Transformer Principles

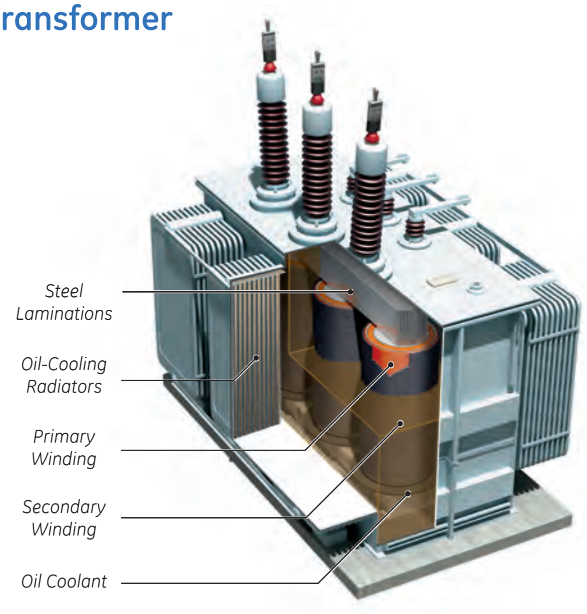
Introduction

The purpose of a transformer is to isolate, phase-shift, and step-up or step down voltage and current levels for either distribution or transmission. They perform these functions with the use of a primary winding and one or more secondary windings located within the transformer casing.

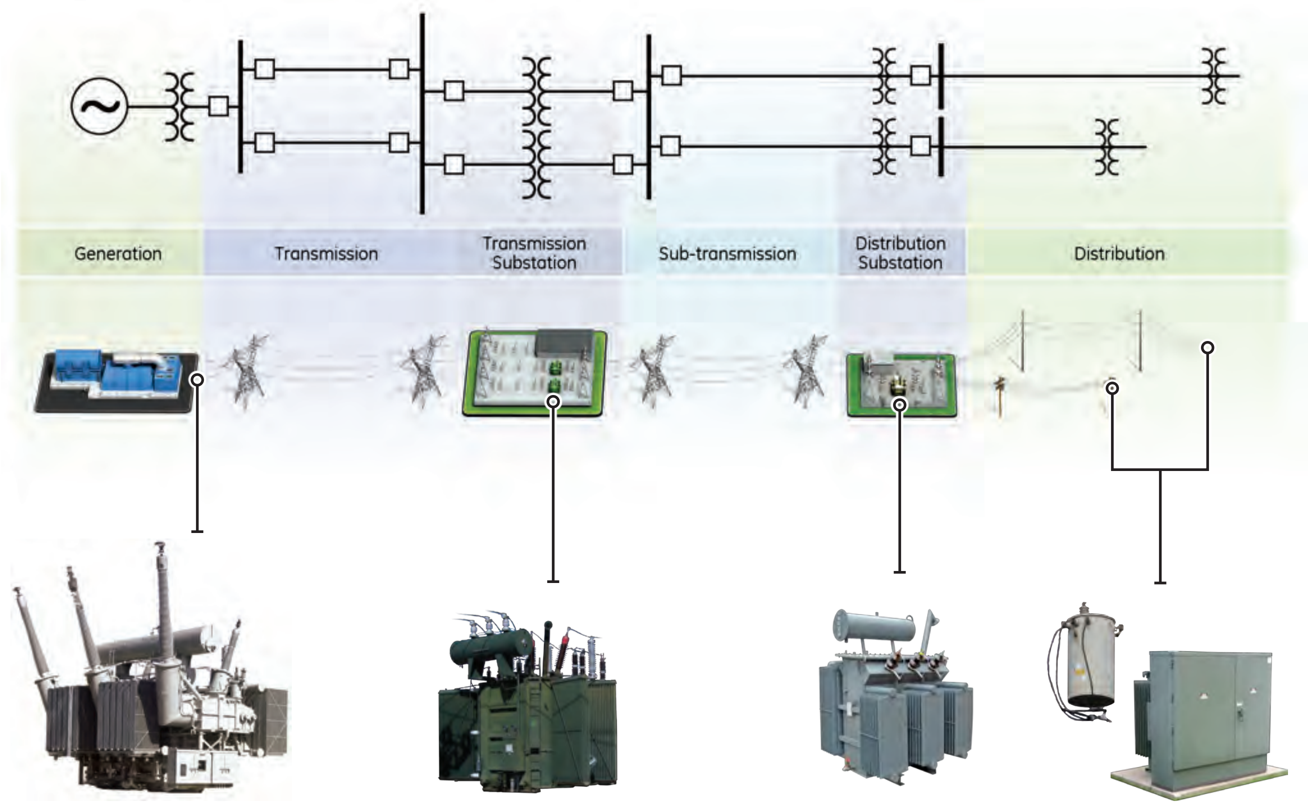
These windings work on the principle of induction, were the primary winding induces the secondary winding(s) with voltage and current. The windings are placed in close proximity, but are electronically isolated from each other.
The power induced into the coils can either be stepped-down, meaning an increase in current and a decrease in voltage, usually required for distribution, or stepped-up meaning a decrease in current and an increase in voltage, usually required for transmission.

