedback signal in the first magnetic amplifier stage because its polarity always opposes the error signal input.

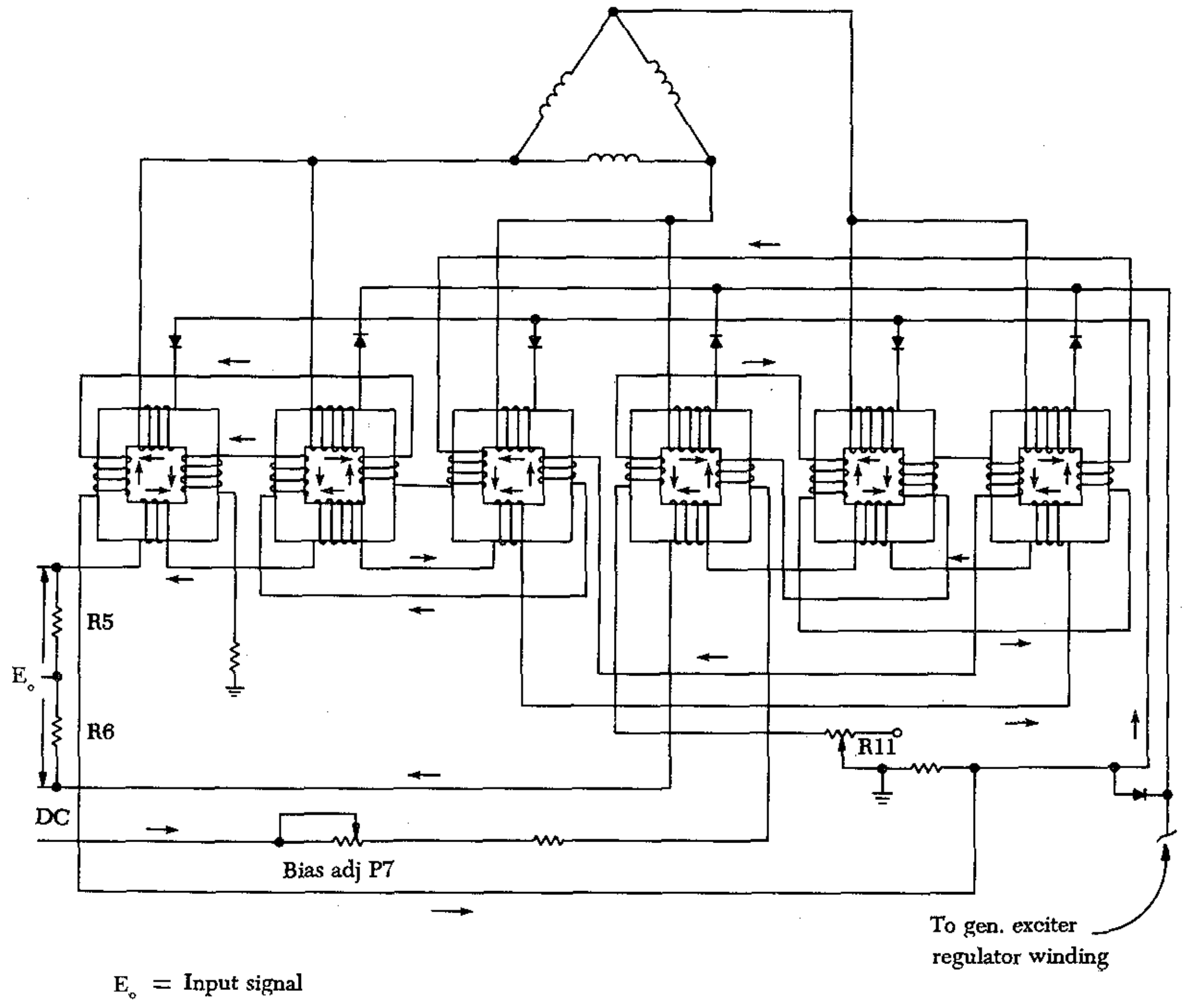


FIGURE 9–45. Second mag-amp stage of voltage regulator.

The magnitude of the damper feedback current is adjusted with potentiometer P4. Its function is to establish the recovery time of the regulator and to provide stable operation. The potentiometer should be adjusted to provide fast voltage recovery during stable operation under normal load conditions.

