DIVISION 5

TRANSFORMERS

CONSTRUCTION, TYPES, AND CHARACTERISTICS

1. A transformer is an apparatus for converting electrical power in an ac system at one voltage or current into electrical power at some other voltage or current without the use of rotating parts.

2. A constant-voltage transformer (Fig. 5.1) consists essentially of three parts: the primary coil which carries the alternating current from the supply lines, the core of magnetic material in which is produced an alternating magnetic flux, and the secondary coil in which is generated an emf by the change of magnetism in the core which it surrounds. Sometimes the transformer may have only one winding, which will serve the dual purpose of primary and secondary coils.

The high-tension winding is composed of many turns of relatively fine copper wire, well insulated to withstand the voltage impressed on it. The low-tension winding is composed of relatively few turns of heavy copper wire capable of carrying considerable current at a low voltage.

3. Transformer terminology. The *primary winding* is the winding of the transformer which is connected to the source of power. It may be either the high- or the low-voltage winding, depending upon the application of the transformer.

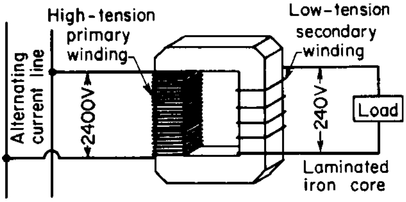


FIGURE 5.1 The elementary transformer.

The *secondary winding* is the winding of the transformer which delivers power to the load. It may be either the high- or the low-voltage winding, depending upon the application of the transformer.

The *core* is the magnetic circuit upon which the windings are wound.

The *high-tension winding* is the one which is rated for the higher voltage.

The *low-tension winding* is the one which is rated for the lower voltage.

A *step-up transformer* is a constant-voltage transformer so connected that the delivered voltage is greater than the supplied voltage.

A *step-down transformer* is one so connected that the delivered voltage is less than that supplied; the actual transformer may be the same in one case as in the other, the terms *step-up* and *step-down* relating merely to the application of the apparatus.

4. Transformer cores. Until recently, all transformer cores were made up of stacks of sheet-steel punchings firmly clamped together. One method of assembly and clamping of the sheets is shown in Fig. 5.2. Sometimes the laminations are coated with a thin varnish to reduce eddy-current losses. When the laminations are not coated with varnish, a sheet of insulating paper is inserted between laminations at regular intervals.

A new type of core construction consists of a continuous strip of silicon steel which is wound in a tight spiral around the insulated coils and firmly held by spot welding at the end. This type of construction reduces the cost of manufacture and reduces the power loss in the core due to eddy currents.

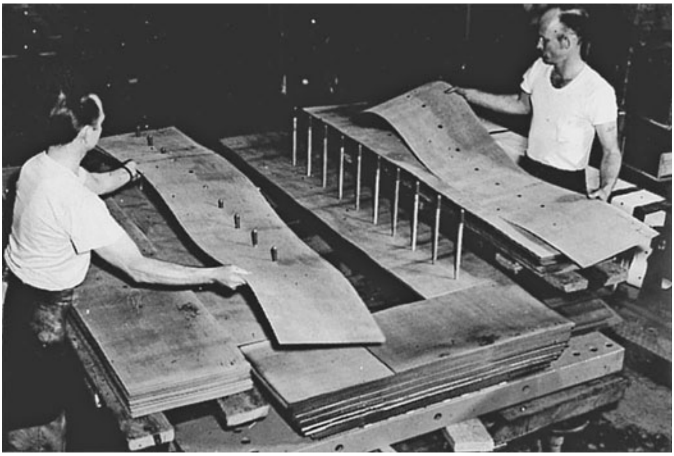


FIGURE 5.2 Assembly of transformer-core laminations.

FIGURE 5.3 Epoxycast step-down transformer assembly. [Isoreg Corp.]

FIGURE 5.4 Eypoxycast high-voltage transformer in a NEMA enclosure. [Isoreg Corp.]

5. Classification of transformers

1. According to method of cooling
   - ***a.*** Self-air–cooled (dry type)
   - ***b.*** Air-blast–cooled (dry type)
   - ***c.*** Liquid-immersed, self-cooled
   - ***d.*** Oil-immersed, combination self-cooled and air-blast
   - ***e.*** Oil-immersed, water-cooled
   - ***f.*** Oil-immersed, forced-oil–cooled
   - ***g.*** Oil-immersed, combination self-cooled and water-cooled
2. According to insulation between windings
   - ***a.*** Windings insulated from each other
   - ***b.*** Autotransformers
3. According to number of phases
   - ***a.*** Single-phase
   - ***b.*** Polyphase
4. According to method of mounting
   - ***a.*** Pole and platform
   - ***b.*** Subway
   - ***c.*** Vault
   - ***d.*** Special
5. According to purpose
   - ***a.*** Constant-voltage
   - ***b.*** Variable-voltage
   - ***c.*** Current
   - ***d.*** Constant-current
6. According to service
   - ***a.*** Large power
   - ***b.*** Distribution
   - ***c.*** Small power
   - ***d.*** Sign lighting
   - ***e.*** Control and signaling

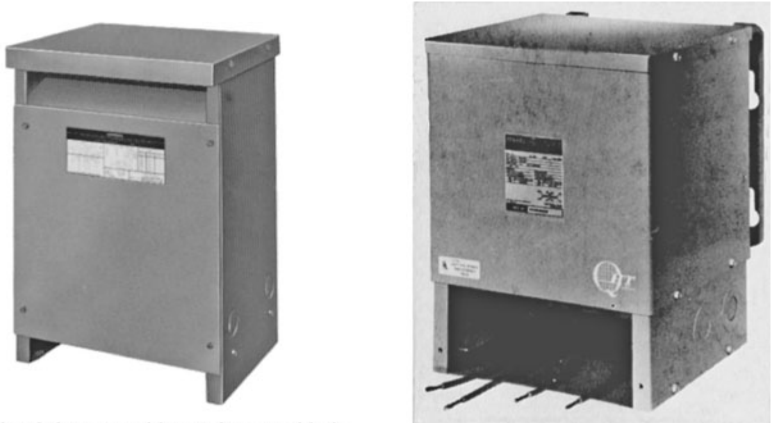
f. Gaseous-discharge lamp transformers
g. Bell ringing
h. Instrument
i. Constant-current
j. Series transformers for street lighting

6. Cooling of transformers. A certain amount of the electrical energy delivered to a transformer is transformed into heat energy because of the resistance of its windings and the hysteresis and eddy currents in the iron core. Means must be provided for removing this heat energy from the transformer and dissipating it into the surrounding air. If this were not done in a satisfactory manner, the transformer would operate at an excessively high temperature, which would destroy or harm the insulation of the transformer. The different methods of cooling employed are listed in Sec. 5 and described below.

