Power transformers - design and manufacture

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This article discusses the important parameters that should be incorporated in the design and manufacturing of transformers in order to achieve more efficiency, environmental acceptability, and low fire risk.

The transformer has always been a major and expensive component in the power system. In growing economies and electrification projects around the world, transformers are very much in demand and their prices continue to increase, with the lead times to source them following the same pattern.

It is always desired that a return on investment be realised on transformers because they require a significant capital investment. In many cases, transformers fail before they reach their expected life span. Studies show that most transformers fail around midlife (appraisal) with the known leading causes of the failures being windings, tap changers and bushings in decreasing order. The main questions then are: What is being done, or can be done, in order to achieve the expected life span from a transformer and how is the issue of the leading causes of failures being addressed?

Transformer owners need to face the reality that a transformer life management practice that will enable the utility to safely, economically, and with a high degree of reliability and availability, utilise its transformers for their entire, expected life span, does not start when the transformer lands on the intended site. The stages prior to the delivery of a transformer are critical and require serious attention.

The life cycle of a transformer can be summarised as:

- Identification
- Specification
- Design
- Design review
- Manufacture
- Test
- Transport
- Install
- Commission
- Operate
- Maintain
- Retire or dispose of

From this, one can see that prior to switching for operation there have been many life cycle stages in making a transformer that will last a certain period, from a few milliseconds to a number of years.

In this discussion of the critical issues of the design and manufacture of a transformer, other aspects or stages of the life cycle are touched on in less detail. This information applies to different types of transformers but is more applicable to oil-filled power transformers (generator step-up, network coupling transformers and distribution sizes).

Identification

The first stage is to identify what transformer is required. This should be determined by the network planners. It involves deciding on the power rating of a transformer, taking into consideration the future demand growth. The primary and secondary (and tertiary, if applicable) voltages of the transformer are decided at this stage.

Specification

A transformer specification document is an important document required to start the journey of acquiring a transformer that will be robust for the network environment in which it will operate. The purchaser is the one who best understands the network and the environment which must be made known to the manufacturer through the specification document. This makes it important for each transformer user to have a specification that is relevant to his network needs and operating environment. Adoption of specifications from other users, especially those with different climate parameters and operating regimes, must be done with care. If this is not carefully considered, it may present the negative effects of either under-specifying or gold-plating the requirements. It is in the specification document that maintenance, safety and risk requirements are clearly defined.

Design

The design is the responsibility of the transformer manufacturer, based on the specifications provided. The manufacturer has to ensure that the design complies with the specification provided by the purchaser in terms of functionality, electrical parameters, choice of material (when specified, eg insulation-type) and, most of all, withstanding the operational conditions detailed in the specification document. When the manufacturer is satisfied the client’s requirement has been met and his design is ready, he can engage with the client concerning the design.

Design review

A design review, in a planned exercise, ensures that there is a common understanding of the applicable standards and specification requirements to provide an opportunity for the purchaser to scrutinise the design and ensure that the requirements have been met. The purpose is not to take away from the manufacturer the responsibility of designing and manufacturing a unit that is fit for purpose. Since purchasers often have limited knowledge of the subject of design, they usually employ experts in transformer design. The expert has to be somebody with vast first-hand experience of design and this is hard to find. Many good transformer designers work for companies and cannot be expected to interrogate the designs of their competitors – hence the need for an independent body.

The exercise offers the manufacturer an opportunity to see if he has correctly interpreted the specification and if he can further optimise the design to be more robust, economical, or both. This will require a utility engineer or representative that is familiar with the network and
other aspects, such as the operations and maintenance regimes of the business. The interest between the two parties, although from different points of view, is common – a transformer that will be fit for purpose. The manufacturer wants this for his reputation and the purchaser wants this for reliability and productivity in his business.

The important point is what items are looked at during the design review meeting and what the options are. The following important points should be discussed during the design review stage of the transformer’s life in order to ensure that both parties are clear about the expected product and the associated capabilities and limitations. The materials for transformer construction should not be procured before the design review is done and concluded, because the design may be completely changed during the review meeting.

