

PROTECTIVE RELAYING

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A THESIS SUBMITTED FOR THE DEGREE OF
BACHELOR OF SCIENCE
ELECTRICAL ENGINEERING COURSE

The University of Tennessee

1931

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Chapter I
Introduction



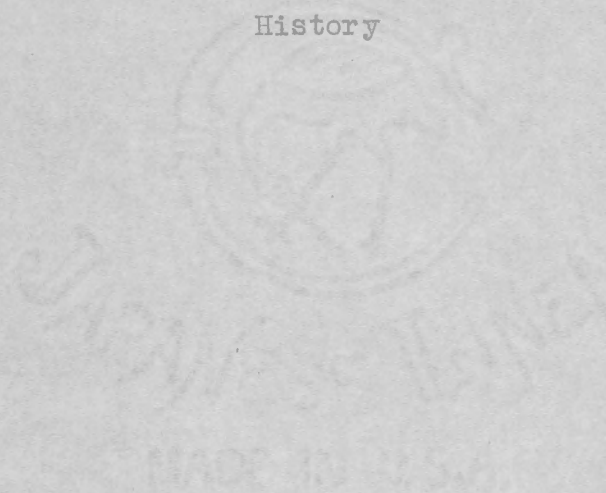
One of the primary interests of a public utility concern is that of continuity of service. To this end, many different methods of safeguarding such service from accidental interruption have been suggested and tried. Today the networks of lines and equipment that are in continuous use for bringing hydro and steam power to the control rooms of our thousands of manufacturing and industrial plants are intricate and complex to a high degree. They have come to be thus because of the absolute necessity of maintaining constant service supply for consumers. In nearly every modernized field of endeavor, every effort is put forth to raise operating efficiency to as high a figure as possible; this is carried out by devoting time and money, and sometimes research, to a thorough examination of each item contributing to ultimate production, with the primary purpose of eliminating error so far as this elimination does not materially affect production capacity per day or cause too high a cost of operation. It is natural and obvious, therefore, that those who utilize electric power as an intermediate factor in the production of their goods should consider critically the elimination of error in that factor. And since these consumers of electric energy to require uninterrupted service during their hours of production, it falls to the part of the power producers to render such service in order to retain the business and good will of the consumers. Except in case of monopoly, those engaged in power production must present the required service or lose the good will of the public they serve.

Power producers, therefore, will follow the same general procedure of examining channels of error in their industry in order to give the public a desirable product. Probably electricity presents no more problems in its handling than an ingot of steel or an enameled bathtub; but obviously the world's knowledge of the behavior of this natural resource is limited. For this reason the industry is said to be in its infancy; no doubt it will remain so for some time yet. Due in part to the peculiar properties of electric energy, and in part to our limited knowledge of its utilization, the present-day systems of equipment for obtaining, transmitting, and consuming this energy are complicated. In many instances this complexity results again and again in trouble of one sort or another. But there has been nothing added that was allowed to remain in use without performing, within reason at least, its intended function.

Not the least important (as well as not the least complicated) of the many classes of equipment developed for the elimination of error in the production of electric energy is the protective relay. At present, relaying systems are in use that detect trouble practically instantaneously and operate with almost human discrimination and subsequent operation of equipment. Such relaying is very essential if energy is to be supplied in a manner meeting the requirements of modernized labor and capital.

Chapter II

History



Probably the first idea utilized along the line of protective devices for electrical equipment was that of fuses. The most outstanding objection to this method of protection was cost of replacement and delay in restoration of service. Hence the development of automatic switches followed closely, although fusing was not abandoned. These automatic switches consisted mainly of a solenoid and core and operated with the current coil directly in series with the line to be protected. A surge or excessive load current, regardless of cause or nature, operated a mechanical tripping notch magnetically, and cleared the connection between service equipment and fault.

With the advent of current transformers, the possibility of handling large load currents indirectly was greatly enhanced, and the method of overload current tripping was improved. Obviously, however, one great objection to this type of automatic protection was that there was no way of delaying the opening of the switch mechanism except by means of dash pots or similar limited devices. If a short time fault occurred, perhaps there was no need of clearing it for a few seconds, since the equipment concerned might handle an overloaded safely for that period of time. Hence the need for delayed timing; and designing engineers turned to the induction current meter disk for a solution. By suitably applying current to the elements of such a meter, rotation of the disk could duplicate surge currents and be made to close a set of small contacts at the end of a certain period of time. Therefore, we have the now common induction relay, which may be set to close its contacts at the end of any desired period, from the instant fault. Later came the over- and under-

voltage relays and the contact-making volt meter; the power relay, and many types of directional and balanced relays.



Chapter III

Types of Relays and Their Purposes



The type of relay that is no doubt in most common use today is the overcurrent relay. This instrument contains a current and a potential element, and operates on the principle of the induction watt hour meter. It is selective only as regards amount of overload; that is, it is non-directional and its speed of closing its contacts is proportional to the amount of current flowing in the winding. In order to provide a definite minimum time of closing, a torque compensator is added in the winding; its action is that of becoming saturated at excessive currents and consequently slowing down the rotation of the disk regardless of the value of overcurrent. This type of relay is obviously almost universal in its application, and from it has been developed the greater portion of the other types of relays to be described presently.

In order to make possible the sectionalizing of lines and equipment after a fault, the directional overcurrent relay has been developed. The directional relay is a combination of the elements of the ordinary overcurrent type and a wattmeter element. Torque will be supplied by the latter element regardless of direction of flow of current, but it actuates a separate disk and on this are mounted contacts that close only when the rotation is in one direction. By connecting the contacts in series with those operated by the current element, the relay as a unit will have directional characteristics--that is, it will close its tripping circuit only when excessive current flows in one direction. The instrument may therefore be connected to operate directionally with respect to the equipment it protects. The time element is also present, of course, provided for by the

damping magnets and torque compensator.

Present-day complicated systems make difficult the accurate sectionalizing of equipment during line trouble, and this fact has brought forth the development of the impedance, or so-called distance, relay. The instrument consists of an overcurrent element and a voltage element. The operation of the voltage element is dependent upon the distance or length of line between relay and fault, and the action of this element is in opposition to that of the current element. Hence, if a fault occurs at a comparatively great distance from the relay, a higher voltage will be impressed on the potential winding and its action will increase the time of contact closing. A short distance from the fault will bring a lower voltage into play and hence less opposition to the closing action provided by the current coil. The use of this type of relay, then, will mean that if there are several relay-operated breakers in a certain line, and a fault occurs, the breakers nearest to the fault on either side of it will open up first and leave the remainder of the two sections in service. No other relays will trip their breakers by the time the nearest ones have cleared the fault, or isolated it; provided, of course, that time settings on all these relays have been computed and adjusted for proper operation. The impedance relay has recently been further improved by the addition of the directional element described in a preceding paragraph. A wider scope of use is possible if such types are available, and the problem of obtaining the most logical sequence of operation of equipment during fault is therefore more nearly solved.