In *self-air–cooled* transformers (Fig. 5.5), the windings are simply surrounded by air at atmospheric pressure. The heat is removed by natural convection of the surrounding air and by radiation from the different parts of the transformer structure. Air cooling has long been employed for transformers of very small capacity. The development of satisfactory coil insulation materials, such as porcelain, mica, glass, and asbestos, which will withstand higher temperatures than the more common insulating materials has made possible the application of air cooling to transformers of large capacity. Except in the smaller sizes, the sheet-metal enclosure is provided with louvers or gratings to allow free circulation of the air over and through the windings. Self-air–cooled transformers are commonly called *dry-type transformers*. The present-day use of self-air–cooled transformers has been extended to units of at least 3000-kVA capacity at 15,000 V.

In *air-blast–cooled transformers* (Figs. 5.6 and 5.7), the core and windings are enclosed in a metal enclosure through which air is circulated by means of a blower. This method has been used for large power transformers in ratings up to 15,000 kVA with voltages not exceeding 35,000.

In *liquid-immersed, self-cooled transformers,* the core and windings are immersed in some insulating liquid and enclosed in a metal tank. The liquid, in addition to providing



I. Ventilated dry-type with openings to aid circulation of air. [Siemens Energy & Automation, Inc.]

II. With solid-metal casing. [General Electric Co.]

FIGURE 5.5 Dry-type transformers.

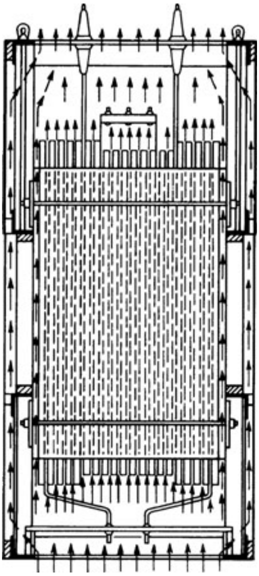


FIGURE 5.6 Longitudinal section of air-blast transformer, showing direction of air currents.

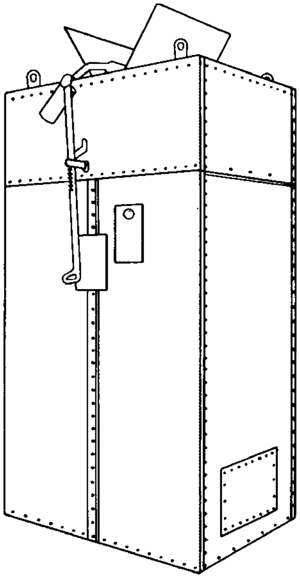


FIGURE 5.7 Exterior view of 1330-kVA air-blast transformer, showing the sheet-steel casing.

some of the required insulation between the windings, carries the heat from the core and windings to the surface of the tank. The heat is then removed into the surrounding atmosphere by natural convection of the surrounding air and by radiation from the tank. In the smaller sizes the tanks have a smooth surface (Fig. 5.8). In larger size, tanks are corrugated or finned or have external tubes (see Figs. 5.9 and 5.10), and in very large units the tanks must be supplied with external radiators (Fig. 5.11) through which the oil circulates by natural convection, owing to differences in temperature in the liquid. This method can be employed for units of any size or voltage rating, although large-capacity units become rather expensive and bulky. The common liquid employed is an insulating oil. Nonflammable and nonexplosive liquids have been developed for use as a cooling and insulating medium for electrical equipment. These liquids are used in transformers where their nonflammable and nonexplosive qualities warrant their additional expense. The use of such a liquid is particularly advantageous for transformers installed in buildings, since the transformer can then be installed in general areas without the use of a fireproof vault enclosure. Transformers insulated with such a liquid are designated as askarel-insulated transformers. Askarel has been banned by the U.S. Environmental Protection Agency and is being replaced in many instances by a listed less flammable nonpropagating liquid. See Sec. 450.23 of the National Electrical Code.

FIGURE 5.8 Small distribution transformer with smooth tank.

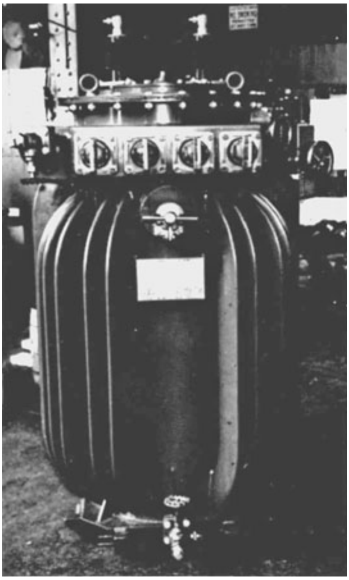


FIGURE 5.9 Medium-size transformer with corrugated tank.

FIGURE 5.10 Tubular-type tank as used on medium-size power transformers.

FIGURE 5.11 Liquid filled transformer utilizing silicone liquid listed by UL as a dielectric medium and less flammable per 450.23 of the NEC. [Dow Corning]

Large oil-immersed transformers are frequently cooled by means of a combination of *self-cooling* and *air-blast* (Fig. 5.12). The construction of the transformer is in general the same as for those which are oil-immersed and self-cooled, with the addition of a motor-driven blower or blowers mounted integrally with the transformer tank. The blowers provide a forced circulation of air up through the radiators to supplement the natural convection air currents. The blower motors are generally automatically controlled by means of a thermostat. When the oil temperature reaches a certain value, the thermostat closes the motor circuit. After the temperature has been reduced to a definite value, the thermostat opens the motor circuit, shutting off the fans.

