ABSTRACT

Transformers are used in the electrical networks everywhere: in power plants, substations, industrial plants, buildings, data centres, railway vehicles, ships, wind turbines, in the electronic devices, the underground, and even undersea. The focus of this article is on transformers applied in the transmission of energy, usually called power transformers. Due to very versatile requirements and restrictions in the numerous applications, ranging from a subsea transformer to a wind turbine transformer, a small distribution transformer to a large phase shifter transformer, it is very difficult to organise a structured overview of the transformer types. Also, different companies supply different markets and each have their own classification of the transformers, which makes the transformer family even more difficult to organise. This paper will attempt to provide a relatively common point of view on most of those transformers types.

Keywords:

classification, distribution transformers, power transformers, reactors, transformers

Classification of Transformers Family

1. Introduction

Transformers basically perform a very simple function: they increase or decrease voltage and current for the electric energy transmission. It is precisely stated what a transformer is in the International Electrotechnical Vocabulary, Chapter 421: Power transformers and reactors [1]:

"A static piece of apparatus with two or more windings which, by electromagnetic induction, transforms a system of alternating voltage and current into another system of voltage and current usually of different values and at the same frequency for the purpose of transmitting electrical power."

The focus of this article is on the transformers which enable transmission of energy in the electrical grid, while all other types, such as the instrument transformers (i.e. voltage and current transformers) and the audio transformers, etc., are excluded. The aim is to provide an overview of different types of transformers in the most systematic way rather than elaborating on each type.

The most important international organisations with focus on such transformers are IEC[1] through E14, its technical committee for the world standards; IEEE[2] through the Transformers Committee mainly for the American standards and CIGRE[3] through the Study Committee A2 Transformers which mainly produces technical brochures and guidelines on many subjects. Main standards for the transformers in question are the IEC 60076 [2] and the IEEE C57 [3] series.

2. Classification of transformers family

As mentioned above, transformers perform a very simple function and they can have many applications. Transformers are

[1] IEC - International Electrotechnical Commission
[2] IEEE - Institute of Electrical and Electronics Engineers
[3] CIGRE - Council on Large Electric Systems

Transformers exist for more than a century and they can be manufactured and used very differently according to customers needs.

used in every power plant, all grid substations, buildings, in the industry, the underground installations, wind turbines, on platforms, marine vessels, under the sea, etc. Due to peculiarities of all these applications, many different types of transformers have been developed in the course of history. To simplify the overview of many transformer types, it is useful to have some kind of systematic classification. However, this is not easy to do because there are many ways of doing it. The transformer types could be classified according to their power rating, voltage, current, weight, type of cooling etc., but such approach would have a limited applicability.

Probably the simplest and the clearest transformer classification is according to the number of phases in:
- single-phase transformers
- three-phase transformers

In a three-phase system, the single-phase units are used in a bank of three transformers linked together. A single three-phase transformer costs approximately 15% less and occupies less space than one unit of three single-phase transformers within the same tank. However, due to limitations during the manufacturing and mainly transportation, particularly of large units, the transformers sometimes must be produced as single-phase transformers. Another reason for using a single-phase unit rather than a three-phase unit, is the possibility of having a fourth identical unit as a spare. Despite its simplicity and clarity, this type of classification does not help in classification of the whole transformers family.

Classification according to basic technology of a transformer design and manufacturing is also often used. There are two main technologies for designing and manufacturing the transformers:
- core type
- shell type

In a shell-formed transformer, the primary and secondary windings are quite "flat" and are positioned on one leg surrounded by the core. In a core-formed transformer, cylindrical windings are like "coils" and cover the core legs. However, this classification is also limited in the large portfolio of either of those two transformer types.

Transformers can be classified according to the insulating/cooling fluid in:
- liquid-filled transformers
- gas-filled transformers (mainly with SF6)
- dry-type transformers

As the dry-type, and particularly gas-filled/insulated transformers have limited applications in a large power system, this classification is also not perfect.

Despite not being a perfect one, perhaps the most practical classification used by the industry is the one according to the transformer application. According to this approach, transformers can be roughly classified as:
- power transformers
- distribution transformers
- reactors

This classification could, however, raise some questions. There are no obvious technical reasons for classifying a transformer as a distribution transformer rather than a power transformer but it is widely used in practice so it is helpful. The term "distribution transformer" is somewhat used in the IEC 60076, while it is commonly used in IEEE C57. Some companies define distribution transformers as the power transformers below 10 MVA. The 2.5 or 5 MVA limits are also used instead of 10 MVA.