**Electrical characteristics and requirements of the network or system**

These will include system frequency (including its variations), voltages (both nominal and maximum continuous), short-circuit fault levels and duration of short-circuit. The agreements regarding lightning impulse, switching impulse and other withstand capabilities that are considered important are agreed, taking into consideration the geographical locations. Voltage regulation requirements and performance are part of the discussion and it must be clear whether such regulation is done on-load or off-circuit. Many purchasers now have requirements regarding Geo-magnetic Induced Currents (GIC), which are solar storms. The parties should discuss this as well as how the withstand capability will be demonstrated before the transformer is dispatched to the purchaser. The total harmonic distortion and values for each harmonic should be assessed.

The purchaser must be involved in the stages prior to installation of the transformer to ensure that quality is built into the product.

**Transformer components**

Both the major components and the auxiliary components are important. The discussion around the major components should cover:

### Core

The type (shell or core), grade of material, surface insulation, cross sectional areas, number of limbs, flux densities, core clamping, cooling ducts, core grounding, thermal performance, core joints (step lap, mitred, butt, etc), and all other core related items. The inrush current characteristics should be reviewed.

### Windings/coils

Each winding of the transformer should be reviewed, and the manufacturer should have supplied detailed information so that all parties understand the physical arrangement of active parts. Such a description will include, but not be limited to, the type of winding (helical or disc – interleaved or inter-shielded), number of turns per phase, conductor dimensions and construction (Continuously Transposed Conductor (CTC), twin, triple, etc), current densities, insulation level, magnetic length, electrical length, winding sizing forces, weight, conductor yield strength for forces, tapping leads arrangement for regulating windings, etc.

It is also important to look at how the insulation system is built around the conductors and verify the performance of that insulation.
against the stresses that will prevail during factory testing and in service. The manufacturer will also state what type or grade of insulating paper is used. The options available for purchasers include netted CTC, normal Kraft paper, thermally upgraded paper, and the conductors themselves may be enamelled or not, depending on the purchaser’s needs and the type of conductor. All these are to be clearly specified and discussed during the design review meeting.

Tap changers
The tap changers should not be the limiting component for the transformer performance; they must be able to withstand all the transformer loading and testing conditions and stresses. For on-load tap changers, the purchaser can specify vacuum or oil technology. Vacuum technology is becoming the technology of choice owing to its advantage of minor to no maintenance requirements. The positioning of the tap changer in the electrical circuit is also an important part of the review to achieve either constant or variable flux regulation. Tap changers can be located on neutral end or line end.

Bushings
Dry technology (Resin Impregnated Paper (RIP)) of bushings has matured up to voltages of 550 kVAC and 800 kVDC and is still in its infancy stage and being developed for higher voltages. RIP is preferred to Oil Impregnated Paper (OIP) bushings because it is maintenance-free and has a low fire risk and a fail safe mode. The types and makes of bushings should be discussed during the review meeting. Composite Insulator Sheds (CIS) technology is preferred to the traditional porcelain one as it is more robust, especially against vandalism.

Other requirements
Other requirements will include insulation design. The review will involve looking at dielectric stresses for normal and abnormal conditions, power frequency, and during transients. The insulating technology can be gas (eg SF₆), oil (mineral, natural or synthetic ester), or other materials like Nomex for dry type transformers. The insulation system should be selected and designed, taking into consideration the thermal stresses that will be encountered in service.

Thermal design i.e., temperature rises, are to be reviewed taking into consideration different loading requirements, selected insulation materials, and what is specified in the standards. Glass fibre optic sensors can be considered for more precise measurement of the hot-spot temperatures and, if specified, the positioning should be discussed during the review.

Short-circuit withstand discussion is important to determine the ability of the transformer to withstand the faults expected on the purchaser’s network. Today’s tools and knowledge allow for optimised designs of the conductor insulation (improved space factor) to avoid spongy windings owing to significant amounts of insulation in the axial dimensions. It is important to check this during a design review; in fact, all aspects related to short-circuit must be reviewed, i.e., materials, thermal behaviour, mechanical behaviour (or stresses), and should be considered at the same time. The ability of a transformer to withstand short-circuit stresses should be verified by calculations, tests, or both.