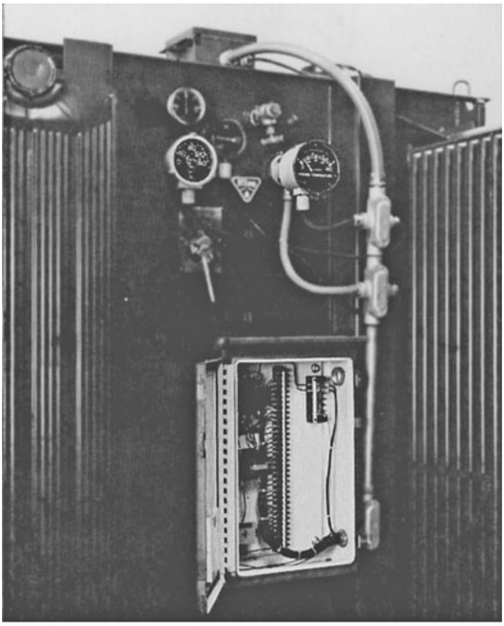
Gas-vapor transformers (Fig. 5.13) are sometimes employed for large units. The transformer is insulated with a quantity of gas necessary for start-up, along with a vaporizable liquid which provides insulation and cooling during operation. During operation, a pump delivers a stream of this liquid from the sump to the upper part of the core and coils. Here, under low pressure, the liquid is evenly distributed over the core structure and all current-carrying parts. Enough of the liquid evaporates to absorb heat from the core and coils. The hot vapors, being heavy, flow downward and enter the cooler-tube headers near the bottom of the tank. Normally, the bottom of the cooling tubes will be hotter than the top. In the cooling tubes, the vapors condense back into liquid, thus releasing their heat to the cooler-tube surfaces. The liquid returns to the pump by gravity for recirculation.

7. The oil used in transformers (*Standard Handbook for Electrical Engineers*) performs two important functions. It serves to insulate the various coils from each other and from the core, and it conducts the heat from the coils and core to some cooler surfaces, where it is either dissipated in the surrounding air or transferred to some cooling medium. It is evident that the oil should be free from any conducting material, it should be sufficiently thin to circulate rapidly when subjected to differences of temperatures at different places, and it should not be ignitable until its temperature has been raised to a very high value. Although numerous kinds of oils have been tried in transformers, at the present time mineral oil is used almost exclusively. This oil is obtained by fractional distillation of petroleum unmixed with any other substances and without subsequent chemical treatment. A good grade of transformer oil should show very little evaporation at 100°C, and it should not give off gases at such a rate as to produce an explosive mixture with the surrounding air at a temperature below 180°C. It should not contain moisture, acid, alkali, or sulfur compounds.

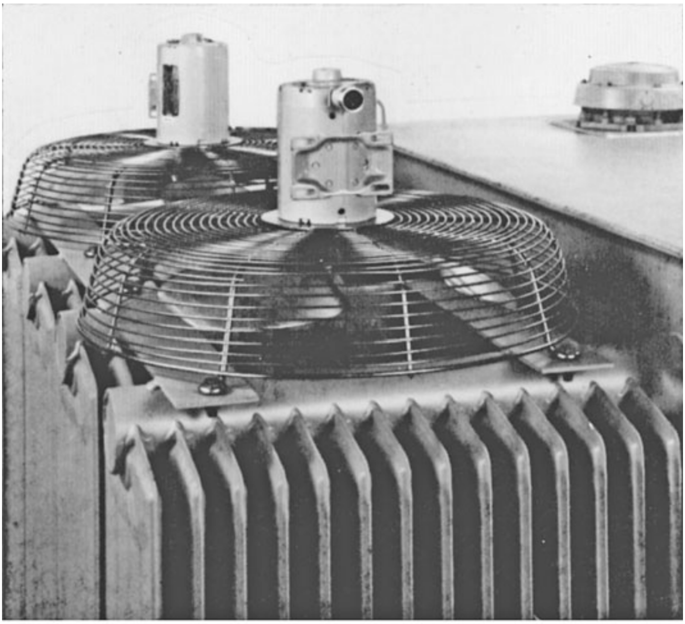
It has been shown by C. E. Skinner that the deteriorating effect of moisture on the insulating qualities of an oil is very marked; moisture to the extent of 0.06 percent reduces the dielectric strength of the oil to about 50 percent of the value when it is free from moisture, but there is very little further decrease in the dielectric strength with an increase in the amount of moisture in the oil.

Dry oil will stand an emf of 25,000 V between two 0.5-in (12.7-mm) knobs separated by 0.15 in (3.8 mm). The presence of moisture can be detected by thrusting a red-hot nail in the oil; if the oil "crackles," water is present. Moisture can be removed by raising the temperature slightly above the boiling point of water, but the time consumed (several days) is excessive. The oil is subsequently passed through a dry-sand filter to remove any traces of lime or other foreign materials.

8. The insulating value of the oil, in oil-immersed transformers (*Standard Handbook for Electrical Engineers*), is depended on very largely to help insulate the transformer; this is done by providing liberal oil ducts between coils and between groups of



I. Liquid-filled transformer with standard and optional accessories.



II. Fan cooling is temperature-activated by a liquid temperature gage.

FIGURE 5.12 Liquid-filled transformer that is self-cooled, forced-air. [Siemens Energy & Automation, Inc.]

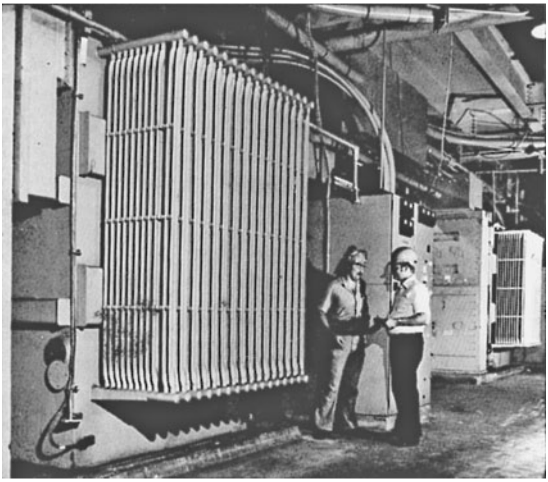


FIGURE 5.13 Gas-vapor substation-type transformer. [Westinghouse Electric Corp.]

coils, in addition to the solid insulation. The oil ducts thus serve the double purpose of insulating and cooling the windings.

Since the oil is a very important part of the insulation, every effort is made in modern transformers to preserve both its insulating and cooling qualities. Oxidation and moisture are the chief causes of deterioration. Oil takes into solution about 15 percent by volume of whatever gas is in contact with it. In the open-type transformer, oil rapidly darkens, owing to the effects of oxygen in solution in the oil and the oxygen in contact with the top surface of the hot oil.

