

A  
DIRECT CURRENT  
DIFFERENTIAL RELAY

by  
Roger Loren Parsons

A Thesis Submitted to the Graduate Committee  
in  
Partial Fulfillment of the Requirements  
For the Degree  
of  
MASTER OF SCIENCE  
in  
ELECTRICAL ENGINEERING

Approved:

---

Thesis Adviser

---

Head of Department

---

Dean of Engineering

---

Chairman, Graduate Committee

Virginia Polytechnic Institute  
1948

### ACKNOWLEDGEMENTS

The writer wishes to express his gratitude to Professor George C. Barnes, Jr., who suggested the subject of this paper. He also wishes to acknowledge his debt to Professor W.A. Murray, for his encouragement, and to Professor Paul Mann for his many helpful suggestions. Finally, he wishes to thank G.S. Briney, R.P. Hensley, S.D. Hathaway, J.J. Stone, and M. Surface, who were of assistance to him in many ways.

## TABLE OF CONTENTS

	Page
Acknowledgements . . . . .	i
I. Introduction . . . . .	1
The Problem . . . . .	1
The Solution . . . . .	2
II. The Investigation . . . . .	6
Preliminary Considerations . . . . .	6
Construction of the Relay . . . . .	9
Testing and Results . . . . .	14
III. Discussion, Criticism, and Application . . . . .	24
Suggested Commercial Design . . . . .	24
Use of the Relay . . . . .	26
A Specific Application of the Relay . . . . .	26
IV. Conclusion . . . . .	31
V. Summary . . . . .	32
Appendix I: Sources . . . . .	34

### Figures and Tables

Figure 1 Preliminary Sketches . . . . .	5
Figure 2 Relay Construction . . . . .	11
Figure 3 Relay Construction . . . . .	12
Figure 4 Completed Relay . . . . .	13
Figure 5 Circuit Diagrams . . . . .	18
Figure 6 Calibrating Curve . . . . .	20
Figure 7 Relay Operating Characteristics . . . . .	22
Figure 8 Proposed Commercial Design . . . . .	27
Figure 9 Relay Application . . . . .	29
Table I Uncorrected and Calibrating Data . . . . .	19
Table II Corrected Data . . . . .	21

## I INTRODUCTION

### The Problem

In a grounded direct current system, internal motor faults present a special problem. A fault may occur which is of such nature that it will not be detected by ordinary protective devices but will nevertheless result in poor motor operation or in the creation of an unsafe condition. Consider, for example, a direct current shunt motor with grounded frame operating in a distribution system which has its negative side grounded. If the winding insulation close to the negative side of the shunt field should fail, the shunt field would be connected to ground, and hence to the negative side of the system, at this point. This would have the same result as reducing the number of shunt field turns, and would have an effect on the operation of the motor. Yet, such a fault would not cause an appreciable change in the amount of current supplied to the motor and would not result in the opening of a circuit breaker. There is, therefore, a need for a device capable of detecting faults of the type just described.

Before considering a device for detecting the fault, it is necessary to determine the symptoms of the fault. The following is at once apparent. If within a motor there is a fault connection to the grounded frame, this provides an additional return path for the current which is supplied to the motor, and consequently there will be more current in one of the supplying leads than in the other. To illustrate, if a current of 50 amperes flows to a direct current motor through the

positive conductor, and if within the machine 5 amperes flow to ground and back to the negative side of the system, there will be only 45 amperes in the return conductor. That is, the result of this type fault is a difference of current in the two supplying conductors.

Therefore, if a relay can be constructed which is able to detect a difference in the currents flowing in the two conductors which supply a direct current motor, it will indicate a fault of the sort under consideration. In short, then, the problem is to devise a direct current differential relay.

#### The Solution

A fundamental relation in the theory of magnetic fields is one known as Ampere's Circuital Law. It is expressed by the following equation:

$$\oint H \cos \angle \frac{dl}{H} = 4 \pi I \text{ . } ^1$$

In words the equation simply states that the magnetomotive force acting about any closed path in a magnetic field is equal to the product of  $4 \pi$  and the net current encircled by the path.

This fact is of significance in the designing of a direct current differential relay. If there is equal, (but, of course, opposite), current in the two leads supplying a direct current motor, the magnetomotive force about a closed loop around the two leads will be equal to

---

<sup>1</sup>William H. Timbie and Vannevar Bush. Principles of Electrical Engineering. New York: John Wiley & Sons, Inc., Third edition. p. 351

zero. If, however, there is a difference in the current in the two leads, a closed loop about them will enclose a net current and there will be a magnetomotive force about the loop.

Another fundamental relation in the theory of magnetic fields is expressed by this equation:

$$F = \frac{B^2 A}{8 \pi \mu} \quad 2$$

The equation has this meaning. The force of attraction between two plane surfaces of magnetic material, which are parallel to one another and which are separated from one another by a short air gap through which magnetic lines of force pass at right angles to the plane surfaces, is directly proportional to the square of the flux density, (B), in the air gap and to the area, (A), of the surfaces. (The symbol  $\mu$  represents the permeability of air in the system of units employed.) This is also of significance in the designing of a differential relay when it is considered together with Ampere's Circuital Law.

Let there be placed about the two conductors which supply a direct current motor a magnetic circuit such as sketched in Figure 1a. The entire magnetic circuit, with the exception of the two air gaps, is made of some magnetic material. The strip which forms the top of the magnetic circuit is carefully balanced on a knife edge as shown. When there is a difference of current in the two supplying leads, a magnetomotive force will act about the magnetic circuit. This magnetomotive

---

<sup>2</sup>ibid. p. 400

force will set up magnetic lines of force, and as a result there will be a force of attraction between the movable and fixed parts of the magnetic circuit. If the movable member is sufficiently well balanced, the force of attraction will cause it to move down against the fixed member.

Therefore, a device such as pictured in Figure 1a will indicate a current differential by the movement of a balanced member. If the device be provided with contacts, the result will be a direct current differential relay.

