American Railway Signaling Principles and Practices

CHAPTER VIII

TRANSFORMERS

Published by the Signal Section, A. R. A.
30 Vesey Street, New York, N. Y.

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A transformer is defined as a form of stationary induction apparatus in which the primary and secondary windings are ordinarily insulated one from another. A transformer does not generate power, but merely changes the power from one voltage to another.

Alternating current for signaling is generally transmitted from a power station to the signal field by high-voltage mains; 2200 to 6600 volts are in general use, although higher and lower voltages are sometimes employed. The high voltages on mains are changed to lower voltages by means of transformers.

One method to lower the voltage is by two successive steps, that is, to use a line transformer to lower the voltage to 55 volts or 110 volts for signal motors, etc., and then further reduce this voltage by using a transformer to feed the track circuits and low-voltage signal lamps.

Another method is to use only one transformer to lower the voltage for all purposes.

In theory and in general construction all transformers, whether line or track, are the same and this chapter will deal principally with signal transformers.

Elements.

The transformer in its simplest form consists of two separate and distinct coils of insulated wire wound around the laminated iron core as shown in Fig. 1.

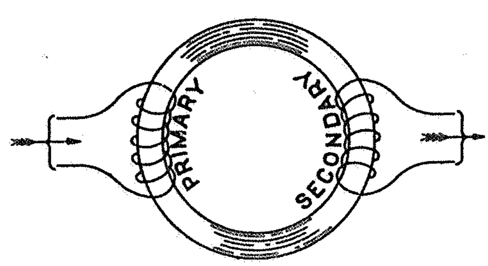


Fig. 1.
Elements of the Transformer.

One coil is attached to an outside source of energy and is the primary coil; the other coil which transmits the energy from the transformer is the secondary coil. A transformer may have more than one secondary coil, or have its secondary coil tapped at different points to produce different voltages.

When a transformer transmits higher voltage than it receives, it is known as a step-up transformer. Step-up transformers are used in power stations to raise the voltage of the generator to the transmission voltage. A transformer that transmits a lower voltage than it receives, is known as a step-down transformer. Step-down transformers are used along the transmission line at signal locations and interlocking towers to transform the higher voltages of the transmission line to lower voltages for signal purposes.

Theory.

A transformer is said to be loaded when current is flowing in the secondary coil.

When the secondary circuit is open and an alternating current from the transmission line flows through the primary coil, it causes an alternating magnetic flux to flow in the core. This magnetic flux rapidly rising, falling and changing direction with the frequency, cuts both primary and secondary coils and induces a voltage in each. The voltage produced in the primary coil is opposite in direction and nearly equal to the voltage of the transmission line. The voltage of the secondary coil is proportional to the number of turns of wire in the primary and secondary coils. The choking effect produced within the highly inductive primary coil allows only a small current to flow continuously through it. This small current, proportional to the difference between the transmission line voltage and the voltage or counter electromotive force of the primary coil, keeps the core magnetized and maintains the voltage in the coils.

When the secondary circuit is closed a current flows through it. This secondary current is opposite to the primary current and its magnetizing action in the core opposes and neutralizes to a certain extent the primary flux and reduces the choking effect or counter electromotive force. In the primary coil when this happens more current rushes into the primary coil from the transmission line and balances the demagnetizing action of the secondary current. Thus, the transformer is made automatic and maintains its core flux practically constant regardless of the load on the secondary. The variation of the load through the primary varies directly with the load on the secondary.

Losses.

All the energy drawn from the transmission line by a transformer is not transformed. The small part used in this process is analogous to the energy lost in a machine through friction. In the modern well-designed transformer, the losses are so small in proportion to the normal load on the transformer that for practical purposes they are rarely considered, but it is well to know them. Energy is lost which is required to maintain a flow of flux in the core to sustain the voltages in the coils; this loss is practically constant with or without load. The alternating magnetic flux causes losses in the iron core, called iron losses and known as hysteresis and eddy current losses.

The hysteresis loss is energy spent in overcoming the friction between the molecules of iron as they move backward and forward with the change of direction of flux; this is theoretical, as some believe it is the natural resistance of the metal to the flow of flux, and that the molecules of iron do not move backward and forward.

The eddy current loss is the energy spent in the heating action of the induced currents in the iron core by the varying flux. Voltages are induced in the core by the alternating flux and these voltages produce eddy currents.

Iron losses are practically constant with or without load and are made manifest by heating.

The energy lost in overcoming the ohmic resistance of both coils of the transformer when current flows through them (I^2R) is known as the copper losses. Copper losses vary directly with the square of the current due to the load on the transformer. The total copper loss in the transformer is (I^2R) of the primary plus (I^2R) of the secondary.

Another loss is the magnetic leakage. When the magnetic lines of force flow through the core some of them do not interlink both coils, thus causing an inductive reactance or counter electromotive force in the primary coil, which is not transmitted to the secondary coil and therefore causes a loss of voltage analogous to the ohmic resistance loss of the primary winding. This leakage is constant with or without load and is very small in modern transformers as the primary and secondary windings are interlaced in several layers. The copper resistance and the magnetic leakage tend to lessen the voltage of the secondary.

Coil resistance and magnetic leakage are shown graphically in Fig. 2.

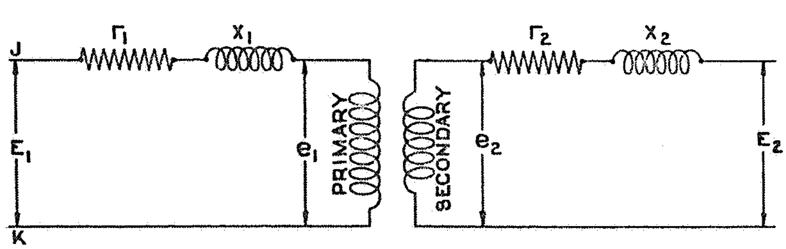


Fig. 2.
Coil Resistance and Magnetic Leakage Diagram.

E_1 is the transmission line voltage
e_1 is the primary terminal voltage after a drop caused by the ohmic resistance r_1 of the primary coil and the reactance X_1 caused by the magnetic leakage
E_1 is greater than e_1
E_2 is the net terminal voltage of the secondary
e_2 is induced voltage in the secondary before it has a drop caused by the ohmic resistance r_2 of the secondary coil and the reactance X_2 caused by the magnetic leakage

Efficiency.

The efficiency equation of a transformer is as follows:

$$\frac{\text{Output of secondary}}{\text{Output of secondary} + \text{transformer losses}} \qquad (1)$$

When the iron loss is small the transformers have a high efficiency on light loads. When the iron loss is equal to the copper loss the transformers have high efficiency on full-load or overload.

An equation often used for the efficiency of a transformer is as follows:

$$\frac{\text{Output in watts of secondary}}{\text{Input in watts of primary}} \qquad (2)$$

Voltage relation of primary and secondary coils.

The fundamental equation used in the design of a transformer is as follows:

The induced voltage in secondary coil or primary

$$\text{coil is} = \frac{4.44\ f\ \Phi\ n}{10^8} \qquad (3)$$

f is the frequency in cycles
Φ is the maximum flux on the sine wave
n is the number of turns in the respective coil

The voltages in the secondary and primary coils are proportional to their respective turns as both have the same frequency and are cut by the same flux.

Due to the automatic action of the transformer which causes the core flux to remain constant regardless of load, the primary and secondary induced voltages remain practically constant. Hence:

$$\frac{\text{Voltage of primary}}{\text{Voltage of secondary}} = \frac{\text{turns of primary}}{\text{turns of secondary}} \qquad (4)$$

Voltage of primary multiplied by turns of secondary is equal to voltage of secondary multiplied by turns of primary.

The ratio of a transformer is the ratio of the primary voltage to the secondary voltage. Thus, a transformer with 2200 volts primary and 110 volts secondary has a ratio of 20 to 1.

Ampere turns.

The magnetic force exerted on a transformer core is (IN) the current in primary coil multiplied by the number of turns in the primary coil; the product is ampere turns.

Notice that the magnetizing force can be increased by increasing either the current or the number of turns, or an equivalent can be produced by decreasing the amount of current and increasing the number of turns, or vice versa.