The classification above is even more dubious with regards to reactors, because they are not transformers at all but are usually grouped with transformers because they share most of the technology with power transformers and they are designed and produced in the transformer factories. It took me some time at the beginning of my carrier to distinguish a reactor from a transformer and I believe that others had a similar experience.

The classification by application will be used in this article.

Since transformers have been in existance, many different types have been produced and consequently their classification is quite challenging!

3. Power Transformers

Power transformers cover the population of the largest transformer units by means of power and voltage ratings. Manufactured units range from 1500 MVA, and up to 1785 kV. Several large phase shifting transformers consisting of two linked units have been manufactured with a combined capacity of 2750 MVA.

There are several different classifications of power transformers according to their power and voltage ratings or size, and/or according to the application.

Classification according to size

Classification according to size is a bit ambiguous because different companies use different power and voltage range for particular types. This discrepancy may be due to the fact that manufacturers divide their portfolio according to the market they supply so, in their specific case, other classifications are considered pointless. Utilities can also have different fleets; therefore a certain classification can be better for each utility. The ranges mentioned here do not render presumption of general validity.

Large Power Transformers (LPT)

This group covers the largest units in the power transformers population with power of normally above 200 MVA (limits used range between 100 and 250 MVA) and High Voltage (HV) of usually at least 220 kV. Within this group there is less competition in the market but technical problems such as insulation problems (high dielectrical stress), magnetic problems (high leakage flux), thermal problems (high heating due to operational losses), mechanical problems (high forces due to short-circuit currents), transportation (large dimensions and very heavy weight), etc. are extremely high.

Figure 1: LPT 265 MVA, 525 kV [4]

Medium Power Transformers (MPT)

This group includes transformers with a power range from 60 to 200 MVA (or 40 to 250 MVA), and a high voltage of up to around 275 kV.

Figure 2: MPT [4]

Small Power Transformers (SPT)

Transformers from roughly 10 to 60 MVA and a maximum service voltage of 170 kV belong to this group. Other limits used are from 5 to 40 MVA and up to 145 kV.

Figure 3: SPT 12,5 MVA with On-Load Tap Changer [4]

Classification according to application

According to the application, power transformers can be divided in several subgroups:
- generator step-up transformers (GSU)
- system intertie (interconnecting) transformers
- step-down transformers
- phase-shifting transformers (PST)
- HVDC converter transformers
- transformers for industrial applications
- traction transformers
- mobile transformers
- test transformers

3.1 Generator step-up transformers (GSU) are essential components of the power plants linking the plant generator to the transmission network. Built as three single-phase or three-phase units in the core or shell technology, they transform voltage from the generator voltage level up to the suitable transmission voltage level, which may go up to 800 kV nowadays.

GSU transformers usually have delta-connected Low Voltage (LV) windings (energised by the generator), and star connected High Voltage (HV) windings (connected to the transmission lines). The connection of such transformers is mainly YNd.

They often operate continuously at full load facing variations in voltage due to changes of the load or the network requirement for reactive power. High rated currents, particularly in the larger units, require a good control of the magnetic field to avoid localised overheating.

GSU transformers can be very heavy for high power rated units which need to deliver the entire power of the power plant to the local grid.

Figure 4: GSU transformer 890 MVA [4]

Power transformers cover the highest power and voltage ratings within the transformers family.

According to their main use, power transformers can be somewhat „classified“ into a few categories.

3.2 System intertie (interconnecting) transformers connect AC systems of different voltage levels so that active as well as reactive power can be exchanged between them. They can have fully separate windings or electrically connected windings, in which case they are called autotransformers.

Transformers with separate windings provide a galvanic insulation between the two voltage systems.

Autotransformer, compared to a transformer with separate windings of the equivalent rating, is a more compact and economical solution. Typical voltage ratio between HV and LV is between 1 and 2 for autotransformers. However, as they have connected windings, there is no galvanic insulation between the two interconnected systems.

Figure 5: Autotransformer 250 MVA [4]

3.3 Step-down transformers can be classified as a variety of the system intertie transformers. Their purpose is a voltage transformation from the transmission voltage level down to an appropriate distribution level. However, with penetration of distributed generation energy direction can change, and when it happens a step-down transformer becomes a step-up transformer.