Closely associated with the directional overcurrent relay is the power relay, which is essentially a contact-making

wattmeter. Contact closing occurs when power flows in one direction only, and only after a definite value of time. The use of such an instrument is necessarily limited, but for its purpose it has shown reliable operation; as a general rule, the power relay is used to prevent excessive interchange of power between two parts of a system, as would be desirable in the case of a small plant and a large plant generating in parallel. In the event that the larger source of power were suddenly disconnected, it would be undesirable to allow the small station to assume the entire system load for an uncertain length of time.

The over-voltage and under-voltage relays mentioned above have been developed primarily for the purpose of protecting certain types of equipment against accidental high voltage or undesirable changes of voltage. Such relays may be set very accurately to actuate a signal when impressed with voltages above or below definite limits, and the use of these instruments for this purpose is almost universal. Recently, the addition of a resistor element has permitted a wider range of adjustment for the limits of potential at which the relay will operate.

The phase-balance current relay has been developed and utilized in the protection of installations including polyphase machinery. A rotary converter or induction motor, if accidentally operating with one phase open or short-circuited, or with one phase reversed through faulty connection, will draw excessive line current and will overheat rapidly. The phase-balance relay brought forth by the Westinghouse company consists of two separate current elements; that is, there are two independent disks mounted in the relay case, each of which is operated by two current elements. The elements for each disk are mounted on op-

posite sides of the shaft, and are so connected that the two torques produced by a flow of current are in opposition to each other. Thus, when a balanced condition exists between the currents in the three phases, neither disk will rotate; in the case of any unbalance, one or both disks will move and close the contacts to the switch control circuit. The contacts on either disk are front and back connected and the two sets are connected in parallel, so that rotation of either disk in either direction will operate the tripping bus. The current elements are so connected that the two right hand elements are in series and inserted in what might be termed the common phase, while the left hand element of one pair is in a second phase and the left hand element of the other pair is in the third phase.

Other types of relays that have importance in the protection of equipment are the temperature, frequency, simple reverse-phase, ratio differential and selective differential, and special types designed for one definite field of operation, as is the case with high voltage installations. The temperature relays have been developed mainly from two principles; the first, the change of resistance of a length of conductor with changing temperature, and the second, the unequal expansion of the two sides of a bimetallic strip.

The development of the type GAX relay by the General Electric Company has followed closely upon the Westinghouse CZ manufacturing, and more recently the latter company has brought forth the first and second designs of a type HZ, which came in response to a call for a comparatively fast-operating impedance directional relay. The American Brown-Boveri design of relays is also of importance in this connection, but will not be dis-

cussed further here. At the present time (August 1931) the latest type HZ relay is creating considerably interest due to its almost instantaneous operation.

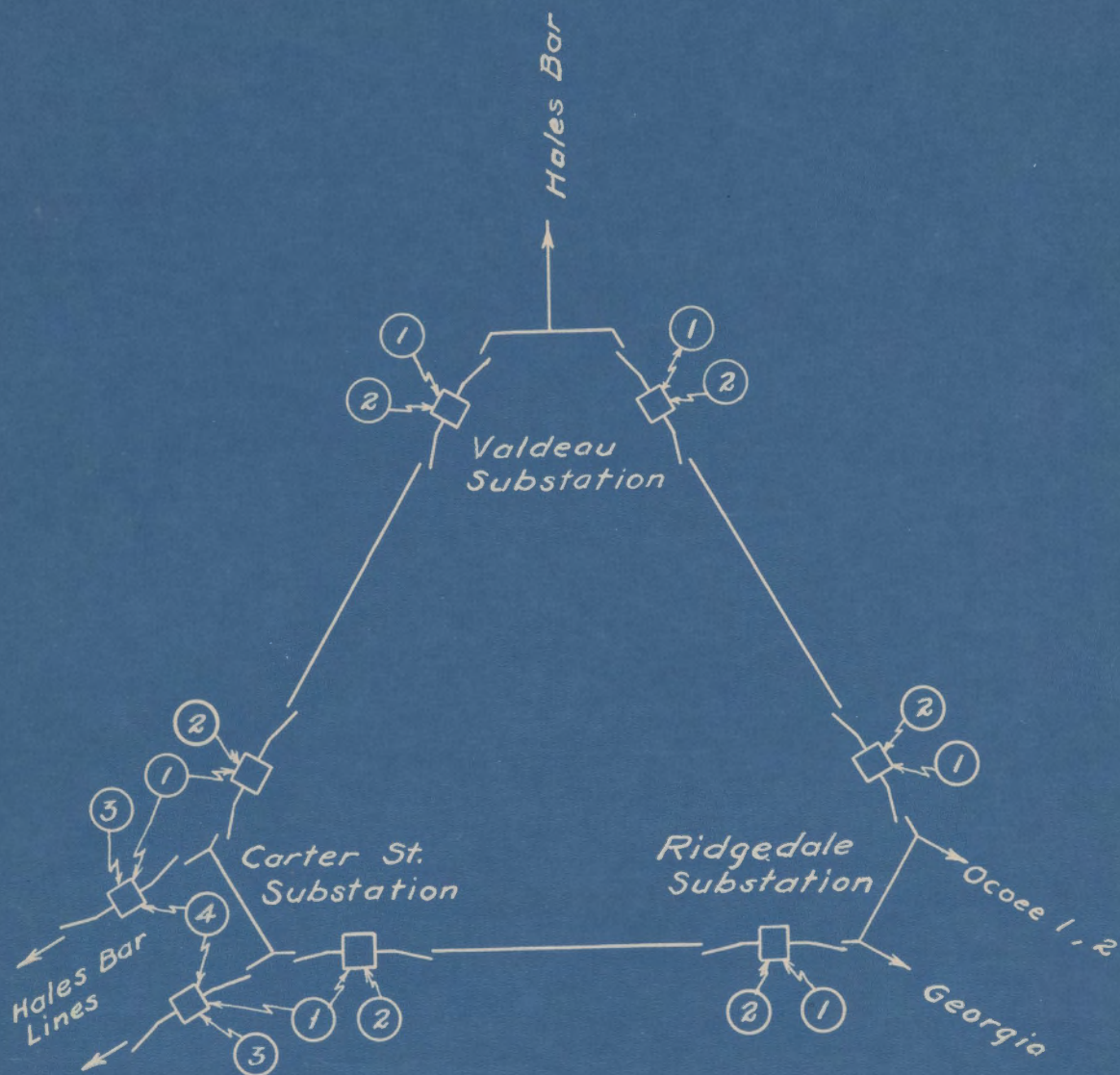
Chapter IV

The 44KV Loop for Chattanooga Distribution

For the purposes of this paper, it is believed that an example of a relaying scheme will be of value in giving a general idea of how such a system is set up and operated. To this end, the writers have chosen the 44,000 volt loop or triangle connecting the three primary Chattanooga substations. This loop is part of the Tennessee Electric Power Company's system, and the information given in the following paragraphs concerning it was furnished through the accomodation of that company's central office in Chattanooga.