1. *Expansion tank (or conservator).* One of the first devices used to reduce oxidation was the expansion tank (or conservator), which consisted of a small tank mounted above and connected with the main tank by means of a constricted connection so that the small tank could act as a reservoir to take up the expansion and contraction of the oil due to temperature changes and reduce the oil surface exposed to air.
2. *Inertaire transformer.* This transformer has the space above the oil in the tank filled with a cushion of inert gas which is mostly nitrogen. The nitrogen atmosphere is initially blown in from a cylinder of compressed nitrogen and is thereafter maintained by passing the inbreathing air through materials which remove the moisture and the oxygen, permitting dry nitrogen to pass into the case. A breathing regulator, which consists of a mercury U tube with unequal legs, allows inbreathing of nitrogen when the pressure in the case is only slightly below atmospheric, but prevents outbreathing unless the pressure in the case becomes 5 psi (34,474 Pa) higher than atmospheric pressure. The elimination of oxygen from within the transformer case eliminates the oxidation of the oil and prevents fire and secondary explosion within the case.

9. Insulation between windings. The great majority of transformers are constructed with two or more windings which are electrically insulated from each other. In some cases a single winding is employed, parts of the winding functioning as both primary and secondary. These transformers are called *autotransformers*. They are frequently used when the voltage ratio is small. Autotransformers should never be used for high voltage ratios, as the low-voltage winding is not insulated from the high-voltage one, so that in case of trouble it would be dangerous to both life and equipment. Refer to Sec. 32 for further discussion.

10. Transformer insulation. The type of insulation used in dry-type–transformer design and construction has a definite bearing on the size and operating temperature of the unit. Currently four classes of insulation, each having a separate NEMA specification and temperature limit, are being used. A look at these will facilitate selection of the proper unit to meet prescribed installation and operating conditions.

1. *Class 130 insulation-system transformers.* When properly applied and loaded in an ambient not over 40°C, these transformers will operate at not more than a 60°C temperature rise on the winding. These units can be used as control-type transformers when higher temperatures might affect other temperature-sensitive devices in the enclosure or as distribution transformers in locations (textile mills, sawmills, etc.) where combustible flyings might be present in the surrounding atmosphere.
2. *Class 150 insulation-system transformers.* These units have a higher-temperature insulating system and are physically smaller and about half the weight of Class A units of corresponding rated capacities. When properly loaded to rated kilovolt-amperes and installed in an ambient not over 40°C, Class 150 units will operate at a maximum 80°C rise on the winding. For years dry-type distribution transformers have been of the Class 150 type.
3. *Class 200 insulation-system transformers.* These units also have a high-temperature insulating system and, when properly loaded and applied in an ambient not over 40°C, will operate at no more than 130°C rise on the winding. The units are smaller in size than similarly rated Class 150 units and currently are available from a number of manufacturers in ratings of 25 kVA and lower, both single- and three-phase design. One manufacturer designs in-wall, flush-mounted dry-type transformers as Class 200 units.
4. *Class 220 insulation-system transformers.* These units are insulated with a high-temperature system of glass, silicone, and asbestos components and are probably the most compact ones available. When properly loaded and applied in an ambient not over 40°C, Class 220 transformers will operate at a maximum 150°C rise on the winding. This class of insulation is used primarily in designs in which the core and coil are completely enclosed in a ventilated housing. Generally, this stipulation covers units with ratings of 30 kVA and larger. Some experts recommend that the hottest spot on the metal enclosure be limited to a maximum rise of 40°C above a 40°C ambient.

It should be noted that Class 150 insulation is being replaced with Class 200 or 220 insulation in transformers of recent design.

Another significant factor which concerns all dry-type transformers is that they should never be overloaded. The way to avoid this is to size the primary or secondary overcurrent device as close as possible to the full-load primary or secondary current for other than motor loads. If close overcurrent protection has not been provided, loads should be checked periodically. Overloading a transformer causes excessive temperature, which, in turn, produces overheating. This results in rapid deterioration of the insulation and will cause complete failure of the transformer coils.

11. Transformers are built in both single- and polyphase units. A polyphase transformer consists of separate insulated electric windings for the different phases,

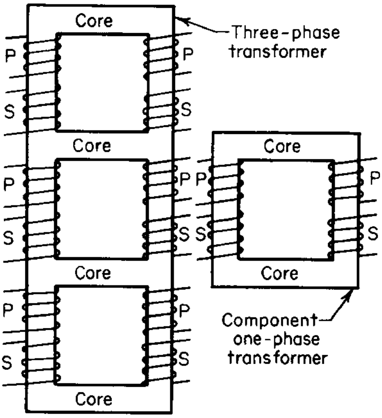


FIGURE 5.14 Three-phase core-type transformer.

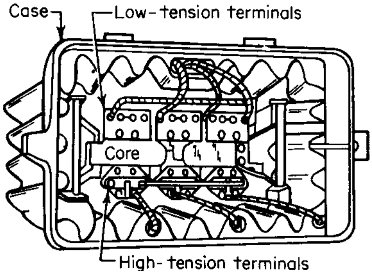


FIGURE 5.15 Interior view of a three-phase transformer.

wound upon a single core structure, certain portions of which are common to the different phases.

Three-Phase Transformers (*Standard Handbook for Electrical Engineers*). Although there are numerous possible arrangements of the coils and cores in constructing a polyphase transformer, it can be stated that a polyphase transformer generally consists of several one-phase transformers with separate electric circuits but having certain magnetic circuits in common. A three-phase transformer is illustrated in Fig. 5.14, together with the component one-phase transformer. It will be observed that a three-phase transformer requires 3 times as much copper as the one-phase component transformer but less than 3 times as much iron. Thus in comparison with three individual transformers, the three-phase unit is somewhat lighter and more efficient. Each component transformer operates as though the others were not present, the flux of one transformer combining with that of an adjacent transformer to produce a resultant flux exactly equal to that of each one alone. Figure 5.15 shows the interior of a Westinghouse three-phase transformer.

12. Application of three-phase transformers (A. D. Fishel). For central stations of medium size, three-phase transformers are rarely superior to single-phase, except when the large sizes can be applied, in which case the transformers are normally installed in substations or central stations. The chief reason for this is the nonflexibility of a three-phase transformer. It is usually purchased for a particular size and type of load, and if that load should be changed, the transformer, representing a comparatively heavy investment, remains on the hands of the central station, whereas a single-phase transformer of one-third the size could usually be adapted for some other service.

