American Railway Signaling Principles and Practices

CHAPTER XI

Non-Coded Alternating Current Track Circuits

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CHAPTER XI

NON-CODED ALTERNATING CURRENT TRACK CIRCUITS

For many years direct current only was used for track circuits, but when it was found to be inadequate for electrified roads, due to the interference of the propulsion return current, the alternating current track relay was developed by Mr. J. B. Struble, and was first used in 1903 on the North Shore Railroad in California. The alternating current track circuit consists of a portion of track sectionalized by means of insulated rail joints, as in direct current track circuits; its energy is derived either from a track transformer receiving energy from a line transformer connected to a transmission line or from a combined line and track transformer. The transformer connected to the track transmits its energy through the rails to an alternating current relay. In the track circuit are various auxiliary attachments which will be considered later.

The first relay designed for the alternating current track circuit was the single-element vane relay. It operates solely by the current received from the transformer through the rails of the track circuit, as shown in Fig. 1.

The development of the two-element alternating current relay followed several years after that of the single-element relay, for use on long track circuits where the single-element relay is impractical due to the excessive power necessary to operate it.

The two-element track relay has a track element and a local element. The energy required in the track element is transmitted through the rails and is comparatively small, while the local element requires more energy, which is usually furnished from a local source. This relay requires the presence of currents in both elements at the same time to operate it, as shown in Fig. 2. The absence of current in either element will de-energize the relay; thus a train entering the track circuit shunts the current from the track element de-energizing the relay.

Alternating current track relays are practically immune to the propulsion current used by the railroad and to stray direct current. This latter feature along with their simplicity and economy in maintenance has been the dominant factor in bringing the alternating current track circuit into extensive use on steam roads. On electric roads the use of the alternating current track circuit is practically imperative, as the signal current and the return propulsion current flow through the same rails.

A low track voltage is necessary, as with direct current track circuits, to minimize the leakage of the track circuit current from rail to rail. The initial voltage depends on the type of relay, the length of track circuit, and various other conditions.

The rectified alternating current track circuit, a later development made in the interest of economy, uses a rectifier, either full-wave or half-wave, and a direct current neutral relay.

Alternating Current Track Circuits on Steam Roads

There are two types of alternating current track circuits in use on steam roads:

1. Those using alternating current relays, either single-element as shown in Fig. 1, or two-element, either two-position as shown in Fig. 2 or three-position as shown in Fig. 6.
2. Rectified alternating current track circuits using a direct current relay and a rectifier. Several arrangements are in use as described under the heading "Rectified alternating current track circuits on steam roads."

Alternating current track circuits with alternating current relays.

This type track circuit was extensively installed in the past on many steam roads for several reasons:

1. To provide track relays immune to stray direct current.
2. To enable in the case of two-element, two or three-position relays, the use of longer track circuits than could be operated using direct current relays.
3. To obtain detection of broken-down insulated rail joints, as hereinafter explained under the heading "Protection against broken-down rail joints."

This type track circuit as in service on steam roads is usually end-fed, although center-fed track circuits are also in service.

Very few extensive installations of alternating current track circuits using two or three-position alternating current track relays have been made on steam roads during recent years; instead, this kind of installation of automatic block signaling is using either coded direct current track circuits, or storage battery fed track circuits with battery on float charge, or the AC primary system with direct current track circuits fed by primary battery.

End-fed track circuits using alternating current track relays as installed on steam roads are shown in Figs. 1 and 2.

On steam roads there are alternating current track circuits in service from a few feet up to approximately 10,000 feet in length. The maximum length of track circuit using a single-element relay is approximately 1,000 feet.

Exhaustive studies indicate that, where the minimum ballast resistance is not less than 4 ohms per 1,000 feet of track, the maximum length for a 60-cycle track circuit using a two-element relay should not exceed approximately 8,000 feet. Where the minimum ballast resistance is as low as 2 ohms per 1,000 feet the maximum length should not exceed 5,500 feet. In 100-cycle territory these maximum lengths should be reduced to 6,000 feet and 5,000 feet, respectively. The maximum permissible length of track circuit will vary somewhat depending upon the operating characteristics of the track relay and other details of the track circuit arrangement. The relay operating characteristics will vary depending upon the particular type of relay and the number of contacts. In general, a relay with only one or two front contacts has a higher ratio of release to normal operating value and can be operated safely on longer track circuits than relays with more contacts.

While track circuits equipped with two-element relays longer than those specified in the preceding paragraph may be operated, it is not advisable to do so for the following reasons: (1) it is impracticable to keep the voltage at the relay track element terminals within the limits to secure shunting value recommended by the Signal Section; (2) added difficulty of wet weather operation, and (3) less broken-rail protection.

The single-element track relay is a two-position relay, as shown in Fig. 1, while the two-element relay may be operated as a two-position relay as shown in Fig. 2, or as a three-position relay as shown in Fig. 6.

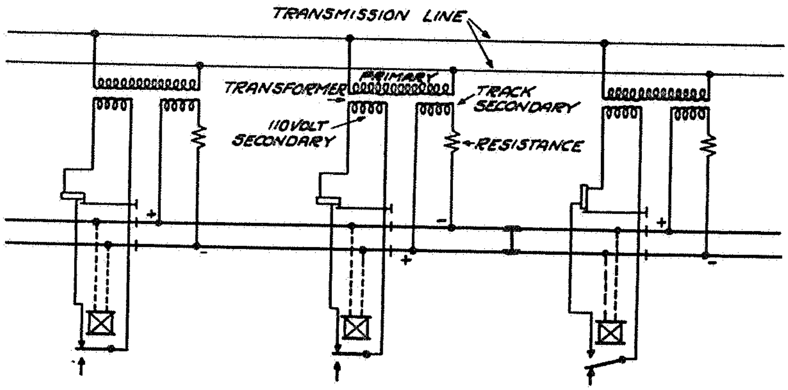


Fig. 1.
Single-Element Relay Alternating Current Track Circuits on Steam Roads.

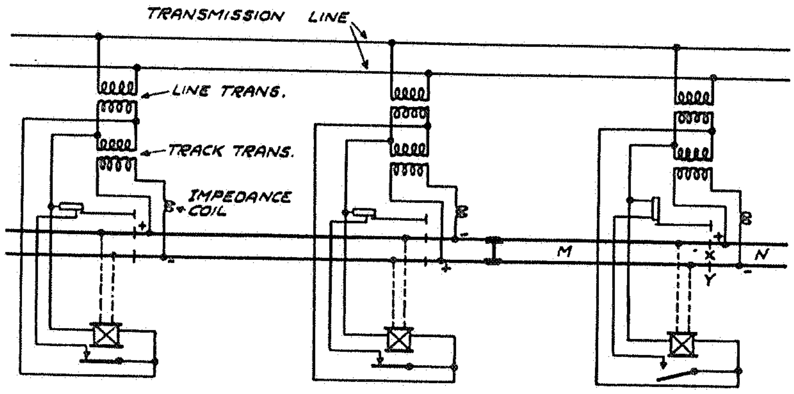


Fig. 2.
Two-Element, Two-Position Relay Alternating Current Track Circuits on Steam Roads.

When the three-position relay is de-energized it assumes the central or neutral position, by means of a counterweight in the relay, as shown at A in Fig. 6. The moving member makes contact to the right or left, depending upon the relative flow of currents in the two elements of the relay. A reversal of the current flow in either element will reverse the movement of the magnetic flux. As the relative polarity of current in the local element is usually fixed, the flow of current in the track element is reversed by means of a pole changer operated by the signal mechanism, as shown in Fig. 6. It is this action of the pole changer that produces a change of phase angle of 180 degrees, as mentioned in Chapter X—Alternating Current Relays.

Rectified alternating current track circuits on steam roads.

The rectified alternating current track circuit, a later development than that using an alternating current track relay, was made to provide a less costly track circuit arrangement that could be used, under certain limited conditions, in place of the alternating current relay type.

There are several kinds of this type track circuit in use:

(a) The full-wave using a transformer-rectifier unit interposed between track and the direct current relay as shown in Fig. 3.

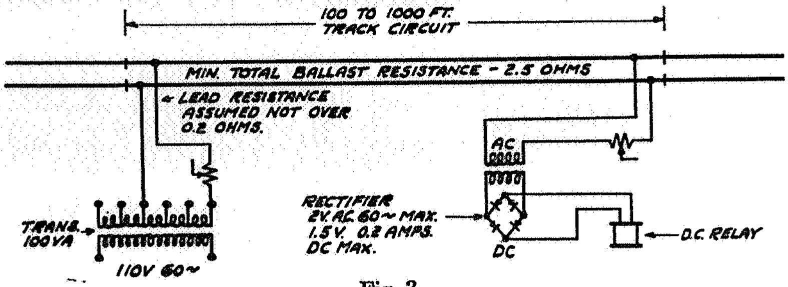


Fig. 3.
Full-Wave Rectified Alternating Current Track Circuit.

(b) The Type A, half-wave as shown in Fig. 4. This circuit uses a half-wave rectifier between transformer and track with a bleeder resistance across the leads to the rails at the feed end of the circuit with a direct current relay at the other end of the circuit with as much resistance as minimum ballast resistance will permit, interposed between track and relay. This circuit, due to its high shunt sensitivity and quick relay release, is particularly suitable for application to detector track circuits at interlockings.

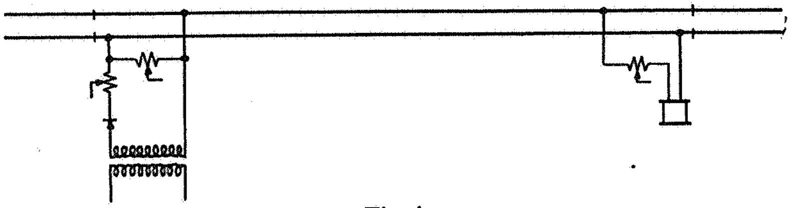


Fig. 4.
Type A Half-Wave Rectified Alternating Current Track Circuit.

(c) The Type C, half-wave as shown in Fig. 5. In this circuit the direct current relay is connected to the track leads at the feed end and a half-wave rectifier is connected between rails at the opposite end of the circuit. The use of this track circuit at highway crossing locations in non-signaled territory avoids running line wires to or installing battery at the far ends of the approach circuits.

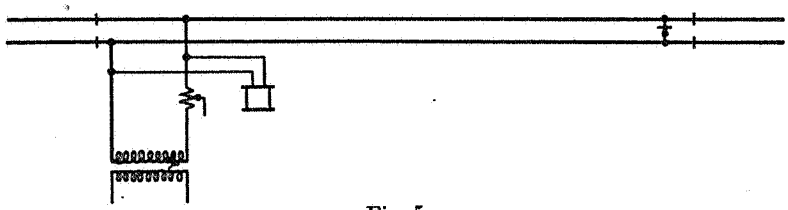


Fig. 5.
Type C Half-Wave Rectified Alternating Current Track Circuit.

Protection against broken-down rail joints.

Some degree of protection against broken-down insulated joints is secured with two-element two-position alternating current relays by staggering or reversing the polarities of adjacent track circuits.

In Fig. 2, the polarities of track circuits M and N are opposite at any given instant and if insulated joints X and Y were to break down, contacts of relay B should open due to a change in phase relation causing the signal to assume its most restrictive indication. This same protection cannot be procured with the two-element three-position or the single-element relays, yet it is customary to stagger the polarities for a three-position relay in order to procure some protection by preventing the signal from displaying a more favorable indication than Approach. This is illustrated in Fig. 6 which shows the conditions when the first track circuit at the left of the diagram is occupied by a train. Statements about changing and reversing polarity simply mean that at any given instant the polarities are reversed or changed from a positive to a negative polarity, since the alternating currents are periodically changing in direction.

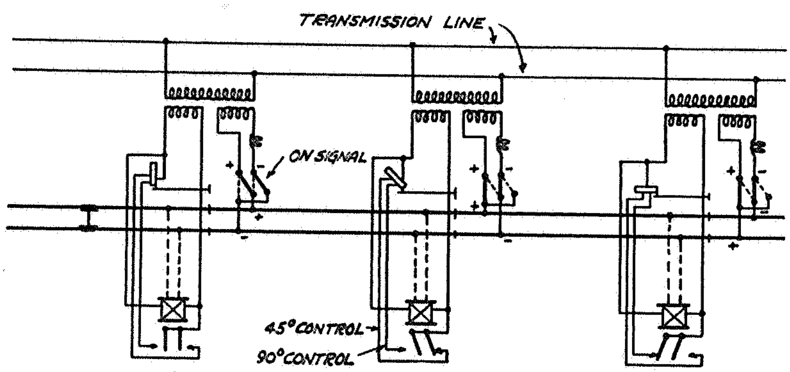


Fig. 6.

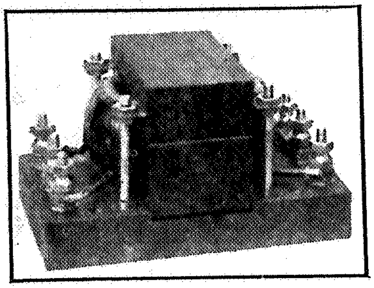
Two-Element, Three-Position Relay Alternating Current Track Circuits on Steam Roads.

While it is possible to feed two track circuits in multiple from one secondary of the transformer, yet it is advisable to feed each track circuit from a separate secondary of the transformer. When one secondary is used to feed more than one track circuit a train occupying one track circuit may cause interference with the other track circuit, and also may lessen the broken-rail protection.

Reactors.

The track transformer having low internal resistance must have a reactor (or resistor) inserted between the transformer and the track to limit the flow of current when the track circuit is shunted, as the transformer might seriously heat or burn up, also power would be wasted. Adjustable track reactors are illustrated in Fig. 7.

The adjustable track reactor consists of a form wound coil well protected against moisture, assembled in a laminated iron core, divided into two parts, the space between them being adjustable. Further adjustment is made through different combinations of the various terminals. The adjustable track reactors are generally used on steam roads instead of resistors. The power factor varies from 0.1 to 0.3 and the voltage drop is practically wattless. With the single-element relay, it is used only as a matter of power economy as it has no bearing on its phase relation.



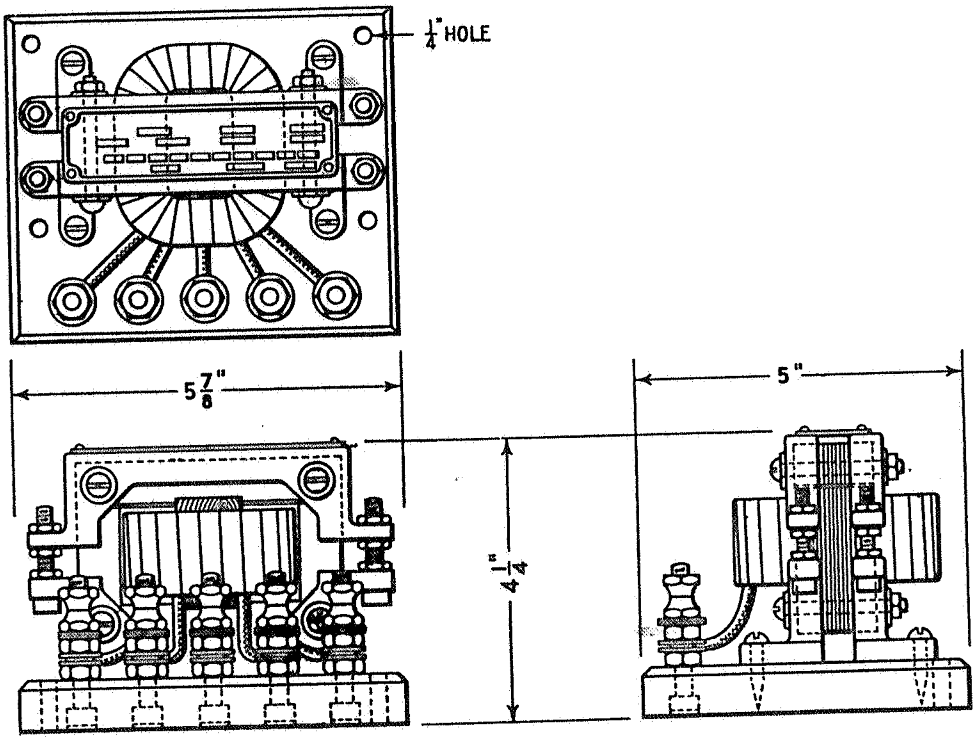


Fig. 7.
Adjustable Track Reactors.

With the two-element relay, the type of relay and the limiting impedance must be selected depending upon the length and other conditions of the track circuit so that the phase relations will be suitable to make the relay operate properly. In the vane or induction motor type of relay commonly used, in general, the magnetic fluxes in the two elements should be 90 electrical degrees or ¼ cycle out of phase with each other for best operation. This usually corresponds to the currents in the two elements also being approximately 90 degrees out of phase and may require some method of phase shifting. For short track circuits, it is common to make use of the inherent phase relations obtained by using a resistor as the current-limiting device in the track circuit so that the current in the control element of the relay will be nearly in phase with the line voltage, lagging by only a small phase angle. The current in the local element inherently lags the line voltage by a large phase angle because of the relatively large inductive reactance of the winding. This arrangement gives phase relations that are not ideal and become rather poor on the longer circuits. The operation is entirely satisfactory on short track circuits, however, and shunting conditions are good because the track shunt tends to make the phase relations worse.

For track circuits longer than approximately 3,000 feet, this type of operation is not practical because of the large amount of phase shift introduced by the track circuit, causing the current in the control element of the track relay to be too far out of phase with the line voltage. On the longer track circuits it is customary to use a reactor as the limiting device, thus introducing further phase shift in the track circuit current, and to provide some other means of getting suitable phase relations at the relay. One method that has been used to a limited extent is to provide a two or three-phase signal power line and energize the local element of the relay with a different phase from the track circuit, but the more common methods are for use on single-phase power supply. One common and very efficient method is to use a capacitor so connected as to be effectively in parallel with the control winding of the relay. In other arrangements a resistor or capacitor, or a combination of both, may be used to provide phase shifting in the local element of the relay.

In the past, some adjustment in the track circuit has been made by changing taps on the limiting reactor, but the usual modern practice is to use a predetermined tap on the reactor (or resistor) as recommended for the particular track circuit conditions, and then to adjust the track transformer secondary voltage in small steps as required for good operation. In calculating, selecting, and adjusting the relay and other apparatus for long track circuits, the aim usually is to obtain nearly ideal phase relations for the least favorable ballast conditions when the track voltage is the lowest. When the ballast conditions are more favorable, the track voltage will be higher and the relay will operate satisfactorily even though the phase relations are not as good.

It is possible to have sufficient energy going through both elements of the relay, but not having proper phase displacement, the relay will fail to operate. Thus the track relay may be made to operate by improving the phase relation, although in the adjustment the track voltage would be lowered by the introduction of impedance.

Sometimes when the track circuit is long and with poor ballast conditions, a non-adjustable reactor or resistor is used in the local element circuit. In some types of relays a small condenser is housed in the relay and used with the track element to aid in securing proper phase relations.

Bonding of rail on steam roads.

Channel Pin Type Rail Bonds

No. 8 B.W.G. galvanized iron or steel bond wires were first used. Two wires per joint, each wire from 3 to 4 feet long, are connected to the web of the rail by channel pins. This type, while still in use to some extent, has been gradually superseded either by No. 6 copper-covered steel or No. 6 copper bond wires on such roads as still employ channel pin type bonds, since these bonds have better conductivity and greater resistance to corrosion where subject to brine drippings, gases, etc.

Plug Type—Web of Rail, Long Rail Bonds

These bonds are used in lengths of 3 to 4 feet. The stranded single-conductor bond is composed of a number of wires, usually 7 or 19, of either copper, copper-covered steel or steel wires with a tapered steel pin welded to each end. The pins are driven into a ⅜ inch hole in the web of the rail.

This type is also made with two stranded conductors each welded to the same single tapered pin at each end. This type bond is stronger, more resistant to corrosion and of lower resistance than the channel pin type having the same kind of wire.

Rail Head Type—Short Bonds

These represent the latest development in rail bonds. They are in extensive use for bonding rail in coded track circuits and in conventional type track circuits where a low and very uniform resistance of bonded rail is desired in order to improve track circuit operation or to operate track circuits of somewhat increased length. They are available in two types: (1) mechanically applied, plug type, and (2) welded to rail type. They usually comprise a single rope lay stranded conductor made up of a center strand of 12 or 19 wires, surrounded by 6 strands of 12 or 19 wires each. Each end of the stranded conductor is attached to a rail terminal of the proper design for its application. These bonds are usually 4 to 6 inches long between terminals. The stranded conductor may be made up of bronze or copper wires, galvanized steel wires or a combination of a copper center strand surrounded by galvanized steel strands. The bonds with bronze wire conductor are in quite extensive use.

