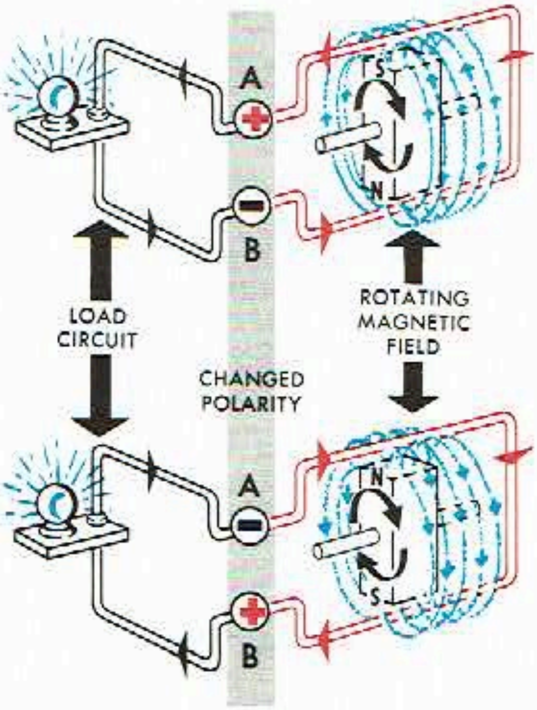
operating principles of Delcotron Integral Charging Systems

In the review of electrical fundamentals, it was observed that a voltage will be induced in a conductor when a magnetic field is moved across the conductor. For example, consider a bar magnet with its magnetic field rotating inside a loop of wire.

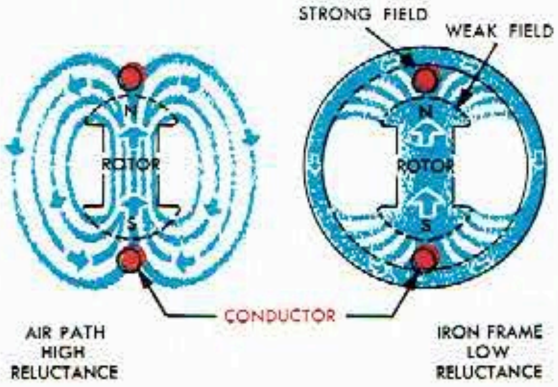


With the magnet rotating as indicated, and with the S pole of the magnet directly under the top portion of the loop and the N pole directly over the bottom portion, the induced voltage, as determined by the Right Hand Rule, will cause current to flow in the circuit in the direction shown. Since current flows from positive to negative through the external or load circuit, the end of the loop of wire marked "A" will be positive (+) polarity and the end marked "B" will be negative (−).

After the bar magnet has moved through one-half revolution, the N pole will have moved directly under the top conductor and the S pole directly over the bottom conductor. The induced voltage as determined by the Right Hand Rule will now cause current to flow in the opposite direction. The end of the loop of wire marked "A" will become negative (−) polarity, and the end marked "B" will become positive (+). Therefore, the polarity of the ends of the wire has changed. After a second one-half revolution, the bar magnet will be back at the starting point where "A" is positive (+) and "B" negative (−).

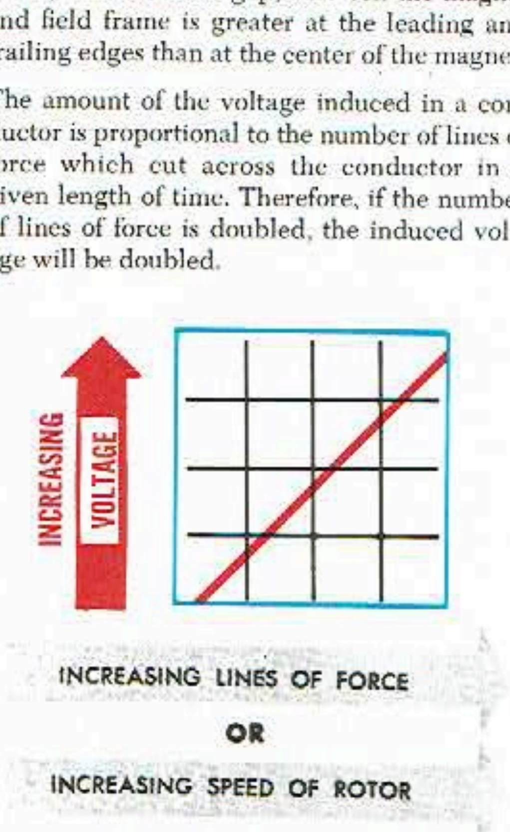
Consequently, current will flow through the load or external circuit first in one direction and then in the other. This is an alternating current which is developed internally by a Delcotron Integral Charging System.

A Delcotron Integral Charging System made with a bar magnet rotating inside a single loop of wire is not practical, since very little voltage and current are produced. The performance is improved when both the loop of wire and the magnet are placed inside an iron frame. The iron frame not only provides a place onto which the loop of wire can be assembled, but also acts as a conducting path for the magnetic lines of force. Without the iron frame, magnetism, after leaving the N pole of the rotating bar magnet, must travel through air to get to the S pole. Because air has a high reluctance to magnetism, only a few lines of force will come out of the N pole and enter the S pole. Since iron conducts magnetism very easily, adding the iron frame greatly increases the number of lines of force between the N pole and the S pole. This means that more lines of force will be cutting across the conductor which lies between the bar magnet and the frame.



It is important to note that a very large number of magnetic lines of force are at the center of the tip of the magnet, whereas there are only a few lines of force at the leading and trailing edges of the tips. Thus, there is a strong magnetic field at the center and a weak magnetic field at the leading and trailing edges. This condition results when the distance, called the air gap, between the magnet and field frame is greater at the leading and trailing edges than at the center of the magnet.

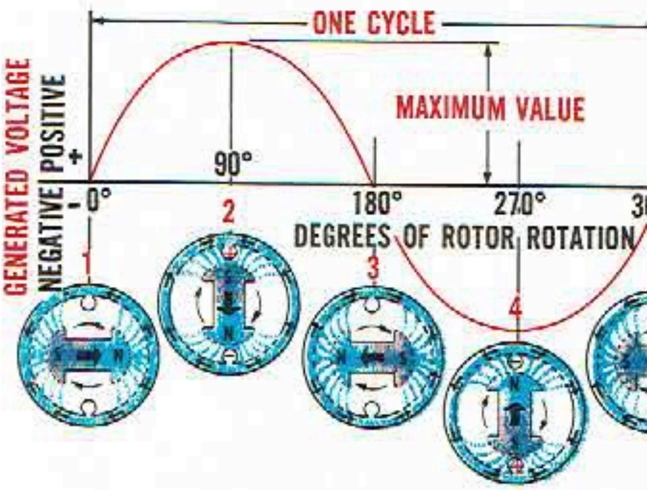
The amount of the voltage induced in a conductor is proportional to the number of lines of force which cut across the conductor in a given length of time. Therefore, if the number of lines of force is doubled, the induced voltage will be doubled.