The magnetic action on the secondary coil is the current in the secondary coil multiplied by the number of turns in that coil. (I_2N_2)

As the magnetic action of the load currents balance each other,

$$NI = N_2I_2 \text{ or } \frac{I}{I_2} = \frac{N_2}{N} \tag{5}$$

The currents in the primary and the secondary windings are in inverse proportion to their number of turns.

For example: A transformer having 6000 turns in the primary coil and 300 turns in the secondary coil and a power supply of 2200 volts, we see by equation 4,

$$\text{the secondary voltage} = \frac{2200 \times 300}{6000} = 110 \text{ volts.}$$

When the secondary transmits 10 amperes, we see by equation 5,

$$\text{current in primary} = \frac{300 \times 10}{6000} = \tfrac{1}{2} \text{ ampere.}$$

Effect of power factor.

Power factor is defined as the ratio of the power to the apparent power.

When the power factor of an alternating current is unity:

$$\text{Watts} = \text{current} \times \text{voltage} \tag{6a}$$

When the power factor of an alternating current is less than unity:

$$\text{Watts} = \text{current} \times \text{voltage} \times \text{power factor} \tag{6b}$$

A transformer transmitting 10 amperes from its secondary to do certain work when the load has unity power factor would require 20 amperes to do the same amount of work if the load had a power factor of 0.5 as often happens in signal work. For this reason, the capacity of a transformer is stated in kv-a. (1000 volt-amperes) and not in k.w. (1000 watts). K. is the abbreviation for Kilo, a Greek prefix meaning one thousand. The capacity of a transformer is the number of kv-a.'s the transformer is designed to carry.

Cosine Θ is the power factor of the secondary current.
Θ is the angle of lag of the secondary.
When the angle Θ is 60 degrees, Cosine Θ, the power factor is 0.5
When the angle Θ is 30 degrees, Cosine Θ, the power factor is 0.87
When the angle Θ is 15 degrees, Cosine Θ, the power factor is 0.97

Calculation of iron losses.

After a great many experiments, Dr. Steinmetz produced the fundamental formula for hysteresis in "V" cubic centimeters of iron.

$$\text{Loss in watts} = \frac{B^{1.6}\ f\ Vn}{10{,}000{,}000} \qquad (7)$$

B is the flux density lines per sq. cm.
f is the frequency
n is the factor depending upon the quality of the iron
In modern silicon steel, "n" is about 0.00093

Hysteresis loss will increase with increase of frequency and flux density, and decrease with any metal having a lower "n" factor.

The fundamental formula for eddy current loss in "V" cubic centimeters of iron is as follows:

$$\text{Loss in watts} = \frac{Vf^2\ B^2\ T^2b}{10{,}000{,}000} \qquad (8)$$

T is the thickness of each lamination in centimeters
b is the factor depending upon the resistance in the iron
B is the flux density lines per sq. cm.
f is the frequency

In silicon steel "B" is about $\frac{0.57}{100{,}000{,}000{,}000}$

Eddy current loss increases with frequency and resistance of the iron and decreases by thinning the laminations.

These eddy currents flow in a plane at right angles to the flux lines and in order to impede their flow, the transformer is built up of thin sheets, painted on both sides to insulate one sheet from another and assembled in such a manner that the eddy current will receive the most obstruction.

Figure 3 is a graphical illustration of formulae 7 and 8. Silicon steel has low initial losses which remain so after long service of the transformers.

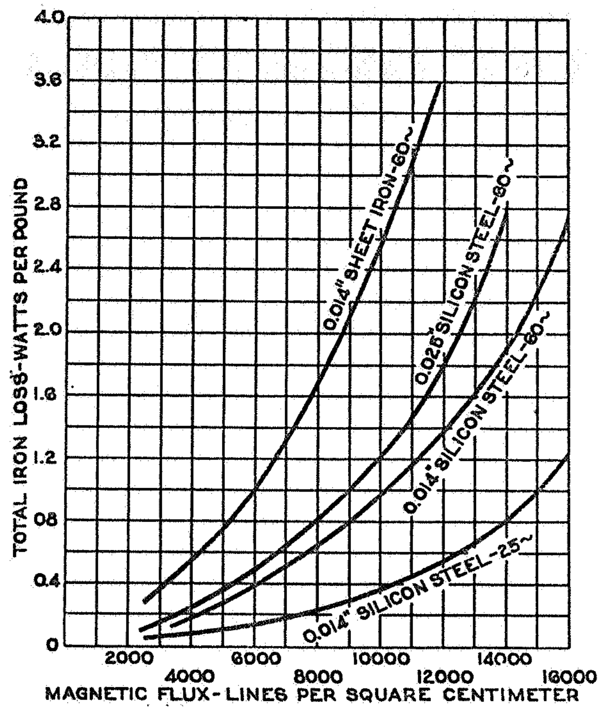


Fig. 3
Iron Loss Curves.

Regulation.

When a secondary is transmitting power and the circuit is opened, or the load removed, the voltage of the secondary will rise. The amount of rise of voltage expressed in per cent of the secondary full-load terminal voltage is called the regulation, the impressed primary voltage being constant.

For example: The secondary full non-inductive load is 110 volts and 114 volts when the load is removed.

$$\text{Regulation} = \frac{114 - 110}{110} = 3.84 \text{ per cent.}$$

As before stated under losses, the above drop is due to the copper losses in both primary and secondary coils, when the load current passes through them in addition to the reactive drop due to magnetic leakage.

It is often necessary to calculate the regulation from predetermined values of the resistance and reactance drop, as the quantities vary with the load and power factor.

The formula recommended by the United States Bureau of Standards at unity power factor (non-inductive load) is:

$$\text{Regulation} = \left(\frac{100\ IR}{E}\right) \% \qquad (9)$$

At 60 per cent power factor:

$$\text{Regulation} = \left[100\left(\frac{0.6\ IR + 0.8\ P}{E}\right)\right] \% \qquad (10)$$

E is the rated primary voltage
P is the reactance voltage drop at full-load
I is the full-load primary current not including the exciting current

The equivalent resistance "R" of combined primary and secondary coils is found by multiplying the secondary resistance by the square of the ratio of primary to secondary turns and adding the primary resistance.

The impedance voltage "e" is found by short circuiting the secondary and measuring the voltage required to send the full-load current through the primary.

The impedance voltage is:

$$e = \sqrt{P^2 + I^2R^2} \qquad (11)$$

Transposing:

$$P = \sqrt{e^2 - I^2R^2} \qquad (12)$$

The way to improve regulation is to use plenty of copper in the coils to decrease the (I^2R) drop and to interlace the primary and secondary windings to decrease the magnetic leakage.

Performance; rating.

Table I shows the performance of high-grade commercial transformers regarding losses, efficiencies and regulation at various voltages and power factors. Signal transformers are designed along the same lines as commercial transformers.

TABLE I

Performance of Commercial Transformers

Kv.-a.	Watts Loss		Per Cent Efficiency			Per Cent Regulation		
	Iron	Copper	Full-Load	½ Load	¼ Load	100% P. F.	80% P. F.	60% P. F.
½	15	13	94.7	93.2	88.7	2.62	3.28	3.16
1	20	24	95.8	95.1	92.0	2.42	3.12	3.04
1½	25	35	96.0	95.5	92.7	2.36	3.07	3.00
2	30	42	96.5	96.2	93.8	2.12	2.88	2.86
2½	33	51	96.8	96.5	94.5	2.08	2.83	2.83
3	34	64	96.8	96.8	95.2	2.16	2.91	2.88
4	40	75	97.2	97.1	95.7	1.90	3.00	3.12
5	45	93	97.3	97.3	96.1	1.90	2.99	3.11
7½	62	125	97.6	97.6	96.4	1.70	2.84	3.00
10	80	148	97.8	97.7	96.5	1.51	2.68	2.89
15	105	212	97.9	97.9	97.0	1.44	2.63	2.85
20	131	268	98.0	98.0	97.1	1.39	2.87	3.21
25	147	319	98.2	98.2	97.4	1.33	2.82	3.17
30	163	374	98.2	98.3	97.6	1.32	2.82	3.16
37½	197	433	98.3	98.4	97.7	1.20	2.72	3.09
50	240	550	98.4	98.5	97.9	1.15	2.68	3.07

Transformers are rated according to the power they can deliver continuously on non-inductive load without over-heating. To secure uniformity in rating, the A.I.E.E. recommend for transformers used continuously that the temperature rise at full-load shall not exceed a room temperature of 25 degrees Centigrade by more than 50 degrees Centigrade.