Data on impedance and power factor of bonded rail is compiled in Table I.

The methods for bonding steam road track circuits have been and are receiving considerable attention and study, and experiments are being made with various other types of bonds than those described.

Insulated rail joints.

Figure 8 shows one of various types of insulated joints used.

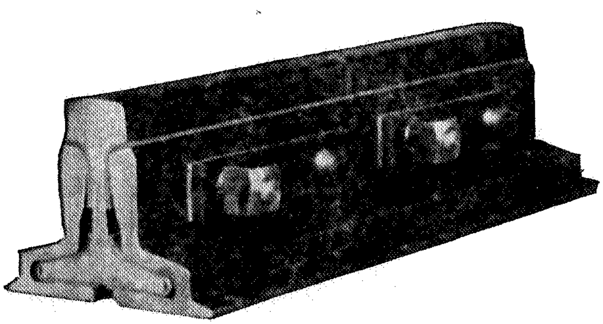


Fig. 8.
Insulated Rail Joint, Continuous Type.

Insulated joints are applied at the limits of each track circuit, also at turn-outs, crossovers, etc., to restrict the flow of current to certain predetermined limits. These joints are applied to the rails in place of the regular splice bars. Fibre, bakelite or other insulating material is used to insulate one rail from the other.

Direct Current Single-Rail Track Circuits on Electrified Roads Using Direct Current Propulsion

Direct current electrification of railroads occurred before alternating current track relays had been invented. Hence attempts were made to use direct current track relays, both neutral and polarized, then available. This practice was soon found to be unsafe, and as a result hastened the development of the alternating current track relay.

Figure 9 shows this type of circuit as used employing a direct current neutral relay. One rail, designated the "power" rail, was used as a common for both the propulsion return current and the track circuit current; the other rail, designated "signal" rail, was insulated at each end of the track circuit. The propulsion return current caused a voltage drop in the power rail between the ends of the track circuit which could be indicated by voltmeter V. This would cause a flow of propulsion current in the multiple path through battery, signal rail and relay coils in an amount directly proportional to the voltage V, and inversely proportional to the resistance of the path through the signal rail. Resistance units and fuses were used in the track leads at the battery and relay ends of the track circuit. However, it was found, as is obvious, that a broken rail or a high resistance rail bond in the power rail created a condition for which sufficient propulsion current could flow through the relay coils to cause it either to fail to release or to pick up improperly with a train in the track circuit. The possibility of the occurrence of this very undesirable condition caused the abandonment of this type track circuit and replacement of those in service with an alternating current single-rail track circuit as soon as the alternating current track relay was available.

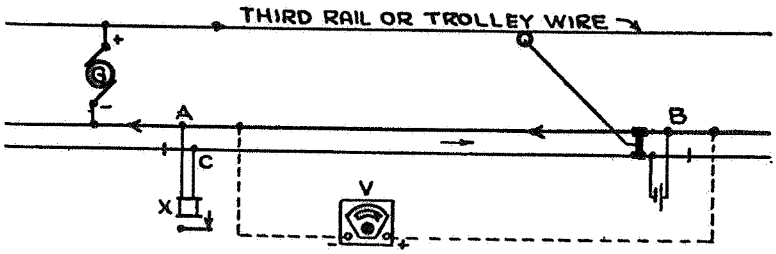


Fig. 9.
Illustrating Effect of Propulsion Drop.

Alternating Current Track Circuits on Electric Roads Using Direct Current Propulsion

Generally, electric road alternating current track circuits and steam road alternating current track circuits are identical, except that on electric roads the return of the propulsion current must be given special consideration.

Single-rail track circuits.

The first development of the alternating current track circuit is shown in Fig. 10.

One rail is used for the propulsion return current and the opposite rail is insulated and used for the signal track circuit.

Using one rail for signal purposes may require an extra cable to be run to carry the propulsion return current. This cable should have at least the same current-carrying capacity as the rail.

At all interlockings where sufficient return carrying capacity is obtained by cross-bonding the return rails, where the single-rail track circuit gives simplicity and adaptability to fouling protection, and where the installation of a two-rail track circuit would be costly and cumbersome, the single-rail track circuit has important advantages.

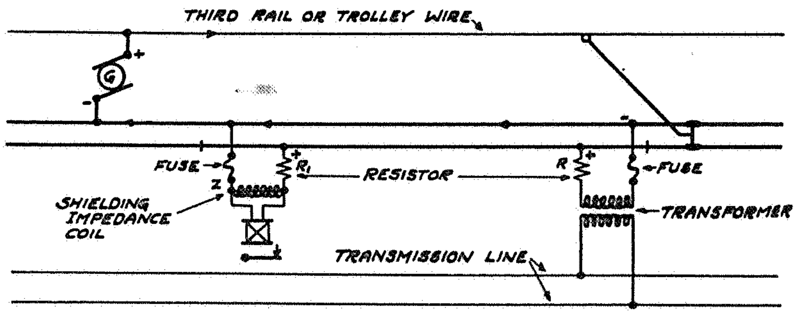


Fig. 10.
Single-Rail Alternating Current Track Circuit.

On a single-track road where one rail is used for the propulsion return current and the other for the signal track circuit, broken-rail protection is provided for the signal rail and a certain degree of protection is provided for the propulsion rail provided an extra cable has not been used to supplement the current-carrying capacity of the propulsion rail. On a multiple-track road using single-rail track circuits where the rails used for the return of propulsion current are cross-bonded, it is possible that a broken propulsion rail will fail to open the front contacts of the relay and detect the broken rail.

As in Fig. 9, a certain direct voltage occurs across the relay terminals. Even when there is no train in the circuit, the signal rail is connected in multiple with the return rail by the transformer and relay track leads and carries a portion of the propulsion return current. The amount is inversely proportional to the resistance offered.

The direct propulsion current does not affect the safety of the alternating current track circuit as the relay is designed to operate only by alternating current. Since the ohmic resistance in the alternating current relay and the secondary of the transformer is quite low a considerable amount of direct propulsion current would flow through them were it not for the insertion of a resistance in the signal track circuit as shown at R and R_1 in Fig. 10.

Resistors.

Formerly, heavy cast-iron grid resistors were used at the transformer and the relay. The present practice is to use resistors, as shown in Figs. 11 and 12. These resistors consist of wire wound on an insulated core. Practically all of them are adjustable for adaptability to varying track circuit conditions. The size of the resistors used depends upon the amount of resistance required and the amount of current to be carried. They are practically non-inductive.

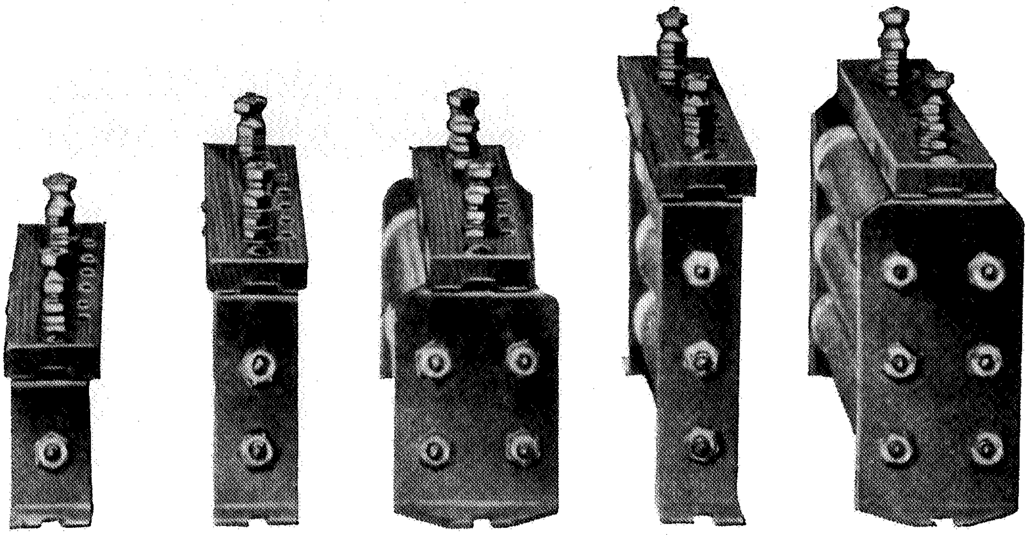


Fig. 11.
Vitreous Enamel Resistor Units Assembled in Various Combinations.

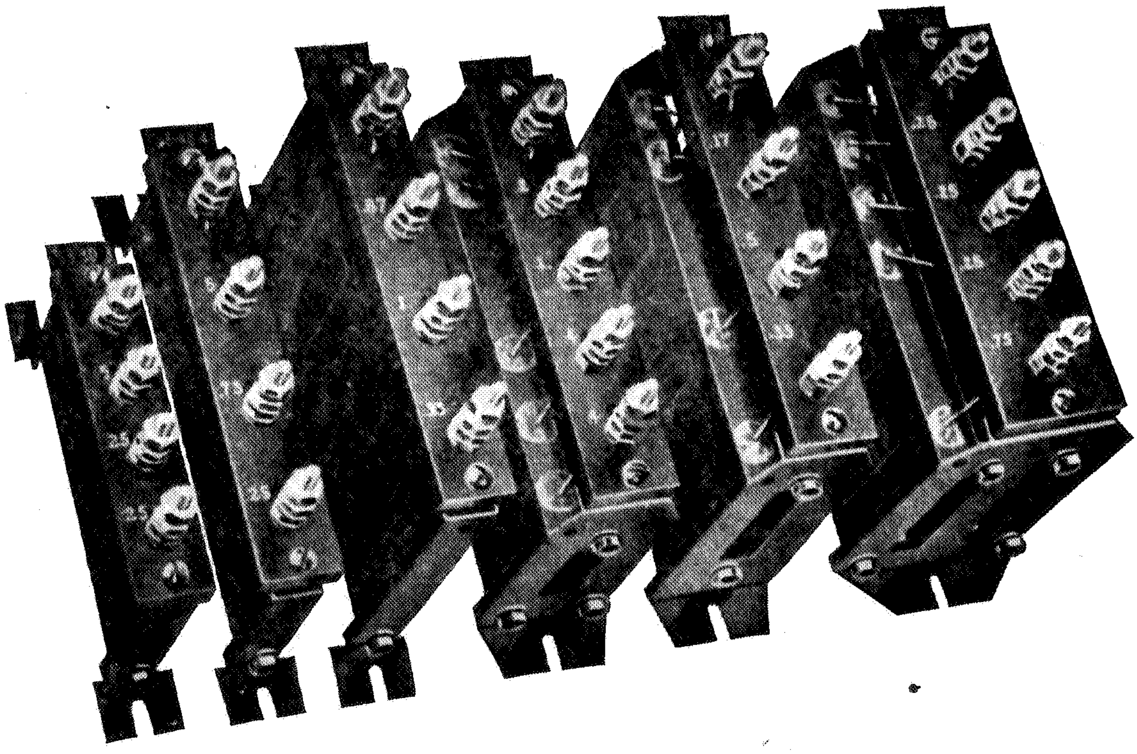


Fig. 12.
Metal-Clad Tapped Resistors.
(Watt Rating Varies with Size of Resistor.)

Shielding impedance.

Where the propulsion current is very heavy, the track relay is further protected by a shielding impedance, Fig. 13, connected across the track terminals of the relay, as shown at *Z* in Fig. 10, to act as a by-pass for this current. The coil, wound around a laminated iron core, has a low ohmic resistance which allows practically all the direct current to flow through it, but possesses a very high impedance due to its self-induction properties, which chokes back a large percentage of the alternating current.

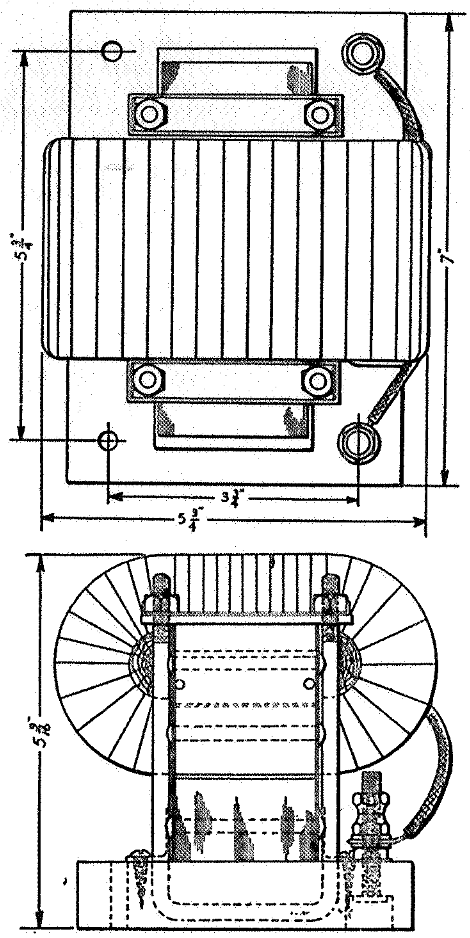


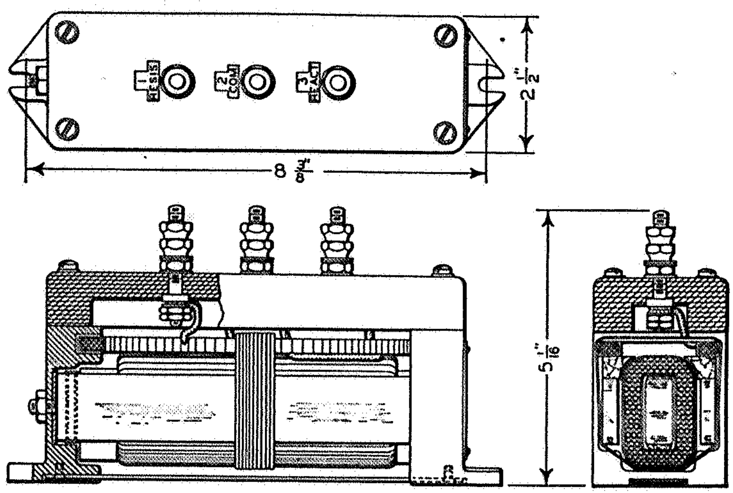
Fig. 13.
Shielding Impedance.

Balancing impedance.

The balancing impedance shown in Fig. 14 illustrates another device that is applied to the track element of a two-element track relay in order to prevent interference by direct current with the normal operation of the relay when it is used on single-rail track circuits.

The application of the balancing impedance to the two equal sections of the relay track element is illustrated by the circuit, Fig. 15. The balancing impedance has two sections, each having equal ohmic resistance, but one section, wound on the laminated magnetic circuit of the device, also offers a high impedance to alternating current. The connections as shown between the balancing impedance and the two sections of the relay track element, each of equal resistance and impedance, cause any direct current from track to relay track element to flow in equal amount and in opposite directions through the two sections of the track element, thereby neutralizing any effect on the relay magnetic circuit.

The alternating current is prevented from flowing through the reactive section of the balancing impedance and its corresponding section of the track element and therefore is directed through the resistive section of the balancing impedance and its corresponding section of the track element, thereby producing relay operation.



BALANCING IMPEDANCE

Fig. 14.
Balancing Impedance.

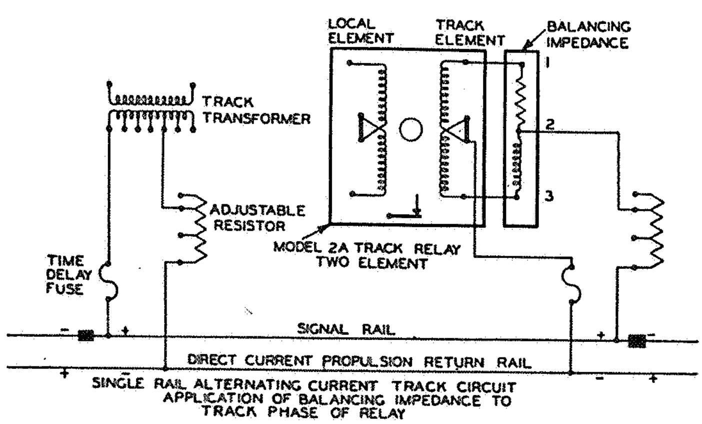


Fig. 15.
Single-Rail Alternating Current Track Circuit.
Application of Balancing Impedance to Track Phase of Relay.

Double-rail track circuits.

Due to the limitations of the single-rail alternating current track circuit and for the purpose of using both rails of the track for propulsion return current, the double-rail track circuit shown in Fig. 16 was devised.

While this circuit (Fig. 16) shows track leads connected direct to track rails and without fuses, some roads connect these leads to terminals inside the impedance bond. However, in such cases the insulated rail joints must be located opposite (matched). This is done to prevent a possible improper relay operation that could result provided a cable from bond to rail became disconnected and a train should stop with its rear axle located in the stagger, if the insulated joints are not matched.

Whereas the length of a single-rail track circuit of a direct current electric road is limited due to the direct current propulsion drop, the double-rail track circuit with impedance bonds does not have this restriction and therefore longer track circuits may be operated. The double-rail track circuit is more stable and the energization of the track relay will not vary greatly with changes in ballast conditions due to the comparatively low impedance of the copper connections across the rails through the impedance bonds.

The insulation of both rails is necessary as in the direct current track circuit, but in addition impedance bonds are used as shown at B in Fig. 16. After the shielding impedance was developed for the relay in the single-rail track system, it was only a step to devise a larger device to carry the entire propulsion return current and choke back the alternating current of the track circuit by its inductance.

Bonding of rail on electrified roads.

For double-rail track circuits with impedance bonds, where the traction return current divides between rails, each rail joint is bonded with the railroad's standard power bond, usually a large, low resistance stranded copper bond either of the plug or welded type. For single-rail track circuits the traction current return rail is bonded with the road's standard copper bond. The rail bonds for the signal rail usually are of the plug, web-of-rail type, as used on steam roads.

When the rail and the power bond used have practically the same ohmic resistance per foot, the rail is said to be bonded to capacity.

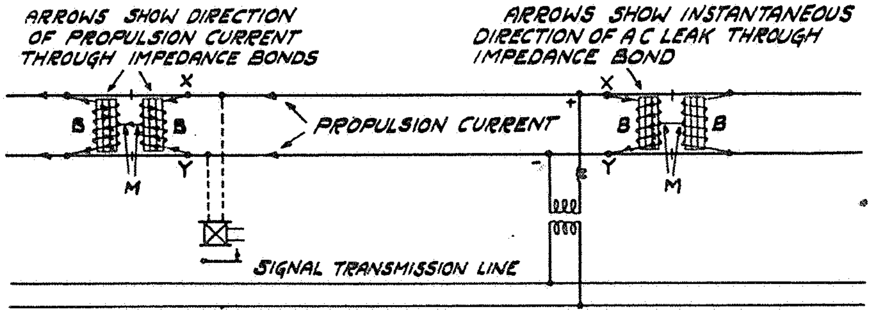


Fig. 16.
Elements of the Double-Rail Alternating Current Track Circuit.

Impedance bonds.

The reactance produced by the track impedance bonds prevents excessive leakage from one rail to the other of the signal current so that sufficient current goes through the track relay to operate it. Practically no signal current will flow from one track circuit to the adjacent one, due to the fact that the two impedance bonds in adjacent track circuits are connected together at points of zero potential.

The track impedance bond is the only special feature which distinguishes the double-rail from the single-rail track circuit. The location and connection of these bonds at the ends of adjoining track circuits is shown by the circuit, Fig. 16. It is seen that the track relay winding and its associated impedance bond are connected in multiple between rails.

The description which follows concerns the type of bond known as "non-resonant." In some special cases installations are made using "resonant" bonds which are similar but include a capacitor in multiple with a secondary coil to produce resonance at a given frequency. As a result, smaller bonds can be constructed where very heavy propulsion currents must be handled, or, for the more common size bonds (500 and 1,000 amperes per rail), the impedance may be increased, thereby reducing the track circuit power requirements. This type bond is used to some extent on the Long Island R.R., and on some direct current electrified roads in the British Isles and Continental Europe.

The bond consists of a two-section laminated iron core usually with both sections slotted to take the winding, although sometimes only the bottom section is slotted with a flat top section. The upper and lower laminated sections are usually separated by an air gap. The winding consists of two sections of heavy copper conductor connected to form a series winding. The ends of the series winding thus formed are connected to the two rail leads. The junction of the two sections or midpoint of the series winding is connected to a third or neutral lead. The number of turns in the winding, the size of the laminated iron structure and the width of the air gap determines the impedance which the bond offers to the alternating interrail voltage. The bond is so designed that the flow of alternating current through it will be held within reasonable limits, thereby maintaining sufficient interrail voltage to cause the required flow of current to the track relay.

