A STUDY OF PROTECTIVE RELAYS

by

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CONTENTS

PREFACE.

Due to the increasing demand for electrical power in most all industries in the past few years large and still larger power plants and transmission systems have been built. Interconnection of the power systems has already proven a success.

In order to keep these large transmission systems functioning properly it is necessary to have very accurate and sensitive protective devices. Many engineers fail to appreciate the great amount of scientific and technical skill used in the design of different relays, and in the operation of a relay system. The object of this paper was to study and discuss the protective relay, its operation under different conditions and the organization and operation of the relay department. It is also hoped that the paper may show the reader the great importance of the protective system. The assumption made, and the results and conclusions arrived at in this paper are not held up as being absolutely correct, but are conclusions that are made after careful study of the subject by the writer. It is thought that the wiring diagrams and relay connections are correct, as was installed by The Tennessee Electric Power Company and checked by the relay department of that company. The writer was present during the installation of part of the equipment and the diagram of connections was made at that time.

Many magazine articles were read, and other reliable sources of information freely consulted while writing this paper. Thr most important of these are listed in the bibliography.

The writer wishes to acknowledge his indebtedness to The Tennessee Electric Power Company for permission to use their transmission system as a basis of study for this paper. Also to express his deep appreciation to Mr. E. E. George and his department for the help and courtesies rendered.

THE PROTECTIVE RELAY AND ITS FUNCTIONS.

Relays are the sentinals of the electric power systems, which keep watch day and night, and are always alert to detect any abnormal condition that might occur on the system. Different relays have different duties to perform, some of them working independently, while others are coordinated together forming one large system. The function of protective relays is to disconnect the faulty equipment or line from the remainder of the system before the fault can spread, and in so doing minimize the interruptions to service and damage to the equipment. In a theoretically properly designed electric transmission system service should be maintained at all times, but practically this condition cannot be reached due to excessive cost and the natural conditions under which the system is built.

The importance of protective relays has been fully realized in the last few years, and many individuals as well as most of the large electric companies have spent much time as well as money in the study and development of protective relays. Most large companies have also created a separate department for the study, development and operation of the protective equipment, and the results can easily be seen by a study of the interruption and operation report of a large electric company over a period of several years.

There are many different kinds and types of protective devices designed to perform certain operations under certain conditions. The most elementary and perhaps the oldest protective device is the fuse. This is nothing more than a piece of wire with a smaller current capacity than the line into which it is inserted, therefore when an overload occurs this is the first part to burn out. The fuse is an excellent protective device in its place, and is still widely used, but it is not flexible enough in its performances to take care of the many complications that arise in a complicated electric transmission system. And so it is with many of the early protective devices such as trip coils, plunger relays, etc., It was to take care of these complications that the protective relay was developed. The protective relay generally operates on one of the following principles:

(1) Induction, using the same principle as the watt hour meter. The Westinghouse type CO overload and the type 1A General Electric overload relays are a good example of this principle of operation.

(2) The solenoid and plunger type. The Westinghouse type PQ relays are a good example of this principle of operation.

The modern relay muct be very accurate, sensitive and must be able to select the faulty equipment or line and separate it from the rest of the system. But the relay should be so designed that it will not operate instantaneously on a small over current or small abnormal condition such as is usually caused by synchronizing, motor starting, ~~changing~~ charging currents, etc., In fact the equipment should be kept energized until it has a chance to clear itself of the trouble, then if after sufficient time has elapsed the trouble has not cleared itself the faulty equipment should be disconnected from the line.

THE RELAY DEPARTMENT.

The satisfactory operation of the relays after they have been properly installed depends to a large extent upon the attention given to the maintainance and test of the relays. This is taken care of in large companies by the relay department. This may be a separate department, or it may be combined with some other department of the company.

The problem of relay protection is different for different companies, and the method of organization and operation is handled in various ways by the different companies. The discussion below refers primarily to the relay department of The Tennessee Electric Power Company, but excluding minor details of organization and management might be applied to the relay department of any large electric transmission company, as The Tennessee Electric Power Company is a representative company. Reports show that this system of organization and operation has proven very successful for this company.

The relay department of The Tennessee Electric Power Company is a part of the system operating and testing department. Its duties are the maintainance and testing of all