Next, the feedback winding receives a voltage that is proportional to the output voltage; this provides stability during steady load conditions. A look at the circuit will disclose that the load winding receives its power from transformer-rectifier terminals T1 and T2. The current flow through these windings and load resistors R5 and R6 is regulated by the degree of magnetization of the reactor cores, established by the current flow in the various control windings.

Figure 9–44 also illustrates that, when the input signal is not zero, the currents through R5 and R6 will not be equal. The unequal currents in these resistors provide a potential difference which is the output signal for this stage, the polarity of which depends on the polarity of the error signal input.

All of the units in the regulator have been discussed except the output stage, which is referred to as the second stage of the regulator. This is a three-phase, full-wave, magnetic amplifier, as shown in figure 9–45. The output of the first stage, which we have just discussed, is fed into the control winding of the second stage. The output of this stage is the generator exciter-regulator field voltage. The magnitude of this voltage is established by the magnitude and polarity of the input signal, the bias current which is adjustable by P7, and also by the feedback current which is proportional to the output.

This type of regulator has a distinct advantage

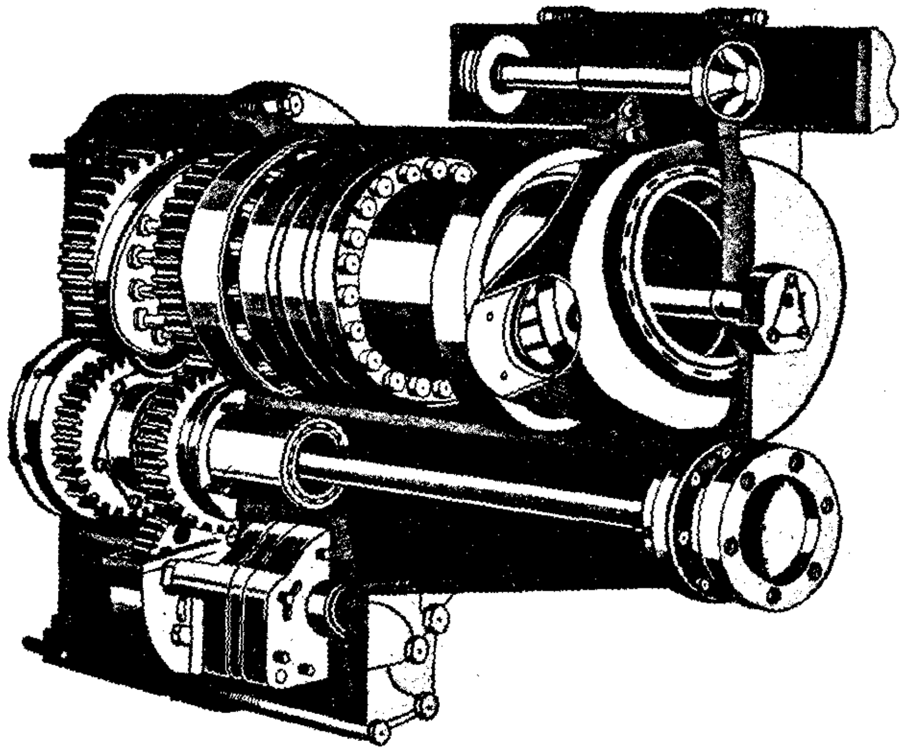


FIGURE 9-46. Constant-speed drive.

over other types, since it will function on a very small change in voltage. Because of the operating characteristics of this type of regulator, variations in the output voltage will be within 1 percent.

The various adjustments on the unit, with the exception of those on P1, have been discussed. Adjustments on P1 are to be accomplished only on the bench, when the regulator is being calibrated. Potentiometer P1 is located in the center of the front face of the regulator adjacent to the voltmeter jacks. The potentiometer may be adjusted while the regulator is installed on the aircraft to set the bus voltage to the desired value.

The voltage regulator is divided into three main parts: the voltage error detector, the preamplifier, and the power amplifier. These three units work together in a closed-loop circuit with the generator exciter regulator winding to maintain nearly constant voltage at the generator output terminals.