This feature becomes of less importance as the central station increases its size, and three-phase transformers for purely power service are now being used by a considerable number of the large central stations in the United States. The three-phase transformer costs less to install, and the connections are simpler, points that are of importance in connection with outdoor installations. The fact that a failure of a three-phase transformer would interrupt service more than the failure of one single-phase transformer in a bank of three is of little importance because of the comparatively few failures of modern transformers. On the other hand, especially for 2200-V service, the single-phase transformer has been carried to a high degree of perfection and is manufactured in much larger quantities, so that better performance is usual and in some cases initial cost is lower. Three-phase distribution transformers are used extensively in underground city network service on account of the smaller space required by them in the manhole, their higher efficiency, and their lower initial cost. For overhead service for pole or platform mounting, three single-phase units are more common on account of the ease of handling and mounting the smaller-sized units.

13. Methods of mounting. Transformers are constructed with different types of metal enclosing structures to meet the requirements of different conditions of installation. One type of enclosure (Figs. 5.8 and 5.19) is designed for *mounting on poles,* either directly or with hanger irons, for use in overhead distribution work. Another type of enclosure, called the *platform type* (Figs. 5.10, 5.11, and 5.12), is suitable for installations in which the transformer stands upon its own base. It can be mounted on any flat horizontal surface having sufficient mechanical strength, such as a floor or a platform between poles. *Subway transformers* have watertight tanks which are designed primarily for underground installations when the transformer may be completely submerged in water. *Vault transformers* also have watertight enclosures so that they will not be injured by total submersion, but they are not designed to operate satisfactorily under such conditions. The vault transformers are intended for operation in underground vaults in which the transformer would not be required to operate for any considerable length of time while submerged. Small transformers for power and special application as listed in Sec. 5 (6*c* to 6*j*) are designed with special types of mounting to meet the requirements of installation for these types of service.

14. Purpose of transformers. Transformers can be classified as in Sec. 5 (5) according to the purpose of transformation for which they are employed.

The function of a *constant-voltage* transformer is to change the voltage of a system. It is designed to operate with its primary connected across a constant-voltage supply and to provide a secondary voltage which is substantially constant from no load to full load. It is the ordinary, common type of transformer. The currents of both primary and secondary vary with the load supplied by the transformer. A *variable-voltage* transformer is also intended for changing the voltage of a system but is so designed that when operated with its primary connected to a constant-voltage supply, the secondary voltage will vary widely with the load. Such transformers are necessary for the operation of many gaseous-discharge lamps.

A *current* transformer is one which is designed for changing the current of a system. The primary winding of such a transformer is connected in series with the circuit of which it is desired to change the current. The voltage of both primary and secondary will change with the value of the current of the system. Such transformers are used for instrument transformers and in some series street-lighting installations. *Constant-current* transformers are designed for supplying a constant value of secondary current regardless of the load on the transformer. The primary is connected to a constant-voltage source. The secondary voltage varies proportionally with the load, while the secondary current remains constant. The primary current and kilovolt-amperes will be constant for all loads, but the kilowatt input and power factor will vary with the load.

15. The most important application of constant-voltage transformers is raising the voltage of an electric transmission circuit so that energy can be transmitted for considerable distances with small voltage drop and small energy loss and then lowering the voltage for safe usage by motors, lights, and appliances.

16. Theory of operation of the constant-voltage transformer (see Fig. 5.1). It has been shown in Div. 1 that turns of wire wound on an iron core have self-induction. When an alternating voltage is applied to such turns, there flows through them a current that generates a countervoltage or emf that opposes the applied voltage. From formulas the transformer designer can compute just how many turns are necessary for a transformer of a given size so that it will generate a countervoltage equal to the applied voltage. So, in designing the primary winding of the transformer of Fig. 5.1, the designer would select such a number of turns for the primary winding that the countervoltage generated by it would be nearly 2400 V. Hence, when the primary winding is connected to a 2400-V circuit, it generates a countervoltage of practically 2400, and no appreciable current flows. A small current, the exciting current, just enough to magnetize the core, does flow, but it is so small that it can be disregarded in this discussion.

Since the primary and secondary windings are on the same core, the magnetic flux generated by the magnetizing or exciting current flowing in the primary winding also cuts the turns of the secondary winding and generates an emf in them. This emf will be, in accordance with a well-known law, opposite in direction to that impressed on the primary. If the secondary circuit is open, no current can flow in it, but if it is closed, a certain current, proportional to the impedance of the secondary circuit, will flow. This current, because of the direction of the emf generated in the secondary, will be in such a direction that the magnetic flux produced in the core by it will oppose the flux due to the primary winding. It will therefore decrease the effective or resultant flux in the core by a small amount which will decrease the counter-emf of the primary winding and permit more current to flow into the primary winding. As noted elsewhere, the ratio of the number of turns in the primary winding to the number of turns in the secondary winding determines the ratio of the primary to the secondary voltage.

If the voltage impressed on the transformer is maintained constant, the voltage of the secondary will be nearly constant also. When more current flows in the secondary, there will be a corresponding increase in primary current. As the load on a transformer increases, the impressed voltage remaining constant, there is actually a slight drop from the no-load voltage of the secondary, due to certain inherent characteristics of the transformer, but in a properly designed device this drop will be very small. Although the construction and elementary theory of the transformer are very simple, a theoretical explanation of all the phenomena involved in its operation is very complicated. Only the principal features have been described. Some minor, though very important, considerations that would complicate the explanation have not been treated.

17. Transformer ratios. The voltage ratio of a constant-voltage transformer, i.e., the ratio of primary to secondary voltage, depends primarily upon the ratio of the primary to the secondary turns. The voltage ratio will vary slightly with the amount and power factor of the load. For general work the voltage ratio can be taken as equal to the turn ratio of the windings.

The current ratio of a constant-voltage transformer will be approximately equal to the inverse ratio of the turns in the two windings. For example, for transforming or "stepping down" from 2400 to 120 V the ratio of the turns in the windings will be 20:1. The currents in the primary and the secondary windings will be, very closely, inversely proportional to the ratio of the primary and secondary voltages because, if the small losses of transformation are disregarded, the power put into a transformer will equal the power delivered by it. For example, for a transformer with windings having a ratio of 20:1, if its secondary winding delivers 100 A at 50 V, the input to its primary winding must receive almost exactly 5 A at 1000 V. The input and output are each practically equal, and each would equal almost exactly 5000 W.