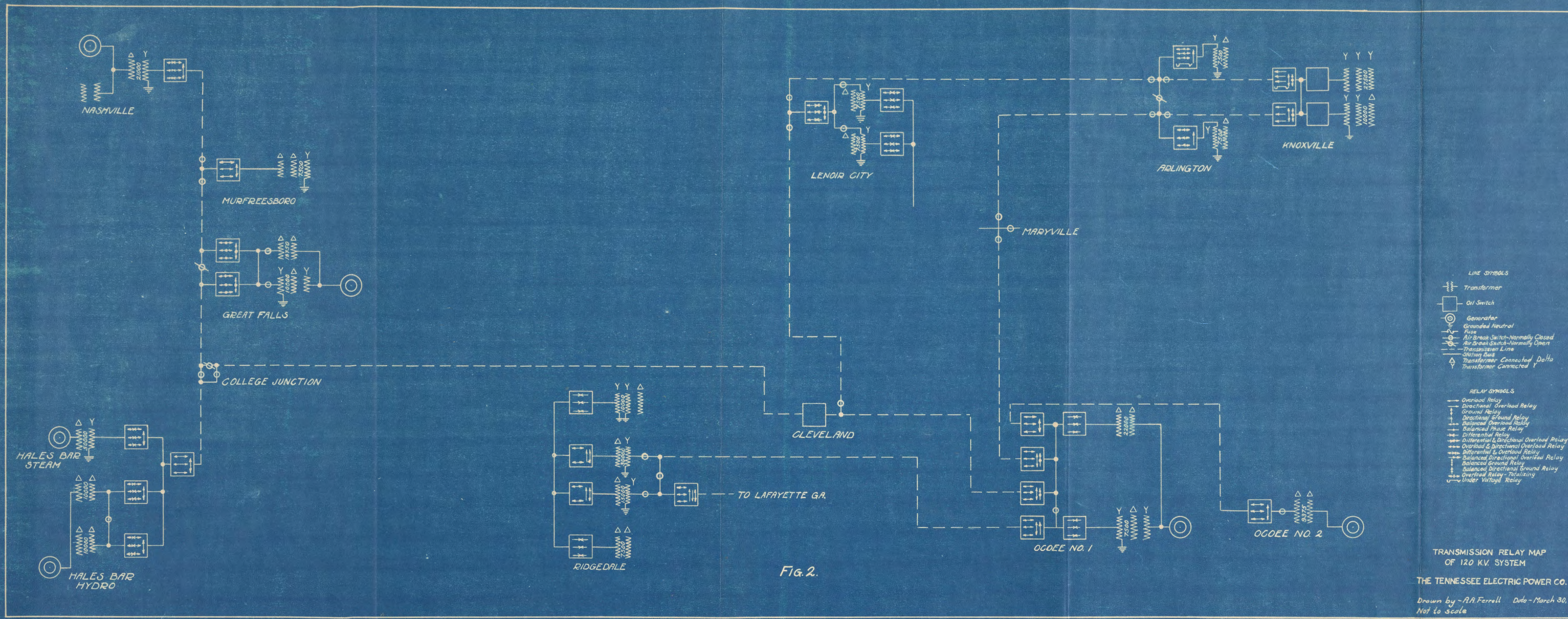

NASHVILLE
MURFREESBORO
GREAT FALLS
COLLEGE JUNCTION
HALES BAR STEAM
HALES BAR HYDRO
RIDGEDALE
TO LAFAYETTE GA.
CLEVELAND
LENOIR CITY
MARYVILLE
ARLINGTON
KNOXVILLE
OCOEE NO. 1
OCOEE NO. 2
LINE SYMBOLS
Transformer
Oil Switch
Generator
Grounded Neutral
Fuse
Air Break Switch-Normally Closed
Air Break Switch-Normally Open
Transmission Line
Station Bus
Transformer Connected Delta
Transformer Connected Y
RELAY SYMBOLS
Overload Relay
Directional Overload Relay
Ground Relay
Directional Ground Relay
Balanced Overload Relay
Balanced Phase Relay
Differential Relay
Differential & Directional Overload Relay
Overload & Directional Overload Relay
Differential & Overload Relay
Balanced Directional Overload Relay
Balanced Ground Relay
Balanced Directional Ground Relay
Overload Relay - Totalizing
Under Voltage Relay
TRANSMISSION RELAY MAP
OF 120 K.V. SYSTEM
THE TENNESSEE ELECTRIC POWER CO.
Drawn by - A.A. Ferrell Date - March 30,
Not to scale

FIG. 2.

relays and control apparatus together with the generators, transformers, oil circuit breakers, etc., The department is composed of carefully trained technical men, who not only know the details of relay testing, but also the theory and principles upon which the relays work. They also have a very thorough knowledge of the detailed operation of the transmission system.

All relays are tested every six months,and very important relays or relay systems are tested as often as it is thought necessary. When there is an indication of faulty relay operation all relays involved are tested following the trouble. Recording ammeters are installed in important neutral ground connections, which assist materially in analyzing the nature of various troubles and in explaining the relay actions. All new equipment is thoroughly tested and checked before putting in operation. All new oil circuit breakers and breakers on which the wiring has been changed are tripped by relay before they are put in operation. Important oil circuit breakers are also tripped by relay at certain intervals, if there has been no recent relay operation to test the control circuit and tripping mechanism. A ratio test is made of all current transformers before they are put in operation. The secondaries of the current transformers are carried through test terminals so that the currents may be shorted out ahead of the relays, and the relays tested without taking the line out of the operation. The line is without protection at this end while the relays are being tested, so it is very necessary that the testers be proficient and skillful in their operations, and get the relays back in operation as soon as possible.

Complete information covering the test and inspection of every relay on the system is kept on file. Fig.1. shows a sample of the relay test sheet which is filed. A monthly record is also kept of the number of relay operations and causes of operation. A monthly report is then made explaining an extraordinary or important relay operation along with the cause and an explanation of any incorrect operation or failure to operate. The report shows a very high percentage of correct operation. A part of the monthly operating report for the last six months in 1927 is given below:

CORRECT OPERATION.

Station	MONTH					
	July	Aug.	Sept.	Oct.	Nov.	Dec.
Murfreesboro		1				
Great Falls	13	9	2	4	1	2
Hales Bar Hydro		8	2	1	1	
" " Steam	17					2
Ridgedale		3	7	1	1	2
Ocoee #1		12	8		2	2
" #2			1			
Arlington	14					
Knoxville	13	7	2			
Lenoir City		9	1		1	1
Nashville Steam				1	1	3
Total Operations	57	60	24	7	7	13

Incorrect Operation

Station	July	Aug.	Sept.	Oct.	Nov.	Dec.
Murfressboro						
Great Falls				1		
Hales Bar Steam			2			
Hales Bar Hydro				1		
Ridgedale						1
Ocoee #1			1			
Ocoee #2						
Arlington	1	1				
Knoxville	3		1		2	
Lenoir City						
Nashville						
Maryville			1			
Total Operations	4	1	5	2	2	1
Percent Correct Operations	.94	98	83	78	78	93

Average percent Correct operation 88

The incorrect operation table includes not only the incorrect relay operations, but also cases where the relays were accidently closed by test men, construction men, operators, etc.,

THE 120 K. V. SYSTEM OF THE TENNESSEE ELECTRIC POWER COMPANY.

Figure 2 shows a map of the 120 K. V. system of The Tennessee Electric Power Company, which is a basis of study for this paper. The map is not geographically correct, nor is it drawn to scale, but it is a schematic diagram of the system. The table to the right of the diagram gives the symbols for the equipment shown. It shows the position of the fuses, transformers, oil circuit breakers, air break switches, etc.,with reference to each other. The switches are shown for normal operation of the system. It can be seen by a study of the map that air break switches are so arranged that the system may be sectionized by the use of these switches alone. For example, suppose the line between Ocoee #1 and Maryville were to go into permanent trouble. This would trip out the circuit breaker on this line, and drop all the load. But by opening the air break switch ahead of Ocoee #1, and the one ahead of Maryville station the bad section of the line would be cut out. Part of the load that was dropped by this line could then be picked up through the other part of the loop.

The map also shows the capacities and connections of the transformers, the generating stations, etc., The small symbols on the oil circuit breakers show the relays installed for that breaker.

This system is operated as a solidly grounded system. That is the neutral of the Y connected transformers and generators are connected directly to the ground without any resistance between the neutral connection and the ground, except the resistance of the ground lead. It has been proven by experience that for a high tension transmission system the best protection can be had by operating the system as a grounded system, and a large percentage of the high tension transmission companies operate their systems grounded. This does not apply in all cases though, for there are several ~~underground~~ ungrounded systems in operation.

There are four groups of grounded neutral systems classified according to the amount of resistance in the ground connection. They are solidly grounded neutral systems, low resistance grounded neutral systems, medium resistance grounded neutral systems and high resistance grounded neutral systems. In a solidly grounded neutral system if one wire becomes accidentally grounded it has the same effect on the relay system as a short circuit between two wires.

THE CONTROL CIRCUIT.

It might be well at this time, before starting into the study of a relay system, to explain the method of application of the relays and control circuit to the circuit breaker. The oil circuit breakers of the system under study are electrically operated, or what is known as remote controlled oil circuit breakers. It seems to be the best engineering methods at the present time to install all of the high voltage equipment such as, high tension fuses, transformers and circuit breakers in out door sub-stations, and install the motors, relays, control equipment, etc.,indoors. The circuit breakers can be either opened or closed from the switch board. Most circuit breakers are also constructed so they may be manually closed in case of emergency or for testing purposes.

There are several different methods of automatically or electrically operating circuit breakers, some of them using an alternating current source of supply and some a D.C. source. Some methods use the same source to trip the circuit breakers as the source protected. One method is to use tripping reactors in the secondary of current transformers. There are several such installations in the lower voltage systems of The Tennessee Electric Power Company. Complications arise here though, that are a disadvantage to using this method and other A. C. source methods. That is, if a short circuit occurs the voltage may drop so low that there is not enough voltage to operate the trip solenoid, and this happens just at the time that full voltage is needed. It is hard in a large transmission system to get an A. C. source that is not to some extent dependant upon or connected in some way with the source protected, and this might result in the failure of the tripping source at the most critical time. It can readily be seen that the tripping source is one of the most important factors in the protective system, and that an absolutely dependable source is necessary. It has been proven by experience that the storage battery is the most reliable source. 125 volt storage batteries are used in the most important stations and 24 volt batteries are used in the smaller and less important stations.