The neutral points of the two adjoining bonds are connected together to provide a path for the propulsion return current to flow from one track circuit to the other. The return current flows in each rail and enters the bond winding from one rail at point X and from the other rail at point Y, Fig. 16, combining at the midpoint of the winding to flow to the midpoint of the adjoining bond where it again separates, the current to each rail being determined by the relative resistance of each rail in this track circuit.

The return currents flow in opposite directions in the two sections of the winding, hence, if these currents are equal in value, no magnetic flux due to their action is set up in the magnetic circuit of the iron core. However, if the current from one rail exceeds that from the other rail, the difference, or unbalanced return current, will produce a flux in the iron core. This flux tends to saturate the core and reduce its permeability, thereby reducing the reactance of the core. If the unbalanced return current is of sufficient magnitude, the resultant flux will decrease the reactance of the bond to such an extent that there will be an excessive flow of alternating current through its winding. This may decrease the alternating interrail voltage enough to prevent the track relay from receiving sufficient current, thereby causing it to release.

Impedance bonds are designed to take care of a certain amount of unbalanced return current, this varying from 12 to 20 per cent. Bonds intended for direct current propulsion are usually so designed that the propulsion current in one-half the winding may exceed that in the other half by 12 per cent of the total (two rail) continuous direct current rating of the bond without decreasing its rated impedance by more than 10 per cent.

The track bonding should be kept in good condition in both rails, so that the amount of return current will be about the same in each rail, thereby insuring a good working condition for the impedance bonds. Sometimes a rail bond or bonds in one rail may develop high resistance due to becoming loose or broken thereby causing this rail to have greater resistance than the other rail in the track circuit. This will cause inequality of the return current flow in the rails, which in turn causes unbalance of the opposing return currents through the two sections of the winding of the impedance bond. The unbalanced current, if of sufficient magnitude, will adversely affect the operation of the track relay as previously described.

Figure 17 shows the unbalancing curves of an impedance bond that will carry 2,000 amperes per rail of propulsion return current. The air gap is $\frac{5}{64}$ inch.

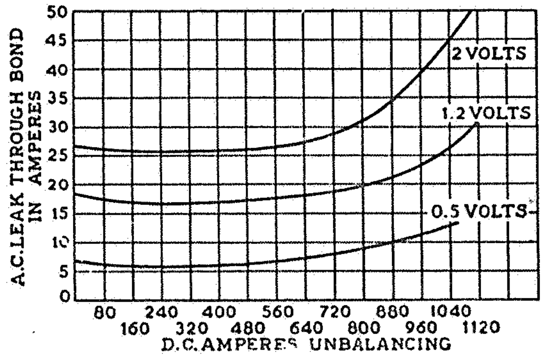


Fig. 17.
Unbalancing Curves for a 2000-Ampere Impedance Bond.

The vertical lines show the unbalancing direct current in amperes; the horizontal lines show the amount of signal current which will leak through the bond with voltage as indicated by curves. Note that the reactance is practically constant up to about 700 amperes unbalancing current, particularly on the lower voltage curves.

Figure 18 shows the construction of an impedance bond. The laminated iron core practically surrounds the heavy coils of bare copper wire. The bare wire is kept from touching the core and adjacent wires by wood or fibre strips used as spacers. The two central straps are connected together when the bond is completed and form the neutral connector M. The two outside straps form the rail terminals X and Y shown in Fig. 16.

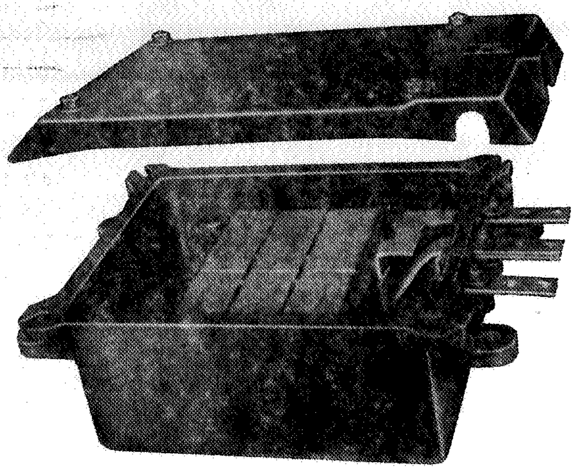


Fig. 18.
Core and Coils of an Impedance Bond.

The impedance bond shown in Fig. 18, when in service, is enclosed in an iron case generally filled with petrolatum compound or insulating mineral oil.

Figure 19 shows two bonds installed in a double-rail track circuit. This type has 500 amperes capacity per rail and is suitable for traction lines. Impedance bonds are designed for various capacities and are installed either between the rails or at the side of the track, as illustrated in Fig. 20.

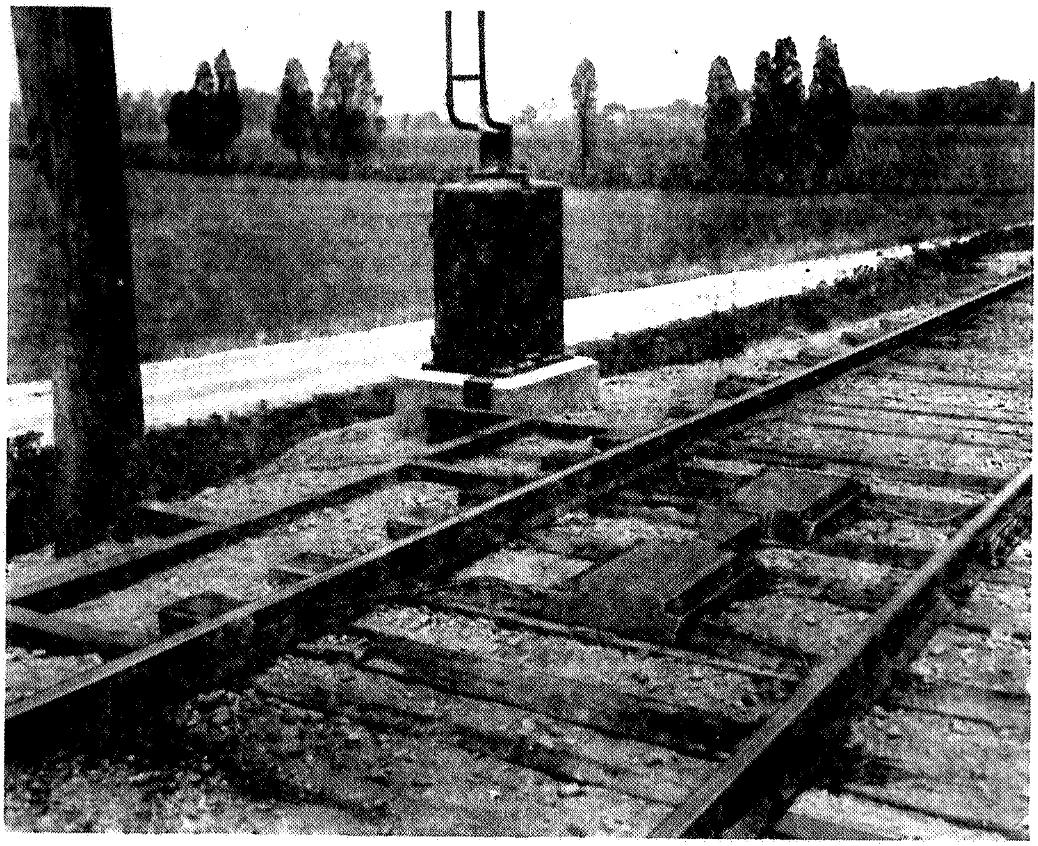


Fig. 19.
Track Layout of Two Impedance Bonds.

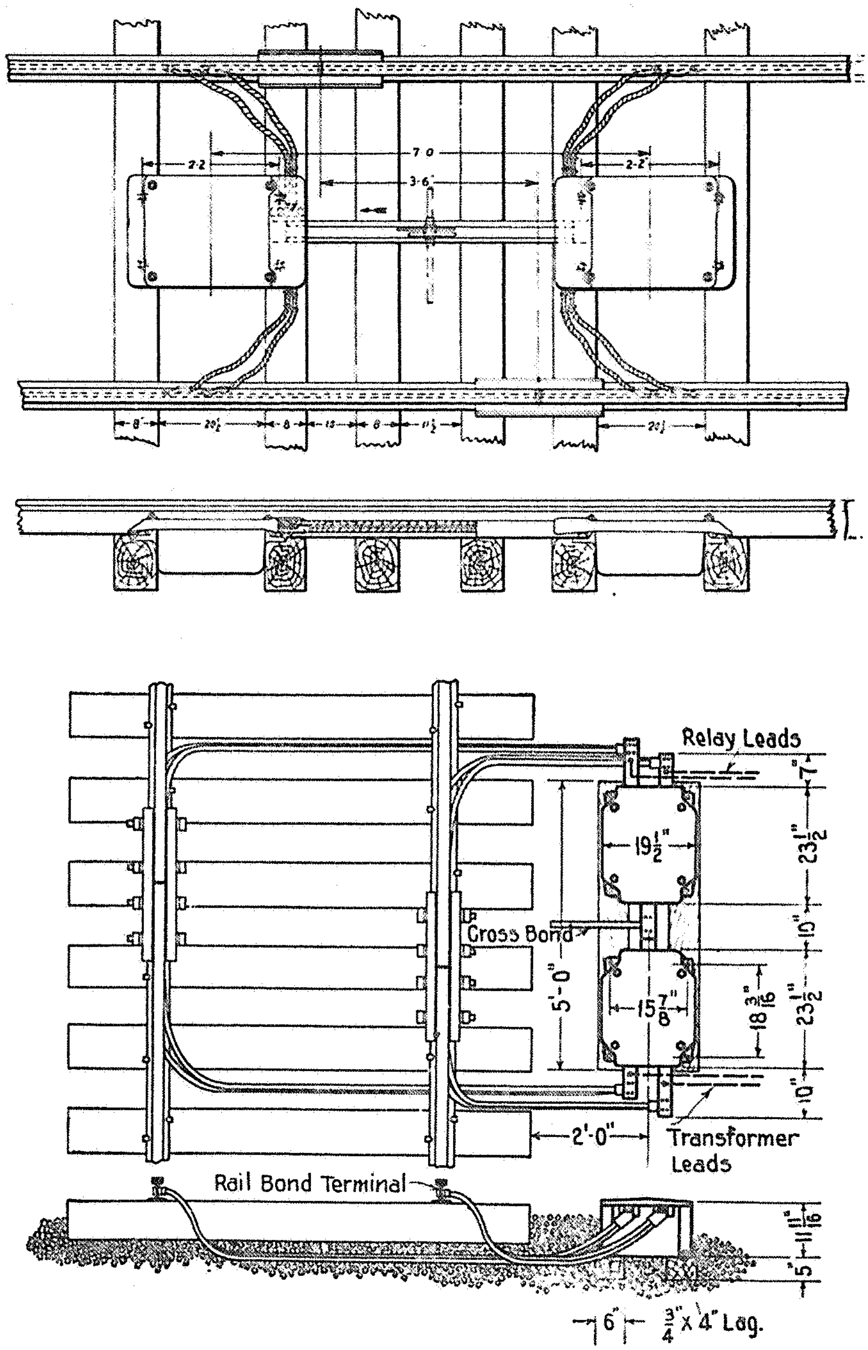


Fig. 20.
Methods of Installing Impedance Bonds.

Cross-bonding.

Methods of cross-bonding, insulating and bonding of sidings and making connection to power house return are shown in Fig. 21. B and C show cross-bonding at end of track circuits. Cross connection to power house return at end of circuit is shown at A. E shows where cross connection is made at a point away from the ends of the track circuit. In this case supplementary single impedance bonds are inserted. This method is undesirable, not only due to the additional cost, but because of the extra leak in the track circuit.

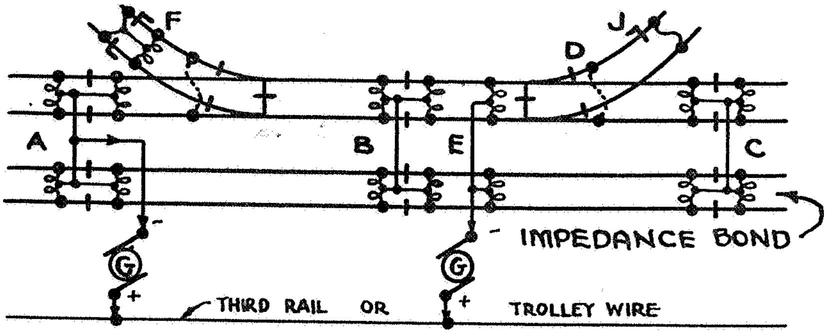


Fig. 21.
Cross-Bonding Connections.

It should be noted that Fig. 21 is intended to show cross-bonding schemes for a number of specific conditions. In actual practice on roads having two or more tracks usually cross-bonding between tracks should not be installed more frequently than every other double impedance bond location. This will reduce the possibility of improper relay operation in case of a broken rail by increasing the impedance of the run-around path through the cross-bonding and the parallel track or tracks.

Relays

Alternating current two-element relays of the induction motor, vane and galvanometer types are in service on many steam and electrified roads. Galvanometer relays are not used for any new installations. When the induction motor or vane types are used in double-rail track circuits on electrified roads, their track element is wound for a lower voltage and higher current than when they are used on steam roads or on single-rail track circuits of electrified roads, in order to keep down the leakage of signal current between rails through the impedance bonds. Three-position track relays are not commonly used in new installations.

Transformers.

The track transformers are similar to those used on steam roads but usually have larger ratings because of the added current drain through the impedance bonds. Adjustable filler type track transformers, which eliminated the need for a separate reactor and which were formerly used to some extent, are not now modern practice.

Reactors and resistors.

Reactors or resistors are used between the transformer and the track depending on which limiting device is required to provide proper phase relations for relay operation. Where either a reactor or resistor will provide satisfactory operation, the reactor will be more economical from a power standpoint. Some relays operate properly only when a reactor is used; others, only when a resistor is used. A reactor, resistor, or capacitor, as conditions require, is sometimes used in series with the local element of the track relay in order to obtain improved phase relation between currents in track and local elements and thereby reduce the energy required from the track transformer.

Alternating Current Track Circuits on Electric Roads Using Alternating Current Propulsion

Relays.

When alternating current is used for propulsion, a relay must be used that is immune to a foreign direct current and inoperative by the alternating propulsion return current. Twenty-five cycle propulsion current is generally used. Track relays are designed to operate selectively on a frequency of 60 cycles or higher but not on the 25-cycle propulsion current. Centrifugal frequency or vane type frequency relays are generally used.

Single-rail track circuits.

On single-rail track circuits through interlockings in non-cab-signaled territory and non-train-control territory, the vane frequency relay has generally been used. The length of the track circuit must be limited to prevent excessive propulsion current (causing injurious heating) flowing through the relay and transformer due to voltage drop in the return rail.

Double-rail track circuits.

On long track circuits and in interlockings in cab signal or train control territory, the double-rail circuit is used and generally equipped with the centrifugal frequency relay.

Impedance bonds.

The impedance bonds for double-rail track circuits on roads using alternating current propulsion employ the same principle of magnetic balancing as characterizes the bonds for direct current roads, for, although the propulsion current is of an alternating character, it is divided between the two opposing windings of the bonds so that the alternating magneto-motive forces are equal and opposite, and hence neutralize each other. The iron core of the bond remains, therefore, unmagnetized by propulsion current, and as a result the bond offers high impedance to the alternating signal current flowing through the two coils in series, the same as with the bonds for direct current propulsion.

Figure 22 shows a single impedance bond used on alternating current roads.

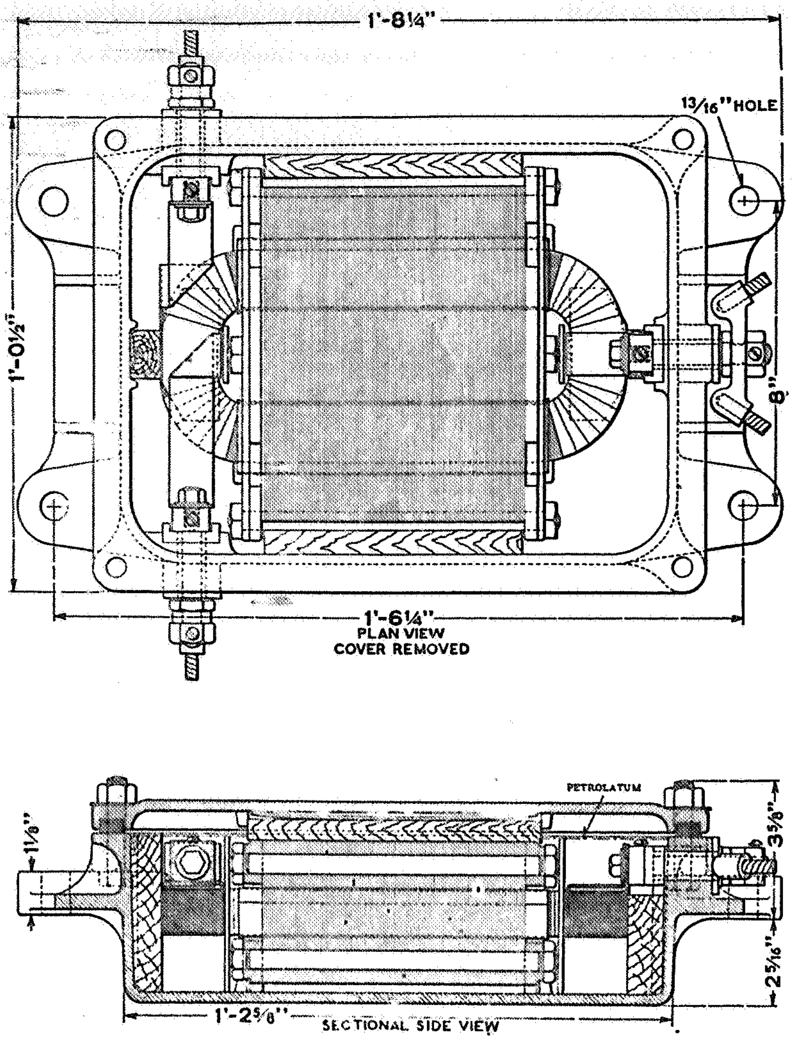


Fig. 22.
Single Impedance Bond for Alternating Current Roads.

These bonds are smaller than those used on direct current propulsion roads and sometimes two bonds are used in one housing as shown in Fig. 23. Whereas on direct current propulsion roads the return current may run as high as 2,500 amperes per rail, that on alternating current propulsion roads will generally be between the limits of 75 and 700 amperes per rail, due to the higher alternating current propulsion voltages ordinarily used. This allows the impedance bonds to be made considerably smaller.

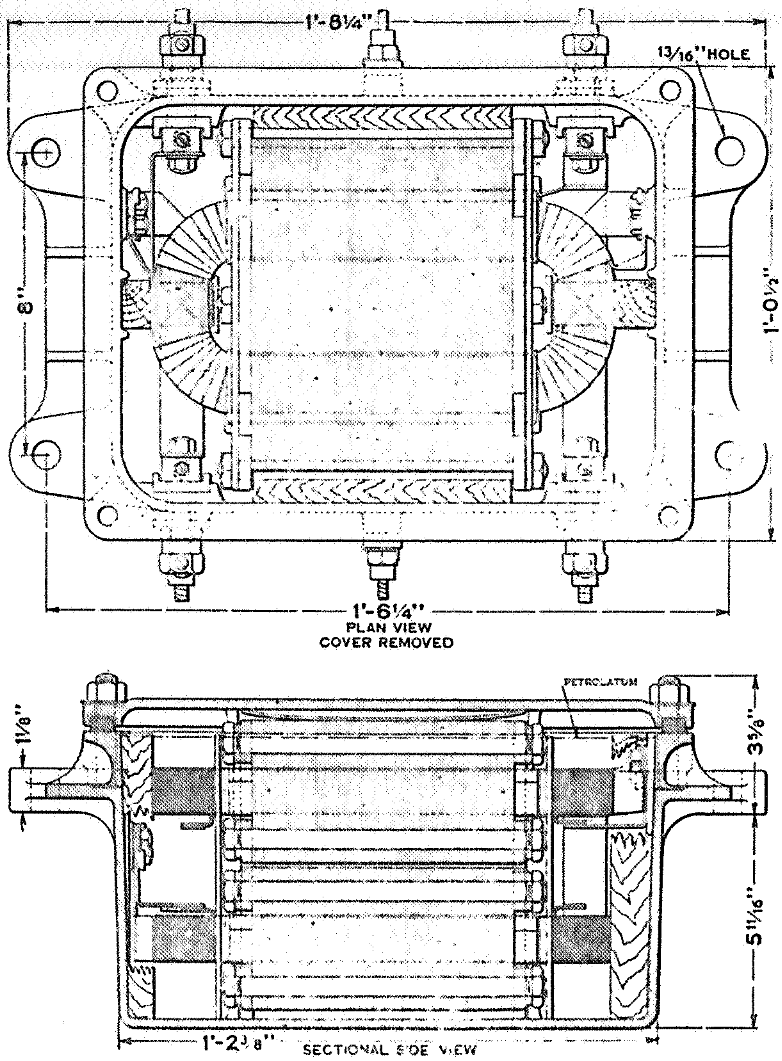


Fig. 23.
Double Impedance Bonds for Alternating Current Roads.

