Chapter 4
Power Transformers

4-1. General

a. Type. Step-up transformers for use with main units should be of the oil immersed type for outdoor operation, with a cooling system as described in paragraph 4-3, suited to the location. General Corps of Engineers power transformer design practice is covered by Guide Specification for Civil Works Construction CW-16320.

b. Three-phase transformers. In the majority of applications, three-phase transformers should be used for generator step-up (GSU) applications for the following reasons:

(1) Higher efficiency than three single-phase units of equivalent capacity.

(2) Smaller space requirements.

(3) Lower installed cost.

(4) Lower probability of failure when properly protected by surge arresters, thermal devices, and oil preservation systems.

(5) Lower total weight.

(6) Reduction in weights and dimensions making larger capacities available within practical weight and size limitations.

c. EHV applications. In applications involving interconnection to EHV (345 *kV* and above) systems, reliability and application considerations dictate the use of single-phase units due to lack of satisfactory industry experience with three-phase EHV GSU transformers. The basic switching provisions discussed in Chapter 2 describe the low-voltage switching scheme used with EHV transformers.

d. Transformer features. Regardless of winding configuration, for any given voltage and *kVA* rating, with normal temperature rise, the following features should be analyzed for their effect on transformer life cycle costs:

(1) Type of cooling.

(2) Insulation level of high-voltage winding.

(3) Departure from normal design impedance.

Examples of typical transformer studies which should be performed are contained in Appendix B of this manual.

e. Transformer construction. There are two types of construction used for GSU transformers. These are the core form type and the shell form type. Core form transformers generally are supplied by manufacturers for lower voltage and lower *MVA* ratings. The core form unit is adaptable to a wide range of design parameters, is economical to manufacture, but generally has a low *kVA*-to-weight ratio. Typical HV ranges are 230 *kV* and less and 75 *MVA* and less. Shell form transformers have a high *kVA*-to-weight ratio and find favor on EHV and high *MVA* applications. They have better short-circuit strength characteristics, are less immune to transit damage, but have a more labor-intensive manufacturing process. Both forms of construction are permitted by Corps' transformer guide specifications.

4-2. Rating

The full load *kVA* rating of the step-up transformer should be at least equal to the maximum *kVA* rating of the generator or generators with which they are associated. Where transformers with auxiliary cooling facilities have dual or triple *kVA* ratings, the maximum transformer rating should match the maximum generator rating.

4-3. Cooling

a. General. The standard classes of transformer cool ing systems are listed in Paragraph 5.1, IEEE C57.12.00. Transformers, when located at the powerhouse, should be sited so unrestricted ambient air circulation is allowed. The transformer rating is based on full use of the transformer cooling equipment.

b. Forced cooling. The use of forced-air cooling will increase the continuous self-cooled rating of the transformer 15 percent for transformers rated 2499 *kVA* and below, 25 percent for single-phase transformers rated 2500 to 9999 *kVA* and three-phase transformers rated 2500 to 11999 *kVA*, and 33-1/3 percent for single-phase transformers rated 10000 *kVA* and above and three-phase transformers rated 12000 *kVA* and above. High-velocity fans on the largest size groups will increase the self-cooled rating 66-2/3 percent. Forced-oil cooled transformers, whenever energized, must be operated with the circulating oil pumps operating. Forced-oil transformers with air coolers do not have a self-cooled rating without the air-cooling equipment in operation unless they are special units with a "triple rating."

c. Temperature considerations. In determining the transformer rating, consideration should be given to the temperature conditions at the point of installation. High ambient temperatures may necessitate increasing the transformer rating in order to keep the winding temperature within permissible limits. If the temperatures will exceed those specified under "Service Conditions" in IEEE C57.12.00, a larger transformer may be required. IEEE C57.92 should be consulted in determining the rating required for overloads and high temperature conditions.

d. Unusual requirements. Class OA/FA and Class FOA meet all the usual requirements for transformers located in hydro plant switchyards. The use of triple-rated transformers such as Class OA/FA/FA is seldom required unless the particular installation services a load with a recurring short time peak.

e. Class FOA transformers. On Class FOA transformers, there are certain considerations regarding static electrification (build-up of charge on the transformer windings due to oil flow). Transformer suppliers require oil pump operation whenever an FOA transformer is energized. Static electrification is important to consider when designing the desired operation of the cooling, and can result in the following cooling considerations:

(1) Decrease in oil flow velocity requirements (for forced-oil cooled units).

