INSTRUCTION BOOK

DISTRIBUTION TRANSFORMERS

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Application, Connections and Testing

Westinghouse Electric Corporation

I. B. 46-100-3

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INSTRUCTIONS

DISTRIBUTION TRANSFORMERS

Application, Connections and Testing

WESTINGHOUSE ELECTRIC CORPORATION
SHARON, PA. • TRANSFORMER DIVISION • SUNNYVALE, CALIF.
SUPERSEDES I.B. 5379-D
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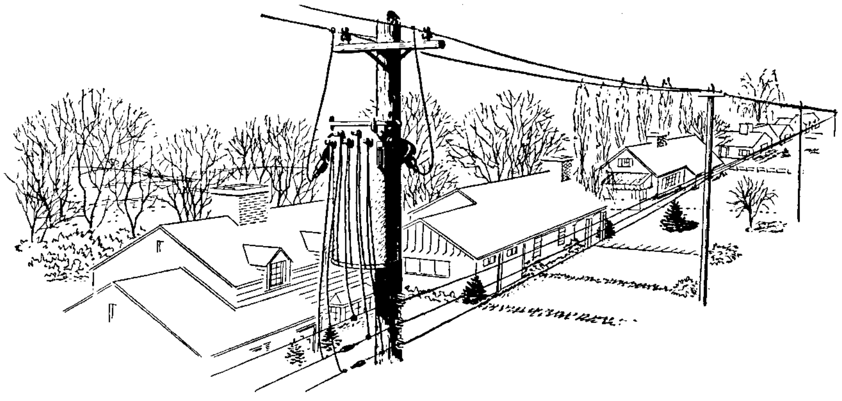


LIST OF ILLUSTRATIONS

PART ONE

APPLICATION

RADIAL AND NETWORK DISTRIBUTION SYSTEMS

Distribution transformers range in capacities from 1½ to 500 kva and are ordinarily used to step down from the sub-transmission or distribution voltage of the power system to the customer's utilization voltage. The radial type distribution system shown in Fig. 1 is the most common form. The primary feeders radiate from a substation and branch into sub-feeders and laterals which extend into all parts of the area to be served. The distribution transformers are connected to the primary feeders and laterals, usually through fused cutouts, and supply the radial secondary circuits, to which the customers' services are connected.

Automatic oil circuit breakers arranged for overload trip are used to connect the feeders to the station bus. A short circuit on a feeder opens its station breaker and interrupts the service to all customers supplied by the feeder. Manually operated sectionalizing switches are often installed, as shown in Fig. 1, at the junctions of the sub-feeders and the main feeder. When the trouble has been located the faulty section may be isolated by opening the proper switches and service restored to the rest of the feeder while repairs are being made.

The fuses in the primary leads of the distribution transformers open the circuit in case of trouble in a transformer or on its associated secondary lines and prevent a possible shutdown of the entire feeder for faults of this kind. The sub-feeders and laterals are sometimes fused to prevent tripping the feeder breaker and thus reduce the extent of the outage when a fault occurs on one of them. Obviously it is necessary that the transformer fuses, branch fuses, and feeder breaker be properly coordinated so that the circuit will be opened at the proper point to keep the outage to a minimum when a fault occurs. However, a number

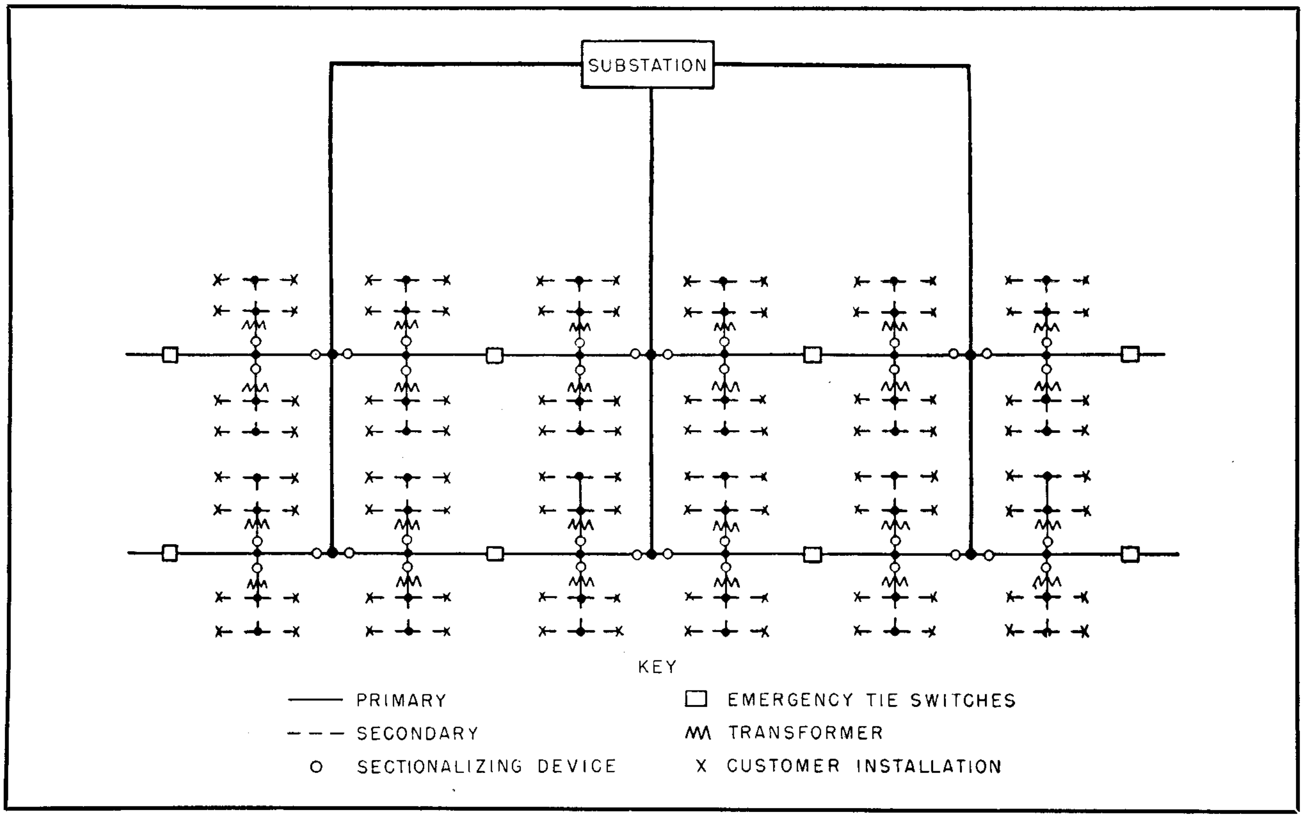


FIG. 1. Alternating Current Radial Distribution System

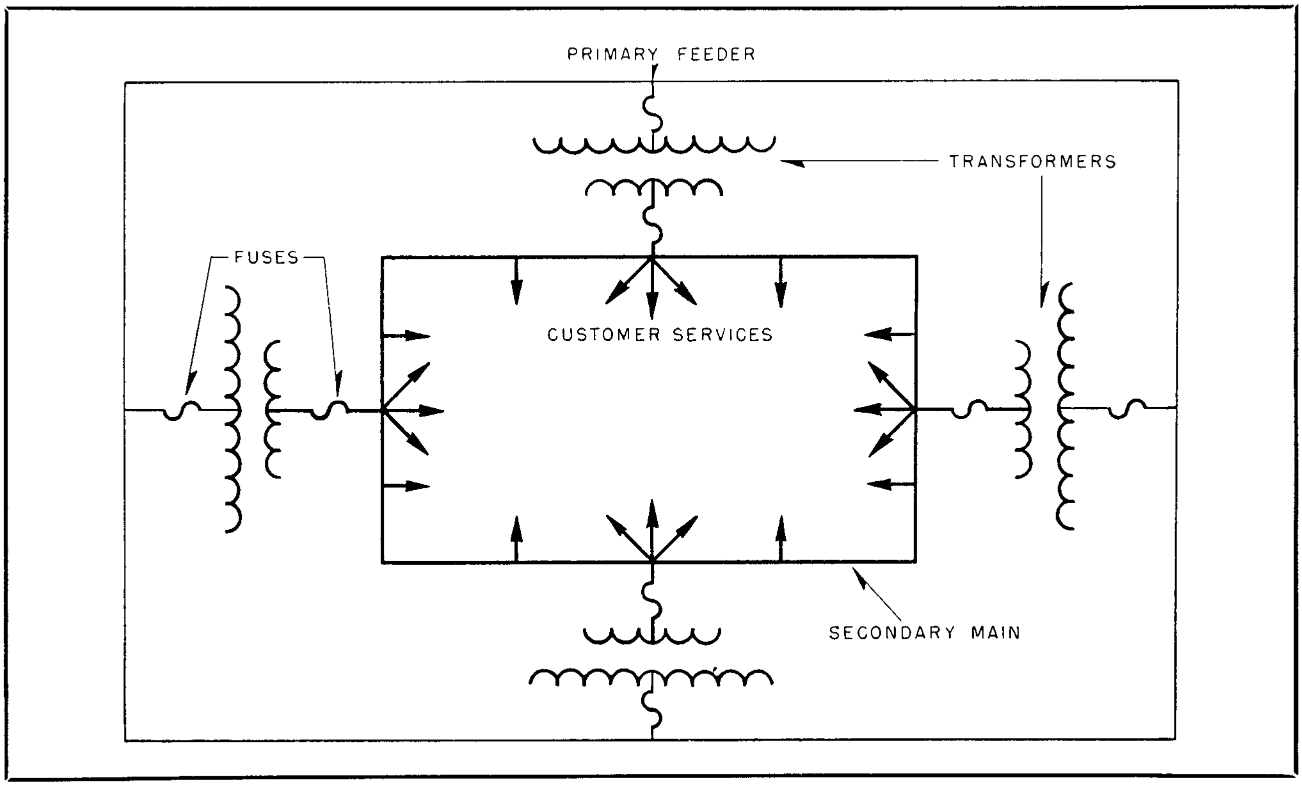


FIG. 2. Banked Transformer System of Distribution with Fuses in Secondary Leads of Transformer

of the customers connected to a feeder will be without service for a considerable period of time whenever a fault which is not self clearing develops on any section of a feeder or its secondary lines. All of the customers will of course be affected if the fault is so located as to cause the feeder breaker at the substation to open. It has been found with faults of this kind that deenergizing the feeder often causes them to clear themselves, and if the station breaker is reclosed it will remain closed in about 80% of the cases. Because of this fact, the feeder breakers are often made automatic reclosing. The reclosing equipment provides for from one to three reclosures before the breaker is locked open.

The lack of continuity of service is the principle defect of the radial system of distribution. Emergency tie switches between adjacent feeders are often used to reduce the time of outage. The system is normally operated with these switches shown in Fig. 1, open. After a faulty feeder has been divided into sections by opening its sectionalizing switches the emergency tie switches are closed to connect the unfaulted sections to the adjacent feeders. Often no extra capacity is allowed in the primary circuits between which ties are provided, and where these circuits are normally heavily loaded serious overloading may occur when sections of a faulty feeder are added to the load already carried.

There are a number of ways in which the necessary excess capacity can be provided to carry the load on the good sections of a faulty feeder until repairs are made. The spare capacity can be built into each feeder so that the two adjacent feeders can safely carry the load of the faulty feeder. The feeder may be arranged in pairs and each feeder provided with enough capacity to carry the entire load of the other feeder of the pair. One feeder in a group may be constructed with a large overload capacity and arranged so that the load of any other feeder in the group can be switched to it in an emergency. A number of feeders may be brought into the area and interlaced so that the load of a faulted feeder can be switched about equally to the other feeders in the area. Obviously when using this interlaced feeder arrangement the spare capacity which must be provided in each feeder decreases as the number of feeders in the area increases. These various arrangements are modifications of the radial type of distribution system where the radial arrangement of both primary and secondary circuits is used giving a single path from the station to each customer's load.

Radial distribution systems are extensively used

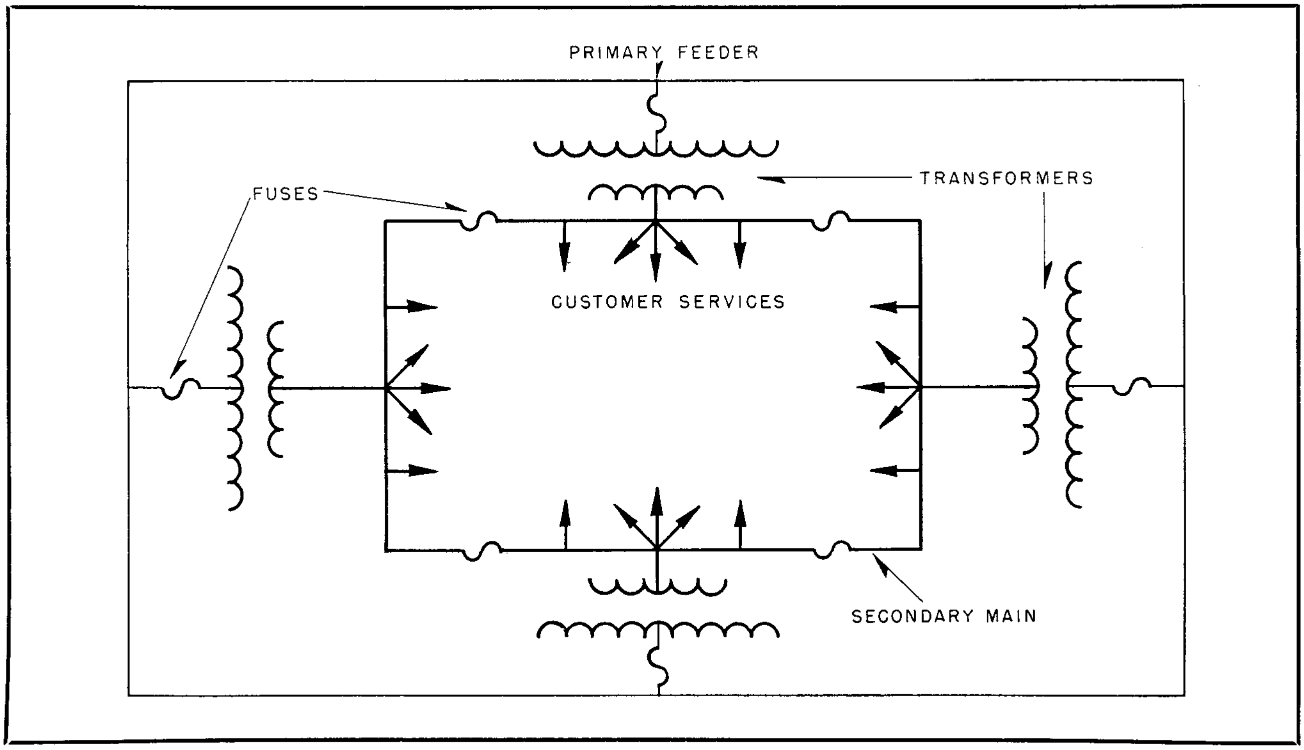


FIG. 3. Banked Transformers with Fuses in Secondary Main

to serve the lighter and medium density load areas where the primary and secondary circuits are usually carried overhead on poles. On these systems the smaller distribution transformers are mounted on poles. Where the weight of the transformer installation exceeds that which can be safely hung on a pole the transformer or transformers may be mounted on a platform supported between two poles. If the reliability of the radial system is considered adequate it may be used to serve the heavier density underground areas. In these cases the distribution transformers are usually located in manholes under the streets or sidewalks or in building vaults. In many of these locations the equipment at times may be partially or wholly submerged in water and submersible type distribution transformers are used. Where there is infrequent or emergency flooding only, a vault type transformer without breakers, or the Sealdaire type may be installed.

BANKED TRANSFORMERS

The banked transformer distribution system illustrated in Fig. 2 may be considered a form of radial system since its primary circuits, to which the distribution transformers are connected, are radial feeders. All or a number of the secondaries of the transformers associated with one feeder are connected to a common secondary circuit or grid. There is no secondary tie between transformers supplied from different feeders.

The banking of transformers provides several advantages not available with the usual radial feed:

1. Reduction of voltage flicker.
2. Better average voltage conditions.
3. Savings in installed capacity because of greater diversity.
4. Reduction in size of secondary conductors.
5. Improved service reliability.
6. Quicker self-clearing of secondary faults.

There are two basic forms of banking: (1) line banking where the secondary mains extend as a line whose ends are not connected together, and (2) loop banking where the secondary forms a closed loop.

There are several methods of connecting fuses or circuit breakers to obtain protection of the transformers and/or the service as shown in Fig. 2, 3 or 4. While the figures show a loop type of bank, the protection methods are also applicable to line type banks. If fuses are used as shown in Fig. 2, they must be used in both primary and secondary leads of the transformer, so as to disconnect a transformer which develops a fault. The transformers must have sufficient capacity so that when one of them fails and is isolated by its fuse blowing, the remainder of the transformers connected to the same secondary grid will continue to carry the load without overheating. Fuses must be very carefully chosen. The secondary fuses should have as long a blowing time as possible and yet protect the transformer against damage from secondary faults which fail to burn clear in a reasonable length of time. Secondary fuses should, however, blow in less time than the primary fuses on any value of current.

If fuses are used as shown in Fig. 3, they must again be very carefully chosen. The fuses in the secondary main should be located as closely as possible to the zero current point. They should be made as small as possible so as to clear all transformer and secondary faults that are not self-clearing; yet they must be large enough to permit a reasonable interchange of load between sections without blowing.

The most successful form of secondary banking is obtained by the use of "CSPB" transformers, which have two internal circuit breakers connected in the secondary circuit for transformer protection and secondary sectionalizing. This form of banking provides several advantages over other forms of banking:

1. Possibility of cascading is eliminated.
2. Fuse coordination problems are eliminated.
3. Definite burnout protection against both short circuits and continued overloads is provided.
4. Fuse outages due to lightning are eliminated.
5. Restoration of service following on operation is simplified.
6. Location of trouble is simplified.

This method of banking is shown in Fig. 4. In case of secondary faults, only the adjacent circuit breakers open, leaving all transformer windings still in service. The circuit breakers also provide positive thermal protection for the windings. In case of internal transformer faults, the secondary circuit breakers and primary protective links open.

This system differs from the usual radial system in that the distribution transformers are operated in parallel. It gives somewhat greater service reliability because a distribution transformer failure or a secondary fault will ordinarily not cause an outage. The probability of such an outage depends on the type of circuit protection used, as described

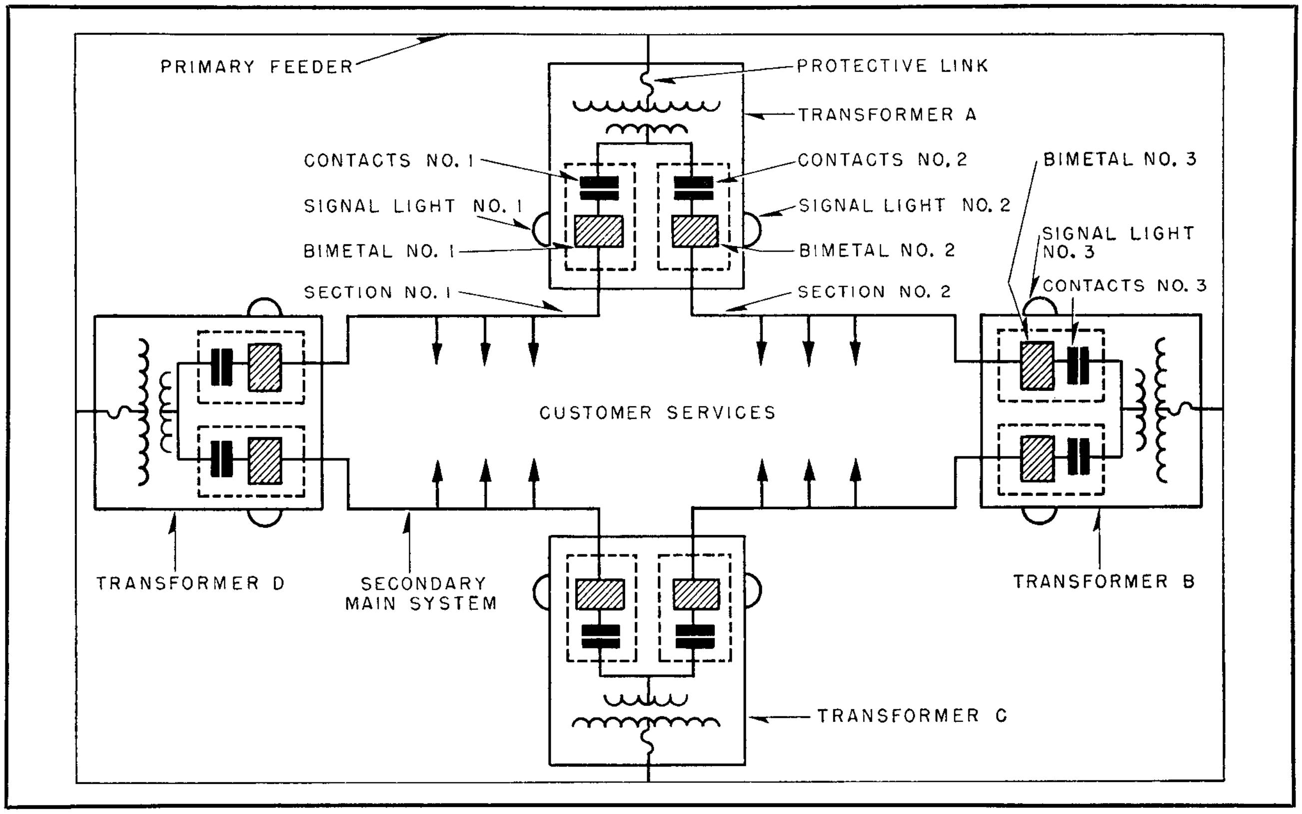


FIG. 4. Banked Transformers Using "CSPB" Transformers Having Two Secondary Breakers

below. Primary faults, however, will cause service interruptions just as in the usual radial system.

The loop feeder system of distribution is sometimes used particularly in commercial and industrial areas where a number of bulk loads are to be served. A diagram of such a loop system for feeding important bulk loads is shown in Fig. 5. The capacity of the loop feeder must be large enough to feed its total load from one end since trouble may occur on either end of the loop close to the station. By using automatic oil circuit breakers controlled by pilot wire or directional over-current relays at each customer's installation a feeder fault may be isolated without interrupting service to any customer. As an example of the operation of this system, suppose a short circuit develops at the point M on the feeder. The circuit breakers nearest the fault at installations B and C will automatically trip and disconnect the faulty section without interrupting service to any customer. Should a fault occur on a customer's bus or in one of his transformers if he has only one bank a service interruption will result. On a system of this kind the distribution transformers will usually be of large capacity. The loop feeder system provides two paths from the substation to the transformer supplying the customer's load, but requires considerable primary switching equipment, and 100% space capacity in each loop feeder.