18. The regulation of a transformer is the change in secondary voltage from no load to full load. It is generally expressed as a percentage of the full-load secondary voltage:

$$\text{Percent regulation} = \frac{\text{no-load secondary voltage} - \text{full-load secondary voltage}}{\text{full-load secondary voltage}} \times 100 \quad (1)$$

The regulation depends upon the design of the transformer and the power factor of the load. Although with a noninductive load such as incandescent lamps, the regulation of transformers is within about 3 percent, with an inductive load the drop in voltage between no load and full load increases to possibly about 5 percent. If the motor load is large and fluctuating and close lamp regulation is important, it is desirable to use separate transformers for the motors.

19. The efficiency of a transformer is, as with any other device, the ratio of the output to input or, in other words, the ratio of the output to the output plus the losses. As a formula it can be expressed thus:

$$\text{Efficiency} = \frac{\text{output}}{\text{input}} = \frac{\text{output}}{\text{output} + \text{copper loss} + \text{iron loss}} \quad (2)$$

Average efficiencies of transformers are given in Secs. 43 to 57.

20. The copper loss of a transformer is determined by the resistances of the high-tension and low-tension windings and of the leads. It is equal to the sum of the watts of I^2R losses in these components at the load for which it is desired to compute the efficiency.

21. The iron loss of a transformer is equal to the sum of the losses in the iron core. These losses consist of eddy- or Foucault-current losses and hysteresis losses. Eddy-current losses are due to currents generated by the alternating flux circulating within each lamination composing the core, and they are minimized by using thin laminations and by insulating adjacent laminations with insulating varnish. Hysteresis losses are due to the power required to reverse the magnetism of the iron core at each alternation and are determined by the amount and the grade of iron used for the laminations for the core.

22. Transformer ratings. Transformers are rated at their kilovolt-ampere (kVA) outputs. If the load to be supplied by a transformer is at 100 percent power factor (pf), the kilowatt (kW) output will be the same as the kilovolt-ampere (kVA) output. If the load has a lesser power factor, the kW output will be less than the kVA output proportionally as the load power factor is less than 100 percent.

EXAMPLE A transformer having a full-load rating of 100 kVA will safely carry 100 kW if the 100 kW is at 100 percent pf, 90 kW at 90 percent pf, or 80 kW at 80 percent pf.

Transformers are generally rated on the kVA load which the transformer can safely carry continuously without exceeding a temperature rise of 60°C for Class 130 insulation or 80°C for Class 150 insulation when maintaining rated secondary voltage at rated frequency and when operating with an ambient temperature of 40°C. (Ambient temperature is the temperature of the surrounding atmosphere.) The actual temperature of any part of the transformer is the sum of the temperature rise of that part plus the ambient temperature. See Sec. 10 for an explanation of transformer insulation classifications.

The usual service conditions under which a transformer should be able to carry its rated load are:

1. At rated secondary voltage or not in excess of 105 percent of rated value.
2. At rated frequency.
3. Temperature of the surrounding cooling air at no time exceeding 40°C and average temperature of the surrounding cooling air during any 24-h period not exceeding 30°C.
4. Altitude not in excess of 3300 ft.
5. If water-cooled, temperature of cooling water not exceeding 30°C and average temperature of cooling water during any 24-h period not exceeding 25°C.
6. The load current shall be approximately sinusoidal. The harmonic factor shall not exceed 0.05 per unit.

GUIDE FOR LOADING OIL-IMMERSED DISTRIBUTION AND POWER TRANSFORMERS

23. The following sections on guidance for loading of transformers are excerpts from the American National Standards Institute's publication C57.92-1981.

The actual output which a transformer can deliver at any time in service without undue deterioration of the insulation may be more or less than the rated output, depending upon the ambient temperature and other attendant operating conditions.

24. Continuous loading on basis of average winding test temperature rise. For each degree Celsius in excess of 5° that the test temperature rise is below the standard temperature rise of 55°C, the transformer load may be increased above rated kilovolt-amperes by the percentages shown in col. 3 of the accompanying table. Making use of this factor gives the kilovolt-amperes that the transformer can deliver with a 55°C temperature rise. The leeway of 5° provides for a negative tolerance in the measurement of temperature rise.

Loading on Basis of Ambient Temperature

	Percent of rated kVA	
Type of cooling	Decrease load for higher temperature each °C	Increase load for lower temperature each °C
Self-cooled	1.5	1.0
Water-cooled	1.5	1.0
Forced-air-cooled	1.0	0.75
Forced-oil-cooled	1.0	0.75

Some transformers are designed to have the difference between hottest-spot and average copper temperatures greater than the nominal allowance of 10°C. This will result in a temperature rise for average copper of less than 55°C, but the hottest-spot copper temperature rise may be at the limiting value of 65°C. Such transformers should not be loaded above rating as outlined under this heading. The manufacturer should be consulted to give information as to design of hottest-spot allowances.

25. Loading on basis of ambient temperature. For each degree Celsius that the average temperature of the cooling medium is above or below 30°C for air or 25°C for water, a transformer can be loaded for any period of time below or above its kilovolt-ampere rating as specified in the table of Sec. 24. Average temperature should be for periods of time not exceeding 24 h with maximum temperatures not more than 10°C greater than average temperatures for air and 5°C for water. On the basis used in this guide for calculating loss of life, life expectancy will be approximately the same as if the transformer had been operated at rated kilovolt-amperes and standard ambient temperatures over that period.

The use of transformers in cooling air above 50°C or below 0°C or with cooling water above 35°C is not covered by the table of Sec. 24 and should be taken up with the manufacturer.

26. Basic loading for normal life expectancy

Basic Conditions

1. The basic loading of a transformer for normal life expectancy is continuous loading at rated output when operated under normal service conditions.[1] It is assumed that operation under these conditions is equivalent to operation in a continuous ambient temperature of 30°C for cooling air or 25°C for cooling water. Normal life expectancy will result from operating with a continuous hottest-spot conductor temperature of 110°C (or equivalent variable temperature with 120°C maximum) in any 24-h period.
2. The hottest-spot conductor temperature determines loss of life due to loading. This temperature cannot be directly measured on commercial designs because of voltage hazard when placing a temperature detector at the proper location. The hottest-spot allowances are based on tests of laboratory models.
3. The hottest-spot temperature at rated load is usually taken as the sum of the average winding temperature and a 15°C allowance[2] for hottest spot. For mineral oil-immersed transformers operating continuously under the foregoing conditions with normal life expectancy, this temperature has been assumed to be a maximum of 110°C.