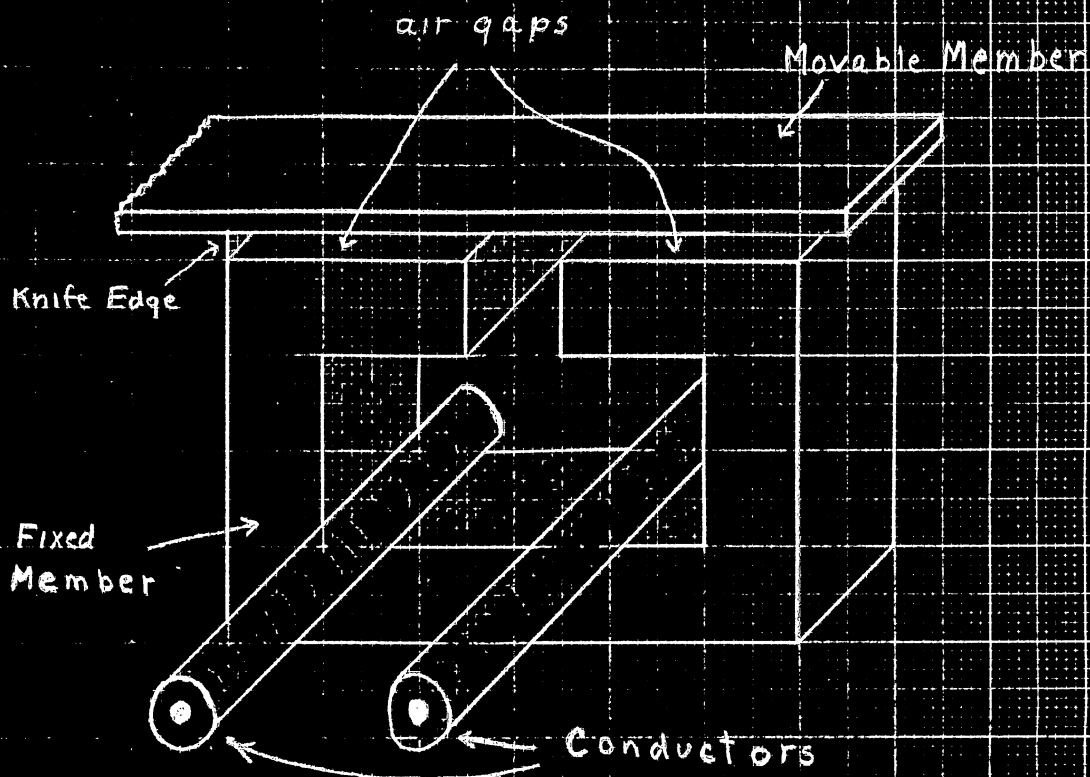
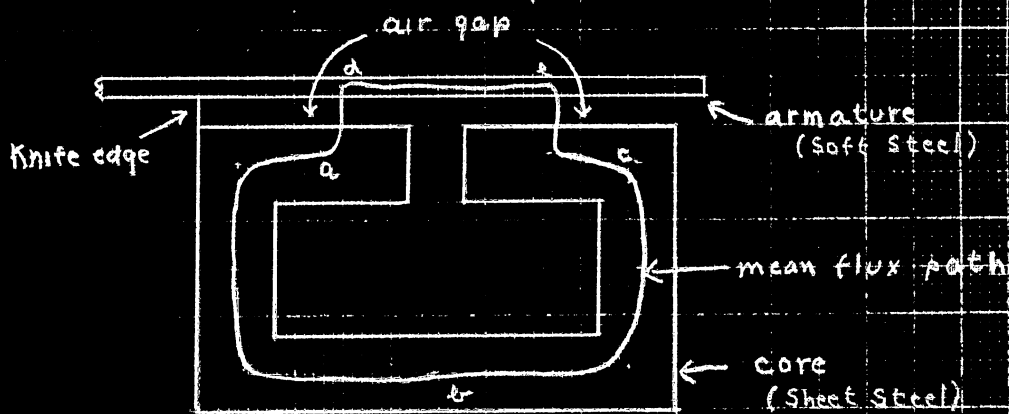


Fig. 1a



Dimensions

path in core,  $l_c$ , =  $a - b - c \approx 10$  in.

area of core,  $A_c$ ,  $\approx 2$  sq. in.

path in armature,  $l_a$ , =  $d - e \approx 2$  in.

area of armature,  $A_a$ ,  $\approx .07$  sq. in.

total length of air gap,  $l_{ag}$ , =  $a - d + e - c \approx .05$  in.

area of air gap,  $A_{ag}$ ,  $\approx 3$  sq. in.

Fig. 1b

## II THE INVESTIGATION

### Preliminary Considerations

In the preceding section, the essential components of a direct current differential relay have been mentioned. There must be a magnetic circuit composed of two parts. One of these parts, a fixed member, will hereafter be referred to as the core of the relay; the other, a movable member, will hereafter be referred to as the armature of the relay. The core of the relay must be so constructed that two supplying conductors may be passed through it. The armature of the relay must be carefully balanced on a knife edge so that it can move under the action of small forces. Finally, the relay must be provided with contacts.

Preliminary calculations, (the nature of which will be indicated shortly), showed that the amount of force between the armature and core of the relay would be very small. Therefore, the first step in constructing the relay was to find something of which the core might be made, and to calculate the force of attraction between an armature and this core for an arbitrarily specified current differential.

A burned out shell type transformer, which had been part of the power supply of a radio, was available. Although this core had three legs, the center leg could be removed which would leave space to pass two conductors through the relay. To get attraction between armature and core, flux has to pass between the two; that is, the magnetic circuit has to be completed through the armature. Therefore, a slot

would have to be cut through the core, and the logical place for it would be in the center of the largest exterior surface of the core, perpendicular to the long dimension. The result of these changes would be the core pictured in Figure 1b. The force of attraction that would be developed between the armature and one of the attracting areas of the core was then determined by calculations based on the dimensions of the proposed core and assumptions concerning the length of the air gap and the size of the armature. This information is given on Figure 1b. The calculations follow.

1. Assumed current differential - 10 amperes

$$mmf = 4 \pi I$$

where mmf is in gilberts

when I is in abamperes.

Since 1 abampere = 10 amperes

and 1 ampere turn, (NI), =  $.4 \pi$  gilberts

$$mmf = 4 \pi \frac{10}{10} = 4 \pi \text{ gilberts} = 10 \text{ ampere turns}$$

2. Refer to Figure 1b.

Length of mean magnetic path in core,  $(l_c)$ , = 10 inches

Area of magnetic path in core,  $(A_c)$ , = 2 square inches

Length of mean magnetic path in armature,  $(l_a)$ , = 2 inches

Area of magnetic path in armature,  $(A_a)$ , = .07 square inch

Length of air gap,  $(l_{ag})$ , = .05 inch

Area of air gap,  $(A_{ag})$ , = 3 square inches

3. Assume a flux,  $(\phi)$ , of 650 lines

$$\text{Flux density, (B), in core} = \frac{\Phi}{A_c} = \frac{650}{2} = 325 \text{ lines/square inch}$$

Field Intensity, (H), in core  $\approx 0$  NI/inch  
 (from B-H curve for annealed sheet steel) <sup>3</sup>

$$\text{NI in core} = \text{NI/inch} \times l_c \approx 0 \times 10 \approx 0 \text{ NI}$$

$$\text{Flux density in armature} = \frac{\Phi}{A_a} = \frac{650}{.07} = 9300 \text{ lines/square inch}$$

Field Intensity in armature = 3.2 NI/inch  
 (from B-H curve for soft steel) <sup>4</sup>

$$\text{NI in armature} = \text{NI/inch} \times l_a = (3.2)(2) = 6.4 \text{ NI}$$

$$\text{Flux density in air gap} = \frac{\Phi}{A_{ag}} = \frac{650}{3} = 217 \text{ lines/square inch}$$

(neglecting fringing)

$$\text{NI in air gap} = .313 B_{ag} l_{ag} = (.313)(217)(.05) = 3.4 \text{ NI}^5$$

4. Then  $\text{NI}_{\text{Total}} = \text{NI}_c + \text{NI}_a + \text{NI}_{ag} = 0 + 6.4 + 3.4 = 9.8$

This closely checks the NI available, (10), so  $\Phi = 650$  is a close approximation.

5. Then force of attraction is given by

$$F = \frac{B^2 A}{8 \pi \mu}$$

<sup>3</sup>ibid. p. 138

<sup>4</sup>ibid. p. 138

<sup>5</sup>ibid. p. 147

when B = flux density in air gap in lines/square cm.

A = area of air gap in square cm.

= permeability of air in c.g.s. system = 1

then F = force of attraction in dynes

$$F = \frac{\left[ \frac{217}{(2.54)^2} \right]^2 \left[ 3 \times (2.54)^2 \right]}{(8 \pi) (1)} = 883 \text{ dynes}$$

Since 1 dyne =  $(2.248 \times 10^{-6})$  (16) ounces

$$F = (883)(2.248 \times 10^{-6}) (16) = .0314 \text{ ounces}$$

So for a current differential of 10 amperes, the amount of force between one of the attracting areas of the available core and the armature would be approximately .03 ounces. This small force points out the necessity for a carefully balanced armature. Although the force was very small, it was considered sufficiently large for successful operation of the relay, so materials for the remaining parts of the device were located. These materials were: a sheet of soft steel for the armature; four transformer laminations for knife edge, stops and supports; a sheet of stiff fiber for the supporting brackets for the fixed contact; and assorted nuts, bolts, and washers for the contacts and for use in assembling the relay.

#### Construction of the Relay

The core for the relay was constructed from the available transformer core. To make the transformer core stronger so that it would stand up under the work that would be done on it, an additional hole was drilled through each outer leg through which bolts were placed.

