



IEEE Guide for Transformers Directly Connected to Generators

IEEE Power and Energy Society

Developed by the
Transformers Committee

IEEE Std C57.116™-2022
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STANDARDS

IEEE Guide for Transformers Directly Connected to Generators

Developed by the

Transformers Committee
of the
IEEE Power and Energy Society

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Abstract: Information on the selection and application considerations for the unit power transformer and unit auxiliary power transformer is provided in this guide. Consideration is given to connections that include direct connection and connections through generator circuit breakers and load-break switches. The considerations referred to in this guide apply to hydroelectric and thermal electric generating stations. Various power transformer connections and possible operating problems under normal and abnormal conditions are treated. Phasing procedures, basic impulse insulation level selection, and loading practices are not covered.

Keywords: back-feed, electrical parameters, generator bus, IEEE C57.116™, load tap changing, overcurrent, overexcitation, transformer connections, transmission system, unit auxiliaries, unit auxiliary transformer, unit power transformer

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Introduction

This introduction is not part of IEEE Std C57.116-2022, IEEE Guide for Transformers Directly Connected to Generators.

Transformers, directly connected to generators, experience excitation and short-circuit duties beyond those covered in other power transformer standards. Therefore, in 1979, the IEEE Transformers Committee decided that an application guide for such transformers was needed. In 1989, IEEE Std C57.116™ was approved and describes the selection, application, and specification considerations for the unit and unit auxiliary transformers (UAT) taking into account their connections, voltage and kilovolt ampere ratings, and excitation and through-fault capabilities during possible operating conditions, both normal and abnormal. Also included are load-tap changing and isolated phase-bus duct heating considerations. This guide does not address phasing procedures, basic impulse level selection, or loading practices.

In 2022, this guide was revised based on the latest knowledge, design, and application experience of the industry including the following:

- A new annex on considerations for specifying transformers directly connected to generators
- A new annex on volts per hertz (V/Hz) considerations
- Added applicable normative references
- Added discussion of capability curve for salient-pole generators
- Expanded guidance on high-voltage winding tap voltage ratings
- Expanded guidance on unit transformer parameter selection
- A new clause on special considerations for three-winding unit auxiliary transformers
- Expanded guidance on unit transformer operation in back-feed configuration
- An updated bibliography
- General edits and figure updates
- General updates to match the current IEEE Standards Style Manual

This standard is intended to provide guidance to application and specification engineers and therefore its use is strictly voluntary. Its use may become mandatory only when required by a duly constituted legal authority or when specified in a contractual relationship.

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IEEE Guide for Transformers Directly Connected to Generators

1. Overview

1.1 Scope

This guide describes selection and application considerations for the unit power transformer and unit auxiliary power transformer. Consideration is given to connections that include direct connection and connections through generator circuit breakers and load-break switches. The considerations referred to in this guide apply to hydroelectric and thermal electric generating stations. Various power transformer connections and possible operating problems under normal and abnormal conditions are treated. Phasing procedures, basic impulse insulation level selection, and loading practices are not covered.

1.2 Purpose

The terminology, function, application, theory of operation and protection, and design of unit power transformers and unit auxiliary power transformers are not covered by existing transformer standards and guides. The purpose of this document is to provide guidance for specifying, designing, and applying these types of power transformers.

1.3 Word usage

The word *shall* indicates mandatory requirements strictly to be followed in order to conform to the standard and from which no deviation is permitted (*shall* equals *is required to*).^{6,7}

The word *should* indicates that among several possibilities one is recommended as particularly suitable, without mentioning or excluding others; or that a certain course of action is preferred but not necessarily required (*should* equals *is recommended that*).

The word *may* is used to indicate a course of action permissible within the limits of the standard (*may* equals *is permitted to*).

The word *can* is used for statements of possibility and capability, whether material, physical, or causal (*can* equals *is able to*).

⁶The use of the word *must* is deprecated and cannot be used when stating mandatory requirements; *must* is used only to describe unavoidable situations.