The voltage will also increase if the bar magnet is made to turn faster because the lines of force will be cutting across the wire in a shorter period of time.

It is important to remember that either increasing the speed of rotation of the bar magnet, or increasing the number of lines of force cutting across the conductor, will result in increasing the voltage. Similarly, decreasing the speed of rotation or decreasing the number of lines of force will cause the voltage to decrease.

The rotating magnet in a Delcotron Integral Charging System is called the rotor, and the loop of wire and outside frame assembly is called the stator.

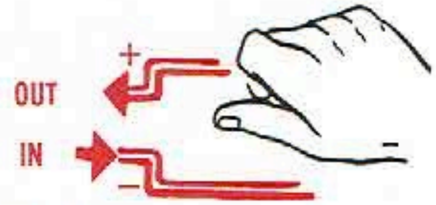


Pictured in the illustration are different positions of the rotor as it rotates at constant speed. In the top portion of the illustration is a curve showing the magnitude of the voltage which is generated in the loop of wire as the rotor revolves.

The voltage curve shows the generated voltage or electrical pressure which can be measured across the ends of the wire, just as voltage can be measured across the terminal posts of a battery.

With the rotor in the first position (1), there is no voltage being generated in the loop of wire because there are no magnetic lines of force cutting across the conductor. As the rotor turns and approaches position (2), the rather weak magnetic field at the leading edge of the rotor starts to cut across the conductor, and the voltage increases. When the rotor reaches position (2), the generated voltage has reached its maximum value, as shown above the horizontal line in the illustration. The maximum voltage occurs when the rotor poles are directly under the conductor. It is in this position that the conductor is being cut by the heaviest concentration of magnetic lines of force.

It should be noted in particular that the magnitude of the voltage varies because the concentration of magnetic lines of force cutting across the loop of wire varies. The voltage curve shown is not a result of a change in rotor speed, because in the illustration the rotor is considered to be turning at a constant speed.



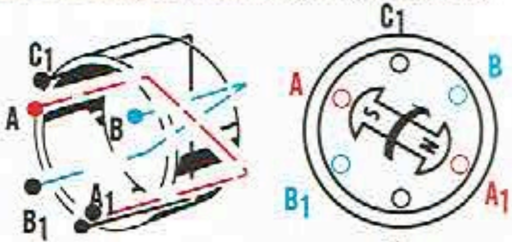
By applying the Right Hand Rule to position (2), it is seen that the direction of current in the loop of wire will be out of the top end of the conductor, and into the bottom end. Thus, the top end of the conductor will be positive, and the bottom end negative. The voltage curve which is shown above the horizontal line represents the positive voltage at the top end of the wire loop which is generated as the rotor turns from position (1) to position (3).

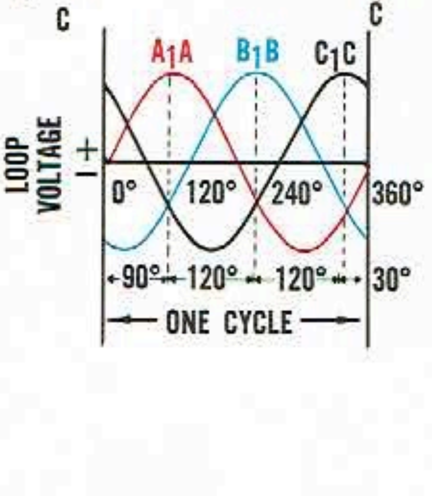
As the rotor turns from position (2) to position (3), the voltage decreases until at position (3) it again becomes zero.

As the rotor turns from position (3) to position (4), note that the N pole of the rotor is now passing under the top part of the wire loop, and the S pole under the bottom part. From the Right Hand Rule, the top end of the loop of wire is now negative, and the bottom end positive. The negative voltage at the top end of the loop is pictured in the illustration by the curve which is below the horizontal line.

The voltage again returns to zero when the rotor turns from position (4) to position (5).

The voltage curve in the illustration represents one complete turn or cycle of the rotor.

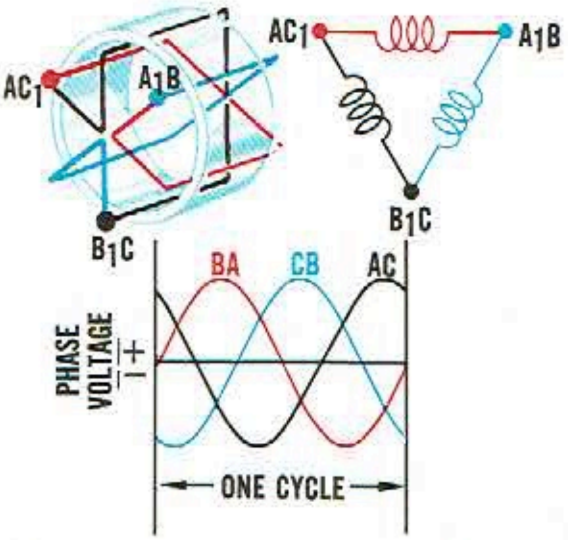




With the rotor making 60 complete turns in one second, there will be 60 such curves, one coming right after the other, resulting in 60 cycles per second. The number of cycles per second is called the frequency. Since the generator speed varies in automotive type applications, the frequency also varies.

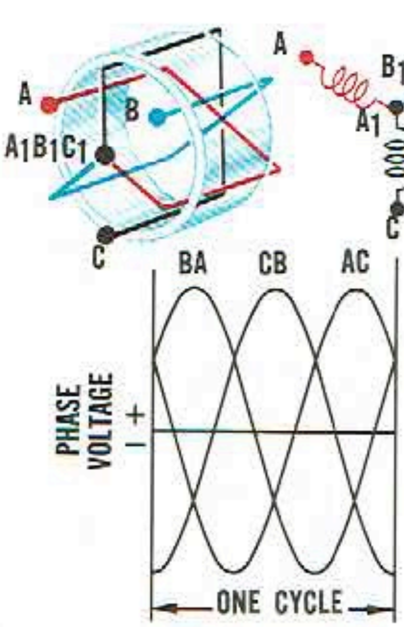
The single loop of wire acting as a stator winding, and the bar magnet acting as the rotor, serve to illustrate how an A. C. voltage is produced in a basic generator. When two more separate loops of wire, spaced 120 degrees apart, are added to our basic generator, two more separate voltages will be produced.

