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GENERAL IMPROVEMENT OF CONTROL ELEMENT OF REVERSE-CURRENT CUTOUTS

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ABSTRACT

An investigation was undertaken to find a means of improving the performance of aircraft reverse-current cutouts. It was decided that, to be satisfactory, an ideal cutout designed for a 28-volt d-c aircraft system should close at a differential voltage between generator and bus of 0.2 volt and open under a reverse-current equal in magnitude to five percent of the generator full-load current. It should operate at the same values for any system voltage between 20 and 30 volts, any temperature between -55° C and +70° C, and severe conditions of vibration, shock, dust, humidity, and at any altitude up to 50,000 feet. It should be small in size and weight, should be simple and dependable in operation, and have a low power consumption. A circuit is proposed herein utilizing a permanent magnet control element to trigger a unique thyratron circuit, which, it is believed, will satisfactorily meet all the rigorous conditions imposed, if properly designed from a mechanical standpoint.

PROBLEM STATUS

This report concludes the work on this problem and unless otherwise advised by the Bureau, the problem will be closed one month from the mailing date of this report.

AUTHORIZATION

The work done on this project was authorized by BuAer ltr to NRL, Aer-E-3122-JAT, Serial No. F36-2(6), dated 2 January 1946, Subject: Reverse Current Cutouts, General Improvement of Control Element.

GENERAL IMPROVEMENT OF CONTROL ELEMENT OF REVERSE-CURRENT CUTOUTS

INTRODUCTION

1. Reverse-current cutouts employed in aircraft at the present time are of the conventional magnetic type and have never been completely satisfactory in operation from the standpoint of dependability, maintenance, and functioning under the wide range of conditions outlined below. The most recently developed type operates on the differential voltage between generator and battery and seems to be more satisfactory than previous types. It, however, still is not completely satisfactory and an investigation of the problem seemed desirable.

2. The purpose of this investigation was to develop a better reverse-current cutout for use in aircraft, to connect its associated generator to the main bus when conditions are such that the generator is capable of delivering power to the bus, and to disconnect the generator when the bus supplies power to the generator. Due to the wide variations in operating conditions encountered in aircraft and the strict specifications imposed on its operation, it has been extremely difficult to obtain a completely satisfactory reverse-current cutout. Existing magnetic-type cutouts have been developed to a relatively high stage and it was considered that, in order to obtain a really significant improvement in size, weight, or performance, work should be concentrated on developing a cutout based on some new principle.

3. An ideal cutout designed for use on present aircraft should operate satisfactorily on any voltage between 20 and 30 volts, independently of the operation of the voltage regulator. It should close the main contactor to connect its generator to the bus when the generator voltage is 0.2 volt higher than the bus voltage, and should reopen it if a reverse current, equal in magnitude to five percent of the generator full-load current, flows through the generator. Its operation must not be affected by wide variations in ambient temperature ($-55^{\circ}C$ to $+70^{\circ}C$). It should not be affected by severe conditions of shock and vibration, dust and humidity. It should compare favorably with existing cutouts in size and weight, and should be simple and dependable in operation. It should not provide a drain on the batteries when the generator is inoperative, and the pilot relay preferably should be universal in design so that the same pilot relay might be used on any generator, regardless of its current rating. Its power consumption should be limited to a reasonable value.

FACTORS INFLUENCING DESIGN OF REVERSE-CURRENT CUTOUTS

4. The difficulties encountered in designing a satisfactory cutout have been very great due to the wide variations in operating conditions outlined above. The low operating voltage (20 volts) and the wide variations that must be tolerated (20-30 volts) limits the usefulness of electronic tubes which, in general, have too low a power output at this voltage to

operate any but a very sensitive relay. This voltage is too low for the use of a gas discharge tube as a voltage-regulating device and is just barely enough to operate a small thyratron tube. Furthermore, since the main switch must, of necessity, be in the positive lead of the generator, the controlling voltage (differential voltage between generator and bus) is in the vicinity of the positive side of the line and precludes the direct application of conventional, grid-controlled vacuum tubes, where the grid voltage is in the vicinity of the cathode potential rather than the plate.

5. Furthermore, the differential voltage coil (or other element) must operate on 0.2 volt in the forward direction, but must be able to stand at least 10 volts continuously in the reverse direction. (This is based on the assumption that an auxiliary relay is used in the differential coil circuit which will not close until the generator voltage builds up to 20 volts. If this is not done, the differential coil circuit must be designed to withstand 30 volts, under normal conditions, and 60 volts if the generator builds up in the reverse direction). This gives a ratio of full-load voltage to operating voltage for this device of 50 to 1, making the use of a larger wire size necessary and, consequently, increasing the weight and size tremendously. Similarly, the coil (or other element), to control the opening of the cutout under reverse current, must have a ratio of full-load voltage to operating voltage of 20 to 1, without allowing for generator overload. Thus, a coil operating under these conditions must, of necessity, either develop a very small operating signal or else be impractical due to size and weight limitations. The insertion of an ideal rectifier or current-limiter in the circuit would reduce these ratios to reasonable values; however, there is no known rectifier having a stable temperature characteristic which will pass appreciable current with 0.2 volt across its terminals and no suitable current-limiter has been found.

6. The operation of any circuit which depends on the characteristics of a nonlinear element will, in general, vary widely with ambient temperature. This restricts the use of such elements very greatly as controlling elements, if stability of operation is desired.

7. Finally, the use of direct-current, while highly desirable from the standpoint of relay operation, does offer drawbacks in the number of circuit elements that are available. Such things as transformers, inductances, and capacitances have no counterparts in steady-state d-c circuits and, consequently, the number of circuit parameters and control elements available are more limited.

8. Early investigations of devices operating on the principle of a fixed voltage pick-up indicated that such a device was not feasible, and investigations were thereafter limited to the use of the <u>differential</u> voltage between generator and battery as the controlling factor. During the course of the investigation, many different ideas were tried, only the most important of which will be explained.