⁷The use of *will* is deprecated and cannot be used when stating mandatory requirements; *will* is only used in statements of fact.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

ANSI C84.1, Electric Power Systems And Equipment—Voltage Ratings (60 Hz).⁸

IEEE Std 666™, IEEE Design Guide for Electric Power Service Systems for Generating Stations.^{9,10}

IEEE Std C50.12™, IEEE Standard for Salient-Pole 50 Hz and 60 Hz Synchronous Generators and Generator/Motors for Hydraulic Turbine Applications Rated 5 MVA and Above.

IEEE Std C50.13™, IEEE Standard for Cylindrical-Rotor 50 Hz and 60 Hz Synchronous Generators Rated 10 MVA and Above.

IEEE Std C57.12.00™, IEEE Standard General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers.

IEEE Std C57.12.10™, IEEE Standard Requirements for Liquid-Immersed Power Transformers.

IEEE Std C57.12.70™, IEEE Standard Terminal Markings and Connections for Distribution and Power Transformers.

IEEE Std C57.12.80™, IEEE Standard Terminology for Power and Distribution Transformers.

IEEE Std C57.19.04™, IEEE Standard for Performance Characteristics and Dimensions for High Current Power Transformer Bushings with Rated Continuous Current in Excess of 5000 A in Bus Enclosures.

IEEE Std C57.131™, IEEE Standard Requirements for Tap Changers.

3. Definitions, acronyms, and abbreviations

3.1 Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* and IEEE Std C57.12.80™ should be consulted for terms not defined in this clause.¹¹

back-feed: Operation of a unit transformer (UT) with the generator disconnected to supply start-up, auxiliary power, or testing power where low magnitude current flows in the opposite direction from normal operation of the transformer.

generator (rotating machinery): A machine that converts mechanical power into electrical power.

station service transformer (SST): A transformer that supplies power from a station high-voltage bus to the station auxiliaries and also to the unit auxiliaries during unit startup and shutdown or when the unit auxiliary transformer is not available or both.

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¹¹*IEEE Standards Dictionary Online* is available at: <http://dictionary.ieee.org>. An IEEE Account is required for access to the dictionary, and one can be created at no charge on the dictionary sign-in page.

underexcitation limiter (UEL): An electronic limiter added to excitation systems to limit the operation of generators in the underexcited region to avoid end iron heating or steady state stability limits.

unit: The generator or generators, associated prime mover or movers, unit auxiliary transformer and unit transformer that are normally operated together as a single source of electric power.

unit auxiliary transformer (UAT): A transformer intended primarily to supply all or a portion of the unit auxiliaries. *Syn:* **unit auxiliary power transformer.**

unit transformer (UT): A power system supply transformer that transforms all or a portion of the unit power from the unit to the power system voltage. *Syn:* **unit power transformer, generator step-up (GSU) transformer.**

4. Background

The unit connected generating system came into usage as generator size and generator bus fault current levels began to exceed the capability of breakers that were available to isolate the generator from the power system. Generally, the generator auxiliary load is fed from a transformer that is connected directly to the generator bus. An alternate source of power is normally supplied from the transmission system by a second transformer during unit startup, shutdown, and other contingencies. Such a system is shown in Figure 1.¹² Typically, an isolated phase-bus is used for connection between the generator and its unit transformer (UT) and unit auxiliary transformer (UAT); thus, the system is unit connected. Studies indicate that through faults for the UT, when a generator breaker is included, are normally not severe in terms of either thermal or mechanical duty. However, the stresses in the UAT, and in any auxiliary transformers connected to the generator bus, can be severe under certain conditions, such as low-side faults, generator load rejection and, if applicable, paralleling out of phase with the station service transformer (SST), and should be designed to withstand all expected abnormal conditions.

On units connected directly without generator breakers, faults at location (3) as indicated by the X in Figure 1 will be fed predominantly by two sources, namely, through the UT from the system and from the generator. Normally the differential relay protection system, which will detect faults at location (3) in Figure 1, will initiate a unit trip that will disconnect the unit from the system and remove the generator excitation. The loss of load may result in a higher voltage on the generator that will continue to feed the fault. This higher voltage due to load rejection will increase the generator's current contribution to a level higher than before load rejection. However, the system contribution will be absent. The generator's contribution will continue at a level and for a period that depends on the generator's fault-current decrement characteristics. The fault-current decrement characteristics are a function of the generator short-circuit parameters and its excitation system. As a result of the generator's fault-current decrement characteristics, faults at location (3) in Figure 1 may exceed the thermal and mechanical capabilities of the UAT if it is designed solely in accordance with IEEE Std C57.12.00™.¹³

Abnormal operating conditions, such as generator load rejection, may result in high generator bus voltages that may also cause overexcitation of the transformers connected to the generator bus. Conditions such as this can vary from location to location and should be studied on a case-by-case basis.