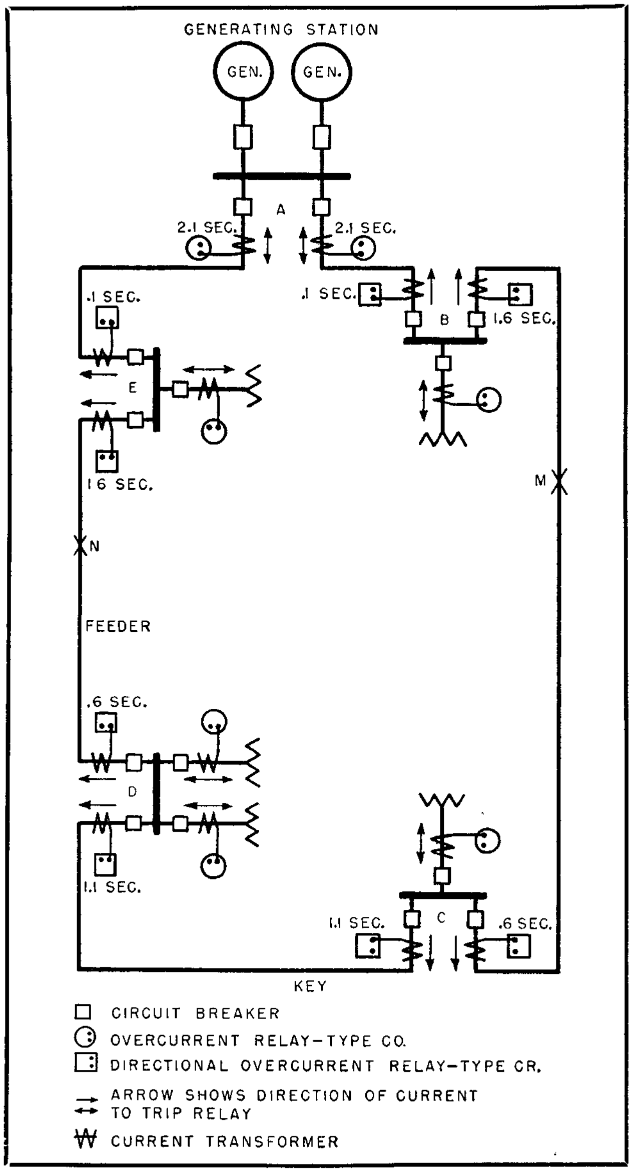


FIG. 5. Loop Feeder System for Alternating Current Bulk Load Distribution

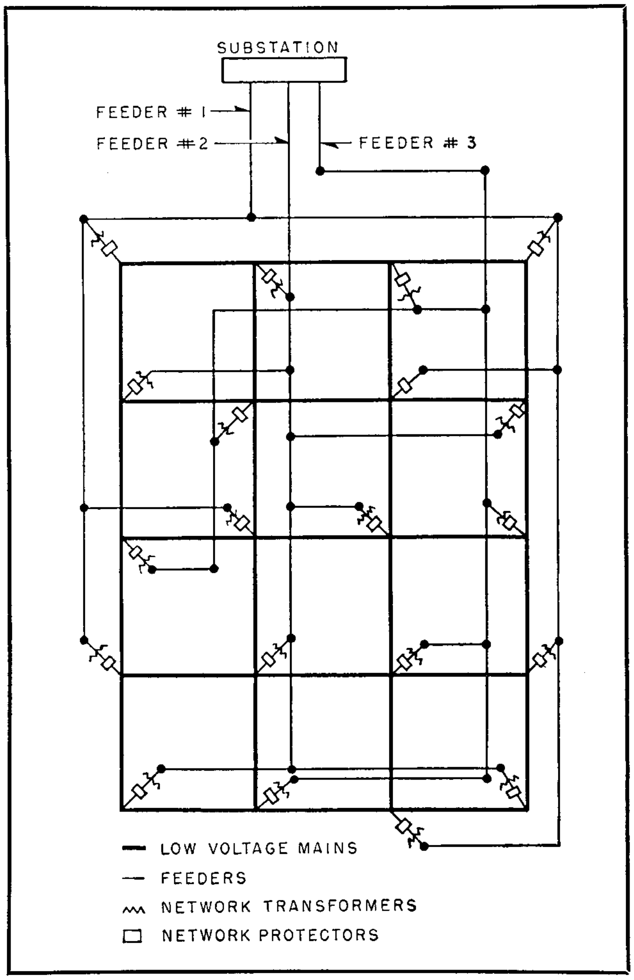


FIG. 6. Automatic Low-Voltage Alternating Current Network System of Distribution

The first automatic low-voltage a-c network system was placed in operation in 1922. Today this type of system is generally recognized as the standard method of supplying power through underground systems to the high load density areas of cities, chiefly because of its economy, flexibility, and the high quality of service it renders. The secondary network system is now used extensively in modern industrial plants for the same reasons that led to its general adoption for city distribution.

In the underground low voltage a-c network system, the secondary mains are solidly connected together to form a network grid or mesh from which the customers' services are taken. The secondary grid or network is supplied over a plurality of high voltage feeders through distribution or network transformers as shown in Fig. 6. In such a system the failure of one feeder does not cause any interruption to service since the load is supplied over the remaining feeders. It is apparent, however, that if a short circuit occurs on a high voltage feeder, even though this feeder is disconnected at the substation by the automatic oil circuit breaker, it is necessary that all distribution transformers on the feeder be disconnected from the network by some form of protective device to prevent a backfeed of energy from the network to the fault. The automatic network protector has been developed for this purpose.

The network protector consists of an air-break switch with closing and tripping mechanism controlled by a suitable relay or relays. A protector is installed in the secondary leads of each network transformer and when a fault occurs on a feeder all of the protectors associated with it open as a result of the flow of power through them from the network to the feeder. They will also open on the small amount of power which flows when the feeder is disconnected at the station and the transformers are excited from the network. It is thus possible to completely isolate any feeder to work on it by merely opening its station breaker. To put a feeder back in service the station operator only has to close the feeder breaker. Then if the secondary voltage of the transformers is slightly higher than and approximately in phase with the

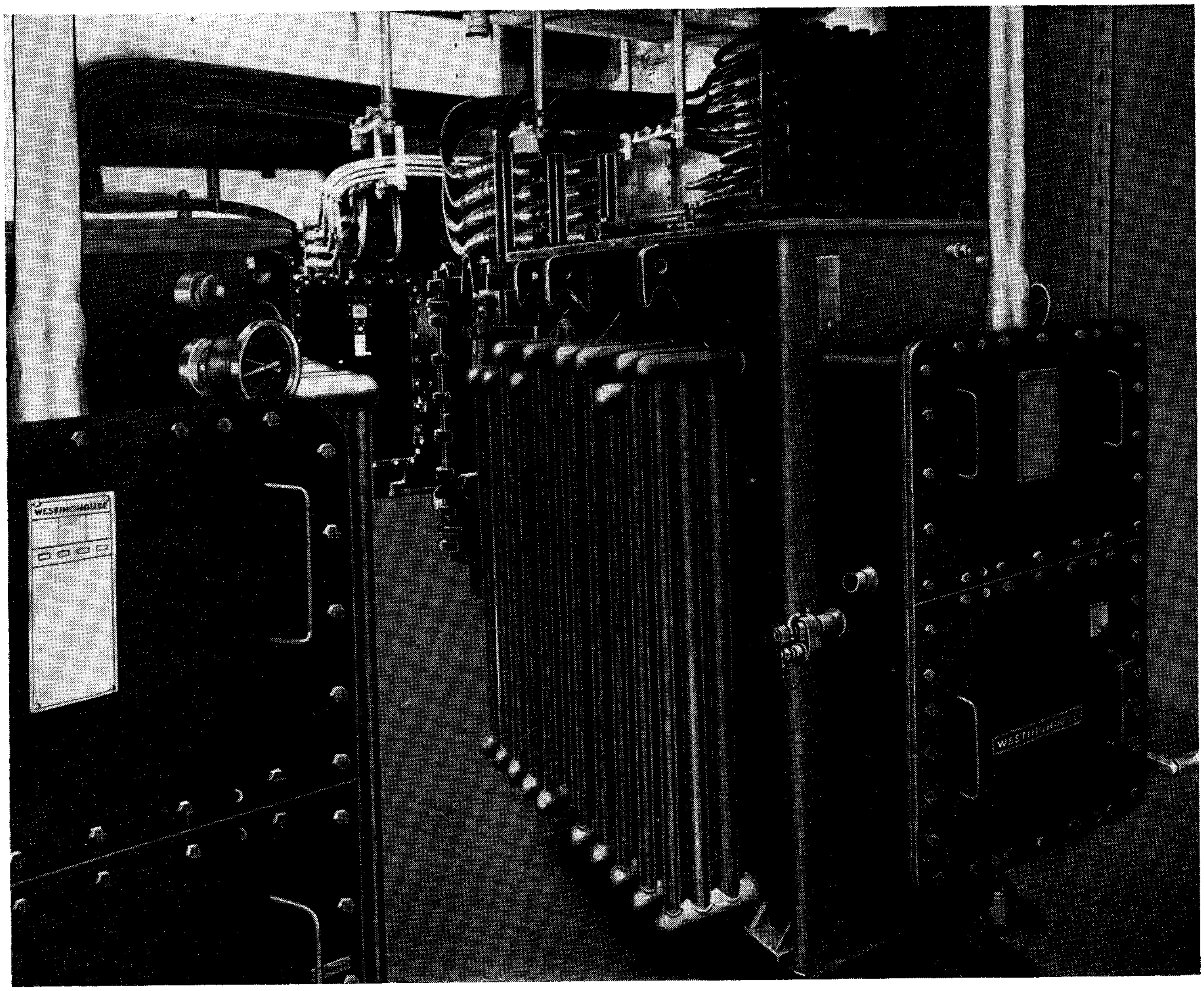


FIG. 7. Vault Installation of 500 Kva, Three-Phase Network Transformers

network voltage the protectors will close and connect the feeder to the network through their associated transformers. The network protectors, however, will not close if any of the phases have become crossed while the feeder was being worked on, or if the voltage relations on the two sides of the open protectors are such that power will flow from the network to the feeder when the protectors close.

High capacity fuses are provided as a part of each network protector to provide backup protection in case a protector fails to trip when a fault occurs on a primary feeder or in a network transformer. These fuses are rated so that they will not ordinarily blow in case of a network short circuit. The system is so designed that secondary faults will burn themselves clear. Fuses in the primary leads are unnecessary and are not used.

Since all customers are supplied from a common secondary grid, advantage may be taken of the diversity between the loads to use less transformer capacity than would be required to serve the same loads with a radial system where each transformer must be able to supply the maximum demand of its connected load. Network systems are designed to operate continuously with at least one feeder out of service without overloading any part of the system. This requires that a certain amount of spare transformer capacity be provided, which may make the total transformer capacity in the network system greater than that required in a radial system to serve the same load area. The use of a network system permits standardizing on a minimum number of transformer sizes and locating the transformers at the most convenient points.

Each load connected to the network is fed from at least two directions and from a number of transformers in parallel. The voltage drop is therefore small and the regulation at the customers' services is much better than on a radial system. The continuity of service obtained with the low voltage a-c network system is superior to that provided on any other type of a-c distribution system and is at least equal to that of a d-c network system without a storage battery. The low voltage a-c network system, therefore, gives about the same quality of service as the d-c network without sacrificing any of the inherent advantages of alternating-current distribution.

In the first underground low voltage a-c network systems the transformers used were of the same type as the distribution transformers used on radial systems. Since that time, however, it has been found desirable to incorporate certain special features, so there has been developed what are commonly called network transformers particularly adapted for service in this type of system. These features include high voltage grounding or grounding and disconnecting switches, manually operated tap changers, and higher than normal impedance. The transformers usually have an impedance of about 5 or 10%. Where a higher than normal impedance such as 10% is used to improve the load division between banks it is usually obtained by designing the transformer so as to increase its inherent reactance by the proper coil spacing and grouping, or by using an external reactor in the secondary leads of the transformer. Network transformers are usually three phase units and are of greater capacity than the transformers normally provided on radial systems. The vault installation in Fig. 5 consists of several 500 kva standard units having grounding and feeder disconnecting switches as integral parts of each unit and a throat connected subway network protector.

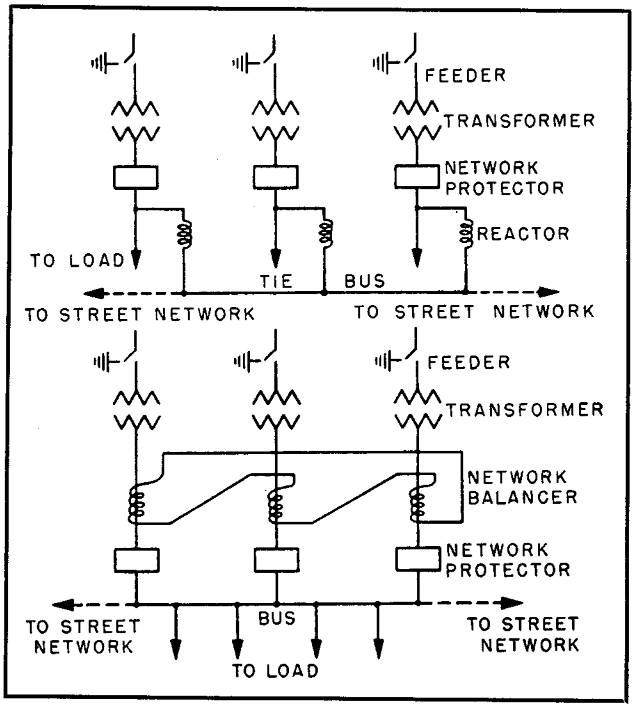


FIG. 8. Single Line Diagrams of Spot Networks for Supplying Bulk Loads: Top—Star Bus Installation with Reactors; Bottom—Network Balancer Installation

Large and important loads such as hospitals, theaters, hotels, apartment houses, department stores, public auditoriums and small manufacturing plants often require a greater reliability of service than can be obtained by supplying the load over a single feeder. This improved service reliability is often provided by means of a second or standby

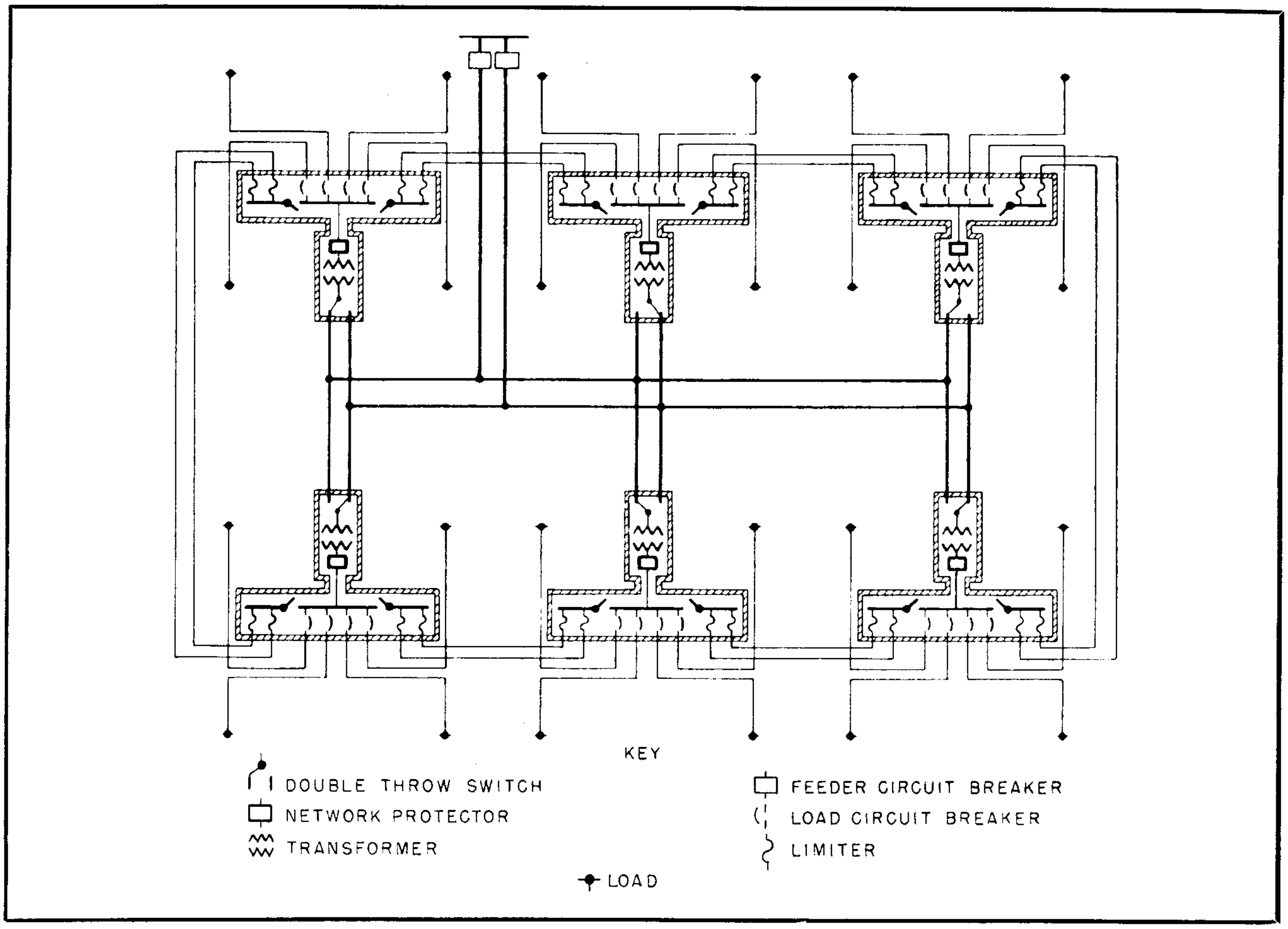


FIG. 9. Primary Selective Network

feeder and the necessary changeover equipment for disconnecting the load from the preferred feeder in the event of trouble on it, and for connecting the load to the standby or auxiliary feeder.

The introduction of the low voltage a-c network system made available equipment for an improved scheme now used in two fundamental systems, the "spot" and "primary selective" networks.

The banked transformers of a spot network are connected to separate primary feeders, the secondaries are paralleled through automatic network protectors to form a loop from which the load is fed radially. Spot networks are now quite generally used in the underground network areas and buildings of the larger cities. While these spot buses are usually connected to the street grid or network for greater reliability and economy these connections are not essential for satisfactory operation. Spot networks not only provide better service but are usually less expensive than automatic change-over installations for supplying loads of 300 kva demand or less. In spot network installations it is frequently necessary to use reactors or network balancers in the secondary leads of the transformers to minimize the possibility of circulating currents between the banks due to differences in the primary voltages and to prevent too frequent operation of the network protectors. The use of balancers usually provides a much more satisfactory installation than can be obtained with reactors. Single line diagrams of two spot networks, one using reactors and the other using network balancers, are illustrated in Fig. 8.

Vertical networks provide a very satisfactory and economic means of supplying power to tall buildings. A vertical network consists of a number of spot network installations located near the load centers in the building. There is usually one installation in the basement and one or more located on the upper floors. The building load is usually fed radially from these points and the several spot buses are tied together by means of vertical risers for improved reliability. In some installations much of the load is fed over taps taken from these risers instead of over radial circuits from the spot buses. In other installations the several spot networks are operated without secondary ties between them. The basement installation usually has its secondary bus tied to the street network.

The more recently introduced "primary selective" low voltage network is an ideal system for most industrial plants because it gives network continuity of service, reliability and maximum flexibility at a minimum cost. The initial cost compares favorably with other systems and the operating and maintenance costs are a minimum.

The usual a-c secondary network system has been modified as shown in Fig. 9 for industrial plant applications so as to reduce to a minimum the amount of spare transformer capacity and materially reduce its cost. This has been accomplished by using a double-throw primary switch with each network transformer and arranging the primary feeders so that any transformer can be connected to either of the two feeders.

Normally, half of the network transformer capacity is connected to each feeder. When a fault occurs on one of the primary feeders the faulty feeder is automatically disconnected from the system without any interruption to service, by the tripping of the circuit breaker at its supply end and the tripping of all network protectors on units fed by that feeder. This leaves the entire system load being supplied over one primary feeder and through half the network transformers.

Under this condition the regulation will be about doubled and the transformers remaining in service will be loaded to nearly 200% until the transformers associated with the faulty feeder are manually switched to the good feeder. It should be possible to complete this switching operation in 45 minutes or less which is fast enough to prevent damaging the overloaded transformers. When this manual switching operation is completed all transformers are again carrying load and substantially normal voltage conditions are restored.

The entire plant load is, of course, being carried over one primary feeder and the system should be designed so that either feeder has sufficient capacity to supply the peak load. After the fault has been located and repaired, the feeder can be put

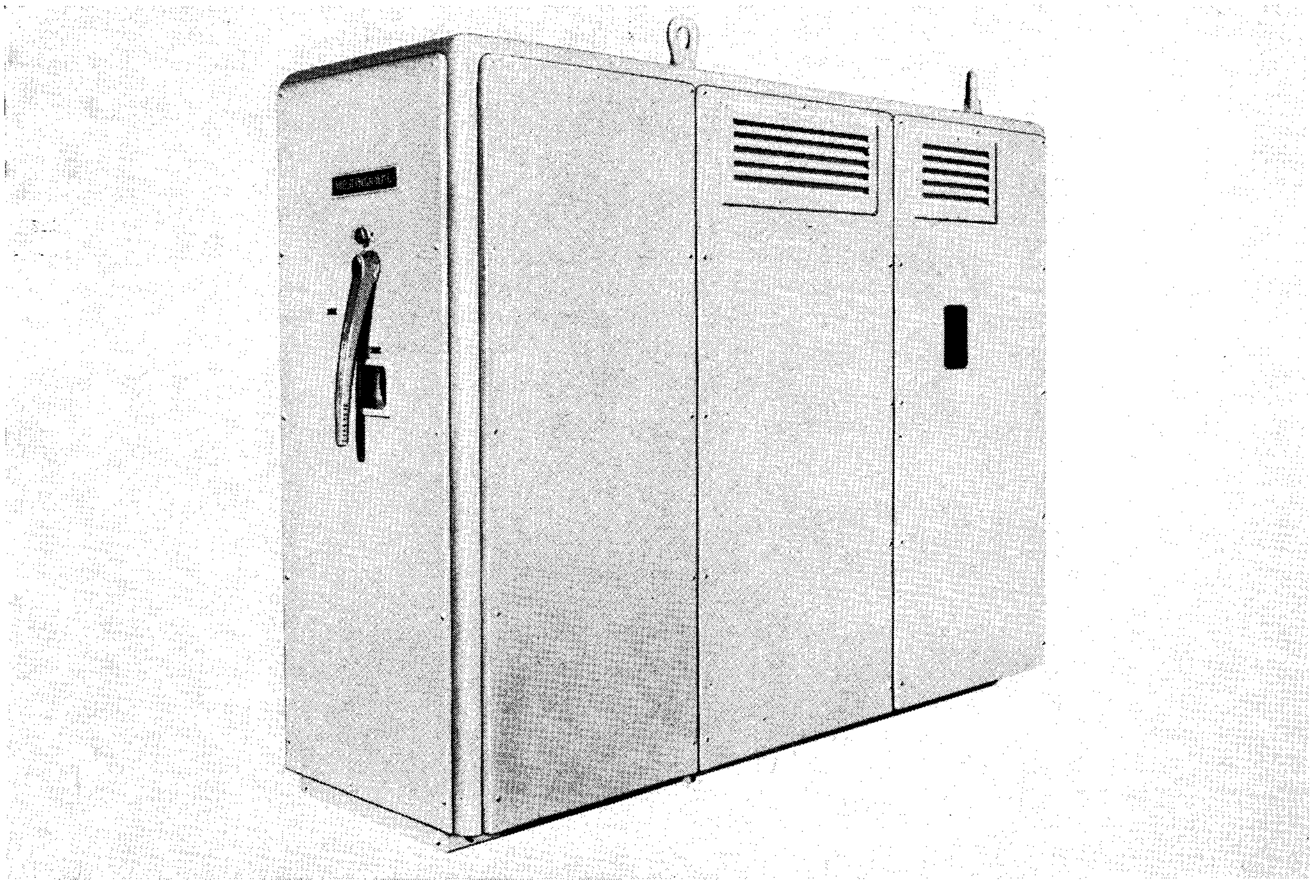


FIG. 10. Air-Cooled Network Unit with Three Position Disconnect and Grounding Switch and Secondary Network Protector

back into service by closing the circuit breaker at its supply end and reconnecting the network transformers normally connected to it by manually operating the primary selector switches. In order to prevent these selector switches from being called on to open load current, each switch is electrically interlocked with the network protector in the secondary leads of its associated transformer so that it cannot be moved from any one of its three positions, namely: "Feeder No. 1", "Open", and "Feeder No. 2", unless the network protector is in the open position.