THYRITE REVERSE-CURRENT CUTOUT

9. Probably the chief difficulty in designing a device to operate under the wide variations in conditions outlined above is caused by the lack of any stable parameter which can be used as a standard for comparison with the desired operating signal. One attempt to obtain a constant magnetic flux for use as a standard utilized a piece of "Thyrite," which is the trade name for a silicon carbide nonlinear resistance element manufactured by the General Electric Company. The circuit which was proposed for use is shown in Figure 1, where A, B, and C are three coils all wound on the same magnetic core so that A and B are opposing, and C aids their resultant when the generator voltage is higher than the battery voltage. The Thyrite sample is designated as T. The operation of this proposed circuit may be explained by means of the characteristics given in Figures 2 and 3.

10. The current voltage characteristic of the Thyrite alone is nonlinear, as shown in Figure 2, but over a limited portion of the curve (between c and d) can be considered as approximately a straight line. Since the coil A has resistance, the combined series circuit will have a current-voltage relation approximated by the straight line e-f over the voltage range under consideration. By properly selecting the desired portion of the Thyrite characteristic curve and adjusting the series resistance in the circuit, the segment e-f can be made to coincide with the operating limits of 20 to 30 volts. Note that this portion of the characteristic if projected as a straight line, does not pass through the origin as a purely linear resistance would do. Since the ampere-turns produced by a given coil are directly proportional to the current, a variation in the number of turns does not affect the linearity but merely changes the slope of the curve. Thus, by a proper selection of the resistances and number of turns of coils A and B, and a proper operating range on the Thyrite characteristic, the ampere-turns versus voltage characteristics for both circuits can be determined and will be approximately straight lines. For the circuit containing coil B it will be g-i which, if projected, will pass through the origin. For the circuit containing coil A it will be h-j, which will be approximately linear and can be made parallel to g-i over the range from 20 to 30 volts. Since A and B are wound in opposition, the net mmf (magnetomotive force) will be given by the difference in their corresponding ordinates for any terminal voltage between 20 and 30 volts and, since g-i is parallel to h-j, this difference will always be substantially constant over the desired range of voltage. This mmf could then be used as a standard to react with that of coil C (when the generator voltage is higher than the battery) to close the pilot relay for the main contactor. Thus, the cutout would be polarized in

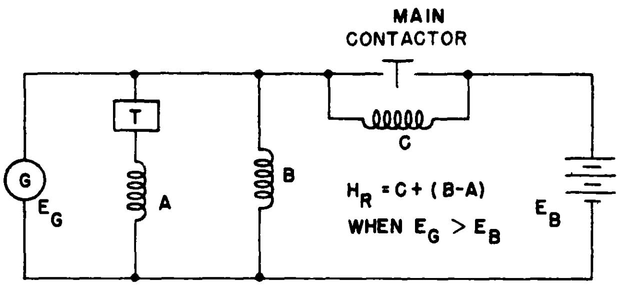

Fig. 1 - Circuit Diagram for Thyrite Reverse - Current Cutout

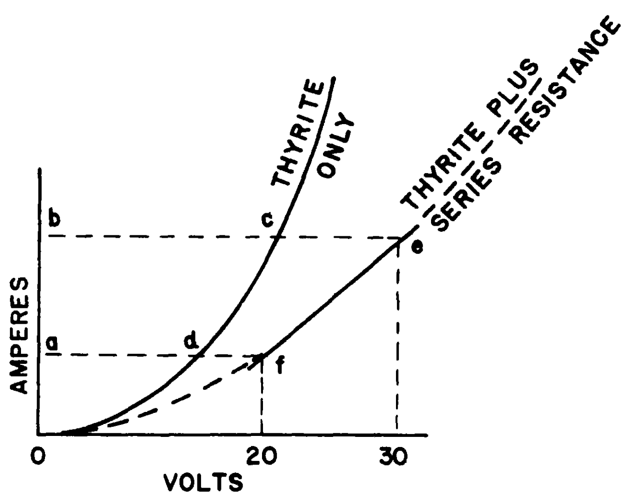

Fig. 2 - Characteristics of Thyrite and Series Resistance

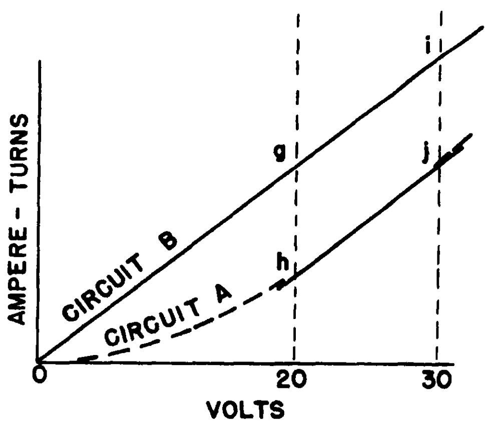

Fig. 3 - Characteristics of Individual Circuits of Thyrite Reverse - Current Cutout

its action and operate uniformly over the desired range of terminal voltage.

11. This circuit operated satisfactorily for a given ambient temperature, and coils A and B did conjointly produce a substantially constant flux. The Thyrite characteristic, however, changes considerably with ambient temperature (as do nearly all other nonlinear circuit elements) and this change, together with the resistance changes in the coils, caused too large a variation in flux to be tolerated under the wide range of ambient conditions encountered in aircraft. Furthermore, the size of the coils, since they were wound in opposition, was larger than could be tolerated in an aircraft relay.