Transformers can range in size from very small coupling transformers that are hidden within a device to large units that are used to interconnect power grids. Transformers have become an essential component for high voltage power transmission as they ensure long distance transmission is economically practical.

Typical Step-Down Distribution Transformer



Transformer locations in a power system:



Medium - High Voltage Step-Up Transformer 100 MVA +

High Voltage Step-Down Transformer 7500 kVA - 100 MVA

Medium - High Voltage Step-Down Transformer 500 kVA - 7500 kVA

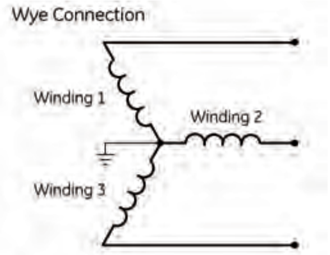
Medium - Low Voltage Step-Down Transformer 75 kVA - 500 kVA

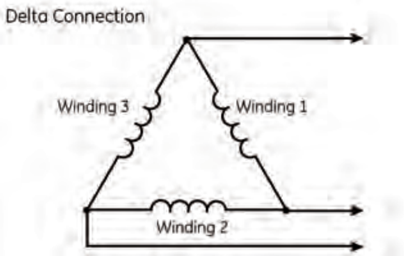
Three-Phase Transformers

As most power is distributed in the form of three-phase AC, we will focus on the various types of three-phase transformers that support this type of power system. By nature, three phase transformers are designed with three primary windings and three secondary windings mounted on a three-legged core.

The windings within a three-phase transformer may be connected in several ways. The primaries may be connected in a delta configuration and the secondaries in a wye configuration or visa versa.

Delta vs. Wye transformers





Most distribution systems utilize a wye connected system as it offers greater advantages to the over-all system performance. As such, most power and distribution transformers are constructed using the same connections.

In a wye connection, one wire from each coil is connected together to form the neutral. In most power systems, the neutral is grounded, providing a low resistance connection to earth and an electrical reference point at zero points. By having this reference point, safety, voltage stability and protection system design are improved.

When determining and comparing which connection type is most suitable for a specific application, the following criteria could be used:

- Ratio of kVA output to the kVA internal rating of the bank
- Degree of voltage symmetry with unbalanced phase loads
- Voltage and current harmonics
- Transformer ground availability
- System fault-current level
- Switching and system fault and transient voltages

Advantages of a grounded-wye connected transformer

- Lower operating voltage as equipment is connected Line-to-Neutral (L-N) as opposed to the higher voltage required by Line-to-Line connections (L-L)
- Smaller transformer size required as equipment is connected at a lower voltage
- Easier to detect line-to-ground faults as any fault current generated, either as an overcurrent or a short-circuit would result in a significant of current on the neutral

Advantages of a Delta connected transformer

- Polarity end of one winding is connected to the non-polarity end of the next, allowing for an isolated ground
- One transformer can be removed (when connected in a bank) while the remaining units deliver three-phase power at 58% of the original output
- Easy system to keep balanced electrical loads with the transformer being electrically grounded or ungrounded, making it more versatile.

Since a 3-phase transformer can have its primary and secondary windings connected the same (delta-delta or wye-wye), or differently (delta-wye or wye-delta). It is important to note that the secondary voltage waveforms will be in phase with the primary waveforms when the primary and secondary windings are connected the same way.

In a situation where the primary and secondary windings are connected differently, the secondary voltage waveforms will differ from the corresponding primary voltage waveforms by 30 electrical degrees. This is called a 30∞ phase shift.

The danger with this phase shift is, if two transformers are connected in parallel, and their phase shifts are not identical, a short circuit will occur when the transformers are energized.