3.4 Phase-shifting transformers (PST) are among the most complex transformers. Their purpose is to control power flow between the parallel power lines or cables; or between the two independent power systems. To achieve this, they are designed not to significantly change the voltage magnitude but mainly its phase angle (hence their name). Voltage magnitude and angle are controlled by superimposing induced secondary voltage and some other voltage with necessary phase displacement to the main line voltage. When transformer has one active part, the additional de-phased voltage can be taken from the winding onto another core limb but two active parts are necessary for higher ratings so the other voltage is taken from the second active part. In such arrangement, the first unit is called the booster or series transformer, and the second magnetising, regulating, or shunt transformer. All those interconnections needed for the production of the desired voltage and phase displacement make the transformer more complex in all stages of manufacturing, from design to production and testing. In addition to these complications, the terminology is also not simple. Besides PST, other names such as phase angle regulating (PAR) transformer or quadrature booster are also used. The reference standard with dual IEC-IEEE logo is IEC 62032 ed2.0 [5] Guide for the application, specification, and testing of phase-shifting transformers.

PSTs are sometimes considered a variety of the system intertie transformers as they are often installed in the substations but from the application point of view, they can be classified as a particular kind of power transformer.

Figure 6: PST 600 MVA, 230 kV [4]

3.5 HVDC converter transformers are in fact AC transformers. The name HVDC comes from the application in the HVDC converter station, which converts AC current and voltage to DC, and vice versa. Hence, a HVDC transformer is the essential component in the HVDC transmission system. Reasons for using the HVDC systems are loss reduction in some transmission lines, like connecting AC systems with different frequencies, connecting non-synchronous systems or using underground or undersea long transmission lines.

Figure 7: HVDC converter transformer [4]

Due to operation in a converter station close to power electronic converters, the transformer is subject to DC electric stress and high current harmonics. Therefore, it has to be designed and manufactured with special consideration for DC insulation and harmonics and as a result, it contains much more solid insulation compared to a classic power transformer.

The reference IEC standard is IEC 61378-2 ed1. Convertor transformers - Part 2 Transformers for HVDC applications [6].

3.6 Transformers for industrial applications are used in the industrial plants for supplying high energy demanding objects like furnaces or converters. Those transformer power ratings are approximately 10 MVA but can be very technical due to specific needs and/or very high operational constraints.

Furnace power transformers have to provide very high currents, close to short-circuit currents, at relatively low voltages in the steel melting and the metallurgical industry. Capacity can range within several hundred MVA with high LV currents, even more than 150 kA; and wide secondary voltage range. Due to extreme LV currents, the OLTC is systematically placed on the HV side. The secondary load can be AC or DC.

Figure 8: Furnace power transformer 95 MVA [4]

Converter transformers face higher load current harmonics due to the distorted waveform caused by the semiconductor converters connected to the transformer. Typical applications are: rectifiers for large drives, electrolysis, scrap melting furnaces and inverters for variable speed drives. Other applications can be chemical electrolysis, DC arc furnaces, graphitising furnaces, traction substations, copper refining etc.

The reference IEC standard is IEC 61378-1 Converter transformers – Part 1: Transformers for industrial applications [7].

3.7 Traction transformers are used to supply traction (railway) system and vehicles (locomotives). Nowadays, there are different types of traction systems worldwide such as:
- DC system (0.6 - 3 kV)
- AC systems:
    - 12 kV 50 Hz
    - 15 kV 16 2/3 Hz (this system tends to decrease worldwide over the years)
    - 25 kV 50 or 60 Hz

The traction transformers are supplied by stationary transformers (line feeder transformers, mainly single-phase substation transformer).

Locomotives with DC drives require a three-phase rectifier transformer, also called an on-board transformer. These transformers can travel as fast as 570 km/h, and it is not surprising that critical parameters for such transformers are weight, size and appropriate cooling capacity. Such compact design uses less material, which increases the losses and temperatures above the limits for the materials normally used like cellulose and mineral oil. Therefore, aramid, a polyamide in combination with high temperature resistant insulating fluids is used.