When switching a transformer back to the reenergized feeder the switch will interrupt the exciting current of the transformer. This is an essential requirement of the primary selector switch, since, if it were not capable of interrupting transformer exciting current it would be necessary to shut down the plant in order to reconnect the transformers to their normal feeder when putting that feeder back in service after it has been out of service as the result of a fault or to permit its being extended or modified.

Faults on the cables of the secondary loop are cleared without any interruption to service by means of limiters located in each end of each secondary cable. A limiter is a specially designed completely enclosed, heavy copper fuse or weak link used only to give protection against short circuits. Limiters have been successfully used for more than ten years.

Two cables per phase are necessary to insure selectivity between limiters under all fault conditions. The cost per ampere of current-carrying capacity will be less when using two small conductors per phase than when using one large conductor per phase.

The Network Units should be connected to the loop at about equal intervals when the load to be supplied is reasonably uniform or as dictated by the major loads when it is not. All units feeding the loop should have the same kva rating. The number of units used should exceed by one the number necessary to supply the peak load on the loop without overloading.

Load bus units are used for connecting the network units into the secondary loop and to tap all loads off the loop.

If the voltage of the secondary loop is 120/208 volts, both the power and lighting loads will be fed directly from the load bus units. The same may be true if the secondary voltage is 480 volts and fluorescent lighting is used. On 480 volt systems, however, 480 volt to 120/208 volt lighting transformers are often used to supply the 120 volt lighting load. These lighting transformers are fed from a number, if not all, of the load bus units.

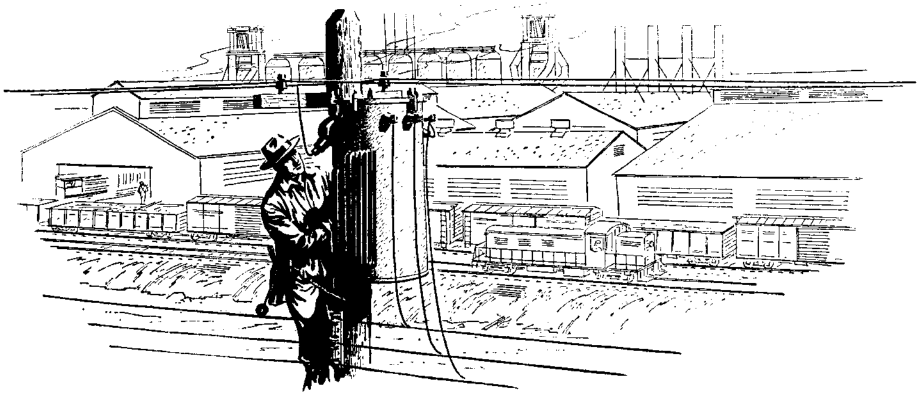
The dry type non-explosive air-cooled transformer unit consisting of a transformer, three position disconnect and grounding switch, and low voltage network protector as shown in Fig. 10 improves the safety, reduces the maintenance of the plant system, and saves valuable manufacturing space.

The network principle of distribution has been extended to the lighter density overhead areas in the form of the overload secondary network system and the primary or medium voltage network system. The overhead secondary network system is similar to the underground low voltage network system except that the secondary mains and usually the primary feeders are overhead circuits. In general, the transformers and network protectors are smaller and lighter than those used in the underground system and they are usually mounted on poles. Single-phase transformers of the type usually found in radial distribution systems can be used in overhead secondary networks. However, it will be found that the economic sizes of transformer banks in an overhead secondary network are larger than in a radial system. Transformers having an impedance of 3 to 5% should be satisfactory for overhead network applications.

In the primary network system it is the circuits to which the primaries of the distribution transformers are connected that are networked. The secondary lines are arranged radially just as in the radial system and consequently this system does not render as high quality service as does the secondary network where the networking is done immediately adjacent to the customers. However, because of its possible economies, greater flexibility, and higher quality of service rendered, the primary network has much to recommend it over the usual radial system employing large distribution substations. Instead of using one large substation to serve a load area the primary network system employs a number of small stations or primary distribution units located at about what would be the load centers of the feeders in a radial system. These units are supplied over different transmission or sub-transmission circuits and are connected together on their secondary sides by medium voltage mains to form a grid or network. A number of laterals, to which the distribution transformers are connected just as in the radial system, are tapped from each main. Each primary distribution unit consists of a three-phase tap-changing-under-load transformer, a high voltage disconnecting switch, a transformer secondary breaker, two to four network main breakers through which the unit is tied to the adjacent units, and the necessary control equipment.

The primary network system provides two or more paths to the load as far as the network mains but beyond there the feed is radial. A fault on one of the sub-transmission circuits feeding the primary distribution units or in one of the units does not cause any interruption to service. When trouble develops on a network main the load connected to it is dropped. The amount of load dropped, however, is usually less than that dropped when a fault occurs on a feeder in a radial system. A failure in a distribution transformer or on a secondary circuit will always result in an outage just as in the radial system unless the transformers supplied from each network main are banked, or unless the transformers connected to the primary network supply a secondary network.

The foregoing general discussion indicates the importance of distribution transformers in distributing electric energy, and gives some idea of the many conditions under which these transformers are installed and operated.



TRANSFORMER CONNECTIONS
(STANDARD)

SINGLE-PHASE CONNECTIONS

Single-Phase; Three-Wire Secondary (Series Connection) (Fig. 11). The most commonly used connection for small distribution transformers is that where a three-wire secondary is supplied at 120/240 volts. A similar connection may be used for 240/480 volt transformers. The primary may be supplied from a single-phase line, two wires of a three-phase line or one line wire and a neutral of a three-phase line.

The 120 volt loads should preferably be balanced in order that both halves of the low voltage winding will be equally loaded. It would not be desirable with this connection to draw more than 50% of the transformer rated load from either half of the low voltage winding as by so doing that half of the winding would be overloaded.

Although most of the following diagrams show two-wire (per phase) secondary systems, many of these connections can be used to supply a single-phase three-wire system by using the midpoint of the secondary winding. In many of the following diagrams it is also possible to supply combined two or three-phase and single-phase (2 or 3 wire) loads. In such cases it may be desirable to use unequal kva ratings for the different transformers in order that all transformers carry the same percentage of rated load.

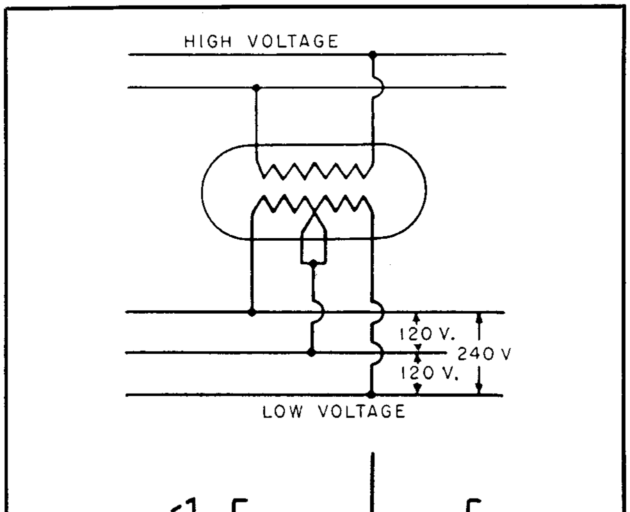


FIG. 11. Three-Wire Secondary (Series Connected)

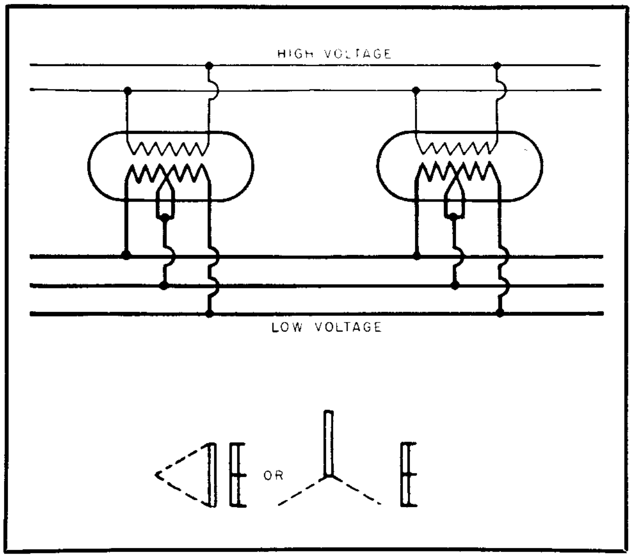


FIG. 12. Parallel Operation of Two Single-Phase Units

Single-Phase; Parallel Operation of Two Single-Phase Units (Fig. 12). The parallel operation of transformers having the same high voltage and low voltage ratings is often utilized in those cases when it is necessary to increase the total bank capacity and a single unit of the correct capacity is not available.

Economically it is not efficient to operate two transformers in parallel where a single unit could be used as by so doing the losses of two units in parallel will be greater than the losses of a single unit of the same equivalent capacity.

When the ratio of reactance to resistance is about the same for both transformers the maximum safe bank capacity may be obtained as the smaller of the two values obtained from the following two formulae:

Bank capacity (based on not overloading transformer No. 1) $= \frac{C_1 Z_2 + C_2 Z_1}{Z_2}$

Bank capacity (based on not overloading transformer No. 2) $= \frac{C_1 Z_2 + C_2 Z_1}{Z_1}$ where C_1 and C_2 are nameplate kva ratings and Z_1 and Z_2 are nameplate percentage impedances for transformers No. 1 and No. 2 respectively.

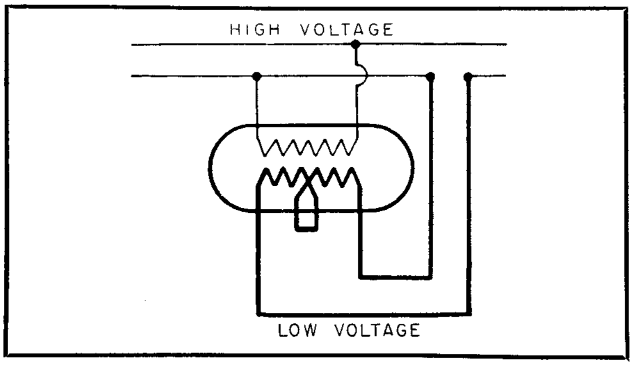


FIG. 13. Standard Transformer as Booster

Transformer as Booster (Fig. 13). The purpose of a booster transformer is to raise the voltage of the circuit from which the transformer is excited. The primary winding is connected in multiple and the secondary winding in series with the line. By reversing the secondary winding its action can be changed from boosting to bucking. In this connection the low voltage winding is subjected to the overvoltages of the high voltage circuit. Transformers specially designed for booster operation are insulated to take care of these voltages. Caution should be used, therefore, in applying standard two-winding transformers as boosters. However, if this connection is used on such transformers with 1.2 kv Class secondaries, it is recommended that one end of the secondary winding be grounded and connected to the tank. Standard "SP" and "CSP" transformers if connected in this manner will be protected, but the secondary bushing gaps may not be self-clearing unless one end of the L.V. winding can be connected to the tank and grounded.

Consideration should also be given to the reduction in effective transformer impedance when connected as a booster. This may involve the addition of series impedance to limit short circuit currents to permissible values.

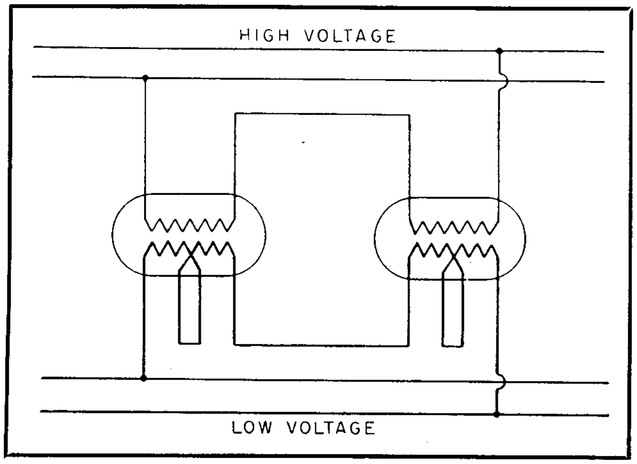


FIG. 14. 60-Cycle Transformers on 25 Cycles

60-Cycle Transformers on 25 Cycles (Fig. 14). When using a 60-cycle transformer on a 25-cycle circuit, a transformer rated at approximately double the voltage of the circuit would be required to prevent magnetic saturation of the iron core. The same result can be accomplished by connecting two transformers of the same voltage in series.

TWO-PHASE CONNECTIONS

Two-Phase; Four-Wire (Fig. 15). In this connection 2-phase, 4-wire is transformed to 2-phase, 4-wire of a different voltage with no connection between the two phases.

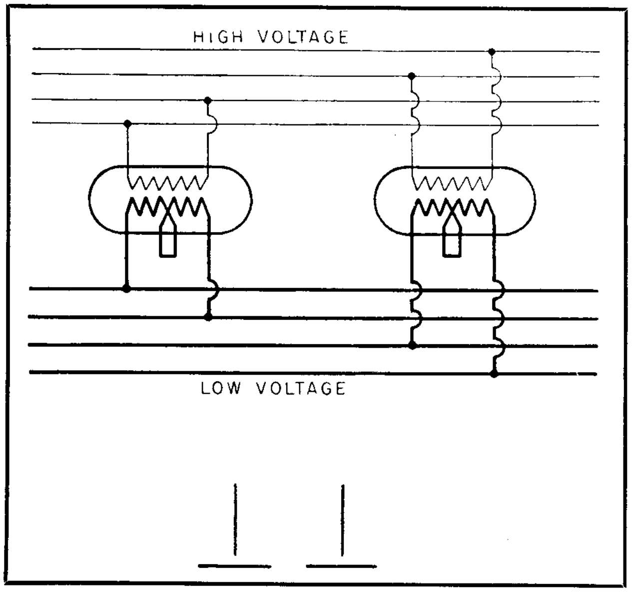


FIG. 15. Two-Phase; Four-Wire

Two-Phase; Four-Wire To Two-Phase—Three-Wire (Fig. 16). The two phases on the

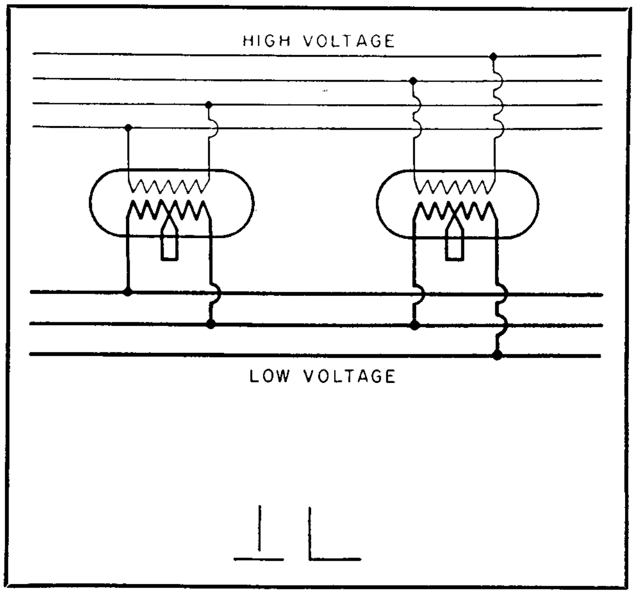


FIG. 16. Two-Phase, Four-Wire to Two-Phase, Three Wire

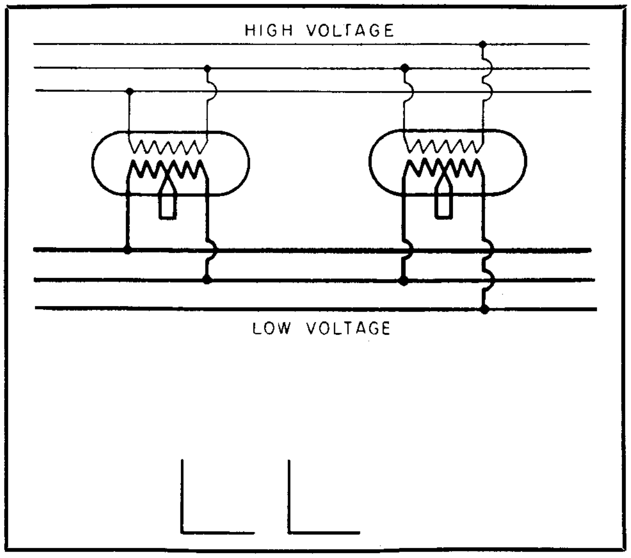


FIG. 17. Two-Phase; Three-Wire Interconnected

low-voltage side are electrically tied together. The common third wire is sometimes grounded. With balanced load the current in the common wire is $\sqrt{2}$ times that in the outside.

Two-Phase; Three-Wire Interconnected (Fig. 17). In this connection the two phases are electrically tied together by the common third wire. This is permissible in certain cases and not in others. This third or common wire is sometimes grounded. With balanced load, the current in the common wire is $\sqrt{2}$ times that in the outside wires.

THREE-PHASE CONNECTIONS

Three-Phase; Closed Delta (Fig. 18). When three transformers are operated in a closed delta bank, care should be taken to make certain that the impedances of the three units are practically the same. Transformers having more than 10 percent difference in impedance rating should not be operated together in a closed delta bank unless a reactor is used to increase the impedance of the unit having the lower impedance rating to a value equal to the other units.

If the voltage ratio of all three of the transformers is not the same there will be a voltage tending to circulate a current inside the delta. The current will be limited by the impedance of the three transformers considered as a series circuit.

It is always best before connecting up three transformers in closed delta to insert a fuse wire between the ends of the two transformers closing the delta bank. The fuse wire should be of sufficient size to carry the exciting current of the transformers. The use of this fuse wire offers a very simple means of making certain that the transformers have the proper polarity.

If the units are "CSP" transformers, they will all have the proper overload protection regardless of any dissymmetry in ratings.

This connection should not be used with "CSP" transformers if used to supply a combined three-phase and single-phase 3-wire load (See Fig. 19).

Three-Phase; Open Delta (Fig. 19). Three to 3-phase may be transformed by the use of two similar transformers in open delta. In this connection the units will transform 86 percent of their rating, i.e., two 100 kva units in open delta transforming 3-phase, 2300 volts to 3-phase 230-115 volts will have a bank capacity of 172 kva.

In the open delta connection it is not necessary that the impedance characteristics be the same, although it is preferable as when it becomes necessary to close the open delta bank with a third unit then all three units must have identical impedances.

The open delta connection is often used as a temporary expedient pending a contemplated increase of load and offers a very simple means of handling this matter. By adding a third 100 kva unit in the above mentioned example the resultant

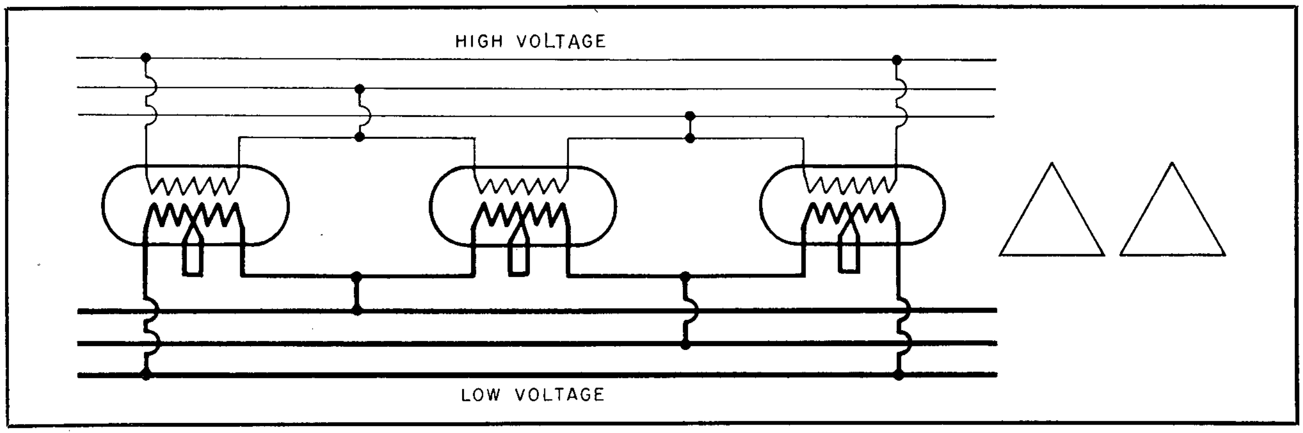


FIG. 18. Three-Phase; Closed Delta

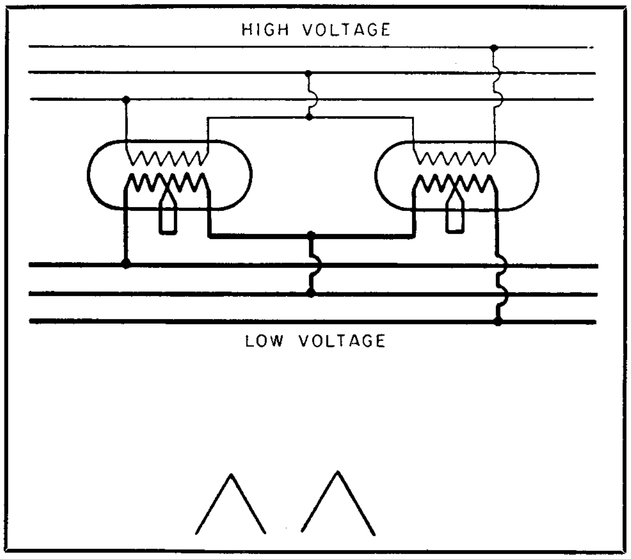


FIG. 19. Three-Phase; Open Delta

bank capacity will be increased from 172 kva to 300 kva.

The regulation of an open delta bank is not as good as a closed delta bank. The drop across the open delta is greater than across each of the separate transformers.

This connection may be used with "CSP" transformers for supplying combined three-phase and single-phase 3-wire loads.

Three-Phase; Star, Three-Wire—High Voltage; Delta, Three-Wire—Low Voltage (Fig. 20). When three transformers are operated with their high-voltage windings in star the incoming line voltage is the $\sqrt{3}$ or 1.732 times the transformer winding voltage. This connection is very popular and presents a very convenient way of boosting the transmission voltage without purchasing additional transformers.

In general, all distribution transformers rated 8660 volts or less, are insulated for star connection on the high-voltage windings. In this connection it is not necessary that the impedance of the three transformers be the same. This connection should not be used with "CSP" transformers since when one breaker opens seriously unbalanced secondary voltages may appear.