(2) Modifying of cooling equipment controls to have pumps come on in stages.

(3) Operation of pumps prior to energizing transformer.

4-4. Electrical Characteristics

a. Voltage.

(1) Voltage ratings and ratios should conform to ANSI C84.1 preferred ratings wherever possible. The high-voltage rating should be suitable for the voltage of the transmission system to which it will be connected, with proper consideration for increases in transmission voltage that may be planned for the near future. In some cases this may warrant the construction of high-voltage windings for series or parallel operation, with bushings for the higher voltage, or windings suitable for the higher voltage tapped for the present operating voltage.

(2) Consideration should also be given to the voltage rating specified for the low-voltage winding. For plants connected to EHV systems, the low-voltage winding rating should match the generator voltage rating to optimally match the generator's reactive capability in "bucking" the transmission line voltage. For 230-*kV* transmission systems and below, the transformer low-voltage rating should be 5 percent below the generator voltage rating to optimally match the generator's reactive capability when "boosting" transmission line voltage. IEEE C57.116 and EPRI EL-5036, Volume 2, provide further guidance on considerations in evaluating suitable voltage ratings for the GSU transformer.

b. High-voltage BIL.

(1) Basic Impulse Insulation Levels (BIL) associated with the nominal transmission system voltage are shown in Table 1 of IEEE C57.12.14. With the advent of metal oxide surge arresters, significant economic savings can be made in the procurement of power transformers by specifying reduced BIL levels in conjunction with the application of the appropriate metal oxide arrester for transformer surge protection. To determine appropriate values, an insulation coordination study should be made (see Appendix B for a study example). Studies involve coordinating and determining adequate protective margins for the following transformer insulation characteristics:

(a) Chopped-Wave Withstand (CWW).

(b) Basic Impulse Insulation Level (BIL).

(c) Switching Surge Level (SSL).

(2) If there is reason to believe the transmission system presently operating with solidly grounded neutrals may be equipped with regulating transformers or neutral reactors in the future, the neutral insulation level should be specified to agree with Table 7 of IEEE C57.12.00.

c. Impedance.

(1) Impedance of the transformers has a material effect on system stability, short-circuit currents, and transmission line regulation, and it is usually desirable to keep the impedance at the lower limit of normal impedance design values. Table 4-1 illustrates the range of values available in a normal two-winding transformer design (values shown are for GSU transformers with

Table 4-1
Nominal Design Impedance Limits for Power Transformers Standard Impedance Limits (Percent)

HIGH-VOLTAGE WINDING		AT EQUIV. 55 °C *kVA*			
NOMINAL SYSTEM *kV*	WINDING BIL *kV*	CLASS OA, OR SELF-COOLED RATING OF CLASS OA/FA OR CLASS OA/FA/FA MINIMUM	MAXIMUM	CLASS FOA OR CLASS FOW MINIMUM	MAXIMUM
15	110	5.0	7.5	8.34	12.5
25	150	5.0	7.5	8.34	12.5
34.5	200	5.25	8.0	8.75	14.33
46	250	5.60	8.4	9.34	14.0
69	350	6.1	9.15	10.17	15.25
115	450	5.9	8.85	9.84	14.75
138	550	6.4	9.6	10.67	16.0
161	650	6.9	10.35	11.50	17.25
230	825	7.5	11.25	12.5	18 .75
500	1425	10.95	15.6	18.25	26.0

13.8-*kV* low voltage). Impedances within the limits shown are furnished at no increase in transformer cost. Transformers can be furnished with lower or higher values ofimpedance at an increase in cost. The approximate effect of higher- or lower-than-normal impedances on the cost of transformers is given in Table 4-2. The value of transformer impedance should be determined giving consideration to impacts on selection of the interrupting capacities of station breakers and on the ability of the generators to aid in regulating transmission line voltage. Transformer impedances should be selected based on system and plant fault study results (see Chapter 2). Impedances shown are subject to a tolerance of plus or minus 7.5 percent. (See IEEE C57.12.00).