SATURATION REVERSE-CURRENT CUTOUT

12. Another attempt to obtain a constant magnetic flux for use as a standard was based on the use of the relatively flat portion of the magnetization curve for iron beyond saturation. The magnetic circuit consisted of two parallel paths, one of which was wound with a coil connected across the generator and would be saturated for all voltages above 20 volts. The other path would be smaller in cross-sectional area and wound with a coil connected across the main cutout contacts so that its flux would be proportional to the differential voltage between the generator and battery. These parallel paths were in series with a magnetic path of larger cross-section (so as to be unsaturated) and the working airgap of the relay. The saturated leg would then provide an approximately constant flux (regardless of terminal voltage) through the airgap to which the signal flux would either add or subtract and, when properly adjusted, could be used as a polarized relay.

13. It was found that the flux produced by the saturated leg was not constant, due to the fact that the magnetization curve continues to rise slowly beyond the "knee" of the curve for increasing values of mmf due principally to the increase in the leakage flux. This increase, when compared to the small signal flux, was too great to be tolerated. Furthermore, the characteristics of such a cutout would be hard to duplicate in manufacture since any minor variations in the airgaps, which must, of necessity, be present in the parallel magnetic paths (due to manufacturing tolerances), will alter the characteristics of the cutout appreciably.

MAGNETICALLY CONTROLLED DIODE REVERSE-CURRENT CUTOUT

14. Another idea investigated for a cutout was based on the characteristic of a magnetically controlled diode, which consists of a concentric circular anode and cathode to which a uniform magnetic field is applied in a direction parallel to the tube elements. Such a tube has a substantially constant plate current for all low values of magnetic field strength, but as the field strength is increased above a certain critical value, depending principally upon the physical dimensions of the tube, the plate current drops rapidly to a very small value. In a tube of this kind, with no magnetic field applied, the electrons will flow radially from the cathode to the anode. As the magnetic field is increased, the electron path will curve with an ever decreasing radius of curvature since the direction of electron flow is at right angles to the magnetic field. Thus, although the path is longer, the electrons will still all reach the anode (maintaining a constant plate current) until some critical value of field strength is reached where the curvature is so great that the electrons never reach the anode but curve back to the cathode and the tube is cut off. If the elements of such a tube were perfectly concentric and parallel, and the magnetic field were uniform and parallel to the tube elements, the cut-off characteristic of the tube would have an extremely steep slope at the critical value of field strength.

15. This phenomenon may be used in the circuit shown in Figure 4 and may be explained by use of the tube characteristic in Figure 5. The four coils (R, M, B and D) are all wound

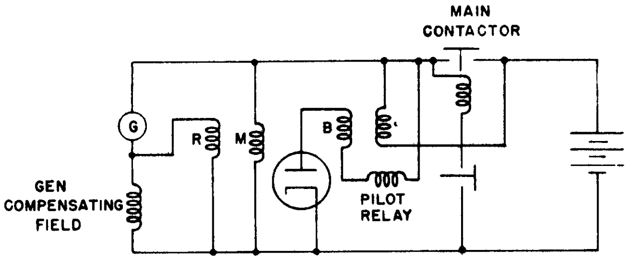

Fig. 4 - Circuit Diagram for Magnetically - Controlled Diode, Reverse Current Cutout

concentric to the tube. Coil M supplies the proper operating "bias" equal to OJ on the tube characteristic (Figure 5). Coil D supplies a flux proportional to the differential voltage between the generator and battery. Coil R furnishes a flux proportional in magnitude and direction to load current (to reopen the cutout under reverse current), and coil B is inserted in the plate circuit of the tube and so designed that it supplies a flux, opposing M, such that their combined effect is given by BJ in Figure 5. Thus, in the normal condition, the tube would be cut off and operating at point C. As the generator voltage becomes slightly higher than the battery voltage, the flux through coil D causes the characteristic BC to shift parallel to itself to the left until it reaches a point of tangency with the tube characteristic at point D. Further movement to the left would cause an unstable condition and the operating point of the tube would shift immediately to point E, causing an increase in plate current to flow in the tube and operate the pilot relay which would, in turn, close the main contactor. This short-circuits coil D, returning the operating point to B, but the relay still remains closed. Should conditions in the circuit change causing a reverse current to flow, coil R would shift BC to position FG where another unstable condition is reached. The operating point then shifts immediately to point G, where reduced plate current cuts off the tube and opens the pilot relay and main contactor. Since the main contactor is open, no current flows in the main circuit and the flux produced by coil R collapses, returning the tube operating point to C, whence the cycle can be repeated.

16. Thus, the characteristics of a circuit of this type may be summarized as follows:

a. The circuit is polarized in its operation, requiring only a relatively small signal for operation.

b. The relay operation is not critical since there are only two stable points of equilibrium (either on or off) resulting in a relatively large change in current which makes possible the use of an insensitive relay.

c. The circuit would not be affected by temperature changes, except minor coil resistance changes.

d. The controlling circuit is insulated electrically from the controlled circuit.

e. The circuit can be made small in size and weight if a sufficiently steep tube characteristic can be obtained.

f. The circuit is partially self-compensating for voltage changes, since both the tube characteristic and the flux produced by coil M shift to the right in Figure 5 as the terminal voltage increases.

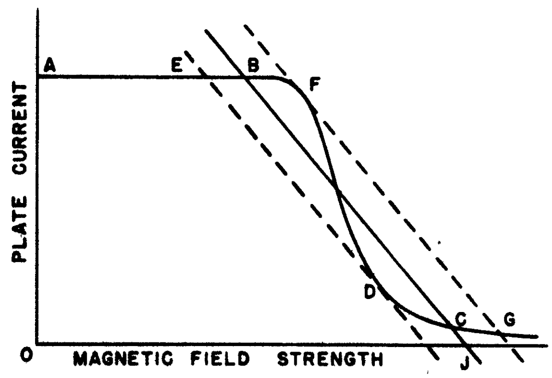

Fig. 5 - Circuit Characteristic of Magnetically - Controlled Diode, Reverse Current Cutout