Unbalancing.

Unbalancing troubles are rare on roads using alternating current propulsion, not only because the propulsion currents themselves are small in volume, but especially because, if more current flows in one-half of the bond than the other, the half winding carrying the heavier current induces a voltage in the weaker half, tending to pull a larger current through that weaker half. Thus an automatic action exists which tends to keep the bond well balanced. For this reason, the bonds are not liable to be unbalanced, and no air gap is required in the magnetic circuit to prevent saturation of the core which would otherwise occur.

Fuses.

On electric roads using alternating current propulsion, fuses are used between relay and track to protect the relay from excessive propulsion current in case of broken rail or broken impedance bond cable.

Fuses in transformer track leads on double-rail track circuit may or may not be used, depending on the practice of the individual railroad. Usually, for direct current propulsion, fuses that are large enough to prevent frequent interruptions are too large to afford much protection to the apparatus and the matter resolves itself into a question of continuity of service versus the protection of the relays and transformers. Fuses are always used in relay and transformer track leads of single-rail track circuits on roads employing either alternating current or direct current propulsion.

Track Circuit Calculations for Alternating Current Signal System

General.

The proper calculation of the track circuit is of prime importance in the design of an alternating current signal system as it enables the engineer to select that type of track circuit apparatus which will operate most economically under the particular set of conditions in question. Furthermore, aside from the matter of economy, maximum safety of the track circuit can only be guaranteed by proper track circuit adjustments as dictated by the calculations.

Resistance, reactance and impedance of rails.

The track circuit is in reality a small single-phase transmission system whose two line wires are represented by the rails, and whose load is represented by the relay at the end of the track circuit. Like the line wires of the transmission line, the rails possess impedance (Z) composed of resistance (R) and reactance (X); the effective resistance of a steel rail is, however, from three to five times the actual resistance to direct current, due to the fact that the flow of alternating current in the magnetic material of which the rail is composed, sets up a magnetic field producing a counter electro-motive force in the body of the rail itself, forcing the current to the outer surface or skin of the rail, rendering thereby but a fraction of the cross-sectional area available for conducting current. This is known as the "skin effect," and is present in a greater or less degree in all conductors carrying alternating currents.

A further increase in the impedance of the rail circuit is introduced by their self-inductance, this depending on the spacing of the rails and their size just as in the case of the two wires of a transmission line. Since the rails are made of magnetic material and are irregular in shape, it is not possible to calculate the impedance of the rail circuit by the methods used for an ordinary transmission line.

Actual measurements have therefore had to be resorted to, and Table I shows the total impedance per 1,000 feet of track (both rails, including bond wires) under various conditions of bonding in common practice, and for values of current commonly used for relay energization. This table has been in use for several years and has been found to give results sufficiently accurate for all practical purposes. While the values shown apply especially to steam road conditions, they may be used for electric road track circuit calculations, since the presence of propulsion current in the rails will only tend to decrease the permeability of the rails and in turn their effective resistance and impedance; hence the voltage at the relay may increase slightly with heavy propulsion currents flowing in the rails and any error introduced will be such as to indicate less current and voltage at the relay than will actually exist. Table II shows separately the resistance of various kinds of bond wires as used in steam road work; on electric roads the rail is bonded to capacity, or nearly so, for propulsion current.

TABLE II

Resistance of Signal Rail Bonds to Direct Current
Ohms per 1,000 Feet of Track at 68 Degrees Fahrenheit

	A.A.R. Signal Section Manual Part No.	30 ft. rails	33 ft. rails	39 ft. rails	Approx. installed resistance of one bond
Number of rail bonds.......		66	60	51	
		Resistance of all bonds			
Rail head bonds					
Welded type—bronze strand (Dwg. 1047).....	141	0.023	0.021	0.018	0.00035
Mechanically applied type (Dwg. 1048)............	142	0.033	0.030	0.026	0.0005
Channel pin bonds					
2 No. 6 A.W.G. copper....	175	0.052	0.048	0.041	0.0008
1 No. 6 A.W.G. copper and 1 No. 8 B.W.G. steel....	175 and 177	0.090	0.082	0.070	0.00137
2 No. 6 A.W.G. copper-covered steel, 40%.....	176	0.135	0.123	0.105	0.00205
2 No. 6 A.W.G. copper-covered steel, 30%......	180	0.180	0.163	0.139	0.00272
2 No. 8 B.W.G. steel......	177	0.315	0.286	0.243	0.00477

Rail head welded type bonds, free strand between terminals 5½ inches.
Rail head plug type bonds, straight length approximately 5 inches.
Channel pin type bonds are 48½ to 49 inches long.

In Table II, no allowance is made for conductance of angle bars. In actual practice, however, a portion of the angle bars will conduct current, which will result in lower values of total resistance for bonded rails than would be obtained by adding the resistance of steel rails alone to the values in the table.

To find the total resistance of bonded rails the resistance of the steel rails alone must be added to the table values. The resistance of the steel rails alone per 1,000 feet of track (2,000 feet of rail) is approximately 0.02 ohm for 100-pound rail and 0.0154 ohm for 130-pound rail. Direct current resistance of steel rail per circular mil foot is assumed as 12 times that of copper.

The resistance of bonded rails per 1,000 feet of track (2,000 feet of rail) should not exceed 0.15 ohm for 2 No. 8 B.W.G. galvanized steel bond wires per joint. The maximum values should be considerably less when mechanical type or welded type rail head bonds are used.

The values shown in the table for rail head bonds are based upon the maximum installed resistance permitted by A.A.R. Signal Section specifications. The actual value may be somewhat less depending upon the conductivity of the conductor used in the bonds.

The values shown in the table for channel pin type bonds are based upon the average resistance per foot permitted by A.A.R. Signal Section specifications for the conductor from which these bonds are cut. For a large quantity of such bonds this average value represents approximately the maximum total to expect in service.

The resistance values in the table for channel pin bonds are based on the total length of wire, neglecting resistance of bond to rail. This assumes the length of wire extending through and somewhat beyond the web of the rail has a resistance at least that of the contact resistance to rail. An installed resistance of 0.00005 ohm per bonded joint is sometimes added to take care of the contact resistance between wire, channel pin and rail.

Ballast leakage resistance and conductance.

The resistance of the leakage path between rails in ohms per 1,000 feet of track varies with the nature of the ballast, the condition of the ties, and the weather conditions. In connection with the calculations involving rail impedance as given in Tables I and II, the following values for resistance of ballast and ties may be used; they are typical values for ballast cleared away from the rails:

	Ohms per 1,000 ft. of track
Wet gravel	2
Dry gravel	3
Wet broken stone	4
Dry broken stone	10

In making track circuit calculations, a leakage resistance of 4 ohms per 1,000 feet is very commonly used as representing the worst condition of well-drained broken stone or rock ballast; 2 ohms per 1,000 feet is a low wet weather value for track with gravel ballast. Poorly drained cinder ballast with old water-soaked ties will run as low as 1 ohm per 1,000 feet. In making the calculations, the wet weather ballast leakage figure should be used because if the track transformer were designed and track circuit adjustments were made on the dry weather basis, the track relay might fail to pick up in wet weather. It is, however, advisable to make a check calculation on the dry weather basis in order to determine the variation in voltage on the track relay from the wet to the dry condition, as in the case of extremely long track circuits with poor ballast, the relay voltage in dry weather may be so high that special means may have to be employed to prevent the relay from being excessively energized. In track circuit calculations it is generally more convenient to represent the ballast leakage factor in terms of conductance rather than resistance; conductance (expressed in mhos) is the inverse of resistance (expressed in ohms), and thus a ballast leakage resistance of 4 ohms per 1,000 feet corresponds to a ballast conductance of ¼ mho per 1,000 feet.

Track circuit formulae and their derivation.

Given the voltage e and the current *i* required at the track relay terminals, the length of the block, the rail impedance with its power factor, and the ballast leakage resistance, the problem which confronts us is the determination of the power to be fed into the track at the transformer end.

To begin with, due to the impedance drop in the rails caused by the relay current, the difference of potential between the rails increases from e at the relay end of the track circuit to some higher value E at the transformer end; thus, the ballast leakage current increases as we proceed from the relay to the transformer. The ballast leakage current itself produces a drop in the rails which again increases the voltage required at the transformer. The fact that the ballast conductance is usually distributed uniformly throughout the length of the track circuit rather complicates matters in that the current in the rails and the voltage across them from point to point changes with the varying magnitude of the ballast leakage current. In order to simplify matters, it is sometimes assumed that the ballast leak is concentrated at the center of the track circuit, but this is not strictly accurate; evidently the concentrated ballast leak is located nearer the transformer end of the track circuit than the relay end, for it is near the transformer end that the voltage is highest and the ballast leakage greatest. The correct determination of the ballast leak is therefore somewhat of an involved process. It can, however, be determined, and in fact this method is quite extensively used in England; the reader who is interested in this phase of the matter is referred to a very interesting and complete discussion given in the January 1915 issue of the *Railway Engineer of London*.

It is evidently more accurate to consider the ballast conductance as uniformly distributed, and by means of the following formulae, originated by Mr. L. V. Lewis and first presented in the July 1911 issue of the *Signal Engineer*, the voltage E and the current I at the transformer end of the track circuit, as well as their phase relationship, can easily be calculated. These general equations are:

$$E = e \cosh \sqrt{ZG} + i \sqrt{\frac{Z}{G}} \sinh \sqrt{ZG} \qquad (1)$$

$$I = i \cosh \sqrt{ZG} + e \sqrt{\frac{G}{Z}} \sinh \sqrt{ZG} \qquad (2)$$

where e and *i* are the relay voltage and current respectively; Z is the total impedance of the rails of the track secured by multiplying the values in Table I by the length of the track circuit in thousands of feet, and G is the total ballast leakage conductance secured by multiplying the reciprocal of the ballast leakage resistance in ohms per thousand feet by the length of the track circuit in thousands of feet. The terms *cosh* and *sinh* (pronounced "cosh" and "shin") are the hyperbolic cosine and sine, respectively, of an imaginary or complex angle represented in this case by the quantity $\sqrt{ZG}$. These formulae may be reduced to workable form by expanding the functions into their corresponding infinite series beginning

$$\cosh x = 1 + \frac{x^2}{\lfloor 2} + \frac{x^4}{\lfloor 4} + \frac{x^6}{\lfloor 6} + \ldots \quad (3)$$

$$\sinh x = x + \frac{x^3}{\lfloor 3} + \frac{x^5}{\lfloor 5} + \frac{x^7}{\lfloor 7} + \ldots \quad (4)$$

where x represents the hyperbolic angle $\sqrt{ZG}$ and the sign $\lfloor$ represents arithmetical multiplication; for example, $\lfloor 3$ is called "factorial three" and is equal 1 x 2 x 3 = 6; likewise, $\lfloor 4$ = 1 x 2 x 3 x 4 = 24. Hence

$$\cosh \sqrt{ZG} = 1 + \frac{ZG}{2} + \frac{(ZG)^2}{24} + \frac{(ZG)^3}{720} + \ldots \quad (5)$$

$$\sinh \sqrt{ZG} = \sqrt{ZG} + \frac{\sqrt{(ZG)^3}}{6} + \frac{\sqrt{(ZG)^5}}{120} + \ldots \quad (6)$$

Substituting the above values in equations (1) and (2)

$$E = \left(e + \frac{eZG}{2} + \frac{e(ZG)^2}{24} + \frac{e(ZG)^3}{720} + \right) + \left(i\sqrt{\frac{Z}{G}}\sqrt{ZG} + \frac{i\sqrt{\frac{Z}{G}}\sqrt{(ZG)^3}}{6} + \frac{i\sqrt{\frac{Z}{G}}\sqrt{(ZG)^6}}{120} + \right) \quad (7)$$

$$I = \left(i + \frac{iZG}{2} + \frac{i(ZG)^2}{24} + \frac{i(ZG)^3}{720} + \right) + \left(e\sqrt{\frac{G}{Z}}\sqrt{ZG} + \frac{e\sqrt{\frac{G}{Z}}\sqrt{(ZG)^3}}{6} + \frac{e\sqrt{\frac{G}{Z}}\sqrt{(ZG)^6}}{120} + \right) \quad (8)$$

Reducing and rearranging the terms of equation (7) and (8)

$$E = e + Zi + \frac{Z}{2}Ge + \frac{Z}{3}\,\frac{G}{2}Zi + \frac{Z}{4}\,\frac{G}{3}\,\frac{Z}{2}Ge + \ldots \quad (9)$$

$$I = i + Ge + \frac{G}{2}Zi + \frac{G}{3}\,\frac{Z}{2}Ge + \frac{G}{4}\,\frac{Z}{3}\,\frac{G}{2}Zi + \ldots \quad (10)$$

The above equations may be carried out to any number of terms by carrying out the above process, noting that the first element of each term of equation (9) is Z, and of equation (10) G, each divided by 1, 2, 3, 4, etc., according to the number of the term in the infinite series, the remaining elements of the term under consideration being identical with the next preceding term in the other equation. Sufficient accuracy for all practical purposes will in most cases be secured by calculating only the first five terms of each series as above shown, the remaining terms being generally small enough in value to be disregarded.

Equations (9) and (10) may also be developed direct from Ohm's Law, stating that E = I Z and I = E G, and consideration of the matter on this basis will enable the reader to grasp fully their physical meaning. To begin with, the first two terms e and *i* of equations (9) and (10) are the relay voltage and current, respectively, and as such are known. Relay current *i* flowing through the rail impedance causes a drop $e_2 = Zi$ and likewise the relay voltage e impressed across the rails throughout the length of the track circuit produces a leakage current $i_2 = Ge$. *Zi* and *Ge* therefore constitute the second terms of their respective series. Obviously $e_2 = Zi$ (where *i* is constant) increases uniformly from the relay to the transformer and its average value is therefore $\frac{e_2}{2}$ and the corresponding ballast leakage current is $i_3 = \frac{e_2}{2} G = \frac{G}{2} Zi$; likewise, it may be shown that $e_3 = \frac{Z}{2} Ge$. These last quantities thus constitute the third term of the current and voltage series, respectively.

The development of the next voltage term e_4 from i_3 presents some difficulty in that we have no reason for assuming that the average value of i_3 is $\frac{i_3}{2}$; as a matter of fact, it is not, since i_3 contains the product of the two factors G and Z, varying with the length of the track circuit, and hence increases with the square of the distance from the relay. It may be demonstrated by the calculus that in any equation of the form $y = x^n$ the average value of y between the limits of y, and o is $\frac{1}{(n+1)}$ of the maximum value of y. Therefore, the average value of i_3 above is $\frac{i_3}{3}$ and the corresponding e.m.f. is $e_4 = \frac{Zi_3}{3} = \frac{Z}{3} \frac{G}{2} Zi$, and likewise, $i_4 = \frac{G}{3} \frac{Z}{2} Ge$; these latter values form the fourth terms of the voltage and current series, respectively, and the process may be carried out until equations (9) and (10) are entirely duplicated. It should be noted that any term in the current series is derived from the preceding term in the voltage series by multiplying by the conductance G, divided by 1, 2, 3, etc., depending on the number of the term, which is perfectly logical since it is that preceding voltage which causes the current in question to flow; conversely, any term in the voltage series is derived from the preceding term in the current series by multiplying it by Z, divided by 1, 2, 3, etc.

Comparison of center leak and distributed leak methods.

If the above terms are developed by the center leak method, in which the entire ballast conductance is considered as being concentrated at the center of the block, we find that

$$E = e + Zi + \frac{Z}{2} Ge + \frac{Z}{2} \frac{G}{2} Zi \qquad (11)$$

$$I = i + Ge + \frac{G}{2} Zi \qquad (12)$$

The first three terms of the above formulae are identical with the corresponding terms of equations (9) and (10) calculated on the distributed leak basis. The fourth term of equation (11) is however 50 per cent greater in value than the corresponding term of equation (9). The center leak method will, therefore, give sufficiently accurate results where the track circuit is short enough in length to permit all terms after the third being disregarded.

Application of track circuit formulae—examples.

Applying formulae (9) and (10) to two of the usual track circuit arrangements, considering, first, a steam road using a vane type relay and, second, an electric road using a vane type relay having different characteristics. Both these relays are of the two-element type. These examples may be considered as representative. Calculations for a track circuit employing a single-element relay would be made in exactly the same manner, the calculations and diagram as used in the case of a two-element relay being discontinued after the track volts, amperes, and power factor at the transformer are determined for the one winding used in the case of the single-element relay.

Model 15 A.C. Vane Type Track Relay (See Vector Diagram, Fig. 24)

Steam road, 130-pound rails, 39 feet long, bonded with rail head (welded bronze strand) bonds.

Track circuit 5,000 feet long, end fed; ballast resistance 3 ohms per 1,000 feet.

Relay: Track, 0.5 volts, 0.5 ampere, 0.906 P.F., on 60 cycles.
Local, 110 volts, 0.44 ampere, 0.475 P.F., on 60 cycles.
Ideal phase relations, track current lags local voltage 97 degrees.

Rail impedance $Z = 5 \times 0.2 = 1.0$ ohm at 0.36 P.F. (See Table I).

Ballast conductance $G = 5 \times \frac{1}{3} = 1.667$ mhos at 1 P.F.

Relay and transformer leads to track — 150 feet No. 9 copper wire for each set = 0.12 ohm.

Voltage drop in relay leads = $0.5 \times 0.12 = 0.06$ volt.

Rail voltage e at relay end = $0.5 + 0.06 = 0.555$ volt.

$E = 0.555 + 0.5 + 0.463 + 0.139 + 0.064 + 0.012 + \ldots\ldots = 1.35$ volts.

$I = 0.5 + 0.926 + 0.417 + 0.257 + 0.058 + 0.021 + \ldots = 1.78$ amperes.

Rail voltage opposite the relay = 0.555 volt, obtained from Fig. 24 by adding vectorially the relay voltage, $e_r = 0.5$ volt, and the relay lead voltage drop, 0.06 volt, the latter being in phase with and hence parallel with the relay current, i = 0.5 ampere, which is drawn at an angle whose P.F. = 0.906 (cosine of the angle) lagging the relay volts, e_r. This P.F. is that shown above for the track element of the relay.

In plotting the various leakage currents and their corresponding voltage drops in Fig. 24 it will be remembered by referring to equation (9) that each term in the voltage series is obtained by multiplication of the preceding term in the current series by a multiple of the rail impedance *Z*. The power factor of *Z* is 0.36, and hence each term of the voltage series is laid off at a leading angle whose P.F. = 0.36 using the preceding term of the current series as a base line. Referring to equation (10) each term in the current series is obtained by multiplication of the preceding term in the voltage series by a submultiple of the ballast conductance G. G being non-inductive, its P.F. = 1, hence each term in the current series is laid off parallel with the preceding term in the voltage series which produces it.

Following the above method, the current at the transformer end of the track circuit is found to be I = 1.78 amperes, this being the vector sum of the relay current and the various ballast leakage currents laid off with due attention to phase relationship. Likewise, the voltage at the rails at the transformer end of the track circuit is E = 1.35 volts, this being the vector sum of the relay voltage and the various rail voltage drops caused by the ballast leakage currents.