Figure 9: Traction transformer for a high speed train [4]

3.8 Mobile transformers are used when power needs to be supplied temporarily to a particular place, like in cases of a system failure, system maintenance, natural disasters, terrorist attacks, civil construction, etc. After system restoration, or completion of the construction work, the requirement for power supply will be significantly changed. Therefore, in such cases, a permanent substation is not an economical solution.

The main drivers for a design of a mobile transformer are weight and size to facilitate road transportation. Mobile transformers for mobile substations are manufactured up to a 100 MVA rating, and up to 245 kV. Those transformers can have many different voltages levels.

3.9 Test transformers are specific transformers designed for a given testing application in the High Voltage industry. They can be very technical with special requirements regarding very high operating voltage, short-circuit withstand capability or ability to provide many different voltage levels on one unit. They are mostly used in test facilities of the High Voltage equipment manufacturers, for example of power transformers or circuit-breakers.

Distribution Transformers

Distribution transformers are those used in distribution of electricity close to consumers. Apart from the substations, their usual environments are buildings, shopping centres, data centres, industry plants, ships, the underground, under the water

Figure 10: Mobile transformer [4]

HVDC transformers are used more frequently worldwide and can be considered as „overdesigned“ classic transformers for their specific requirements.

Phase shifting transformers are among the most complex transformers. They are mainly used to balance the exchange between two networks over two parallel lines as precisely as possible.

etc. We can see different classifications used by the industry. According to the coolant used, they can be classified as:
- liquid-filled distribution transformers
- dry-type transformers

Figure 11: Liquid-filled hermetically sealed distribution transformer [4]

Figure 12: Dry-type transformer [4]

Liquid transformers can have a conservator or they can be hermetically sealed.

According to the application, they can be classified as:
- substation transformers
- unit substation transformers
- padmount transformers
- polemount transformers
- drives transformers
- wind turbine transformers
- underground transformers
- subsea transformers, etc.

This is not an exhaustive list of distribution transformers but it is deemed enough for the purpose of this article.

Figure 13: Substation transformer 5 MVA [4]

4.1 Substation transformers are transformers used in distribution substations which transfer power from the transmission system to the area distribution system. Transmission voltage level is up to 110 kV, while the distribution level is usually up to 36 kV.

4.2 Unit substation transformers are used in commercial and industrial applications to convert distribution voltage to the utilisation voltage designed for an easy interconnection with primary and secondary switchgear, and for an indoor or outdoor placement.

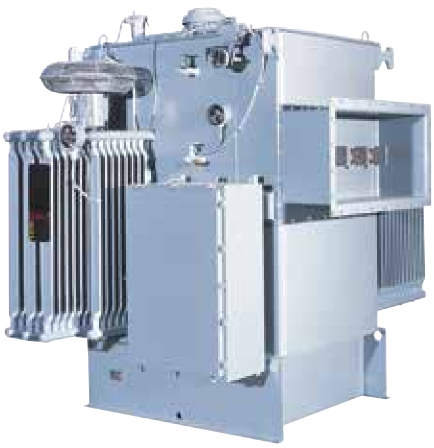

Figure 14 : Unit substation transformer [4]

4.3 Padmount transformers or padmounted transformers are ground mounted distribution transformers placed in a locked steel cabinet mounted on a concrete pad. All energised parts are securely enclosed in a grounded metal housing so that the transformer can be installed in places that do not have room for a fenced enclosure.

Figure 15: Padmount transformer [4]

4.4 Polemount transformers or polemounted transformers, as the name says, are mounted on utility poles. These transformers typically service rural and urban residential and commercial areas. In rural areas they typically supply households or farms, while in urban areas, they are used for industrial and commercial lighting applications. Due to weight restrictions, the polemount transformers are built for voltages up to 36 kV.

Figure 16: Polemount transformer [4]

4.5 Drives transformers or Variable Speed Drive (VSD) transformers are used in speed regulation systems of the electronic motors in many industrial applications, such as pumps, ventilators, compressors, rolling mills, paper machines and an innumerable amount of different machines used in manufacturing and other industries. They can be built as liquid-filled or dry-type, with the capacity of up to approximately 5 MVA.

Figure 17: VSD transformer for high speed compressor 6 MVA [4]

4.6 Wind turbine transformers steps up turbine generator output voltage from a few hundred volts to the collector system's medium voltage level. Besides restrictions and requirements for size, weight, and fire behaviour, they are exposed to the severe service conditions such as variable loading, harmonics, switching surges and transient over-voltages. Consequently, there are problems in the operation which lead to the use of insulating materials like aramid in combination with high temperature insulating fluids. They have characteristic slim form and are hermetically sealed. Liquid-filled transformers have capacity up to 4 MVA but dry-type transformers are also used up to 2 MVA.