17. No tubes were available to operate on such low voltages, and it was not known

whether suitable characteristics could be obtained. A perfectly constructed tube should have a characteristic curve with an extremely steep slope at cut-off; but, using such low voltage, it was necessary to use a close spacing between cathode and anode in order to obtain a reasonably large plate current to operate a relay, thus magnifying the problem of obtaining exact concentricity between cathode and anode. To obtain an idea of the practical limitations that might reasonably be expected from a tube of this type, two were constructed by the Laboratory and tested. It was important that the tube have a steep characteristic since the weight and size of coil B depends directly upon the steepness of the tube characteristic. Also, the resistances of both the relay and coil B must be kept low, or the tube output will be decreased and the effective steepness of the tube characteristic will be decreased. The best tube characteristic obtainable was not deemed sufficiently steep for operation at such low voltages. If a larger spacing could be used between cathode and anode, such as in the 2B23 tube manufactured by General Electric Company (designed for 150 volts), a sufficiently steep characteristic can be obtained, but the output is then too low to operate a relay satisfactorily on 20 volts.

18. In an attempt to obtain suitable overall characteristics, many different types of auxiliary circuits were investigated for use with this basic circuit, but none were satisfactory. The best of these circuits employed a thyratron tube in lieu of an ultra-sensitive relay, which was triggered by the output of the magnetically-controlled diode impressed on the grid of the thyratron. This circuit worked satisfactorily at a given terminal voltage, but changes in voltage changed the firing point of the thyratron much more than could be tolerated. Unless further research should indicate a means of obtaining a sharper tube characteristic, the use of a magnetically controlled diode as the controlling element in a reverse-current cutout is not deemed practical at such low voltages because of the extreme accuracy required in the construction of such tubes. These tubes do, however, offer possibilities at higher voltages. It is recognized that some of the same difficulties will be encountered at high voltages as at lower voltages, such as the effect of resistance in the plate circuit tending to decrease the apparent steepness of the tube characteristic. Tube output, however, will be greater than at low voltages, and gas discharge tubes can be used to regulate the voltage in a manner which is not possible on the low-voltage system. It is also possible that further research might produce a tube with a steeper characteristic, possibly by the addition of a suitable grid.

MAGNETICALLY CONTROLLED THYRATRON REVERSE-CURRENT CUTOUT

19. The circuit shown in Figure 6 was also tried, utilizing the magnetic control of a thyratron tube whose action may be explained by Figure 7. With zero magnetic field applied, the thyratron will fire and current OA will flow (limited by its plate resistance). As the magnetic field is increased, the plate current decreases slowly to point C beyond

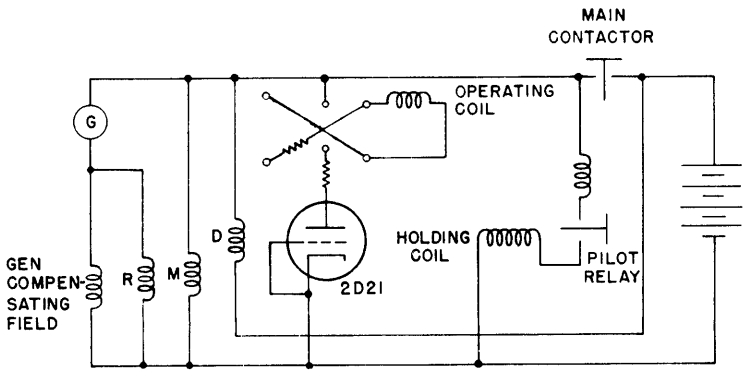

Fig. 6 - Circuit Characteristic of Magnetically - Controlled Thyratron Reverse Current Cutout

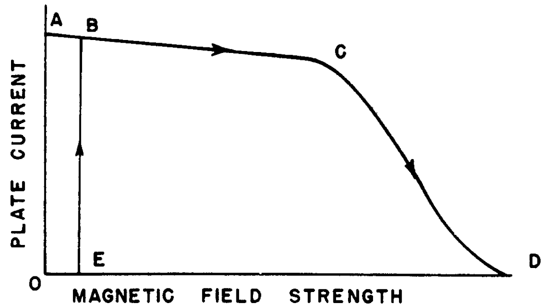

Fig. 7 - Circuit Characteristic of Magnetically-Controlled Thyratron Reverse Current Cutout

which the tube begins to cut off. In general, the curve between C and D is not very steep. With the tube cut off at point D, it will not fire again until the field strength is reduced below OE, at which the plate current increases immediately to value EB. It is the portion EB of this tube characteristic which was used in the circuit shown in Figure 6.

20. In the initial condition, the main contactor would be open and the double-pole double-throw switch would be thrown to the right-hand position. Coils R, M, and D are wound around the 2D21 thyratron tube. Coil M would produce a flux greater than OE of Figure 7. As the generator voltage increases, the flux from coil D, which is proportional to the differential voltage between generator and battery, opposes the flux from coil M until the tube fires, thus operating the pilot relay and the main contactor. The holding coil on the pilot relay would keep it closed, regardless of subsequent action by the thyratron. When the main contactor closes, it mechanically throws the double-pole double-throw switch to the left-hand position and, in so doing, momentarily interrupts the plate circuit of the thyratron causing it to be extinguished. The tube does not fire again in the new position, since coil D has been short-circuited by the closing of the main contacts. The switch remains in this position until reverse-current flowing through the generator field produces a flux through coil R that causes the tube to fire again. Due to the reversing connection on the double-pole double-throw switch, the flux produced by the operating coil would oppose that of the holding coil allowing the pilot relay and the main contactor to open. A resistance is inserted in one leg of the reversing-switch connections to limit the current through the operating coil to a value just sufficient to overcome the holding coil, but not enough to close the pilot relay with reversed flux. When the main contactor opens, it returns the double-pole double-throw switch to the right-hand position, momentarily interrupting the plate circuit of the thyratron and allowing it to be extinguished, thus returning the circuit to its original condition and completing the cycle.