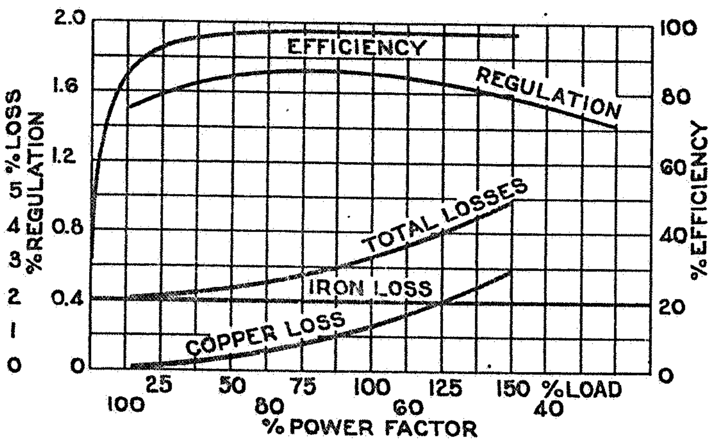


Fig. 4
Test Characteristics 100 kv-a. Transformer.

In signal practice, transformers are rarely subjected to continuous full-load, so the Signal Section, American Railway Association, in preparing transformer specifications only provided for a run of one hour under the same conditions, but to meet approximately the same requirements.

Figure 4 is the characteristic test of a 100 kv-a. transformer.

Different frequencies.

The lower the frequency the larger must be the transformer in order to deliver a given output without over-heating. The frequencies generally used in signal work are 25, 60 and 100 cycles.

A transformer designed for a certain work at 25 cycles would perform the same work on a 60-cycle transmission line with less heat than on the 25-cycle transmission line; the same applies to a 60-cycle transformer used on a 100-cycle transmission line. A 25-cycle ansformer connected to a 60-cycle transmission line would have coils cut by the magnetic flux more than twice the rate they uld be cut by a 25-cycle transmission, therefore requiring less lines of force to perform the function of sustaining the voltage in the coils and a smaller iron core to accommodate them. It is, therefore, evident that transformers designed for a certain frequency should not be used on lines having a lower frequency as excessive current will flow in the primary coil thus causing a partial short circuit.

Vector diagrams.

The vector diagrams of an ideal transformer working on no-load are shown in Fig. 5.

The ideal transformer is considered as having no losses and a resistance so small as to be negligible. The flux generated in the iron core varies periodically and accompanies in phase the magnetic current which produces it.

The voltages induced in the primary and secondary coils by the changing flux must lag 90 degrees behind the flux because it is when the flux is changing most rapidly at the zero point of the sine curve that the induced voltage is the greatest.

These relations are illustrated by Diagram A at the left of Fig. 5. Where (e_1) and (E_2) are the voltages induced in the primary and secondary coils respectively by the flux caused to flow in the iron core of the transformer by the primary magnetizing current (M), itself proportional to the difference between (E_1), the voltage impressed on the primary by the mains and (e_1), the primary induced counter electromotive force in the primary.

The actual transformer vector diagram working on no-load is shown in Diagram B of Fig. 5. The eddy currents are in phase with the induced voltages producing them. These voltages lag 90 degrees behind the flux. Opposite voltages and currents which must be supplied to the primary to compensate for the iron losses are 90 degrees ahead of the flux. Therefore, an iron loss component (MI_0) must be added to the magnetizing current (OM).

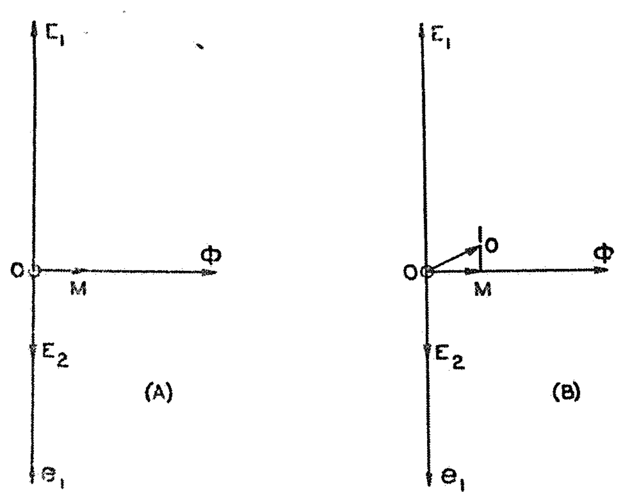


Fig. 5.
Vector Diagrams of Transformer
Working on No-Load.

The total primary no-load current is (OI_0). The two components (OM) and (MI_0) cannot be added arithmetically as they are not in phase, but are added geometrically combined by the parallelogram of forces.

When a transformer is supplying power at approximately unity power factor, the secondary current is approximately in phase with secondary voltage. The corresponding load current in the primary is opposite to and balances the secondary turns to maintain the automatic transfer of power between primary and secondary. These relations are shown in Diagram A of Fig. 6.

When the secondary is operating at nearly unity power factor on a non-inductive load, the total primary current (OI_1) is much nearer in phase with the primary impressed voltage than the no-load current (OI_0). When the secondary is feeding highly inductive load at a low power factor, the secondary current (OI_2), in Diagram B, lags far behind the secondary voltage (E_2) and consequently the total primary current (OI_1) lags farther behind the primary impressed voltage than does the no-load current (OI_0).

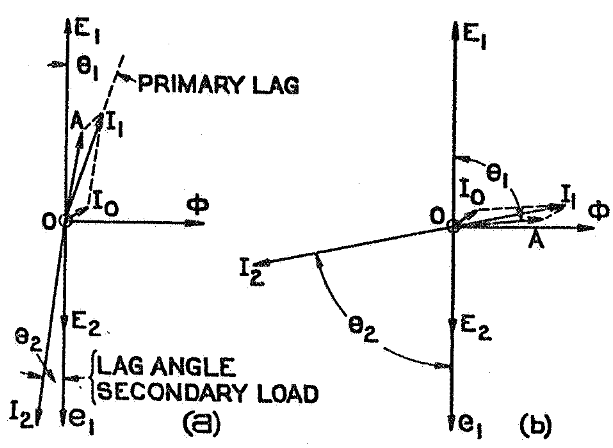


Fig. 6.
Effect of Secondary Power Factor on Primary Current Vector.

OI_2 is the secondary current

OA is the balancing primary load current

OI_0 is the no-load primary current

OI_1 is the total primary current composed of load and magnetizing components OA and OI_0

OE_1 is the impressed primary voltage

A complete transformer vector diagram is shown in Fig. 7.

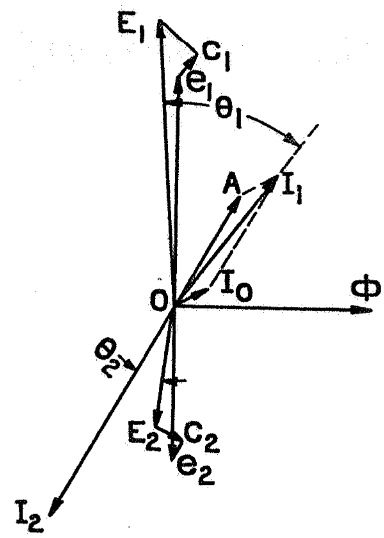


Fig. 7.
Complete Transformer Vector Diagram.

Oe_2 = induced e.m.f. in the secondary (hypothetical)
Oe_1 = induced e.m.f. necessary to overcome counter e.m.f. in primary; opposed and proportional to Oe_2 by ratio r
r = ratio of transformation of the transformer
$O\Phi$ = useful flux
OI_0 = primary no-load current
OI_1 = total resultant primary current
E_1C_1 = primary reactance drop at 90 degrees to OI_1
e_1C_1 = primary resistance drop parallel to OI_1
OI_2 = secondary current
Cos.Θ_2 = power factor of load on secondary
OE_1 = total voltage to be applied at primary terminals
e_2C_2 = secondary resistance drop in volts in phase with OI_2
E_2C_2 = secondary reactance drop in volts due to one-half leakage flux at 90 degrees to OI_2
OA = primary load current; opposed and proportional to OI_2 by ratio $^1/r$
OE_2 = net secondary terminal voltage
OC_2 = secondary terminal e.m.f.
Cos.Θ_1 = power factor of transmission line

The voltage (OE_1) must be larger than (Oe_1) by an amount necessary to overcome ($e_1C_1 + E_1C_1$).