Three-Phase; Star, Four Wire—High Voltage; Delta, Three-Wire—Low Voltage (Fig. 21). This connection permits 3-phase power to be transmitted at the star voltage. At the same time single-phase power may be taken from the mains

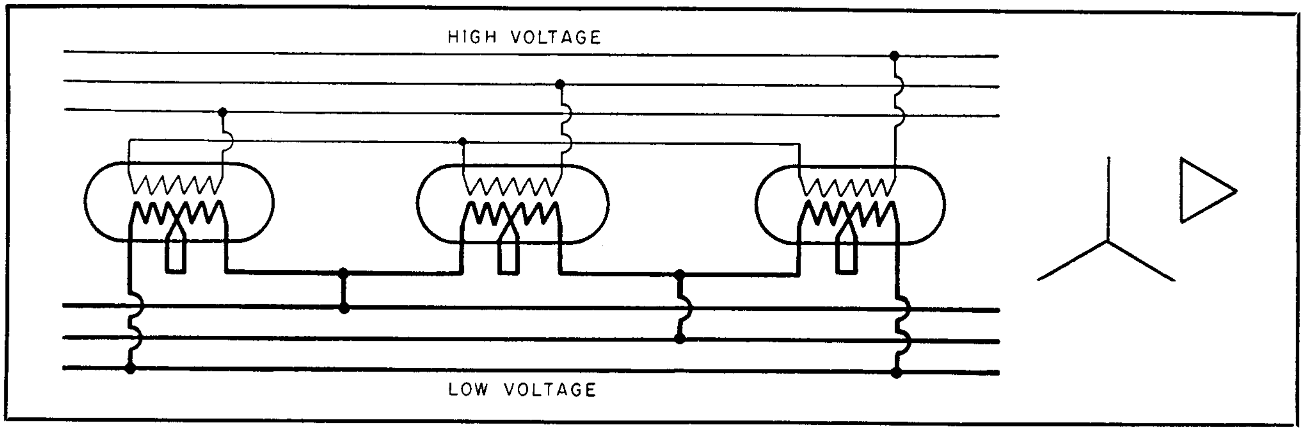


FIG. 20. Three-Phase; Star, Three-Wire (High Voltage)—Delta, Three-Wire (Low Voltage)

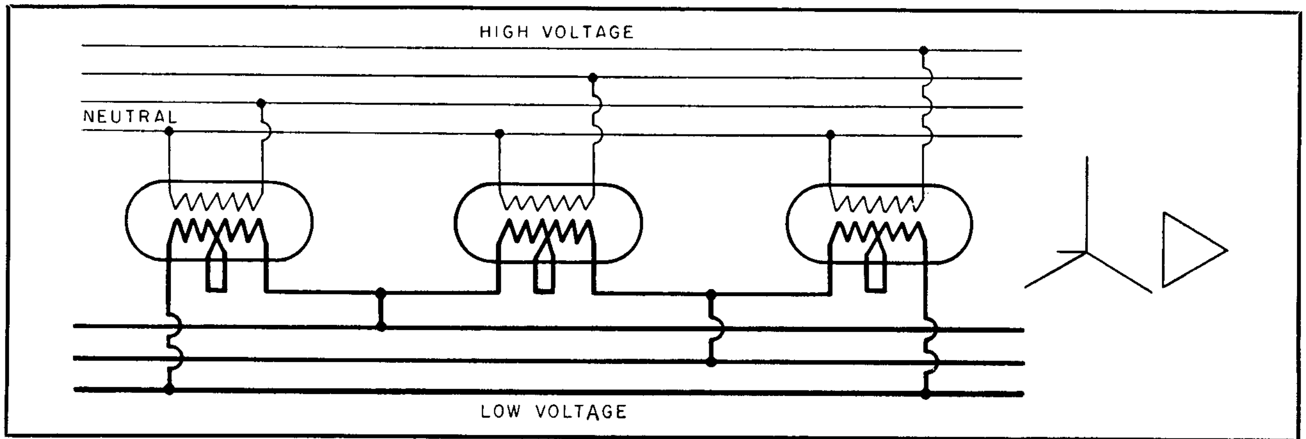


FIG. 21. Three-Phase; Star, Four-Wire (High Voltage)—Delta, Three-Wire (Low Voltage)

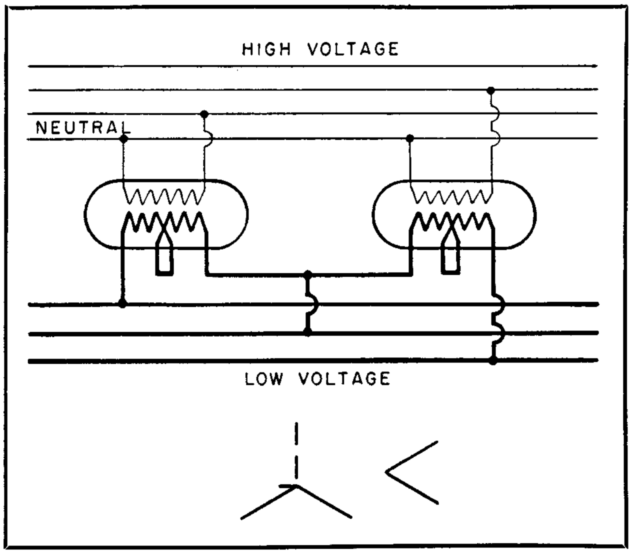


FIG. 22. 3-Phase; Star, 4-Wire, One Leg Out (H.V.)—Open Delta, 3-Wire (L.V.)

by connecting the transformer between the neutral and any of the three-phase wires. In this connection it is not necessary that the impedance of the three transformers be the same. The high voltage neutral is usually grounded. This connection should not be used with "CSP" transformers to supply combined three-phase and single-phase three-wire loads, for should the breaker in the phase supplying the three-wire load open due to overload, the load would be fed from the resulting open delta and the balancing effect of the neutral wire would be lost. On the other hand, "CSP" transformers are ideally suited for supplying combined three-phase and single-phase two-wire loads with the neutral on the supply side grounded. This is especially true when there is a possibility of single-phase loads being applied across the primary supply, for, in this case, the additional balancing current circulating in the delta may result in burnouts if thermal protection is not provided.

MISCELLANEOUS

Three-Phase; Star, Four-Wire, One Leg Out—High Voltage; Open Delta, Three-Wire—Low Voltage (Fig. 22). This is similar to a V connection. The primary of each transformer is connected between the neutral and one of the three-phase wires. The secondaries are connected to the secondary mains, the same as for the delta connection, except that the third transformer is not used. (The secondaries are in open delta). 86.6% of the rated capacity of the two transformers can be obtained.

Three-Phase; Star, Interconnected (Fig. 23). The primary side of this group may be connected either in star or in delta. Each half of the secondary winding of each transformer has a voltage of 57.7 percent of the interconnected star voltage. A bank of transformers designed for connection in this manner must have a capacity 7½ percent greater than the kva to be transformed. The purpose of the interconnected star winding is to permit the unbalanced d-c current from the third wire of the three-wire circuit of a rotary converter to get back into the alternating current system feeding the converter. Since this d-c current divides into two equal parts in each transformer and also these parts flow in opposite directions magnetically in the two parts, the d-c current does not magnetize the core. If this current would flow in one direction through the winding the d-c magnetic flux would add to the a-c flux and perhaps saturate the core.

Three-Phase, Inside Delta Taps; High Voltage; Closed Delta—Low Voltage (Fig. 24). The purpose of this connection is to permit the use of a tap without re-connecting the transformers at the corners of the delta. There are two objections to the use of inside delta taps.

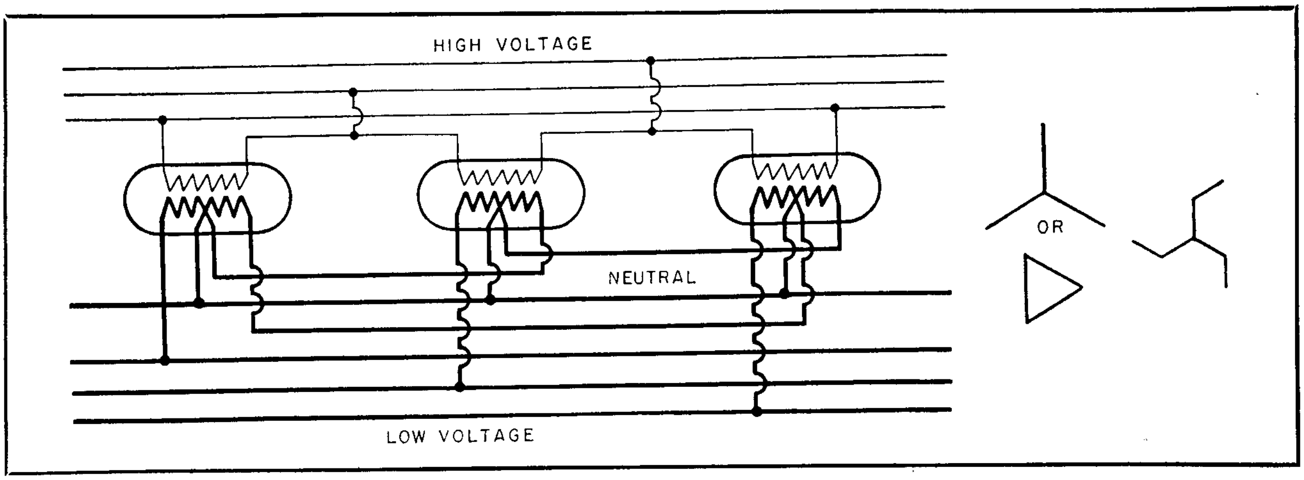


FIG. 23. Three-Phase; Star, Interconnected

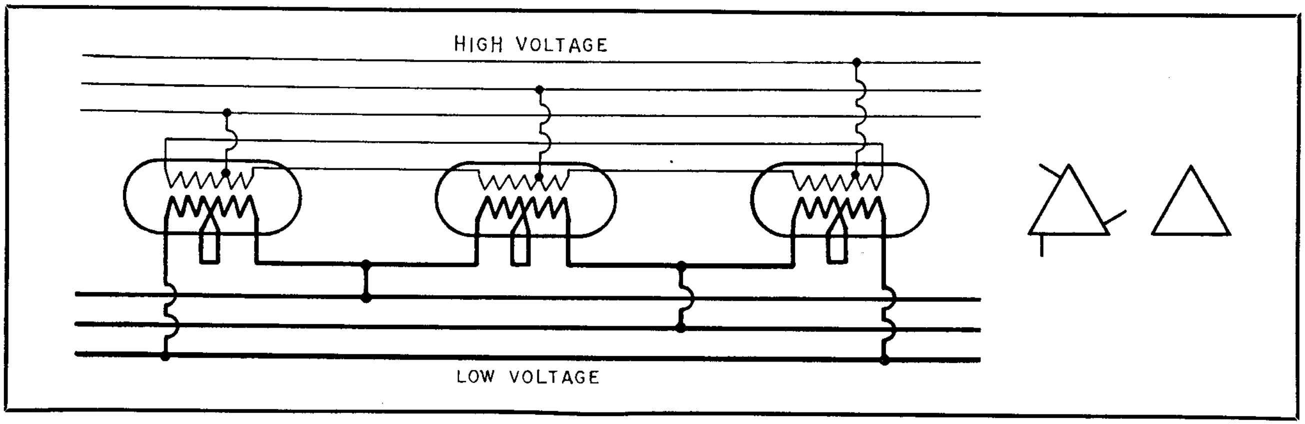


FIG. 24. Three-Phase; Inside Delta Taps (H.V.)—Closed Delta (L.V.)

1. All of the winding is in circuit even when it is not needed.

2. There is a phase shift between the primary and secondary voltages, which would not be present if the straight delta connection was used. This shift in voltage is objectionable if the transformer is to be paralleled with a straight delta-delta transformer.

Three-Phase; Three or Four-Wire, Star-Star with Auto-Transformers (Fig. 25). In this connection the high and low-voltage windings are electrically connected together, and for this reason the low-voltage side and connected apparatus will under fault conditions be subjected to the voltage of the high voltage circuit. The material in the auto-transformer is less than that in a two-winding transformer, transforming the same power. The saving in material is quite large when there is but a small difference in the primary and secondary voltages, and the saving becomes less and less as the difference between the primary and secondary voltages increases.

Three-Phase; Three-Wire—Open Delta With Auto-Transformer (Fig. 26). In this connection the high and low-voltage windings are electrically connected together, and for this reason

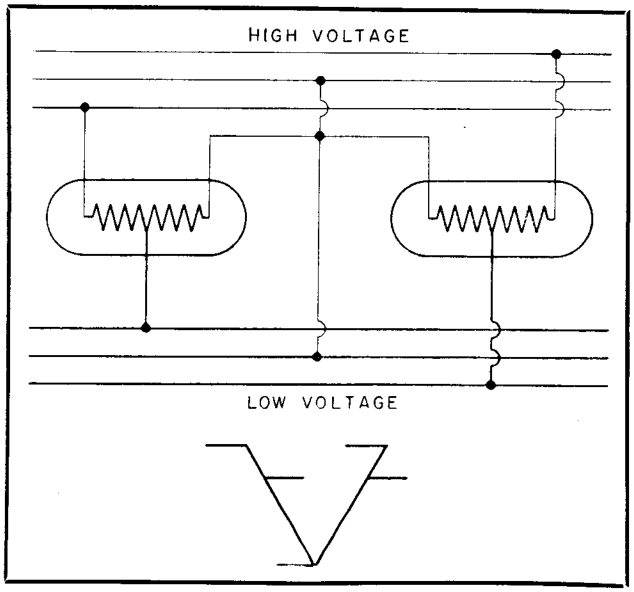


FIG. 26. Three-Phase; Three-Wire Open Delta With Auto-Transformers

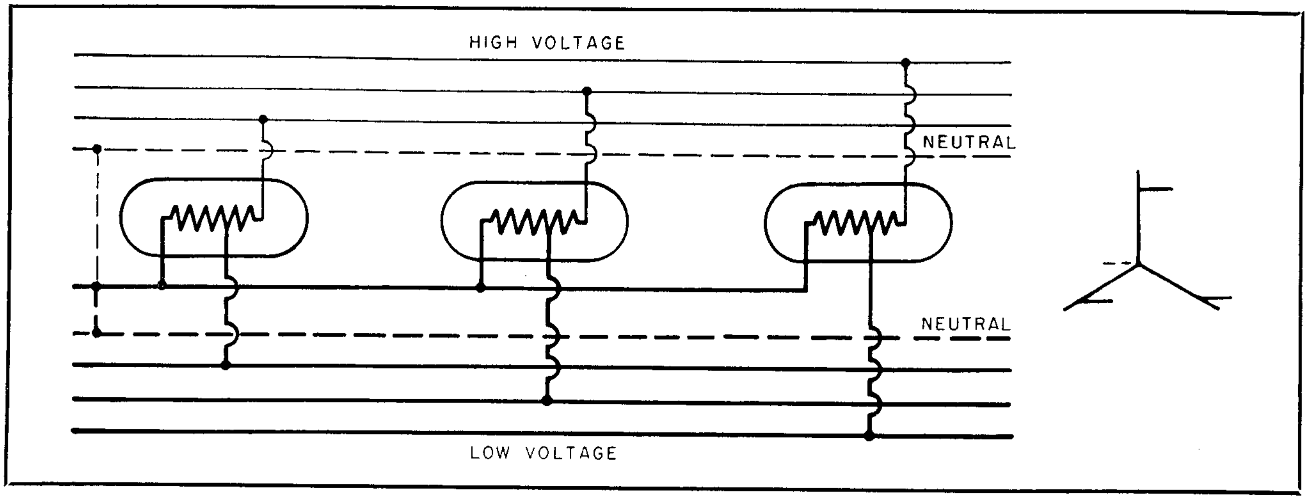


FIG. 25. Three-Phase; Three or Four-Wire; Star-Star with Auto-Transformers

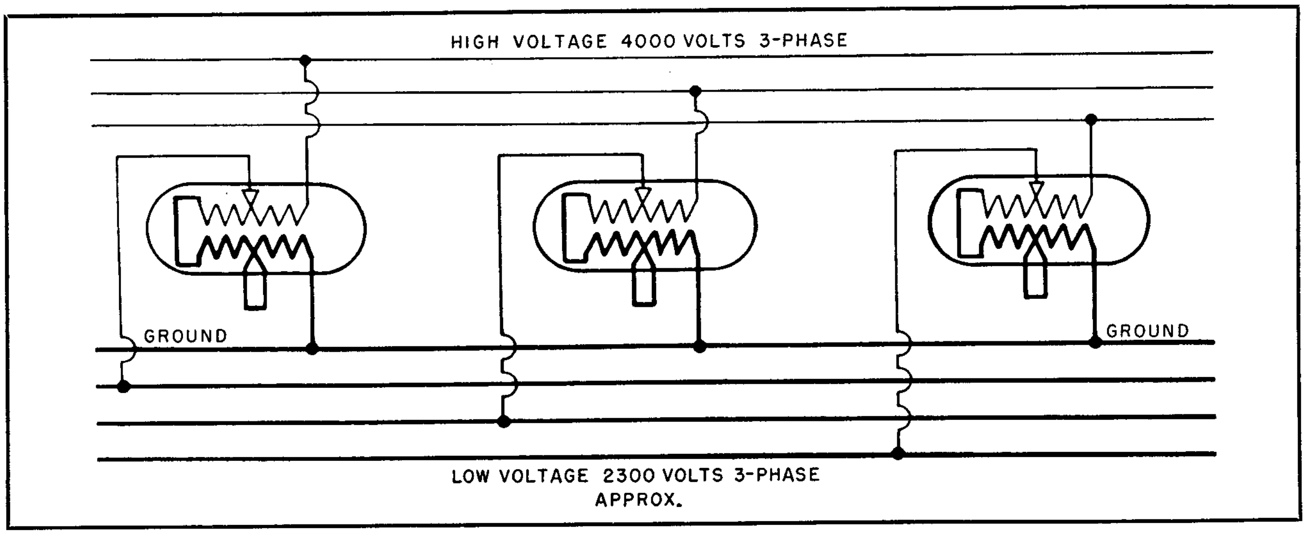


FIG. 27. Transforming 4000 V. to 2300 V. by Use of Standard 2-Winding, Class 400 Transformers

the low-voltage side and connected apparatus will under fault conditions be subjected to the voltage of the high voltage circuit. The material in the auto-transformer is less than that in a two-winding transformer, transforming the same power. The saving in material is quite large when there is but a small difference in the primary and secondary voltages, and the saving becomes less and less as the difference between the primary and secondary voltages increases. This connection requires 17 percent larger transformer capacity than the star-star auto-transformer connection.

4000 to 2300 Volts by Use of Standard 2-Winding, Class 400 Transformers (Fig. 27). This diagram gives a method of hooking up three standard 2300-volt, class 400 transformers so as to transform from 4000 to 2300 volts, three-phase.

Find the middle point of the high-voltage winding which is generally available either at the terminal block or on a crossover lead of the coils. Connect the left-hand, high-voltage lead to this point and connect outside the case as indicated.

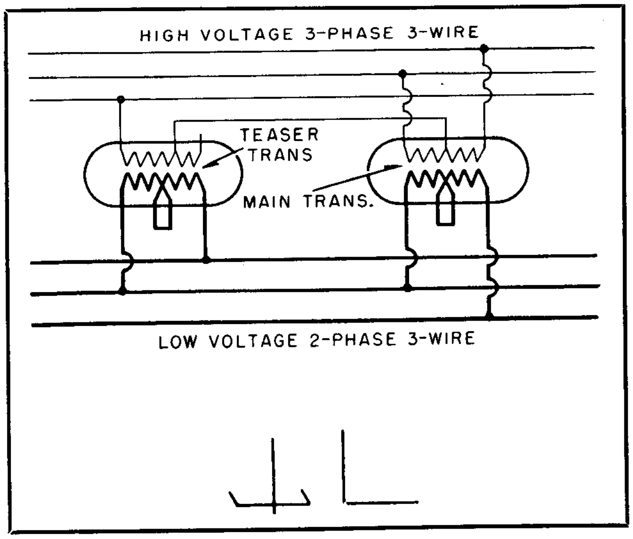


FIG. 28. Phase Transformation; 2-Phase, 3-Wire to 3-Phase, 3-Wire or Scott; 3-Phase to 2-Phase

Connect inside the case the left-hand end of high-voltage winding to the left-hand end of the low-voltage winding as indicated.

Connect low-voltage coils in series as indicated. Follow schematic diagram. Note that actual voltages of 4730 and 2790 bear the same ratio as 4000 and 2300; therefore, if 4000 only is impressed then the required 2300 volts will be delivered.

Transformers over 50 kva are not adapted for connection in this manner for motor starting.

Caution: The neutral point must be grounded. Do not impress a higher voltage than 4000 volts, as the insulation is not built to withstand higher stresses.

Phase Transformation, Scott; 2-Phase, 3-Wire to 3-Phase, 3-Wire or Scott; 3-Phase, 3-Wire to 2-Phase, 3-Wire (Fig. 28). This is a phase transformation, from three-phase to two-phase, or from two-phase to three-phase. Either the primary or secondary side may be made three-phase. The three-phase side must have special taps to make this transformation. One unit must have an 86.6 percent tap, and the other unit a 50 percent tap. A three-wire circuit is used on the two-phase side. This is formed by merely joining together two of the wires forming the two phases. In this manner the two phases are electrically connected together.

Distribution transformers are ordinarily designed so that the full rated capacity of the bank can be utilized without exceeding normal temperature rises.

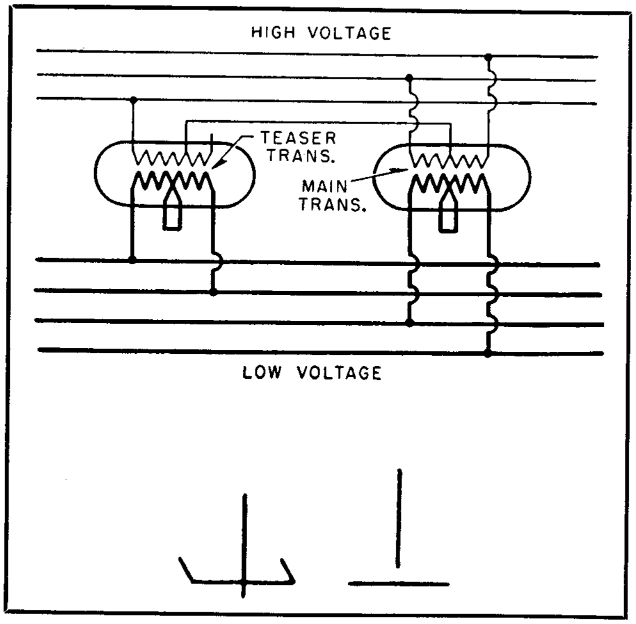


FIG. 29. Phase Transformation, Scott; See Description Below

If the transformers are to be used with motors interconnected at mid-points, the connection shown at the right cannot be used and 4-wire connection illustrated in Fig. 29 is recommended.

Phase Transformation, Scott; 3-Phase, 3-Wire to 2-Phase, 4-Wire or Scott; 2-Phase, 4-Wire to 3-Phase, 3-Wire (Fig. 29). This connection is exactly the same as the previous one except the two-phase side is made 4-wire. In this manner the two two-phase circuits are electrically separated.