The function of the error detector is to sample the generated voltage, compare it with a fixed standard, and send the error to the preamplifier. The detector includes a three-phase rectifier, a variable resistor for voltage adjustment, and a bridge consisting of two voltage reference tubes and two resistors. In operation, if the generator voltage ranges above or below its rated value, a current will flow either in one direction or the other, depending on the polarity developed in the bridge circuit.

The preamplifier receives an error signal from the voltage error detector. With the use of magnetic amplifiers, it raises the signal to a sufficient level to drive the power amplifier to full output, required for proper excitation.

The power amplifier delivers a signal to the exciter regulator winding; its magnitude depends on the signal from the preamplifier. This will raise or lower the voltage of the exciter regulator winding, which, in turn, will raise or lower the output voltage of the generator.

ALTERNATOR CONSTANT-SPEED DRIVE

Alternators are not always connected directly to the airplane engine like d.c. generators. Since the various electrical devices operating on a.c. supplied by alternators are designed to operate at a certain voltage and at a specified frequency, the speed of the alternators must be constant; however, the speed of an airplane engine varies. Therefore, some alternators are driven by the engine through a constant-speed drive installed between the engine and the alternator.

A typical hydraulic-type drive is shown in figure 9–46. The following discussion of a constant-speed drive system will be based on such a drive, found on large multiengine aircraft.

The constant-speed drive is a hydraulic transmission which may be controlled either electrically or mechanically.

The constant-speed drive assembly is designed to deliver an output of 6,000 r.p.m., provided the input remains between 2,800 and 9,000 r.p.m. If the input, which is determined by engine speed, is below 6,000 r.p.m., the drive increases the speed in order to furnish the desired output. This stepping up of speed is known as overdrive.

In overdrive, an automobile engine will operate at about the same r.p.m. at 60 m.p.h. as it does in conventional drive at 49 m.p.h. In aircraft, this principle is applied in the same manner. The constant-speed drive enables the alternator to produce the same frequency at slightly above engine-idle r.p.m. as it would at takeoff or cruising r.p.m.

With the input speed to the drive set at 6,000 r.p.m., the output speed will be the same. This is known as straight drive and might be compared to an automobile in high gear. However, when the input speed is greater than 6,000 r.p.m., it must be reduced to provide an output of 6,000 r.p.m. This is called underdrive, which is comparable to an automobile in low gear. Thus, the large input, caused by high engine r.p.m., is reduced to give the desired alternator speed.

As a result of this control by the constant-speed drive, the frequency output of the generator varies from 420 c.p.s. at no load to 400 c.p.s. under full load.

This, in brief, is the function of the constant-speed drive assembly. Before discussing the various units and circuits, the overall operation of the transmission should be discussed.

Hydraulic Transmission

The transmission is mounted between the generator and the aircraft engine. Its name denotes that hydraulic oil is used, although some transmissions may use engine oil. Refer to the cutaway view of such a transmission in figure 9–47. The input shaft *D* is driven from the drive shaft on the accessory section of the engine. The output drive *F*, on the opposite end of the transmission, engages the drive shaft of the generator.

The input shaft is geared to the rotating cylinder block gear, which it drives, as well as to the makeup and scavenger gear pumps *E*.

The makeup (charge) pump delivers oil (300 p.s.i.) to the pump and motor cylinder block, to the governor system, and to the pressurized case, whereas the scavenger pump returns the oil to the external reservoir.

The rotating cylinder assembly *B* consists of the pump and motor cylinder blocks, which are bolted to opposite sides of a port plate. The two other major parts are the motor wobbler *A* and the pump wobbler *C*. The governor system is the unit at the top of the left side in the illustration.

The cylinder assembly has two primary units. The block assembly of one of the units, the pump, contains 14 cylinders, each of which has a piston and pushrod. Charge pressure from the makeup pump is applied to each piston in order to force it outward against the pushrod. It, in turn, is pushed against the pump wobble plate.

If the plate remained as shown in part *A* of figure 9–48, each of the 14 cylinders would have equal pressure, and all pistons would be in the same relative position in their respective cylinders. But with the plate tilted, the top portion moves outward and the lower portion inward, as shown in part *B* of the illustration. As a result, more oil enters the interior of the upper cylinder, but oil will be forced from the cylinder of the bottom piston.