Out-of-phase paralleling of the UAT with the SST can produce high currents that may exceed the mechanical capability of these transformers. Frequency mismatch between the generator and system voltages also can cause severe mechanical stresses on the transformers.

¹²Notes in texts, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

¹³Information on references can be found in Clause 2.

A generator breaker at location (2) in Figure 1 would not completely eliminate all of the system problems described in the preceding paragraphs. Generally, it can be shown that thermal and longtime overexcitation exposures of the UAT can be eliminated by the use of a generator breaker, but the mechanical aspects of paralleling two sources out-of-phase or of frequency mismatch should still be given consideration in the design of the UAT.

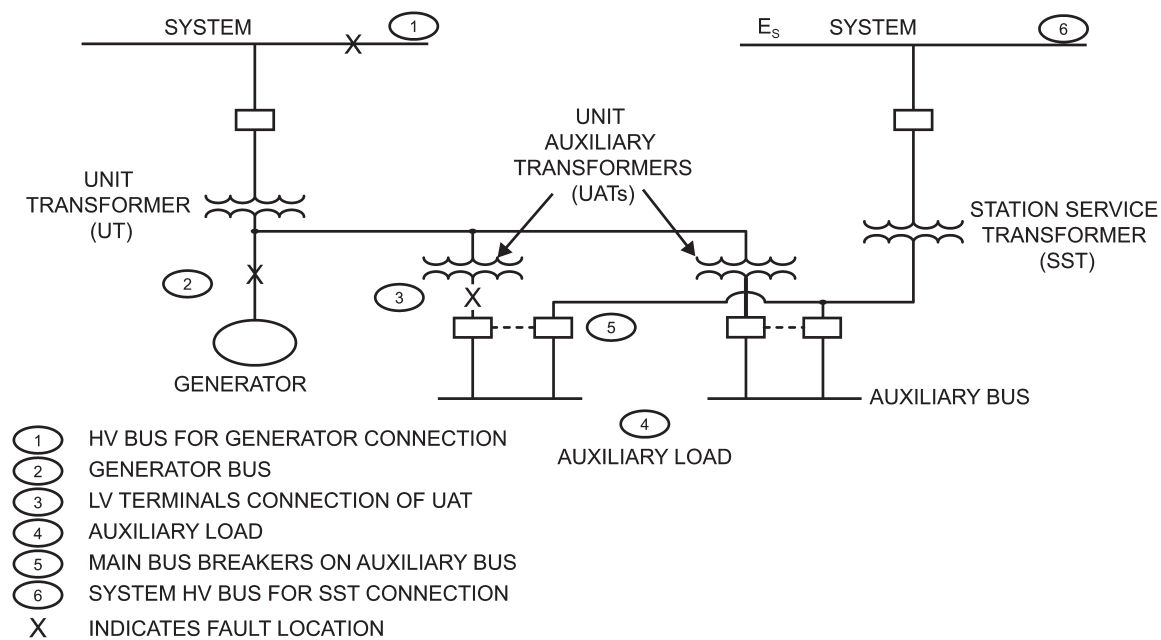
A generator breaker at location (2) in Figure 1 could simplify operation by eliminating the need for transferring auxiliary power during startup or maintenance. Depending on the plant's configuration, a generator breaker could eliminate the need for a station service transformer and associated circuit breakers; and will isolate the generator if a unit trips or a fault occurs as indicated by the X in Figure 1.

In addition to the characteristics of a UT, the application of a UT must consider the installation and operation of it within the system. Two important subjects in this context are the concerns for UTs connected by Isolated Phase-Bus, and for the operation of UT transformers in back-feed configurations. Both are discussed in additional detail in this guide.

The following is a list of other considerations that should be evaluated in the selection and application of UTs and UATs.