To prevent the flow of an injurious short circuit current through the transformer secondary with a train in the track circuit, it is necessary to insert some current limiting device between the transformer and the track. In order to obtain maximum power economy for this track circuit arrangement, a track

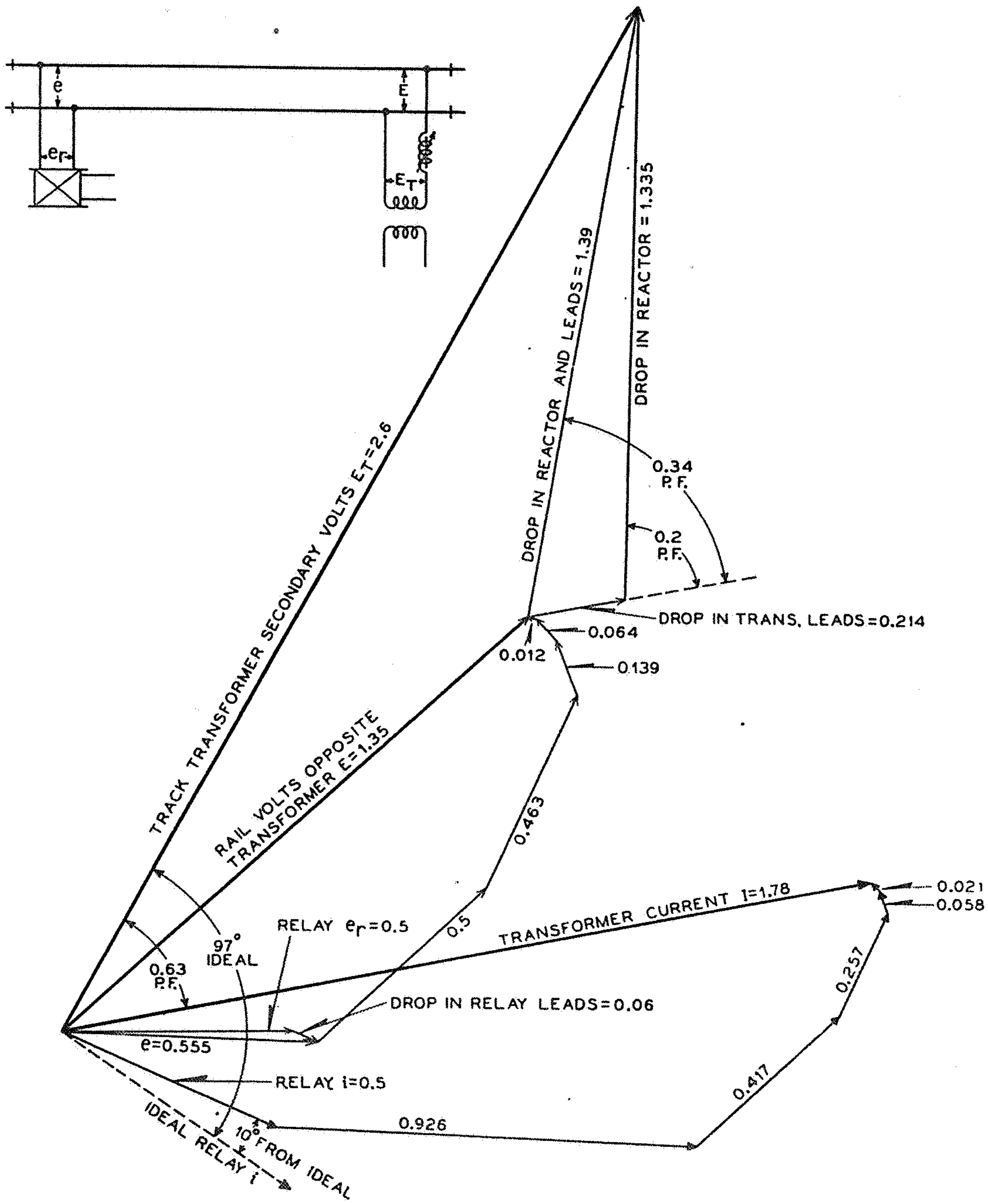


Fig. 24.
Vector Diagram for a Track Circuit Using a Model 15 Relay.

reactor as shown in Fig. 25 is used in preference to a track resistor. From the taps available on the reactor, one is selected so that the voltage drop in this unit when combined with the voltage drop in the track leads at the transformer end will result in the transformer secondary voltage E_T approximately double the rail voltage E at the transformer end. In this case the 0.75 ohm tap is

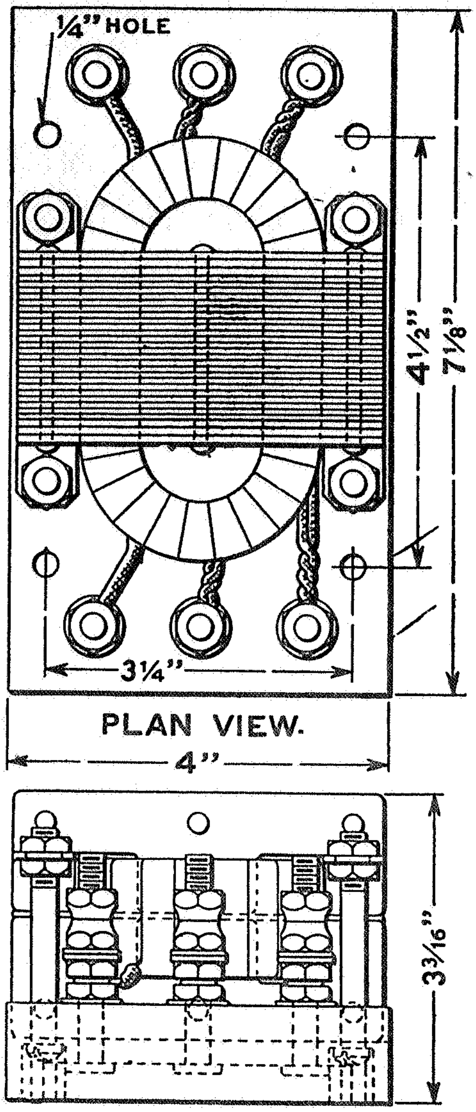


Fig. 25.
Adjustable Track Reactor.

selected. The voltage drop in the reactor, with 1.78 amperes flowing through it, is $1.78 \times 0.75 = 1.335$ volts. This vector is laid off at a P.F. = 0.2 with the current I as a base.

The transformer current of 1.78 amperes flowing through the leads between the transformer and the track gives a voltage drop of $1.78 \times 0.12 = 0.214$ volt, laid off parallel to the current since the leads are non-inductive.

The resulting values of transformer secondary volts E_T and current I are the values required to obtain the voltage e_r and current i delivered at the relay if the phase relations between the two elements of the relay are ideal. The ideal phase relations for this relay as listed previously, occur when the current in the track element lags the voltage of the local element 97 degrees. Since there is practically no change in phase between the secondary and primary of the track transformer, and since the primary of the track transformer is fed from the same source of power supply as the local element of the relay and consequently in phase with the same, then the phase difference between the track and local elements of the relay may be obtained by measuring the angle between the track transformer secondary volts E_T and the relay current i in the vector diagram. This measured angle is 87 degrees, a difference of 10 degrees from the ideal angle of 97 degrees. In order to compensate for this difference between the measured and ideal phase relations, the track transformer secondary voltage E_T and current I must be increased. The ratio by which these values must be increased is $\frac{E_T}{\text{Cos } 10^\circ}$ and $\frac{I}{\text{Cos } 10^\circ}$ resulting in the following:

$$E_T \text{ (corrected)} = \frac{E_T}{0.985} = \frac{2.6}{0.985} = 2.64 \text{ volts}$$

$$I \text{ (corrected)} = \frac{I}{0.985} = \frac{1.78}{0.985} = 1.81 \text{ amperes}$$

Another method of correcting the transformer secondary voltage and current is to use the curves shown in Fig. 62 of Chapter X—Alternating Current Relays.

If, instead of a reactor unit, a resistance unit having unity power factor had been used, a greater angle difference from the ideal would result which would require greater corrected voltage and current supply values with greater power input.

The angle between the transformer secondary voltage E_T and the current I may be scaled from the vector diagram. The cosine of this angle or P.F. = 0.63, hence the total power with the track circuit unoccupied is

$$E_T \text{ (corrected)} \times I \text{ (corrected)} \times \text{P.F.} = 2.64 \times 1.81 \times 0.63 = 3.01 \text{ watts.}$$

With a train occupying the track circuit opposite the transformer, the current flowing will be equal to the corrected transformer secondary voltage divided by the vectorial sum of the inserted reactance and the resistance of the transformer track leads. The voltage drop in this part of the circuit as scaled from the diagram is 1.39 volts and this is due to the current I = 1.78 amperes, hence the combined impedance value of the reactor and leads is $Z = \frac{1.39}{1.78} = 0.78$ ohm.

With a train in the track circuit as above, there will be only 0.78 ohm in series with the transformer secondary, and neglecting the comparatively small resistance of the wheels and axles of the train, the short circuit current flowing will be $\frac{2.64}{0.78} = 3.385$ amperes. The corresponding power factor is 0.34 as scaled from the diagram, this being the power factor of the voltage drop in the reactor and leads with respect to the transformer current I. Therefore, the total power with the block occupied is $2.64 \times 3.385 \times 0.34 = 3.04$ watts.

Style PTV-42 Alternating Current Vane Type Track Relay
(See Vector Diagram, Fig. 26)

Electric road, 100-pound rails, 39 feet long, bonded to capacity.
Track circuit 4,000 feet long, end fed; ballast resistance 3 ohms per 1,000 feet.
Relay: Track, 0.34 volt, 0.84 ampere, 0.407 P.F., on 60 cycles.
Local, 115 volts, 0.165 ampere, 0.358 P.F., on 60 cycles.
Ideal phase relations, track voltage leads local voltage 90 degrees.
Rail impedance $Z = 4 \times 0.21 = 0.84$ ohm at 0.3 P.F. (See Table I).
Ballast conductance $G = 4 \times \frac{1}{3} = 1.333$ mhos at 1 P.F.
Impedance bond at each end of track circuit, 1,000 amperes direct current propulsion current per rail with unbalancing capacity of 270 amperes, impedance to 60 cycles = 0.5 ohm at 0.2 P.F.
Relay and transformer leads to track — 150 feet No. 9 copper wires for each set = 0.12 ohm.
Voltage drop in relay leads $= 0.84 \times 0.12 = 0.101$ volt.
Rail voltage e at relay end $= 0.34 + 0.101 = 0.393$ volt.
Bond current at relay end $= \frac{0.393}{0.5} = 0.786$ ampere at 0.2 P.F.
Total current i at relay end $= 0.84 + 0.786 = 1.58$ amperes.
$E = 0.393 + 1.327 + 0.22 + 0.248 + 0.02 + \ldots\ldots = 1.905$ volts.
$I = 1.58 + 0.523 + 0.885 + 0.098 + 0.082 + \ldots\ldots = 2.38$ amperes.

Referring to Fig. 26, the relay voltage, $e_r = 0.34$ volt, and relay current, $i_r = 0.84$ ampere, are laid off at a P.F. = 0.407 as in the previous example, taking into account the voltage drop in the relay leads of 0.101 volt laid off parallel to the relay current, the rail voltage at the relay end of the track circuit is found to be e = 0.393 volt. At this voltage, the current through the impedance bond A at the relay end $= \frac{0.393}{0.5} = 0.786$ ampere laid off at a lagging angle corresponding to 0.2 P.F. with the rail voltage, e = 0.393 volt. The total current at the relay end of the track circuit is the vectorial sum of the relay current and the bond current and equals $0.84 + 0.786 = 1.58$ amperes = i. Applying formulae (9) and (10) and laying off the various ballast leakage currents and voltages listed above in the same manner as for the previous diagram, Fig. 24, the voltage and current values at the rails opposite the track transformer are found. E = 1.905 volts and I = 2.38 amperes. With this voltage applied to impedance bond B at the transformer end, the current through the bond $= \frac{1.905}{0.5} = 3.81$ amperes which is laid off at a lagging angle corresponding to 0.2 P.F. with E. The total current I_T fed into the track measures 6.01 amperes being the vectorial sum of the track current, I = 2.38 amperes, and the impedance bond current, 3.81 amperes.

For greater power economy in this case, a resistor unit is used instead of a reactor, selecting a tap so that the track transformer secondary voltage E_T is approximately double the rail voltage E. A resistor tap of 0.33 ohm is selected which when combined with the lead resistance of 0.12 ohm = 0.45 ohm. The voltage drop for the combined resistance = 6.01 $\times$ 0.45 = 2.7 volts laid off parallel to the current vector I_T. The track transformer secondary voltage E_T measures 3.87 volts.

For ideal phase relations of this relay the relay voltage e_r leads the local voltage E_T 90 degrees. From the vector diagram, the measured angle between the relay voltage e_r and the local voltage E_T is 32.5 degrees. The phase difference between the ideal and actual conditions is 90 degrees minus 32.5 degrees = 57.5 degrees. Compensation of the track transformer secondary voltage E_T and current I_T is obtained by the following:

$$E_T \text{ (corrected)} = \frac{E_T}{\text{Cos } 57.5^\circ} = \frac{3.87}{0.537} = 7.2 \text{ volts.}$$

$$I_T \text{ (corrected)} = \frac{I_T}{\text{Cos } 57.5^\circ} = \frac{6.01}{0.537} = 11.2 \text{ amperes.}$$

With the track circuit clear, the total power is E_T (corrected) $\times$ I_T (corrected) $\times$ P.F. = 7.2 $\times$ 11.2 $\times$ 0.895 = 72.2 watts, the power factor of 0.895 being the cosine of the angle between E_T and I_T as scaled from the diagram. With a train occupying the track circuit opposite the transformer, the maximum current is equal to the transformer volts E_T divided by the total resistance between the transformer and the track and equals $\frac{7.2}{0.45}$ = 16 amperes at 1 P.F. since the resistance is non-inductive. Thus, the power with the track circuit occupied is 7.2 $\times$ 16.0 $\times$ 1.0 = 115.2 watts.

It is apparent that, if a reactor instead of a resistance unit had been used as the current limiting device between the rails and the track transformer, the difference in phase angle would have been much greater than the 57.5 degrees found above and the relay would not have been operable due to the imperfect phase displacement.

The train shunt.

In general, alternating current track relays have a much lower internal impedance than the ordinary track relays used in direct current practice; for example, the Model 15 vane relay which was considered in connection with Fig. 24 has an impedance of $Z = \frac{E}{I} = Z_r = \frac{e_r}{i} = \frac{0.5}{0.5} = 1.0$ ohm while the PTV-42 vane relay discussed in connection with Fig. 26 has an impedance of $\frac{0.34}{0.84} =$ 0.405 ohm as compared to the resistance of 4 ohms of the standard direct current relays. Since, with two circuits in parallel, as in the case of the track relay

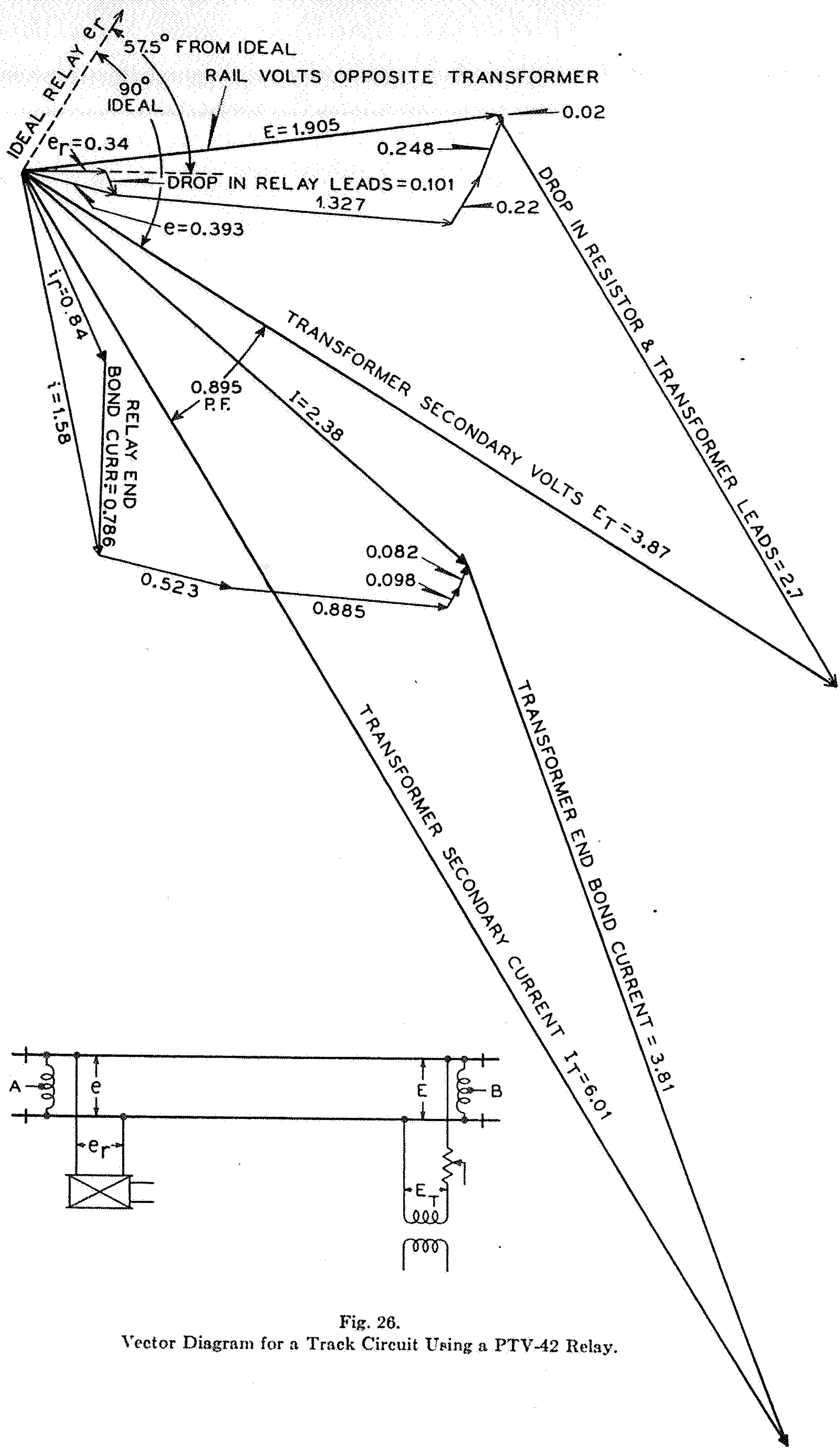


Fig. 26.
Vector Diagram for a Track Circuit Using a PTV-42 Relay.

and the car wheels across the rails, the current in each circuit is inversely proportional to the resistance of that circuit, it follows that with a train shunt of given resistance the alternating current track relay will take a larger proportion of the current than would be the case with a direct current relay; hence, the train shunt is not so effective in the former case.

The value of the train shunt in ohms is, of course, equal to the impedance of the axles added vectorially to the ohmic contact resistance between rails and car wheels. The impedance of the wheel and axle part of the shunt circuit is negligible, and hence the reactance factor in the circuit may also be neglected. It is also true that in the case of the heavy rolling stock employed in steam and electric trunk line service, the wheel-rail contact resistance may likewise be considered as insignificant. Table III was compiled from a series of tests made on rails with a clean bearing surface in which a single pair of wheels and their axle was submitted to various loads. It will be noted that the total resistance of the shunt thus formed is practically independent of the loading. While the total shunt resistance is extremely low in all cases, it is to be noted that, as might be expected, the total apparent resistance increases with the frequency. Compared to any of these shunt resistances, the impedance of the relays above given is so enormously high that the shunt may be considered as practically perfect.

TABLE III

Contact Surface of Wheels and Rails Clean Metal

Frequency cycles	No. of test	Total lb. weight on track	Amps. axle current	Volts across rails	Apparent ohmic resistance between rails via wheels and axle
25	1	18,700	185	0.133	0.0007
	2	23,052	175	0.13	0.0007
	3	27,404	180	0.134	0.0007
	4	36,108	180	0.14	0.0008
60	1	18,700	112.5	0.12	0.001*
	2	27,404	112.5	0.114	0.001
	3	36,108	112.5	0.11	0.00097
d.c.	1	18,700	55	0.022	0.0004
	2	27,404	56	0.021	0.00037
	3	36,108	55	0.018	0.00033

* 2 feet 9 inches of axle gave drop of 0.048 volt. From this point (on either side) to rail average drop 0.035 volt.

It is only when rusty or dirty rail surfaces are encountered that the resistance of the train shunt becomes significant and this statement applies equally well to direct current track circuits. Every signalman is familiar with the occasional difficulties experienced on heavily sanded track. Table IV indicates what the surface contact resistance may amount to, the tests having been made on a four-wheel truck loaded so that the total weight on the rails was 40,900 pounds.