If the pump block were rotated while the plate remained stationary, the top piston would be forced inward because of the angle of the plate. This action would cause the oil confined within the cylinder to be subjected to increased pressure great enough to force it into the motor cylinder block assembly.

Before explaining what the high-pressure oil in the motor unit will do, it is necessary to know something about this part of the rotating cylinder block assembly. The motor block assembly has 16 cylinders, each with its piston and pushrod. These are constantly receiving charge pressure of 300 p.s.i. The position of the piston depends upon the point at which each pushrod touches the motor wobble plate. These rods cause the wobble plate to rotate by the pressure they exert against its sloping surface.

This is how the action works: the piston and pushrod of the motor are pushed outward as oil is forced through the motor valve plate from the pump cylinder. The pushrods are forced against the motor wobble plate, which is free to rotate but

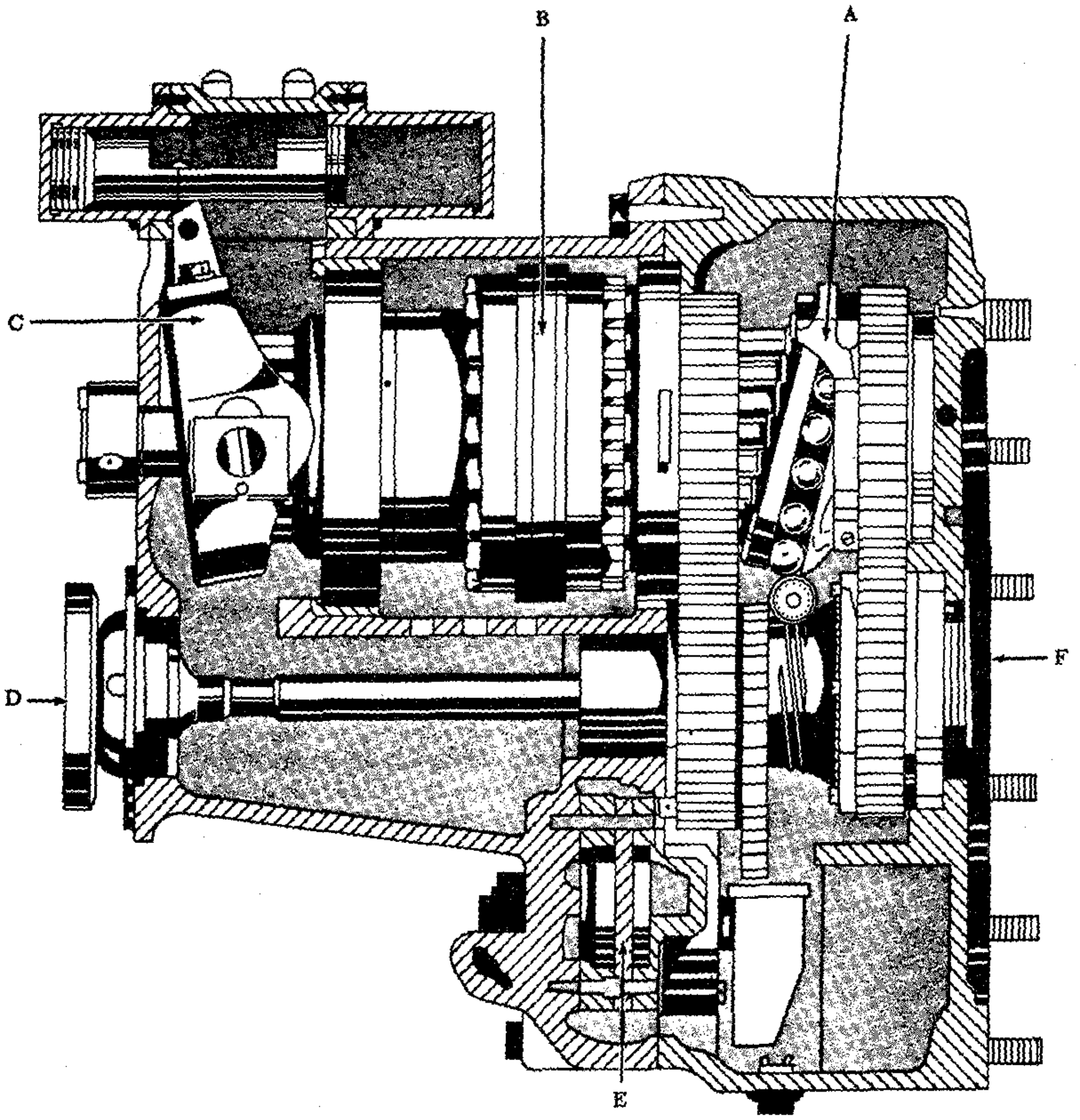


FIGURE 9-47. Cutaway view of a hydraulic transmission.

cannot change the angle at which it is set. Since the pushrods cannot move sideways, the pressure exerted against the motor wobble plate's sloping face causes it to rotate.