With the S pole of the rotor directly under the A conductor the voltage at A will be maximum in magnitude and positive in polarity. After the rotor has turned through 120 degrees, the S pole will be directly under the B conductor and the voltage at B will be maximum positive. Similarly, 120 degrees later, the voltage at C will be maximum positive. This means that the peak positive voltages at A, B and C in each loop of wire occur 120 degrees apart. These loop voltage curves are shown in the illustration.



When the ends of the loops of wire marked A_1, B_1 and C_1 are connected to the ends marked B, C and A respectively, as illustrated, a basic three phase "delta"-connected stator is formed. The three A. C. voltages available from the delta-connected stator are identical to the three voltages previously discussed, and may now be denoted as the voltages from B to A, C to B, and A to C, or more simply BA, CB and AC. An inspection of the illustration will show the logic of this notation. Example: The voltage formerly called A_1A may now be called BA.

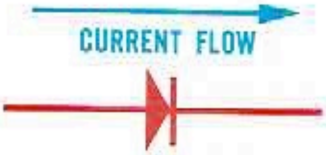
When the ends of the loops of wire marked A_1, B_1 and C_1 are connected together, a basic three-phase "Y"-connected stator is formed. The three voltages available from the "Y"-connected stator may be labeled BA, CB and AC.



From the illustration it may be seen that each of these voltages consists of the voltages in two loops of wire added together. For example, the voltage measured from B to A consists of the voltages in loops B_1B and A_1A added together. This addition yields a voltage curve BA similar in shape and form to the individual loop voltages, except that the voltage curve BA will be approximately 1.7 times as large in magnitude as an individual loop voltage. The addition of the loop voltages involves a mathematical process which will not be presented here, since it is only necessary to remember that three A. C. voltages spaced 120 degrees apart are available from the "Y"-connected stator, as illustrated. These voltage curves will be considered in more detail in the following sections.

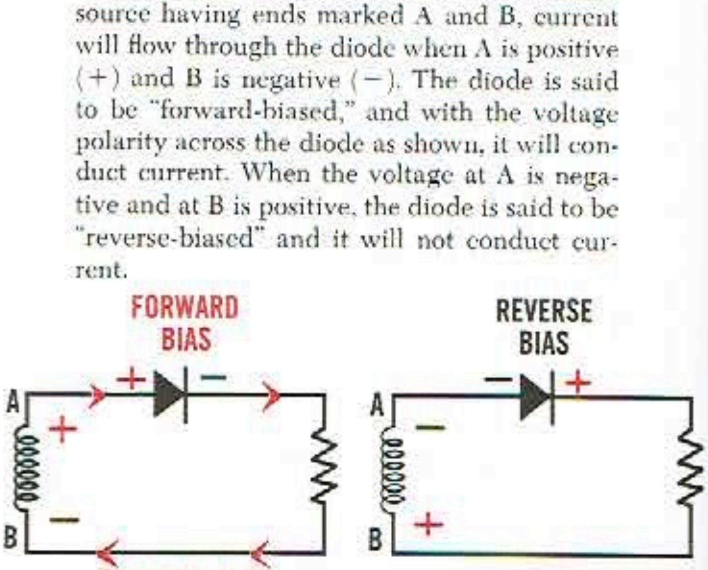
At this point in our discussion we have developed the two basic types of stator windings, and have shown how three separate complete cycles of A. C. voltage spaced 120 degrees apart are developed for each complete revolution of the rotor. We now turn our attention to the diode, and will see how six diodes connected to the stator winding change the three A. C. voltages to a single D. C. voltage needed for the D. C. electrical system.

A complete description of the operating principles of diodes is covered in Delco-Remy Training Chart Manual DR-5133J, entitled, "Fundamentals of Semiconductors." For the purposes of this section, we need know only that a diode is an electrical device that will allow current to flow through itself in one direction only. The diode is often pictured by this symbol, and current can flow through the diode only in the direction indicated by the arrow.

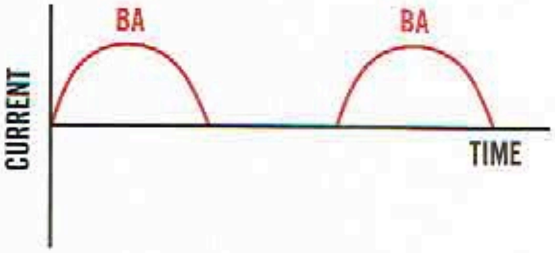


DIODE SYMBOL

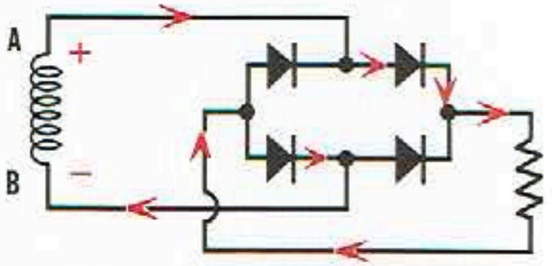
When a diode is connected to an A. C. voltage source having ends marked A and B, current will flow through the diode when A is positive (+) and B is negative (−). The diode is said to be "forward-biased," and with the voltage polarity across the diode as shown, it will conduct current. When the voltage at A is negative and at B is positive, the diode is said to be "reverse-biased" and it will not conduct current.

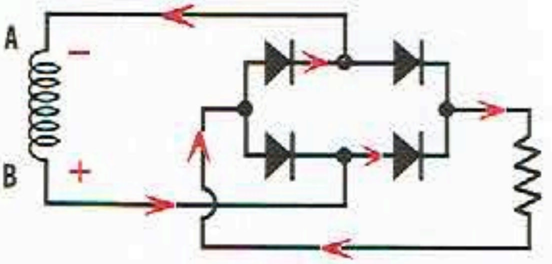


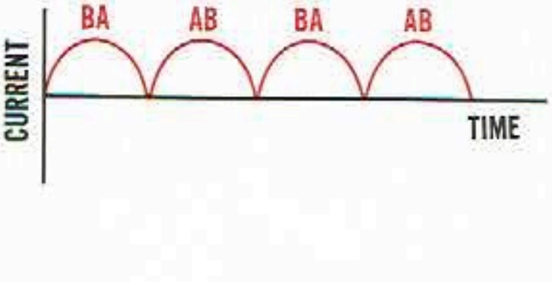
The current flow that would be obtained from this arrangement is illustrated. Since the current flows only half the time, the diode provides what is called "half-wave rectification." A generator having only one diode would provide very limited output.