- Cooling requirements
- Single-phase versus three-phase transformers for UT applications
- Short-circuit withstand of UTs with single high-voltage winding and split low-voltage windings
- Overall economic evaluation of equipment costs, installation costs, and the cost of losses

Due to limited scope, these other considerations are not discussed in this guide. However, they should be considered in the selection of transformer parameters.



NOTE 1—UT HV and UAT LV groundings are design dependent.

NOTE 2—UT and UAT neutral connections are omitted for simplicity.

Figure 1—Typical generating station auxiliary power system one-line diagram

5. Transformer connections

5.1 Unit transformer connections

The most common connections used for large UTs are shown in Figure 2. For voltages above 115 kV where the neutral is normally solidly grounded, the high-voltage wye connection is advantageous due to the economics of reduced neutral dielectric insulation.

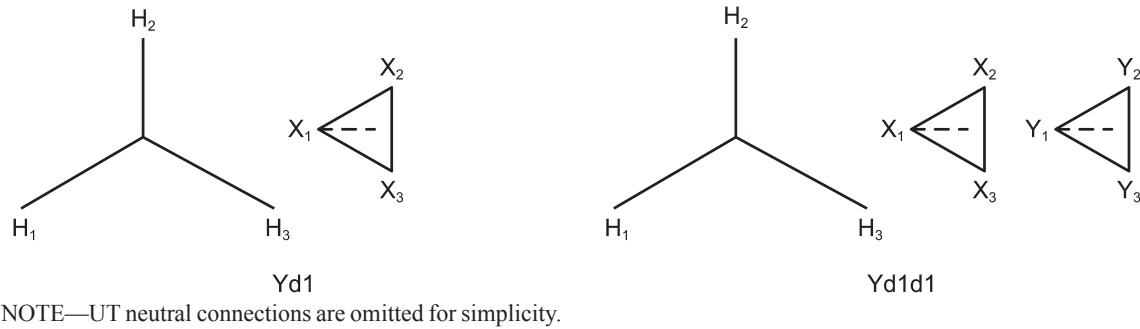


Figure 2—Typical unit transformer connections

5.2 Unit auxiliary transformer connection

The most common connections used are shown in Figure 3. The Dy11 or Dy11y11 connections shown in Figure 3 are the most common connections used, but the Dy1 or Dy1y1 connections shown in Figure 3 can also be used if reconnected as shown to replace Dy11 or Dy11y11 transformers when necessary.