Circuit breakers are usually opened by releasing the tension on strong springs, which almost instantly open the contacts of the breaker. The tension on the spring is usually released by a small trigger or latch. The switch is closed, and at the same time the spring compressed, by means of solenoids or a motor. Figure 3 is a diagram of a control circuit, and a discussion of the operation follows:

The small auxiliary switch marked "A" is called an "A" switch, and this switch is closed when the circuit breaker is

CONTROL CIRCUIT FOR ELECTRICALLY
OPERATED CIRCUIT BREAKER

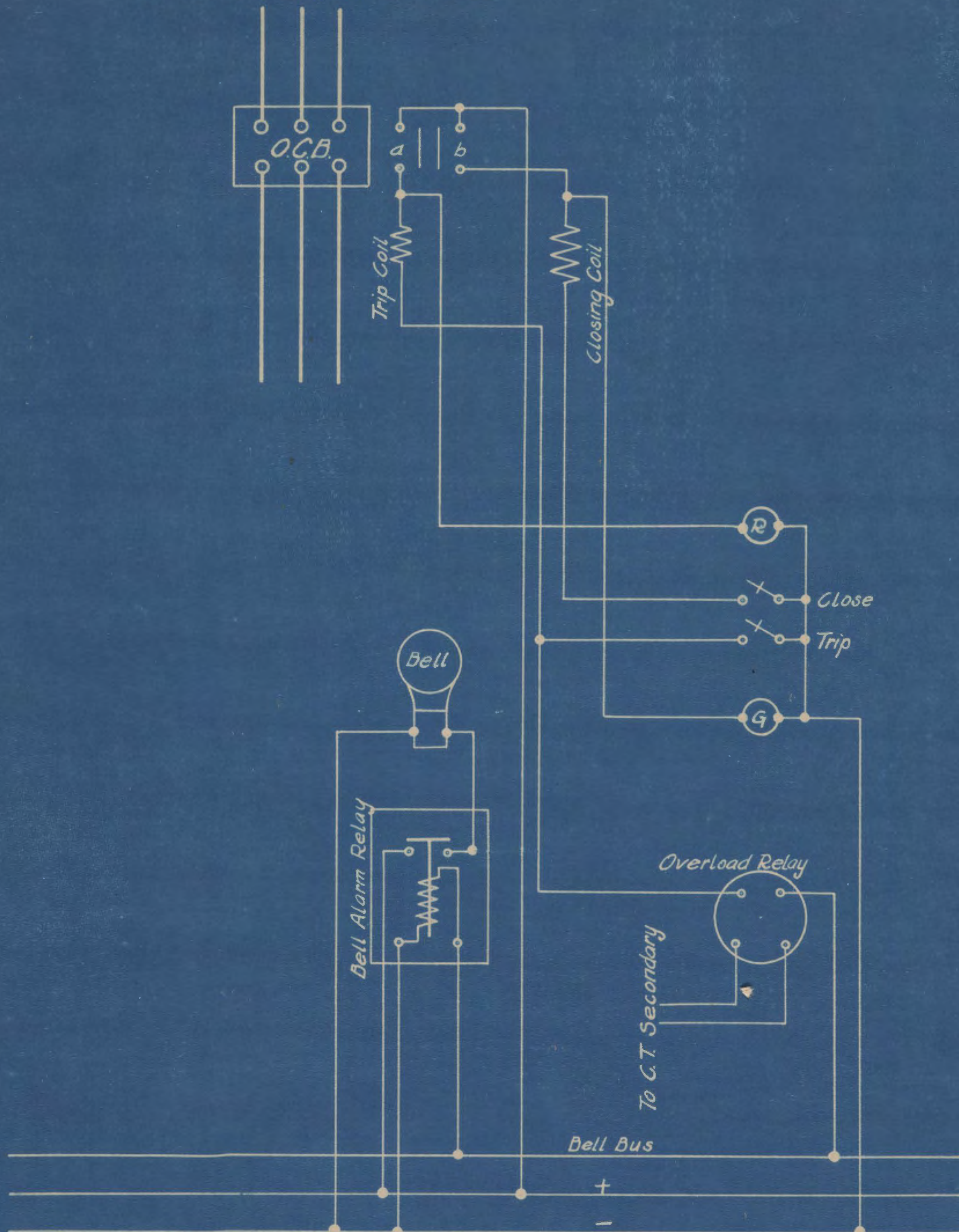


FIG. 3.

Drawn by – A.A. Ferrell   Date – April 18, 1928 closed. The one marked "b" is called a "b" switch and is open when when the circuit breaker is closed. The piece of apparatus marked "R" is a red light, and by tracing the circuit it can be seen that this light burns when the circuit breaker is closed. Likewise "G" is a green light and burns when the circuit breaker is open. By means of these lights the operator can look at the board and immediately tell which circuit breakers are open or closed.

Assume that the circuit breaker is closed and that it is to be tripped manually by remote control. The small switch marked trip is closed, thus completing the circuit from the positive bus bar through the "A" switch, the trip coil, the trip switch and to the negative bus bar. The trip coil then operates, releasing the tension on the spring which opens the circuit breaker. The opening of the circuit breaker also opens the "A" switch and closes the "b" switch. This cuts out the red light and cuts in the green light. The trip switch automatically opens when the circuit breaker opens. The circuit breaker than can be closed by closing the switch marked close. The operation is just the reverse of the one described, except that the closing coil operates instead of the trip coil.

Now suppose the circuit breaker is closed and a fault occurs on the line. The relay has two contacts, one of which is stationary and the other one mounted on the moving element of the relay. The fault on the line causes the moving element of the relay to start turning, and this closes the trip contacts. This completes the trip circuit through the positive bus bar, the "A" switch, the trip coil and the relay to the bell bus. From the bell bus the circuit goes through the bell alarm relay to the negative bus bar, thus completing the circuit and tripping the circuit breaker. But when the bell alarm relay was energized it started a bell to ringing, which gave the signal to the operator that the circuit breaker had opened. The bell alarm relay is so constructed, that once tripped it will ring the bell continuously until reset by hand. As can be seen the same bell alarm can be used for any number of sets of relays by merely hooking one side of the relays to the bell bus. Usually the current required by the trip circuit is too great to pass through the relay contacts, and an auxiliary contactor is used which is operated by the closing of the relay contacts, the contactor in turn closing the trip circuit. Usually the auxiliary contactor is mounted inside the relay case, and is a part of the relay. The auxiliary switch "a" opens the trip circuit when the circuit breaker opens. This prevents the trip coil from being damaged in case the relay contacts stick, and also relieves the relay contacts from opening the trip circuit, which is usually highly inductive, and would cause arcing, which would burn the relay contacts.

A STUDY OF THE RELAY SCHEME FOR THE PROTECTION
OF THE 120 K. V. LINE OF THE TENNESSEE ELECTRIC POWER COMPANY
AT THE KNOXVILLE STRAM PLANT.

A study and discussion will now be made of the relay scheme used on The Tennessee Electric Power Company's lines at the Knoxville Steam Plant.

At the Knoxville Steam Plant there are two 120 K.V. lines feeding into the station through two electrically controlled oil circuit breakers. The load is carried by two banks of transformers. A 10,000 K.V.A. bank and a 27,000 K.V.A. bank, both banks Y-Y connected with their neutral tied together and run through a K-81 current transformer to ground. These two lines are a part of the 120 K.V. loop between Ocooe #1, Maryville, Knoxville, Lenoir City and Cleveland. The loop is completed through this station. The Knoxville Power & Light Company has no generating plants, so the whole system load is fed by these two lines. Normally both circuit breakers are operated closed, so that either line may supply the demand, but it is very desirable that one of the lines be kept energized at all times, except in a very exceptional case of trouble. This being the case the relaying of the lines is so arranged that both of the circuit breakers cannot trip at the same time. This complicates the relaying somewhat.