The secondary terminal voltage (OE_2) is less than the full secondary induced voltage (Oe_2) by the amount lost in the ohmic drop ($e_2C_2 + E_2C_2$), the reactance drop. These losses must be subtracted from the original induced voltage (Oe_2), thus the net terminal voltage of the secondary (OE_2).

Types of transformers.

The essential parts of a transformer are: the coils with their insulation, the iron core, the terminal board and leadout wires, and the case, if any, with its insulation.

Transformers used in signal work may be either air or oil-cooled depending on the capacity of the transformer. Up to 1 kv-a. air-cooled transformers will operate successfully; above 1 kv-a. oil-cooled transformers are used generally.

Some railroads having center fed track circuits use transformers with an adjustable filler block with which a 3 per cent variation in the secondary can be obtained. Thus, resistors or reactors between the secondary and the track can be eliminated.

Another type of transformer used in signaling is the auto-transformer as shown in Fig. 8.

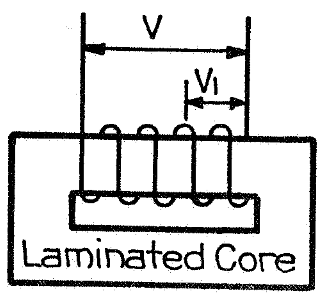


Fig. 8.
Auto-Transformer.

The auto-transformer consists of one coil tapped at certain points dividing it into parts, any part of which can be used as a primary or secondary. The ratio depends upon the number of turns in each part.

V is the primary

V_1 is the secondary

This form of transformer is hazardous on high voltage and should be used only where there is a small variation between the primary and secondary, or on low voltage.

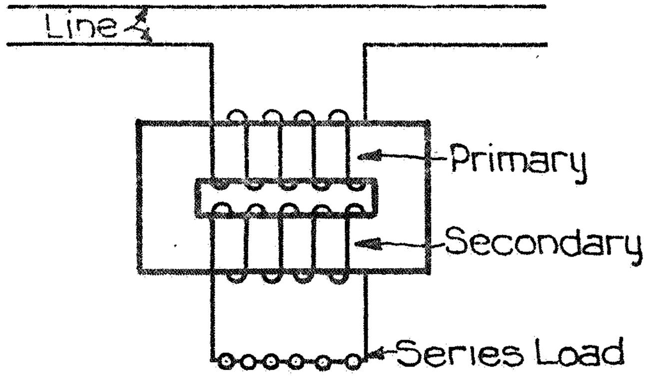


Fig. 9.
Series or Current Transformer.

Another type of transformer used in signal work is the insulating transformer which has the same number of turns in the primary and secondary winding (usually called one-to-one transformer). This type is used generally as lightning, surge or ground protection between the transmission lines and operated units, or where power is purchased from an outside source of supply, as additional protection between the outside source of supply and the transmission line.

There is also the series or current transformer, shown in Fig. 9.

In the series or current transformer, the primary coil is in series with one of the line wires, and the secondary in series with the apparatus to which it transmits its energy. When the voltage in the primary varies, the voltage in the secondary varies with it. This type of transformer is used generally to operate ammeters and wattmeters.

The relative arrangement of core and coil divides the transformers, generally used for signal work, into core type, shell type and distributed core type.

The three types are shown in Fig. 10.

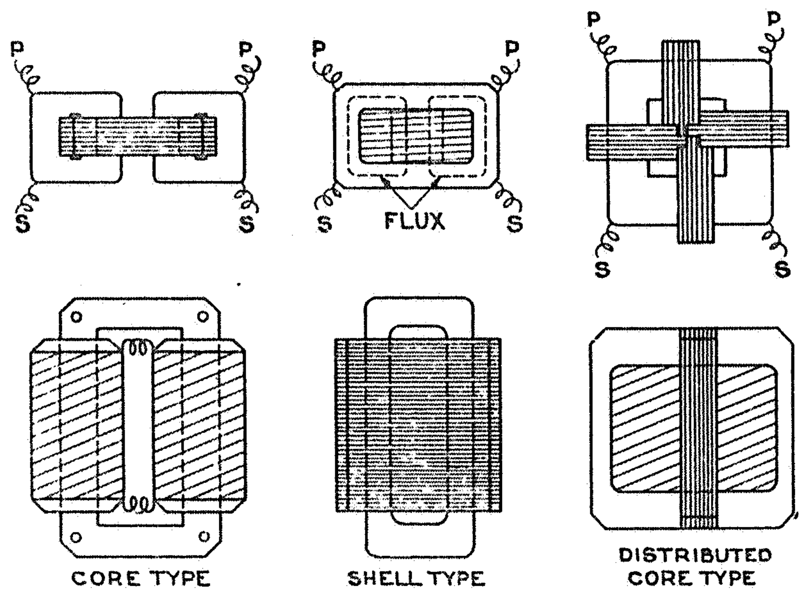


Fig. 10.
Transformer Core Construction.

The core type has both vertical legs surrounded by a winding. Half of the primary and half of the secondary are wound one over the other on each leg. This method of winding, which may be called interlacing, reduces magnetic leakage.

The shell type has both primary and secondary wound interlaced, one with the other, over the center leg of the iron core which almost entirely surrounds the coils.

Figure 11 illustrates the shell transformer. The transformer and terminal board are shown at left and the transformer enclosed in iron case, with lid off, is shown at right.

The distributed core type transformer is a combination of the core type and shell type. The iron core consists of four magnetic circuits of equal reluctance in multiple. Each circuit consists of a separate core. One leg of each magnetic circuit is built up of two different widths of punchings, forming such a cross-section that when the four circuits are assembled together they interlock to form a central leg upon which the windings are placed. The four remaining outside legs occupy a position surrounding the coil at equal distance from the center on the four sides. The complete core with its coils is shown in Fig. 12.

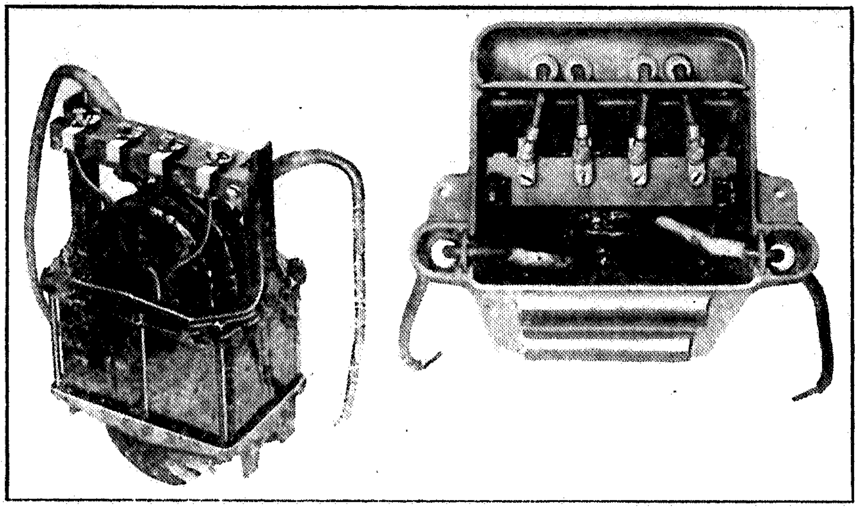


Fig. 11.
Shell Transformer.

Relative advantage of core and shell types.

The core type has a lighter core of smaller sectional area than the shell type, so that more copper with a larger number of turns is required with the core type, although the turns are of a lesser mean length. Then again, cylindrical form wound coils can be rapidly wound for the core type; these coils have a large surface exposed for cooling. The core type is better suited for high voltages which may require many turns and considerable insulation. The shell type is suited for moderate voltages requiring few turns and little insulation. The distributed core type combines the best features of both core and shell type, *i.e.*, a short mean length of turns in the coil and a short length of magnetic circuit.

Coils; insulation.

In transformers, extreme care is taken to insulate the primary coil from the secondary coil and to insulate both coils from the core, because of the high voltage impressed generally on the primary, and to the interlacing of the coils to prevent magnetic leakage. A breakdown on the primary would perhaps put a high voltage on the secondary.

Insulation test.