21. All the elements of this circuit worked perfectly, except that point E in Figure 7 varied with the temperature of the tube over a considerable range. Thus, as the tube warmed up, point E shifted steadily toward the left until stable conditions were obtained in the tube. This warm-up time was too great to be tolerated in a device of this kind; furthermore, it would be affected by ambient temperatures.

PERMANENT MAGNET THYRATRON REVERSE-CURRENT CUTOUT.

22. The most promising idea for a reverse-current cutout that has been investigated to date is embodied in Figure 8. It consists, essentially, of two units.

A. The main contactor with auxiliary contacts comprising a triple-pole double-throw switch.

B. The control element which consists of:

1) a small balanced permanent magnet mounted on pivots and free to rotate between two contacts without any restraining springs of any kind and actuated by three coils (differential, reverse, and residual) all wound on the same magnetic core between whose poles the permanent magnet is free to rotate,

2) a 2D21 thyratron tube and associated current regulator for its heater,

3) a pilot relay having an operating coil, a holding coil, and a safety coil, and

4) a small insensitive polarized relay in the differential coil circuit.

These two components do not need to be located in physical proximity with each other. Figure 8 shows the schematic electric circuit, and Figure 9 shows the same circuit with the elements grouped according to their physical location.

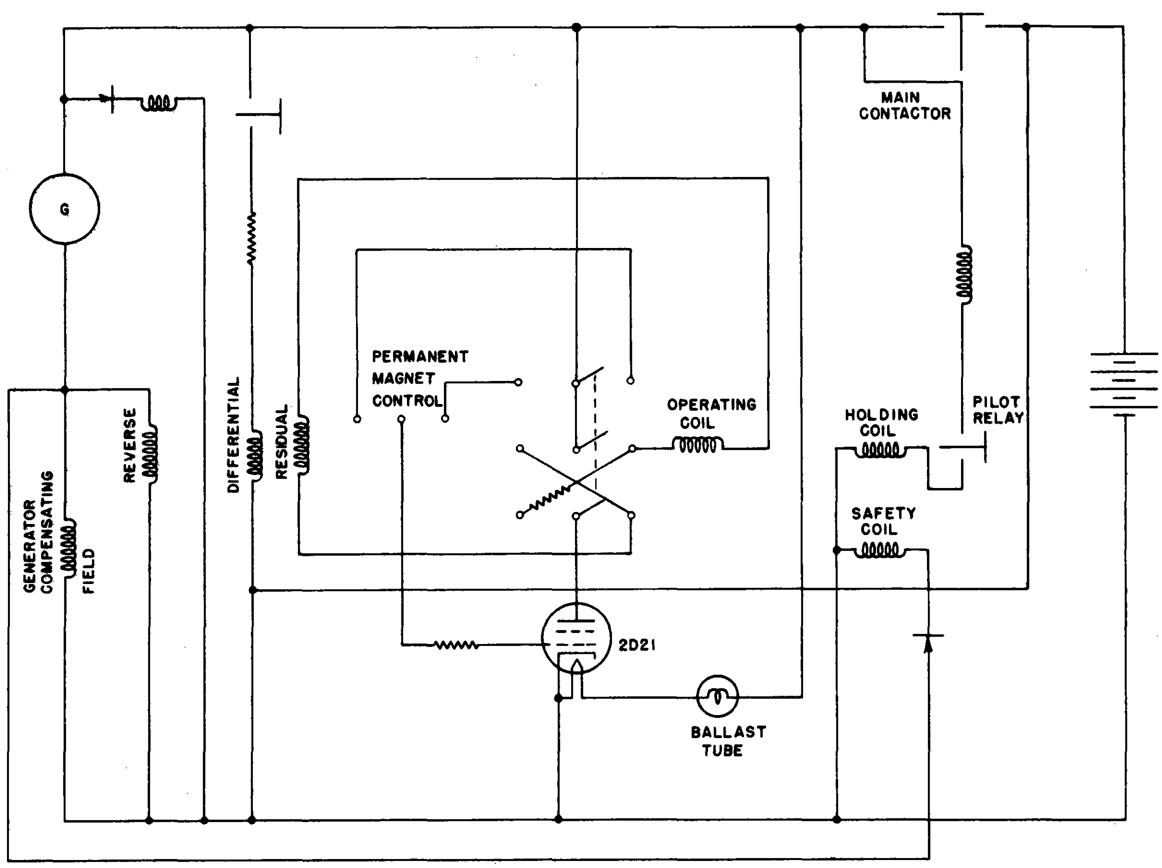

Fig. 8 - Circuit Diagram for Permanent Magnet-Thyratron Reverse Current Cutout

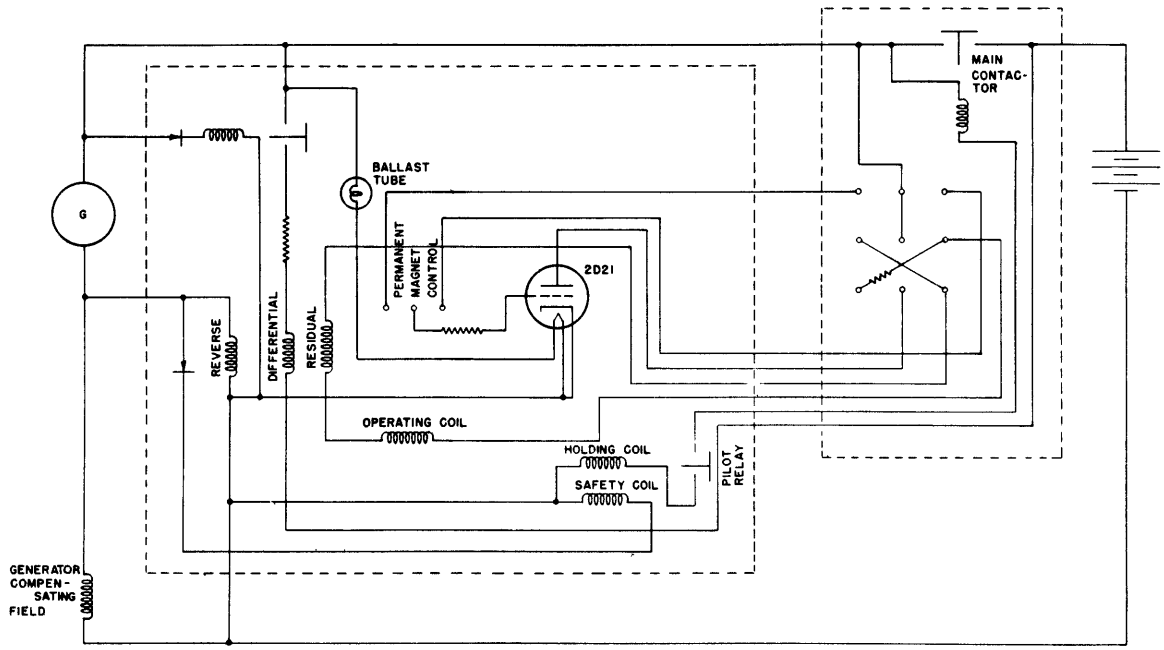

Fig. 9 - Circuit Diagram for Permanent Magnet-Thyratron, Reverse Current Cutout (Components Grouped According to Physical Location)

23. To explain its operation, assume that the main contactor is open and the generator voltage is zero. In this condition, since the relay in the differential circuit is open, there is no connection either across the battery or between the generator and battery, and no stand-by power is consumed. The triple-pole double-throw switch is in the right-hand position as shown, and the permanent magnet control element is also in the right-hand position. When the generator voltage increases to approximately 17 volts, the auxiliary relay in the differential circuit closes, thus making the cutout operative. This relay should be polarized to prevent closing if the generator voltage builds up in the wrong direction and could be accomplished very simply by use of a series rectifier in its operating coil circuit. Since the battery voltage, however, is still higher than the generator voltage, current will flow through the differential coil in the reverse direction and hold the permanent magnet in the original position, and the cutout will not close. As the generator voltage rises, it reaches a value 0.2 volt higher than the battery voltage, at which time the flux from the differential coil is sufficient to overcome the residual flux in the magnetic core. This causes the permanent magnet to rotate and make instantaneous contact with the left-hand contact. This contact does not need to be continuous; therefore, no contact springs are required and the mechanical force developed between the permanent magnet and the operating coil can be very small. This instantaneous contact impresses the full positive voltage on the grid of the thyratron tube, through a suitable limiting resistor, and causes the tube to fire continuously regardless of the grid voltage. The plate current of this tube