The relays on each of the circuit breakers consist of three IA-205 overload relays, one 1C-5-Y1 directional ground relay, one IK-105 reverse power relay and a CY low voltage relay on the Cleveland switch only. In addition the trip circuits are interlocked through two PQ-33 lock-out relays. In interlocked relays one relay is inoperative unless a certain other relay closes. A lock out relay is a relay that under certain operations will open the trip circuit of some other rely, and hold it open until the operation started is completed, or for a determined definite time.

The type IA-205 over-current relays are circuit closing relays, and operate with a time which is inverse at low current values, but which approaches a definite time at high current values.

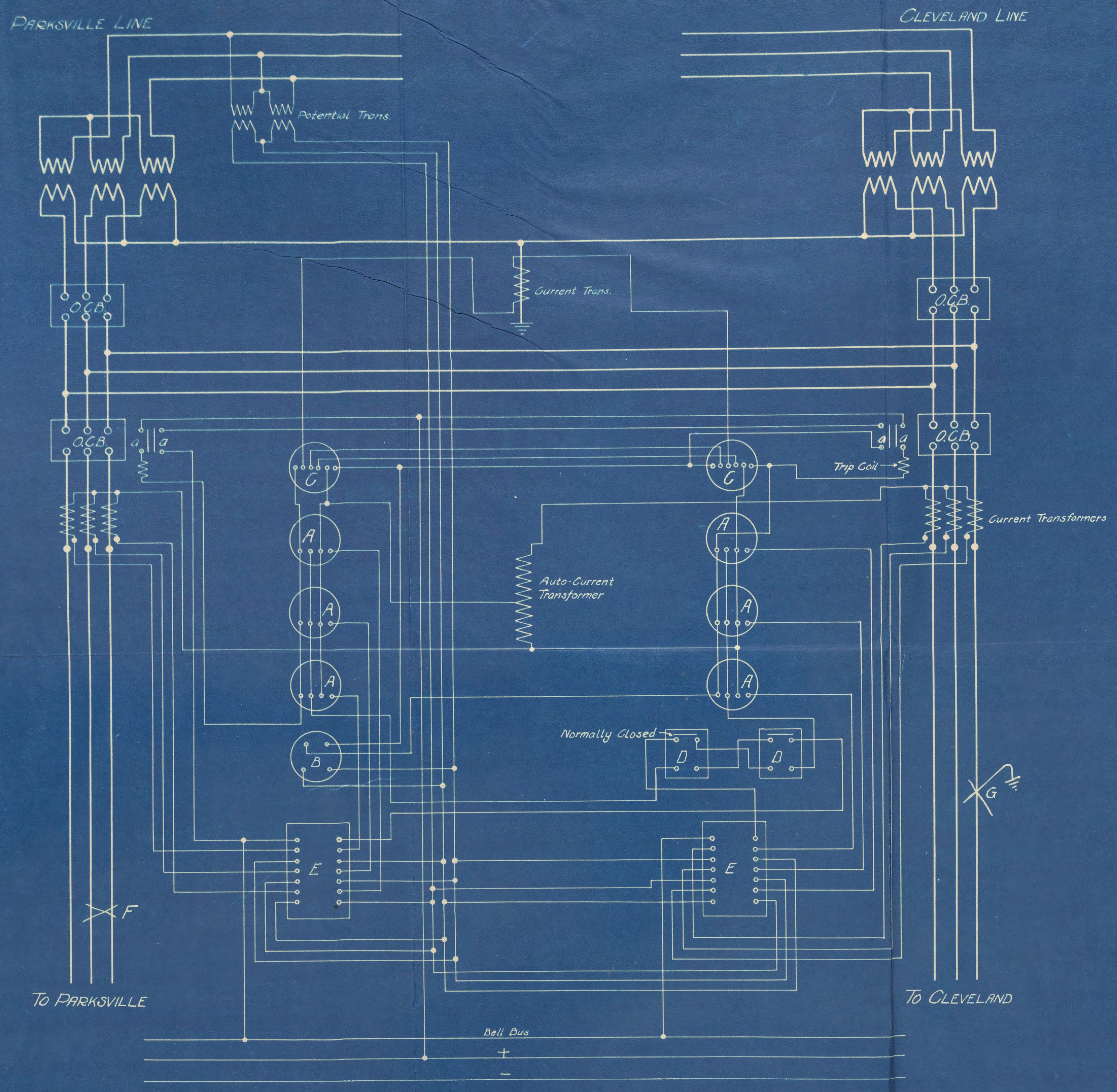
The rotating part of the relay is a copper disk. It is mounted on jewelled bearings which are almost frictionless, therefore the relay acts with great accuracy.

There is a permanent magnet in the front part of the relay, which dampens or has a retarding effect on the rotation of the disk. It is due to this retarding effect that the relay requires time in its operation.

The disk is driven by a U-shaped electromagnet. The current element of the relay is wound on the legs of the U-shaped iron core which energizes this magnet. The torque required to drive the disk is obtained by means of shading coils on the pole pieces of the electro-magnet. The pole pieces are divided into two unequal parts. A short- circuited coil is wound around the smaller part. In this short-circuited coil induced currents flow which retard the setting of the flux inside the shading coil as compared to the flux in the main part of the pole. The combination of the two fluxes causes a distorted magnetic field. Then when alternating current flows in the current coil a distorted magnetic field is produced, which passes through the copper disk and causes a torque to be exerted on the disk. The amount of torque exerted depends on the amount of current flowing. There is a small spring used to return the disk to its original position after the operation of the relay. Slots are cut in the disk to varying depths to compensate for the variation of the retaining torque due to this spring. The deeper the slots the less the torque.

The relay has two trip circuit contacts. One of the contacts is mounted on the stationary part of the relay and the other one on the moving element. When the relay operates it closes these contacts which closes the trip circuit.

Variations of operating current are obtained by bringing out taps from different points on the main current coil, which changes the ampere turns. Variations in time are obtained by means of a small lever called the time lever. By changing the position of the time lever the arc through which the disk has to rotate to close the contacts is changed, thus changing the time of operation. The relay may be made almost



A= IA-205 Overload Relay
B= CV Undervoltage Relay
C= IC-5-Y1 Directional Ground Relay
D= PQ-33 Auxiliary Lockout Relay
E= IK-105 Reverse Power Relay

Wiring Diagram
Relay connections for 120 Kv. switches
at Knoxville Steam Plant

FIGURE 7

Drawn by - A.R. Farrell   Date - April 18, 1928 instantaneous in operation by setting the time lever on zero. This relay will operate if sufficient current is flowing regardless of the direction of the current. Since there is only one coil, which is the current coil, the hook-up of this relay is not very complicated.

The 1C-5-Y1 relay is used for sensitive protection against ground faults in low resistence grounded neutral systems. The moving element of the relay consists of a copper disk mounted on a vertical shaft and carrying one of the trip circuit contacts. The disk is rotated by a driving magnet with two current coils. The principle of operation is the same as that of the watt hour meter, or a two phase motor. The lower current coil is connected in the common return of the current transformers, and the upper current coil is connected in series with the secondary of a current transformer in the grounded neutral lead of the power transformer. The flux which results from the passage of current through these coils exerts a torque on the copper disk. If the ground current is flowing in the proper direction the disk tends to rotate to the right, or in the direction to hold the relay contacts open, but if the direction of the ground current is reversed the torque on the disk is reversed, the same as the direction of rotation of a watt hour meter is reversed by reversing the connections on the potential coil, and the disk rotates to the right and closes the relay contacts. After the relay is deenergized a small spring pulls the disk back to its original position. There is also a permanent damping magnet on this relay similar to the one on the over-current relay.