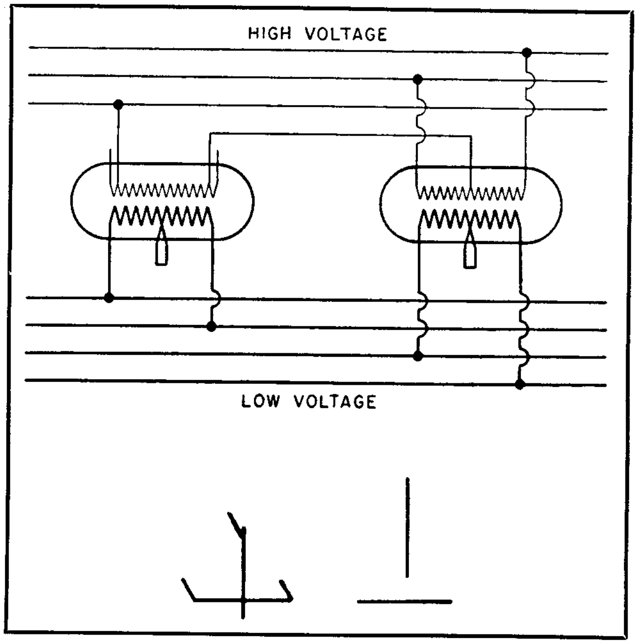


FIG. 30. Scott Transformation; Standard 10 to 1 Ratio Used

Scott Transformation; Standard 10 to 1 Ratio Used (Fig. 30). If a Scott transformation is desired, and a transformer having an 86.6 percent tap is not available, a unit having a 10 percent tap or two 5 percent taps may be used to give approximate results. With this arrangement the two-phase voltages will be unbalanced by about 4 percent.

The high voltage windings of standard core form transformers, unless specifically designed for Scott operation, are not interlaced and therefore an additional source of unbalance will be introduced.

Phase Transformation; Fortesque Connection (Fig. 31). This is a transformation from three-phase to two-phase, by the use of three transformers, one of which is standard and the other two have special taps on the low-voltage side. One advantage of this connection is that both two and three-phase current may be delivered at the same time. The sum of the power delivered at two-phase and at three-phase must be somewhat less than the normal rating of the transformers, in order not to overload the transformers.

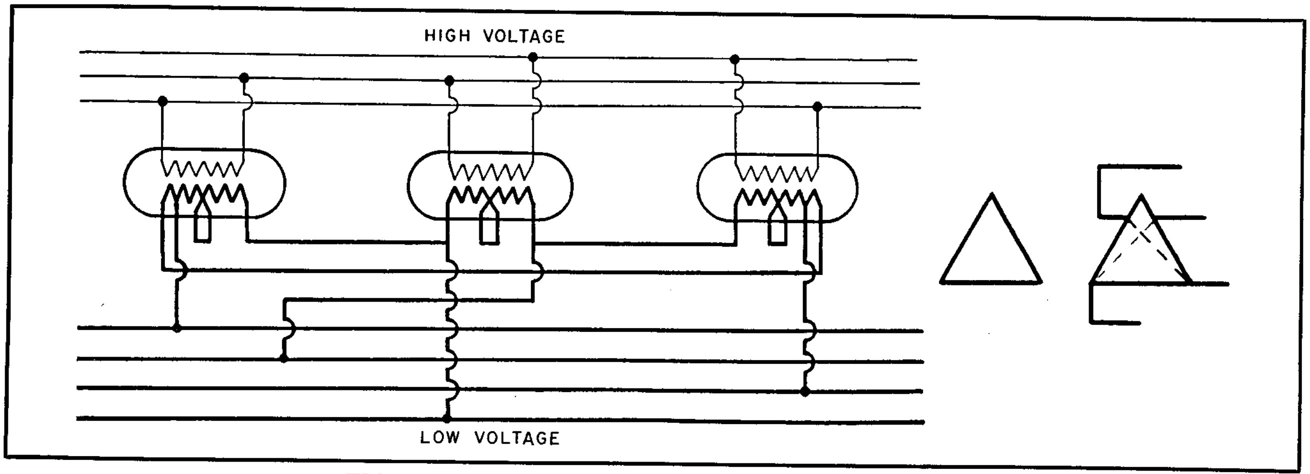


FIG. 31. Phase Transformation, Fortesque Connection

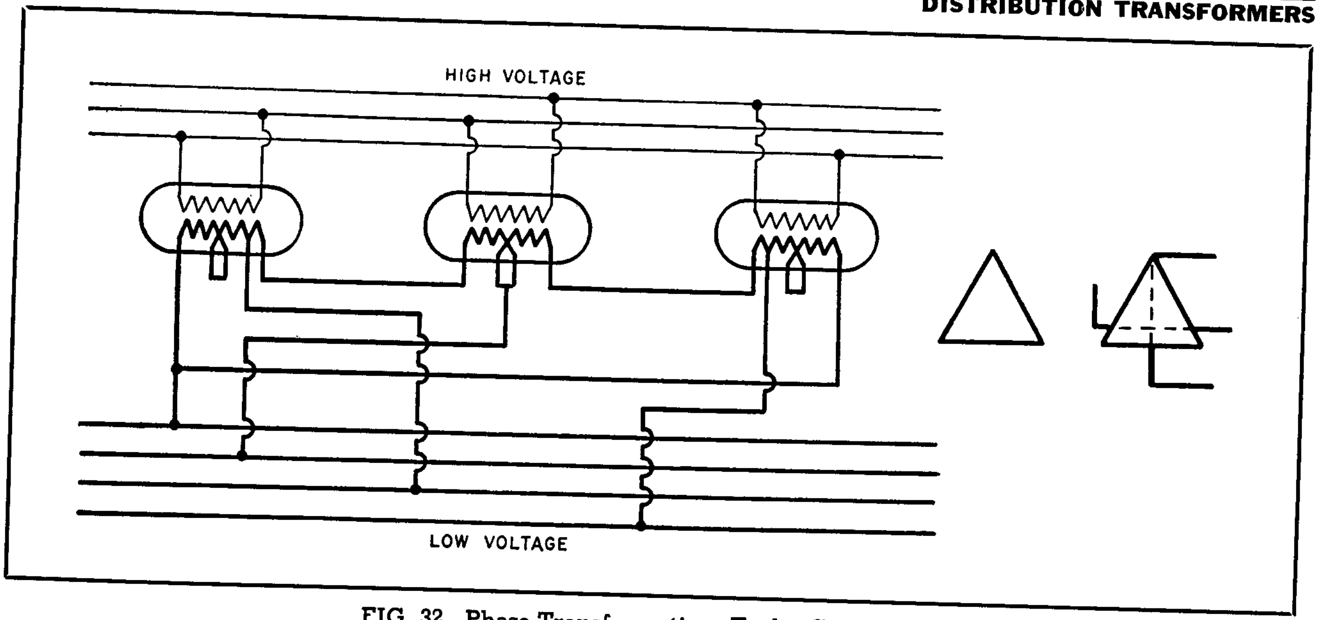


FIG. 32. Phase Transformation; Taylor Connection

Phase Transformation; Taylor Connection (Fig. 32). This connection is very similar to the Fortesque connection as far as results go. One standard and two special transformers are used.

Six-Phase; Diametrical (Fig. 33). This connection requires one low-voltage winding on each transformer, which is connected to diametrically opposite points on the converter winding. The middle points of the diametrical windings can be connected together, and brought out for the third wire of a direct-current circuit. When full output is required at the same voltage at either three-phase or six-phase, the double-delta connection is usually used.

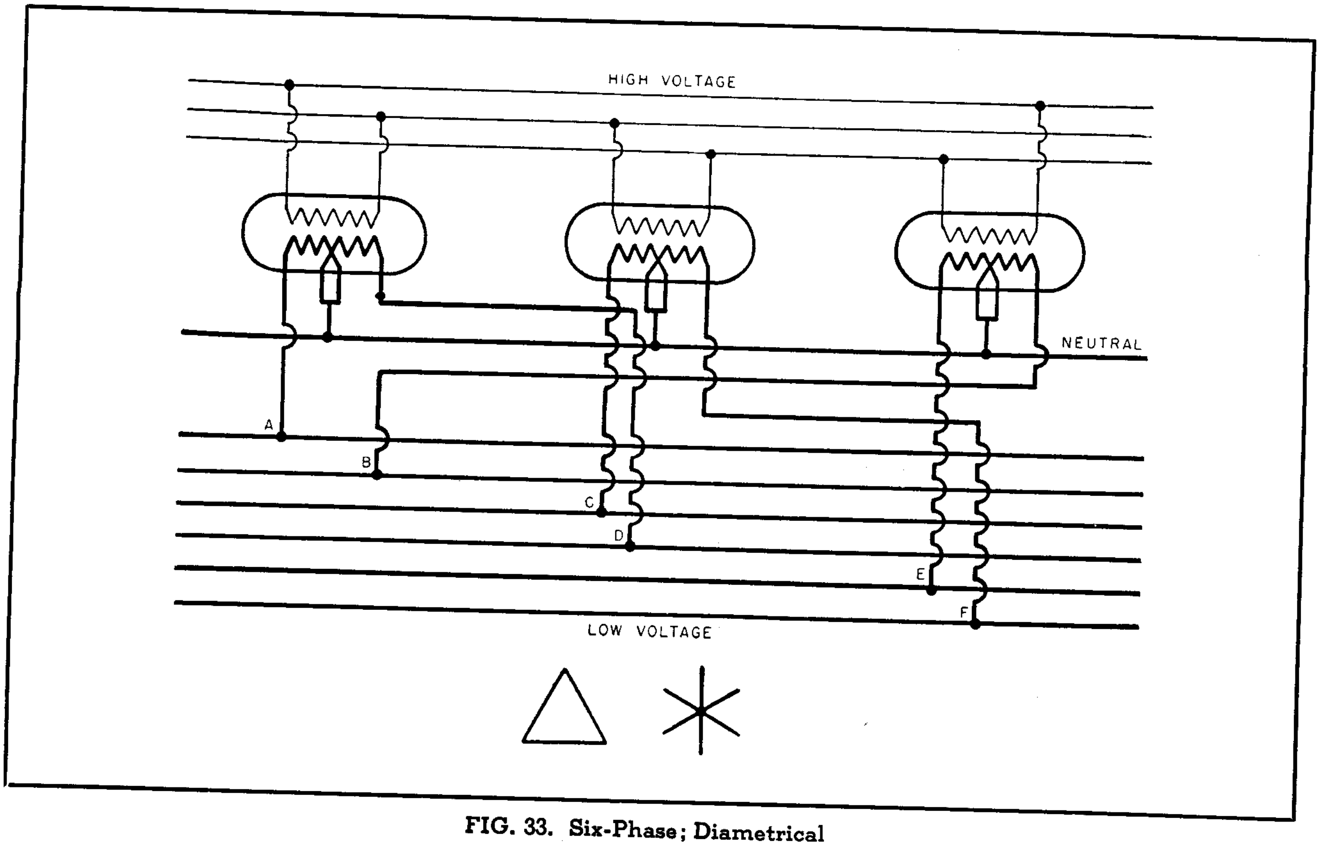


FIG. 33. Six-Phase; Diametrical

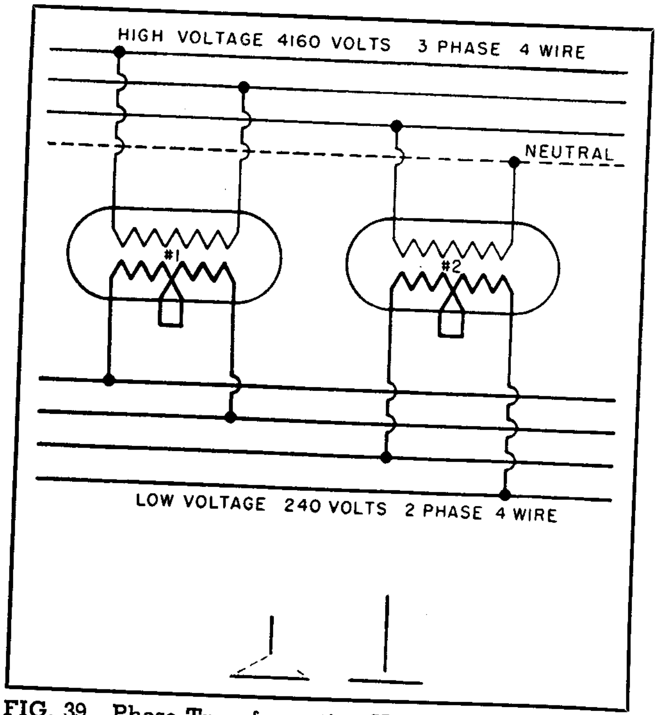


FIG. 39. Phase Transformation Using Standard Transformers of Different Voltage Ratings

Phase Transformation Using Standard Transformers of Different Voltage Ratings (Fig. 39). This is a phase transformation from three-phase to two-phase employing standard transformers. Transformer No. 1 is rated 4160 volts to 240/-120 volts. Transformer No. 2 is rated 2400 to 240/120 volts. Each transformer will have a rating equal to one-half the two-phase load.

COMPUTING SIZE OF MAIN AND TEASER TRANSFORMERS IN THREE TO TWO-PHASE TRANSFORMATIONS

Three-Phase to Two-Phase, Four-Wire and Three-Wire Transformation by Scott-Connected Auto-Transformers. The accompanying curves are intended to assist in determining the approximate physical sizes of the main and teaser auto-transformers required in a three-phase to two-phase transformation. (These curves should not be used as a basis for pricing Scott-connected auto-transformers.)

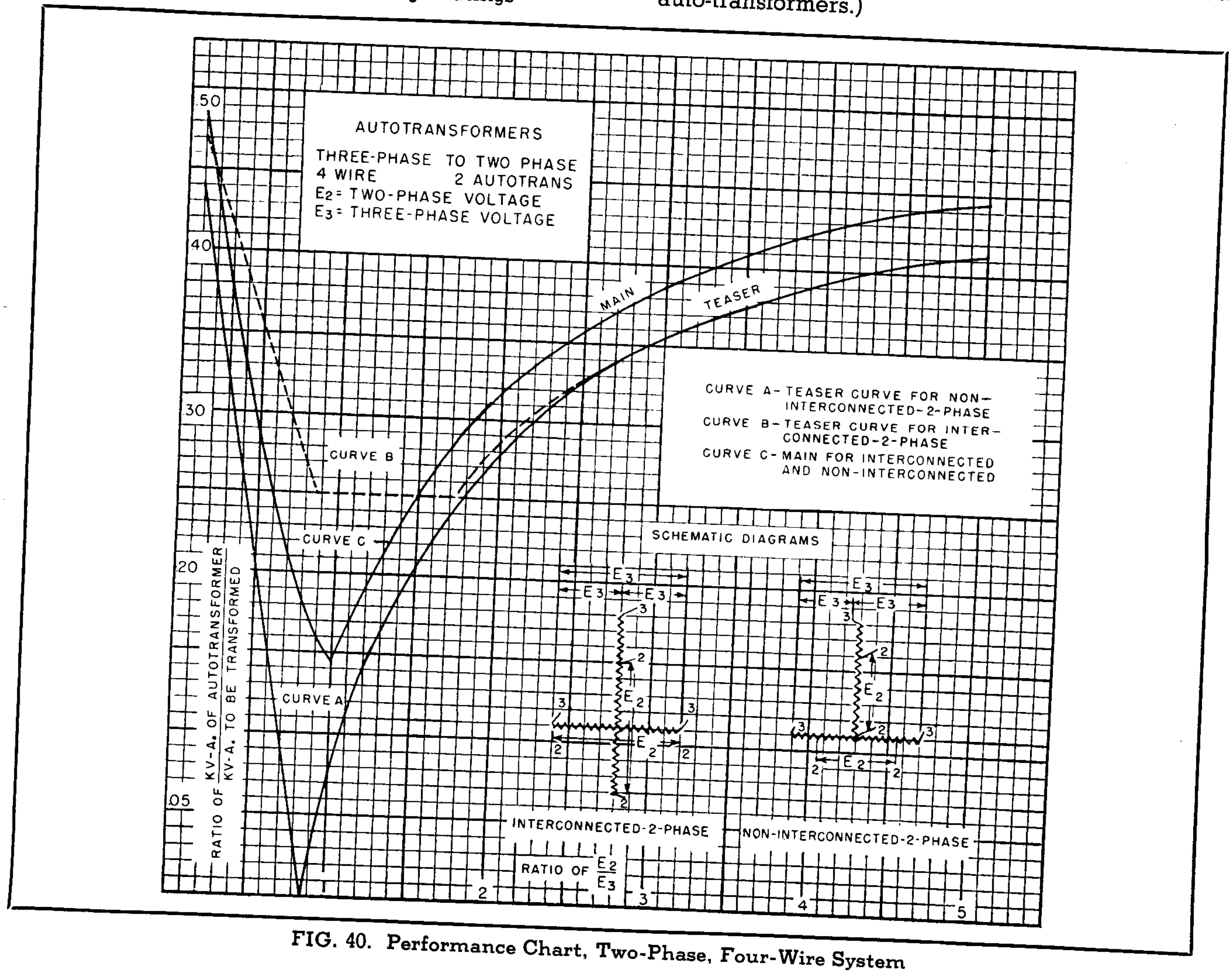


FIG. 40. Performance Chart, Two-Phase, Four-Wire System

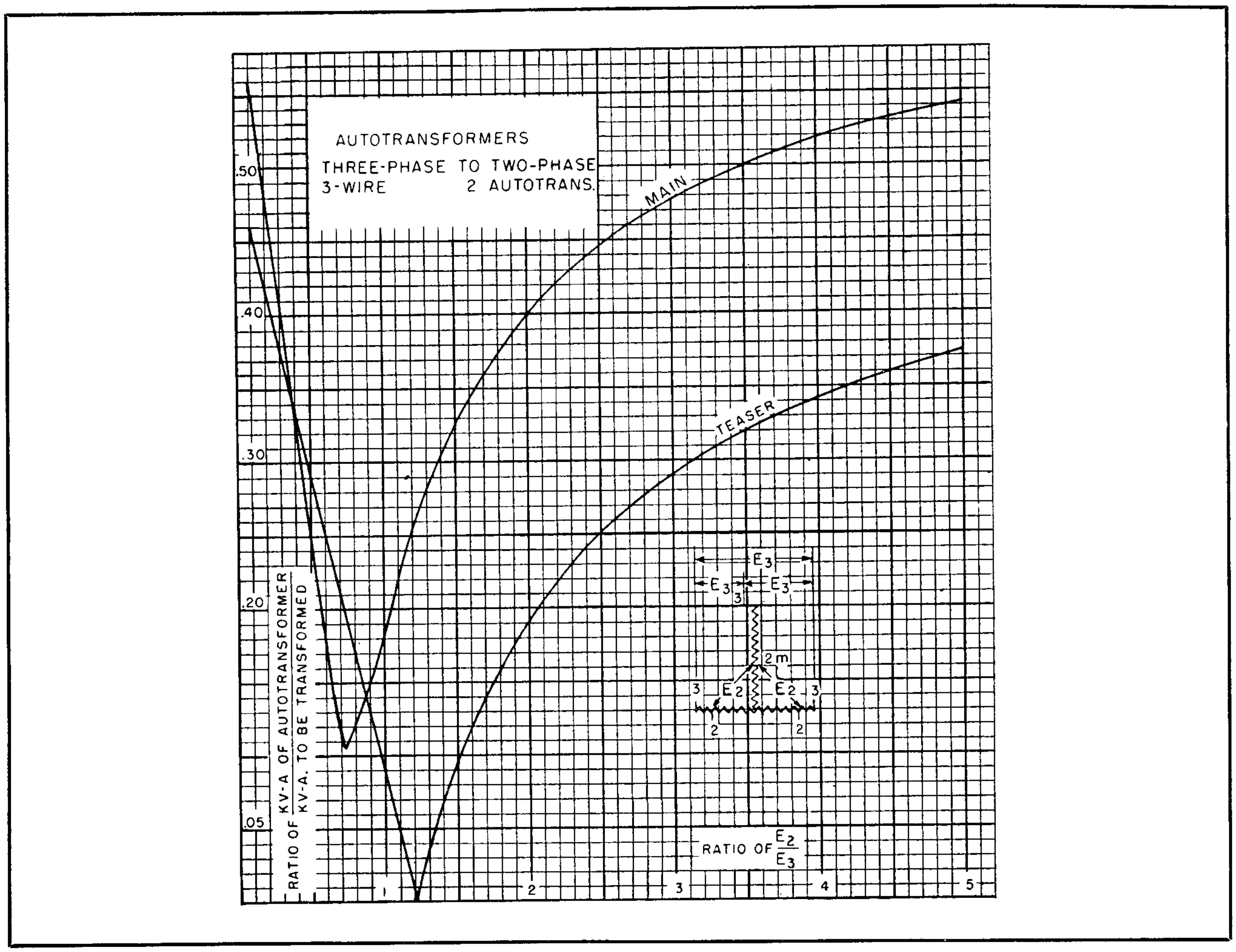


FIG. 41. Performance Chart, Two-Phase, Three-Wire System

Fig. 40 applies to a two-phase, four-wire system.

Fig. 41 applies to a two-phase, three-wire system.

EXAMPLES BASED ON FIG. 40

Example 1. What will be the size of the main and teaser auto-transformers required to transform 100 kva from 230 volts, three-phase to 230 volts two-phase, four-wire **non-interconnected?**

$$\frac{E_{2\varnothing}}{E_{3\varnothing}} = \frac{230}{230} = 1$$

From the curves A & C

$$\text{Ratio of } \frac{\text{kva of auto-transformer}}{\text{kva to be transformed}} = 0.144$$

for main and 0.067 for teaser.

Then:

0.144 x 100 = 14.4 kva
0.067 x 100 = 6.7 kva

Therefore, the main will be approximately the size of a standard 15 kva transformer and the teaser will be approximately the size of a standard 7.5 kva, 230-volt, two-winding transformer.

Example 2. What will be the sizes of the main and teaser auto-transformers required to transform 100 kva from 460 volts three-phase to 575 volts two-phase, four-wire **interconnected?**

$$\frac{E_{2\varnothing}}{E_{3\varnothing}} = \frac{575}{460} = 1.25$$

From the curves B & C

$$\text{Ratio of } \frac{\text{kva of auto-transformer}}{\text{kva to be transformed}} = 0.21$$

for main and 0.25 for teaser

Then:

0.21 x 100 = 21 kva
0.25 x 100 = 25 kva

Therefore, the main and teaser auto-transformers will be approximately the size of standard 25 kva, 575-volt, two-winding transformers.

PART THREE

TESTING INSTRUCTIONS

DISTRIBUTION TRANSFORMER TESTING FOR CENTRAL STATIONS

A large portion of the following instructions has been reprinted from A.S.A. Standard C57.22 "American Standard Test Code for Distribution, Power, and Regulating Transformers" Published 1948.★

General. In alternating-current systems of distribution, the transformer which intervenes between the central station, the sub-station or the transmission line and the customer, is called a distribution transformer. Since these transformers are the medium through which the energy is delivered to the consumer, they must be capable of giving continuous service and, at the same time, must be economical in operation. If the insulation is weak, or the working temperature is high, the transformer is dangerous to both life and property, and its early failure will cause a temporary and perhaps permanent loss in the earnings of the central station. If the regulation of the transformer is poor, the customer will become dissatisfied with the service, while, if the losses in the transformer are high or excessive, the operating expenses of distributing the electrical energy will be increased.

This section describes the various tests which are used to determine the characteristics of a transformer and the methods of making such tests. The following tests are required to obtain a complete knowledge of the performance of the transformer:

1. Preliminary—ratio and polarity.
2. Continuity of service—temperature and insulation.
3. Quality of the service—resistance, impedance and regulation.
4. Economy of operation—iron loss, copper loss, exciting current and efficiency.

The variation between individual transformers in some of the foregoing properties is very small and a complete set of tests will be unnecessary except possibly for one unit out of every lot to be installed.

In the course of manufacture and before shipment from the factory, every Westinghouse transformer is subjected to the following tests; ratio and polarity of the windings, iron loss, exciting current, insulation test and a run at over potential. In addition to the tests just mentioned, the first three units of every style of transformer are tested for resistance, impedance, and copper loss. A full load temperature run is also made on each new style.