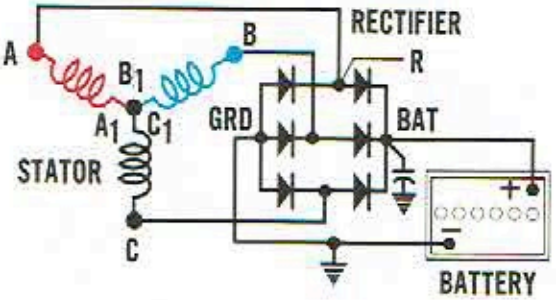


The output is increased when four diodes are used to provide "full wave rectification." Note that the current is more continuous than with one diode, but that the current varies from a maximum value to a zero value. It is particularly important to observe that the current flow through the external load resistor is in one direction only. The A. C. voltage and current have, therefore, been rectified to a unidirectional or D. C. voltage and current. This circuit arrangement could be used to charge a D. C. battery, but it does not produce the most output that can be obtained in an Integral Charging System.



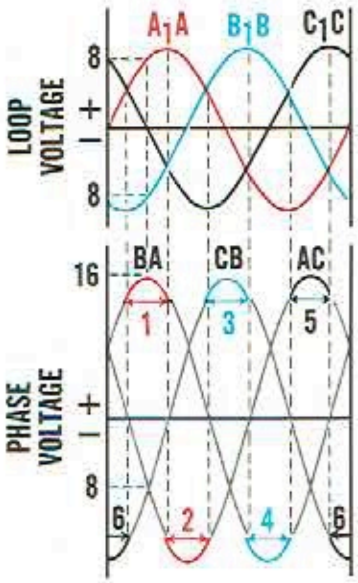






In order to obtain a higher output and a smoother voltage and current, a three-phase stator is connected to six diodes which together form a "three-phase full-wave bridge rectifier." The operation of the "Y"-connected stator will be illustrated first, then that of the delta-connected stator. A battery connected to the D. C. output terminal will have its energy restored as the Integral Charging System provides charging current. Note that the blocking action of the diodes prevents the battery from discharging directly through the rectifier.

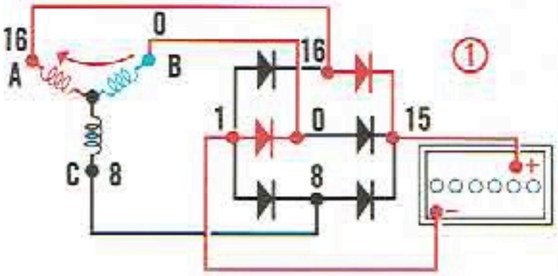
In order to explain the direction of current flow in the stator-rectifier combination, we will review briefly our previous discussion concerning the three A. C. voltage curves produced in the "Y"-connected stator winding. Our first reference was to the voltages developed in each loop. These loop voltage curves A_1A, B_1B and C_1C are reproduced here for reference. However, these individual loop voltages do not appear across the rectifier diodes, because the rectifier is connected only to the A, B and C terminals of the stator. Therefore, the voltages which appear across the rectifier diodes are the phase voltages BA, CB and AC.



The phase voltage curves BA, CB and AC are also reproduced here, and are obtained as previously explained by adding together each pair of loop voltages. As an example, phase voltage BA is obtained by adding together the voltages in loops A_1A and B_1B. In order to obtain the phase curve BA, we add together the voltage from B to B_1, and the voltage from A_1 to A. Consider the instant when the voltage in curve BA is maximum in magnitude and positive in polarity. At this same instant the voltage B_1B is minus 8, or the voltage from B to B_1 is plus 8. This value added to the A_1A loop voltage of plus 8 volts yields a maximum positive voltage of 16 volts for curve BA. By taking different instants of time, the entire curve BA and curves CB and AC, can be obtained in this same manner.

For convenience, the three A. C. voltage curves provided by the "Y"-connected stator for each revolution of the rotor have been divided into six periods, 1 through 6. Each period represents one-sixth of a rotor revolution, or 60 degrees.

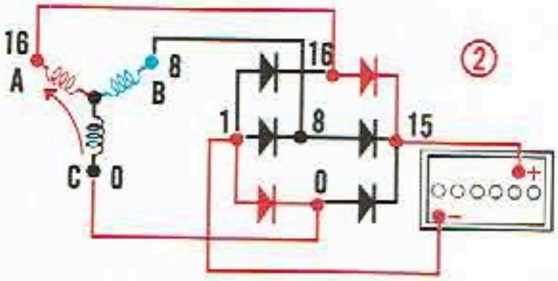
An inspection of the voltage curves during period 1 reveals that the maximum voltage being produced appears across stator terminals BA. This means that the current flow will be from B to A in the stator winding during this period, and through the diodes as illustrated.



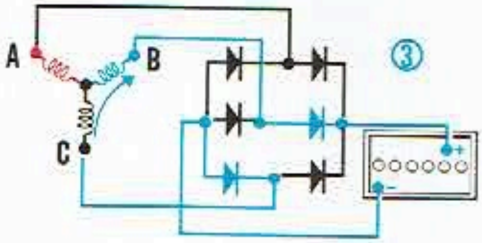
In order to see more clearly why the current flows during period 1 as illustrated, assume that the peak phase voltage developed from B to A is 16 volts. This means that the potential at B is zero volts, and the potential at A is 16 volts. Similarly, from the curves the phase voltage from C to B at this instant is minus 8 volts. This means that the potential at C is 8 volts, since C to B, or 8 to zero, represents a minus 8 volts. At this same instant the phase voltage from A to C is also minus 8 volts. This checks, since A to C, or 16 to 8, represents minus 8 volts.