The three primary substations mentioned are known as Carter Street, Ridgedale, and Valdeau. The 44,000 volt line connecting the points forms a sort of triangle within the limits of the city, and at each point the substation equipment converts its supplied power to voltages suitable for more local distribution. At the Ridgedale substation, located in the eastern portion of the city, are incoming lines from the Georgia interconnection and from the Ocoee #1 and #2 hydro plants of the Tennessee company, both at 110,000 volts. At Valdeau substation, in the northern section of the city, there is an incoming line from the Hales Bar generating station of the Tennessee company, operating also at 110,000 volts. And at Carter Street, there are two lines coming from the Hales Bar plant, called the North and South lines respectively, operating at 44,000 volts. The points, while at each substation there are smaller radial feeders supplying different desired voltages to local customers. Figure I shows the system as taken from a drawing of October, 1930, made by the company's engineering department.

The location of relays operating from the 44,000 volt triangle will be described separately for each substation. At Carter Street,



- ① — 3-CZ Relays
- ② — 1-CWC Relay
- ③ — 3-CD Balanced Current Relays
- ④ — 1-CD Balanced Ground Relay

Figure 1

there are three type CZ relays (one per phase) on each of the four lines coming to that station: Valdeau, Ridgedale, and the North and South lines to Hales Bar. There is also, on each of the first two lines, to Valdeau and Ridgedale, a type CWC directional ground relay. On the Hales Bar North and South lines are similar sets of one type CD balanced overload relay per phase, and one CD balanced ground relay per line. Relaying for these two lines is identical.

The Valdeau relaying is similar to that at Carter Street, except that of course there is no 44,000 volt connection to Hales Bar. The relaying scheme of the 110,000 volt Hales Bar line will not be taken up. There are three CZ relays on each of the two outgoing lines to Ridgedale and Carter Street, and one type CWC directional ground on each of these lines.

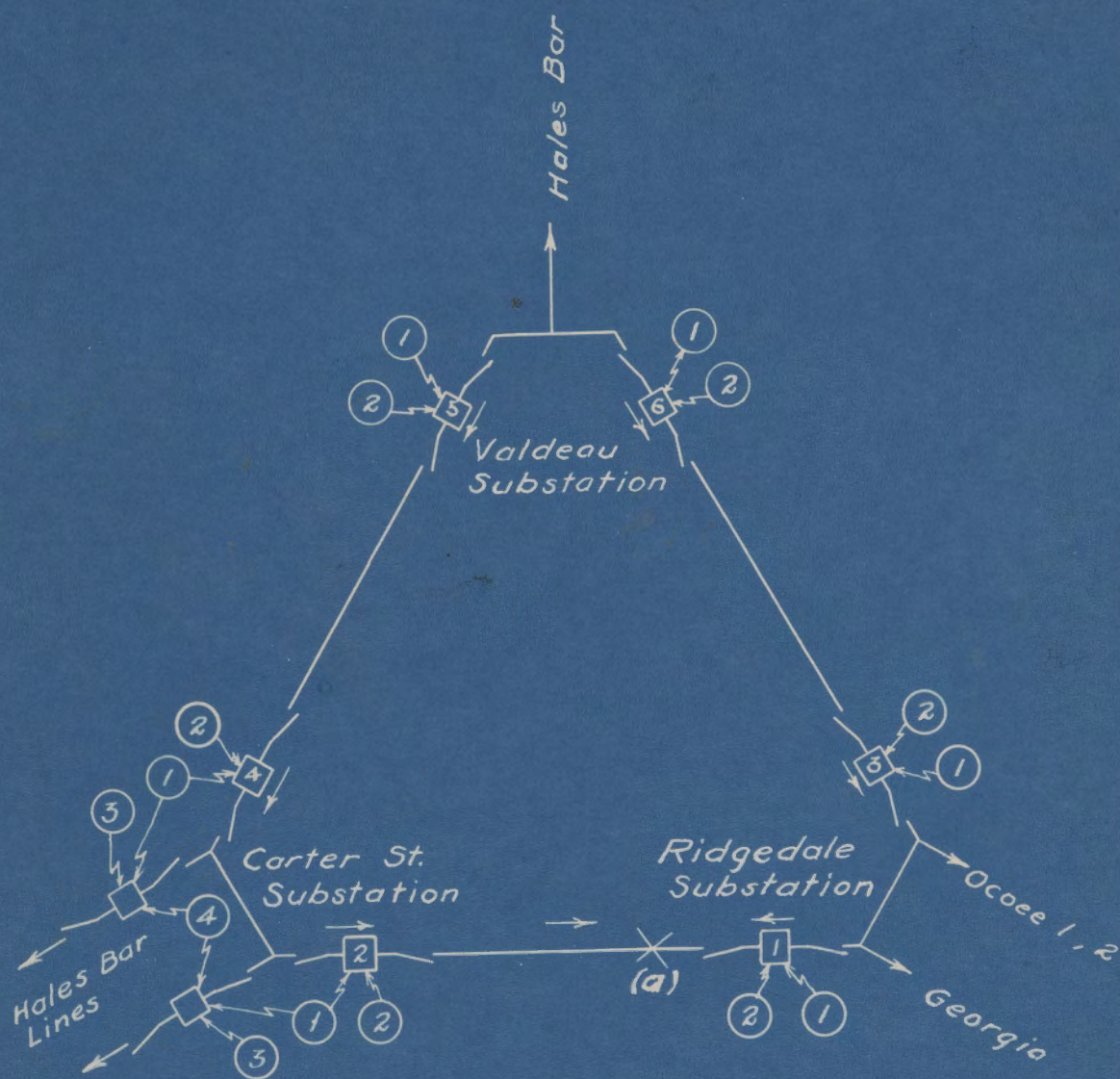
At Ridgedale substation, the relaying duplicates that at Valdeau on the lines at our selected voltage of 44,000: three CZ relays on the Carter Street line and three on the Valdeau line, with one directional ground on each of these lines. The location of these various relays may be more easily seen by referring to figure I, which shows the scheme diagrammatically.