In the actual transmission, there is an adjustable wobble plate. The tilt of the pump wobble plate is determined by the control cylinder assembly. For example, it is set at an angle which causes the motor cylinders to turn the motor wobble plate faster than the motor assembly, if the transmission is in overdrive. The result described is produced by the greater pressure in the pump and motor cylinders.

With the transmission in underdrive, the angle is arranged so there is a reduction in pumping action. The subsequent slippage between the pushrods and motor wobble plate reduces the output speed of the transmission. When the pump wobble plate is not at an angle, the pumping action will be at a minimum and the transmission will have what is known as hydraulic lock. For this condition, the input and output speed will be about the same, and the transmission is considered to be in straight drive.

To prevent the oil temperature from becoming excessively high within the cylinder block, the

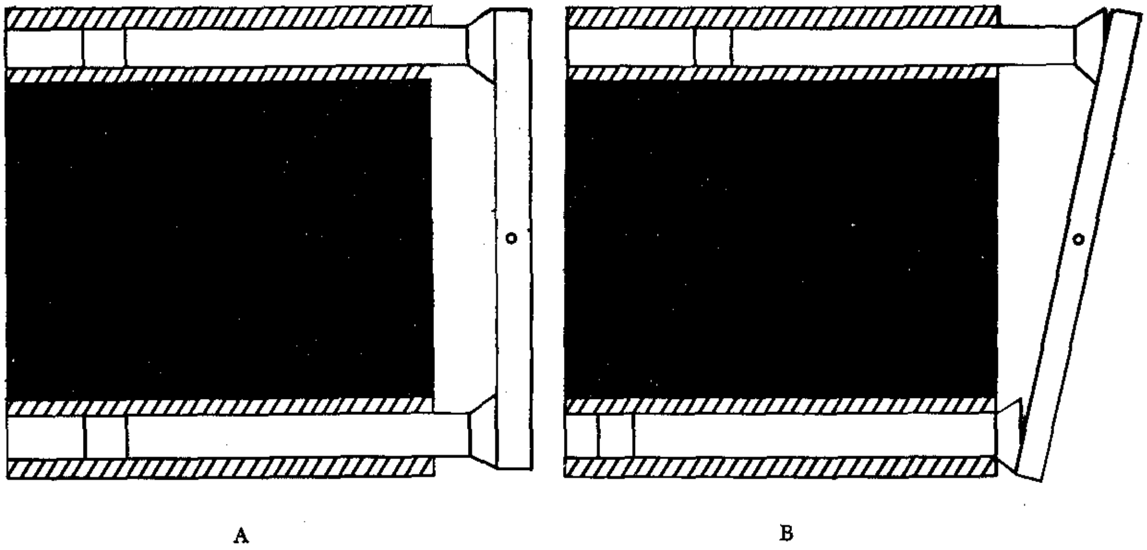


Figure 9–48. Wobble plate position.

makeup pressure pump forces oil through the center of this block and the pressure relief valve. From this valve, the oil flows into the bottom of the transmission case. A scavenger pump removes the oil from the transmission case and circulates it through the oil cooler and filter before returning it to the reservoir. At the start of the cycle, oil is drawn from the reservoir, passed through a filter, and forced into the cylinder block by the makeup pressure pump.