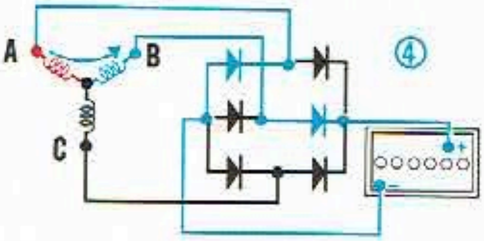
Neglecting voltage drops in the wiring, and assuming a one volt drop in the conducting diodes, the voltage potentials are noted on the rectifier. Only two of the diodes will conduct current, since these diodes are the only ones in which current can flow in the forward direction. The other diodes will not conduct current *because they are reverse biased.* For example, the lower right-hand diode is reverse biased by 7 volts (15 − 8 = 7), and the right-hand middle diode is reverse biased by 15 volts (15 − 0 = 15). *It is the biasing of the individual diodes, provided by the stator, that determines how current flows in the stator-rectifier combination.* Throughout period 1 the current flows as indicated, because the bias direction across the diodes does not change from that shown. Although the voltage potentials across the diodes will vary numerically, this variation is not sufficient during period 1 to change a diode from reverse bias to forward bias and from forward bias to reverse bias.

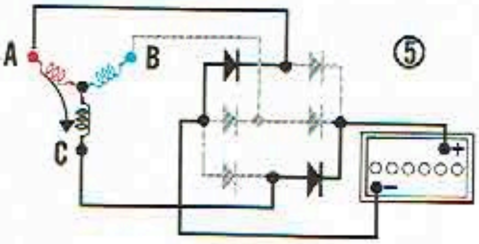
An inspection of the phase voltage curves will reveal that between periods 1 and 2 the maximum voltage being impressed across the diodes changes or switches from phase BA to phase AC. This means that as the maximum voltage changes the current flow will change from BA to CA.

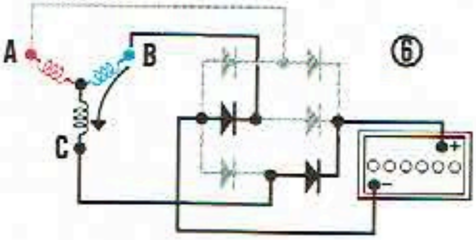


It is important to note that the maximum voltage being produced in the stator windings during period 2 appears across phase AC and that this voltage is negative from A to C. Taking the instant of time at which this voltage is 16 volts, the potential at A is 16, and at C is zero (A to C, or 16 to 0, is a negative or minus 16). Similarly, at this same instant, the voltage across phase BA is 8 volts, and across phase CB is 8 volts. This means that the potential at B is 8 volts, as shown. The direction of current flow during period 2 is illustrated.



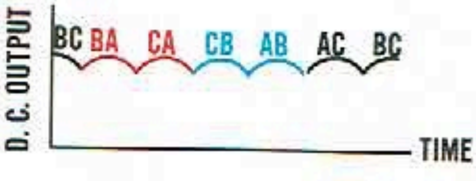


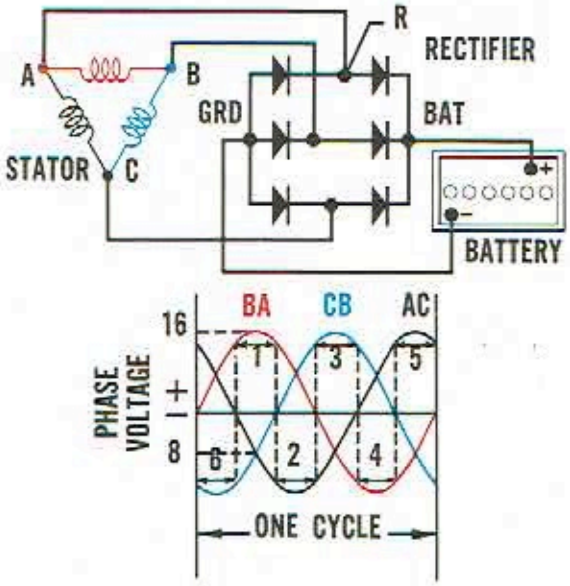




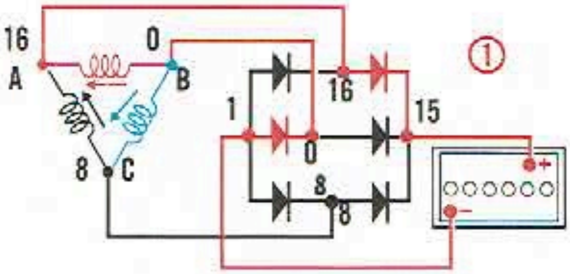
Following the same procedure for periods 3-6, the current flow conditions can be determined, and are shown in the illustrations. These are the six major current flow conditions for a three-phase "Y"-connected stator and rectifier combination.

The voltage obtained from the stator-rectifier combination when connected to a battery is not perfectly "flat," but is so smooth that for all practical purposes the output may be considered to be a non-varying D. C. voltage. The voltage, of course, is obtained from the phase voltage curves, and can be pictured as illustrated.



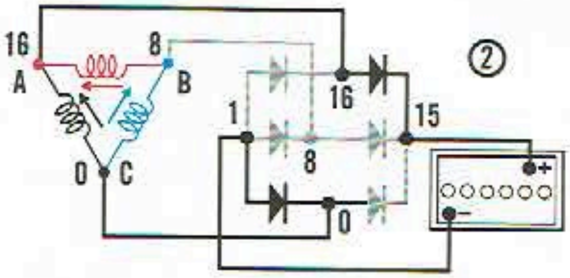


A delta-connected stator wound to provide the same output as a "Y"-connected stator also will provide a smooth voltage and current output when connected to a six-diode rectifier. For convenience, the three-phase A. C. voltage curves obtained from the basic delta connection for one rotor revolution are reproduced here and have been divided into six periods.



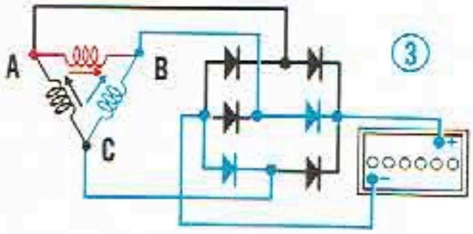
During period 1, the maximum voltage being developed in the stator is in phase BA. To determine the direction of current flow, consider the instant at which the voltage during period 1 is at a maximum, and assume this voltage to be 16 volts. The potential at B is zero, and at A is 16. From the curve, it can be seen that the voltage of phase CB is a negative or minus 8 volts. Therefore, the potential at C is 8 (C to B or 8 to 0 is a minus 8 volts). Similarly, the voltage of phase AC is minus 8 volts. This checks, since A to C, or 16 to 8, is a minus 8. These voltage potentials are shown in the illustration. The current flow through the rectifier is exactly the same as for a "Y"-connected stator, since the voltage potentials on the diodes are identical.