In the following paragraphs, one example of each different type of relay will be considered. The purpose of locating the particular type of relay at a particular point will be given with the intended principle of operation, while some information will be included as to the theory of the operation of the relay, and possibly some data on the time and current or voltage settings of the instrument where such information is considered of importance in this paper. For the first example, it may be well to take one of the impedance ~~directional~~ relays, since they are used

universally in this network and therefore are of importance. In the schemes outlined above, the type CZ or impedance directional relay is used for phase protection; that is, for the purpose of clearing equipment in case of a phase-to-phase short. At Carter Street and at Hales Bar, impedance directional relaying is provided only for the purpose of backing up the operation of the balanced current relays; but this type of relay was installed at each substation in the 44,000 volt loop in order to furnish phase protection primarily.

All calculations for relay operations have been made by assuming faults immediately at the substation bus; this has been done because any fault on lines between these stations will be safely handled if the relays have been set to cover faults at the bus as before mentioned. Figure II shows the Ridgedale-Carter-Valdeau loop, supplied merely with impedance directional relays at each switch, for the purpose of explanation of the way these relays afford phase protection. Figure III shows a wiring diagram of impedance relaying as followed on the Tennessee Electric Power Company system, showing also the removable terminal blocks on the switch board below the relays, used for routine testing. In actual service, of course, the directional, balanced, ground, and balanced current relays are also in the scheme.

Assuming then, one impedance directional relay per phase on each end of each of the three lines forming the loop, consider a fault on one of the substation busses; say at Ridgedale, at the point marked (a). It may be assumed also that each of the substations acts as a source of power, and therefore that current, instantaneously for this assumption, flows toward the fault from each side. Since the assumed fault is at the point (a), the two



(1) - 3-CZ Relays

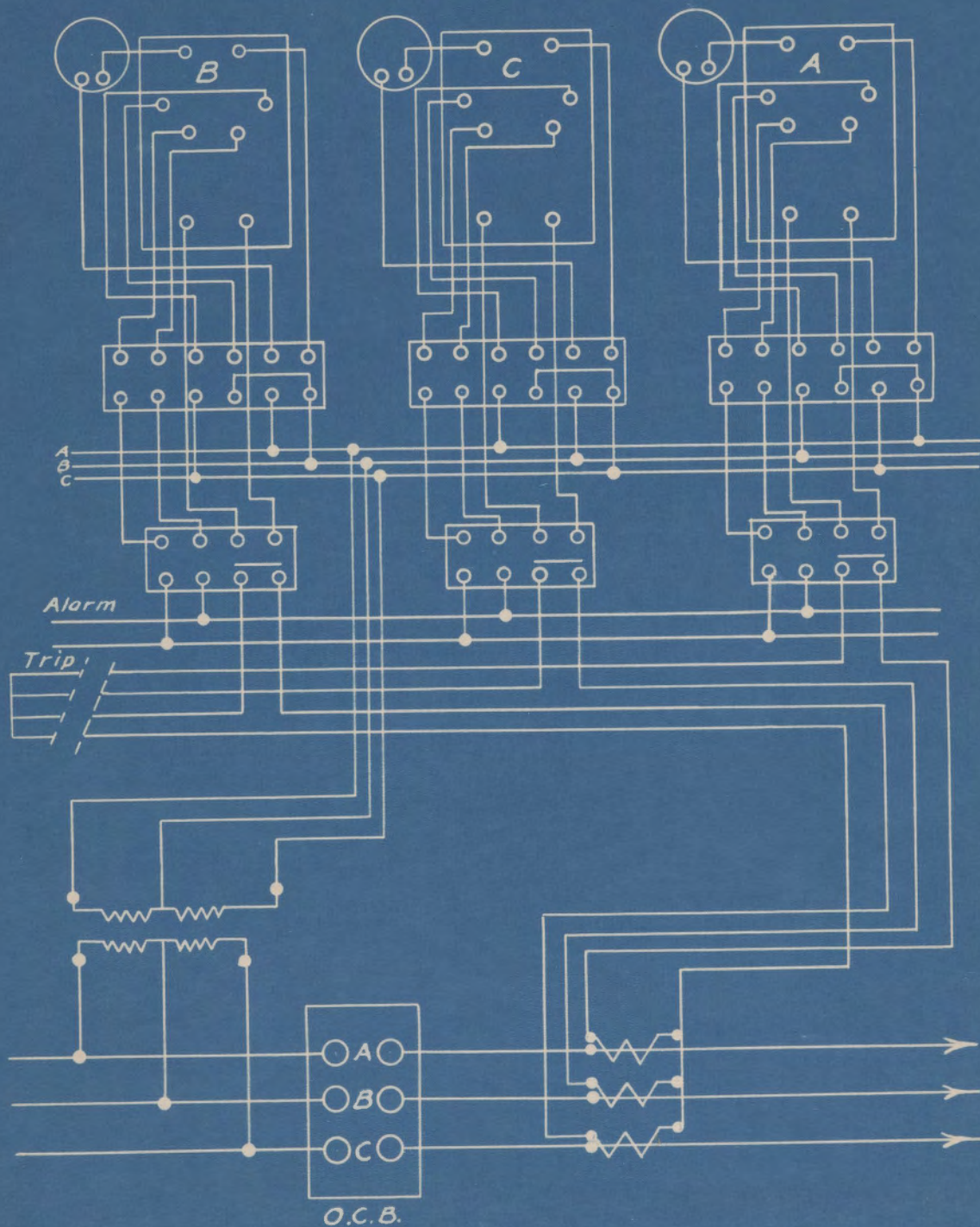
(2) - 1-CWC Relay

(3) - 3-CD Balanced Current Relays

(4) - 1-CD Balanced Ground Relay

Figure 2

Rear View
Phase Sequence is ACB



Wiring Diagram of Type CZ Impedance Relays
Fig. 3

3-17-31 J.L.W.

breakers 1 and 2 should open before any others, and leave the other two sides of the triangle in service. Current will flow at different points on the loop in the instantaneous direction of the arrows. Due to the low voltage impressed on the relays operating from bushing type current transformers on switch 1, this breaker opens first. As a general rule, when the calculations were made for the settings of the relays on this loop, twenty cycles were allowed for operation of the switch, and twenty cycles for leeway. Thus, if a relay is set to close at twenty cycles from the instant of over-current, a total time of sixty cycles, or one second, is assumed as being the elapsed time until the fault is cleared--that is, until the contacts of the switch have been drawn completely past each other, and the arc has died out. The relays operating from switch 3 are inactive due to their directional elements. They are set for outfeed of current at all points. Switch 2 opens next, since there is an outfeed of current through it. It may safely be assumed that, with a relay setting similar to that on switch 1, about twenty cycles more will elapse than in the case of 1, due to the added impedance of the length of line from 2 to the fault. There is an outfeed of current through switches 5 and 6, but they are still farther behind due to line impedance present from there to the fault. They will tend to operate, but after 1 and 2 have isolated the fault they will return to normal position. Any phase-to-phase fault will be relayed similarly to the one assumed above. The impedance of different sections of the loop, under conditions of short-circuit of fault, will determine the operation of the CZ relays at different points. However, in the case of a system of parallel feeders that does not have the characteristics of the loop return, the impedance

relaying would be much different. The return circuit through the earth is relatively long, and it is believed that such a large hypothetical loop has relatively high reactance and hence low power factor on short circuit. This has much to do in determining the time of relaying done by this type of relay.

