ABSTRACT

To secure the quality of the installed asset base, in this case power transformers, utilities and industries rely on quality assurance. This paper will focus on quality assurance in the early phases of the lifecycle, prior to operation. Elements contributing to this quality assurance are specification, design review, quality review of the manufacturer or production, and testing. The question will be addressed what quality assurance options are available and meaningful. Moreover, the paper presents specification as one of the possibilities of quality assurance and discusses the specification requirements and options in more detail.

These days, transformer requirements increasingly involve sustainability aspects. Such aspects may include the environmental impact, energy efficiency and losses, and the lifetime and recycle options of the materials. This paper will discuss how such sustainability aspects may be incorporated in the transformer specification, and reflect on present practice using experience from decades of projects worldwide.

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To secure the quality of power transformers, utilities and industries rely on quality assurance, which includes specification, design review, quality review of the manufacturer or production, and testing

Power transformer lifecycle

Transformer specification and sustainability

1. Introduction

To secure the quality of the installed asset base, in this case power transformers, utilities and industries rely on quality assurance (QA). Here quality may be defined in terms of 'the ability of a product (or service) to satisfy stated or implied needs.' Such needs are to be identified up front and may be related to safety, reliability, sustainability, compliance and other so-called "business values". In short, transformer quality assurance needs to secure that:

- the transformer meets the requirements stated;
- the transformer is fit for its intended purpose;
- no latent defects are present that form a risk to future operation.

Quality assurance may be regarded as one of the ways to control transformer related risks, namely by limiting the failure probability in service. The most common causes of power transformer failures are well documented in a recent CIGRÉ brochure named "Transformer Reliability Survey" [1]. It presents an international transformer failure survey including calculated failure rates and failures classifications with respect to failure location, cause, mode and effects.

This paper is focused on quality assurance in the early phases of the lifecycle, prior to operation. The question will be addressed what quality assurance options are available and meaningful. Specification is presented as one of the possibilities of quality assurance, and the different specification requirements and options are discussed in more detail.

These days, transformer requirements increasingly involve sustainability aspects. Such aspects may include the environmental impact, energy efficiency and losses, and the lifetime and recycle options of the materials. This paper discusses how such sustainability may be incorporated in the transformer specification.

2. Quality assurance in the early lifecycle phase

Quality assurance is relevant throughout the transformer lifecycle but, in this contribution, we focus on the early lifecycle phases, ending with the Site Acceptance Test or Commissioning Test. The Transformer Reliability Survey quoted earlier [1] shows that roughly 30 % of all failures may be attributed to causes that find its

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Table 1. The most important early lifecycle failure causes, and the related options for quality assurance

Early lifecycle failure causes	Early lifecycle quality assurance
Design	Specification
Manufacturing	Design review
Materials used	Quality review of the manufacturer/production
Installation	Testing

In requirement specifications, the customer describes functional, technical and project specifications, standards to comply with, tests to be performed, commercial conditions to be met, environmental and sustainability requirements, etc.

root in this early lifecycle phase. The most important early lifecycle failure causes, and the related options for quality assurance, are presented in Table 1.

Specification: you get what you ask for, so ask SMART!

In a specification, the customer describes all requirements that need to be fulfilled. This may include functional, technical and project specifications, standards to comply with, tests to be performed, commercial conditions to be met, environmental and sustainability requirements, et cetera. The transformer specification will be dealt with in more detail in the next chapter.

Design review: powerful but insufficient!

CIGRÉ brochure 529 named "Guidelines for conducting design reviews for power transformers" [2] defines design review as: "a planned exercise to ensure both parties to the contract understand the application and the requirements of the applicable standards and specification". The goal of a design review is to establish that what is being delivered is fit for its intended purpose, and that materials, design tools, methodology and experience are adequate to assure that the product will meet the requirements.