Then the middle leg of the transformer was removed, and a quarter inch slot was milled in the face of the transformer which had the largest surface area. The two attracting areas were smoothed by filing. The resulting core is shown in Figure 2a.

A transformer lamination was used for the knife edge. Segments were cut out of the lamination and holes were drilled in it as shown in Figure 2b. Then the lamination was bent at right angles on the lines marked on Figure 2b, and the knife edge was mounted on the core as shown in Figure 2b.

The armature of the relay was cut from a sheet of soft steel. Its length is roughly twice that of the core, while its width is approximately equal to that of the core. The movable contact was mounted on that end of the armature which is not to be attracted to the core. The armature is shown in Figure 2c.

To help keep the armature balanced, two stops were fashioned from transformer laminations. They are shown in Figure 2d. They were attached to the core in such a position that when the armature is balanced on the knife edge, it just rests on the stops as indicated in Figure 2d.

Two brackets were made from fiber for the purpose of supporting the fixed contact. They are shown, together with the way in which they are attached to the core, in Figure 3a and Figure 3b. The fixed contact was mounted on a cross piece which was made of a transformer lamination that was drilled, bent, and attached to the brackets as shown in Figure 3c. The dimensions of the brackets, the core, and the armature

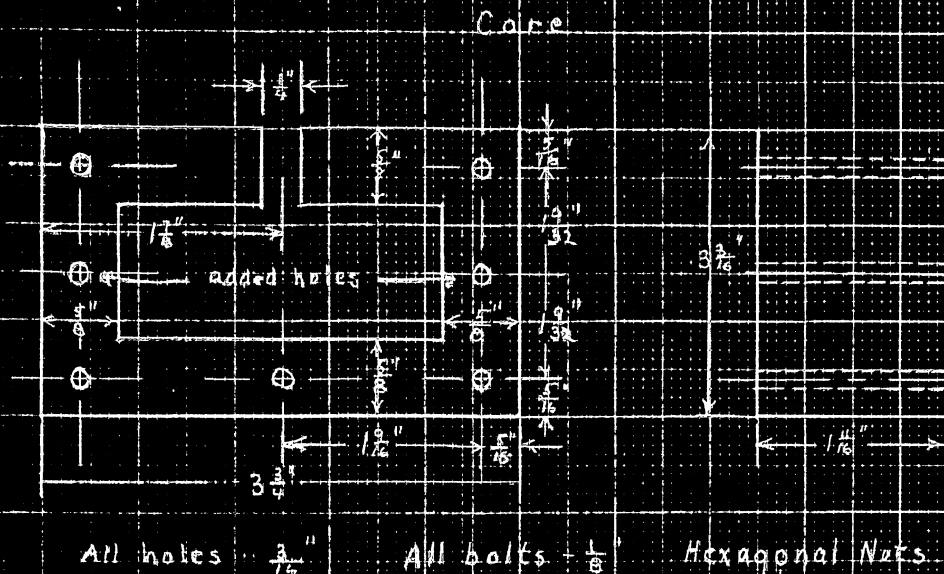


Fig 2a

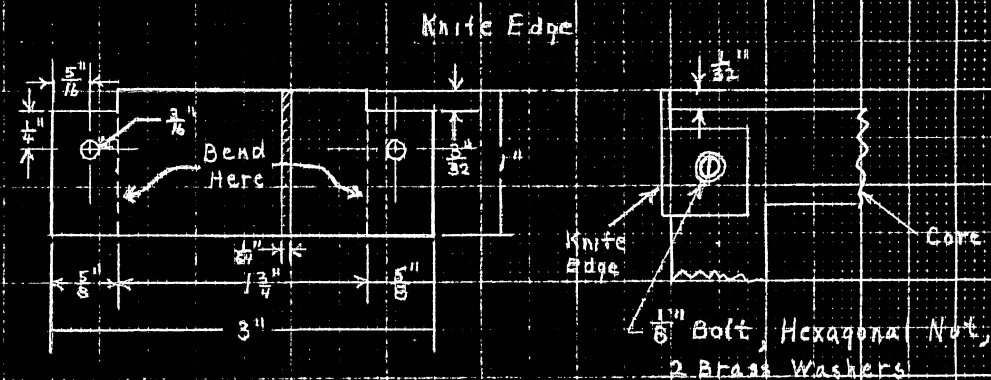


Fig. 2 b

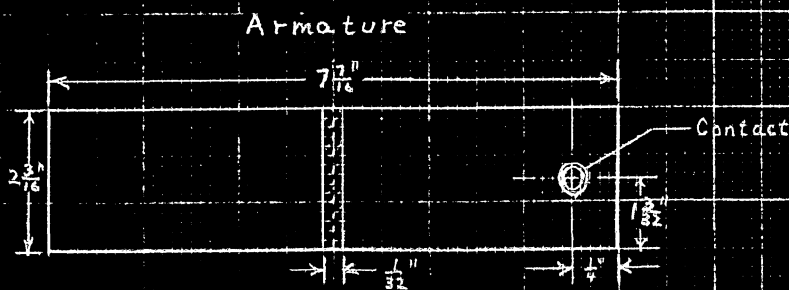


Fig. 2c

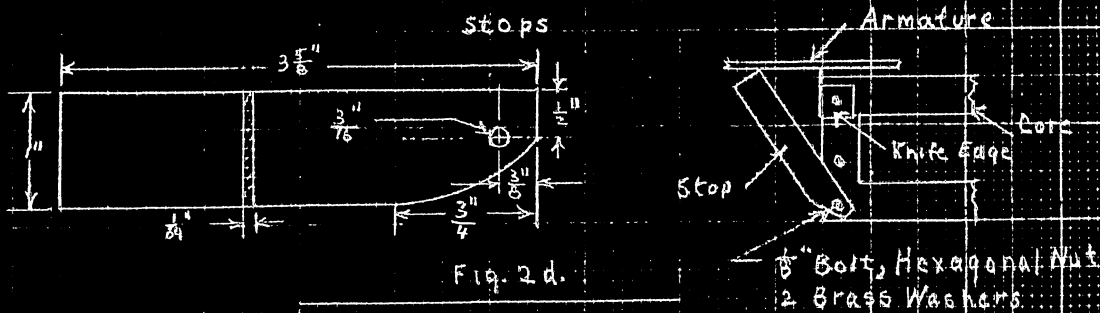


Fig. 2 d.