When the instantaneous currents are flowing in the same direction in the two current coils the disk tends to rotate to the left and closes the relay contacts, but when the instantaneous current in the two coils are in opposite directions in the two coils the disk tends to rotate to the right and holds the relay open. The disk rotates against a stop to the left and is held in place. Fig. 4 shows the instantaneous directions of the currents for the closing and opening of the relay.

The type 1K-105 relay is an induction type polyphase power directional relay. Its construction and principle of operation are similar to a polyphase watt hour meter. There are three watt hour meter elements consisting of a current coil and a potential coil. There are two discs mounted on a vertical shaft. One of the watt hour elements acts on the top disk and two on the bottom disk. When power flows in the normal direction the disks tend to revolve to the right or to hold the relay contacts open, but when the power reverses the rotation of the disks reverse, thus closing the relay contacts. This is an instantaneous relay.

The maximum torque is obtained when the current in

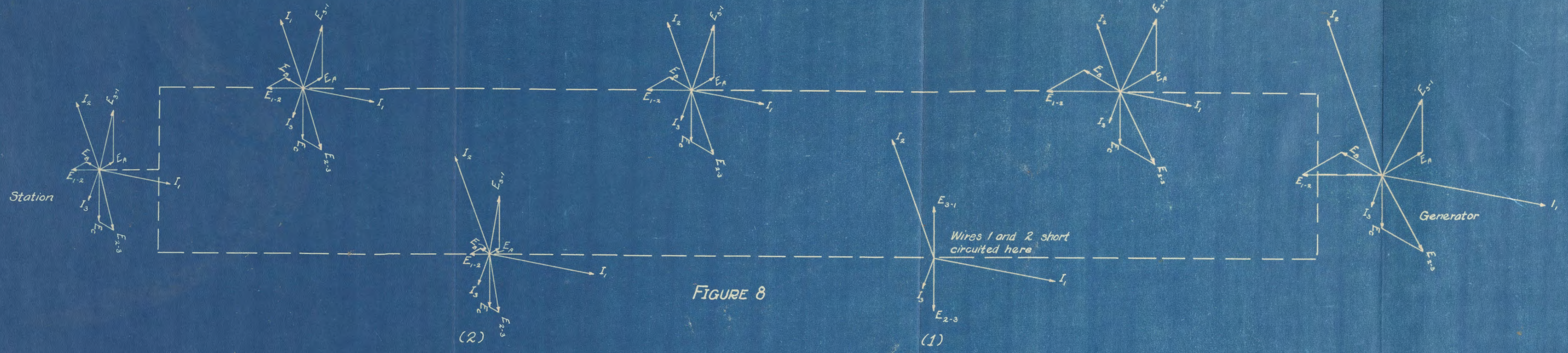


FIGURE 8

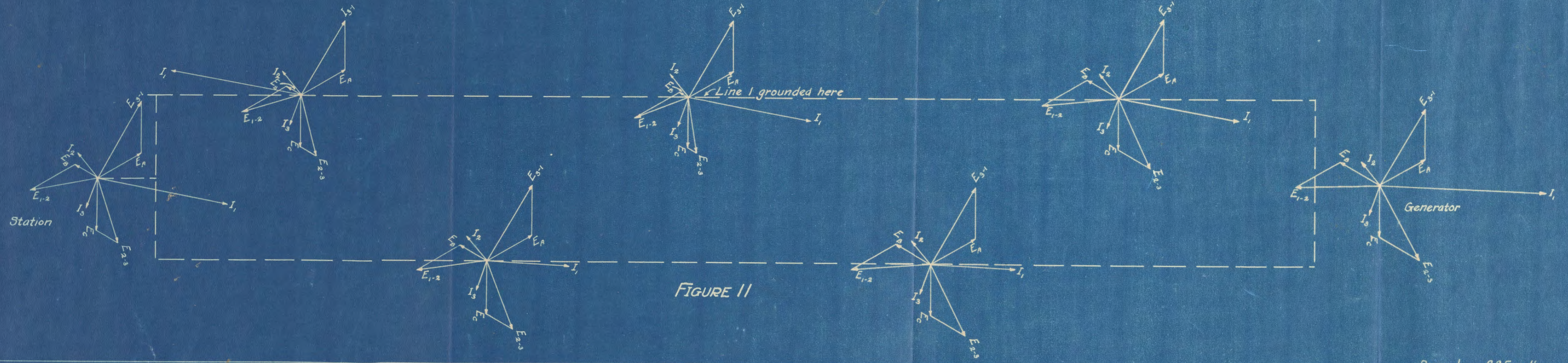


FIGURE 11

Drawn by — A.A.Ferrell

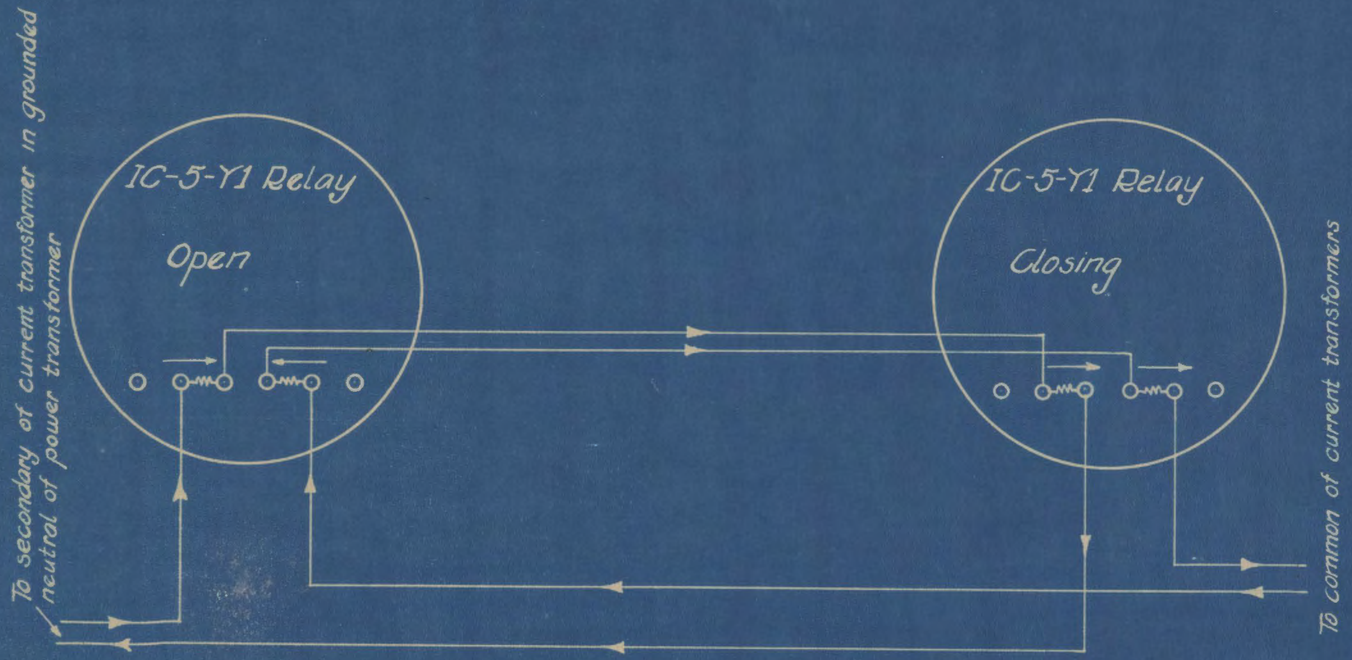


FIGURE 4

Arrows show direction of currents for operation of IC-5-Y1 directional ground relay the current coil and the current in the potential coil are in quadrature, the same as in a watt hour meter. But in the case of the relay it operates only on fault currents when the power is reversed. In all serious faults there is a large angle of lag between the current and the voltage. This angle has been proven by experiment to be about 40° lagging current for the average fault.# This is taken care of in the construction and hook-up of the relay.