In this respect, based on practice experience, one should emphasize that a design review as such is not capable of full assurance. As stated earlier, design errors are only one of the causes of defects or anomalies. Others include the quality of manufacturing, the materials used, and the transport and installation.

Quality review of the manufacturer/production: gaining trust!

The transformer buyer may find it useful to assess the manufacturer capability. This may depend on:

- whether the transformers are commodities or specials;
- what is the strategic importance of the order (by volume, functionality, and so on);
- what are the references, what is the proven track record of the manufacturer.

The assessment may focus on the company quality or on the production quality.

- When assessing **company quality**, the focus of the assessment is on the company's management and quality (monitoring) systems, human resources, competences and training, methodologies, tools and software for design and development, quality control over suppliers, and the like.
- Quality review of the **production process** usually involves a document review and factory visits during which steps in the production process are inspected, and possibly witnessed.

Special attention shall be paid to important events in the production of the transformer, such as coil pressing and alignment, pre-tanking inspection, etc. These shall be considered as 'witness points', as these are the last possibility for timely detection of anomalies.

Guidance for quality review of the manufacturer and the production process is given in CIGRÉ brochure 530 named "Guide for conducting factory capability assessment for power transformers" [3].

Testing: the (only) proof of the pudding!

The CIGRÉ survey mentioned earlier shows that about 30 % of transformer failures are attributed to design, manufacturing, materials used and installation. Part of these failures are related to short-circuit withstand capability. The IEC standard 60076-5 (on the ability to withstand short circuit) [4] provides guidance for a theoretical evaluation of the transformer ability to withstand dynamic short circuit effects. This theoretical evaluation is based on design review and manufacturing practices. However, a recent evaluation of over 20 years of short circuit testing by DNV GL KEMA laboratories has shown that, despite design reviews and quality control, 23 % of the transformers tested initially failed.

Based on hundreds of failure investigations over the last decades, it may be concluded that defects may not only be caused by the design or the production process as such, but by small deviations in quality, cleanliness, assembly or finishing. For example, discharge activity may be induced by tiny sharp edges on metallic surfaces, or by contaminations or by micro inclusions in dielectric materials. Heat conduction may be reduced by using the wrong paint, additional heat production may be induced by increased contact resistance due to improper installation or the use of inferior core material.

A recent evaluation of over 20 years of short circuit testing by DNV GL KEMA laboratories has shown that, despite design reviews and quality control, 23 % of the transformers tested initially failed

From these evaluations, it is concluded that, although design review and manufacturer (company or production) assessment may reduce the failure probability, testing remains a powerful and necessary tool to timely detect such pre-life defects. The main reasons may be summarized as such:

- Design models usually assume (axial and/or rotational) symmetry for the ease of calculation, whereas failures are often found at symmetry discontinuities such as transpositions and cross-overs;
- Often, defects are not caused by the design or the production process as such, but by small deviations in quality, cleanliness, assembly or finishing.

Different kinds of tests are being used. First, we may distinguish between the factory acceptance test and the site acceptance test. The factory acceptance test shows that, after production, the transformer fulfills the stated requirements. The site acceptance test shows that, after transport and installation, these requirements are still met.

The factory acceptance test is divided in three categories: routine tests, type tests and special tests. All transformers shall be individually tested by a routine test, showing that the built transformer is fit for purpose. The design of a transformer is verified by type tests. For relatively small transformers or commodities generally a type test is performed on one transformer, and the test result is valid for all transformers of that design, provided the production process is not changed. Larger transformers are often tested individually, and routine and type tests are performed on the individual transformer. Special tests are performed on special request, and must be specified explicitly. Special tests may comprise e.g. short circuit withstand tests and sound level measurements.

3. Transformer specification

As stated earlier, the specification is a document that states all customer requirements that need to be fulfilled. A specification may be generic for several transformers of the same type, or it may be a project specification which is applicable to one individual transformer. Guidance for transformer specification is given in CIGRÉ brochure 528 named "Guide for preparation of specifications for power transformers" [5]. Table 2 presents some aspects often encountered in a specification.