### Bracket

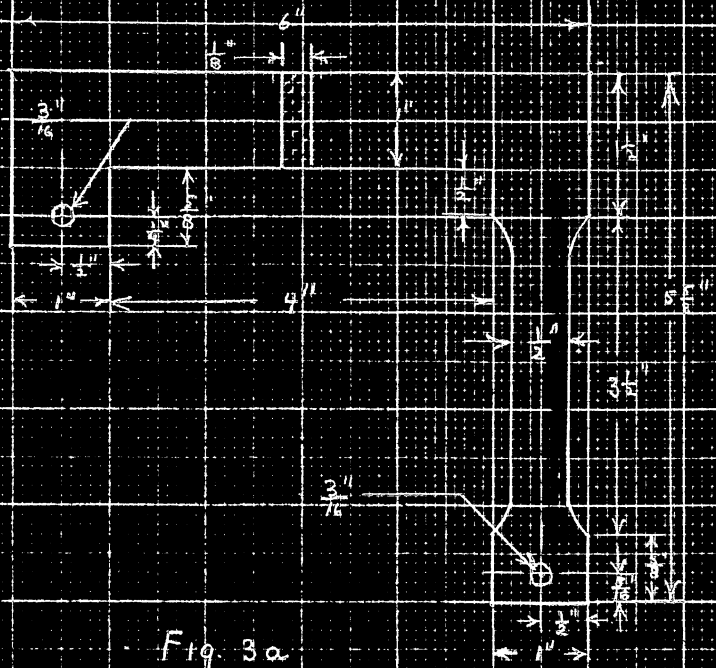


Fig. 3a

### Bracket

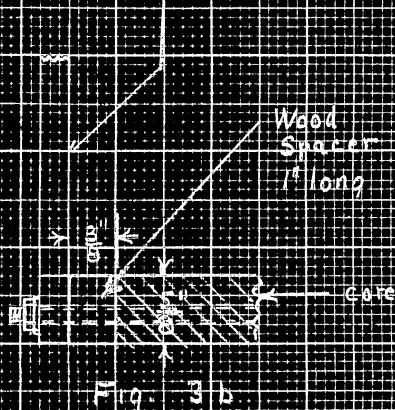


Fig. 3b

### Crosspiece

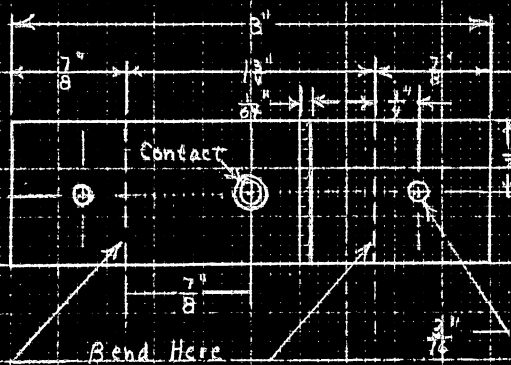
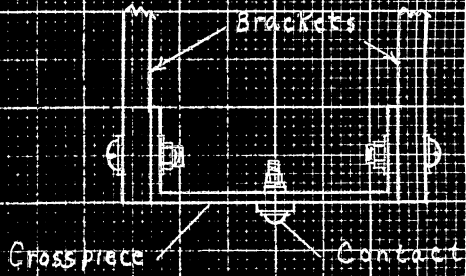
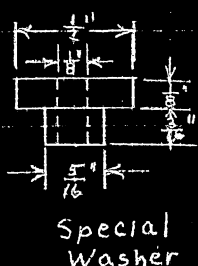


Fig. 3c



### Contacts



Special Washer

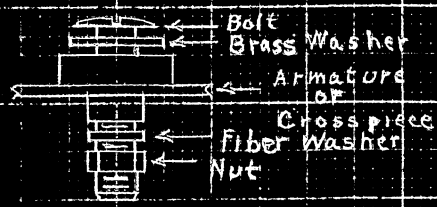
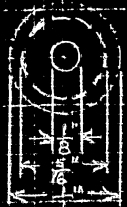


Fig. 3d

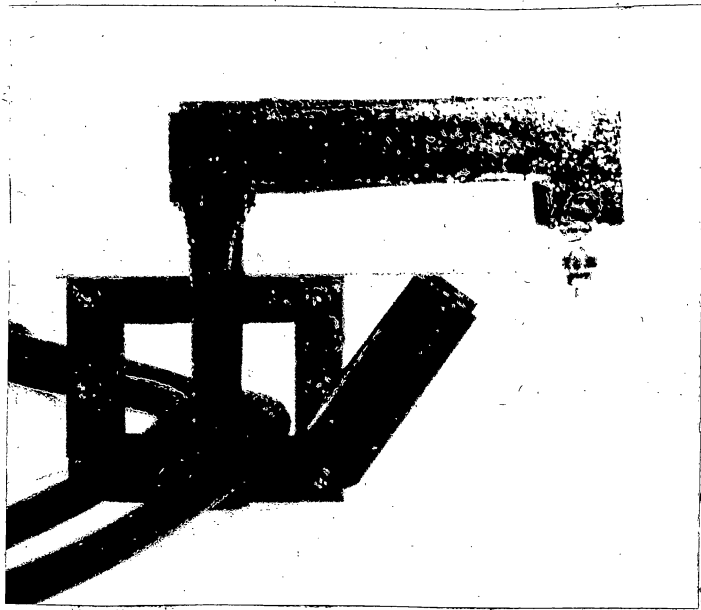
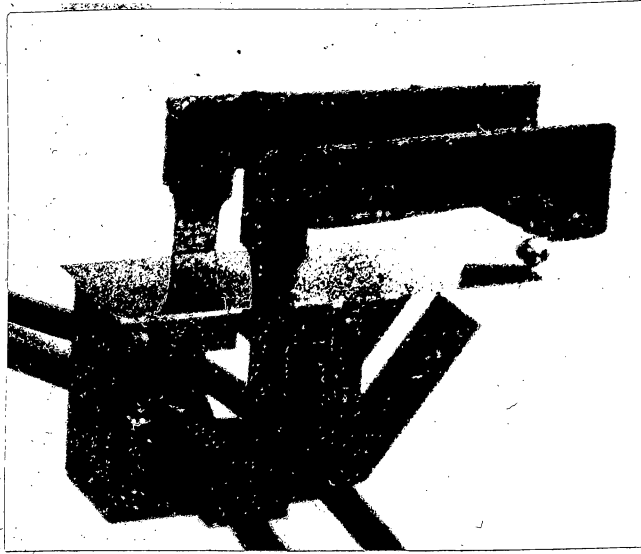


Fig. 4

are such that when the armature is balanced, the fixed contact is directly above the movable contact, and separated from it by such a distance that the two contacts will touch one another when the armature moves down against the core.

The contacts were made in this way. A hole was drilled through the armature and through the cross piece on the brackets. A special fiber washer such as shown in Figure 3d was placed in each hole. The holes were drilled of such size that the washers had to be forced into them. Then a brass washer was placed on what was to be the contact side of the special washer, and a fiber washer was placed on the other side. The whole was fastened together by a nut and bolt, with the bolt head on the contact side. The slot in the bolt head was filled with solder and thus formed the contact. This type of construction insulates the contacts from the rest of the relay. The contacts are as shown in Figure 3d.

Two photographs of the completed relay are shown in Figure 4.

#### Testing and Results

The following test was run on the relay. The circuit shown in Figure 5a was set up and the following procedure was followed. First the armature of the relay was carefully balanced. Then with  $R_2$  open,  $R_1$  was adjusted until a small value of current flowed. Notice that if  $R_2$  is open, the current flowing in one lead through the relay will be equal and opposite to that flowing in the other lead. Thus the magnetomotive force about the two leads will be zero and the relay will not

operate. Then  $R_2$  was decreased from its open circuit value. If this is done, the current in the two leads passing through the relay will no longer be the same, and a magnetomotive force will exist about the two leads.  $R_2$  was slowly decreased until the relay operated, at which point both ammeters were read. The actual difference in these two currents represents the current differential for which the relay will operate.

Then  $R_2$  was slowly increased, thus reducing the difference between the currents in the two leads passing through the relay. When the point was reached where the relay released, both ammeters were read again. The actual difference in these currents represents the value to which the current differential must be reduced for the relay to release after it has once operated.

This procedure was repeated for increasing values of total current and the results of this test are tabulated in Table I, A.

Now, the significant data which is to be obtained from the test just described are the current differentials for which the relay will operate and release. In order that these differentials be determined accurately, the following was done. The circuit shown in Figure 5b was set up. The resistance  $R_L$  was adjusted so the current in the circuit varied through the same range as in the preceding test. At regular current intervals both ammeters were read. The data obtained is tabulated in Table I, B. From this data a curve of readings of Ammeter "1" against readings of Ammeter "2" was plotted. This is the curve of Figure 6.

The curve was used in this way. Each reading of Ammeter "1" in the relay test was converted by means of the curve to that value which Ammeter "2" would have read had it been located in the position of "1". The difference between the corrected reading of Ammeter "1" and the reading of Ammeter "2" is the true current differential for which the relay will either operate or release. This data is tabulated in Table II.