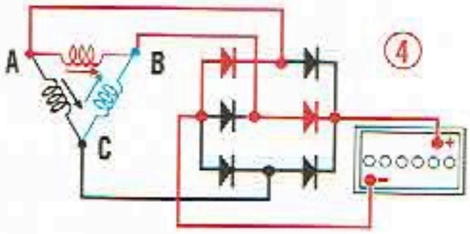
An inspection of the delta stator, however, reveals a major difference from the "Y" stator. Whereas the "Y" stator conducts current through only two windings throughout period 1, the delta stator conducts current through all three. The reason for this is apparent, since phase BA is in parallel with phase BC plus CA. Note that since the voltage from B to A is 16, the voltage from B to C to A also must be 16. This is true since 8 volts is developed in each of these two phases.

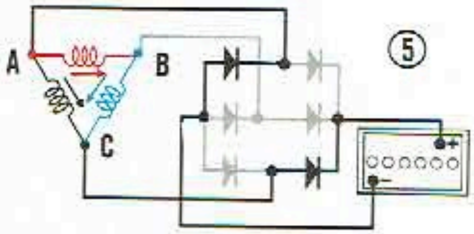


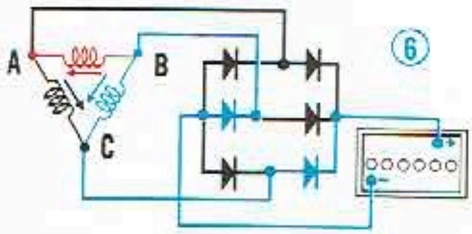
During period 2, the maximum voltage developed is in phase AC, and the voltage potentials are shown on the illustration at the instant the voltage is maximum. Also shown are the other phase voltages, and again, the current flow through the rectifier is identical to that for a "Y" stator, since the voltages across the diodes are the same. However, as during period 1, all three delta phases conduct current as illustrated.

Following the same procedure for periods 3-6, the current flow directions are shown. These are the six major current flow conditions for a delta stator.





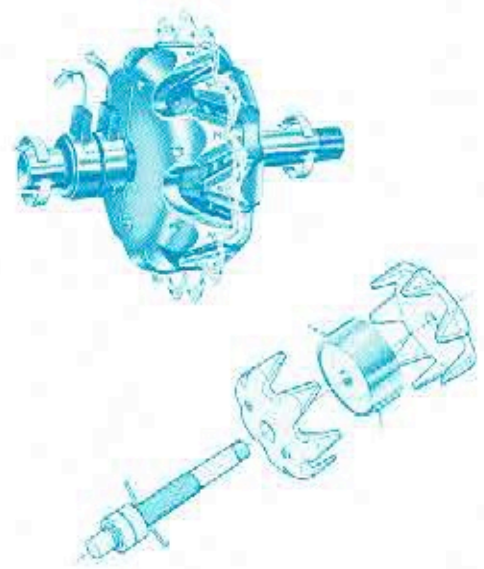




This concludes our study of the fundamental principles by which a simple, basic generator develops three A. C. voltages which are then rectified to a single D. C. voltage and current for use in the electrical system. Although the typical voltage values used in the recent illustrations ignore line drops, they serve very well to show in simplified fashion the sequence and direction of current flow through the stator and diodes.

The Delcotron Integral Charging System is constructed with more than just a bar magnet as a rotor and three single loops of wire as a stator.

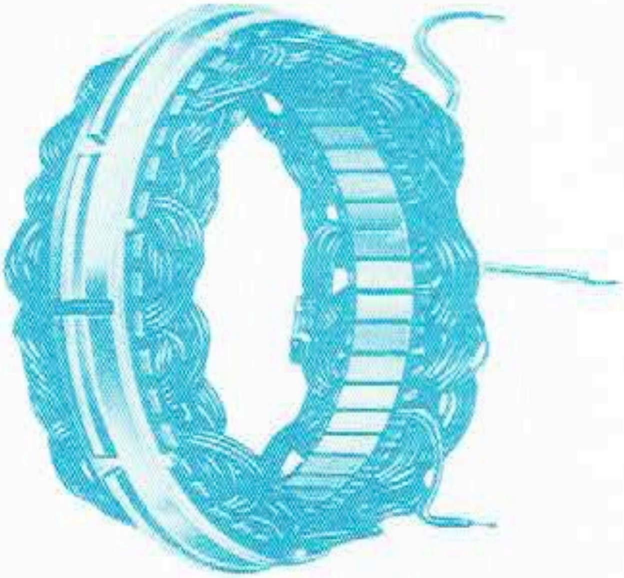
A typical rotor assembly consists of two iron pole pieces with interlacing fingers mounted over many turns of wire which are wound over the rotor core mounted on the shaft. The rotor coil is connected electrically to the two slip rings, which are then connected to the battery through the brushes and leads. When energized, the rotor coil is an electromagnet which produces alternate North and South poles. The rotor shown has a total of 14 poles.



A typical stator assembly consists of three separate windings mounted on a laminated iron frame. The windings are connected together to form a "Y" or delta connected stator. An incomplete stator assembly with only one of the windings is illustrated.

Each winding consists of seven coils, and each coil contains many turns of wire. There is one coil for each pair of rotor poles. A complete cycle of A. C. voltage will be generated in each coil as a North and South pole pass by the coil. With seven coils in series, each being influenced by a North and South pole simultaneously, there will be seven coil voltages adding together to provide a complete winding voltage. In the previous section, a two-pole magnet type of rotor was used to show that a complete cycle of A. C. voltage will be produced for each rotor revolution. With a 14-pole rotor, seven complete cycles of A. C. voltage will be produced for each rotor revolution.

Two more identical windings mounted on the iron frame complete the assembly. These windings are spaced so that the stator delivers three-phase A. C. voltage as covered in the previous section.