passing through the operating coil of the pilot relay causes it to close, and this relay is subsequently held closed by means of the holding coil wound on the same relay core. This causes the main contactor to close. When the main contactor closes, it mechanically throws the triple-pole double-throw switch to the left-hand position and, in passing from one position to the other, instantaneously opens the plate circuit of the thyratron tube extinguishing it, but the pilot relay and main contactor remain closed. The permanent magnet is now in the left-hand position and is held there by the action of the reverse coil (as long as the current flows from the generator to the battery) and also the residual magnetism of the core.

24. Assume that conditions in the circuit now change so that the generator voltage is less than the battery voltage, causing reverse current to flow from the battery to the generator. This causes a voltage drop across the generator series field which is proportional to the line current. This voltage is impressed on the reverse coil and, at its operating point, is sufficient to overcome the residual magnetism of the core, causing the permanent magnet to move to the right-hand position. This impresses a positive voltage on the grid of the thyratron causing it to fire. This time, however, the current passes through the operating coil in the opposite direction and overcomes the holding coil, allowing the pilot relay and main contactor to open. The current through the operating coil of the pilot relay is limited by a suitable resistor to preclude the possibility of the pilot relay being closed by current in this direction. In other words, the current through the operating coil is just sufficient to overcome the holding coil, but not sufficient to close the relay. As the main contactor opens, it returns the triple-pole double-throw switch to the right-hand position and the cycle can be repeated.

25. The residual coil is inserted in the plate circuit of the tube to insure uniform operation of the control element, regardless of the magnetic history of the core. Its design is not critical but should be sufficient to carry the flux density well above saturation, with the operating coil of the pilot relay, the residual coil and the limiting resistor (for reverse-current conditions) all included in the plate circuit of the tube. By insuring that the flux density in the core exceeds its saturation value on each operation of the cutout, the core will follow substantially the same hysteresis loop and the cutout will operate at the same value each time. In addition, a high value of residual flux is guaranteed to prevent operation under conditions of vibration. It will be necessary to include a ballast lamp in series with the heater of the thyratron tube so as to insure operation of the tube without injury under the wide variations of terminal voltage encountered. In addition, a third coil should be wound on the pilot relay and connected in series with a rectifier (probably germanium crystal) across the generator series field, and designed to open the pilot relay for large reverse-currents. It should be designed with a time constant large enough so that the pilot relay will always have sufficient time to open, regardless of the steepness of the surge characteristic, before a coil current is reached sufficient to hold the relay closed. This coil normally would not operate the relay, but is merely included as a safety device in the event that the thyratron tube burned out while the main contacts were closed. It would insure that the cutout "fail-safe."