TABLE IV

	Clean rails 25 cycles	Clean rails 60 cycles	Rusty rails 25 cycles	Rusty rails 60 cycles
Total amperes through axles	220	180	70	125
Volts across rails	0.232	0.1	0.82	0.37
Train shunt in ohms	0.00105	0.00055	0.0117	0.003

On steam and electric trunk lines where the rolling stock is generally heavy and the train movements are frequent enough to keep the rails clean, it may be safely assumed that the train shunt resistance is so extremely low as to be negligible. On some of the interurban trolley lines, however, where light single car trains are operated and movements are not frequent enough to keep the rails bright, the value of the train shunt must be taken into consideration; in such cases, it has been found to run much higher than the values in Table IV and since the relay should be shunted out to a point at least 50 per cent below its minimum shunt point, it is often customary to make electric road track circuit shunt calculations with a train shunt value of 0.06 ohm. In those cases on electric roads where it is suspected that the train shunt may be of comparatively high resistance due to light rolling stock and rusty rails resulting from infrequent train service, it is therefore generally advisable to check with track circuit calculations as described in the following, in order to be certain that the relay will be shunted open with a train in the block.

Methods of controlling track circuit shunting sensitivity.

NOT ALWAYS

The train shunt is least effective when the train is opposite the relay. At that time the entire rail impedance will be in the circuit between the train shunt and the track transformer with the result that the track feed current and the consequent drop in the resistance or impedance between the transformer and the track will be less than with the train opposite the transformer. Since the voltage at the rails opposite the transformer is the vectorial difference between the transformer voltage and the drop in the resistance or reactance inserted between the transformer and the track, it follows that with the train opposite the relay, the voltage at the track opposite the transformer and in turn that opposite the relay will be greatest when the train is at the relay end of the track circuit. Since this latter is the worst condition encountered, calculations to improve the effectiveness of the track circuit should be made on this basis. *

It is desirable to reduce, to the lowest point possible, the voltage at the relay with a train in the block. It will be apparent from the foregoing that where the impedance or resistance (as the case may be) is inserted between the transformer and the track, there is a very effective means of controlling the voltage at the rails opposite the transformer, since, as this voltage decreases, so also will the voltage at the relay decrease. Hence, with an impedance or resistance of high value the short circuit current with a train in the block will cause a correspondingly heavy drop between the transformer and the track and as a result the track voltage opposite both transformer and relay will be low. It is customary to use sufficiently high impedance or resistance so that with the block clear, the voltage at the track opposite the transformer will be about one-half that at the transformer secondary, and it was with the train shunt in mind

* Not valid. This error also appears on p. 456 of McCready

that these values were employed in connection with Figs. 24 and 26. With such an adjustment the track voltage will generally fall to a perfectly safe figure when a train comes on the track circuit. Inserting impedance or resistance to give a transformer voltage greater than twice the track voltage will rarely be justified since after the relay is once shunted out with a large margin of safety, any further increase in inserted impedance or resistance will only result in a useless waste of power.

With the aid of the vector diagrams shown in Figs. 24 and 26, it is not a difficult matter to ascertain whether the inserted impedance or resistance, determined on the basis of the transformer volts being twice the track volts with the block unoccupied, will insure that the front contacts of the track relay open with a train opposite it. It is assumed, of course, that all the track circuit constants are known, including the shunting point as well as the normal operating point of the relay. With a train shunt of given value across the rails at the relay, use the normal operating voltage of the relay plus the drop in the track leads as the first term e of equation (9), and considering the train shunt as an impedance bond of unity power factor, construct a diagram like Fig. 26, leaving the propulsion bonds out if a steam road track circuit is being investigated; in the case of an electric road circuit, the train shunt will simply constitute an extra bond at the relay end in multiple with the propulsion bond. The vector diagram thus obtained will, of course, indicate a transformer voltage considerably greater than what is actually existent as determined from the calculation with the block clear. Calling this hypothetical transformer voltage E_{TS} and the actual existent transformer voltage E_T, the volts e at the relay end of the block must be reduced in the proportion of $\frac{E_T}{E_{TS}}$; in turn, the relay voltage and current will be decreased in like ratio and if with this reduction it is found that the relay current is below the shunting point of the instrument, the impedance or resistance chosen for the "block clear" condition may be considered as satisfactory. If the reduction is not sufficient, the impedance or resistance inserted between the transformer and the track will have to be arbitrarily increased until the calculations prove that the relay is effectively shunted.

Power factor triangle.

In laying out vector track circuit diagrams such as those shown in Figs. 24 and 26, the value of the various angles are given by the calculations in terms of their cosines, these being the power factors of the corresponding angles. The phase spacing of vectors is, therefore, much more easily effected through the use of a triangle marked off in cosines, such as that shown in Fig. 27, than through the employment of a protractor indicating degrees, since in the latter case the angles corresponding to the cosine would have to be looked up in a table. A transparent triangle should be used as it is often necessary to use it upside down; the lines 0.1 to 0.7, as drawn from vertex A, are laid off with a protractor at angles with base line B C corresponding to cosines of 0.1 to 0.7 as given in standard cosine tables; the lines 0.8 to 0.99, as drawn from vertex B, are laid off from base line B C, likewise at angles corresponding to cosines of 0.8 to 0.99. Considerable care should be exercised in using the triangle at first, especially when reversing it, as otherwise one may be using the complement of the angle instead of the angle itself.

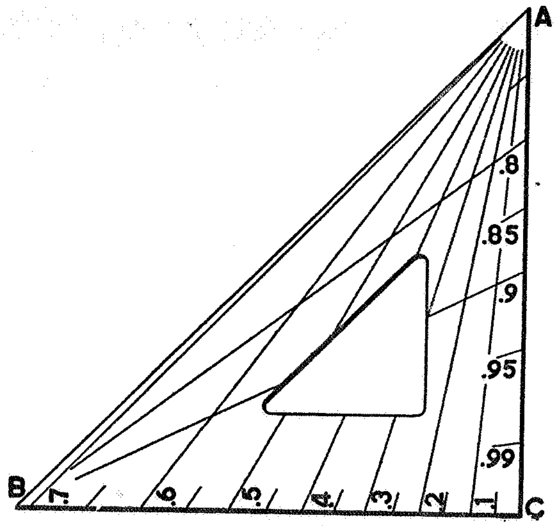


Fig. 27.
Power Factor Triangle for Constructing Track Circuit Vector Diagrams.

Instructions

Non-coded alternating current track circuits should be maintained and tested in accordance with Signal Section, A.A.R. instructions, as follows:

Adjustments.

1. The adjustment of alternating current track circuits depends on many factors, such as the type of track circuit; whether double or single rail with steam or electric traction; the length of the track circuit; the ballast condition; the desired shunting values at both relay and transformer ends of the track circuit; the type of relay; and the weight of train equipment.

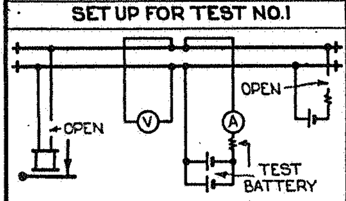
2. When making train shunt resistance test it should be made in accordance with Form 7003. (See Fig. 28.)

3. For single-element relays, the voltage at the relay track terminals under wet ballast or other adverse conditions must be at least 10 per cent higher than the values given on the manufacturer's tag or name plate to take care of varying ballast and bonding. For two-element relays, the voltage on the relay track terminals under wet ballast or other adverse conditions should be 10 per cent higher than that necessary to energize the relay with normal front contact compression. On account of varying phase angle conditions the necessary voltage on the track element may be considerably in excess of the values marked on the manufacturer's tag or name plate. A check for the proper voltage to be applied across the track terminals of a relay under wet or other unfavorable conditions, is to shunt the relay so that its contacts open half way, then remove the shunt, and if the contacts come up to the front stop, sufficient energy is passing through the track windings.

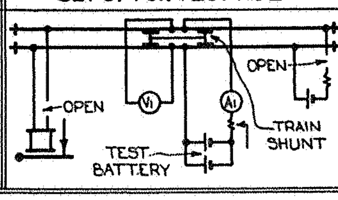
TRACK		EQUIPMENT					TEST NO. 1			TEST NO. 2 EQUIPMENT STANDING												TEST NO. 2				
										1 AXLE				2 AXLES				ENTIRE EQUIPMENT				EQUIPMENT MOVING				
CIRCUIT NUMBER	RAIL SURFACE CONDITION	KIND	INITIAL	NUMBER	WEIGHT	WHEEL SURFACE CONDITION	V	A	R	V_1	A_1	R_1	R_2	V_1	A_1	R_1	R_2	V_1	A_1	R_1	R_2	MPH	V_1	A_1	R_1	R_2

REMARKS

SET UP FOR TEST NO. 1



SET UP FOR TEST NO. 2



METER RECORD

METERS	MFG	TYPE	RANGE USED	RESISTANCE OF RANGE
AMMETER-A				
VOLTMETER-V				
AMMETER-A_1				
VOLTMETER-V_1				

$R = \frac{V}{A}$ JOINT RESISTANCE OF BALLAST AND VOLTMETER

$R_1 = \frac{V_1}{A_1}$ JOINT RESISTANCE OF BALLAST AND TRAIN SHUNT

$R_2 = \frac{1}{\frac{1}{R_1} - \frac{1}{R}}$ CUMPUTED RESISTANCE OF TRAIN SHUNT

EXAMPLE $R = 5$ $R_1 = .059$ $R_2 = \frac{1}{\frac{1}{.059} - \frac{1}{5}} = \frac{1}{16.95 - .2} = \frac{1}{16.75} = .0597$

INSTRUCTIONS

1 METERS MUST BE IN ACCORDANCE WITH SPECIFICATION 85.
2 UNDER RAIL AND WHEEL SURFACE CONDITIONS INDICATE AS WET, BRIGHT, DULL, LIGHT, RUST, HEAVY, RUST, SAND, ETC
3 CURRENT AND VOLTAGE READINGS MUST BE TAKEN SIMULTANEOUSLY
4 TESTS SHOULD NOT BE MADE WHERE FOREIGN CURRENT AFFECTS THE READINGS
5 TEST BATTERY AND RESISTANCE SHOULD BE ARRANGED TO OBTAIN APPROXIMATELY BUT NOT EXCEEDING FULL SCALE DEFLECTION OF AMMETER WITH SHORT CIRCUIT ACROSS RAILS AT POINT OF TEST.
6 TEST MUST BE MADE WHILE EQUIPMENT IS STANDING AT OR MOVING PAST THE POINT WHERE TEST SET IS CONNECTED.
7 RAIL JOINTS ON TEST SECTION MUST BE WELL BONDED.

APPROX. TEMP. DEGREES F ______________ DATE OF TEST __________ TEST MADE BY ____________

ARA SIG. SEC. 7003

TRAIN SHUNT RESISTANCE TEST

SEPT 1924 | MAR 1925 | M-1926

Fig. 28.

4. Voltage at the relay local terminals must be as near as possible the normal voltage given on the manufacturer's tag or name plate. If less than the normal voltage value is impressed across the local terminals, more energy will have to be used in the track element to cause proper operation, except for centrifugal frequency relays. While a reduction in the local voltage of a centrifugal frequency relay generally does not require additional energy to the track element, this reduction in the local voltage should be avoided as it tends to increase the time of shunting.

5. When shunting two-element track relays, shunt must be applied at the terminals of the track element and not the local element.

6. On steam road track circuits the voltage on the rails at transformer end should be not more than one-half that at the transformer secondary under the worst track conditions. Where reactive transformers are in use, the voltage on the rails at transformer end should be not more than one-half the open-circuit transformer secondary voltage.

7. On electric road track circuits to obtain adequate broken-rail protection it may be necessary to make adjustments so that under worst track conditions the voltage at the rails opposite the transformer is two-thirds that of the transformer secondary. Where reactive transformers are in use the voltage on the rails at transformer end should be not more than two-thirds the open-circuit transformer secondary voltage.

Phase angle measurement.

8. To obtain the best operation of two-element track relays under adverse ballast conditions, phase measuring instruments should be used to determine that the phase angle relations in the relay approach the ideal value. These measurements may indicate that adjustments should be made to improve phase relations.

Circuit controllers.

9. Switch circuit controllers must be maintained and tested in accordance with Instructions for Switch Circuit Controllers.

Ballast resistance and rail impedance.

10. Ballast resistance should be kept as high as possible by keeping ballast free from rail and rail fastenings and providing proper drainage. Broken track spikes must not be driven through the ties.

11. Bonding must be installed and maintained in condition to insure low resistance. Bolts in angle bars should be kept tight.

12. Alternating current track circuit tests must be made in accordance with A.C. Track Circuit Characteristics.

13. Resistance of rails and bonding per 1,000 feet of track shall not exceed the assigned value for the particular type of bonding employed.

14. Resistance of ballast per 1,000 feet of track should preferably be not less than 2 ohms when wet.

Bonding and track circuit connections.

15. Bonding and track circuit connections must be inspected as instructed and renewed when necessary.

16. Switch frogs must be so bonded that when removed, track circuit will be opened.

17. When fastening shunt wires or track circuit connections care must be taken so that staples do not ground the circuit. The staples and wires must be kept in place and in good condition.

18. Fouling circuits must be so maintained as to avoid breaks or undue resistance.

Cross-bonding and bonding on electric propulsion roads.

19. To obtain broken-rail detection, it is desirable that cross-bonds between neutral connections of impedance bonds on parallel tracks or between a neutral connection and a negative propulsion return cable should not be located closer than at alternate impedance bond locations. Calculations should be made and checked by field tests under the most adverse conditions so that the cross-bonding as installed does not interfere with the desired broken-rail detection.

20. Both rails of a double-rail track circuit should be equally well bonded because defective bonding in one rail will cause an unbalanced condition of the track circuit due to unequal amounts of return propulsion current in the two rails.

(a) With direct current propulsion and double-rail track circuits, unbalanced propulsion current may saturate the iron core of the impedance bonds. This may lower the bond impedance to such a point that the track relay may be shunted.

(b) With alternating current propulsion and double-rail track circuits, unbalanced propulsion current will cause the impedance bond to act as an auto-transformer. Since the track relay is connected in multiple with the bond the auto-transformer voltage may cause sufficient alternating current of propulsion frequency to flow in the relay to cause it to open its contacts, or to blow the protective fuse.

Insulated rail joints.

21. Insulated rail joints must be maintained and tested in accordance with Instructions for Insulated Rail Joints.

Broken-down insulated rail joint protection.

22. Where two-element track relays are used, polarities of adjacent track circuits must be staggered when the signals are in the clear position.

Resistors.

23. Where single-rail track circuits are used on electric roads, care must be taken to adjust the resistors at the relay and transformer ends so that the amount of propulsion current permitted to flow through the relay track winding is less than the allowable amount specified for a given relay. Where heavy direct current propulsion is present, a shielding or a balancing impedance may also be installed in connection with the track relay to protect against direct current in the relay windings.

Reactor.

24. The current limiting device used in the transformer track lead should be a reactor if possible, as the losses in a reactor are less than in a resistor. A resistor in place of a reactor should be used only when required to give correct phase relations in two-element track relays or to protect the relay and transformer from propulsion return current.

Fuses.

25. Fuses must be inspected as instructed and replaced in kind when necessary.

Relays.

26. Relays must be maintained and tested in accordance with Instructions for Alternating Current Relays.

Testing.

27. In testing alternating current track circuits, it is not possible to obtain the relay current by simply inserting an ammeter between the relay and track since the resistance of alternating current ammeters is so high that they considerably reduce the current to the relay when thus inserted. To measure the current the relay is receiving from the track circuit, measure first the voltage across the relay track terminals, then insert the ammeter in the track leads and again measure the terminal voltage. This voltage divided by the current gives the impedance of the relay which corresponds to the resistance of a direct current relay. Divide the relay terminal voltage, read with the ammeter removed, by the impedance, and the relay current will be obtained.

28. Ground resistance test must be made in accordance with Instructions for Resistance of Made Grounds.

Shunting sensitivity.

29. Shunting sensitivity test of a track circuit is made by determining the maximum resistance that can be placed across the rails opposite the relay and opposite the transformer to cause the relay contacts to open. If this resistance is less than 0.06 ohm, corrective measures must be taken at once. (15 feet of No. 16 A.W.G. copper wire has a resistance of 0.06 ohm.)

30. Shunting tests must be made as follows:

(a) Turnouts: Switch point side of insulated joints in lead rails and at each end of fouling circuit.

(b) Crossovers: Switch point side of insulated joints in lead rails and both sides of insulated joints at center of crossover. Where center insulated joints are not used, make test as specified in Instruction 30-a.

31. Shunting tests must be made during dry weather conditions when the maximum current is flowing through the relay coils.

32. Top of rails should be kept free from sand, rust, and other foreign matter that affects proper shunting of track circuit.

33. If the shunting sensitivity of a track circuit is lower than that of similar track circuits, check against the following possible causes:

(a) Improper amount of limiting impedance or resistance between transformer and track or between track and relay.

(b) Excess energization of the relay under minimum ballast resistance.

(c) Defective or sluggish relay.

General.

34. When track or other conditions are such that they may cause signal interruption or unsatisfactory operation of signal apparatus, the person immediately responsible must be requested to correct the condition. If such request is not acted upon within a reasonable time the matter must be reported to proper authority in writing.

35. Wire and cable must be maintained and handled in accordance with Instructions for Wire and Cable.

36. Lightning arresters must be properly connected and maintained.

37. Pipe lines under rail must clear base of rail at least ½ inch.

38. If a track circuit fails to operate properly, check for the following possible causes:

(a) Broken rail.

(b) Loose connections.

(c) Defects in bonding.

(d) Defects in insulated rail joints.

(e) Defects in switch rod, gage-plate or pipe-line insulation.

(f) Low ballast resistance.

39. Experiments or changes must not be made in track circuits except by permission of proper authority.

40. Any unusual occurrences or developments in track circuits must be promptly reported to proper authority.

Precautions to be Observed in Taking Readings in the Field for Rail Impedance and Ballast Resistance

1. Insulated joints should be tested to insure that there is no leakage through them. This can be most easily done by shunting the track circuit on the other side of the joints and noting that this causes no change in the reading of the ammeter in the transformer leads.

2. Bonding should be tested by taking voltage readings across the track every 15 rail lengths, or as required by special length track circuits, with the track circuit in its normal operating condition. Poor bonding or ballast will be indicated by unusual voltage drops between the successive readings. It should be noted if there are any poor sections of ballast or bonding in the track circuit which would make the distribution of the leakage non-uniform and also give erratic voltage readings. If an unusual voltage drop is found between successive readings, take readings across the rails every rail length, at the same time inspecting the individual bond wires in this particular section, which steps will usually enable the defective bond to be detected.

3. The sets of readings, first with relay disconnected and second with the track short circuited, should be taken, if possible, without an intervening train movement through the track circuit which might change conditions of bonding or insulated joints.

4. The jumper indicated in Fig. 29 for short circuiting the track at the relay end, should not have a higher resistance than 5 ft. of No. 9 A.W.G. copper wire and it can best be connected to rails by the use of the low-resistance test clamp.

5. The resistance of the voltmeter should not be less than 20 ohms per volt.

6. In case it is desired to measure the rail impedance and ballast resistance of double-rail electric road track circuits it will be necessary to disconnect the impedance bonds before taking readings.

Formula for Calculating Rail Impedance and Ballast Resistance for A. C. Track Circuit

(See Figs. 29 and 30)

Disconnect Impedance Bonds (if any) and Relay

Observed readings:

E_o = volts across rails opposite transformer, track open circuited.

E_s = volts across rails opposite transformer, track short circuited opposite track relay.

I_o = amperes to track from transformer, track open circuited.

I_s = amperes to track from transformer, track short circuited opposite track relay.

$E_{0.4}$ = volts across rails 0.4 length of track circuit from feed end.

Calculated values:

$$Z_o = \frac{E_o}{I_o} = \text{impedance of track circuit on open circuit.}$$

$$Z_s = \frac{E_s}{I_s} = \text{impedance of track circuit with short circuit opposite track relay.}$$

$$R = \frac{E_{0.4}}{I_o} = \text{total ballast resistance of track circuit.}$$

Then

$r = R \times L$ (L = length of track circuit in thousands of feet) = ballast resistance per 1000 ft. of track.

$$z = \frac{Z_o \times Z_s}{r} = \text{rail impedance per 1000 ft. of track.}$$

ϕ = phase angle of rail impedance and can be obtained directly from curve chart Fig. 30 by taking value corresponding to z for particular track circuit frequency.