The value of impedance of a section of line between two stations will not be a straight line if plotted against the distance; at each station it will leave a sharp slope, becoming more horizontal between stations. Hence, in case of a fault near to one station in a system of parallel feeders, a much higher value of impedance would be available due to the earth circuit than that due to line impedance, with consequent delayed timing on any CZ relays near the fault. Hence, it has become advantageous to use plain directional ground relaying on such systems, and to include directional elements in relaying loop systems. What may be called the standard system of directional ground protection for the Tennessee Electric Power Company consists of a grounding bank and two directional ground relays. The high side of the transformers may be connected in Y, with the neutral grounded through a current transformer. The secondary of this transformer supplies current to one element on each of the two relays, while the other element of each is supplied by the totalized currents from each side of the transformer bank. The load at such a station would be supplied by a low side winding in delta or some similar arrangement.

At all three of the substations on the Chattanooga loop, a directional ground protection scheme similar to the above is used, but all three have a so-called cross-connection of current leads supplying the lower coils of each pair of CWC ground relays. At Valdeau and Ridgedale, when grounding banks are installed, the

lower coils of the directional ground relays are in series and receive differential current from the cross-connection of the two sets of current transformers of the two 44,000 volt lines coming to each station. Figure IV shows the scheme used at these two substations, and shows in addition an auto-balance current transformer used to compensate the neutral connection to reduce secondary current to one-half its normal value. The purpose of the cross-connected current leads in to provide double relaying current in case of fault, speeding up the switch tripping. Under condition of fault, the current transformer secondaries are substantially in parallel, giving twice normal or rated current to flow through the lower coils of the directional relays. As may be seen from the diagram of figure IV, however, only one switch has its trip coil energized; the opening takes place on the faulty side of the transformer bank, due to the directional connection of the ground relay contacts. Due to the difference in the impedance of lines on either side of the Ridgedale, Valdeau, and Carter substations, an unbalanced of current would be present under fault conditions, if it were not for the current balance effected by the proper adjustment of the auto current transformer shown in figures IV and V.

A slightly different arrangement of the cross-connection is in service at the Carter Street substation, since at this point no grounding bank is available. A glance at figure IV will show that a current transformer in the neutral ground lead of the transformer bank supplies current for the upper elements of the directional relays at Ridgedale and Valdeau. Figure V shows the totalizing connection of the current transformer leads that supplies the corresponding pair of elements in the directional relays at