Sizing and Selecting a Transformer

Transformer size is determined by the kVA of the load. To determine the size of the transformer you need to determine the following requirements:

- Load Voltage
- Load Current/Amps
- Line Voltage

Equation (three-phase transformers):
(volts x amps x 1.732) / 1000 = kVA

The kVA rating of your transformer should be greater than or equal to the kVA resulting from the above equation.

Typical Nameplate Data

GE Energy			
Transformer			
KVA Rating:	154700/206300/257800	Primary Voltage (volts):	138000
Class:	ONAN/ODAF/ODAF	Primary Vector:	Wye
MFG:	General Electric Inc.	Secondary Voltage (volts):	18000
Year:	1998	Secondary Vector:	Delta
Serial Number:	TP-310	HV Range (volts):	131100 - 144900
Impedance:	11.753% @ 257MVA	LV Range (volts):	None
Oil Capacity (gals.):	14500	LTC High Voltage:	No Load
Ship Length (inches):	280	LTC Low Voltage:	None
Ship Height (inches):	190	HV BIL (kv):	650
Ship Width (inches):	142	LV BIL (kv):	125
Shipping Weight (lb):	240000	Neutral BIL (kv):	110
Core/Coils (lbs):	208790	CT HV:	Qty (2) per phase 1200:5 MR
Tank/Fittings (lbs.):	75275	CT LV:	Qty (2) per phase 1000:5 MR
Test Available:	Yes	Tertiary:	
LV Bushing:	Top	Drawing	Yes
HV Bushing:	Top	Assembled:	No
HV TAPS (volts):	**131100, 134550, 138000, 141450, 144900**	PCB (ppm):	None
LV TAPS (volts):	**1800**		

Transformer Nameplate Data:

Correct transformer protection setup and configuration is essential to ensuring, not only proper but, optimized transformer operation (in terms of both performance and efficiency). The key pieces of data required to maximize transformer operation can be found on the transformer nameplate, which is supplied by every manufacturer.

Defined by codes and standards, depending on the kVA rating of a transformer, there is a minimum amount of data that must be shown on a nameplate. For transformers rated above 500 kVA the following information is required:

- Name of manufacturer
- Serial number
- Month/year of manufacture
- Cooling class
- Number of phases
- Frequency
- KVA or MVA rating
- Voltage Ratings
- Tap Voltages
- Rated Temperature Rise (degree C)
- Phase or vector diagram (for polyphase transformers)
- Percent impedance
- Basic lightning impulse insulation levels (BIL ratings). Note: The BIL rating for each winding and each bushing are indicated
- Approximate mass of the entire unit. Individual weights are provided for the core and coils, as well as the tank and fittings
- Connection diagram showing all winding terminations with a schematic plan view showing all fixed accessories
- Installation operating instructions references
- Suitability for step-up operation
- Maximum positive and negative operating pressures of the oil preservation system
- Liquid level below the top surface of the highest point of the highest manhole flange at 25 degrees C
- Change in liquid level per 10 degree C change
- Oil volume of each transformer compartment
- Type of insulating liquid
- Conductor material of each winding

Transformer Protection

Introduction

Transformers are a critical and expensive component of the power system. Due to the long lead time for repair of and replacement of transformers, a major goal of transformer protection is limiting the damage to a faulted transformer. Some protection functions, such as overexcitation protection and temperature-based protection, may aid this goal by identifying operating conditions that may cause transformer failure. The comprehensive transformer protection provided by multiple function protective relays is appropriate for critical transformers of all applications.

Transformer Protection Overview

The type of protection for a transformer varies depending on the application and the importance of the transformer. Transformers are protected primarily against faults and overloads. The type of protection used should quickly isolate the transformer for internal faults to reduce the risk of catastrophic failure, and to simplify eventual repair. Any extended operation of the transformer under abnormal condition such as overexcitation or overloads compromises the life of the transformer, which means adequate protection should be provided for such conditions.