Example of a 5,000 Ft. A.C. Track Circuit—Track Circuit Frequency 60 Cycles

Observed readings:

$E_o = 4.35$ volts, $I_o = 3.1$ amperes.
$E_s = 3.4$ volts, $I_s = 3.18$ amperes.
$E_{0\cdot4} = 3.1$ volts.

From these values

$$Z_o = \frac{E_o}{I_o} = \frac{4.35}{3.1} = 1.4$$

$$Z_s = \frac{E_s}{I_s} = \frac{3.4}{3.18} = 1.07$$

$$R = \frac{E_{0\cdot4}}{I_o} = \frac{3.1}{3.1} = 1.0$$

$r = R \times L = 1.0 \times 5.0 = 5.0$ ohms per 1,000 ft. ballast resistance.

$$z = \frac{Z_o \times Z_s}{r} = \frac{1.4 \times 1.07}{5} = \frac{1.5}{5} = 0.3 \text{ ohm per 1,000 ft. rail impedance.}$$

From curve Fig. 30
Phase angle of z (0.3 ohm @ 60 cycles) = 37° or P.F. = 0.8 (cos 37°)

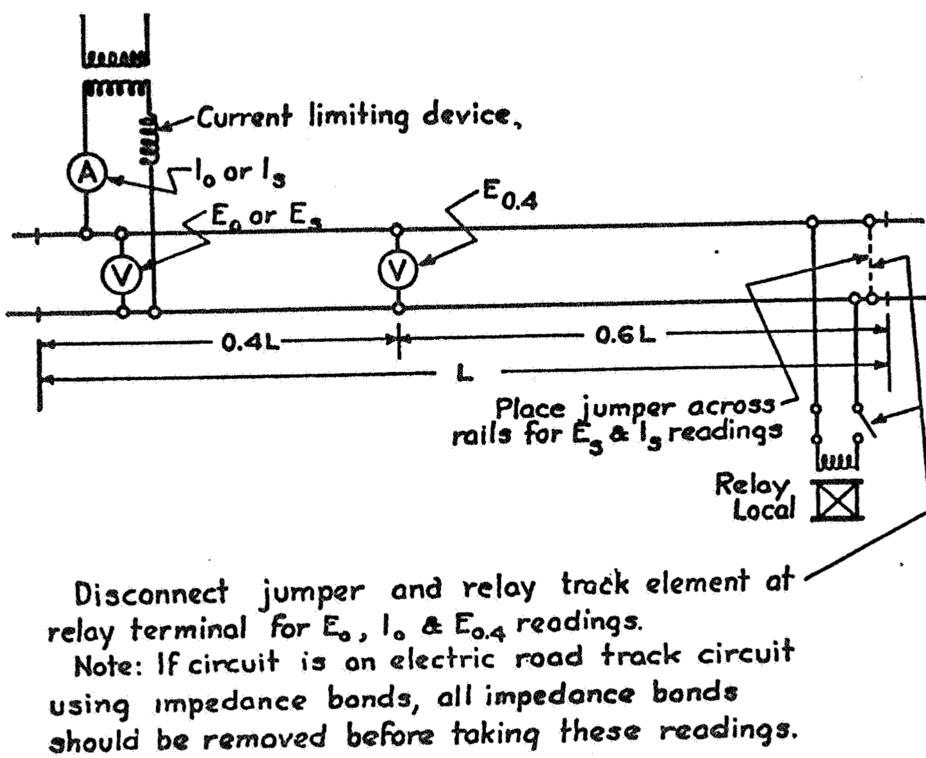
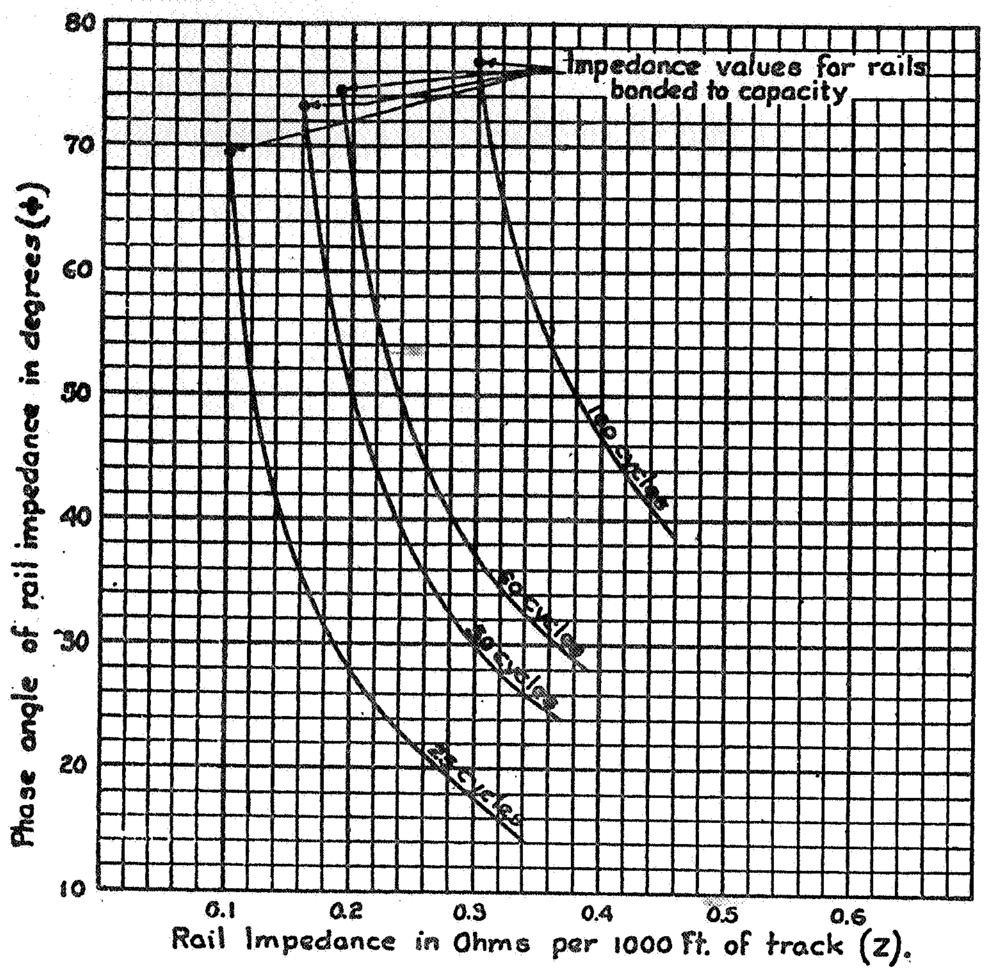


Fig. 29.
Track Circuit Connections.



CURVE SHOWING APPROXIMATE RELATION BETWEEN RAIL IMPEDANCE AND PHASE ANGLE

Note:
These curves based on 130 lb. rail are practically correct for other weight rails.

Fig. 30.

Example of Typical Instructions

The instructions for the adjustment of 60-cycle alternating current track circuits on steam lines are as follows:

General.

1. The adjustment of alternating current track circuits depends on many factors, such as the type of track circuit; whether double or single rail with steam or electric traction; the length of the track circuit; the ballast condition; the desired shunting values at both relay and transformer ends of the track circuit; the type of relay; and the weight of train equipment.

Voltage values.

2. Voltage at the relay local terminals must be as near as possible the normal voltage given on the manufacturer's tag or name plate. If less than the normal voltage value is impressed across the local terminals, more energy will have to be used in the track element to cause proper operation, except for centrifugal frequency relays. While a reduction in the local voltage of a centrifugal frequency relay generally does not require additional energy to the track element, this reduction in the local voltage should be avoided as it tends to increase the time of shunting.

3. The voltage at the relay track terminals will vary with changes in the ballast and bonding resistances.

4. Figures 31, 32 and 33 are curves showing the maximum voltage at the relay terminals on track circuits 5,000 feet long at various ballast resistances where the minimum ballast resistance of the track circuit involved is not less than 4 or 5 ohms, per 1,000 feet of track. Figure 34 also gives curves for track circuits 4,000 and 6,000 feet in length.

5. Figures 34, 35 and 36 are similar curves and are to be used where minimum ballast resistance is 2 ohms per 1,000 feet of track.

6. It has been found that best results are obtained on track circuits from 4,000 to 5,500 feet in length with Model 15 condenser relays when using 1.3 ohms on the reactor in the circuit and making the adjustment for voltage by using the nearest voltage on track transformer secondary to give desired voltage at relay. Where the transformer secondary does not have sufficient taps to do this in all cases it may be necessary to use the next higher impedance on the reactor to keep the voltage within proper limits.

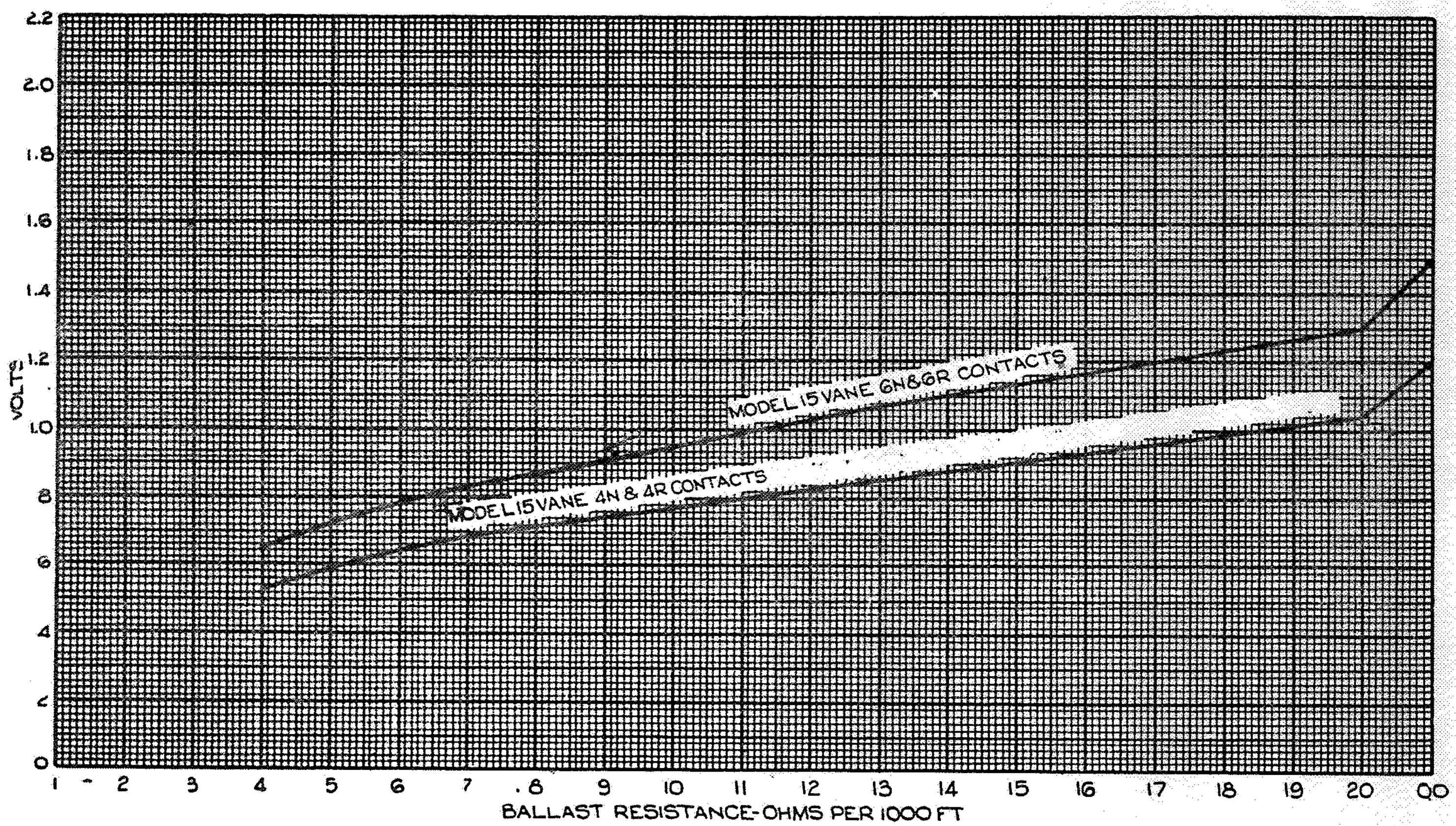


Fig. 31.

CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

Length of track circuit..............................5000 feet
Minimum ballast resistance....................4 ohms per M. ft.

For track circuits longer or shorter than 5000 ft., the required maximum voltage shown should be raised or lowered proportionally as follows:—

For a 5500-foot track circuit, increase 10 per cent
For a 5250-foot track circuit, increase 5 per cent
For a 4500-foot track circuit, decrease 5 per cent
For a 4000-foot track circuit, decrease 10 per cent

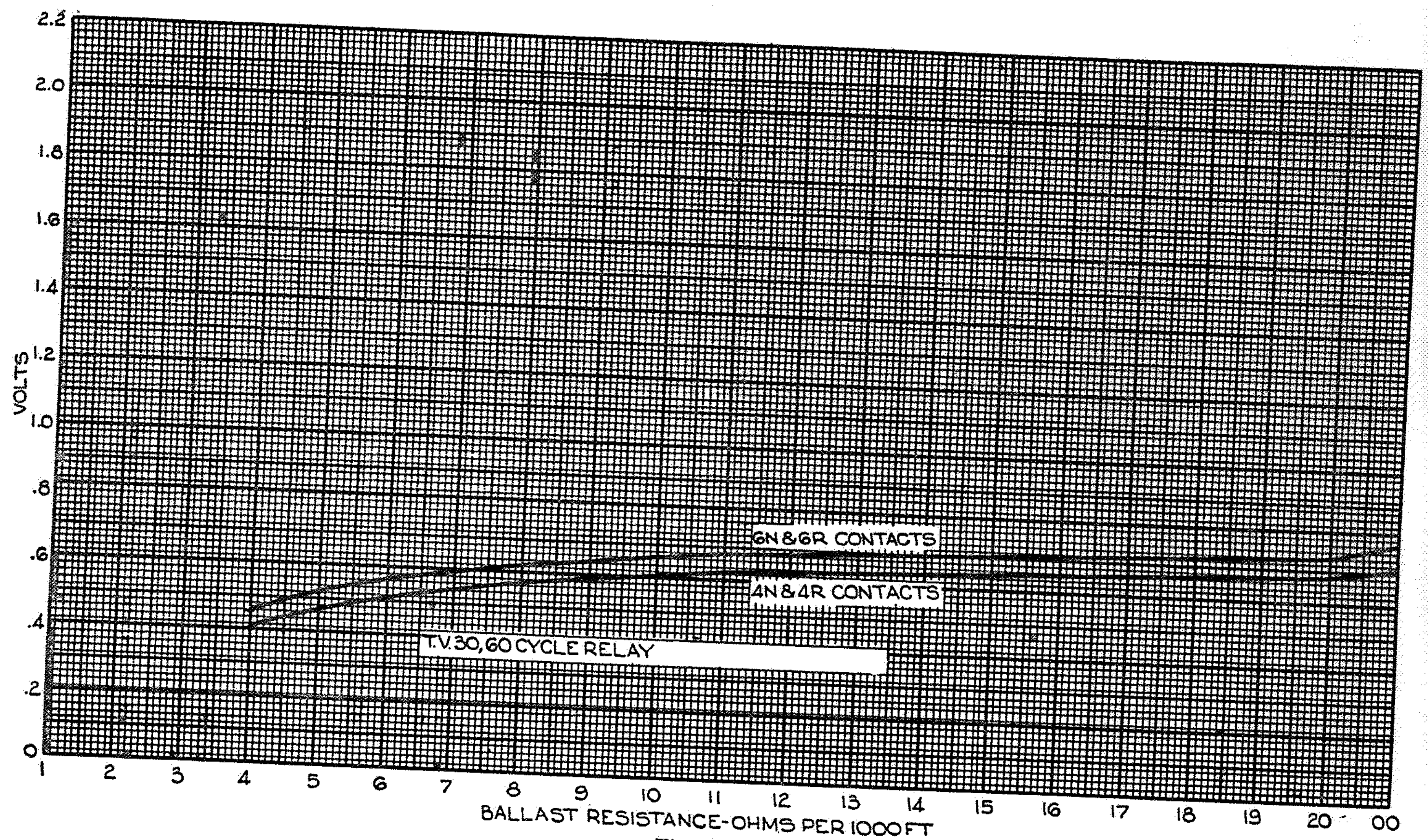


Fig. 32.

CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

Length of track circuit............................5000 feet

Minimum ballast resistance................4 ohms per M. ft.

For track circuits longer or shorter than 5000 ft., the required maximum voltage shown should be raised or lowered proportionally as follows:—