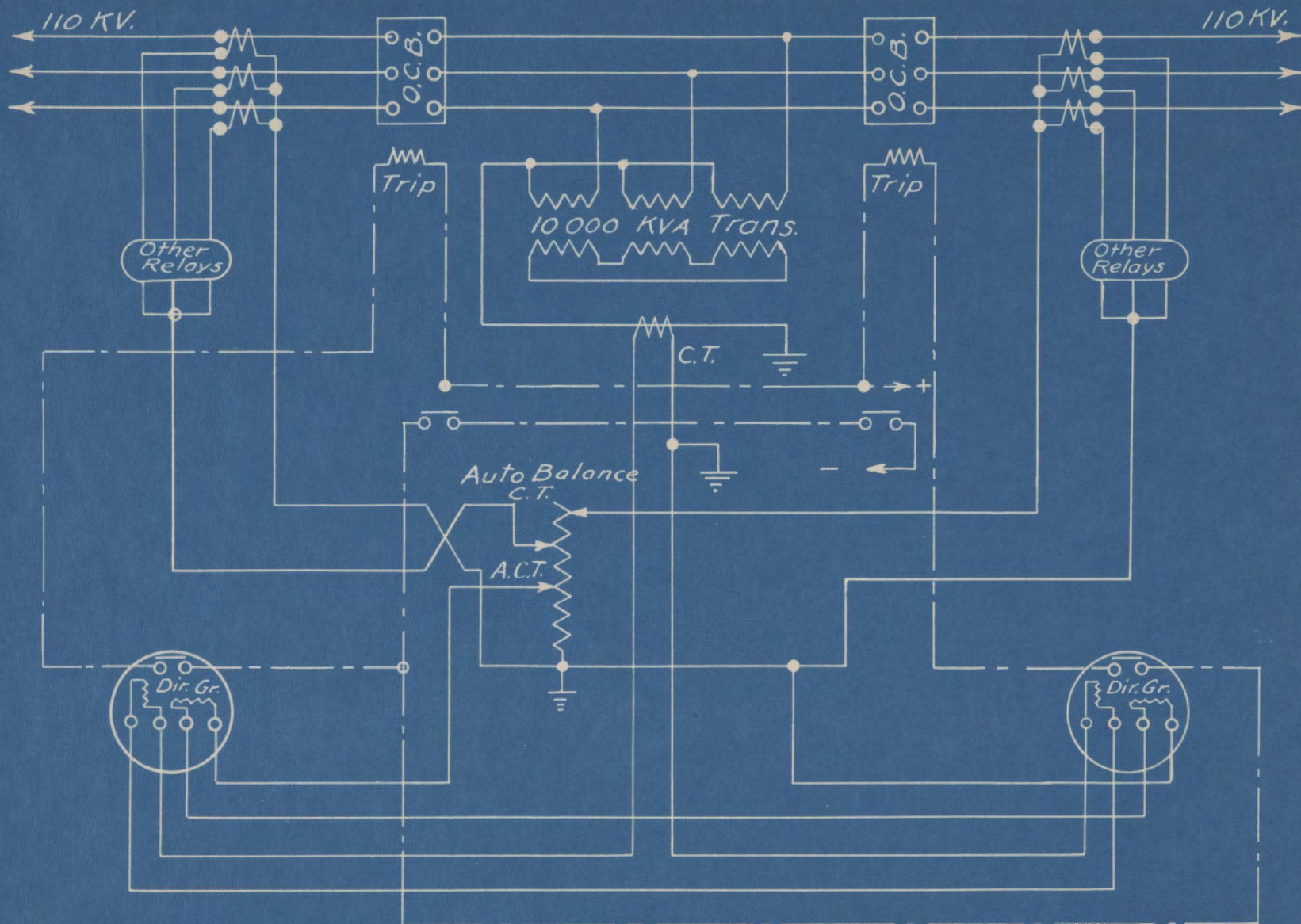


Fig. 4

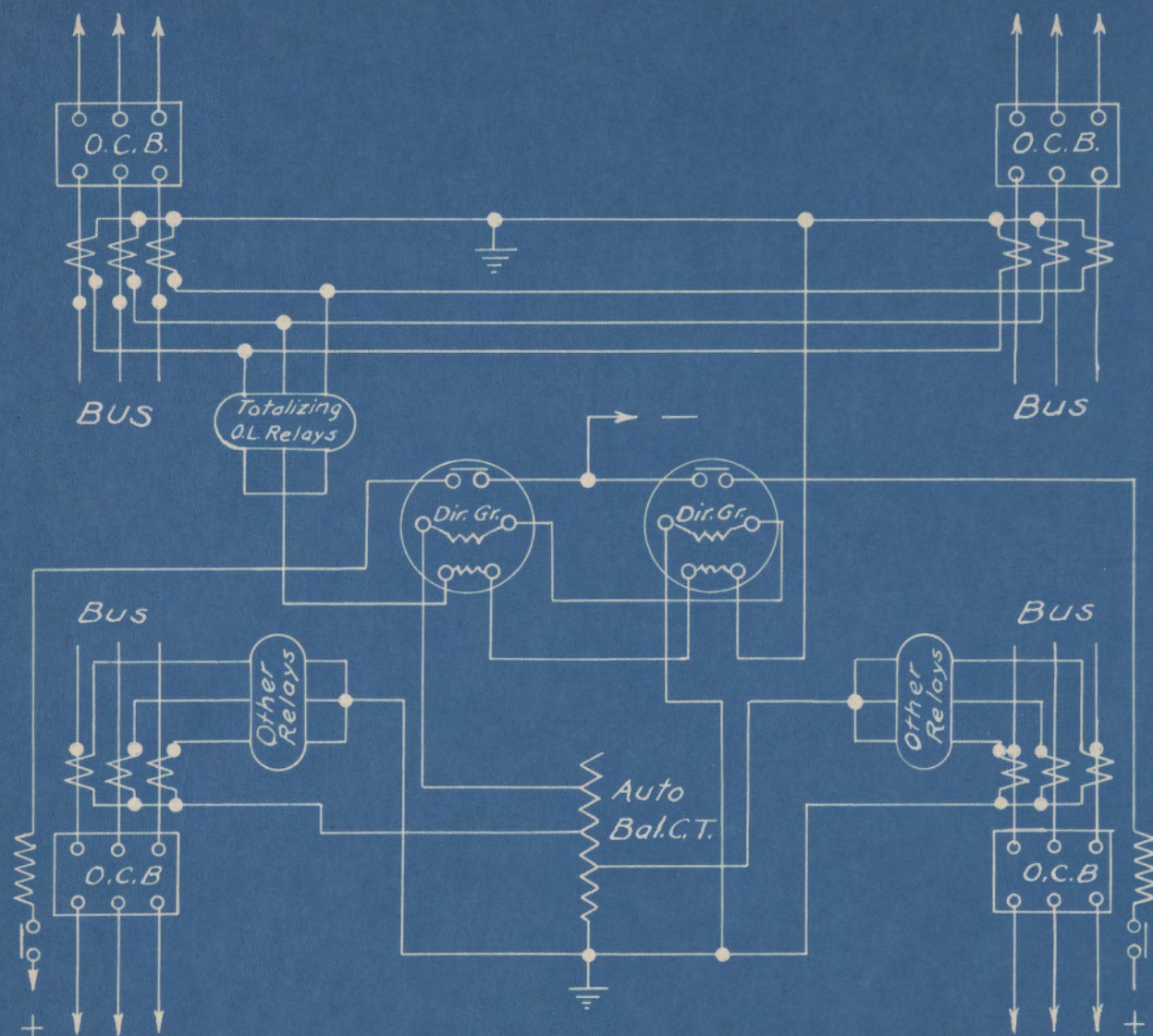
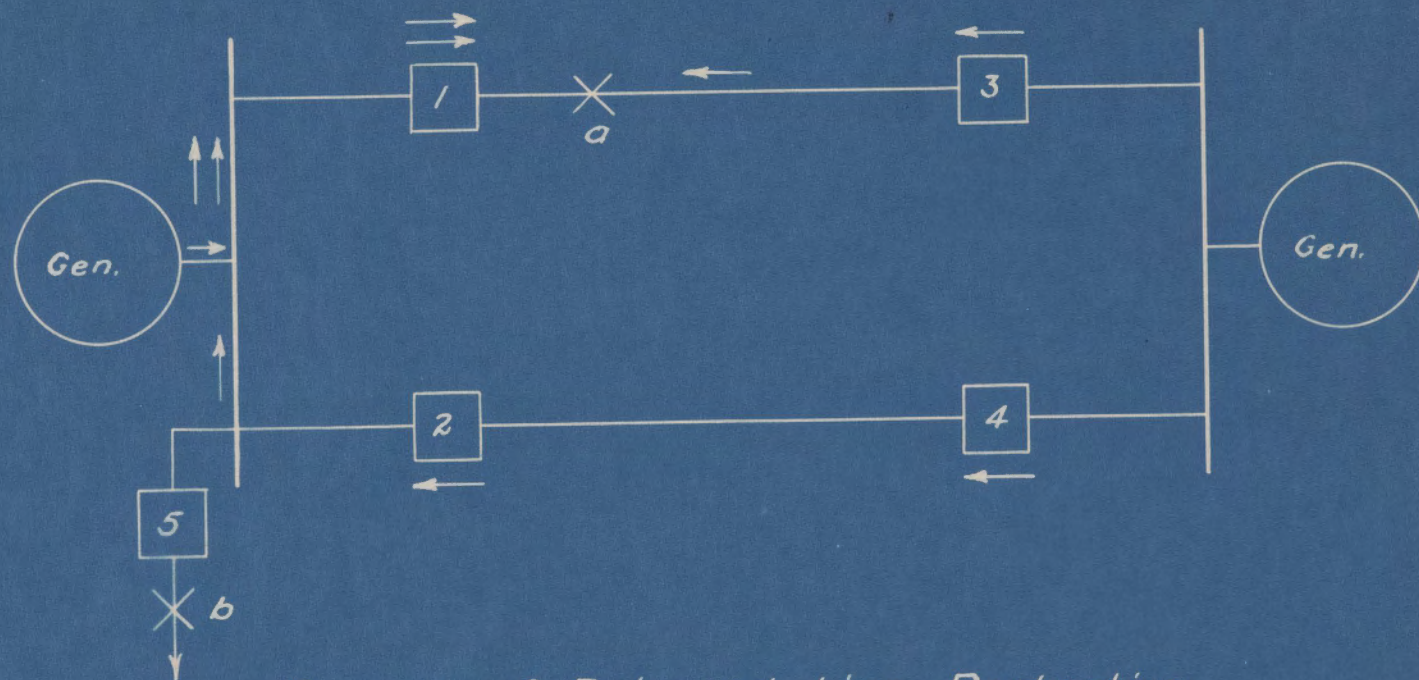


Fig. 5

Carter Street. The other set of elements is supplied with current from the same phases, and in much the same manner as those described at Valdeau and Ridgedale. The so-called auto balance current transformer is shown in the scheme and serves the purpose described above for the other stations. Incidentally, the directional ground relays at Valdeau are the only type CWC used. This relay is manufactured by the Westinghouse Electric Company; at Ridgedale and Carter Street, type IC-5-Y1 relays are used, which are practically the same in operation although of slightly different design. The type IC-5-Y1 relay is manufactured by the General Electric Company.