The curve of Figure 7 is obtained from the data of Table II. The two current differentials, that for operating the relay and that for releasing the relay, are shown as functions of the total current supplied to the load. The information presented on this curve is that which defines the operating characteristics of the relay. Two facts may be determined from this curve. First: the relay will operate when the current differential becomes as large as approximately one and one-half amperes, and will release again when the differential is reduced to approximately four-tenths amperes. Second: the current differential at which the relay will operate or release is independent of the magnitude of the total current involved. (Although there is some point to point variation in the differentials, this variation is slight and does not indicate any definite trend. Since the current differentials are very small in comparison with the total current involved, the small variations can easily result from slight inaccuracies in reading meters and in converting one ammeter to the standard of the other.)

These results agree with what was expected. Although preliminary calculations demonstrated that the forces involved in the operation of

the relay are very small, they will be sufficient if the armature is well balanced. The fact is, of course, that if an armature were balanced more carefully than was the armature employed, operation could be achieved for smaller current differentials than those required for this relay. The fact that the current differentials did not change with the amount of total current involved is perfectly logical also.

For a given relay, the force which operates the relay depends upon the flux density which in turn depends upon the amount of magnetomotive force available. Since the magnetomotive force is a direct function of the net current encircled by the relay, a current of 52 amperes in one lead and 50 in the other will produce the same force as would a current of 22 amperes in one lead and 20 in the other.

In testing the relay two other facts were noticed which are of importance. The first of these is this. If as the result of some fault there is a large difference in the two currents which pass through the relay, it will remain partially magnetized after the differential disappears. If the metal used in the relay has a high residual magnetism, the result may be that the relay will not release after a large current differential has occurred. Demagnetization of the core and armature will be necessary before the relay can be used again. This means that the materials out of which a relay is to be constructed should be chosen with this consideration in mind. Investigation of the current differentials which will cause relays of different materials to require demagnetization for further operation would be a necessary preliminary to commercial production of the relay.

### Circuit for Testing Relay

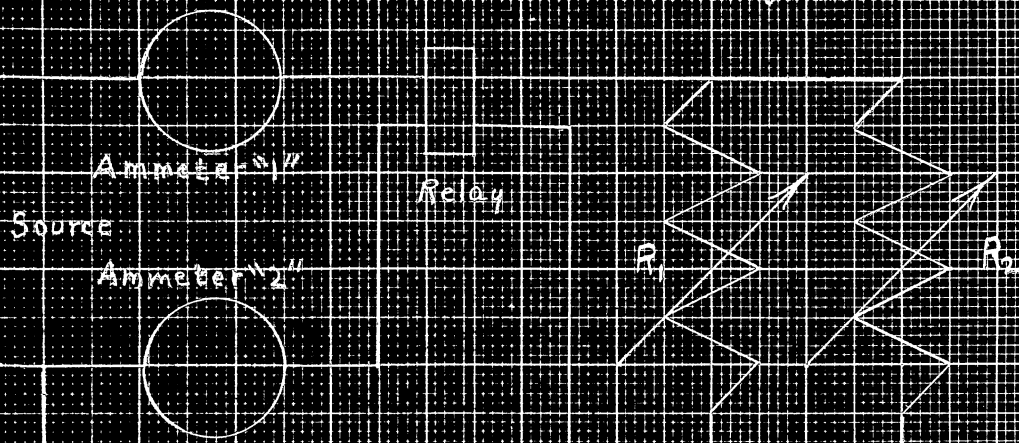


Fig. 5a

### Circuit for Calibration

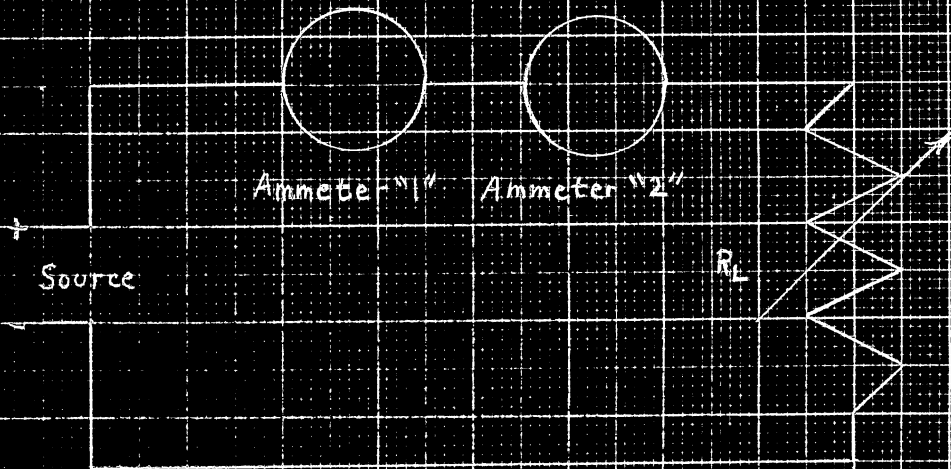


Fig. 5b

TABLE I

A

Uncorrected Data: Results of Test of Figure 5a

Operation		Release	
Ammeter "1"	Ammeter "2"	Ammeter "1"	Ammeter "2"
Amperes	Amperes	Amperes	Amperes
6.5	5.0	5.4	5.0
11.5	9.7	10.1	9.6
16.1	14.3	14.5	14.2
21.4	19.0	20.0	19.0
26.4	24.0	25.0	23.8
31.3	28.7	32.2	29.1
36.0	33.7	35.2	34.0
42.0	39.1	41.1	39.4
44.5	42.0	43.7	42.1
48.7	46.1	48.0	46.5

B

Calibrating Data: Results of Test of Figure 5b

Ammeter "1"	Ammeter "2"
Amperes	Amperes
5.2	5.2
10.3	10.0
15.0	14.7
20.1	19.5
25.0	24.2
30.0	29.0
35.0	34.0
40.9	39.3
45.9	44.5
48.7	47.6

### Calibrating Curve

Readings of Ammeter "1"  
plotted as a function of  
Readings of Ammeter "2"  
(See Fig. 5a and Fig. 5b)