In testing electrical apparatus, accurate results can be obtained only when strict attention is paid to all the details of the test. To avoid appreciable errors in results obtained, the following points should be observed.

Conductors. The conductors employed in making connections for tests should have a cross section sufficient to carry the maximum current employed and should be as short as possible. In order to avoid accident, it is necessary that the insulation of the conductors be in good condition. This is particularly necessary when high potentials are used. All points where connections are made should be thoroughly cleaned so that a low resistance connection will be obtained.

Meters. The meters used in making tests should have the proper scale, and their capacity should be sufficient to handle the maximum voltage or current values necessary. Meters give the most accurate readings when the deflection ranges between 25 and 75 percent of their full scale.

Calibration. All meters should be calibrated before being used or it should be known that they are correct. It is necessary to calibrate meters at intervals in order to assure their accuracy. Errors in the instruments cannot be eliminated by making several readings and therefore it is important that the meters used be accurate or the entire test may be invalidated.

Observation. In making meter readings, the line of vision must be at right angles to the plane of the meter scale. The scales of some meters are provided with mirrors and when the needle and its image in the mirror are coincident, the line of vision and the plane of the instrument are at right angles and correct observations can be made.

In tests where more than one meter is employed, and where the current is drawn from a circuit on which voltage variations usually occur, observa-

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★ Paragraph numbers and figure numbers agree with the A.S.A. Standard.

tions must be made simultaneously to assure accuracy. In some of the tests, accuracy depends largely upon the rapidity with which the adjustment of the current values is made and the readings of the meter are taken.

The error caused by variation of voltage can be approximately eliminated by taking several readings. For practical purposes, however, more than four or five observations are unnecessary. Wrong frequency will produce errors, especially in the iron loss, exciting current and impedance tests.

In many of these tests, a slight error will be introduced by reason of one of the meters measuring the energy consumed in another meter or in itself. A suitable correction must be made to cover this error, when accurate results are desired. Under certain conditions, the impedance of the meters may influence the wave form of the electromotive force so as to introduce an error.

RESISTANCE MEASUREMENTS

22.010 Necessity for Resistance Measurements. Resistance measurements are of fundamental importance for two purposes:

(a) For the calculation of the copper or I^2R loss,

(b) For the calculation of winding temperatures at the end of a temperature test.

22.011 Determination of Cold Temperature. The cold temperature of the winding shall be determined as accurately as possible when measuring the cold resistance. The following precautions shall be observed:

(a) Transformer Out of Oil. The temperature of the windings shall be recorded as the average of several thermometers inserted between the coils, with extreme care used to see that their bulbs are as nearly as possible in actual contact with the copper of the windings. It should not be assumed that the windings are at the same temperature as the surrounding air.

(b) Transformer Immersed in Oil. The temperature of the windings shall be assumed to be the same as the temperature of the oil, provided the transformer has been under oil with no excitation and with no current in its winding from three to eight hours before the cold resistance is measured, depending upon the size of the transformer.

(c) General. Cold resistance measurements shall not be taken on a transformer when it is located in drafts or when it is located in a room in which the temperature is fluctuating rapidly.

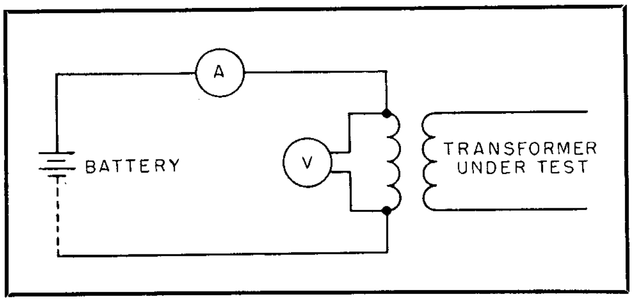


FIG. 42. (22.012) Connections for the Drop-of-Potential Method of Resistance Measurement

22.012 Drop-of-Potential Method.

(a) The drop-of-potential method is generally more convenient than the bridge method for measurements made in the field. It should be employed only if the rated current of the transformer winding is one ampere or more.

(b) Measurement is made with direct current and simultaneous readings of current and voltage are taken using the connections of Figure 42. The required resistance is calculated from the readings in accordance with Ohm's law.

(c) If the current is too low to be read on an available ammeter, a shunt and a potentiometer shall be used. If the drop of potential is less than one volt, a potentiometer or millivoltmeter shall be used.

(d) In all cases, greater accuracy may be obtained by the use of potentiometers for the measurement of both current and potential although the setup may be rather cumbersome.

(e) The current used shall not exceed 15 percent of the rated current of the winding whose resistance is to be measured. Larger values may cause inaccuracy by heating the winding and thereby changing its temperature and resistance.

(f) In order to minimize errors of observation, the measuring instruments shall have such ranges as will give reasonably large deflections.

(g) The voltmeter leads shall be independent of the current leads and shall be connected as closely as possible to the terminals of the winding to be measured. This is to avoid including in the reading the resistances of current-carrying leads and their contacts and of extra lengths of leads.

(h) If the direct current is supplied by a commutating machine, the pointer of the voltmeter may vibrate on account of the commutator ripple in the voltage. In such cases, some winding of the transformer other than the winding under test should be short circuited; this will damp the ripple and reduce or eliminate the vibration of the voltmeter. The current in the winding which is being measured should have become practically constant before short-circuiting the other winding; otherwise, erroneous values of resistance may be obtained. It has been found by experience that the relative time constants under these two conditions are such that steady direct current is reached more quickly under the open-circuit conditions than under the short-circuit conditions.

(i) To protect the voltmeter from injury by off-scale deflections, the voltmeter should be disconnected from the circuit before switching the current on or off.

(j) Readings shall be taken with not less than 4 values of current when deflecting instruments are used. The average of the resistances calculated from these measurements shall be considered to be the resistance of the circuit.

(k) Readings shall not be taken until after the current and voltage have reached steady-state values.

Note: When measuring the cold resistance, preparatory to making a heat run, the time required for the readings to become constant should be noted. The period thereby determined should be allowed to elapse before taking the first reading at the termination of the heat run.

If the winding under test has an appreciable time constant, the current can be made to attain its steady-state value more rapidly by first raising the voltage to a value greater than that required under steady-state conditions, to maintain the desired current value, and then decreasing the voltage as the current approaches the desired value.

22.013 Bridge Methods.

(a) The bridge methods are generally preferred because of their accuracy and convenience, since they may be employed for the measurement of resistances up to 10,000 ohms. They should be used in cases where the rated current of the transformer winding to be measured is less than one ampere.

(b) Bridge methods are especially recommended for all measurements which are to be used in connection with temperature-rise determinations.

RATIO TESTS

22.020 Ratio Tests.

(a) If the transformer has taps, the turn ratio shall be determined for all taps as well as for the full winding.

(b) The ratio test shall be made at rated or lower voltage and rated or higher frequency.

(c) Transformers having capacities of 500 watts or less and having an exciting current of more than 10 percent shall be tested only at normal voltage and frequency.

22.021. Three methods are in use for the ratio test:

(a) The voltmeter method.

(b) The standard transformer method.

(c) The resistance-potentiometer method.

22.022 Ratio by Voltmeter Method.

(a) Two voltmeters are used (with potential transformers if necessary), one to read the voltage of the high-voltage winding, the other that of the low-voltage winding.

(b) The two voltmeters shall be read simultaneously.

(c) A second set of readings shall be taken with the instruments interchanged, and the average of the two sets of readings taken, to compensate for instrument errors.

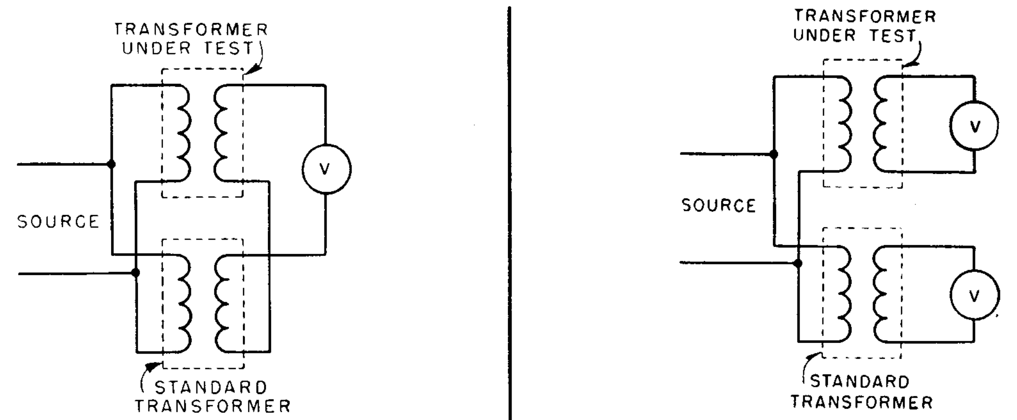
(d) Potential-transformer ratios should be such as to yield about the same readings on the two voltmeters; otherwise compensation for instrument errors by an interchange of instruments will not be satisfactory, and it will be necessary to apply appropriate corrections to the voltmeter readings.

(e) Tests shall be made at not less than 4 voltages in approximately 10 percent steps, and the average result shall be taken as the true value. These several values should check within 1 percent. Otherwise, the tests shall be repeated with other voltmeters.

(f) When several transformers of duplicate ratings are to be tested, work may be expedited by applying the foregoing tests to only one unit, and then comparing the other units with this one as a standard, in accordance with the Standard-Transformer Method discussed below.

22.023 Ratio by Standard Transformer.

(a) A convenient method of measuring the



A. VOLTMETER ARRANGED TO READ THE DIFFERENCE BETWEEN THE TWO SECONDARY VOLTAGES.

B. VOLTMETERS ARRANGED TO READ THE TWO SECONDARY VOLTAGES; THE READINGS ARE REPEATED AFTER INTERCHANGING VOLTMETERS.

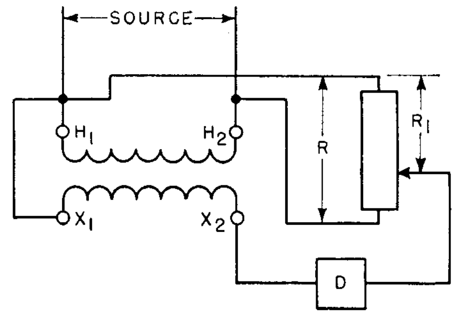
FIG. 43. (22.023) **Connections for Ratio Test by Comparison with a Standard Transformer**

ratio of a transformer is by comparison with a standard transformer of known ratio.

(b) The transformer to be tested is excited in parallel with a standard transformer of the same nominal ratio, and the two secondaries connected in parallel but with a voltmeter or detector in the connection between two terminals of similar polarity (Figure 43a). This is the more accurate method because the voltmeter or detector indicates the difference in voltage.

(c) The transformer to be tested is excited in parallel with a standard transformer of known ratio, and voltmeters are arranged to measure the two secondary voltages (Figure 43b). The voltmeters shall be interchanged and the test repeated. The average of the results is the correct ratio.

22.024 Ratio by Resistance Potentiometer. A resistance potentiometer having a suitable range, preferably graduated in terms of the ratio of the tapped portion to the total, may be used to determine the transformer ratio when arranged as shown in Figure 44. The slide contact is moved along the potentiometer resistance until the detector reads zero, when the ratio of the potentiometer resistance R/R_1 equals the transformer ratio.



WHEN BALANCE IS SHOWN BY DETECTOR D, THE TRANSFORMER RATIO IS R/R_1.

FIG. 44. (22.024) **Resistance Potentiometer for Ratio Test**

POLARITY AND PHASE-RELATION TESTS

22.050 Polarity

(a) Phase-relation tests are made to determine polarity, angular displacement, and relative phase sequence. These are of interest primarily on account of their bearing on paralleling or banking two or more transformers.

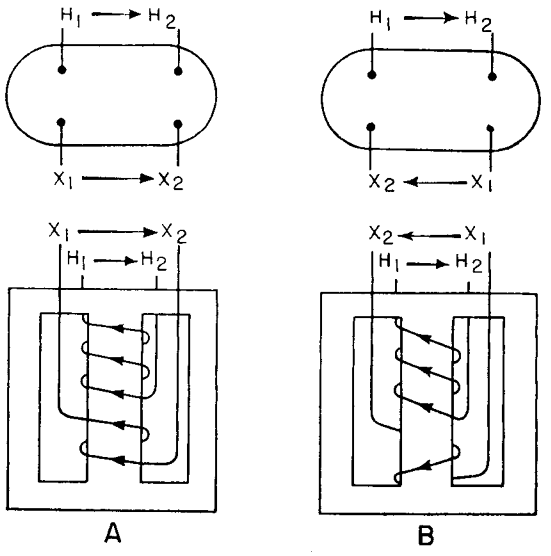


FIG. 45. (22.051) **A—Subtractive Polarity, B—Additive Polarity**

(b) Three methods are in common use for testing the polarity and checking the lead markings of single-phase transformers:

(1) Comparison with a standard transformer.

(2) Inductive kick with direct current.

(3) A-c voltage test.

22.051 Polarity by Standard Transformer.

(a) Windings arranged for subtractive polarity and additive polarity are shown in Figures 45a and 45b. When a standard transformer of known polarity and of the same ratio as the unit under test is available, the polarity can be checked by comparison as follows, similar to the ratio test by the standard-transformer method (see Figure 45a):—Connect the high-voltage windings of both transformers in parallel, by connecting similarly marked leads together. Connect also the left-hand-side low-voltage leads (facing the low-voltage side) of both transformers together, leaving the right-hand-side leads free. With these connections, apply a reduced value of voltage to the high-voltage windings and measure the voltage between the two free leads. A zero or negligible reading of the voltmeter will indicate that the relative polarities of both transformers are identical.

(b) An alternative method of checking the polarity is to substitute a low-rated fuse or suitable lamps for the voltmeter. This procedure is recommended as a precautionary measure in the first method before connecting in the voltmeter.

22.052 Polarity by Inductive Kick.

Polarity may be determined at the time of making the resistance measurements as follows: With direct current passing through the high-voltage winding, connect a high-voltage, d-c voltmeter across the outlet terminals of the same windings so as to get a small positive deflection of the pointer. Then transfer the two voltmeter leads directly across the transformer to the adjacent low-voltage leads respectively.* The direct-current excitation is then broken, thereby inducing a voltage in the low-voltage winding (inductive kick) which will cause a deflection in the voltmeter. If the pointer swings in the same direction as before (positive), the polarity is additive. If the pointer swings in a negative direction, the polarity is subtractive.

Note: (For instance, in Figure 45b, the voltmeter lead connected to H_1 will be transferred to X_2 as the adjacent lead, and that connected to H_2 to X_1.)

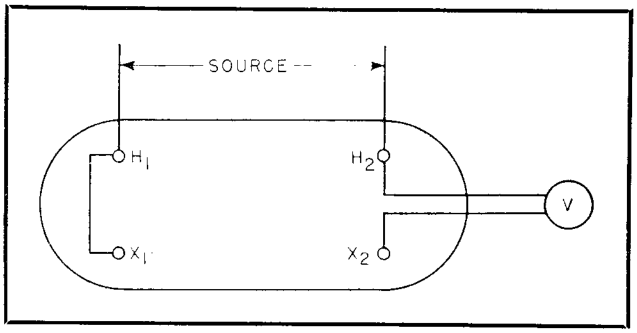


FIG. 46. (22-053) Polarity by A-C Voltage Test

22.053 Polarity by A-C Voltage Test.

(a) Connect the adjacent left-hand high-voltage and low-voltage outlet leads together facing the low-voltage side of the transformers (such as H_1 and X_1 in Figure 46). Apply any convenient value of alternating current voltage to the full high-voltage winding and take readings of the applied voltage and the voltage between the right-hand adjacent high-voltage and low-voltage leads. If the latter voltage reading is less than the former (indicating the approximate difference in voltage between that of the high-voltage and low-voltage windings), the polarity is *subtractive.* If the latter reading is greater than the former, the polarity is *additive.*

(b) This method is practically limited to transformers in which the ratio of transformation is 30 to 1 or less, since otherwise the difference between the two readings will not be very marked.

LOSS TESTS, EFFICIENCY, AND REGULATION

22.060 Excitation Loss—General.

(a) The excitation loss of a transformer consists principally of the iron loss in the transformer core, and is a function of the magnitude, frequency, and wave-shape of the impressed voltage. The excitation loss and the exciting current are particularly sensitive to differences in wave-shape; and, therefore, excitation-loss measurements will vary markedly with the wave-shape of the test voltage. Peaked voltage waves (form factor greater than 1.11), resulting generally from the distorted character of the exciting-current load of the transformer on the test generator, give smaller excitation losses than a sine-wave voltage. Flat-topped waves, rarely encountered in such tests, give larger excitation losses.

(b) Ordinary variations of temperature do not influence excitation losses materially and no correction for temperature variation is made.

(c) The excitation loss determination shall be based on a sine-wave voltage, unless a different wave-form is inherent in the operation of the apparatus.

(d) One of the following three methods shall be used for correcting the measured excitation losses to a sine-wave voltage basis:

(1) Average-voltage voltmeter.
(2) Iron-loss voltmeter.
(3) Standard core.

22.061 Excitation Loss by Average Voltmeter Method.

(a) The average voltmeter method is the most accurate method and is recommended. The excitation loss is largely a hysteresis loss, and this is a function of the maximum flux density in the core, independent of the wave shape of the flux. But the maximum flux density corresponds to the *average* value of the voltage (not to the rms value), and therefore if the *average* value of the test voltage is adjusted to be the same as the average value of the desired sine wave of voltage, and the proper frequency held, the hysteresis loss will be the desired sine-wave value. The average-voltage method* therefore utilizes an average-voltage indicating voltmeter consisting of a d'Arsonval voltmeter having in series with itself a full-wave rectifier. These instruments are generally graduated to give the same numerical indication as an rms voltmeter on sine-wave voltage; that is, they are marked in equivalent sine-wave rms values.

(b) Figure 47a shows the necessary equipment and connections when no instrument transformers are needed; Figure 47b, when they are needed, which is the general case. As indicated in Figure 47a, the voltmeter should be connected nearest to the load, the ammeter nearest to the supply, and the wattmeter between the two with its potential coil on the load side of the current coil.

(c) Large transformers are not suitable for use as instrument transformers, since they introduce a large tare as potential transformers, and large ratio and phase errors as current transformers.

(d) Resistance multipliers may be used in series with the potential coil of instruments instead of potential transformers if desired, provided suitable precautions are taken to make their use safe. When such multipliers are used they shall be calibrated with the instruments.

(e) Low power-factor wattmeters shall be used to obtain accurate results.

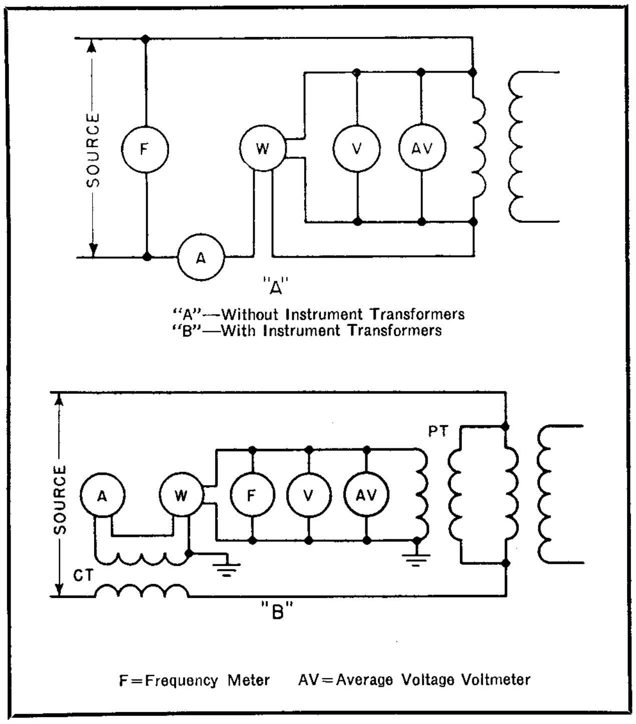


FIG. 47. (22.061) Connections for Excitation Test of a Single-Phase Transformer

(f) Either the high- or the low-voltage winding of the transformer under test may be used, but it is generally more convenient to make this test on the low-voltage winding. In any case, the full winding (not merely a portion of the winding) should be used if possible. If for some unusual reason only a portion of a winding is excited, this portion shall be not less than 25 percent of the winding.

(g) Adjust the frequency to the desired value as indicated by the frequency meter, and the voltage to the desired value by the average-voltage voltmeter. Record the simultaneous values of frequency, rms voltage, watts, average-voltage voltmeter readings, and amperes. Then disconnect the transformer under test and read the tare on the wattmeter which represents the losses of the connected instruments (and potential transformer if used), and which is to be subtracted from the earlier wattmeter reading to obtain the excitation loss of the transformer under test.

**Note: The temperature error of an average-reading voltmeter utilizing a rectifier (especially instruments for less than 75 volts) is likely to be greater than that of rms voltmeters; therefore, the temperature characteristic of such an instrument should be ascertained for dependable results.*

(h) The correct total excitation loss of the transformer shall be determined from the measured value by means of the following equation:

$$P = \frac{P_m}{P_1 + kP_2} \qquad \text{(Equation 22.061a)}$$

P = Total sine-wave excitation loss at rated voltage

P_m = measured excitation loss using average-voltage voltmeter

P_1 = per unit hysteresis loss, referred to P_m

P_2 = per unit eddy current loss, referred to P_m

$$k = \left(\frac{E_m}{E}\right)^2 \qquad \text{(Equation 22.061b)}$$

E_m = test voltage (rms) measured during excitation loss test.

E = rated voltage (rms)

The actual percentage values of hysteresis and eddy-current losses should be used; but in the absence of definite knowledge as to the relative values, the former may be taken as 80 and the latter as 20—typical values for the better grades of silicon steels at customary flux densities.

The eddy-current loss in the core varies with the square of the rms value of the excitation voltage and is substantially independent of the voltage wave shape. When the test voltage is held in accordance with the average-voltage voltmeter, the actual rms value of the test voltage may not be the rated value, and the eddy-current loss in the test will be related to the correct eddy-current loss at rated voltage by Equation 22.061b.

22.062 Excitation Loss by Iron-Loss Voltmeter Method.

(a) The iron-loss voltmeter is essentially a wattmeter measuring the excitation loss in a small self-contained laminated core of silicon steel. The exciting winding of this core is in series with the stationary coil of the wattmeter. The instrument is graduated in volts and calibrated on a sine wave of voltage.

(b) The principle of the use of this instrument is based on a comparison of the losses in its reference core when excited from a circuit having a sine wave, with its losses when excited from the source of excitation for the transformer under test. If these losses are unlike for the same rms voltage, it is obvious that the wave form of the proposed test voltage deviates from a sine wave. By adjusting the value of the test voltage until the loss in the core is the same as when excited from a circuit having a sine-wave voltage of the desired value, the measurement of the excitation loss of the transformer under test is placed on a sine-wave basis.