The clutch, located in the output gear and clutch assembly, is an overrunning one-way, sprag-type device. Its purpose is to ratchet if the alternator becomes motorized; otherwise, the alternator might turn the engine. Furthermore, the clutch provides a positive connection when the transmission is driving the alternator.

There is another unit of the drive which must be covered, the governor system. The governor system, which consists of a hydraulic cylinder with a piston, is electrically controlled. Its duty is to regulate oil pressure flowing to the control cylinder assembly, as shown in figure 9–49.

The center of the system's hydraulic cylinder is

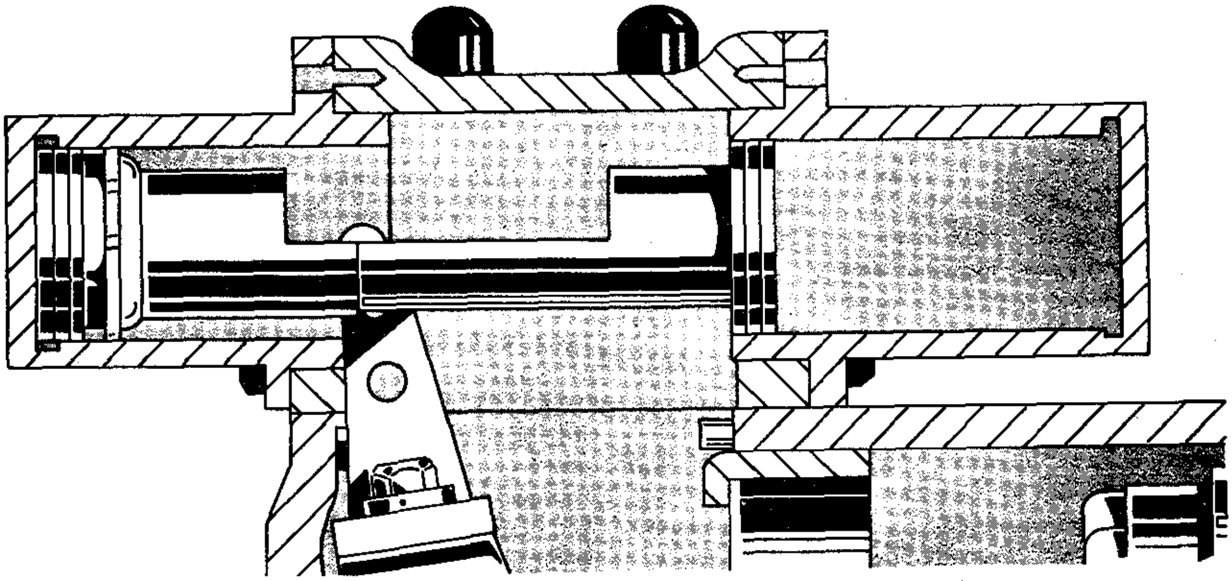


Figure 9–49. Control cylinder.