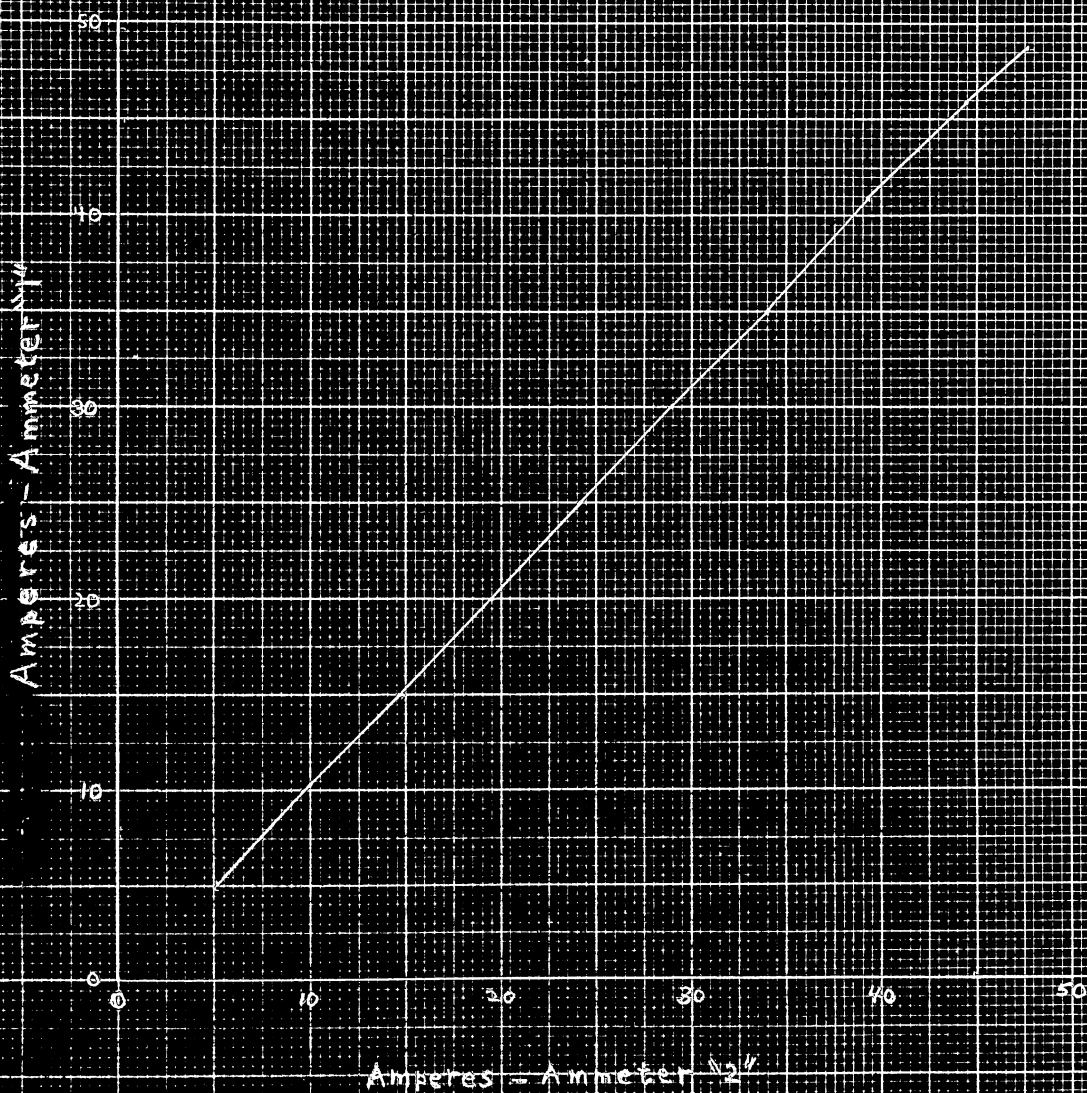


Fig. 6

TABLE II

Corrected Data for Test of Figure 5a

Operation		
Corrected Readings of Ammeter "1"	Ammeter "2"	Differential
Amperes	Amperes	Amperes
6.4	5.0	1.4
11.2	9.7	1.5
15.7	14.3	1.4
20.8	17.0	1.8 ?
25.5	24.0	1.5
30.3	28.7	1.6
35.0	33.7	1.3
40.5	39.1	1.4
43.1	42.0	1.1 ?
47.6	46.1	1.5

Release		
Ammeter "1"	Ammeter "2"	Differential
Amperes	Amperes	Amperes
5.4	5.0	0.4
9.8	9.6	0.3
14.2	14.2	0.0 *
19.5	19.0	0.5
24.2	23.8	0.4
31.2	29.1	2.1 *
34.3	34.0	0.3
39.6	39.6	0.2 ?
42.4	42.4	0.3
46.9	46.9	0.4

\* in error

? doubtful

# Operating Characteristics of a Direct Current Differential Relay

Operating and Releasing Current Differentials  
plotted as functions of  
Total Supply Current

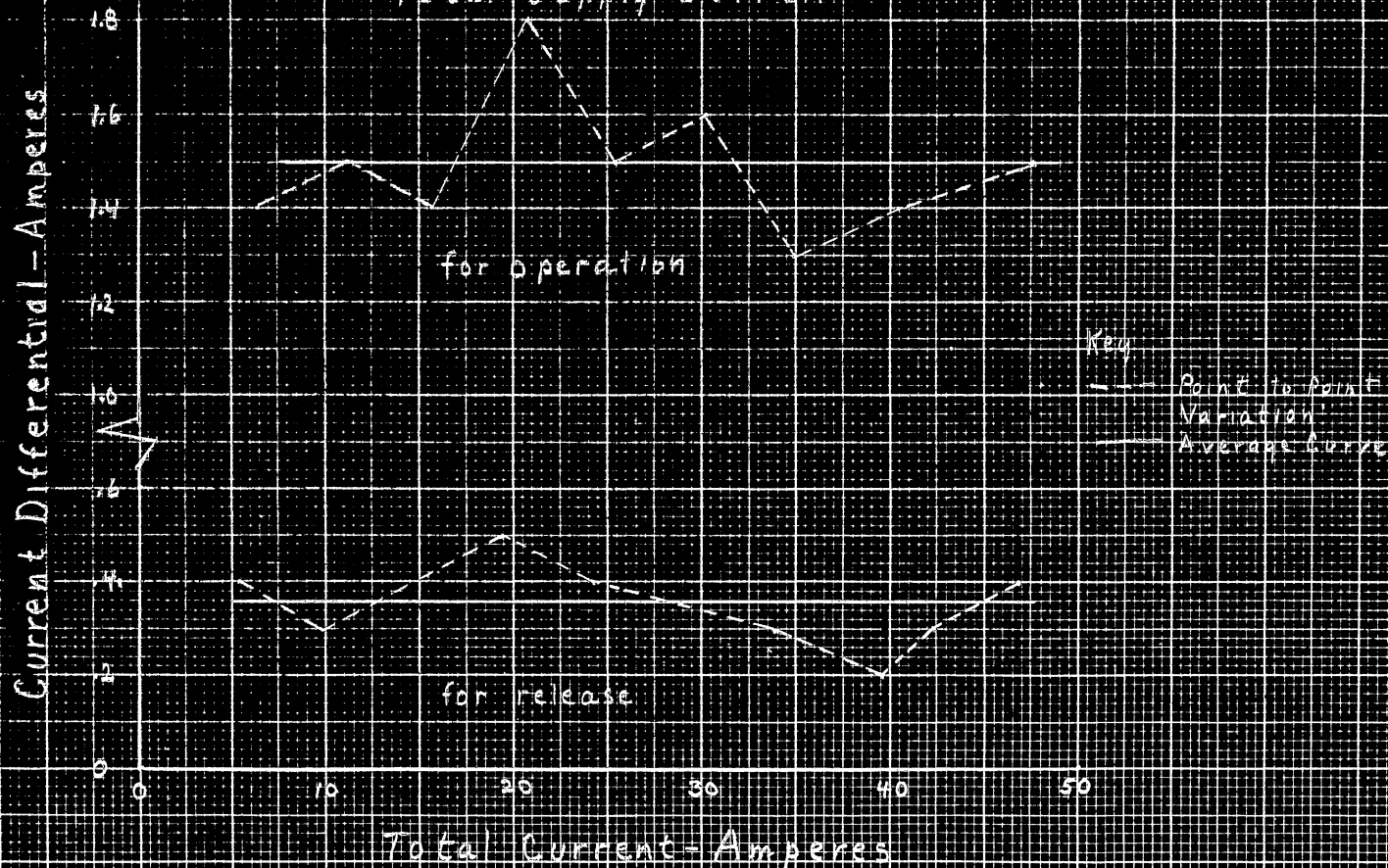


Fig. 7

The second fact is this. Since the armature has a certain mass, the speed at which the relay operates depends upon the forces acting upon the armature. Therefore, the smaller the current differential, the smaller the force, and the slower will be the operation of the relay. If to speed up the operation of the relay, the armature were made smaller, thus reducing its cross sectional area, there is this to consider. An examination of the preliminary calculations will show that reducing the cross sectional area of the armature will reduce the amount of flux and the amount of force which operates the relay. Of course, a fault which would cause only a very slight differential in current would not be of such nature that a lag of even one second in the operation of the relay would be crucial. Also, a fault requiring faster operation would be characterized by a greater current differential which would automatically produce faster operation. However, investigation of the proper size of the armature for quickest possible relay operation would also be a necessary preliminary to commercial production.