Transformer Failures

Failures in transformers can be classified into

- winding failures due to short circuits (turn-turn faults, phase-phase faults, phase-ground, open winding)
- core faults (core insulation failure, shorted laminations)
- terminal failures (open leads, loose connections, short circuits)
- on-load tap changer failures (mechanical, electrical, short circuit, overheating)
- abnormal operating conditions (overfluxing, overloading, overvoltage)
- external faults

Innovative GE Multilin Solutions to Transformer Protection Applications

Differential Characteristic

The major operating challenge to transformer differential protection is maintaining security during CT saturation for external faults while maintaining sensitivity to detect low magnitude internal faults. CT saturation reduces the secondary output current from the CT, and causes a false differential current to appear to the relay. GE Multilin differential relays meet this challenge in the following ways:

- the restraint current is based on the maximum measured winding current, as opposed to the traditional magnitude sum of the currents. This ensures ideal restraint for the actual fault condition, balancing sensitivity and security.
- the differential element uses a dual slope-dual breakpoint characteristic. The differential element can be set to account for both DC and AC saturation of the CTs, ensuring security, while maintaining sensitivity.

Available in the T60, T35.

Conditions	Protection Philosophy
Internal	
Winding Phase-Phase, Phase-Ground faults	Differential (87T), overcurrent (51, 51N) Restricted ground fault protection (87RGF)
Winding inter-turn faults	Differential (87T), Buchholz relay
Core insulation failure, shorted laminations	Differential (87T), Buchholz relay, sudden pressure relay
Tank faults	Differential (87T), Buchholz relay and tank-ground protection
Overfluxing	Volts/Hz (24)
External	
Overloads	Thermal (49)
Overvoltage	Overvoltage (59)
Overfluxing	Volts/Hz (24)
External system short circuits	Time overcurrent (51, 51G), Instantaneous overcurrent (50, 50G)

Inrush Inhibit during Transformer Energization:

The differential current present during transformer energization resembles the condition of an internal fault. If no inhibiting mechanism is provided, the differential element will trip. Since the magnetizing inrush current has significant 2nd harmonic content, the level of 2nd harmonic current can be used to differentiate between inrush and a fault condition. The UR T60 and T35 GE Multilin transformer relays use two different 2nd harmonic modes to inhibit the differential element for inrush.

Traditional 2nd harmonic blocking – The traditional 2nd harmonic restraint responds to the ratio of the magnitudes of the 2nd harmonic and the fundamental frequency currents.

Adaptive 2nd harmonic blocking– The adaptive 2nd harmonic blocking responds to both magnitudes and phase angles of the 2nd harmonic and the fundamental frequency currents. The differential element correctly distinguishes between faults and transformer energization, when the 2nd harmonic current is less than the entered 2nd harmonic setting. While levels of 2nd harmonic during inrush often do not go below 20%, many transformers are susceptible of generating lower 2nd harmonic current during energization. Setting the 2nd harmonic restraint below 20% may result in incorrect inhibit of the differential element during some internal fault events. The adaptive 2nd harmonic blocking allows settings in the traditional 20% range, while maintaining the security of the differential element against inrush.

Available in the T60, T35.

An alternative method for inrush inhibit is also available, where current, voltage, or breaker status is used to indicate a de-energized transformer. The threshold can be lowered during energization of the transformer as indicated either by breaker contact, current or voltage sensing, and will last for a settable time delay. This allows settings of less than 20% for inrush inhibit during transformer energization.

Available in the 745.

Sensitive Ground Fault Protection to limit Transformer Damage

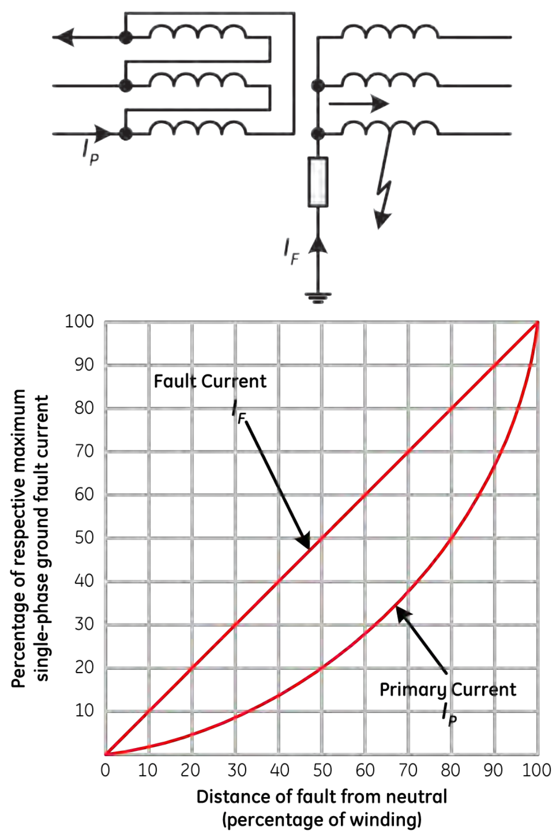
Differential protection and overcurrent protection are not sensitive enough to detect faults close to the neutral of wye-connected transformers with grounded neutrals. Such faults produce less fault current as shown by the current distribution curve. The restricted ground fault function can be used to provide differential protection for such ground faults, down to faults at 5% of the transformer winding. Restricted ground fault protection can be a low impedance differential function or a high impedance differential function. The low impedance function can precisely set the sensitivity to meet the application requirement. This sensitive protection limits the damage to the transformer for faults close to the neutral. The restricted ground fault element uses adaptive restraint based on symmetrical components to provide security during external phase faults with significant CT error. This permits the function to maximize sensitivity without any time delay.