The windings should withstand the following test voltages for one minute, the transformer being filled with oil at the time the tests are made:

Winding	Rated voltage of winding	Test voltage to all other windings and from windings to core
High or low voltage	0-549	Twice rated voltage plus 1000 volts
Low voltage	550-5000	Twice rated voltage plus 1000 volts
High voltage	550-5000	10,000 volts
High or low voltage	5001 and above	Twice rated voltage plus 1000 volts

In case of a one-to-one transformer, one winding should be considered as high voltage, and should be insulated in accordance with the test for a high-voltage winding of the rated voltage specified therefor.

The windings should withstand for one minute an impressed voltage at a suitable frequency of two times the rated no-load voltage.

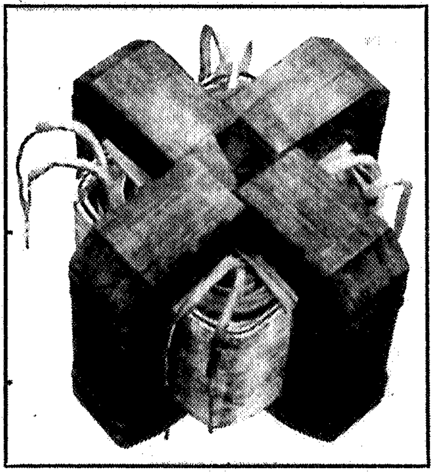


Fig. 12.
Distributed Core Transformer.

Track transformer.

Unless otherwise specified, electrical apparatus assembled should withstand for one minute an insulation test of 3000 volts alternating current between all parts of electric circuits and other metallic parts insulated therefrom.

A surface leakage distance of not less than ⅜ inch should be provided between any exposed metallic part of the apparatus carrying current and any other metallic part thereof.

A potential of twice the normal operating requirements at a suitable frequency should be impressed across the windings without any excessive flow of current indicating a short circuit.

As an additional safeguard, a metal plate or ground shield is placed directly between the primary and secondary coils and connected to the iron case and thence to a satisfactory ground in the vicinity of the transformer, to lead off the testing current should the primary coil break down.

Impregnating.

After the core is completely wound, it is thoroughly dried by heating in a vacuum tank, after which a hot insulating compound is forced by high pressure into every part of the windings and insulation until it is thoroughly saturated. This process is to make it moisture-proof and is called impregnation.

Assembly.

Practically all transformers have terminal boards attached to the core, to which are attached the coil leads, but where the primary voltage is very high the primary leads are not brought to the terminal board. When the transformer is put into a case, it is firmly attached to the case to keep it steady during transit.

The leads from terminal board to the outside of the case are covered at the case openings with a hard insulating compound to make the case waterproof, and to prevent the leads from being pulled away from their inside terminals.

Case, with oil.

Transformers of 1 kv-a. capacity or less, not enclosed in a regular transformer case, are called air-cooled transformers. Most transformers of over 0.75 kv-a. capacity are provided with an iron case.

The case, besides giving the core mechanical and weather protection, is generally filled with a fine grade of mineral oil, free from acid, alkali and moisture. Oil is a good insulator and is used to convey the heat generated by the transformer from the core to the case. Oil is a better medium for performing this function than air.

An oil-cooled transformer always shows a much lower temperature rise than a similar air-cooled transformer. Oil keeps moisture out of the windings and also keeps them soft and pliable. This softening is disadvantageous if there is vibration, as the soft insulation gives way readily to friction.

Case, without oil.

Some transformers, being specially impregnated, may be encased without oil. The use of oil depends largely upon the load on the transformer. Where there is not much heat generated by the transformer, an iron case ventilated in such a manner to keep out the rain and snow is sufficient without oil.

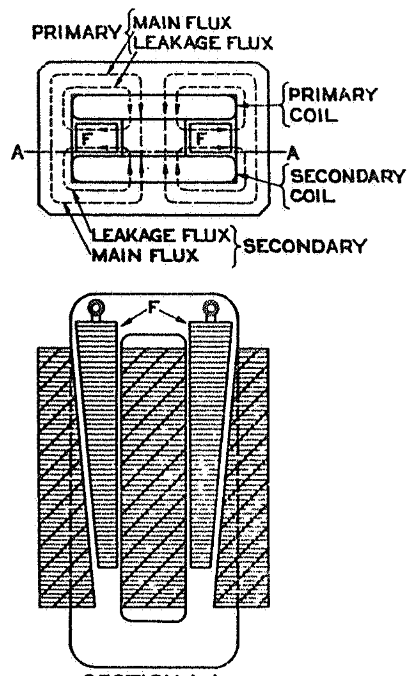


Fig. 13.
Adjustable Filler Transformer.

Adjustable filler block track transformer.

By increasing the magnetic leakage in a transformer, the secondary voltage is decreased, and vice versa. This variable magnetic leakage is accomplished by the adjustable filler as seen in Fig. 13.

This adjustable filler transformer is made for feeding track circuits direct and to eliminate external impedance between the secondary and the track. The construction is illustrated in Fig. 13. The transformer is of the shell type. Sufficient space is left between the primary and secondary coils for the two laminated wedge-shaped iron filler blocks "F.F." These filler blocks are supported from the terminal board and the magnetic leakage can be regulated as desired in order to secure the desired secondary voltage on the track. The magnetic leakage is greatest when the fillers are fully entered and least when the fillers are withdrawn.

The transformer shown in Fig. 13 is generally provided with a case and is oil-cooled. This type of transformer is becoming obsolete.

These transformers were used generally only on center fed track circuits on electric roads, provided with high-voltage transmission line. They are connected directly to the transmission line and have one track secondary where a center fed track circuit is used, and a transformer with high-voltage primary and a secondary for feeding signal motors, slots, lights and local elements of track relays is used at the end of the block.

When a train enters the track circuit, the reactance drop due to the magnetic leakage rapidly increases and the voltage at the secondary falls. This action is illustrated in Fig. 14 which shows how rapidly the secondary voltage falls as the current increases, the filler block being ¼ inch out in one curve and nearly all the way in for the other curve. Were it not for the reactance drop, the secondary short circuit current would be exceedingly greater than shown by the curve.

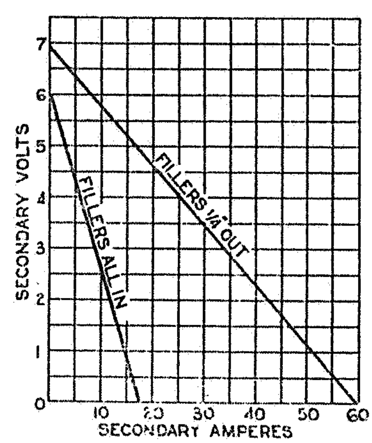


Fig. 14.
Characteristics of the Adjustable Filler Transformer.

Details of air-cooled transformers.

Air-cooled transformers are built for 25, 60 and 100 cycles. Their capacity varies from 0.20 kv-a. to 1 kv-a. They have one or more secondary windings for track circuits as required.

The voltages of the secondary windings for track circuits vary from 0.3 to 20 volts. Figures 15 and 16 are air-cooled track transformers.

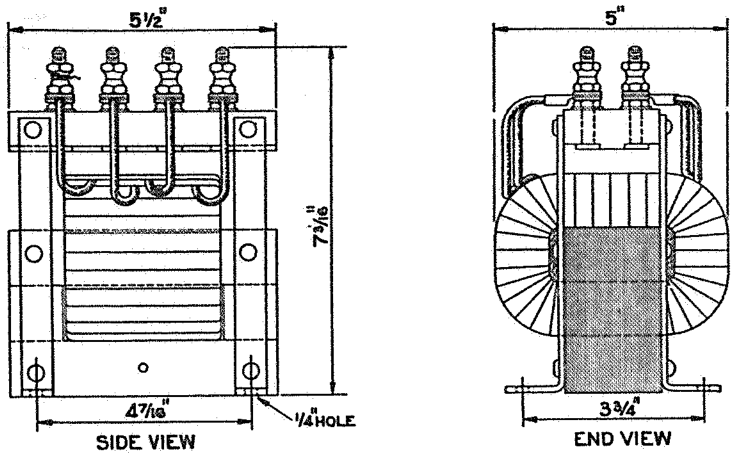


Fig. 15.
Air-Cooled Track Transformer, Single or Double Secondary.