### III DISCUSSION, CRITICISM, AND APPLICATION

#### Suggested Commercial Design

The results obtained from the direct current differential relay which was constructed as a test model indicate that a commercial relay of this type could be built which would be of practical use. That is, if a model made by an unskilled workman from materials chosen largely because of availability is responsive to a current differential and one and one-half amperes, it should be possible to make a relay responsive to current differentials of well under one-half ampere if the best of materials and precision workmanship are available. However, there is at least one serious disadvantage in the general design of the test relay which must be overcome in a practical model.

The disadvantage is this. If the relay is to operate successfully, the armature must be very carefully balanced. On the test relay this balance was achieved by resting the armature on a knife edge. Needless to say, a slight jolt would upset the balance of the armature. But in any industrial application for which the relay might be used, a certain amount of vibration and jarring is inevitable. This consideration alone would rule out the test model as a practical device unless certain modifications were made. In addition to this, there are certain other features which would be desirable on a practical model that can be more conveniently provided on a relay of slightly different design.

These features are the following. First, it is generally pre-

ferable to have the contacts of a relay mounted so that the separation between them is a vertical one. If this is done, much less dust and dirt will collect on the contacts than will if the separation between contacts is horizontal as is the case on the test relay. Also, the flexibility of the relay would be increased if it were possible to adjust it for operation at various current differentials. Although this could be done on the test model by means of a spring connected between the brackets and the armature, such adjustment can be more conveniently accomplished on the model which will be described presently. Finally, as mentioned in the section which preceded this, it would be desirable to reduce the mass of the armature of the relay without reducing the force which operates it a corresponding amount, thereby increasing the speed at which the relay will operate. A commercial relay should provide all these features in addition to having its armature mounted in such a way that vibrations and jarring will not affect the operation of the relay.

All these things are possible if the relay is constructed as shown in Figure 8. Here the core is of circular form with a circular gap cut in it. Located in this gap is a metal vane, the armature of the relay, which is mounted on a shaft supported in jewelled bearings. The vane is held in a position slightly off the vertical by means of a spiral spring. An arm is mounted on the shaft which supports the armature, and on the end of this arm is the movable contact. The fixed contact is so mounted that the movable contact will move against it when the armature rotates.

The operation of the relay is exactly like that of the test model. The two leads which supply power to a motor are passed through the relay core. When a current differential exists the vane will rotate in a clockwise direction thus bringing fixed and movable contacts together. In this relay, however, the armature is delicately, yet solidly, balanced, the separation between contacts is vertical, by adjusting the tension of the spring the differential current for which the relay will operate can be varied, and the armature can be made light without reducing the operating force to the extent that would be done on the test model. Finally the core of this relay can be hinged in such a way that the relay could be installed by simply clamping it around the two conductors which supply power to the device to be protected.

#### Use of the Relay

In practical applications, the direct current differential relay would be used in conjunction with another relay and a circuit breaker. The core of the second relay would be energized through the contacts of the differential relay, and the circuit breaker would be tripped by this second relay. The action would be this. Upon the occurrence of a current differential, the differential relay would operate. This would cause the core of the second relay to be energized and its closing would open the circuit breaker.

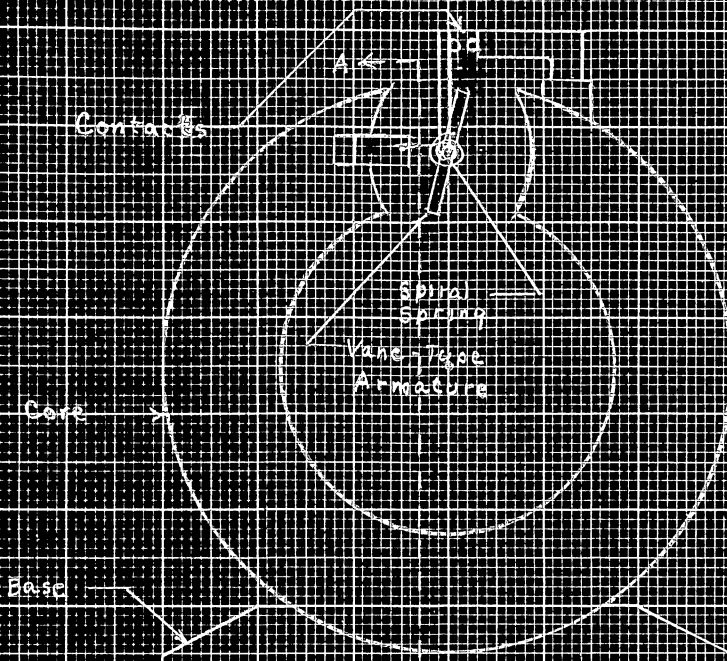
#### A Specific Application of the Relay<sup>6</sup>

As an illustration of the use of the direct current differential

---

<sup>6</sup>See Appendix I

# Proposed Commercial Design



Note: Bearings and supports for armature are not shown on this view.

## Section A-A'

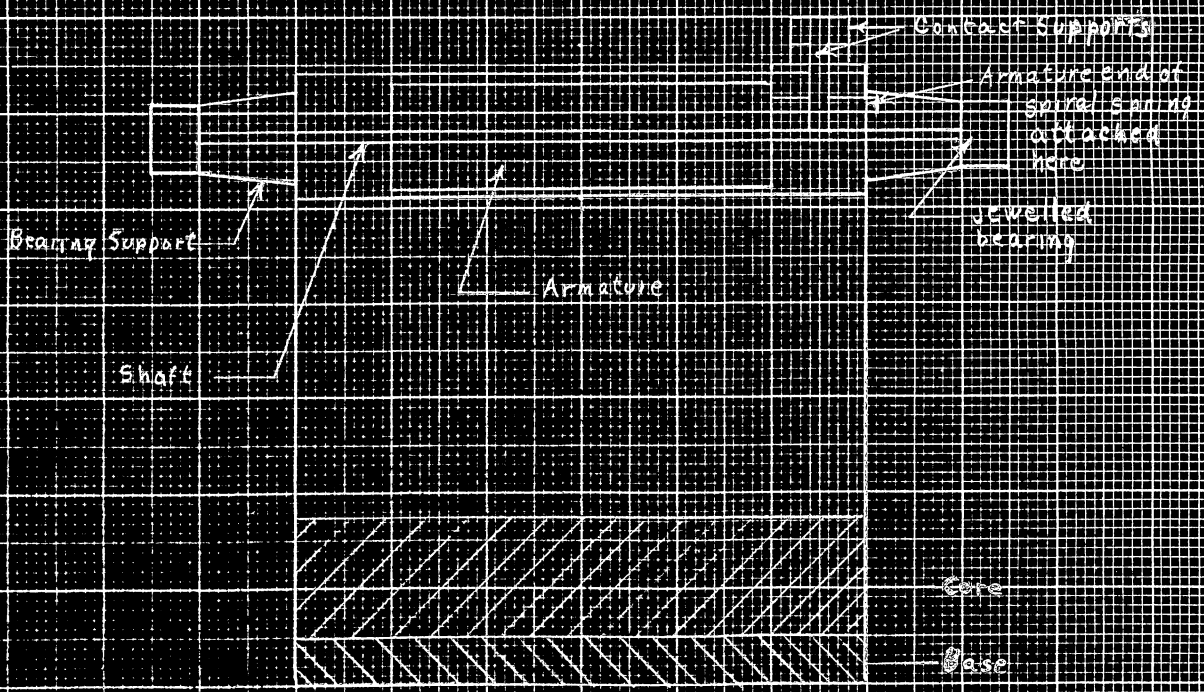


Fig. 8

relay, consider the following application. The distribution of direct current energy underground in coal mines is somewhat as indicated in Figure 9. That is, the main distribution line will run down a central passageway with an overhead trolley wire serving as the positive conductor and with a grounded rail serving as the negative conductor. Distribution to machinery in corridors where mining is being done is by means of a two conductor cable, one conductor of which is connected to the trolley wire, the other of which is connected to the rail.