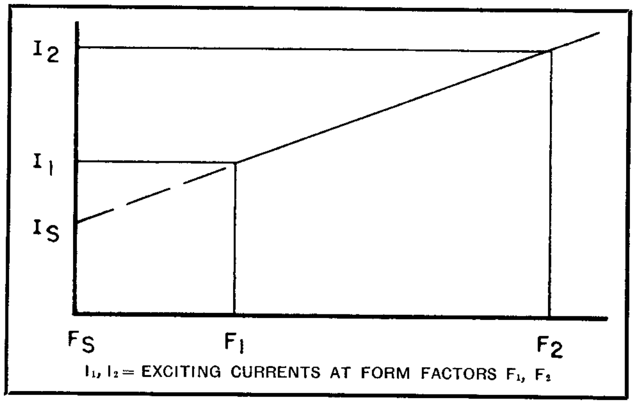


FIG. 48. (22.069) **Form-Factor Plot to Reduce Exciting Current to Sine-Wave Basis (IsFs)**

(c) The circuit is arranged as in Figures 47a or 47b, the iron-loss voltmeter replacing the average-voltage voltmeter. The voltage of the circuit is then adjusted by any convenient means until the iron-loss voltmeter indicates the desired test voltage. Then the losses of the transformer under test, like the losses of the core in the iron-loss voltmeter, correspond substantially to a sine-wave voltage of the indicated magnitude and frequency.

(d) It is necessary to verify that the core material of the iron-loss voltmeter is representative of the core materials of the transformers to be tested.

(e) If a potential transformer is used, its rating should be large enough so that the burden of the iron-loss voltmeter does not materially change its ratio or phase angle or wave shape.

22.063 Excitation Loss by Standard-Core Method. The standard core is a miniature representative sample of the transformers to be tested. Its excitation loss is accurately determined with a sine wave of applied voltage over a wide range of flux density on each of the several taps of the winding; the flux density in any transformer under test can thus be closely duplicated. The sample core is usually supplied from a potential transformer which is connected in multiple with the transformer under test; the losses of the sample and of the transformer are determined at the rated voltage of the transformer. The ratio between the loss of the sample with a sine wave of applied voltage of the same effective value (read from a curve) and the loss with the actual test voltage applied, constitutes the necessary multiplier for the measured excitation loss of the transformer under test to correct it to a sine-wave basis. This method ordinarily is not suitable for field work. It is also limited as in 22.062 (d) and (e).

22.065 Methods of Measurement of Exciting Current. Circuit connections for the measurement of exciting current are the same as those for the measurement of the excitation loss. The different methods of measurement, based on the instruments used, are as follows:

(a) Rms voltmeter and ammeter.

(b) Average-voltage voltmeter and rms ammeter.

Refer to 22.068 for necessary correction to sine-wave basis.

22.066 Measurements with Rms Instruments.

(a) Measurements of exciting current are ordinarily made with rms voltmeters and ammeters. This method of measurement is reasonably accurate only when the applied voltage is practically of sine-wave form. In cases where the voltage-wave shape departs appreciably from a sine wave as when a transformer is large in rating compared with the generator used for test, the exciting current will be lower in value than that obtained with a sine wave of applied voltage.

(b) The value so obtained shall be corrected to a sine-wave basis.

22.067 Measurements with Average-Voltage Voltmeter and Rms Ammeter.

(a) When using an average-voltage voltmeter and an rms ammeter, the measured rms value of exciting current will generally be higher than that obtained with a sine-wave of voltage, when the voltage-wave shape departs appreciably from a sine wave.

(b) When the value obtained by this method is within the guaranteed limits, no correction is required.

22.068 Corrections of Exciting Current to a Sine-Wave Basis. The measurement of the exciting current shall, when necessary, be corrected to a sine-wave basis by one of the following methods:

(a) Form-factor method.

(b) Crest-ammeter method.

(c) Average method.

22.069 Exciting Current by Form-Factor Method.

(a) This method is based on the fact that a substantially straight line relation exists between the rms value of the exciting current and the form factor of the applied-voltage wave over a wide range of form factors. It is the most accurate method of measurement when waves of sufficiently different form factor to provide effective extrapolation are available (Figure 48).

(b) The exciting current is measured with an rms ammeter at two or more applied voltages having different form factors but held at the same value with an average-voltage voltmeter such as is used for the reduction of excitation loss to a sine-wave basis. Form factors may be varied conveniently by changing the excitation of the generator field or by inserting an impedance in the test circuit. Form factors may be determined by taking simultaneous voltage readings with rms and average-voltage voltmeters; their values will be indicated by the ratio of the rms reading to the average-voltage voltmeter reading.

(c) The exciting current (I_s) corresponding to sine-wave voltage shall be determined from the foregoing data by the following formula:

$$I_s = I_2 - \frac{I_2 - I_1}{F_2 - F_1}(F_2 - 1.11) \qquad \text{(Equation 22.069)}$$

where I_1 and I_2 are the rms currents corresponding respectively to the form factors F_1 and F_2.

22.070 Exciting Current by Crest Ammeter Method.

(a) In the crest-ammeter method, use is made of an average-voltage voltmeter (the same instrument used for the reduction of excitation loss to a sine-wave basis) and a crest ammeter for reading the instantaneous maximum value of the corresponding currents. Simultaneous readings are taken on these two instruments at 100 percent, 86.6 percent, and 50 percent voltage. These data determine approximately the fundamental, third, and fifth harmonics of the exciting current.

(b) The exciting current (I_s) corresponding to sine-wave voltage shall be determined from the foregoing data by the following formula:

$$I_s = \sqrt{\frac{I_1^2}{6} + \frac{I_2^2}{3} + \frac{I_3^2}{3}} \qquad \text{(Equation 22.070a)}$$

in which I_1, I_2, and I_3 are the instantaneous maximum values of exciting current corresponding to excitation voltage of 100 percent, 86.6 percent, and 50 percent of rated voltage.

22.071 Exciting Current by Average Method. When the voltage wave shape is not too distorted the following simplified method may be used. This method is based on the fact that the value of exciting current obtained is too low when a voltmeter is used (22.066) and too high when an average-voltage voltmeter is used (22.067). The procedure is as follows:

(a) First, determine the exciting current as in 22.066;

(b) Second, determine the exciting current as in 22.067, reading also the rms voltage;

(c) If the rms reading of voltage, and the average-voltage voltmeter reading of voltage, in the test made according to 22.067 do not differ by more than 10 percent, the exciting current on a sine-wave basis shall be taken as the average of the values obtained by tests 22.066 and 22.067.

22.072 Impedance Test.

(a) The impedance voltage comprises an effective resistance component corresponding to the impedance losses, and a reactance component corresponding to the leakage-flux linkages of the windings. It is not practical to measure these components separately, but after the total impedance loss and total impedance voltage are measured, the components may be separated by calculation.

(b) The voltage required to circulate the rated current of the transformer under the short-circuit conditions specified above is the impedance voltage of the transformer as viewed from the terminals of the excited winding. Its value generally falls between 3 percent and 15 percent of the rated voltage of the excited winding, and this fact may be used as a guide in planning for the voltage supply for the impedance test.

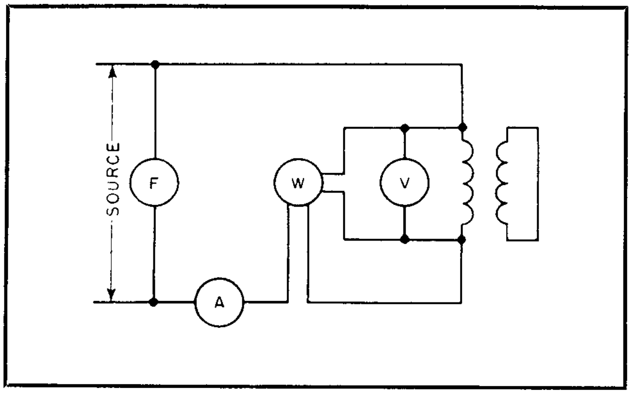


FIG. 49. (22.072) Single-Phase Transformer Connections for Impedance-Loss and Impedance-Voltage Tests. Instrument Transformers to Be Added When Necessary.

(c) One of the two windings of the transformer (either the high-voltage winding or the low-voltage winding) is short-circuited, and voltage at rated frequency is applied to the other winding and adjusted to circulate rated currents in the windings (Figure 49).

(d) With current and frequency adjusted to the rated values as nearly as possible, simultaneous readings should be taken on the ammeter, voltmeter, wattmeter, and frequency meter. The transformer under test should then be disconnected and tare readings taken on the wattmeter, representing the losses of the measuring equipment, similar to the procedure in the excitation-loss test.

(e) It is sufficient to measure and adjust the current in the excited winding only, because the current in the short-circuited winding will be the correct value (except for a negligible exciting-current error) when the current in the excited winding is correct. To introduce measuring equipment in series with the short-circuited winding to measure its current may introduce a greater error into the impedance data due to the losses and voltage drop of that equipment.

(f) The temperature of the windings shall be taken immediately before and after the impedance measurements in a manner similar to that described in 22.011. The average shall be taken as the true temperature.

(g) Conductors used for short-circuiting low-voltage, high-current transformers should have a cross section equal to or greater than the corresponding transformer leads. They should be as short as possible and should be kept away from magnetic masses. Contacts should be clean and tight.

These precautions are of importance in avoiding extraneous impedance voltage and losses which might otherwise be introduced into the measurements.

(h) The I^2R losses of the two windings are calculated from the ohmic resistance measurements (corrected to the temperature at which the impedance test was made) and the currents which were used in the impedance measurement. These I^2R losses subtracted from the impedance watts give the stray losses of the transformer.

(i) Resistance and reactance components of the impedance voltage are determined by the use of the following formulas:

$$E_r = \frac{P_z}{I} \qquad \text{(Equation 22.072a)}$$

$$E_x = \sqrt{E_z^2 - E_r^2} \qquad \text{(Equation 22.072b)}$$

where:

E_r—resistance voltage, in-phase component
E_x—reactance voltage, quadrature component
E_z—impedance voltage
P_z—Watts measured in impedance test
I—current in amperes in excited winding

(j) Per unit values of the resistance and reactance components of the impedance voltage in (i) and of the impedance voltage are obtained by dividing E_r, E_x, and E_z by the rated voltage. Percentage values are obtained by multiplying per unit values by 100.

(k) The I^2R component of the impedance loss *increases* with the temperature, the stray-loss component *diminishes* with the temperature, and, therefore, when it is desired to convert the impedance losses from one temperature to another, as for instance when calculating efficiency which calls for 75°C losses, the two components of the impedance loss are converted separately. Thus,

$$P_r' = P_r \frac{234.5+\theta'}{234.5+\theta} \qquad \text{(Equation 22.072c)}$$

$$P_s' = P_s \frac{234.5+\theta}{234.5+\theta'} \qquad \text{(Equation 22.072d)}$$

where P_r' and P_s' are desired resistance and stray losses respectively at the specified temperature θ', and P_r and P_s are measured resistance and stray losses at temperature θ.

22.073 Impedance Test of an Auto-Transformer.

(a) An auto-transformer can be tested for impedance with its internal connections unchanged. The test can be made by short-circuiting its input (or output) terminals, and applying voltage to the other terminals, to cause its appropriate rated line current to flow, the external connections being as in Fig. 22.073.

(b) The series and common windings of the auto-transformer may be treated as separate windings, one being short-circuited, the other excited, for the impedance test. When this procedure is followed, the current held must be the rated current of the exciting winding which may or may not be the same as the line current of (a) above.

(c) With the above precaution followed, the impedance watts and volt-amperes will be the same by either method. The impedance voltage measured across the series winding will correspond to that between the high-voltage terminals of the auto-transformer, while that measured across the common winding will correspond to that between the low-voltage terminals of the auto-transformer.

22.075 Impedance Test of Three-Winding Transformers.

(a) In a three-winding transformer, which may be either single-phase or three-phase, two winding impedance measurements are made with each pair of windings (which means three different impedance measurements), following the same procedure as for two-winding transformers.

If the kva capacities of the different windings are not alike, the current held for the impedance test should correspond to the capacity of the lower rated winding of the pair of windings under test. However, all of these data when converted into percentage form should be based on the same output kva, preferably that of the primary winding.

(b) The individual equivalent impedance characteristics of the separate windings may be determined with the following expressions:

$$Z_1 = \frac{Z_{12} - Z_{23} + Z_{31}}{2} \qquad \text{(Equation 22.075a)}$$

$$Z_2 = \frac{Z_{23} - Z_{31} + Z_{12}}{2} \qquad \text{(Equation 22.075b)}$$

$$Z_3 = \frac{Z_{31} - Z_{12} + Z_{23}}{2} \qquad \text{(Equation 22.075c)}$$

Z_{12}, Z_{23}, Z_{31} = measured impedance values between pairs of windings, as indicated, all expressed on the same kva base.

These equations involve complex numbers, but they may be used for the resistance (in phase) component, or reactance (quadrature) component, of the impedance voltage, or of impedance volt-amperes.

(c) The treatment of the individual impedance losses for temperature correction, etc., is the same as for two-winding single-phase transformers.

(d) The total loss for a three-winding transformer is approximately the sum of the losses in the three windings as determined for the load conditions of the windings.

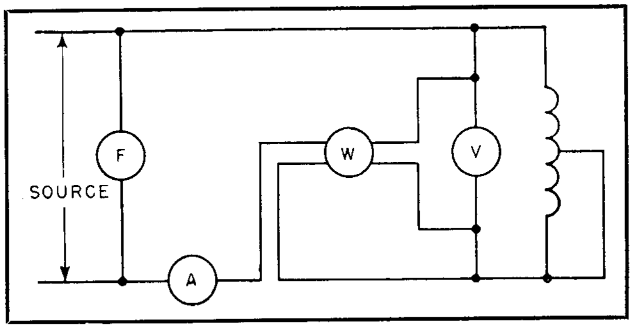


FIG. 50. (22.073) Connections for Impedance-Loss and Impedance-Voltage Tests of an Auto-Transformer

22.076 Determination of Transformer Regulation.

(a) The regulation of a transformer shall be determined by calculation based on the measured values of impedance volts and impedance watts.

(b) Exact formulas for the calculation of regulation are

(1) when the load is lagging

$$\text{reg} = \sqrt{(r+p)^2+(x+q)^2}-1 \qquad \text{(Equation 22.076a)}$$

(2) When the load is leading

$$\text{reg} = \sqrt{(r+p)^2+(x-q)^2}-1 \qquad \text{(Equation 22.076b)}$$

in which

p = power factor of load

$q = +\sqrt{1-p^2}$

r = resistance factor of transformer

x = reactance factor of transformer

The quantities p and q, x and r are on a per-unit basis so that the result must be multiplied by 100 to get the regulation in per cent.

(c) Approximate formulas generally used for the calculation of regulation are:

(1) When the load is lagging

$$\text{reg} = pr+qx+\frac{(px-qr)^2}{2} \qquad \text{(Equation 22.076c)}$$

(2) When the load is leading

$$\text{reg} = pr-qx+\frac{(px+qr)^2}{2} \qquad \text{(Equation 22.076d)}$$

The terms are on a per-unit basis, as in (b), and the result is to be multiplied by 100 to express the regulation in per cent. This approximation gives results very close to the exact method.

(d) A general expression for the calculation of transformer regulation which permits calculations to any degree of precision justified by the supporting data is,

$$\text{reg} = a-\tfrac{1}{2}a^2+\tfrac{1}{2}a^3-\tfrac{5}{8}a^4+\tfrac{7}{8}a^5-\tfrac{21}{16}a^6+\tfrac{32}{16}a^7 \qquad \text{(Equation 22.076e)}$$

reg = regulation on a per unit basis

a = a quantity depending upon the angle and magnitude of the transformer impedance, the power factor of the load, and the number of windings in the transformer. (See 22.077 and 22.078(c))

22.077 Two-Winding Transformers.

The quantity a for use in Equation 22.076e for the calculation of the per unit regulation of a two-winding transformer is determined as follows:

$$a = z\cos(\varnothing+\theta)+\frac{z^2}{2}$$

r = resistance factor = $\dfrac{\text{impedance loss in kw}}{\text{rated kva}}$

z = impedance factor = $\dfrac{\text{impedance kva}}{\text{rated kva}}$

x = reactance factor = $+\sqrt{z^2-r^2}$

$\varnothing$ = impedance angle of transformer impedance

$\cos\varnothing = \dfrac{r}{z}$

p = power factor of load = $\cos\theta$

θ = phase angle of load current
(positive for leading current,
negative for lagging current)

22.078 Three-Winding Transformers.

(a) Unless some simplifying assumptions are made, it is extremely difficult to calculate the regulation of a three-winding transformer. The following assumptions are made:

(1) The current in the secondary winding not being considered shall be assumed as remaining constant even though its voltage actually does change.

(2) The phase angle of the currents in both secondaries shall be taken as given in reference to the voltage of the secondary winding being considered.

(b) In the calculation of the regulation of a three-winding transformer it is customary to utilize the equivalent impedance of each individual winding. See 22.075(b). The regulation is calculated from the primary winding to each of the secondary windings separately.

(c) The quantity a for use in Equation 22.076e for the calculation of the per unit regulation of a three-winding transformer is determined as follows:

(1) For the per unit regulation from primary to secondary

$$\begin{aligned} a_{12} = z_{12}\cos(\varnothing_{12}+\theta_s)+\frac{z_{12}^2}{2} \\ +m_t\cos(\varnothing_m+\theta_t)+\frac{m_t^2}{2} \\ +z_{12}m_t\cos(\varnothing_{12}+\theta_s-\varnothing_m-\theta_t) \end{aligned} \qquad \text{(Equation 22.078a)}$$

(2) for the per unit regulation from primary to tertiary

$$\begin{aligned} a_{13} = z_{13}\cos(\varnothing_{13}+\theta_t)+\frac{z_{13}^2}{2} \\ +m_s\cos(\varnothing_m+\theta_s)+\frac{m_s^2}{2} \\ +z_{13}m_s\cos(\varnothing_{13}+\theta_t-\varnothing_m-\theta_s) \end{aligned} \qquad \text{(Equation 22.078b)}$$

(d) The quantities used in the determination of a_{12} in Equation 22.078a are:

z_{12} = per unit impedance factor, primary to secondary winding, on basis of secondary load.

$\varnothing_{12}$ = impedance angle of primary to secondary impedance, z_{12}.

θ_s = phase angle of secondary load current (positive for leading current, negative for lagging current)

m_t = per unit mutual impedance factor, tertiary to secondary winding, on basis of tertiary load current.

$\varnothing_m$ = impedance angle of mutual impedance, tertiary to secondary, m_t.

θ_t = phase angle of tertiary load current (positive for leading current, negative for lagging current)

(e) The quantities used in the determination of a_{13} in Equation 22.078b are:

z_{13} = per unit impedance factor, primary to tertiary winding, on basis of tertiary load

$\varnothing_{13}$ = Impedance angle of primary to tertiary impedance, z_{13}.

θ_t = phase angle of tertiary load current (positive for leading current, negative for lagging current)

m_s = per unit mutual impedance factor, secondary to tertiary winding, on basis of secondary load current

$\varnothing_m$ = Impedance angle of mutual impedance tertiary to secondary, m_t

θ_s = phase angle of secondary load current (positive for leading current, negative for lagging current)

(f) The mutual impedance between the secondary and tertiary winding is the same in magnitude and phase angle as the individual equivalent impedance of the primary winding as determined by use of Equation 22.075a.

(g) Example

(1) Assume a three-winding transformer

	Secondary	Tertiary
Kva	12,500	6,000
Pf	0.8 lag	0 lead
Phase angle (θ)	—36.87	+90

Per unit impedance factors at 10,000 kva

$z_{12} = 0.02 + j\,0.08 = 0.0825 \quad \varnothing_{12} = 75.96$

$z_{23} = 0.015 + j\,0.05 = 0.0522 \quad \varnothing_{23} = 73.30$

$z_{31} = 0.03 + j\,0.15 = 0.1530 \quad \varnothing_{31} = 78.69$

From the foregoing

$z_1 = m_{23} = 0.0175 + j\,0.09 = 0.0917$

$\varnothing_1 = 79.00$

When substituted into the equations the impedance factors must be translated to the proper base as indicated in (c), (d), and (e) respectively.

(2) for primary to tertiary

$$\begin{aligned} a_{12} &= 0.1031 \cos(75.96 - 36.87) + \frac{0.1031^2}{2} \\ &\quad + 0.05502 \cos(79.00 + 90) + \frac{0.05502^2}{2} \\ &\quad + (0.1031)(0.05502) \cos(75.96 - 36.87 - 79.00 - 90) \\ &= 0.08531 - 0.05249 - 0.00364 \\ &= 0.02918 \end{aligned}$$

$$\begin{aligned} \text{reg} &= 0.02918 - \frac{0.02918^2}{2} \\ &= 0.02875 \\ \text{reg} &= 2.875\% \end{aligned}$$

(3) For primary to tertiary

$$\begin{aligned} a_{13} &= 0.0918 \cos(78.69 + 90) + \frac{0.0918^2}{2} \\ &\quad + 0.1146 \cos(79.00 - 36.87) + \frac{0.1146^2}{2} \\ &\quad + (0.0918)(0.1146) \cos(78.69 + 90 - 79.00 + 36.87) \\ &= -0.0858 + 0.09152 - 0.00626 \\ &= 0.00054 \end{aligned}$$

$$\begin{aligned} \text{reg} &= 0.00054 \\ \text{reg} &= 0.054\% \end{aligned}$$

22.079 Three-phase to Two-phase Transformers. For the calculation of the regulation for three-phase to two-phase transformers, proceed as follows:

(a) For the per unit regulation of main phase, use the impedance of the main transformer for substitution in the formula selected for use.

(b) For the per unit regulation of the teaser phase, use the sum of the impedance of the teaser transformer plus the interlacing impedance of the main transformer for substitution in the formula selected for use.

(c) To determine the interlacing impedance, connect the two ends of the primary winding of the main transformers together and impress between this common connection and the 50% tap a voltage sufficient to pass three-phase line current in the supply lines. The voltage thus determined is the interlacing impedance voltage and is to be put on a per unit basis by reference to the primary voltage of the teaser transformer on the teaser connection.

22.080 Efficiency.

(a) The efficiency of a transformer is the ratio of its useful power output to its total power input. That is,

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{input—losses}}{\text{input}}$$

$$= 1 - \frac{\text{losses}}{\text{input}} = 1 - \frac{\text{losses}}{\text{output} + \text{losses}}$$

(Equation 22.080)

(b) Efficiency shall be calculated on the basis of the excitation losses and the impedance losses at 75°C. Rated voltage, frequency, and unity power-factor full load are assumed, unless otherwise specified.

TEMPERATURE TESTS

22.100 Methods of Loading for Temperature Tests.

(a) Whenever practicable, transformers should be tested under conditions that will give losses approximating, as nearly as possible, those obtained under the specified load conditions.

(b) Various methods are available for this test and experience has shown that the short-circuit method gives the same result as the other methods, and is preferable because the tests can be carried out more conveniently.

(c) Transformers of small output may be tested under actual load conditions by loading them on a rheostat, bank of lamps, water box, etc. This method is expensive in energy requirements for large transformers.

(d) Duplicate single-phase transformers may be tested in banks of two by connecting both the high-voltage and low-voltage windings in parallel and by applying rated excitation voltage at rated frequency to one set of parallel windings. In order to circulate load current, the connections of the other pair of windings should be opened at one point and a voltage impressed across the break just sufficient to circulate rated currents through the windings. The circulated current should preferably (but not necessarily) be at rated frequency (Figure 51.) If at other than normal frequency, the value of the current should be adjusted to yield the true impedance watts of the transformer.