Let figure 5, represent the vector diagram of the three phase circuit that the relay is going to be used on. Let E_A, E_B, E_C, I_A, I_B, and I_C represent the phase voltages and phase currents at unity power factor, & E_{A-B}, E_{B-C}, and E_{C-A}, represents the voltage between wires. Then when hooking up the relay the potential circuit of each element is connected in quadrature with the current coil. Therefore the current I_A and voltage E_{B-C}, would have to be hooked to the same element, likewise I_B, and E_{C-A}, and I_C and E_{A-B}.

Now if the relay were built the same as the watt hour meter the current in the potential coil would lag the voltage nearly 90°. This is not so in the relay though. A resistence is placed in series with the potential coil to decrease the angle of lag of the current. This can easily be seen by referring to figure 6. Let O E represent the voltages acorss the potential coil. R I is the resistence component

General Electric Bulletin #47810-1.

Vector Diagram Showing Current, Voltage and Phase Relations for the IK-105 Reverse Power Relay

FIGURE 5

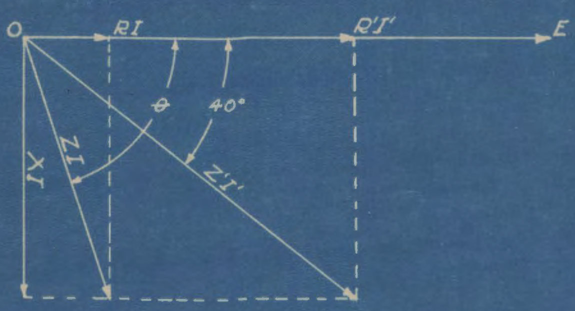


FIGURE 6

Drawn by A.A. Ferrell   Date – May 9, 1928 in phase with the voltage, and XI the reactive component in quadrature with the voltage. ZI shows the direction of the current lagging behind the voltage. Then by increasing the resistance component, as is shown by R'I' , the angle of lag of the current is reduced, as is shown by Z'I'. Enought resistance is put into the circuit to make the angle of lag of the current 40°. These currents are shown in fig. 5 by I_{A-B}, I_{B-C} , and I_{C-A} , lagging the potential voltages E_{A-B}, E_{B-C}, and E_{C-A} respectively by 40°. Then let I'_A, I'_B and I'_C represent the currents in the current coils at time of fault, lagging the phase voltages by 40°. It can now be seen that the current in the current coil is in quadrature with the current in the pitential coil, which will give maximum torque. In the case of a ground or short circuit the voltage drops very low, but this type relay will operate on 1% of normal voltage.

It is very essential that the relay be phased out correctly. That is a current and voltage that are 90° out of phase with each other are connected to the same element. This can easily be done with a phase meter.

The phase meter is built on the same principle as a power factor meter, but the scale is calibrated to indicate degrees from 0 to 360 instead of power factor percentages. It readily shows the exact phase relation between voltage and current to which it is connected. Then by alternatingly trying the currents and voltages, the currents and voltages that are 90° out of phase with each other, and with the correct phase sequence, can readily be picked out, and these go to the same element of the relay.

The CV relay connected to trip the Cleveland line circuit breaker is an induction low voltage relay. It hasinverse time characteristics and operates on the same principle as the induction overload relay, except that the torque compensator is omitted and potential coils are used instead of current coils. It operates when the voltage drops a certain percent below normal.

The wiring diagram for the relays and control circuit is shown in figure 7. The current transformers are bushing type and are connected in Y as is shown. The currents from the two lines are balanced through the auto current transformer. The auto-current transformer is installed to counteract the difference in resistance, inductance and capacity of the two lines due to their difference in length.

The overload trip circuit is in series with the IK-105 trip circuit, so the overload relays cannot trip the circuit breaker unless the power reverses and the IK-105 relay operates. An overload or fault on the Knoxville Power and Light Company's system cannot trip the circuit breaker by overload. It is assumed that a fault or overload on this system will be taken care of by the Knoxville Power and Light Company's relays. If they were to fail to take care of the trouble the line would trip by overload from the generating end of the line at Ocoee #1 or Hales Bar. The overload and reverse power relays are for protection on The Tennessee Electric Power Company's system only. The trip circuits are also inter-locked through two PQ-33 auxiliary relays. The PQ-33 relay is an auxiliary time reclosing relay. The relay contacts are normally closed, but when the relay is energized the contacts are opened. The trip circuit for the relays on one line is carried through the coil of one of the PQ-33 relays and the contacts of the other PQ-33 relay. The other line is connected in a similar manner. Normally both trip circuits are complete through the PQ-33 relays to the protective relay terminals, so that either circuit breaker may be tripped by the closing of the protective relays. But as soon as one trip circuit is completed by the closing of a protective relay one of the PQ-33 relays is energized, which opens its contacts, thus opening the trip circuit of the other line. In this way it is impossible for both circuit breakers to trip at the same time. The PQ-33 relay is set so that it takes it two minutes to reclose its contacts after it has been de-energized. This gives the system time to come back to normal, if the trouble has been cleared by the opening of the first circuit breaker, before the trip circuit for the other circuit breaker can be closed. If the trouble was not cleared by the first circuit breaker then the second circuit breaker would open. If the trouble were very serious the line would be tripped by ground relay or from the other end of the line or by overload before the two minute interval was up.

The CV relay is a low voltage relay, so connected that if the lines are de-energized from the generating end the CV relay will, open the Cleveland line circuit breaker, which opens the loop. The lines can then be energized from the generating end and the loop closed back through the Cleveland line circuit breaker at Knoxville.

The circuit breakers may be tripped regardless of the direction of power if the 1C-5-Y1 relays close. Only one 1C-5-Y1 relay can operate at a time because of direction and interlocking through an "A" switch. This will be brought out and explained in an example of operation below. The neutral of the two power transformers are tied together and grounded through a K-81 current transformer. The secondary of this current transformer is hooked in series with a current element of each of the 1C-5-Y1 relays.

EXAMPLE I.

Suppose a short circuit occurs between two phases as at F in fig. 7.

The current and voltage conditions at the point of short circuit and also at points along the line are shown by the vectors in figure 8. The power transformer is Y connected with the neutral grounded. Call the three coils A, B and C and the three conductors I, 2 and 3. Then E_{3-1} is the algebraic sum of the voltages E_A and E_C, E_{1-2} the algebraic sum of E_B and E_B and $E_{2-3}$the algebraic sum ofE_B and E_C. The currents in the conductors are the same as the currents in the coils of the transformer.