Consider that insulation fails or rubs off a conductor somewhere within the motor on the piece of mining machinery. The point at which the insulation rubs off will be at something above ground potential. This point will be connected by a high resistance return through the frame of the machine, to ground, and back to the grounded rail which is the negative side of the system. The current which flows in this path is small because the path is a poor one.

But, when the insulation fails or rubs off a conductor, the frame of the machine is established at a potential above ground, which makes it possible for a workman to get shocked and perhaps injured or killed. To prevent this, present safety codes require that a third conductor be provided which will connect the frame of the machine to the grounded rail, the negative side of the system. This connection will prevent the frame of the machine from rising above ground potential and will eliminate the possibility of a workman being shocked. However, it will do something else as well. This connection changes what otherwise would be a high resistance return from fault to the negative side of

# Application of Direct Current Differential Relay

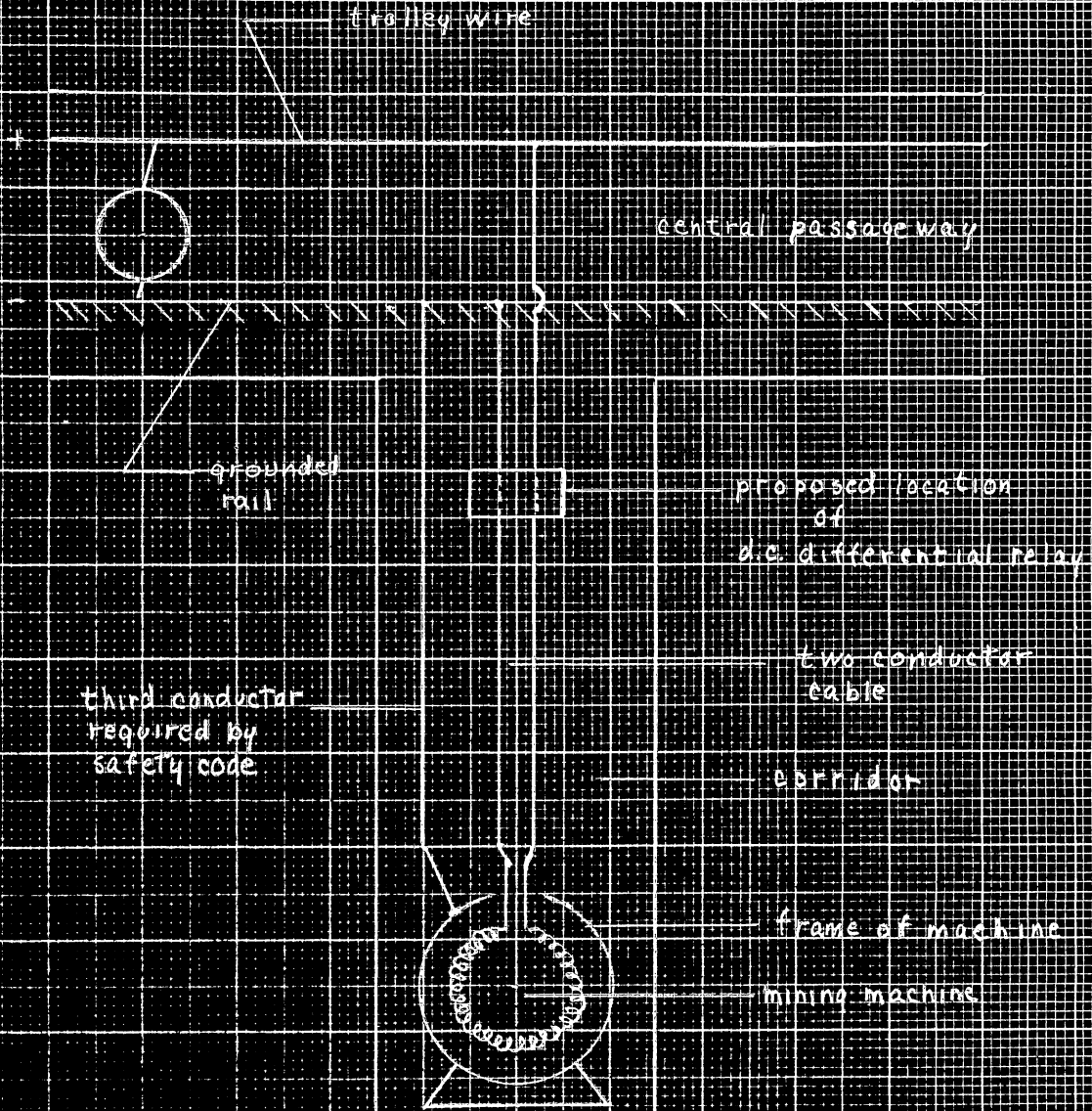


Fig. 9

the system into something close to a dead short circuit. The small current that previously flowed will become a large one, possibly large enough to cause an arc between the conductor and frame. If this arc exists for any length of time, it will burn through the frame of the machine and be exposed to the surrounding atmosphere. This could cause an explosion, in mine atmospheres.

Therefore, instead of connecting a third conductor between the frame of the machine and the grounded rail, suppose that around the two conductor cable which supplies the mining machine with power is placed a direct current differential relay. This relay will be adjusted to operate at a current differential substantially less than that current which will cause a fatality. Then if insulation weakens or rubs off a conductor and a ground current flows, there will exist a current differential through the relay. The relay will operate and, through the process described in the preceding section, the machine will be disconnected from its source of power. Thus the use of the relay prevents the possibility of a workman being shocked and does so without increasing the danger of a mine explosion.

#### IV CONCLUSIONS

Since the test model of a direct current differential relay displayed good operating characteristics, and since these characteristics can be greatly improved as a result of the further investigation and change in relay design which have been suggested in this paper, it is concluded that the direct current differential relay would be a practical device, capable of fulfilling an important control function.

## V SUMMARY

In a grounded direct current system, motor faults may occur which will not be indicated by ordinary protective devices, but which will affect motor operation or create unsafe conditions. All such faults are manifested by the fact that the current in one lead supplying the motor will be greater than that in the other.

This current differential can be made to operate a direct current differential relay. About the two supplying leads, when such a fault occurs, will exist a magnetomotive force. This mmf will set up a flux in the core and armature of a relay which forms a magnetic circuit about the supplying conductors. Since the armature of the relay is balanced on a knife edge, the force of attraction between core and armature which is caused by the flux passing from one to the other will move the armature, and in so doing close a pair of contacts.

A model relay was built which operates on this principle. Testing demonstrated that it would operate on a differential of approximately one and one-half amperes and that the relay would release when the differential was reduced to approximately four-tenths amperes. The test also showed that these differentials did not vary when the total currents involved changed.

These results indicate that a relay built with a slightly different design, (so as to overcome the shortcomings of test model, notably the insecure armature mounting, and so as to provide certain other features, such as control of the current differential for which the relay will

operate), would be responsive to current differentials of less than one-half ampere. Such a relay would be a practical device and would be capable of performing, in conjunction with a second, conventional, relay and a circuit breaker, an important control function.

## APPENDIX I: SOURCES

The following expressions,

$$H \cos \left\langle \begin{array}{l} dl \\ H \end{array} \right. dl = 4 \pi I$$

$$F = \frac{B^2 A}{8 \pi r}$$

$$NI = .313 Bl$$

which appear in this paper, may be found in any text treating magnetic fields. The writer's source was the third edition of Principles of Electrical Engineering, by Timble and Bush.

At one point in the paper reference was made to curves of flux density versus field intensity for annealed sheet steel and soft steel. These curves may be found in many texts also, but again the writer's source was Principles of Electrical Engineering, by Timble and Bush.

The information concerning the distribution of power in coal mines and the safety code requirements relating to the problem discussed in the section dealing with a specific application of the relay was obtained from Professor George C. Barnes, Jr. In fact, it was this specific problem which lead to the development of the direct current differential relay.