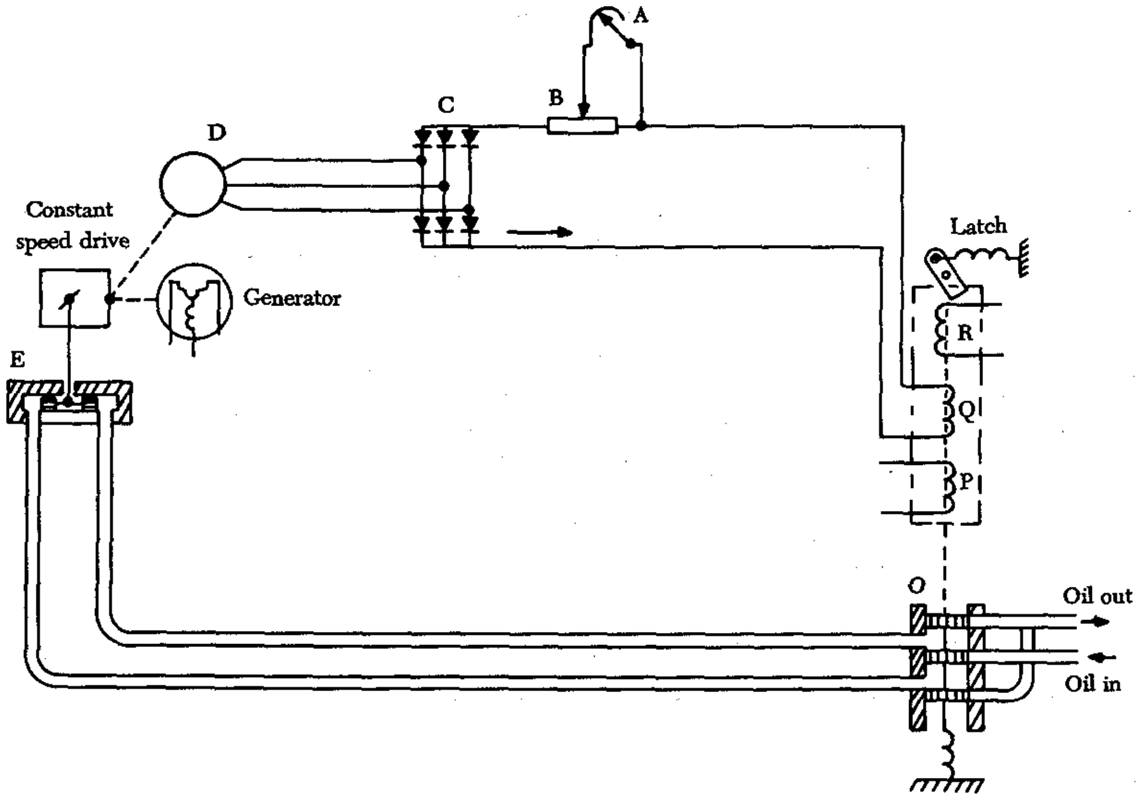


FIGURE 9–50. Electrical hydraulic control circuit.

slotted so the arm of the pump wobble plate can be connected to the piston. As oil pressure moves the piston, the pump wobble plate is placed in either overspeed, underspeed, or straight drive.

Figure 9–50 shows the electrical circuit used to govern the speed of the transmission. First, the main points of the complete electrical control circuit will be discussed (figure 9–50 and 9–51). Then, for simplification, two portions, the overspeed circuit and the load division circuit, will be considered as individual circuits.

Note, then, in figures 9–50, that the circuit has a valve and solenoid assembly *O* and a control cylinder *E*, and that it contains such units as the tachometer generator *D*, the rectifier *C*, and adjustable resistor *B*, rheostat *A*, and the control coil *Q*.

Since it is driven by a drive gear in the transmission, the tachometer (often called tach) generator, a three-phase unit, has a voltage proportional to the speed of the output drive. Its voltage is changed from a.c. to d.c. by the rectifier. After rectification, the current flows through the resistor, rheostat, and valve and solenoid. Each of these units is connected in series, as shown in figure 9–51.

Under normal operating conditions, the output of the tach generator causes just enough current to enter the valve and solenoid coil to set up a magnetic field of sufficient strength to balance the spring force in the valve. When the alternator speed increases as the result of a decrease in load, the tach generator output increases also. Because of the greater output, the coil in the solenoid is sufficiently strengthened to overcome the spring force. Thus, the valve moves and, as a result, oil pressure enters the reduced speed side of the control cylinder.

In turn, the pressure moves the piston, causing the angle of the pump wobble plate to be reduced. The oil on the other side of the piston is forced back through the valve into the system return. Since the angle of the pump wobble plate is smaller, there is less pumping action in the transmission. The result is decreased output speed. To complete the cycle, the procedure is reversed.

With the output speed reduction, tach generator output decreases; consequently, the flow of current