Assume that conductors 1 and 2 are short circuited. The current and voltage relations at the short circuit are given by diagram 1 figure 8. There is very little resistance between conductors 1 and 2, therefore the voltage between conductors 1 and 2 is so small as to be negligible. But the voltage E_{1-2} is made up of E_A and E_B.

The circuit breakers may be tripped regardless of the direction of power if the 1C-5-Y1 relays close. Only one 1C-5-Y1 relay can operate at a time because of direction and interlocking through "a" switch. This will be brought out and explained in an example of operation below. The neutral of the two power transformers are tied together and grounded through a K-81 current transformer. The secondary of this current transformer is hooked in series with a current element of each of the 1C-5-Y1 relayd.

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Assume that conductors I and 2 are short circuited. The current and voltage relations at the short circuit are given by diagram 1 figure 8. There is very little resistance between conductors 1 and 2, therefore the voltage between conductors 1 and 2 is so small as to be negligible. But the voltage E_{1-2} is made up of E_A and E_B or the voltage between the conductors and the neutral which is the phase voltage. Then the voltage E_A and E_B are so small as to be negligible. This then changes the phase relation of the voltages E_{3-1} and E_{2-3} for E_{3-1} is made up of E_A and $-E_C$ and E_{2-3} is made up of E_C and $-E_B$. It can be seen that if E_A and E_B are 0 that E_{3-1} and E_{2-3} are equal to $-E_C$ and E_C respectively. Therefore there are now two voltages which are equal in magnitude, but opposite in direction, or 180° apart, where they were originally three voltages 120° apart. But these two voltages E_{3-1} and E_{2-3} are only 58% of the normal phase to phase voltage.

The phase relations and magnitude of two of the currents will also be changed. Assume that under normal conditions

I_1 I_2 and I_3 lag the voltages E_A E_B and E_C by 20°. Figure 9 gives the victor relations under normal conditions. The currents are 120° apart. The fault increases the magnitude of currents I_1 and I_2 several hundred percent as well as shifts their phase position. It has been proven by experiment that the average lag of the current due to short circuit is approximately 40°. Then the currents I_1 and I_2 will lag the voltages E_A and E_B by 40°. This makes I_1, lag E_{3-1} by 30° + 30° + 40° or 100°, for E_{3-1} has changed its phase position by 30° in the positive direction due to the dropping out of the component E_A. I_2 lags the infinitesmally small voltage E_{1-2} by 30° + 40° or 70°. The voltage E_{1-2} increases as the distance from the point of short circuit increases, and the phase relations between currents and voltages can be seen better in diagram 2. Due to a shift of 30° in phase voltage E_{2-3}, current I_3 is now lagging voltage E_{2-3} only 20°.

Figure 10 shows that the phase relations for the short circuit condition are satisfactory for the current operation of the watt hour element of the I K - 105 reverse power relay. As was explained above, the relay has maximum torque when the current in the current coil is in quadrature with the current in the potential coil. In the diagram I_1 and E_{2-3} are hooked to the same element in the relay. The current I_{2-3} in the potential coils lags the voltage E_{2-3} by 40° as was explained above. Then when a short circuit occurs both current I_1 and potential E_{2-3} are shifted in phase relation with respect to

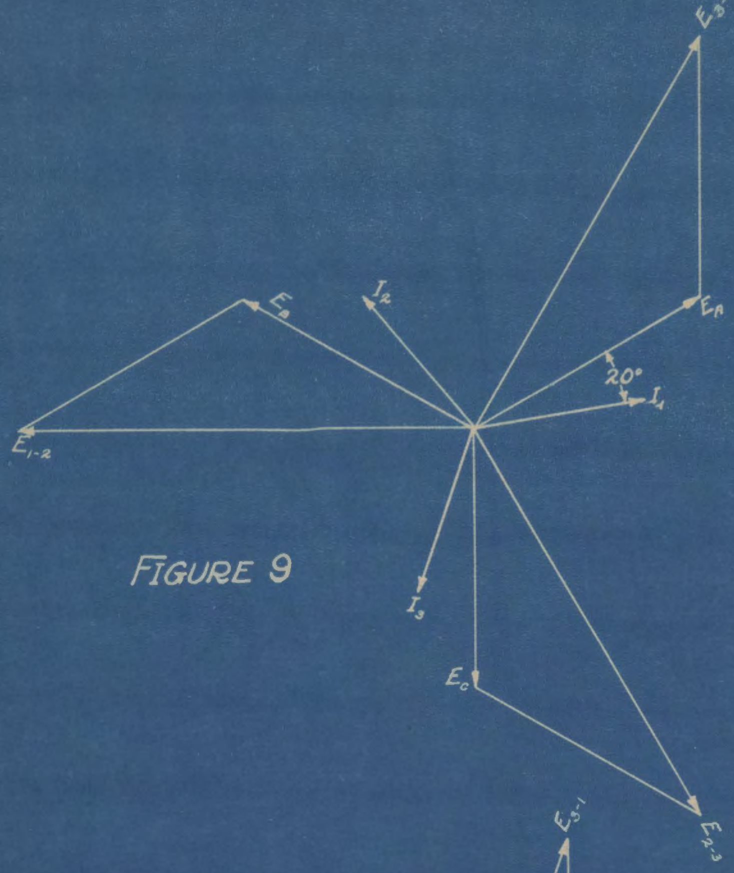


FIGURE 9

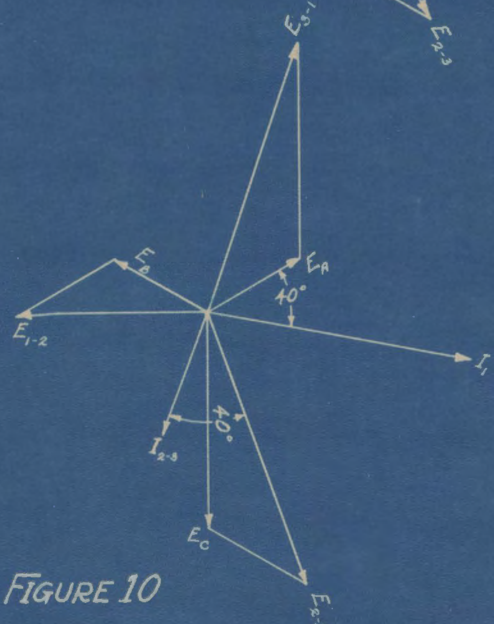


FIGURE 10

normal operating position. But it can be seen that I_1 and I_{2-3} are approximately 90° apart which gives nearly full torque on the relay.