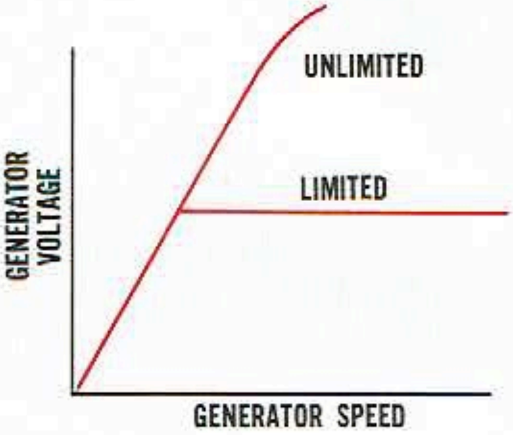


A typical diode is of the small "button" type, with six assembled between two heat sinks to form a rectifier bridge. The stator is connected to three studs on the rectifier bridge to form an electrical circuit as previously shown.

With a rectifier bridge containing six diodes, a stator with many turns of wire, and a rotor producing a strong magnetic field, the Integral Charging System becomes an efficient source of voltage and current in the charging circuit.

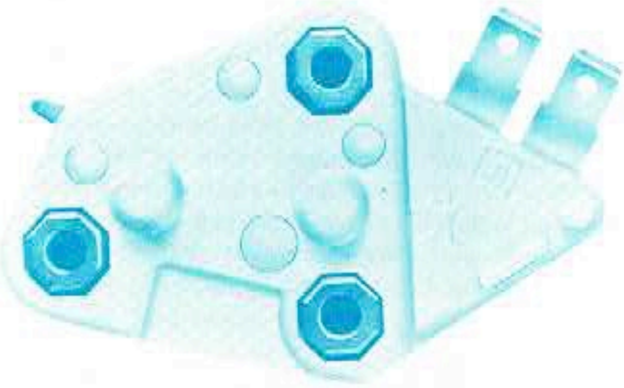
We now turn our attention to the regulator, which is assembled inside the Integral Charging System.

The need for a regulator in the charging circuit is brought about by the fact that the generator voltage increases with increases in generator speed. Since sufficient voltage must be developed at low speeds to charge the battery and operate electrical accessories, this voltage if uncontrolled at high generator speeds would increase to values that would overcharge the battery and damage the accessories. The sole function of the regulator is to prevent high voltage by limiting the generator voltage to a safe, preset value.



The regulator limits the generator voltage to a preset value by controlling the generator field current. It operates electronically to alternately "turn off" and "turn on" the voltage across the field winding. In a sense, the transistor regulator is nothing more than a very fast-acting electronic switch. This switching, between open and closed and back again, can occur at a rate as low as 10 times per second, and as high as 7000 times per second.

There are two types of regulators used in Integral Charging Systems. One type is a discrete component assembly, which can be serviced and repaired by replacement of defective components. The other type is an integrated circuit regulator, which contains micro-miniature electronic components too small to be seen in detail without a microscope. The integrated circuit regulator is serviced by complete replacement only.



Both types of regulators use the same basic electronic circuit. Since this circuit contains transistors, the regulator is commonly called a transistor regulator.

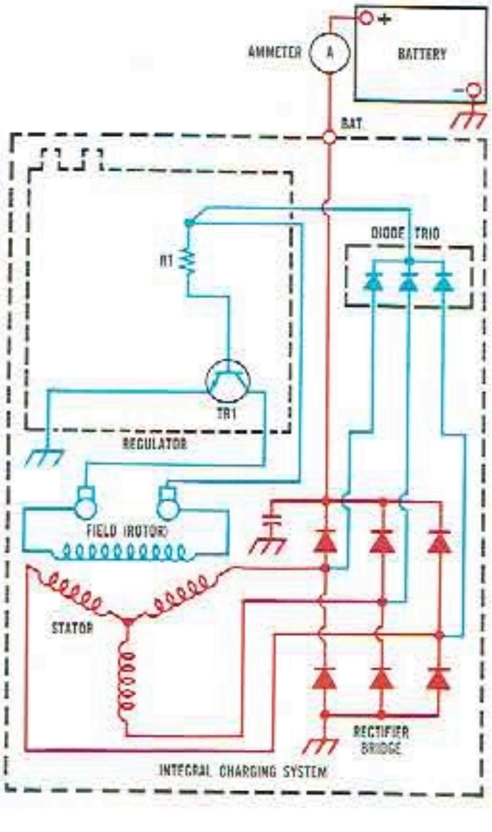
In order to simplify our explanation of this circuit, we will use a basic Integral Charging System (stator, rectifier bridge, and rotor field) connected with a negative ground battery to the regulator. More detailed diagrams of the circuits found in the various types of Integral Charging Systems will be presented in the next section. At this point in our story, we are concerned only with seeing how a transistor regulator works.

In order to do this, we will "build up" the typical regulator circuit step by step, adding components as we go until the circuit has been completed.

Our "build up" of the basic circuit begins with an output transistor TR1, a resistor R1, and three diodes which together comprise the diode trio. A typical diode trio is illustrated.

Note that the diode trio is a separate unit and is not inside the regulator. Our Integral Charging System now consists of a stator, field or rotor, rectifier bridge, diode trio and regulator. This assembly is connected to the battery through an ammeter which indicates the battery charge rate.

The operation of this sytem is explained as follows: Voltages are generated in the stator initially by residual magnetism in the rotor. These voltages are impressed through the diode trio and across R1 to forward bias the emitter-base of TR1.



As rotor speed increases, the voltages increase, and current flows from the stator, through the diode trio, R1, the base-emitter of TR1, through the ground circuit, and back to the stator through the grounded diodes in the rectifier bridge. With TR1 turned on, current also flows from the stator through the diode trio, the field, TR1, the ground circuit and the grounded diodes in the rectifier bridge back to the stator.

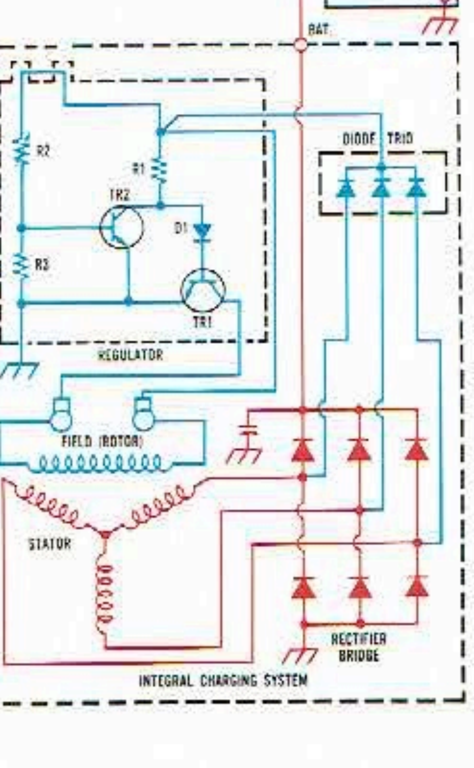
With current flow through the field, a strong magnetic field is produced in the rotor, and high voltages that would overcharge the battery would be induced in the stator at high speeds. We now proceed to add more components to the regulator, toward our final objective of a regulator that will regulate the Integral Charging System voltage by turning the voltage across the field on and off, thus controlling field current. *In the following discussion, current through the regulator will be supplied as before, through the diode trio.*