In addition to the impedance and directional ground relaying at the Carter Street substation, there is balanced overload protection on the Hales Bar North and South lines, provided by the installation of type CD current balance relays. The diagrammatic scheme shown by figure VI gives the idea of parallel line operation as utilized by these two lines. Impedance relays are in service on each line, but are set for slow operation in order to give the CD's time to beat them out. In other words, the CZ relays ordinarily back up the operation of the balanced relays, but are of importance in time of single line operation. One type CD balanced ground relay is also in the scheme, on each of the two lines at either end; these relays back up the operation of the overload ground and directional ground relays on the same circuits.

Assuming, then, such a double circuit line, there are two three-phase circuits in parallel, a bus at either end of this particular section of the system being fed by generation of some sort: Hales Bar hydro plant supplying its end, while the equivalent of supplied power is present at Carter Street, coming from



Example of Balanced Line Protection

Figure 6

Georgia and Ocoee #1 and #2 through the substation at Ridgedale. An additional tap feeder is shown in figure VI for the purpose of explanation. As explained previously, the operation of the type CD balanced current relays is based on the principle of opposing torques. When normal conditions of parallel line operation exist, then, no movement of the relay disk is possible, since the torques produced by the load currents of either line cancel out. In case of a fault at the point marked (a), however, this current will flow, instantaneously, in the direction of the arrows. Due to the length of the lines, the current through switches 3 and 4 will, in all probability, be nearly alike in magnitude and hence will not operate these relays before switch 1 has opened. The line current through switch 2 will add to generator current on this bus, and will cause an unbalanced of current in the two relay elements on this particular phase that has gone into fault. Therefore, switch 1 will come out almost instantly. Switch 2 will not be affected, since the disk rotation will be in the direction to close the other's tripping circuit. In order to prevent 2's opening after a reversal of current flow following the opening of switch 1, the tripping bus connection is interlocked through a series "A" finger on the operating mechanism of switch 1. The term "A" finger is applied to a small current switch that follows the position of the main oil circuit breaker; that is, it opens when the latter opens, and closes when the latter is closed. Current is now flowing back through switch 2 in order to go to the fault through the bus at switches 3 and 4. This causes a current unbalance at this point, and 3 trips, isolating the fault. Another interlocking finger opens the tripping bus to switch 4.

Any fault occurring on an external feeder, such as is indi-

cated by the point marked (b) at the bus of switch 5, will be cleared by relays operating from bushing current transformers on that switch. A plain radial feeder from the main bus of switches 1 and 2 would be protected by straight overload relays, and any other types called for by the characteristics of the service to which the line is put. No operation of the current balance relays would result from a fault at (b), since the fault current drawn from the main bus would presumably divide equally over the two lines coming from the farther point of generation.

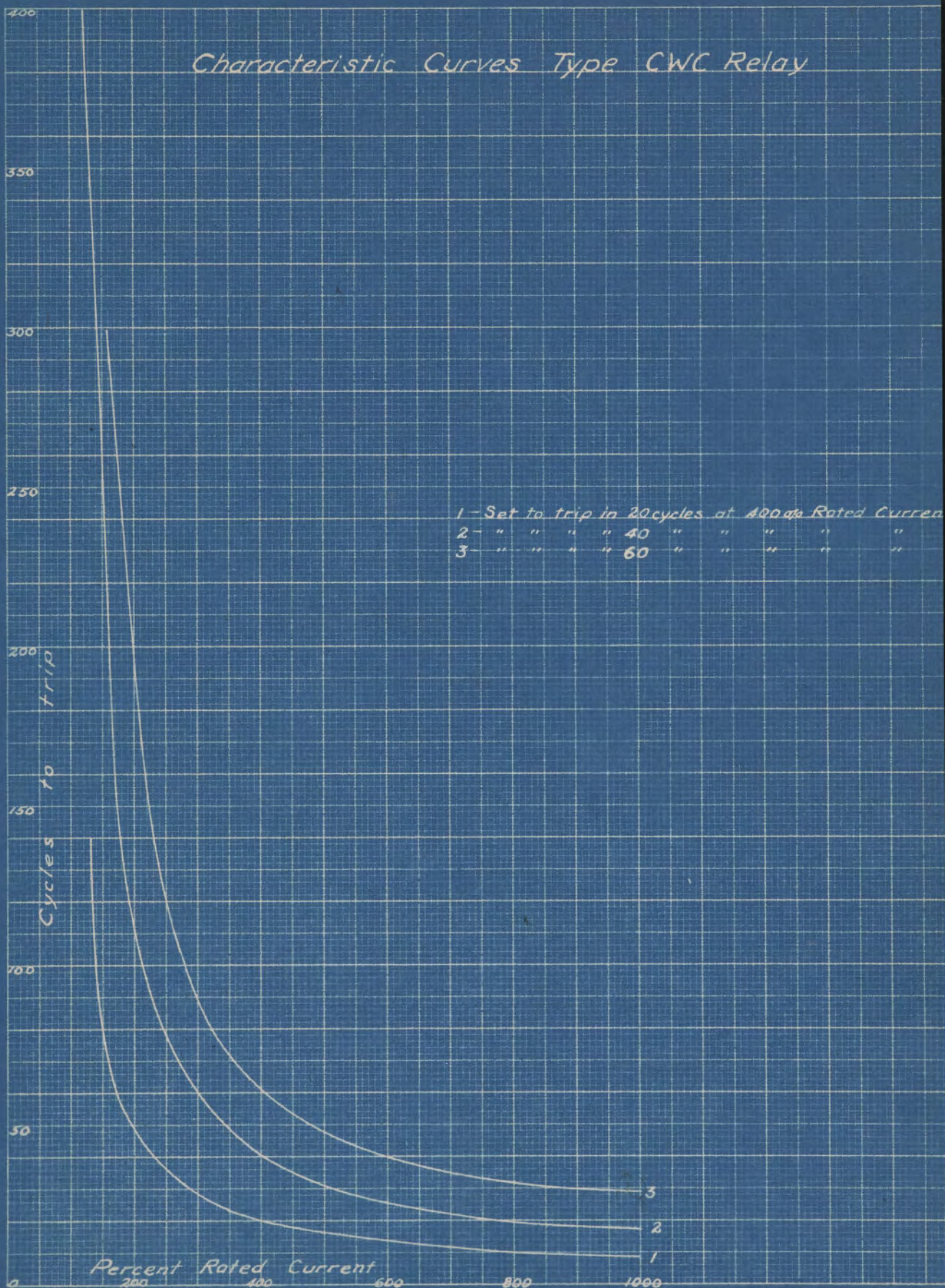
The balanced overload relays described above are accompanied by balanced ground relays, also of the type CD. The former provide phase-to-phase protection, while the latter serve similarly in case of phase-to-ground fault, and at the same time back up the operation of the ordinary overload ground and directional ground relays at both Carter Street and Hales Bar on this double circuit line.