Table 4-2
Increase In Transformer Cost For Impedances Above and Below The Standard Values

STANDARD IMPEDANCE X	INCREASE IN TRANSFORMER COST
1.45-1.41	3%
1.40-1.36	2%
1.35-1.31	1%
0.90-0.86	2%
0.85-0.81	4%
0.80-0.76	6%

(2) In making comparisons or specifying the value of impedance of transformers, care should be taken to place all transformers on a common basis. Impedance of a transformer is a direct function of its rating, and when a transformer has more than one different rating, it has a different impedance for each rating. For example, to obtain the impedance of a forced-air-cooled transformer at the forced-air-cooled rating when the impedance at its self-cooled rating is given, it is necessary to multiply the impedance for the self-cooled rating by the ratio of the forced-air-cooled rating to the self-cooled rating.

d. Transformer efficiency. Transformer losses represent a considerable economic loss over the life of the power plant. A study should be made to select minimum allowable efficiencies for purposes of bidding. Included in the study should be a determination of the present worth cost of transformer losses. This value is used in evaluating transformer bids that specify efficiency values that exceed the minimum acceptable value. Examples of typical studies are included in Appendix B of this manual. IEEE C57.120 provides further guidance on transformer loss evaluation.

4-5. Terminals

Where low-voltage leads between the transformer and generator are of the metal-enclosed type, it is desirable to extend the lead housing to include the low-voltage terminals of the transformer. This arrangement should be indicated on the specification drawings and included in the specifications in order that the manufacturer will coordinate his transformer top details with the design of the housing. It is sometimes preferable to have the transformer builder furnish the housing over the low-voltage bushings if it simplifies the coordination. All bushing characteristics should conform to the requirements of IEEE C57.19.01. The voltage rating should correspond to the insulation level of the associated winding. Where transformers are installed at elevations of more than 3,300 ft above sea level, bushings of the next higher voltage classification may be required. Bushings for neutral connections should be selected to suit the insulation level of the neutral, as discussed in paragraph 4-4.

4-6. Accessories

a. Oil preservation systems. Three different oil preservation systems are available, as described below. The first two systems are preferred for generator step-up transformers:

(1) Inert gas pressure system. Positive nitrogen gas pressure is maintained in the space between the top of the oil and the tank cover from a cylinder or group of cylinders through a pressure-reducing valve.

(2) Air-cell, constant-pressure, reservoir tank system. A system of one or more oil reservoirs, each containing an air cell arranged to prevent direct contact between the oil and the air.

(3) Sealed tank. Gas is admitted to the space above the oil and the tank is sealed. Expansion tanks for the gas are provided on some sizes. Sealed tank construction is employed for 2,500 *kVA* and smaller sizes.

b. Oil flow alarm. Transformers that depend upon pumped circulation of the oil for cooling should be equipped with devices that can be connected to sound an alarm, to prevent closing of the energizing power circuit, or to deenergize the transformer with loss of oil flow. In forced-oil-cooled units, hot spot detectors should be provided which can be connected to unload the transformer if the temperature exceeds that at which the second oil pump is expected to cut in. FOA transformers should employ control schemes to ensure pump operation prior to energizing the transformer.

c. Surge arresters. Surge arresters are located near the transformer terminals to provide protection of the high-voltage windings. Normal practice is to provide brackets on the transformer case (230-*kV* HV and below) for mounting the selected surge arrester.

d. Fans and pumps. The axial-flow fans provided for supplementary cooling on Class OA/FA transformers are equipped with special motors standardized for 115-V and 230-V single-phase or 208-V three-phase operation. Likewise, oil circulating pumps for FOA transformers are set up for single-phase AC service. Standard Corps of Engineers practice is to supply 480-V, three-phase power to the transformer and have the transformer manufacturer provide necessary conversion equipment.