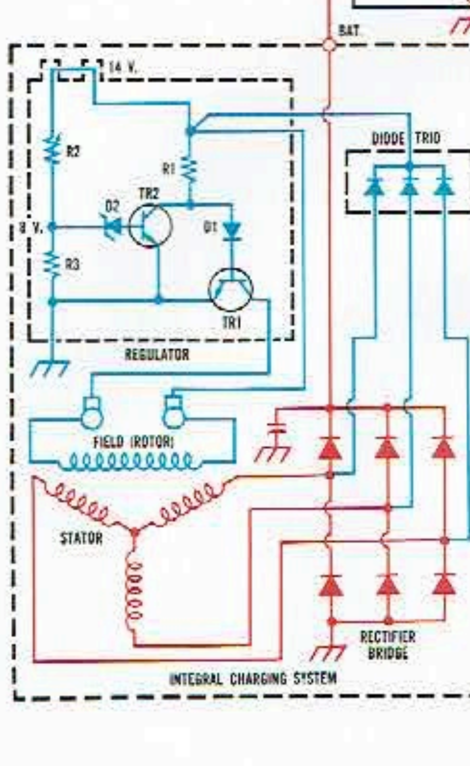
In this illustration, a back-bias diode D1, a driver transistor TR2, and a series of resistors R2 and R3 have been added.

With current flow through R2 and R3, the voltage between R2 and R3 is applied to the base of TR2, turning TR2 on. Transistor TR2 acts like it has essentially zero resistance, so the voltage at the emitter of TR1 is the same as the voltage between R1 and D1. This means that the base-emitter of TR1 is no longer forward biased, so it turns off, and the field current is turned off. Now some means must be found to turn the field current and voltage back on, which will be done in the next circuit.

If current were to flow through D1 and the base-emitter of TR1, the voltage drop across D1 would make the voltage between R1 and D1 higher than at the collector of TR1. This condition is prevented by TR2.

In our next circuit, we have added a zener diode D2, which is connected in the circuit to block current flow through the base-emitter of TR2. With TR2 turned off, it acts like an open switch, and current flow is re-established through R1, D1, TR1, and the field.





Since zener diode D2 is a special kind of diode that will allow current to flow when the voltage across the diode reaches a certain value, let us assume to illustrate how this diode works, that the Integral Charging System is operating at 14 volts. With 14 volts across R2 and R3, the voltage divides such that 8 volts appears between R2 and R3. This same 8 volts is impressed across D2 and TR2, and we are assuming that 8 volts is the breakdown voltage of D2.

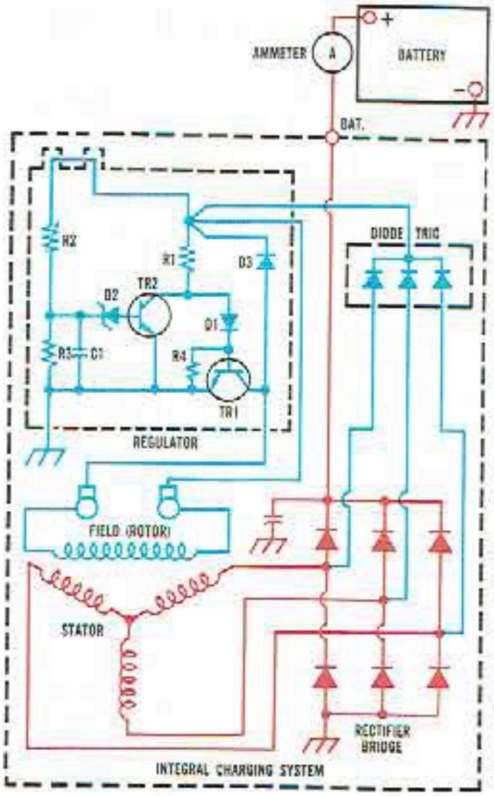
Therefore, when the system voltage increases to 14 volts, D2 and TR2 suddenly conduct current to "turn on", and TR1 is forced to "turn off". The field current decreases a very small amount and the system voltage decreases very slightly below 14 volts. D2 and TR2 "turn off", TR1 turns back on, the field current increases very slightly, and the system voltage increases back to 14 volts. This switching of TR1 between on and off and back on again controls the field current and limits the voltage essentially to 14 volts. We now have a workable regulator — one that limits the field current and hence the voltage over a very narrow range to give what for all practical purposes, is a steady 14-volt regulator setting.

Different regulators, of course, may have different voltage settings, depending on the voltage requirement of the system involved. Also, the voltage setting may vary with temperature, with the regulator operating at a lower voltage when hot to better meet the voltage requirements of a hot battery. Other systems may not be temperature compensated, operating at a constant voltage throughout the temperature range.

The wiring circuit illustrated is temperature compensated. The arrow in R2 indicates that this is a special kind of resistor that *decreases* its resistance with *increases* in temperature. The hotter the regulator, the lower will be the voltage setting, which is explained as follows:

The important thing to remember is that the regulator operates when 8 volts appears across D2. Thus, the regulator must operate to provide a constant current through R2 and R3 in order to get 8 volts across R3. If R2 decreases with temperature increases, the system voltage decreases also, giving a constant current through R2 and R3. Thus, at 80°F, the voltage setting might be 14.0 volts and at 100°F, the setting might be 13.7 volts.

In the next illustration, C1, R4 and D3 have been added. These components make the regulator more stable and prevent damage to the transistors.



Capacitor C1 smooths out the system voltage variations that appear across R3, giving more stable and constant voltage control.

Resistor R4 prevents leakage current from the base to emitter of TR1 that could occur at high temperatures, even though TR2 has turned TR1 off.

Diode D3 is connected across the field to prevent high induced voltages in the field when TR1 turns the field off. High induced voltages could damage TR1, causing it to become shorted or open.

This completes our story on how the basic circuit in an Integral Charging System works. In the next section, we will look at some of the various types and designs of Integral Charging Systems.