Although design review and manufacturer assessment may reduce the failure probability, testing remains a powerful and necessary tool to timely detect pre-life defects

Table 2. Overview of specification aspects

Overview of specification aspects (not exclusive)	
The scope of the project	Tests to be performed
Functional requirements	Commercial conditions and warrantee
Technical requirements	Additional services (transport, installation support, spares, maintenance and repair)
Standards to comply with	Legal or governmental requirements

Only referring to an IEC standard while ordering a transformer is not sufficient, as an IEC standard is the product of world-wide consensus and thereby does not specifically reflect the customer needs and requirements

In practice, there are different approaches towards specification. One may:

1) focus on functional requirements that define what is needed, and leave it to the manufacturer's expertise to find the best solution, or
2) prescribe what technical solution is to be used.

In that respect, the specification may or may not require a design (review), the manufacturing process, the materials used, and so on. It is recommended that buyers focus on specifying requirements rather than technical solutions, which in fact is the expertise and the competence of the manufacturer. To avoid possible conflicts, it should be noted that in whatever way the transformer is specified, the requirements need to be SMART and thus allow verification. It is the customer's responsibility to state the right requirements, it is manufacturer's responsibility to convince the customer that the requirements are being met.

In case of recurring orders, it is regarded useful to split the specification in a generic part, listing all generic requirements, and a specific part, containing the specific (technical) requirements for the specific order.

Further, I would like to emphasize that only referring to an IEC standard while ordering a transformer is not sufficient, as an IEC standard is the product of world-wide consensus and thereby does not specifically reflect the customer needs and requirements.

4. Specification and sustainability

These days, transformer requirements increasingly involve sustainability aspects. Sustainability is a term that may be interpreted in different ways, and usually concerns 'the ability to continue a defined behavior indefinitely'. This may be interpreted as "a transformer having an infinite lifetime", or it may focus on the production (materials that do not deplore natural resources, recyclability, low environmental or ecological impact) or on the operation (low energy losses, low environmental stress in terms of oil spills, electric and magnetic fields, noise, and so on).

Sustainability aspects have become more urgent with the issue of the EU Ecodesign Directive [6], which aims at improving the environmental performance of energy-related products. The directive is aiming at a reduction of greenhouse gas emission, an increase of renewable energy and a reduction of energy consumption through energy efficiency. For the present subject of this paper especially the Transformer Directive EU No. 548/2014 [7] is relevant, as it covers the implementation of the Ecodesign Directive to small, medium or large power transformers".

In this chapter, several sustainability aspects will be presented and it will be discussed how they may be incorporated in the transformer specification. In particular, transformer losses, environmental and safety aspects, oil stability and design will be treated.

Transformer losses

Some electrical losses in power transformers are inevitable. A distinction can be made between no-load losses and load losses. The contribution of dielectric losses (in insulating materials) is negligible.

No-load losses are associated with the magnetizing current that maintains the magnetic field in the core (even without load). The core losses consist of hysteresis loss and eddy current loss. Minimizing hysteresis losses involves proper choice of materials, whereas eddy current loss is reduced by using laminated cores with electrically insulating laminations. Both types of losses can be effectively reduced by application of high quality core materials and proper manufacturing processes.

Load losses are associated with the presence of a load current and involve resistive losses in (winding) conductors and contacts, and so-called additional losses due to eddy currents in the winding conductors and in the tank and structural steelwork. Resistive losses can be reduced by the choice and dimensions of conductor materials, and by proper contact materials and installation practices. The additional eddy current losses can be reduced by choice of materials and design, and the use of additional elements like magnetic shunts.

Next to the above-mentioned base-frequency loss mechanisms, additional loss may be introduced by harmonic distortions, often associated with non-linear loads, such as variable speed drives, inverters, computers and UPS systems.