27. Continuous loading on basis of average winding test temperature rise. For each °C in excess of 5° that the average winding test temperature rise is below 65°C, the transformer load may be increased above rated load by the percentages given in the table in Sec. 24. A 5° margin is used to provide a tolerance in the measurement of temperature rise. The loadability thus obtained is that which the transformer can carry at 65°C rise. Since this may increase the loading beyond that contemplated by the designer, the limitations should be checked before taking full advantage of this increased loadability. Among these limitations are: oil expansion, pressure in sealed units, bushings, leads, tap changers, and stray flux heating as well as the thermal capability of associated equipment such as

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[1] When air cooled, the temperature of the cooling air (ambient temperature) shall not exceed 40°C and the average temperature of the cooling air for any 24-h period shall not exceed 30°C. The top liquid temperature of the transformer (when operating) shall not be lower than −20°C. Starting temperatures below −20°C are not considered as usual service conditions. When water cooled, the temperature of cooling water (ambient temperature) shall not exceed 30°C and the average temperature of the cooling water for any 24-h period shall not exceed 25°C. Minimum water temperature shall not be lower than 1°C, unless the cooling water includes antifreeze suitable for −20°C operation. The altitude shall not exceed 3300 ft (1000 m). The supply voltage wave shape shall be approximately sinusoidal, and the phase voltages supplying a polyphase transformer shall be approximately equal in magnitude and time displacement. The load current shall be approximately sinusoidal. The harmonic factor shall not exceed 0.05 per unit.

[2] If cooler inlet and outlet temperatures are available, a better estimate of the hottest-spot temperature is possible by making an adjustment in the 15°C allowance. Consult with the manufacturer.

cables, reactors, circuit breakers, disconnecting switches, and current transformers. High ambient temperatures will also restrict a transformer's loadability. Any of these items may limit loading, and manufacturers should be consulted for advice on such limitations.

Some transformers are designed to have the difference between the hottest-spot and average conductor temperatures greater than the 15°C allowance. This will result in an average winding temperature rise of less than 65°C, but the hottest-spot winding temperature rise may be the limiting value of 80°C. Such transformers should not be loaded above their rating as outlined in this section. The manufacturer should be consulted for information on the hottest-spot allowances used for these designs. This condition may exist in transformers with large differences (greater than 30°C) between top-and-bottom-oil temperatures. Whenever possible, data on hottest-spot and oil temperatures obtained from factory temperature should be used in calculating transformer loadability or when calculating temperatures for loads above rating.

28. Unusual temperatures and altitude service conditions. Transformers may be applied at higher ambient temperatures or at higher altitudes, but performance may be affected and special consideration should be given to these applications. The effect of the decreased air density due to high altitude is to increase the temperature rise of transformers since they are dependent upon air for the dissipation of heat losses. Transformers may be operated at rated kVA at altitudes greater than 3300 ft (1000 m) without exceeding temperature limits, provided the average temperature of the cooling air does not exceed the values of Table 28A for the respective altitudes. Transformers may be operated at altitudes greater than 3300 ft (1000 m) without exceeding temperature limits, provided the load to be carried is reduced below rating by the percentages given in Table 28B for each 330 ft (100 m) that the altitude is above 3300 ft (1000 m).

TABLE 28A Maximum Allowable Average Temperature* of Cooling Air for Carrying Rated kVA

	1000 m (3300 ft)	2000 m (6600 ft)	3000 m (9900 ft)	4000 m (13,200 ft)
Method of cooling apparatus	Degrees C			
Liquid-immersed self-cooled	30	28	25	23
Liquid -immersed forced-air-cooled	30	26	23	20
Liquid -immersed forced-oil-cooled with oil-to-air cooler	30	26	23	20

*It is recommended that the average temperature of the cooling air be calculated by averaging 24 consecutive hourly readings. When the outdoor air is the cooling medium, the average of the maximum and minimum daily temperatures may be used. The value obtained in this manner is usually slightly higher, by not more than 0.3°C, than the true daily average.

TABLE 28B Rated kVA Correction Factors for Altitudes Greater than 3300 ft (1000 m)

Types of cooling	Derating factor (%)
Liquid-immersed air-cooled	0.4
Liquid-immersed water-cooled	0.0
Liquid-immersed forced-air-cooled	0.5
Liquid-immersed forced-liquid-cooled with liquid-to-air cooler	0.5
Liquid-immersed forced-liquid-cooled with liquid-to-water cooler	0.0

29. Effect of various factors existing at one time. When two or more of the following factors affecting loading for normal life expectancy exist at one time, the effects are cumulative and the increase in loads due to each can be added to secure the maximum suggested load (each increase must be based on rated kilovolt-amperes):

1. Loading on basis of test temperature rise
2. Loading on basis of ambient temperature
3. Either loading on basis of load factor or loading on basis of short-time overloads

Do not use both

30. Capacities of Transformers for Induction Motors

(General Electric Co.)

	kVA per transformer		
Size of motor, hp	Two single-phase transformers	Three single-phase transformers	One three-phase transformer
1	0.6	0.6	
2	1.5	1.0	2.0
3	2.0	1.5	3.0
5	3.0	2.0	5.0
7½	4.0	3.0	7.5
10	5.0	4.0	10.0
15	7.5	5.0	15.0
20	10.0	7.5	20.0
30	15.0	10.0	30.0
50	25.0	15.0	50.0
75	40.0	25.0	75.0
100	50.0	30.0	100.0

31. Capacities of transformers for operating motors (General Electric Co.). For the larger motors the capacity of the transformers in kilovolt-amperes should equal the output of the motor in horsepower. Thus a 50-hp motor requires 50 kVA in transformers. Small motors should be supplied with a somewhat larger transformer capacity, especially if, as is desirable, they are expected to run most of the time near full load or even at slight overload. Transformers of less capacity than those noted in Table 30 should not be used even when a motor is to be run at only partial load.