Sound levels as per IEC 60076-10 [1], seismic requirements, cooling requirements (for oil filled transformers: ONAN, OFAF, and ODAF [O – Oil, A – Air, N – Natural, F – Forced, D – Directed] are popular cooling modes), losses (which are important for network efficiency) and tender evaluation (loss evaluation for total cost of ownership) are other important requirements. For the losses, the manufacturer will provide the calculated total service losses, and these will the guaranteed values that will be checked during factory testing. The purchaser may apply penalties if these are exceeded, depending on the contractual agreements.

Manufacture
This is another critical stage in the transformer life cycle. A well
designed transformer can fail to perform to the expected level just because of the way it was manufactured. The design engineer needs to ensure that during the design stage, the production engineers (e.g., the winders) are consulted to make sure that the design is executable and that the production staff is clear of the criticality of certain activities related to that particular design.

Purchasers have intervention points during the construction of the transformer in order to satisfy themselves that quality is being built into the product they are purchasing. Some shortfalls in quality cannot be picked up during the factory high voltage testing stage, and in-process inspections are vital. The points to check during the manufacture of transformers include, but are not limited to, the following:

**Materials**
Check that the materials procured for the transformer comply with the agreements of the design review and specification. An example of this is checking whether or not the conductors are insulated with a thermally upgraded paper, depending on what was agreed. Check that the core steel grade is correct, etc.

**Core**
Verify that clamping is done correctly (using straps or through bolts). Through core bolts are not favoured anymore, especially on large transformers because of the failure mode they have demonstrated in the past. Straps are preferred. Check that burrs do not exceed set quality limits, which are normally 0.02 mm. There should be no core snaking or any form of damage, and one should verify the core duct (the number and size) against the design.

**Coils**
For coils it is important to check the dimensions of the conductors and the insulation used. In certain cases the conductors are to be enamelled (e.g., when specified or in CTCs) and this must be verified. The manufacturer will have adequate quality checks for these; however, witnessing the processing of the coils is important for the purchaser as well. Drying of the coils is important and cannot be avoided; however, every time this is done some paper life is lost.

**Assembling, drying, oil and testing**
The assembling techniques for transformers are improving in terms of available tools and equipment. Some factories will have fully automated core cutting and stacking; however, better methods using human resources still exist. Platforms for better construction, which enable the production staff to keep to the design dimensions, are available and being improved. Drying methods are continually improving and advanced vapour phase ovens are available that provide optimum drying without severe loss of paper life. Vapour phase technology (heat and vacuum) is superior to the traditional ovens using hot air or kerosene, the latter has been found to contribute to the problem of corrosive sulphur in the insulating oils. The oil specified, especially for transformers that will be highly loaded and are in critical circuits, must be non-corrosive. The additives in the oils must be known and understood. Classic utilities will have proper oil specifications and quality control on the oils coming into their pool. Both inhibited and uninhibited oils are used. The Poly-Chlorinated Biphenyl (PCB) oils are no longer accepted on new units. Green oils (environmentally friendly) are preferred nowadays, but should be selected from the start as dielectric requirements are different for mineral oils. Finally, the transformer will be tested according to IEC 60076 [1] requirements and these are clearly specified in parts two and three of this standard.

**Conclusion**
Transformers are a critical component of a power system and continue to be in demand. There is a strong drive for transformers that last to expected life so that capital funds can be used for network growth rather than replacement projects. The design and manufacture of transformers have a significant role to play to achieve this. Good specification documents, good relationships and collaboration between the purchaser and the manufacturer will make this possible, to the benefit of both. There are various new technologies that can enhance the life of the transformer and make it robust, and these must be integrated into the specification documents. The purchaser must be involved in the stages prior to installation of the transformer, to ensure that quality is built into the product.

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**References**