Windings

Cycles	Primary Volts	Secondary Volts	Secondary Amperes
25	110	1, 2, 3, 4, 5, 6, 7, 8, 9	10
25	110	2, 4, 6, 8, 10, 12	10
60	110	3, 5, 7, 10, 12, 15	15
60	110	5.5, 6, 6.5, 7	16
60	220	3, 6, 9, 12, 15, 18	10
60	55	3, 5, 7, 10, 12, 15	15

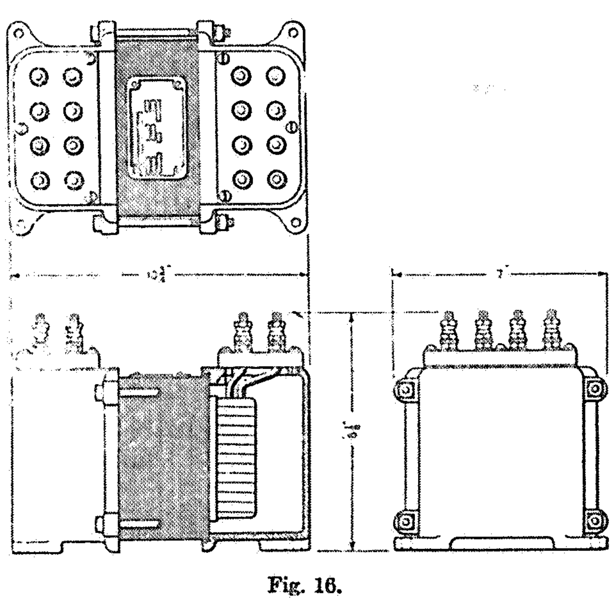


Fig. 16.
K-2 Transformer.

Windings

Cycles	Primary volts	Total kv-a. capacity	Secondary — Line: No. of wind ings	Line: Volts	Line: Amperes	Secondary — Track: No. of windings	Track: Volts	Track: Amperes
25	110	0.60	1	110 (55-55)	3.63	1	14 (2-3-4-2-1-1-1)	14.3
25	220/110	0.25	1	110/55	0.455/0.91	1	14 (2-3-4-2-1-1-1)	14.3
25	550 (390-160)	0.30	..	......	....	1	24 (20-2-2)	12.5
60	110/55	0.35	1	110/55	0.455/0.91	1	20 (2-3-4-5-3-2-1)	15.0
60	220	0.60	1	110	2.27	1	14 (8-1-1-1-1-1-1)	25.0

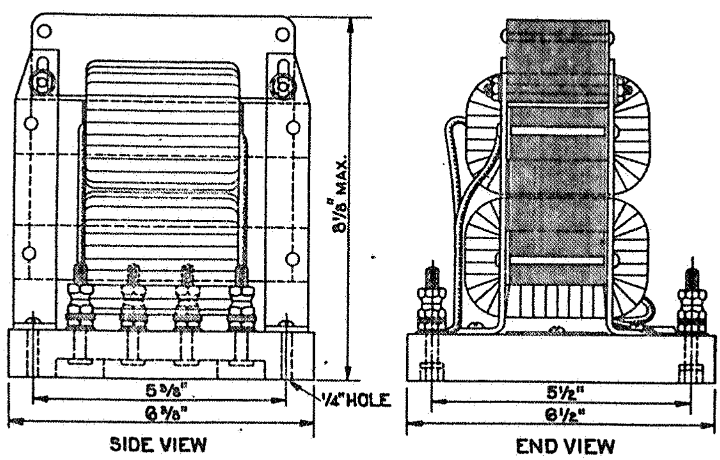


Fig. 17.
Reactive Air-Cooled Track Transformer.

The reactive air-cooled track transformer is of the core type, but in appearance it resembles the series current type, having its primary on the upper leg and its secondary on the lower leg. Its primary is connected across the transmission line instead of being in series with one of the wires of the transmission line. It operates on the principle of the adjustable filler transformer and is illustrated in Fig. 17.

The filler blocks shown in Fig. 14 are replaced by a V-shaped magnetic shunt which sets with the "V" inverted on the top of the upper leg of the transformer. This laminated iron block is adjusted vertically to vary the air gap between it and the upper leg. This block shunts the flux out of the secondary coil and produces the same results as the filler blocks in Fig. 14. The electrical action of the two transformers is identical. This transformer has but one secondary tapped for different voltages and is intended for feeding a single-track circuit on electric roads using alternating current propulsion. Its primary should not exceed 220 volts and the open circuit voltage of its secondary varies from 2.7 to 16 volts.

Line transformers.

All transformers connected directly to the transmission line are line transformers. Some line transformers do not have track secondaries and those that have are named combined line and track transformers. The former are used as step-down transformers with auxiliary track transformer for track circuits. These transformers are of the distributed core type.

Figures 18 and 19 show such a transformer with table of weights and capacities as manufactured.

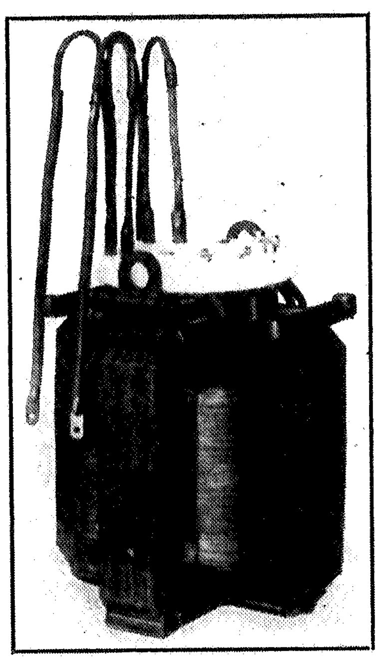


Fig. 18.
Complete Core and Termina Board Distributed Core Type Transformer.

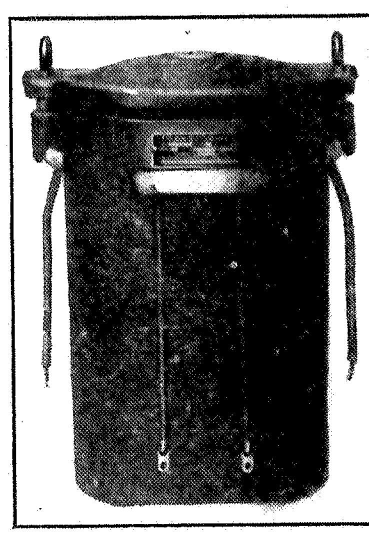


Fig. 19.
Oil-Cooled Line Transformer.

Fig. no.	Kv-a.	25 Cycles Approximate shipping weight	25 Cycles Quarts oil	60 Cycles Approximate shipping weight	60 Cycles Quarts oil
1	0.6	180	10	130	6
2	1.0	180	10	130	6
3	1.5	200	13	145	7
4	2.0	235	16	160	9
5	2.5	275	21	195	10
6	3.0	350	32	210	13
7	4.0	375	32	245	16
8	5.0	455	40	295	21
9	7.5	615	68	395	32
10	10	755	88	455	40
11	15	955	116	660	68
12	20	1,110	135	800	88
13	25	1,280	170	925	116
14	30	1,550	225	1,045	135
15	40	2,070	230	1,410	170
16	50	2,350	240	1,635	225
17	75	2,400	280	1,930	220

Line transformers with track secondaries are of the oil-immersed shell type with an iron core. These transformers have a high efficiency due to their construction and special preparation to overcome transformer losses and to prevent increase of losses as the transformer ages. They are subjected to high insulation tests to prevent breakdown.

Figure 20 shows a combined line and track transformer.