In recent decades, manufacturers have put increasing effort in producing equipment with lower losses. This has resulted in modern transformers having lower loss levels compared to previous generations.

When specifying a transformer one may consider to specify the transformer losses allowed. One may do so for sustainability reasons (energy consumption, CO_2 emission reduction), or for economic reasons. In the latter case it is advisable to use lifecycle costing (LCC) analysis involving a trade-off between (usually higher) purchase price and the economic benefits of reduced losses. For sustainability reasons one might need to perform a "cradle-to-cradle" analysis (including the reuse of materials) or determine the CO_2 footprint.

Environmental and safety aspects

The use of biodegradable liquids

Traditionally large power transformers are oil-filled. The primary functions of the oil are electrical insulation and cooling. Next to that, the oil serves as a source of diagnostic information. For a long time, transformer oil was based on mineral oil, produced from natural oil (or more recently by gas-to-liquid techniques, GTL). It has good thermal and dielectric properties, and there is a lot of experience gained over the years.

In recent years, manufacturers have studied the use of biodegradable liquids. The forms mostly used are synthetic esters and natural esters. Synthetic esters are produced (synthesized) from natural or synthetic alcohols and carboxylic acids. They exhibit a high thermal stability and a high flash point, can absorb some water without affecting the dielectric properties, have low smoke generation in case of fire, and are biodegradable. Natural esters are of organic origin. They are renewable, have a high flash point, can absorb some water without affecting the dielectric properties, and are biodegradable. In recent years, transformer designs based on synthetic esters have become mature, using natural esters is considered as the next step.

The use of synthetic esters reduces the requirements for environmental protection as well as for fire related risks. Next to that, natural esters have an environmental advantage, and manufacturers also claim a longer life expectancy due to the reduced ageing rate of solid insulation.

A drawback of changing from mineral oil to esters is that is has an impact on transformer monitoring and diagnosis. Most utilities have experience with mineral oil analysis as a standard diagnostic basis, and have built a history that serves as a reference for trending and analysis. New knowledge rules need to be applied, and a new history needs to be built up.

When specifying a transformer with biodegradable oil, it is therefore recommended that one also considers to (re)specify the oil analysis, either with the manufacturer or with another party (laboratory).

Dry-type versus oil-filled transformers

In the past, most power transformers were oil-filled. In recent years, the percentage of dry-type transformers has significantly increased. While in the oil-filled transformer oil serves both the insulation and cooling function, these functions are split in the dry-type transformer: the insulation is provided by solid insulation materials and the cooling is provided by air.

The main drivers for dry-type transformers are safety and environment. Safety gets more important because our society is increasingly urbanizing, which results in having substations in or nearby densely populated areas. Environmental policies and legislation make dry-type solutions more attractive because of the lack of oil spills and oil-fueled fires.

At present, the application area of dry-type transformers is still limited to indoor applications at limited power (≤ 63 MVA) and medium voltage (≤72.5 kV). However, manufacturers are presently developing dry-type transformers for higher power and voltage ratings (a 63 MVA / 123 kV design has already been demonstrated).

When looking at size and weight, initial cost, losses, noise and overload capability, the dry-type transformer does not com-

pete well with the oil-filled transformer. The main advantages are fire safety, environmental safety, total cost of installation, maintenance and short circuit strength.

When specifying a transformer, it is therefore recommended to evaluate how critical safety and environment are for the decision at hand. In such cases, and as far as available, one may consider dry-type transformers.

Oil stability

The long-term oxidation stability of transformer oil is achieved with natural or synthetic additives (anti-oxidants or AO). Transformer oil based on mineral oil contains a certain amount of 'natural' anti-oxidants, but the stability can be improved by means of synthetic additives. Modern transformer oil produced by gas-to-liquid techniques does not contain any 'natural anti-oxidants, so the oxidation stability is purely based on synthetic anti-oxidants; therefore, GTL transformer oil is generally 'inhibited'. Regarding oxidation stability, the applicable IEC standard (IEC 60296) [8] discerns three categories, depicted in Table 3.