26. A cutout based on this principle would be practically independent of temperature, altitude, and voltage (from 20 to 30 volts) and, since it operates on a very small number of ampere-turns, the coils can be designed for a 5000 percent overload and still be relatively small, thus overcoming the problem outlined in paragraph 5. Also, since the voltage drop across the series fields of all generators is approximately the same, regardless of rating, for the equalizer connection to the voltage regulator, the same cutout could be used on any system regardless of generator rating. With suitable modifications in design, the same principle could be used on higher voltage d-c systems. Furthermore, the components may be located remotely for convenience, accessibility, etc., it merely being necessary to connect the contactor and control element by means of a suitable cable, and it would lend itself to an installation wherein the control element is made in a hermetically sealed, plug-in type unit which could be removed and a new one installed quickly in case of failure. The cutout can be made small and light since it operates on a pulse technique and, thus, the operating coil on the pilot relay, the residual coil on the control element and the thyratron tube can be overloaded instantaneously. Furthermore, the holding coil on the pilot relay, although designed for continuous operation, only operates when the relay is closed under conditions of zero airgap and would thus be smaller than the conventional relay. The power loss in the cutout would be low since no additional shunts or other devices are required in the power circuit, and the only appreciable power input would be that to the heater of the thyratron tube. Since there are no springs or mechanical restraining torques on the control element

and no contact springs (instantaneous contact only needed), it can be made quick-acting and the permenent magnet will never be subjected to surges in the reverse direction that might reverse its polarity. Provided the surge did not build up faster than the magnet could move, the magnet would never be subject to reverse polarity, since it always lines up mechanically with the existing field. If the control element magnet is made sufficiently light and friction-free, this reverse polarity would not be a problem since, the faster the surge increased, the greater the mechanical force and the quicker the element would move. It should be pointed out that such a cutout would not give positive protection to a fault which occurred at every point in the system. This is a function of the circuit breaker. This cutout, however, would perform its required function of protecting the generator from large reverse currents.

27. In the design of the cutout, certain points should be kept in mind. The control element should be hermetically sealed to prevent interference by dust and moisture and prevent "adjustment" by poorly trained technicians. If the cover were made of iron or steel, it would also serve as a magnetic shield to prevent interference by any stray fields that might be present. If sealed in a dry atmosphere, it would prevent interference by frost or ice on the operation of the control element. The permanent magnet should be balanced and mounted so that vibration, shock, position, or physical changes in dimensions due to extremes of temperature would not affect its operation. It should also be as small and light as practical in order to be quick-acting. Should future investigations indicate adverse reactions due to transients on the system, the speed of response can be easily decreased by placing a short-circuited copper slug around the magnetic core of the control element. Additional investigations should be made concerning the best construction for the pilot element with regard to physical dimensions, airgap length, type of core material, type of permanent magnet material, etc. The core material should have a relatively high residual magnetism to insure stability under generator no-load conditions by developing sufficient force to hold the permanent magnet stationary under conditions of vibration, and also have a low coercive force so that a small applied signal, of the proper polarity, will operate the cutout. It is suggested that possibly use of some of the newer magnetic materials having "square" hysteresis loops might be advantageous. The permanent magnet should be constructed of a material having a high coercive force and should be made as light and small as possible.

28. An experimental model was constructed using a relatively large airgap, an Alnico permanent magnet and a core of laminated Allegheny Ludlum 4750 steel. This model operated quite satisfactorily on eleven ampere-turns and had a sufficiently large restraining torque due to residual magnetism. It was quite satisfactory in size and weight, even with the 50-1 and 20-1 ratios built into the differential and reverse coils, respectively, to overcome the problem outlined in paragraph 5. It is believed, however, that further research could improve these characteristics still more.

29. The general appearance of the experimental model is shown in Figures 10, 11, and 12. Figure 10 shows the main contactor, which is a standard 300-ampere aircraft contactor equipped with three single-pole double-throw micro-switches in lieu of auxiliary contacts constructed as part of the contactor. Figure 11 shows the various components of the control unit. These components were not designed for size, weight, or compactness, or for considerations of vibration, shock, hermetic sealing, etc., all of which should be taken into account on a practical working model. These two units are shown connected together in Figure 12. The principal dimensions and type of construction used in the control element of the experimental model are given in Figure 13. This type of construction might need alterations in a practical model designed to take the above-enumerated factors into consideration.

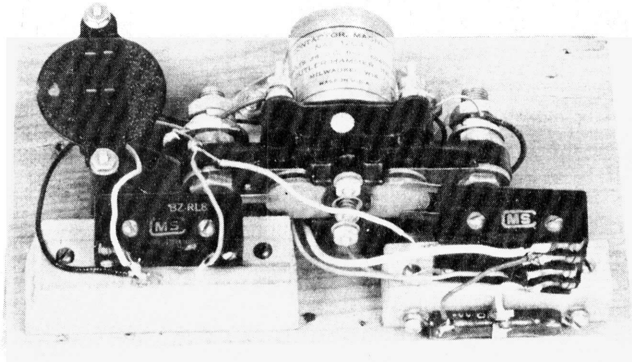

Fig. 10 - Photograph of Main Contactor Unit of Experimental Model of Permanent Magnet - Thyratron Reverse-Current Cutout.