Figure 18: Wind turbine transformer [8]

4.7 Underground transformers are placed completely below the ground level. They are designed for installation in an underground vault – a structure or a room where power transformers, network protectors, voltage regulators, circuit breakers, meters, etc. are housed. The capacity can range from small distribution units, to medium sized power transformers, up to 50 MVA. Larger units are used in the underground substations in cities and megacities with an extreme scarcity of space where high costs of land can justify the construction costs of an underground substation twice as high.

Figure 19: Underground Submersible Transformer [4]

4.8 Subsea transformers are used in distribution systems to supply subsea equipment like pumps, compressors and other electrical components used in the underwater installations mainly in oil and gas industry. As they can be placed at depths down to 3000 m, this requires double barriers to compensate temperature and pressure changes associated with seawater. They are oil-filled with voltage rating of up to 72 kV and variable power rating. Due to the requirement for a maintenance-free service, natural heat of sea water convection is used.

Figure 20: Subsea transformer 1.6 MVA [4]

Reactors

As mentioned above, reactors are not transformers but are included here only because they share most of technology with transformers and are very briefly described. They have different applications, but here only two types are mentioned:
- shunt reactors
- series reactors

Basically a reactor can be considered as a "one winding transformer" and can be either a single or three phase. Reactors are covered by the IEC standard IEC 60076-6 Part 6: Reactors [9]. They are rated in reactive power: MVAR.

5.1 Shunt reactors are used in a power system to moderate the effect of voltage increase along the power line when the line is energised but is either not loaded or slightly loaded. This effect is called Ferranti effect. This is because the line capacitance, which draws capacitive cur-

Distribution transformers are units closer to the final electrical energy consumption.

Distribution transformers are close to residential areas or industrial areas, even the ones with some specific electrical needs.

Figure 21: Shunt reactor 30 MVAr [4]

rent, can cause voltage increase. One way to compensate that effect is by using the shunt inductance (reactor). That way, the energy efficiency of the system is improved. To improve the compensation of reactive power, a shunt reactor can have an OLTC with typical regulating range from 50 % to 100 % power. Shunt reactors can be connected directly to the power line (mainly several hundred kV) or to a tertiary winding of a transformer (mainly around 20 kV).

5.2 Series reactors or current limiting reactors are used in a power system to reduce short circuit currents with the aim to use circuit breakers with lower short circuit breaking capacity. Theoretically they could also be used to “adapt” the short-circuit impedance of a newly replaced transformer within an existing installation, mainly to adapt the short-circuit capability of the circuit breaker, and to somehow achieve the same voltage drops as with the previous unit. They can be also used to limit inrush current of large motor drives.

Acknowledgement

During the preparation of this article authors consulted books [10] and web sites of transformer manufacturers [4], other sources on the Internet [8], as well as IEC [2], [5], [6], [7] and [9], and IEEE [3] standards.

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Bibliography:

[1] *International Electrotechnical Vocabulary*, Chapter 421 : Power transformers and reactors

[2] IEC chapters 1 to 21 of the 60076 *Power Transformers Standards*, IEC

[3] IEEE C57.12.00 IEEE *Standard for General Requirements for Liquid-Immersed Distribution, Power, and Regulating Transformers*, IEE Power & Energy Society, 2010

[4] ABB Group, www.abb.com, Courtesy of ABB

[5] IEC 62032 ed2.0 *Guide for the application, specification, and testing of phase-shifting transformers*, IEC, 2012

[6] IEC 61378-2 ed1. *Convertor transformers - Part 2 Transformers for HVDC applications*, IEC, 2001

[7] IEC 61378-1 *Converter transformers – Part 1: Transformers for industrial applications*, IEC, 2011

[8] Paul Anderson, *Turbine Base and Transformer of Tower No 24*, http://s0.geograph.org.uk/photos/79/81/798125_4ff07f9e.jpg, current 18.03.2014.

[9] IEC standard IEC 60076-6 *Part 6: Reactors*

[10] *Handbook for Transformers*, 3rd edition, ABB, 2010

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