There are included, at the end of this chapter, some examples of relay characteristic curves. The curves are plotted for different time settings of some particular type of relay, and the points are determined by time of contact closing against per cent of rated tap amperes. Usually, several taps are provided, to give the necessary adjustment that will make the relay suitable for the current circuit in which it is used. Curves similar to those shown are very useful in calculating relay settings on some particular service, since the value of "short circuit KV-A" may be calculated for a given line under an assumed fault, and from this the per cent of rated tap current that will flow in the relay circuit may be found. By placing this value on the curve sheet, the time of closing the contacts of the relay may be found for any desired

time lever setting by taking the ordinate to the curve drawn from test results using that setting. All three curve sheets shown herewith were plotted by using 400 per cent tap amperes as a basis for the time lever setting. Some definite minimum time is always present, as was mentioned in Chapter I; this is due to the torque compensator. In other words, above some particular per cent overload, the amount of current will make almost no change in the length of time required to close the relay contacts. Also, the relays shown by these curves all possess inverse time characteristics: the higher the current the less the required cycles to close the trip circuit. Hence, it is of some importance to keep the operation of the relay at points of the curve nearest the origin, or where a change of slope is easily brought about by a change in current.

No actual records of relay operations on this 44,000 volt loop will be given here, but it has been safely estimated that the relaying scheme used is something over 99 per cent accurate; this means that faults occurring on the three lines, or in the substation busses, have been cleared exactly as calculated more than 99 per cent of the time. Less than one fault in a hundred occurs that is not relayed and cleared as is desired.

Characteristic Curves Type CWC Relay



Characteristic Curves Type CD Overload Relay

150

100

50

Cycles to trip

- 1 - Set to trip in 20 cycles at 400% Rated Current
 2 - " " " " 40 " " " " "
 3 - " " " " 60 " " " " "

3

2

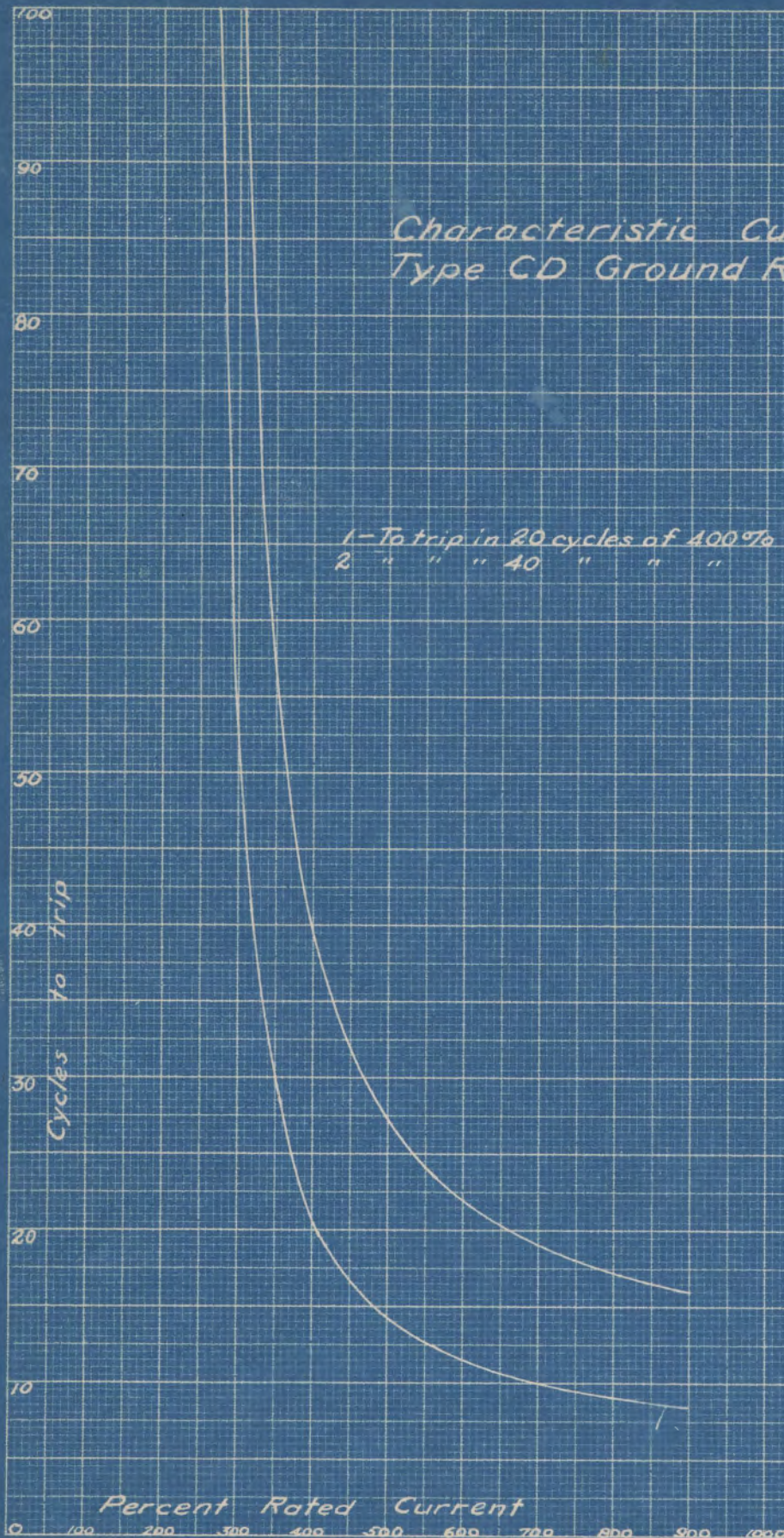
1

Percent Rated Current

0 100 200 300 400 500 600 700 800 900 1000

Characteristic Curves Type CD Ground Relay

1- To trip in 20 cycles of 400% Rated Current
2 " " " 40 " " " " "



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- III. Records Filed in the Offices of the Tennessee Electric Power Company at Chattanooga.

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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