32. The autotransformer (*Standard Handbook for Electrical Engineers*). The most efficient and effective method of operating a stationary transformer (when the ratio of transformation is not too large) is as an autotransformer, i.e., with certain portions of the windings used simultaneously as the primary and the secondary circuits. The electrical circuits of a one-phase autotransformer (sometimes called a *compensator* or a *balance coil*) are indicated in Fig. 5.16. The autotransformer has only one coil, a certain portion of which is used for both the high-tension and the low-tension windings. The number of turns of this coil is the same as would be required if it were used exclusively for the high-tension winding and a separate additional coil were used for the low-tension winding. Moreover, when the ratio of transformation is 2:1 or 1:2, the amount of copper in the one coil is exactly the same whether it is used as an autotransformer or as a high-tension coil of a two-coil transformer of the same rating. Not only is less copper required for an autotransformer than for a two-coil transformer, but less iron is needed to surround the copper.

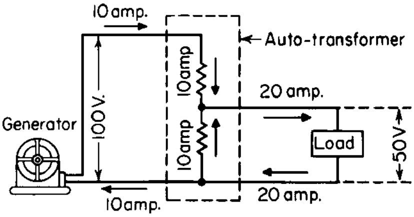

FIGURE 5.16 Electric circuits of a 1-kVA single-phase autotransformer.

Referring again to Fig. 5.16, note that the one-coil transformer is designed for 10 A throughout and for a total emf of 100 V. The voltage per turn is uniform throughout, so that to obtain 50 V it is necessary merely to select any two points on the continuous winding such that one-half of the total number of turns is included between them. The load current of 20 A (required for 1000 W at 50 V) is opposed by the superposed 10 A of primary current, so that even in this section of the coil the resultant current is only 10 A.

If an ordinary two-coil transformer had been used, the circuits would have been as noted in Fig. 5.17, while the required constructive material would have been approximately as indicated in Fig. 5.18, I. With respect to its constructive material, a 1-kW 2:1-ratio autotransformer is the equivalent of a 1:1-ratio 0.5-kW two-coil transformer as shown in Fig. 5.18, II. The latter transformer requires about 14 lb (6.35 kg) of copper and 28 lb (12.7 kg) of iron as compared to about 22 lb (10 kg) of copper and 34 lb (15.4 kg) of iron for the transformer of Fig. 5.18, I. Moreover, the losses of the autotransformer are correspondingly less than those of a two-coil transformer. Refer to Sec. 116 for limitations in the allowable use of autotransformers.

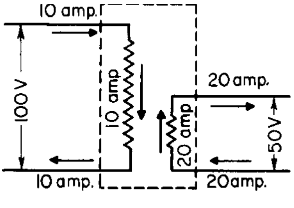

FIGURE 5.17 Electric circuits of a 1-kVA single-phase two-coil transformer equivalent to the autotransformer of Fig. 5.16.

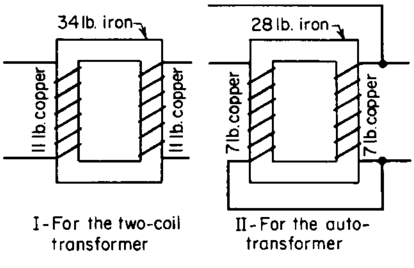

FIGURE 5.18 Comparison of constructive material required for a two-coil transformer and for an autotransformer.

33. Constant-voltage transformers for the transformation of a large amount of power, more than 500 kVA, are called *power transformers*. Transformers for general constant-voltage power transformation, whose rating is 500 kVA or less, are called *distribution transformers*. All the methods of cooling are employed for power transformers. The choice depends upon which will result in the best overall economy, including first cost, operating expense, and space occupied. Distribution transformers generally are liquid-immersed, self-cooled. Power and distribution transformers are normally of the standard type with the windings insulated from each other, although those with autotransformer construction can be obtained for special applications in which the voltage ratio is small. Power

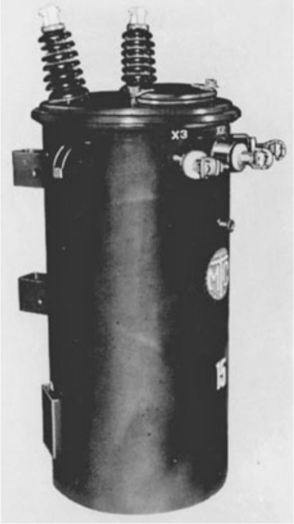

FIGURE 5.19 Distribution transformer for pole mounting.

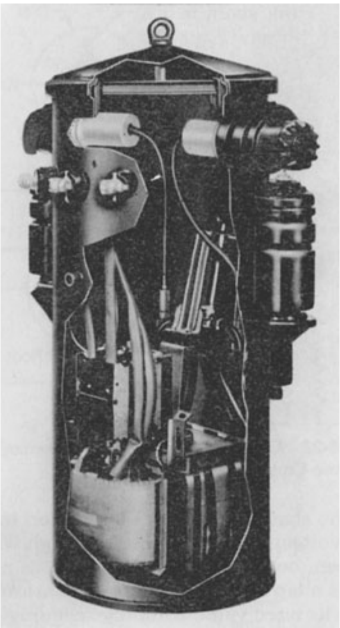

FIGURE 5.20 Sectional view of CSP transformer. [Westinghouse Electric Corp.]

transformers are always of the platform type. Distribution transformers are made with tanks for pole and platform mounting and with tanks of the subway and vault types. The tanks of the platform-type transformers of 50-kVA capacity and smaller are equipped with lugs or brackets (Fig. 5.19) for direct pole mounting or for the attachment of hanger irons for crossarm pole mounting. A constant-voltage transformer maintains an approximately constant voltage ratio over the range from zero to rated output.

34. Network transformers are distribution transformers specially constructed and equipped with attached auxiliaries such as junction boxes and switches for disconnecting and grounding the high-voltage cable to meet the requirements of transformers for supplying low-voltage networks. A network transformer is designed for use in a vault to feed a variable capacity system of interconnected secondaries.

35. Self-protected distribution transformers are equipped with lightning and overload protective equipment built integrally with the transformers. They are made in two types: completely self-protecting (CSP), i.e., having both overload and lightning protection, and with only surge protection (SP). The connections of the lightning protective equipment can be made in different ways to satisfy any desired grounding practice. A sectional view of such a CSP transformer is shown in Fig. 5.20.