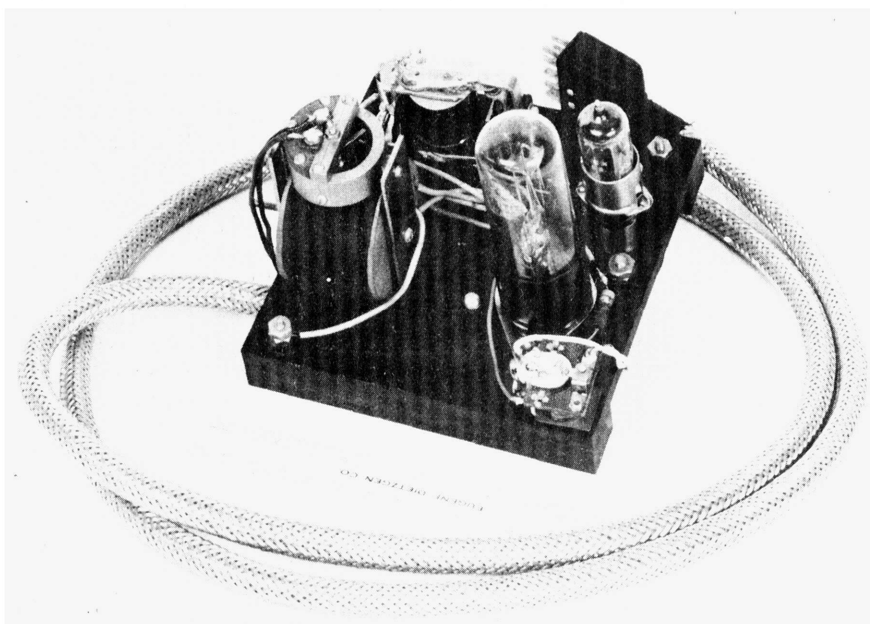

Fig. 11 - Photograph of Control Unit of Experimental Model of Permanent Magnet - Thyratron Reverse-Current Cutout.

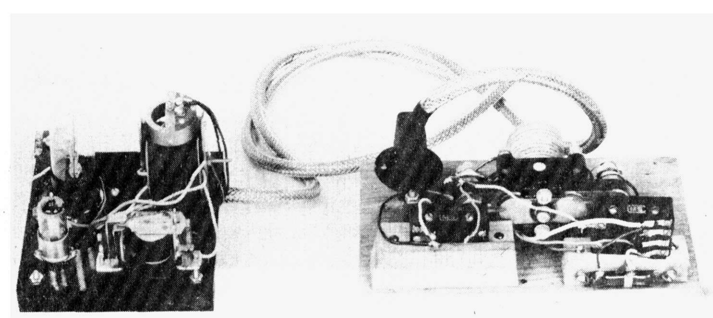

Fig. 12 - Photograph of Complete Assembly of Experimental Model of Permanent Magnet - Thyratron Reverse-Current Cutout.

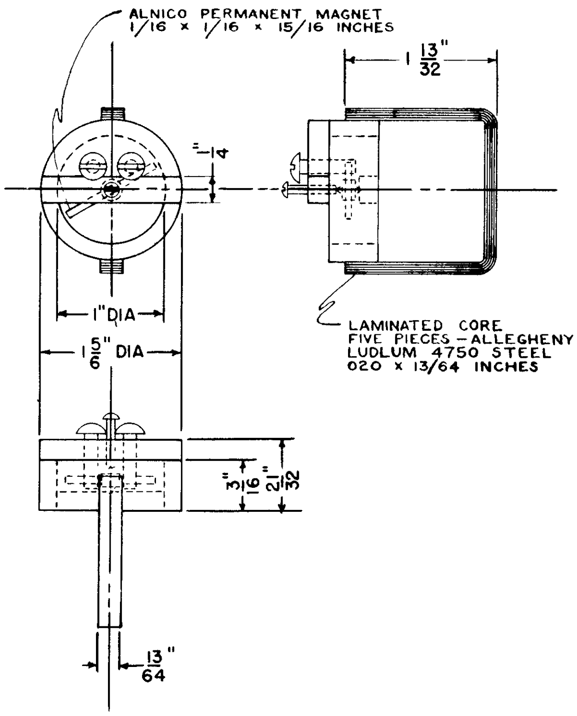

Fig. 13 - Control Element of Permanent Magnet, Thyratron Reverse Current Cutout

RESULTS AND CONCLUSIONS

30. For satisfactory operation, the reverse-current cutout must operate on the differential voltage of the proper polarity between the generator and battery. Any cutout operating on absolute values of either generator or battery voltage will chatter under certain conditions of operation.

31. The control element of the reverse-current cutout must operate satisfactorily on an extremely small applied signal, in order that the weight and size be kept to a minimum. This is caused by the necessity of the device to operate on a very small percentage of the voltage it may be required to stand (in the reverse direction) continuously. The only alternative is to discover a satisfactory ideal rectifier or current-limiting device which is not affected by ambient temperature, and which should be instantaneous in response to an applied voltage. No such device is known at present.

32. Nonlinear circuit elements have, in general, a limited application to a device of this nature and are not directly applicable without auxiliary compensation, due to their wide variations in characteristics under different ambient temperatures.

33. Thermally operated circuit components have, in general, only limited use for an application of this kind because of the thermal lag usually inherent in such components and because of the effects of ambient temperature.

34. Thyratrons can be made to operate satisfactorily on the voltage available, but their firing characteristics change with the plate voltage. Also, their application to this problem must take into consideration the fact that the grid loses control after the tube fires.

35. Electronic tubes are limited in their application because of their low power output at the low voltage available. Thus, in order to obtain a reasonable output from the tube, most of the 20 volts available for operation must occur across the tube leaving only a few volts drop across any output device. Furthermore, in general, the output of the vacuum tube varies with the plate voltage. Due to this fact and also the nature of this particular problem, wherein the signal voltage to be used as the controlling voltage (differential voltage between generator and battery) is, of necessity, in the vicinity of the plate voltage rather than that of the cathode since the main contactor must be placed in the positive lead of the generator, the grid-controlled vacuum tube is not directly applicable as a control element.

36. The magnetically controlled diode is not practical at such low voltages unless either a tube with a much steeper plate-current versus magnetic field-strength characteristic can be manufactured or a more dependable ultra-sensitive low-resistance relay can be produced. Such a tube does, however, offer possibilities if operated on a higher voltage system.

37. The most practical cutout devised to date, to operate under the variety of conditions outlined above, is the type explained in paragraphs 22 - 29 inclusive. In preliminary tests, an experimental model has operated quite satisfactorily, but a commercial model designed for actual use should be developed and tested.

RECOMMENDATIONS

38. A cutout based on the principles and circuit outlined in paragraphs 22 - 29 inclusive, should be considered for development by the Bureau of Aeronautics.

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