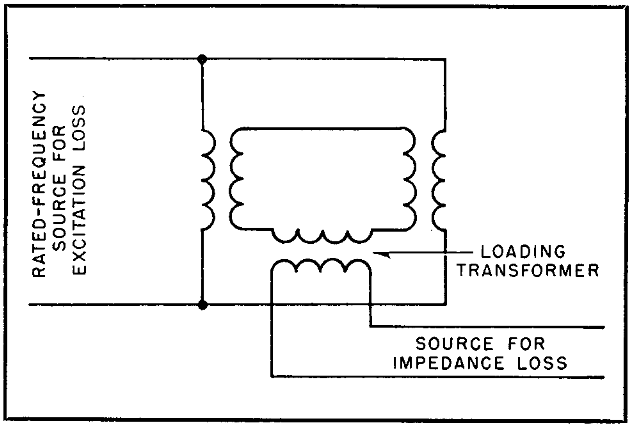


FIG. 51. (22.100a) **Two Single-Phase Transformers in Opposition**

(i) (1) The loading for temperature test of a single unit can be conducted (unless otherwise specified) by first determining the equivalent top-oil rise of the unit above the ambient corresponding to its total losses, and then the winding rise above the top oil corresponding to its normal impedance loss, with one winding (or set of windings in three-phase) short-circuited.

(2) With normal conditions of the means or method of cooling, short-circuit the high-voltage or the low-voltage winding (or windings) and circulate sufficient current at normal frequency through the other winding (or windings) so that the losses in the windings under this condition will equal the *sum* of the excitation loss and the impedance loss at rated voltage, frequency, and ultimate temperature. Run until conditions become constant, and note the top-oil rise over ambient.

(3) Reduce the currents in the windings to their normal rated values and hold them constant until the temperature rise of the windings above the top-oil temperature has become constant. This may require from one to two hours. Then shut down and measure the temperature of the windings by resistance, and calculate their rise over the top-oil temperature. Correct the measured winding temperatures back to the instant of shut-down by methods described later.

If it is necessary to use currents that are not rated values and make correction in winding temperature rise above oil temperature rise, the correction should be based upon the average winding temperature rise and the average oil temperature rise.

An approximate method of determining the average oil temperature rise is as follows:

Average oil temperature rise is equal to the top-oil temperature rise of the transformer minus one-half the temperature drop of the oil flowing through the external cooling means, as determined by measurement at the top and bottom surfaces of the external cooling means.

(4) The winding temperature rise at full load, in the method under consideration, is the *sum* of the top-oil temperature rise over the ambient and the winding temperature rise over top oil.

22.101. Temperature Tests.

(a) All Transformers.

(1) Transformers shall be completely assembled and if oil-immersed they shall be filled to the proper level.

(2) If the transformers are equipped with thermal indicators, bushing-type current transformers, etc., such apparatus shall be assembled with the transformer.

(3) The temperature test shall be made in a room as free from drafts as practicable.

(4) The temperature of the surrounding air shall be determined by several thermometers placed at different points around and approximately half way up the apparatus at a distance of 3 to 6 feet (1 to 2 meters) and protected from drafts and abnormal heating. All reasonable precautions should be taken to avoid errors due to time lag between the temperature of the apparatus and the variations in the cooling-air temperature. For example, mercury thermometers immersed approximately two inches in a suitable heavy metal cup containing oil may be used.

(5) Provision should be made to measure the top-oil temperature of oil-immersed transformers by a thermocouple or alcohol thermometer immersed approximately two inches below the top-oil surface.

(6) Provision should be made also to measure the surface temperature of iron or alloy parts surrounding or adjacent to the outlet leads or terminals carrying large currents. Readings should be taken at intervals or immediately after shutdown.

(7) The bulbs of thermometers used for taking temperatures of apparatus other than oil-immersed shall be covered by felt pads cemented to the apparatus, except that when pads may interfere with ventilation, as in ventilation ducts between coils, grooved wooden sticks may be used. Dimensions of felt pads for use with large apparatus shall be 1½ in. by 2 in. by ⅛ in. (4 cm by 5 cm by 3 mm).

(8) The temperature rise of the windings shall be determined by the resistance method, and also by thermometer when so specified.

(9) It is permissible to shorten the time required for the test by the use of initial overloads, restricted cooling, or any other suitable method.

(b) Self-Cooled and Forced-Air-Cooled Transformers.

(1) The ambient temperature shall be taken as that of the surrounding air which should be not less than 10°C nor more than 40°C.

(2) No corrections for variations of ambient temperature within this range shall be applied.

(3) Temperature tests may be made with ambient temperatures outside the range specified if suitable and agreed upon correction factors are available.

22.102 Hot Resistance.

(a) All readings shall be completed within four minutes after shut-down. If this cannot be accomplished, the temperature test shall be resumed until normal temperatures are again obtained after which the remainder of the readings should be taken.

(b) Record the elapsed time between the instant of shutdown and each resistance measurement.

(c) When transferring the measuring leads from one winding to another, maintain the same relative polarity with regard to the measuring leads and the transformer terminals.

(d) The relation between the average temperature of a copper winding and its resistance is given by the following equation:

$$\theta_1 = \frac{R}{R_0}(234.5 + \theta_0) - 234.5 \quad \text{(Equation 22.102)}$$

where

θ_1 = temperature in degrees C corresponding to hot resistance R_1

θ_0 = temperature in degrees C corresponding to cold resistance R_0

22.103 Correction of Observed Temperature Rise to Time of Shutdown.

(a) The observed temperature rise at a measured time from shutdown shall be corrected back to the actual time of shutdown.

(b) This correction may be determined approximately by making a series of resistance measurements and from these calculating and plotting a time-temperature curve which is extrapolated back to the instant of shutdown.

(c) When the copper loss of oil-immersed apparatus, as determined by wattmeter measurement, does not exceed 30 watts per pound, the correction in degrees Centigrade may be taken as the product of the watts loss per pound of copper for each winding multiplied by a factor that depends upon the time elapsed between the instant of shutdown and the time the resistance measurement is taken, as given in the following table:

Time in Minutes	Factor
1	0.19
1.5	0.26
2	0.32
3	0.43
4	0.50

For intermediate times the values of the factor may be obtained by interpolation.

The factors in the preceding table represent average results from usual commercial designs. It should be recognized that for some transformers, particularly those designs which deviate considerably from usual commercial proportions, these factors may not give sufficiently close results. In such cases a cooling curve should be taken.

(d) When the copper loss for oil-immersed apparatus, measured by wattmeter, does not exceed seven watts per pound, an arbitrary correction of 1°C per minute may be used, provided the time elapsed between the instant of shutdown and the measurement of the hot resistance does not exceed four minutes.

(e) An arbitrary correction of 1°C per minute may be used for air-blast transformers provided the time elapsed between the instant of shutdown and the measurement of the hot resistance does not exceed four minutes.

(f) For determining the copper loss in watts per pound, the total loss in both windings as measured by wattmeter may be apportioned between high and low-voltage windings, in the ratio of their respective calculated I^2R losses, if the conductor I^2R and eddy losses cannot be determined conveniently.

22.104 Correction of Observed Temperature Rise for Variation in Altitude.

(a) When tests are made at an altitude not exceeding 3300 feet (1000 meters) above sea level, no altitude correction shall be applied to the temperature rise.

(b) For standard air-cooled apparatus tested at an altitude in excess of 3300 feet (1000 meters) above sea level, it shall be assumed that their temperature rise at any altitude less than 3300 feet (1000 meters) will be the temperature rise observed at the higher altitude reduced by the following amounts for each 330 feet (100 meters) that the altitude exceeds 3300 feet (1000 meters):

For oil-immersed, self-cooled apparatus	0.4 per cent
For dry-type apparatus	0.5 per cent
For oil-immersed, forced-air-cooled apparatus	0.6 per cent
For air-blast apparatus	1.0 per cent

22.105 Winding Temperature Under Short-Circuit Condition. The temperature of the copper* due to the short-circuit currents may be computed with the following formula which is based on the assumption that all the heat due to the current is stored in the copper:

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*Note: Equation 22.105a is not rigorously correct but for temperatures up to 350°C gives results accurate enough for practical purposes. Accurate results under any or all assumed conditions will be obtained by the following formula:

$$\theta = 309.5\sqrt{\left[\left(\frac{\theta_\circ + 234.5}{309.5}\right)^2 + K\right] \text{Log}\ _{10}^{-1}\ (Ft) - K} - 234.5 \qquad \text{(Equation 22.105b)}$$

where

θ = final temperature degrees centigrade
$\theta_\circ$ = initial temperature degrees centigrade
K = ratio of eddy current loss to the I^2R loss at 75°C
t = time in seconds
F = as follows:

$$F = \begin{cases} F = 4.0 \times 10^{-11} S^2 \ldots\ldots \text{where } S = \text{amperes per square inch of conductor} \\ \text{or } F = 1.56 \times 10^{-5} P \ldots\ldots \text{where } P = \text{watts per pound } (I^2R \text{ at } 75^\circ\text{C}) \\ \text{or } F = 65\ \text{M}^{-2} \ldots\ldots \text{where } M = \text{circular mils per ampere} \end{cases}$$

$$\theta = Ft\left(\frac{f}{2\theta_1} + \frac{618.4K}{f}\right) + \theta_0$$

(Equation 22.105a)

where

θ = final temperature, degrees C

θ_0 = initial temperature, degrees C

$\theta_1 = (\theta_0 + 234.5)$

t = time in seconds

K = ratio of eddy current loss to the I^2R loss at 75°C

$F = \frac{\text{watts per pound (at } \theta_0\text{)}}{180}$ or

$F = 4.6\ S^2\theta_1 \times 10^{-11}$ or

$F = \frac{75\,\theta_1}{M^2}$

$f = 2\theta_1 + F\,t$

M = circular mils per ampere

S = amperes per square inch of conductor

DIELECTRIC TESTS

22.110 Test Procedure.

(a) Unless otherwise specified, dielectric tests shall be made in accordance with American Standard Measurement of Test Voltage in Dielectric Tests, C68.1-1942, or its latest revision.

(b) Exception: the protective resistances used with the spheres may all be mounted in series with the grounded sphere.

22.111 Factory Dielectric Tests.

(a) The purpose of dielectric tests in the factory is to check the insulation and workmanship and, when required, to demonstrate that the transformer has been designed to withstand the insulation tests required by the purchase specifications.

(b) The impulse test, when required, shall precede the low-frequency tests.

22.112 Low-Frequency Dielectric Tests.

(a) Dielectric tests should preferably be made at the temperature assumed under normal operation or at the temperature attained under the conditions of commercial test.

(b) If the oil in the transformer has to be replaced for any reason, the transformer should be allowed to stand until bubbling ceases, or one hour for each 50 kv of the test voltage, but not longer than four hours. This action may be accelerated by applying approximately 50 per cent of the test voltage until bubbling ceases.

22.113 Applied Potential Tests.

(a) The terminal ends and taps brought out of the case of the winding under test should all be joined together and to the line terminal of the testing transformer. All other terminals and parts (including core and tank) should be connected to ground and to the other terminal of the testing transformer. Small bare wire may be used in connecting the respective taps and line terminal together, but care must be taken to keep the wire on the high-voltage side well away from the ground. The high-voltage lead from the testing transformer should preferably be at least 1/8 inch in over-all diameter. The ground connections between the apparatus being tested and the testing transformer must be a substantial metallic circuit. All connections must make a good mechanical joint without forming sharp corners or points.

(b) No appreciable resistance should be placed between the testing transformer and the one under test. It is permissible, however, to use reactive coils at or near the terminals of the testing transformer.

(c) A relief gap set at a voltage 10 per cent or more in excess of the specified test voltage shall be connected during the applied-potential test.

(d) For transformers of 100 kva and less to be tested at 50 kv or less, it is permissible to depend on the ratio of the testing transformer to indicate the proper test voltage.

(e) For transformers of 100 kva and less to be tested at 15 kv or less, it is permissible also to omit the spark gap.

(f) If the neutral bushing specified is not capable of withstanding the applied-potential test, the neutral bushing shall be disconnected from the winding for the test, or special insulation shall be provided for test purposes.

22.114 Induced-Potential Tests.

(a) As this test over-excites the transformer, the frequency of the applied potential should be high enough to prevent the exciting current of the transformer under test from exceeding about 30 per cent of its rated-load current. Ordinarily this requirement necessitates the use of a frequency of 120 cycles per second or more, when testing 60-cycle units. When frequencies higher than 120 cycles per second are used, the severity of the test is abnormally increased and for this reason the duration of the test should be reduced in accordance with the following table.

Frequency in Cycles	Duration in Seconds
120 and less	60
180	40
240	30
360	20
400	18

(b) The voltage should be started at one-quarter or less of the full value and be brought up gradually to full value in not more than 15 seconds. After being held for the duration of time specified in the preceding paragraph, it should be reduced slowly (in not more than 5 seconds) to one-quarter of the maximum value or less, and the circuit opened.

(c) When transformers have one winding grounded for operation on a grounded-neutral system, special care should be taken to avoid high electrostatic stresses between the other windings and ground.

(d) In the case of single-phase transformers having one end of the high-voltage winding solidly grounded, the low-voltage winding should be grounded during the induced-potential test. If the maximum test voltage across the low-voltage winding exceeds 10,000 volts, this ground must be made at the middle of the winding itself or at the middle of the winding of a step-up transformer which is used to supply the voltage or which is merely connected for the purpose of furnishing the ground. If the maximum test voltage across the winding does not exceed 10,000 volts, the ground may be made on the terminal having the same polarity as the grounded terminal of the high-voltage winding.

(f) If there is a third winding on the transformer, it also should be grounded in accordance with the foregoing.

22.115 Wave to Be Used for Impulse Tests.

(a) A nominal 1.5 x 40 microsecond wave shall be used for impulse tests. Either, but not both, positive or negative waves may be used. Waves of negative polarity for oil-immersed apparatus and of positive polarity for dry-type or compound-filled apparatus are recommended and shall be used unless otherwise specified. If in testing oil-immersed apparatus the atmosphere conditions at the time of test are such that the bushings will not withstand the specified polarity wave, then a wave of the opposite polarity may be used.

(b) The time on the front from the virtual time zero to actual crest shall not exceed 2.5 microseconds for crest voltages up to and including 650 kv, and shall not exceed 3.0 microseconds for crest voltages above 650 kv.

(c) The time on the tail to the point of half-crest voltage of the applied wave shall be not less than 40 microseconds from the virtual time zero.

(d) The virtual time zero can be determined by locating points on the front of the wave at which the voltage is, respectively, 30 and 90 per cent of the crest value and then drawing a straight line through these points. The intersection of this line with the time axis (zero-voltage line) is the virtual time zero.

(e) For convenience in measurement, the time to crest may be considered as 2.0 times the actual time between points on the front of the wave at 30 percent and 90 percent of the crest value.

(f) If there are oscillations on the front of the wave, the 30 and 90 percent points should be determined from the average smooth wave front sketched in over the oscillations. The magnitude of the oscillations preferably should not exceed 10 percent of the applied voltage.

(With superimposed oscillations of high magnitude, evaluation of wave crest is difficult, while if generator characteristics are such as to give a completely smooth wave it may be difficult to detect failures of small portions of the winding insulation by means of the cathode-ray oscillograph. If the impulse generator is sufficiently flexible, a good compromise is the use of generator constants such that the transformer impedance largely determines the length of the tail of the applied wave.)

(g) All impulses applied to a transformer shall be recorded by a cathode-ray oscillograph if their crest voltage exceeds 40 percent of the crest of the full wave in accordance with 11.030* and Table 11.030*. When reports require oscillograms, those of the first reduced full wave, the last two chopped waves, and the last full wave of voltage shall represent a record of the successful application of the impulse test to the transformer. See 22.116 (c), (d), and (e).

22.116 Standard Impulse Tests

(a) The standard impulse test consists of applying in the following order, one reduced full wave, two chopped waves, and one full wave. (Exception 22.118.)

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* ASA Standard C57.11

(b) During the impulse tests, the transformer may be excited at normal voltage, or the excitation may be omitted by mutual agreement between manufacturer and purchaser.

If the transformer is excited, the impulse shall be timed within 30 electrical degrees of the crest of the normal voltage of opposite polarity. Best results in failure detection by this means will be secured when the power source and associated step-up transformer are of the largest practicable kva capacity.

(c) Reduced Full Wave. For this test, the applied voltage wave shall have a crest value between 50 and 70 percent of the full wave in accordance with 11.030* and Table 11.030*. Crest voltages near the lower limit are preferable. Normal frequency excitation may be omitted for this test.

(d) Chopped Wave. For this test, the applied-voltage wave shall be chopped by a suitable air gap. It shall have a crest voltage and time to flashover in accordance with 11.030 and Table 11.030.

(e) Full Wave. For this test, the voltage wave shall have a crest value in accordance with 11.030 and Table 11.030, and no flashover of the bushing or test gap shall occur.

(To avoid flashover of the bushing during adverse conditions of humidity and air density, the bushing flashover may be increased by appropriate means. To avoid recovery of insulation strength if failure has occurred during a previous impulse, the time interval between application of the last chopped wave and the final full wave should be minimized, and preferably should not exceed five minutes.)

22.117 Connections for Impulse Tests

(a) General. The tests shall be applied to each terminal one at a time. (For exception see 22.117, 22.118, 22.119, and 22.120.)

(b) Terminals Not Being Tested. One terminal of the winding under test shall be grounded directly or through a small resistance if current measurements are to be made. One terminal of each of the other windings may be grounded. It is desirable that the voltage on ungrounded terminals should not exceed 80 percent of the full-wave voltage for their voltage class. (A suitable range is 40 to 70 percent.)

(1) In some cases the inductance of the winding is so low that the desired voltage magnitude and the duration to the 50-percent point on the tail of the wave cannot be obtained with available test equipment. Where possible, the terminals of such windings may be tied together for the test. Low-inductance windings may also be tested by inserting a resistor of not more than 500 ohms in the grounded end of the winding.

(2) Because of a difference in insulation class at the two ends of the winding, it is sometimes impossible to tie the terminals together for the impulse test. In such cases, shorter waves may be used, but preferably not shorter than 15 microseconds to the 50-percent point on the tail of the wave.

(3) Without Normal-Frequency Excitation. All ungrounded terminals shall be protected by limiting the voltage.

Such protection may be provided by gaps set to limit the voltage to approximately 80 percent of the full-wave level for the voltage class or by grounding through a linear resistor.

(c) All grounds shall be direct, except as described in (b) above, and at neutral terminals which may be grounded through the same neutral grounding impedance as is to be used in service. If this impedance is unavailable, the neutral shall be directly grounded.

(d) Windings for series or multiple connection shall be tested on both series and multiple connections and the windings not being tested shall be connected for the highest rated voltage during tests on other windings. When the impulse test is made on the multiple connection, the test voltage will be that corresponding to the insulation class of the multiple-voltage rating.

(e) Tap connections (both transformers and autotransformers) shall be made with minimum turns in circuit in the winding under test and maximum turns in circuit in the other windings.

(f) When protective devices are permanently connected as an integral part of series transformer windings, or of other portions of windings, these devices shall be connected during the test. Where the nature of the protective device and the design of the transformer permit, the impedance of such device may be varied for the full wave and reduced full-wave tests as an optional refinement in the technique of failure detection (22.121).

(g) Windings of Very Low Impedance.

(1) In some cases the inductance of the winding is so low that the desired voltage magnitude and the duration to the 50-percent point on the tail of the wave cannot be obtained with available

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* ASA Standard C57.11

test equipment. Where possible, the terminals of such windings may be tied together for the test. Low-inductance windings may also be tested by inserting a resistor of not more than 500 ohms in the grounded end of the winding.

(2) Because of a difference in insulation class at the two ends of the winding, it is sometimes impossible to tie the terminals together for the impulse test. In such cases, shorter waves may be used, but preferable not shorter than 15 microseconds to the 50-percent point on the tail of the wave.

(h) The secondaries of current transformers, either in transformer bushings or permanently connected to the equipment being tested, shall be short-circuited and grounded.

(i) The core and tank shall be grounded for all impulse tests.

22.118 Impulse Tests on Transformer Neutrals.

(a) Impulse tests on the neutral of a transformer intended for grounded neutral service only may be applied by the methods given below. Use whichever method is most convenient.

(b) The test on the neutral shall precede the test on the line terminals.

(c) Low-frequency excitation is not required for the test on the neutral.

(d) Methods of Test.

(1) The test voltage on the neutral is induced by the application of an impulse to the line terminal with the neutral grounded through a suitable impedance so that the required full-wave test voltage is obtained from the neutral terminal to ground. Three 1.5 x 40 microsecond waves (or longer) shall be applied to the line end of the winding with a crest voltage equal to, or less than, the full wave level of the line end. The other windings shall be short-circuited for this test. The voltage oscillogram shall be taken at the neutral.

(2) The test voltage is applied directly to the neutral.

(3) The test voltage on the neutral is induced by the application of an impulse in another winding.

22.121 Detection of Failure during Impulse Test. Because of the nature of impulse test failures, one of the most important matters is the detection of failure. There are a number of indications of insulation failure. Some of these are:

(a) Noise within the transformer; presence of smoke or bubbles; excessive current or drop in voltage in the normal-frequency excitation circuit; failure of the gap or bushing to flashover although the oscillogram indicates a chopped wave;

(b) Any difference between the reduced full wave and the final full wave detected by superimposing the two oscillograms or any difference between the two chopped waves from each other or from the full wave up to the time of flashover similarly detected. Such deviations may, however, be caused by conditions in the impulse test-circuit external to the transformer or by the operation of protective devices (22.117(b)2) and should be fully investigated;

(c) Measurement of the current in the grounded end of the winding tested. The current is measured by means of a cathode-ray oscillograph connected to a suitable shunt inserted between the normally grounded end of the winding and the grounded tank. Any deviation of current-wave shapes obtained during the reduced full wave and full-wave tests indicates changes in impedance arising from insulation breakdown within the transformer, or changes in the impulse circuit external to the transformer, and the cause should be investigated. In some cases, it may be possible and desirable to include the current to other grounded windings and the tank in such a measurement. When this method of failure detection is employed, it is desirable to omit normal-frequency excitation because of the wave-shape variations which arise from the action of protective devices and separating gaps.

22.130 Insulation Resistance.

(a) The insulation resistance of machinery is of doubtful significance as compared with the dielectric strength. It is subject to wide variation with temperature, humidity, and cleanliness of the parts. When the insulation resistance falls below prescribed values it can, in most cases of good design and where no defect exists, be brought up to the required standard by cleaning and drying the machine. The insulation resistance, therefore, may afford a useful indication as to whether the machine is in suitable condition for application of the dielectric test.

(b) The insulation-resistance test shall be made with all circuits of equal voltage above ground connected together. Circuits or groups of circuits of different voltage above ground shall be tested separately.

22.140 Periodic Dielectric Tests in the Field.

(a) It is recognized that dielectric tests impose a severe stress on the insulation, and if applied frequently will hasten breakdown or may cause breakdown, the stress imposed, of course, being the more severe the higher the value of the applied voltage. Hence, practice in this matter has varied widely among operating companies, and the advisability of periodic testing may be questionable.

(b) It is recommended that field tests of insulation should not be in excess of 75 per cent of the factory test voltage; that for old apparatus rebuilt in the field, tests should not be in excess of 75 per cent of the factory test voltage; and that periodic insulation tests in the field should not be in excess of 65 per cent of the factory test voltage. These recommendations relate to dielectric tests applied between windings and ground and to induced-voltage tests.

(c) Under some conditions transformers may be subjected to periodic insulation tests using direct voltage from kenotron sets. In such cases, the test direct voltage should not exceed the original factory test rms alternating voltage; e.g., if the factory test was 26 kv rms, then the routine test direct voltage should not exceed 26 kv.

(d) Periodic kenotron tests should not be applied to transformers of higher than 34.5 kv voltage rating.

BUSHINGS

22.150 Tests on Bushings. When tests are required on bushings separately from the transformers, the tests shall be made in accordance with American Standard Apparatus Bushings and Test Code Apparatus Bushings, C76.1—1943 or the latest revision thereof approved by the American Standards Association.

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