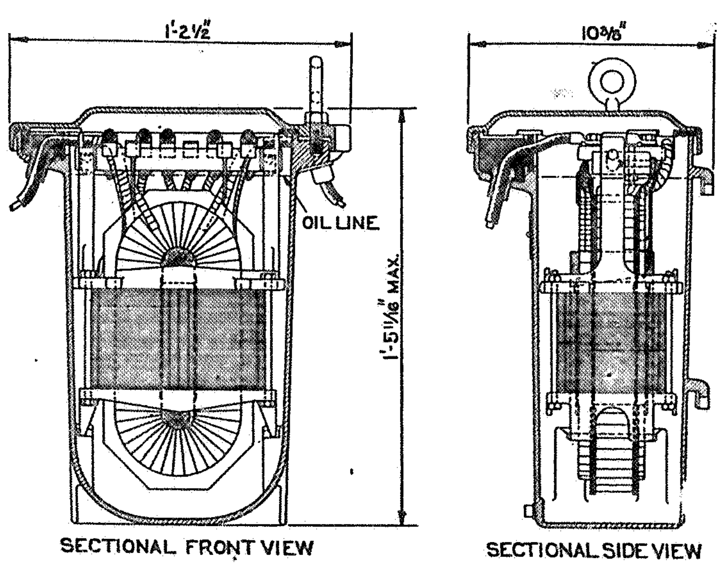
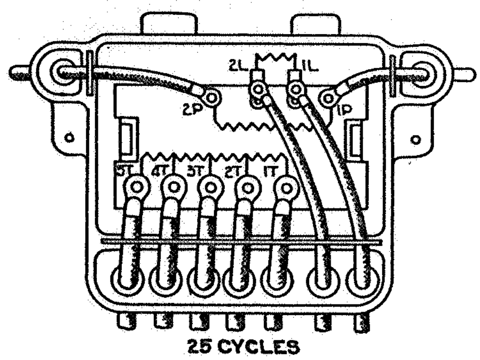


Fig. 20.
Combined Line and Track Transformer

Figure 21 is the panel board of the transformer shown in Fig. 20.



PRIMARY	
VOLTS	TAPS
550	1P-2P

TRACK SEC.	
VOLTS	TAPS
10	1T-5T
8	1T-4T
6	1T-3T
4	1T-2T
2	2T-3T
2	3T-4T
2	4T-5T

LIGHTING SEC.	
VOLTS	TAPS
55	1L-2L

Fig. 21.

These transformers also are made with adjustable fillers. With adjustable fillers they may have one or two secondaries, one for lights or for signal operation and the other for the track feed. They are never built with two track secondaries.

Manufacturers' table of the transformer shown in Fig. 20 is as follows:

Fig.	Cycles per second	Primary volts	Lighting Volts	Lighting Amperes	Track No. coils	Track Volts	Track Amperes
1	60	2200	61–58–56–53	10	1	15–12.5–10–7.5–5 –2.5	20
2	60	110	55	3	1	11	10
3	60	225	....	..	1	15.7	25
4	60	110	....	..	1	23–19.5–14.4–10.9	50
5		2200	122–116–110–105	1.5	..	....	..
6	60	2200	115–110–105	1	1	19.7–16–14.5–10.5	40
7	60	220	120–115–110	7	1	15–12–9–6	20
8	60	500	58–55–52–49	1.5	1	13–10–6.5–3.3	50
9	60	2200	115–110–109–106	1	1	28–24.5–16–12– 8.5–3.5	28
10	60	2200	60–57.5–55–52.5	4	1	18–15–12.5–9– 5.8–3.4	40
11	60	110	....	..	2	12–10.3–8.2–6.2– 4.1–2	50

Fig.	Cycles per second	Primary volts	Lighting Volts	Lighting Amperes	Track No. coils	Track Volts	Track Amperes
12	60	1100	120–117–114–110	9.1	..	....	..
13	60	220	120–117–114–110	9.1	..	....	..
14	60	110	....	..	1	21.2–15.9–11.3–6	50
15	60	110	....	..	1	11.3–10.6–10–9.4	100
16	60	110	....	..	1	15.2–14.5–13.7–13	75
17	50	2200	120–115–110–105–10	2	2	3.7–3.1–2.5–1.9–1.2–0.6	5.6
18	40	2300	120–117–113–110	7.2	1	12–9.4–6.7–5.3–2.7	24
19	40	2300	120–117–113–110	7.2	1	12.6–11.9–11.2	24
20	40	2300	....	..	1	18.1–14.1–10.2–6.2	48
21	25	400	....	..	1	15	24
22	25	500	2 coils				
		455	55–52	2.6	1	9.6	5
23	25	2300	120–115–110–105	3.6	..	12–6–4–2	20
24	25	55	....	..	2	7.5–6.2–5–3.8–2.5–1.3	54

Figures 22 and 23 show a line transformer.

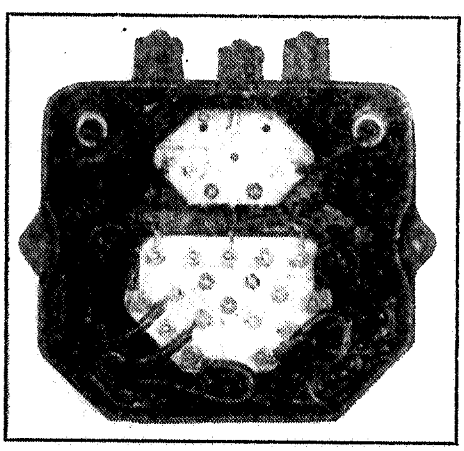


Fig. 22.
L Transformer Showing Terminal Board.

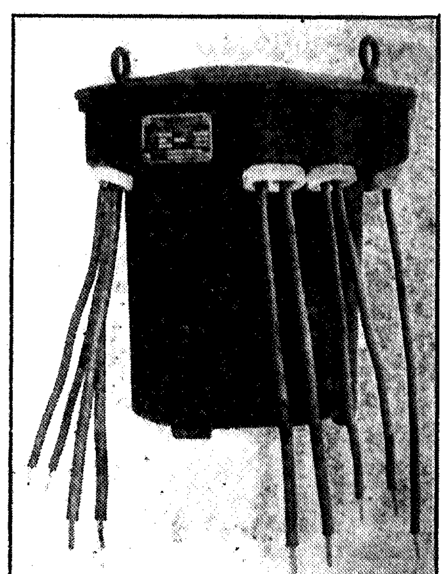


Fig. 23.
L High Tension Line Transformer.

Figure 24 is the general dimensions of transformer shown in Fig. 23.

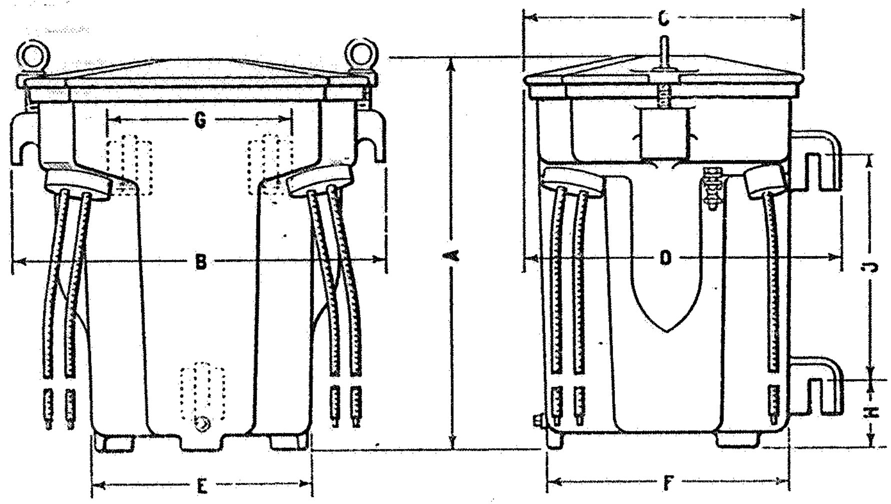


Fig. 24.
L Transformer

Size	A Inches	B Inches	C Inches	D Inches	E Inches	F Inches	G Inches	H Inches	J Inches
1	13 13/16	12 3/4	10	11 1/4	7 7/8	8 5/8	6 1/2	2 5/16	8
2	15 1/4	13 5/8	11 13/16	13 1/16	8 5/8	10	6 1/2	3 9/16	8
3	17	14 7/8	13 13/16	14 15/16	9 7/8	12	6 1/2	5 1/4	8
4	19 7/8	18 1/4	17 1/8	18 5/8	11 1/2	13 3/8	8 1/2	4 1/4	9 3/4
5	23 3/4	21	17	18 1/2	13 1/8	15 1/4	8 1/2	7 3/4	9 3/4
6	31 3/4	25 1/4	21 1/2	23 1/8	15 1/2	18 1/4	11	7	17

Manufacturers' table of the transformer shown in Figs. 22 and 23 is as follows:

Windings

			Secondary					
			Line			Track		
Cycles	Primary volts	Total kv-a. capacity	No. of windings	Volts	Amperes	No. of windings	Volts	Amperes
25	440	0.60	1	110/55	3.63/7.26	1	12 (1-2-4-5)	16.7
25	4400	0.60	1	440/220	1.36/2.72	..	....	....
25	4400	0.60	1	110/55	3.64/7.28	1	12 (1-2-4-5)	16.7
60	2200	1.00	1	110/55	5.45/10.9	2	10 (1-2-3-4)	20
							10 (1-2-3-4)	20
60	2200	1.25	1	110/55	7/14	2	12 (1-2-4-5)	20
							12 (1-2-4-5)	20
60	3300	1.00	1	110/55	9.1/18.2	..	....	....
60	3300	1.50	1	110/55	13.6/27.2	..	....	....
60	4400	1.50	1	220/110	6.82/13.64	..	....	....
60	6600	1.00	1	110/55	9.1/18.2	..	....	...