For a 5500-foot track circuit, increase 10 per cent

For a 5250-foot track circuit, increase 5 per cent

For a 4500-foot track circuit, decrease 5 per cent

For a 4000-foot track circuit, decrease 10 per cent

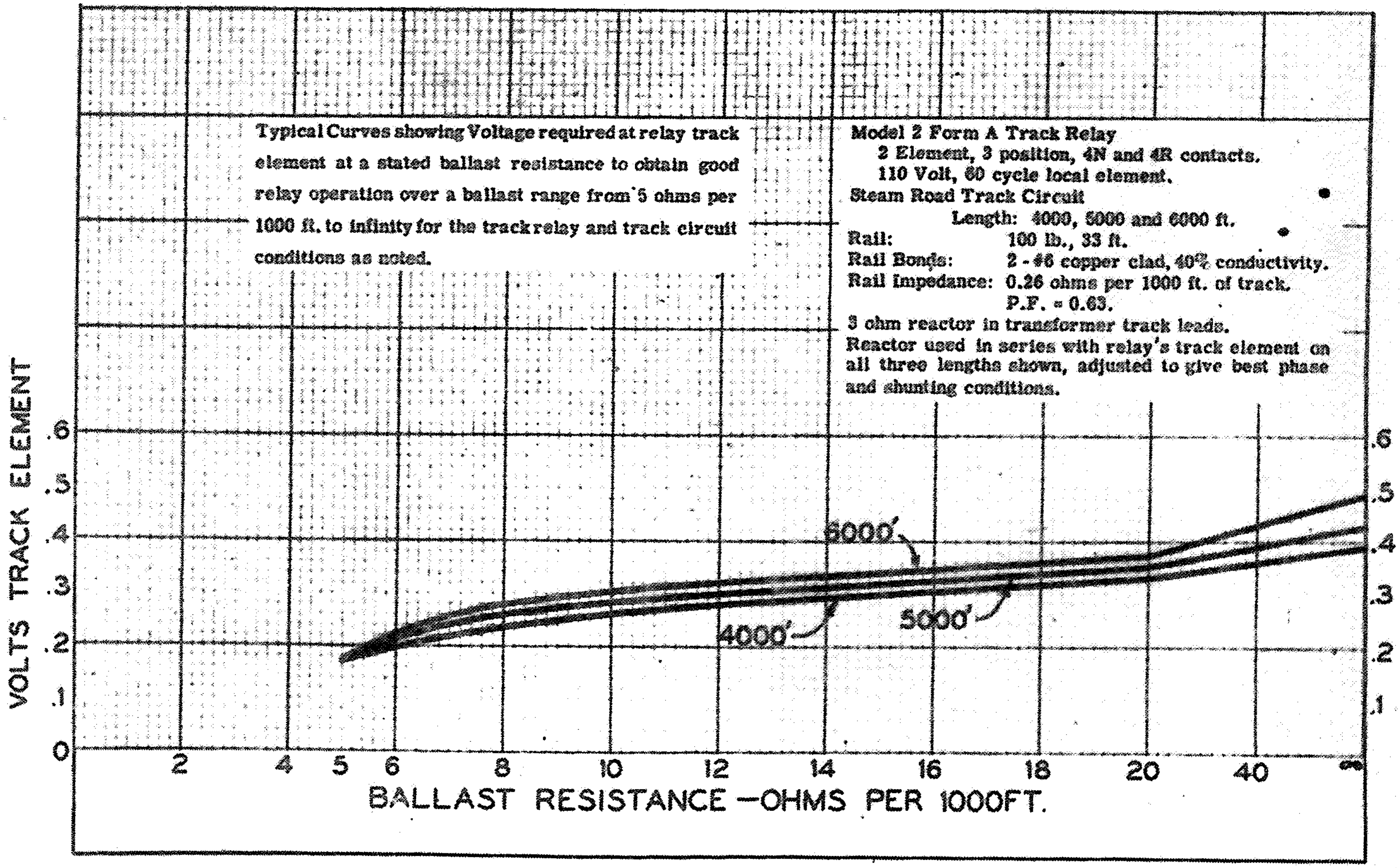


Fig. 33.
CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

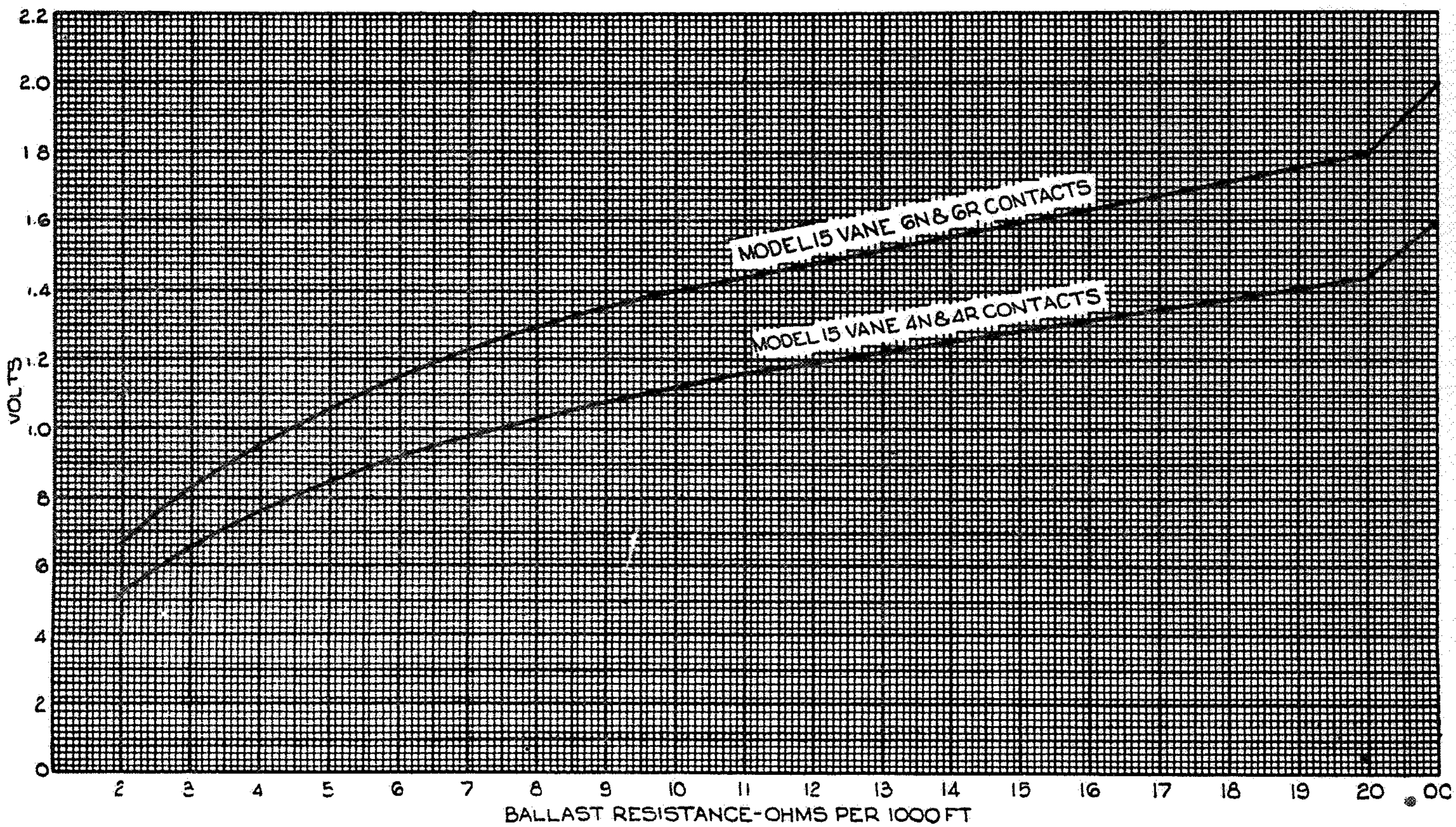


Fig. 34.

CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

Length of track circuit............................5000 feet

Minimum ballast resistance.................2 ohms per M. ft.

For track circuits longer or shorter than 5000 ft., the required maximum voltage shown should be raised or lowered proportionally as follows:—

For a 5500-foot track circuit, increase 10 per cent

For a 5250-foot track circuit, increase 5 per cent

For a 4500-foot track circuit, decrease 5 per cent

For a 4000-foot track circuit, decrease 10 per cent

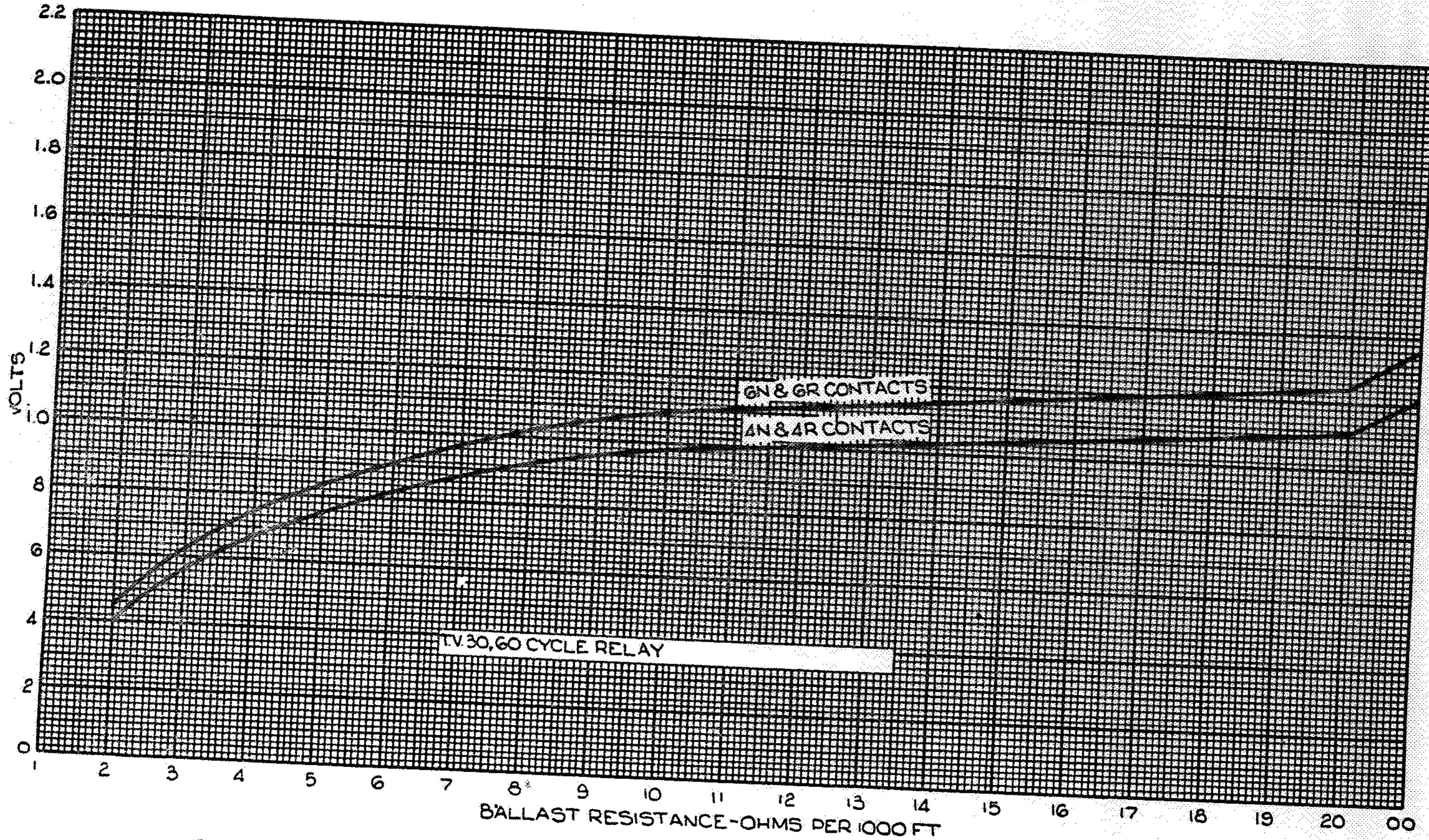


Fig. 35.

CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

Length of track circuit............................5000 feet

Minimum ballast resistance................2 ohms per M. ft.

For track circuits longer or shorter than 5000 ft., the required maximum voltage shown should be raised or lowered proportionally as follows:—

For a 5500-foot track circuit, increase 10 per cent
For a 5250-foot track circuit, increase 5 per cent
For a 4500-foot track circuit, decrease 5 per cent
For a 4000-foot track circuit, decrease 10 per cent

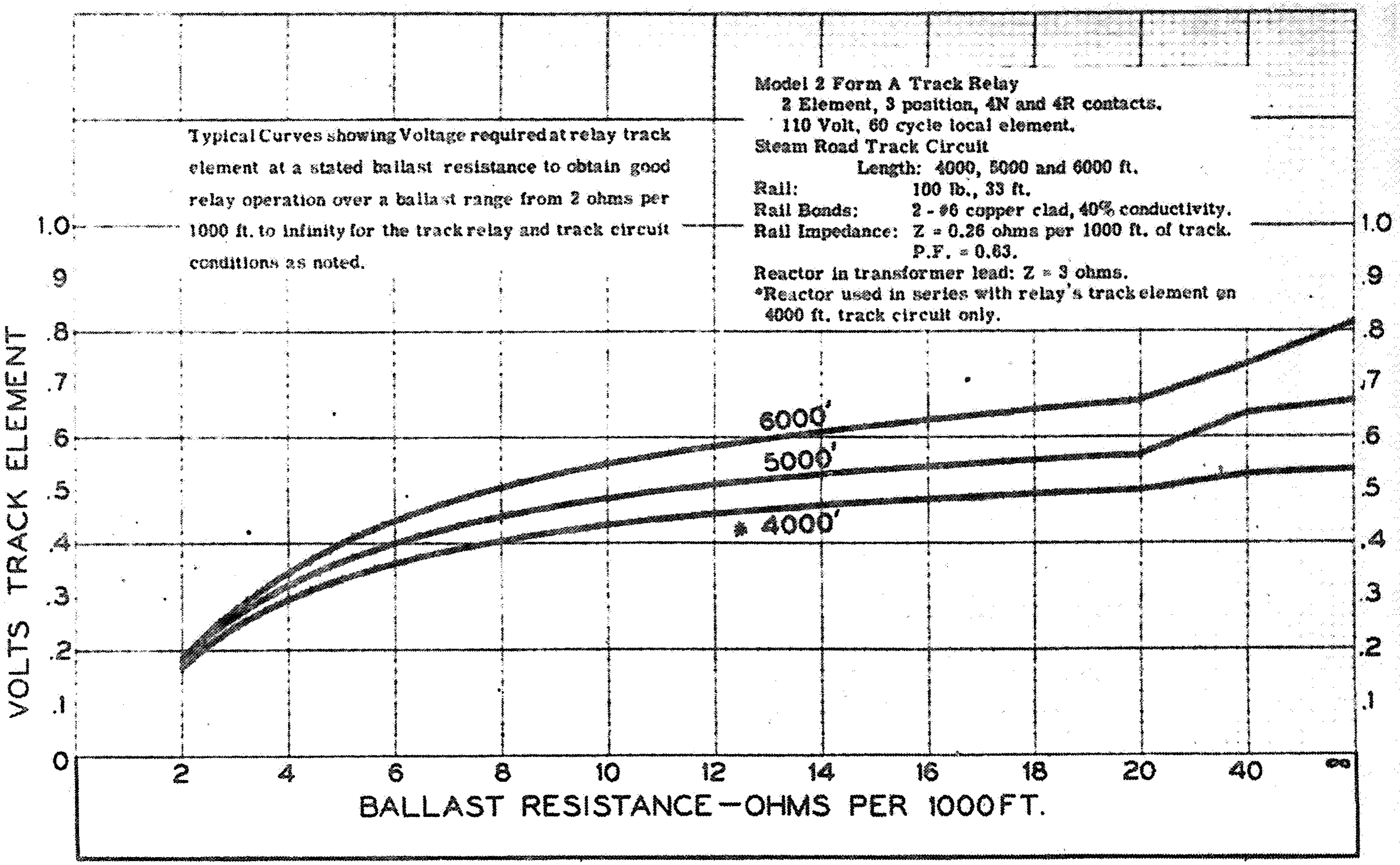


Fig. 36.
CURVES SHOWING MAXIMUM VOLTAGE REQUIRED AT RELAY TRACK ELEMENT.

Ballast resistance.

7. Ballast resistance is the resistance of the ballast ties, etc., to leakage of current from one rail of a circuit to the other. This resistance is constantly changing and may vary in dirty track circuits from 2 ohms per 1,000 feet when wet to 80 or 100 ohms when frozen. It is this wide variation which makes it difficult to adjust the track circuit to operate satisfactorily when the ballast is wet and not over-energize the relay when the ballast is dry or frozen.

8. To find the actual ballast resistance of an alternating current track circuit requires considerable apparatus and time, but the approximate ballast resistance of such a circuit close enough for practical purposes may be determined quite easily as follows:

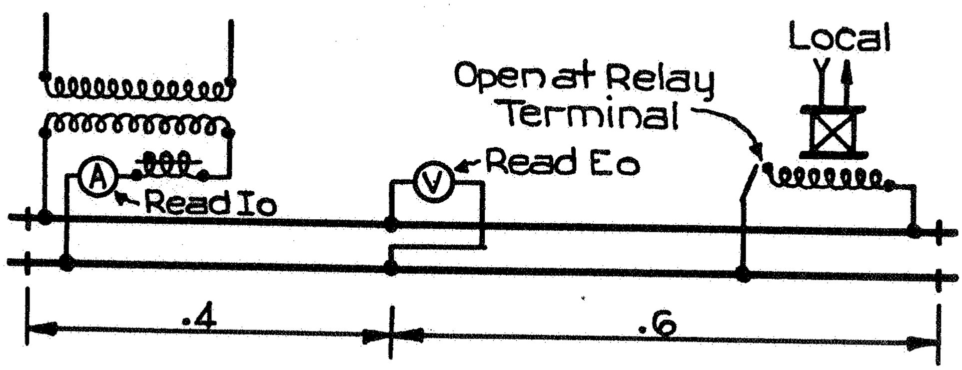


Fig. 37.

9. As shown in Fig. 37, insert ammeter in circuit, open circuit at track element of track relay, then take voltmeter reading on track four-tenths of the way through the track circuit from the feed end. The reading of the ammeter and voltmeter should be taken simultaneously if practicable, or at least within a few minutes of each other and without the track being occupied between the readings.

10. The formula for obtaining the ballast resistance by the method outlined in Instructions 8 and 9 is:

$$Rb = \frac{E_o}{I_o}$$; where Rb is the ballast resistance.

Example: Assume that the meters indicate 4.16 volts and 1.2 amperes,

$$\text{Then, } Rb = \frac{E_o}{I_o} = \frac{4.16}{1.2} = 3.47 \text{ ohms.}$$

The ballast resistance for the entire circuit is 3.47 ohms. To secure the ballast resistance per 1,000 feet of track, multiply the ballast resistance in ohms for the entire circuit by the length of the circuit in thousand feet. Thus, if the circuit is 4,900 feet long, the ballast resistance per 1,000 feet of track would be 3.47 × 4.9 = 17 ohms.

11. A test to determine the minimum ballast resistance of each track circuit should be made during or immediately after a shower or late in the winter or early spring when ballast is wet from melted snow or from thawing. If track circuit should fail on account of wet and dirty track, minimum ballast resistance test should be made at that time. When the minimum ballast resistance is obtained it will not be necessary to make similar tests until the ballast conditions get materially better or worse.

Phase angle.

12. To secure proper and efficient operation of two-element alternating current relays also requires the proper phase displacement between the currents in the two elements of the relay; this is especially true when the voltage is low on the track element of the relay.

13. Where a single-phase transmission line is used, this displacement of the phase is obtained by the insertion of a reactor or resistor, or both, in the circuit for one or both elements of the relay. The phase displacement is further affected by the impedance of the rails and the ballast resistance. The impedance of the rails is practically constant with the bonding in good condition. The variation of phase displacement due to changes in ballast resistance is great in a dirty track circuit. For example: on a 5,000-foot track circuit with a Model 15 vane relay there would be a variation of about 40 degrees in the phase in the track element of the relay with the ballast resistance at 20 ohms per 1,000 feet of track on a circuit having a minimum ballast resistance of 2 ohms per 1,000 feet. To secure reliable operation of the relay it is necessary to adjust the phase so that nearly ideal phase relation exists when the ballast resistance is at or near its minimum. The term "ideal phase relation," as used in these instructions, means the phase displacement at which the relay operates most efficiently.

14. The term "proper phase relation" is understood to mean the phase adjustment at which the relay will operate most efficiently under low ballast resistance, and shift far enough from ideal, under dry or frozen track conditions to afford some protection against high track voltage. Track circuits adjusted in accordance with these instructions will meet this condition.

Method of adjustment.

15. Model 15 vane relays.

(a) Find ballast resistance per 1,000 feet of track as outlined in Instructions 8, 9 and 10, having previously determined the minimum ballast resistance for the circuit. If minimum ballast resistance per 1,000 feet of track is 4 ohms or better, consult Fig. 31 to determine the maximum permissible voltage at relay terminals for ballast resistance conditions then existing. If the minimum ballast resistance is less than 4 ohms per 1,000 feet of track, use Fig. 34.

(b) Connect the reactor so that 1.3 ohms are in the circuit between the track transformer secondary and the track, then adjust the voltage on the secondary to give the correct voltage (as secured from the proper curve) at the terminals for the track element of the track relay. As stated in Instructions 3, 4, 5 and 6, it may then be necessary to increase the impedance of the reactor in the circuit if voltage steps on the secondary are too great.

(c) The impedance of the reactor should be checked with a voltmeter and ammeter, to be sure that the values are approximately the same as given for the taps used. This is very essential where the reactor has an adjustable air gap.

16. TV-30 relays.

(a) Proceed as outlined in Instructions 15-a, b and c, except Figs. 32 and 35 are to be used in place of Figs. 31 and 34.

17. Model 2, form A, three-position induction motor type relays.

(a) For adjustment of track voltage, proceed as outlined in Instruction 15-a, except Figs. 33 and 36 are to be used in place of Figs. 31 and 34. Connect the tapped reactor used between the track transformer and track so that its 3-ohm tap is in circuit; then adjust the voltage on the secondary of the transformer to give correct voltage (as secured from the proper curve for this type of relay) at the terminals for the track element of the relay. Check of the impedance of the reactors should be made as described in Instruction 15-c.

18. Method of test to approximate low (wet) ballast resistance.

(a) Measure ballast resistance on the day of the test.

(b) Find total ballast conductance of track circuit by taking the reciprocal of the total ballast resistance found in Instruction 18-a.

(c) Determine total wet weather conductance by dividing length of track circuit in thousands of feet by ballast resistance in ohms per 1,000 feet.

(d) Subtract actual conductance (Instruction 18-b) from wet weather conductance (Instruction 18-c).

This result will give the additional conductance which must be added and which should be added by distributing it in parts along the track circuit as indicated by the following table:

Table for Distribution of Ballast Conductance,
4,000 to 6,000-Foot (60 Cycle) Track Circuit

Min. ballast resistance per 1,000 ft.	Portion of added conductance to be placed across rails at different locations: Relay end	¼ block length	½ block length	¾ block length	Trans. end
4 ohms	¼	..	½	..	¼
2 ohms	¼	..	½	..	¼
1 ohm	⅛	¼	¼	¼	⅛

For example, if it is desired to set up a 1-ohm per 1,000-foot ballast resistance condition on a 5,000-foot block having on the day of test ballast resistance of 10 ohms per 1,000 feet, the total actual conductance of the track circuit is $\frac{5}{10} = 0.5$ mho. The wet weather conductance desired is $\frac{5}{1} = 5$ mhos. The additional conductance will be 5 minus $0.5 = 4.5$ mhos. This conductance should be divided into 5 parts, 3 of 1.123 mhos (0.89 ohm) and 2 of 0.563 mho (1.78 ohms). The three 0.89 ohm resistors should be placed across the rails at 1,250, 2,500 and 3,750 feet from the relay end of the circuit. The two 1.78 ohm resistors should be placed one each across the relay and the transformer end of the track circuit.

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