e. On-line dissolved gas monitoring system. The detection of certain gases, generated in an oil-filled transformer in service, is frequently the first available indication of possible malfunction that may eventually lead to the transformer failure if not corrected. The monitoring system can provide gas analysis of certain gases from gas spaces of a transformer. The system output contacts can be connected for an alarm or to unload the transformer if the gas levels exceed a set point. The type of gases generated, during the abnormal transformer conditions, is described in IEEE C57.104.

f. Temperature detectors. A dial-type temperature indicating device with adjustable alarm contacts should be provided for oil temperature indication. Winding RTDs should be provided, and monitored by the plant control system or a stand-alone temperature recorder, if one is provided for the generator and turbine RTDs. At least two RTDs in each winding should be provided.

g. Lifting devices. If powerhouse cranes are to be used for transformer handling, the manufacturer's design of the lifting equipment should be carefully coordinated with the crane clearance and with the dimensions of the crane hooks. The lifting equipment should safely clear bushings when handling the completely assembled transformer, and should be properly designed to compensate for eccentric weight dispositions of the complete transformer with bushings.

h. On-line monitoring systems. In addition to the on-line dissolved gas monitoring system described in paragraph 4-6*e*, other on-line systems are available to monitor abnormal transformer conditions. These include:

(1) Partial discharge analysis.

(2) Acoustical monitoring.

(3) Fiber-optic winding temperature monitoring.

(4) Bearing wear sensor (forced-oil-cooled units).

(5) Load tap changer monitor (if load tap changers are used).

Early detection of the potential for a condition leading to a forced outage of a critical transformer bank could more than offset the high initial costs of these transformer accessories by avoiding a more costly loss of generation.

i. Dial-type indicating devices. Dial-type indicating devices should be provided for:

(1) Liquid level indication.

(2) Liquid temperature indicator.

(3) Oil flow indicators (see paragraph 4-6*b*).

These are in addition to the dial-type indicators that are part of the winding temperature systems (see paragraph 4-6*f*).

4-7. Oil Containment Systems

If any oil-filled transformers are used in the power plant, provisions are made to contain any oil leakage or spillage resulting from a ruptured tank or a broken drain valve. The volume of the containment should be sufficient to retain all of the oil in the transformer to prevent spillage into waterways or contamination of soil around the transformer foundations. Special provisions (oil-water separators, oil traps, etc.) must be made to allow for separation of oil spillage versus normal water runoff from storms, etc. IEEE 979 and 980 provide guidance on design considerations for oil containment systems.

4-8. Fire Suppression Systems

a. General. Fire suppression measures and protective equipment should be used if the plant's oil-filled transformers are located in close proximity to adjacent transformers, plant equipment, or power plant structures. Oil-filled transformers contain the largest amount of combustible material in the power plant and so require due consideration of their location and the use of fire suppression measures. Fires in transformers are caused primarily from breakdown of their insulation systems, although bushing failures and surge arrester failures can also be causes. With failure of the transformer's insulation system, internal arcing follows, creating rapid internal tank pressures and possible tank rupture. With a tank rupture, a large volume of burning oil may be expelled over a large area, creating the possibility of an intense fire.

b. Suppression measures. Suppression measures include the use of fire quenching pits or sumps filled with coarse rock surrounding the transformer foundation and physical separation of the transformer from adjacent equipment or structures. Physical separation in distance is also augmented by the use of fire-rated barriers or by fire-rated building wall construction when installation prevents maintaining minimum recommended separations. Economical plant arrangements generally result in less than recommended minimums between transformers and adjacent structures so water deluge systems are supplied as a fire prevention and suppression technique. The systems should be of the dry pipe type (to prevent freeze-up in cold weather) with the system deluge valves actuated either by thermostats, by manual break-glass stations near the transformer installation, or by the transformer differential protective relay.