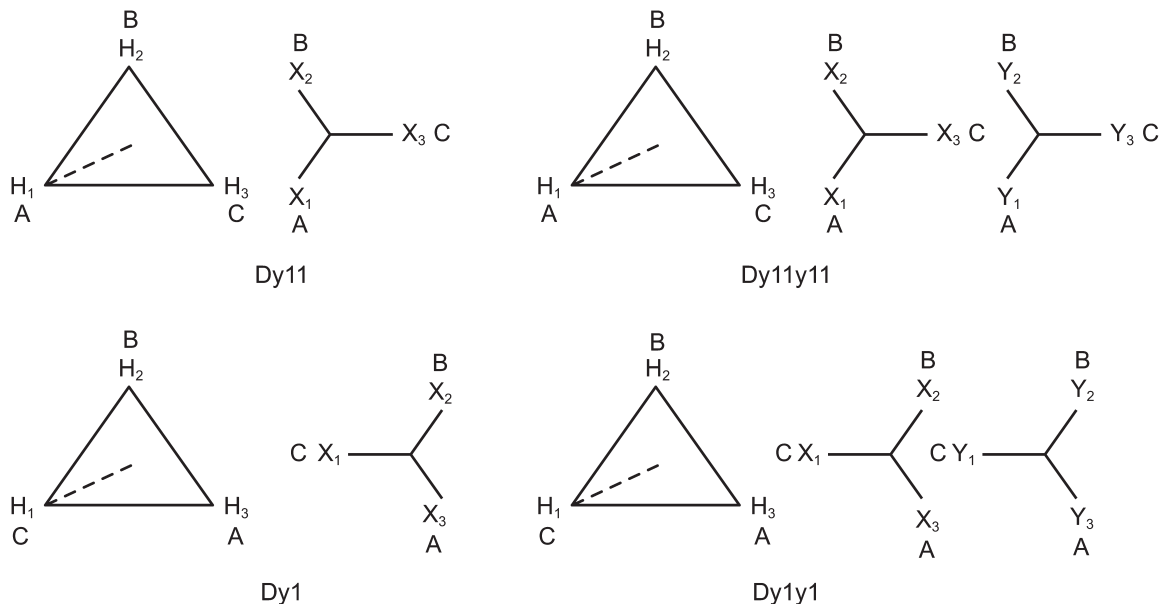


Figure 3—Typical unit auxiliary transformer connections

5.3 Unit transformer and unit auxiliary transformer external connections

In [Figure 2](#), in order for the voltages supplied by both the UATs and the SST to have the same magnitude and be in-phase at the auxiliary bus for bus transfer considerations, the transformation ratios and phase displacement of the UT, UATs and SST need to be properly selected and connected.

The UT is normally constructed with a wye-connected HV winding and a delta-connected XV winding or XV and YV windings, with the XV or XV and YV phase voltages lagging the HV by 30° as shown in [Figure 2](#). The UAT transformers are then connected as shown in the Dy11 or Dy11y11 upper pair of connections in [Figure 3](#), with the XV, or XV and YV, phase voltages leading the HV voltages by 30° , making the auxiliary bus in-phase with the system bus connected to the UT's HV terminals. If the SST is connected to the same system bus as the UT, the SST should then be connected Wye-wye or Wye-wye-wye, or alternately Delta-delta or Delta-delta-delta, with no phase displacement between the HV and XV or YV phase voltages.

If a UAT is not available with the XV, or XV and YV phase voltages leading the HV phase voltages by 30° , a UAT with the XV or XV and YV phase voltages lagging the HV phase voltages by 30° can be connected to provide the required phase displacement if two of the system phase voltages are interchanged on the HV and XV, or HV XV and YV terminals. For example, if the UT terminals are connected, A to H1, X1 and, if equipped, Y1, B to H2, X2 and Y2, and C to H3, X3 and Y3, the XV or XV and YV windings will lag the HV phase voltages by 30° . For the UATs, if the transformers are constructed with the XV or XV and YV phase voltages lagging the HV phase voltages, the A and C phase system voltages terminals should be reconnected, connecting A phase to H3, X3 and, if equipped, Y3, B phase to H2, X2 and Y2, and C phase to H1, X1 and Y1, as shown in the lower pair of Dy1 or Dy1y1 connections in [Figure 3](#). This will change the phase rotations and displacement so the XV or XV and YV phase voltages will lead the HV phase voltages by 30° . It should be noted, however, that there may be practical difficulties in making these phase interchanges, particularly when the UATs are connected to isolated phase-bus that may make this a less-than-optimal option. For further information on this subject, see IEEE Std C57.12.70™.

6. Selection of parameters of unit transformer

6.1 Overview

The primary function of the UT is to transform the power output of the generator (less auxiliaries power and unit transformer losses) from the generator terminal voltage to the transmission system voltage. Thus, the correct selection of UT parameters should be governed by the electrical characteristics of the generator system and the transmission system to which the UT connects.

6.2 Generator bus electrical characteristics

6.2.1 Generator capability curve

A typical round rotor generator reactive power capability curve is shown in [Figure 4](#) at rated generator voltage. The curve is based upon three thermal limits of typical hydrogen cooled generators. At the top of [Figure 4](#), the limit as labeled, is the field heating limit. When operating in this region the generator is overexcited and the field is carrying greater than rated dc field current. The I^2R losses in the field reach the limit of the maximum amount of heat that can be dissipated by the rotor without overheating. Toward the right side of [Figure 4](#), the limit as labeled is the stator heating limit. When operating in this region, the ac stator output current has reached the limit of the winding design to dissipate I^2R losses in the stator at near unity power factor. At the bottom of [Figure 4](#), the limit is due to end iron heating. In this region, the generator is operating underexcited, that is with minimal field current, and is not limited by I^2R losses like the other two limits, but rather by heating of the core laminations at the end of the generator stator core. When operating in this region, the generator flux enters the end laminations almost perpendicular to the core stack and produces large eddy current losses. In addition, system stability may also become a limitation when operating in this region.