Generally, in moderate climates and at moderate transformer loading, the oxidation stability of a good-quality uninhibited mineral transformer oil is such that no corrective actions are required during the transformer life. Application in warm climates and at high transformer loading may require the use of inhibited oil.

When specifying a transformer one shall define whether uninhibited oil or inhibited oil is to be used. For guidance, we refer to the applicable standards IEC 60296 [8] and IEC 60422 [9].

Oxidized oil can be reclaimed on-site by means of chemical cleaning processes, including filtering over fuller's earth. During such a process, all natural inhibitors are removed from the oil, so a synthetic inhibitor must be added afterwards, and the oil shall be considered as inhibited oil.

Sustainability and design

The prospect lifetime of new equipment is usually based on statistics. However, due to the lack of failure data, this is not applicable for newly designed or modified equipment. One may, however, gain some insight in the prospect lifetime by analyzing the design and the materials used, using knowledge of failure modes and material aging characteristics. This field of lifetime estimation of new equipment is still rather young. One possible approach is the "KLEaR" approach (KEMA Lifetime Estimation and Replacement), which was earlier applied to switchgear.

5. Concluding remarks

In this paper, the necessity of and the options for transformer quality assurance are presented and discussed, focusing on the early phases of the transformer life. Different QA options such as specification, design review, quality review of the manufacturer or production, and testing, are introduced and the possibilities and drawbacks are discussed. This paper emphasizes transformer specification. Next to the common requirements of a specification, a number of sustainability aspects are treated, which become increasingly important as society urbanizes further, and environmental policies and legislation come into place and become more stringent.

Table 3. Categories of oil, as per IEC standard (IEC 60296)

Uninhibited oil	only contains natural anti-oxidants
Trace-inhibited oil	AO < 0.08 % generally caused by initial filling with inhibited oil for testing and final filling with uninhibited oil
Inhibited oil	0.08 % < AO < 0.4 %

In moderate climates and at moderate loading, transformers usually do not require corrective action to ensure oxidation stability; however, this may be required in warm climates and at high loading

Throughout the article the author has used DNV GL experience from decades of projects worldwide to reflect on present practice. Some of the highlights covered include:

1. To secure the quality of power transformers, utilities and industries rely on quality assurance, which includes specification, design review, quality review of the manufacturer or production, and testing;
2. Next to functional, technical and project specifications, standards to comply with, tests to be performed and commercial conditions to be met, these days, transformer requirements increasingly involve sustainability aspects, such as the environmental impact, energy efficiency and losses, and the lifetime and recycle options of the materials;
3. Only referring to an IEC standard while ordering a transformer is not sufficient, as an IEC standard is the product of world-wide consensus and thereby does not specifically reflect the customer needs and requirements;
4. A recent evaluation of over 20 years of short circuit testing by DNV GL KEMA laboratories has shown that, despite design reviews and quality control, 23 % of the transformers tested initially failed. Although design review and manufacturer assessment may reduce the failure probability, testing remains a powerful and necessary tool to timely detect pre-life defects;
5. The use of esters instead of mineral oil reduces the requirements for environmental protection as well as for fire related risks. Next to that, esters are biodegradable. A drawback of changing from mineral oil to esters is that new knowledge rules need to be developed for transformer monitoring and diagnosis;
6. Dry-type transformers are becoming available for increasing but still limited ranges of power and voltage. They do not yet compare well with oil-filled transformer in terms of size and weight, initial cost, losses, noise and overload capability, but are in some cases preferable because of fire safety, environmental safety, total cost of installation, maintenance and short circuit strength;
7. In moderate climates and at moderate loading, transformers usually do not require corrective action to ensure oxidation stability. This may however be considered in warm climates and at high loading.

Literature

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