The short circuit causes abnormal conditions in the relay and control circuits. As soon as the short circuit is imposed on the line the power reverses and the current flows from the station over the conductors to the short instead of from the conductors to the station. This reverses the direction of the instantaneous current in the secondarys of the current transformers, which reverses the torque on the IK-105 relay, thus closing it. The overload relays also begin closing at the same time, but they have a longer time setting than the 1K-105. As soon as the overload relay closes its contacts the trip circuit on the Parksville line oil circuit breaker is closed. This energizes the PQ-33 relay, which opens its contacts, thus opening the trip circuit of the Cleveland line circuit breaker, so that this breaker cannot trip at the same time as the Parksville line circuit breaker. The trip coil on the Parksville line circuit breaker is also energized by the closing of the overload relay, and this trips the Parkersville line circuit breaker which separates the station from the trouble. The circuit breaker is also tripped on the other end of the line, which completely clears the system of the trouble. When the Parksville line circuit breaker opened it also opened an auxiliary switch which broke the trip circuit. The

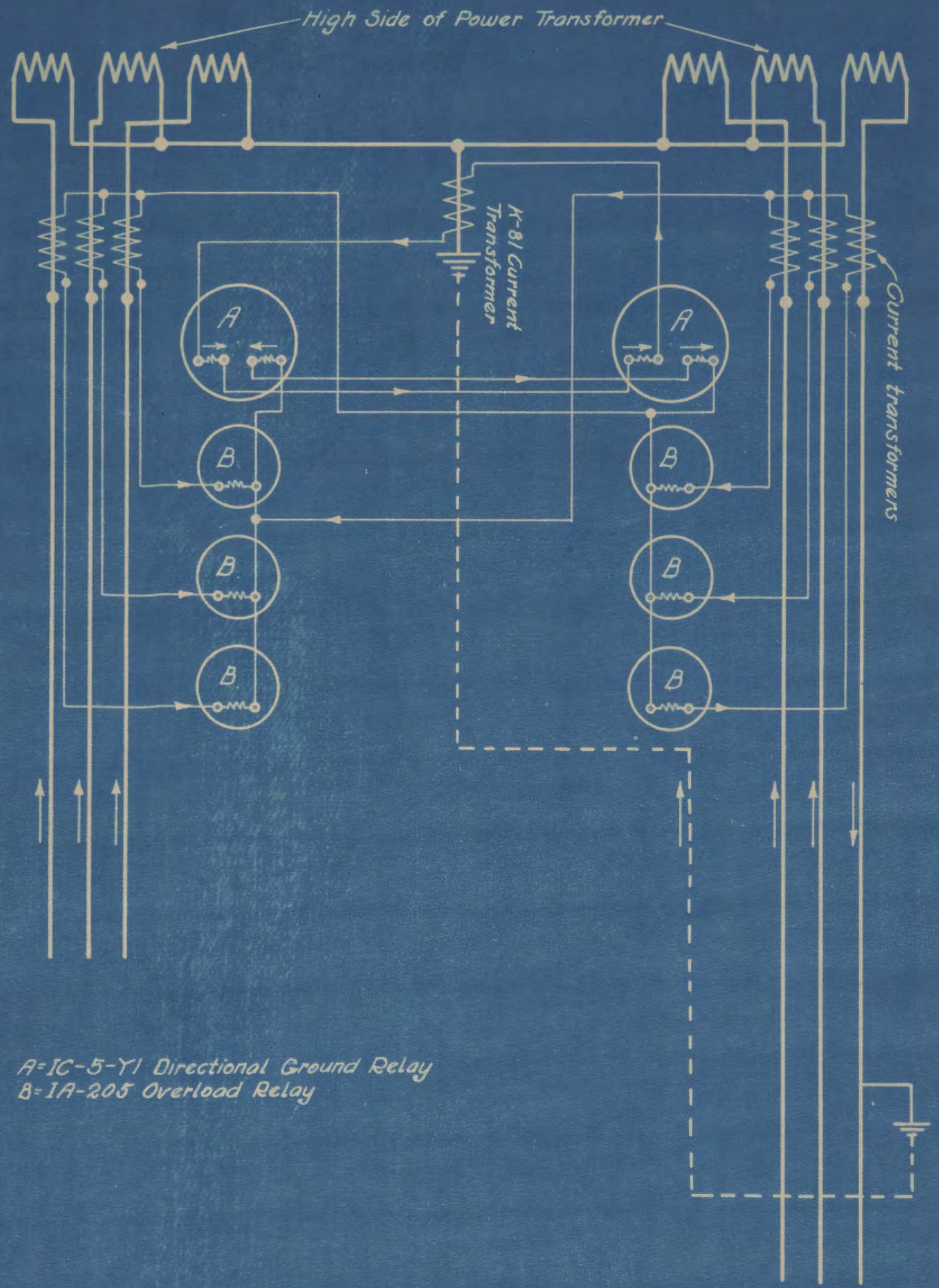
PQ-33 relay was then de-energized and after two minutes reclosed its contacts. This completed the trip circuit of the Cleveland line circuit breaker up to the relays, and this breaker could then trip in case of trouble. The two minute interval between the de-energizing of the PQ-33 relay and the closing of its contacts gave the system time to come back to normal.

EXAMPLE II.

Suppose one phase of the Cleveland line becomes grounded as at G. figure 9.

Then there will be a circulating current flowing from this grounded line through the ground to the neutral of the power transformer. This circuit is shown in figure 12. Figure 11 shows the current and voltage phase relations at the point of the ground and at points along the line. The diagram is constructed similar to figure 8. The difference is that only one phase current and voltage are directly effected by the fault. This indirectly tends to shift the phase position of two of the line voltages as is shown. They are E_{1-2} and E_{2-3}. At the point of ground there is still a little voltage E_A because of the resistance of the ground to the flow of the current. The fault also causes current I_1 to lag 40° and increases it several times in magnitude.

Normally there is no current flowing in either



A=IC-5-Y1 Directional Ground Relay
B=IA-205 Overload Relay

FIGURE 12

element of the 1C-5Y1 relays. The right current element of the two 1C relays are hooked in series, but so that the currents flow in opposite directions in the two relays. That is the connections are reversed on the two coils. The common of each set of current transformers is then connected to these relays as is shown in the schematic diagram in figure 12. The currents from the two lines are balanced through the auto-current transformer as is shown in figure 7. With a balanced load on the lines there will be no current in the common of the current transformers, therefore no current in this element of the 1C relay. The other two current elements of the relays are hooked in series with each other and also in series with the secondary of the K-81 current transformer in the grounded neutral of the power transformer. Normally there is no current in this grounded neutral, therefore no current in the secondary of the current transformer and the relays. But as soon as one of the lines becomes grounded as at G. figure 7, the three phase load becomes unbalanced. There is then an excess current flowing in the grounded line due to the heavy ground current. The direction of flow of power in this line is also opposite to the normal direction of flow at this end. This unbalances the currents in the common of the current transformers. There is then a current flowing in the common of the current transformers and also in the 1C relays. The instantaneous direction of current flow is opposite in the two relays though because the connections are reversed as was explained above.

The grounding of the line also causes current to flow in the grounded neutral. This causes current to flow in the secondary of the current transformer connected in the neutral lead and also in the 1 C relays which are in series with the secondary of the transformer. This instantaneous current flows in the same direction through both relays. It can be seen that the torque exerted on the moving elements of the two relays are in opposite directions, because the connections to the right current coils are reversed on the two relays. In other words one of the relays tends to hold its contacts open while the other relay closes its contacts. In figure 12 the arrows show the instantaneous directions of current. It can be seen that the currents are in the correct direction to close the Cleveland line relay and hold the Parksville line relay open, which is the correct operation.

The overload relays act as back up relays and would trip the circuit breaker if the directional ground relays did not, provided the ground resistance was low enough to allow sufficient current to flow. Since there is normally no current in the ground relay it may be given a lower current setting than the relays for line to line protection and the time is usually set lower. A large percentage of faults on transmission lines cause ground currents to flow and this low current and quick time setting increases the speed of clearing a large percentage of faults.

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Approval

The foregoing thesis is hereby approved as a creditable study of an engineering subject, carried out and presented in a manner sufficiently satisfactory to warrant its acceptance as a prerequisite to the degree for which it has been submitted. It is to be understood that by this approval the undersigned does not necessarily endorse or approve any statement made, opinions expressed, or conclusions drawn therein, but approves the thesis only for the purpose for which it is submitted.

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