Available in the 745, T60.

Overflux Protection

Transformer overfluxing can be a result of system overvoltages, or low system frequency. A transformer is designed to operate at or below a maximum magnetic flux density in the transformer core. Above this design limit the eddy currents in the core and nearby conductive components cause overheating which within a very short time may cause severe damage. The magnetic flux in the core is proportional to the voltage applied to the winding divided by the impedance of the winding. The flux in the core increases with either increasing voltage or decreasing frequency. During startup or shutdown of generator-connected transformers, or following a load rejection, the transformer may experience an excessive ratio of volts to hertz, that is, become overexcited. When a transformer core is overexcited, the core is operating in a non-linear magnetic region, and creates harmonic components in the exciting current. A significant amount of current at the 5th harmonic is characteristic of overexcitation.

Available in the 745, T60, and T35.



Ground fault current for impedance grounded neutral transformer for faults at different % of the winding.

Winding hot-spot temperature protection

The transformer winding hot-spot temperature is another quantity that should be used for protection of transformers. Protection based on winding hot-spot temperature can potentially prevent short circuits and catastrophic transformer failure, as excessive winding hot-spot temperatures cause degradation and eventual failure of the winding insulation. The ambient temperature, transformer loading, and transformer design determine the winding temperature. Temperature based protection functions alarm or trip when certain temperature conditions are met.

GE Multilin relays use IEEE C57.91 compliant thermal models to calculate the winding hot-spot temperature and the loss of life of the winding insulation. The top-oil temperature may be directly measured, or calculated from the ambient temperature, load current, and transformer characteristics. In addition, the calculations may use a monthly model of ambient temperature, eliminating the need for external connections to the transformer and relay. This winding hot-spot temperature and transformer loss of life information is used in thermal overload protection to provide alarming or tripping when unacceptable degradation of the transformer winding insulation is occurring.

Available in 745, T60.

Application Capabilities

GE Multilin transformer protection relays are suitable for different transformer protection applications, including medium voltage and high voltage transformers of any size, dual secondary transformers, auto-transformers, three-winding transformers, transformers with dual-breaker terminals.

In addition, these relays are designed for both new and retrofit installations. New installations typically use wye-connected CTs, and internally compensate the measured currents for the phase shift of the protected transformer. Traditional installations may use delta-connected or wye-connected CTs that externally compensate the measured currents for the phase shift of the protected transformer. GE Multilin accommodates both methods as simple configuration settings.

Beyond these typical applications, GE Multilin transformer protection relays can be applied on more advanced applications.

Acquiring transformer measurements

Transformer protection requires the use of currents measured from each winding, and possibly system voltages and transformer top-oil temperatures. Current measurements are normally taken from bushing CTs mounted at the transformer, voltages from nearby VTs, and top-oil temperatures via RTDs from the transformer cooling controls. Each measurement must be brought back individually by copper wiring to the transformer protection relay. Top-oil temperatures, for example, are rarely brought back to the transformer protection relay because of the need to run RTD wires across the switchyard. Each copper wire requires numerous terminations that are designed, documented, field installed, and tested one at a time.

The HardFiber IEC 61850 Process Bus Solution simplifies the acquisition of measurement signals for transformer protection. The Brick interface device is mounted at the transformer. Winding currents (for 2 windings), ground current, top-oil temperatures, and sudden pressure relays / Bucholtz relay trips are wired to the Brick. One fiber optic cable, transmitting sampled values from all transformer measurements, and digital status information, is pulled across the switchyard to connect to the transformer protection relay. The copper wiring and fiber optic cabling uses simple connectors to attach to the Brick.