Generally, these combined line and track transformers vary in capacity from 6 kv-a. to 4 kv-a. as shown in the manufacturers' table. These ratings are the continuous output of all the secondaries. The primary may be any voltage up to 2300 and secondaries any voltage desired for signal purposes.

The open magnetic circuit type of combined line and track transformer is shown in Fig. 25.

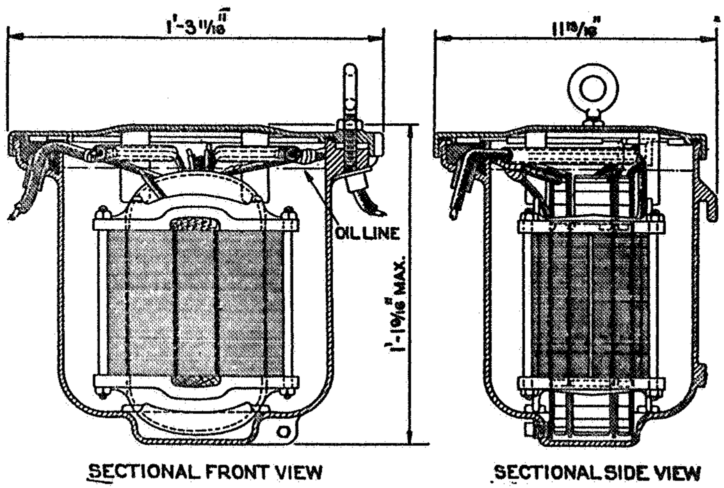


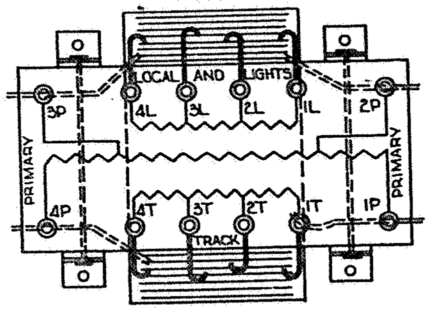
Fig. 25
Combined Line and Track Transformer, Open Magnetic Circuit Type.

The above type of transformer, Fig. 25, is used on single and double-rail track circuits on electric roads using direct current propulsion. The core has an open magnetic circuit (as shown in the vertical white line between the halves of the core in the right-hand view) so that the direct current passing through the track coil will not saturate the iron. The transformers are equipped generally with two secondaries, one for the track feed and the other for signals, relays or lights. Their maximum capacity is 1 kv-a., 60 cycles, or 5 kv-a., 25 cycles, and their primaries may be any voltage up to 2300.

Combined line and track transformers, air-cooled.

Where the transmission voltage is reasonably low, say 110 to 550, the track transformers as shown in Figs. 15 and 16 are developed into a combined line and track transformer.

A plan of this type of transformer is shown in Fig. 26 taken from the information book of the Signal Department, Interborough Rapid Transit Company.



PRIMARY	
VOLTS	TAPS
550	1P-4P
505	1P-3P
390	2P-4P
345	2P-3P

TRACK SEC.	
VOLTS	TAPS
12.5	1T-4T
10.3	1T-3T
8.1	2T-4T
6.0	2T-3T
4.4	1T-2T
2.2	3T-4T

LIGHTING SEC.	
VOLTS	TAPS
58	1L-4L
56	1L-3L
54	2L-4L
52	2L-3L

Fig. 26.

Manipulation.

The secondaries of the transformers that are connected to the same transmission line may be manipulated in the same manner that batteries are manipulated in order to obtain higher voltages or more current.

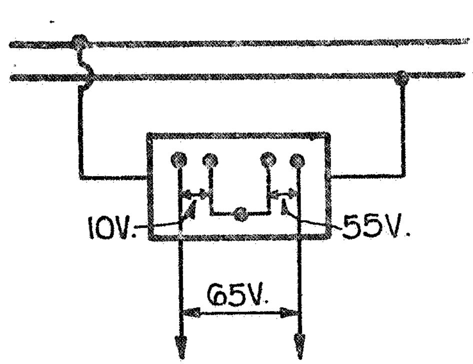


Fig. 27.

Figures 27, 28 and 29 show transformers connected in series. Figure 30 shows transformer connected in multiple.

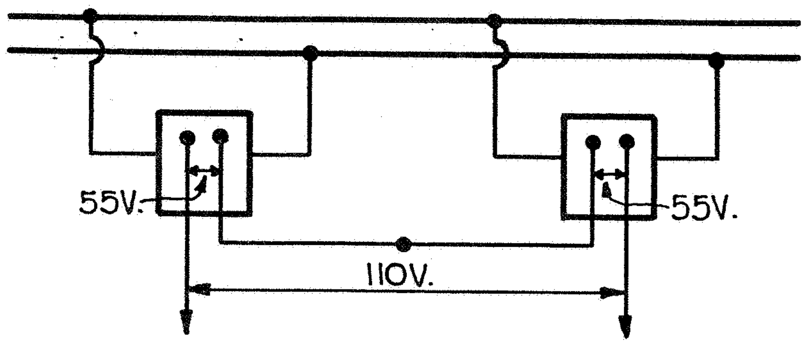


Fig. 28.

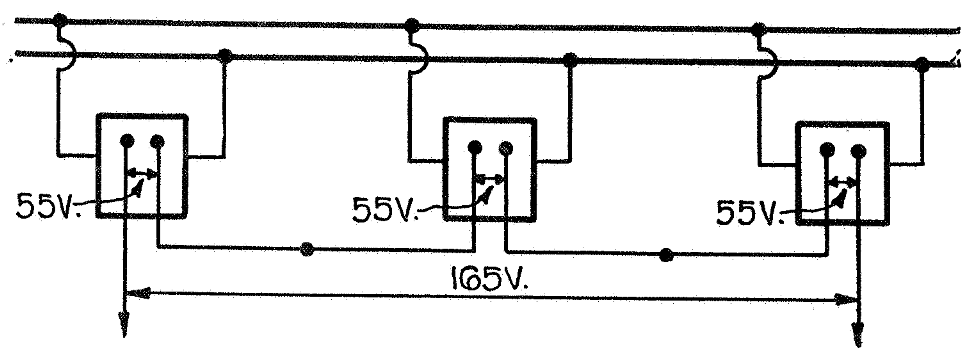


Fig. 29.

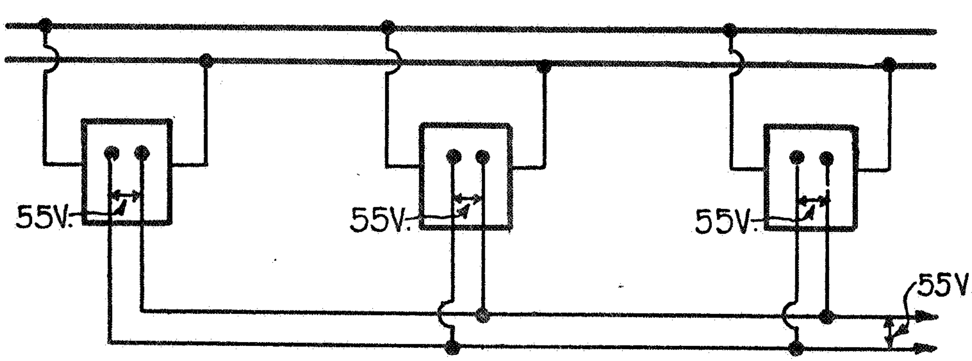


Fig. 30.

Transformers for uses such as trickle charge, train control, etc., are covered in the chapters under these specific subjects. The theory, however, in general is the same as already described.

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