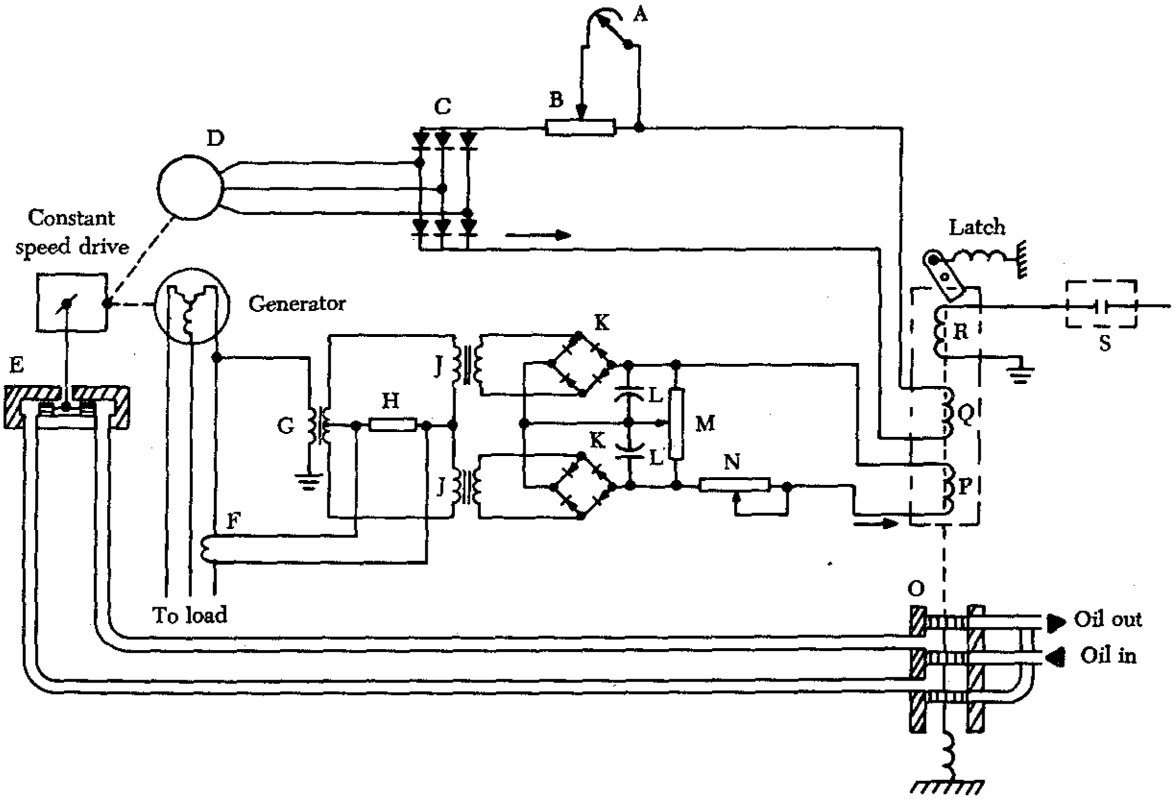


FIGURE 9–51. Speed control circuit.

to the solenoid diminishes. Therefore, the magnetic field of the solenoid becomes so weak that the spring is able to overcome it and reposition the valve.

If a heavy load is put on the a.c. generator, its speed decreases. The generator is not driven directly by the engine; the hydraulic drive will allow slippage. This decrease will cause the output of the tach generator to taper off and, as a result, weaken the magnetic field of the solenoid coil. The spring in the solenoid will move the valve and allow oil pressure to enter the increase side of the control cylinder and the output speed of the transmission will be raised.

There are still two important circuits which must be discussed: the overspeed circuit and the load division circuit. The generator is prevented from overspeeding by a centrifugal switch (*S* in figure 9–52) and the overspeed solenoid coil *R*, which is located in the solenoid and valve assembly. The centrifugal switch is on the transmission and is driven through the same gear arrangement as the tach generator.

The aircraft d.c. system furnishes the power to operate the overspeed coil in the solenoid and coil assembly. If the output speed of the transmission reaches a speed of 7,000 to 7,500 r.p.m., the centrifugal switch closes the d.c. circuit and energizes the overspeed solenoid. This component then moves the valve and engages the latch which holds the valve in the underdrive position. To release the latch, energize the underdrive release solenoid.

The load division circuit's function is to equalize the loads placed on each of the alternators, which is necessary to assure that each alternator assumes its share; otherwise, one alternator might be overloaded while another would be carrying only a small load.

In figure 9–53, one phase of the alternator provides power for the primary in transformer *G*, whose secondary supplies power to the primaries of two other transformers, J_1 and J_2. Rectifiers *K* then change the output of the transformer secondaries from a.c. to d.c. The function of the two capacitors, *L*, is to smooth out the d.c. pulsations.

The output of the current transformer *F* depends