Transformer

Short-circuit withstand capability of power transformers – Part II

ABSTRACT

This article discusses verification of the ability of a transformer to survive short circuit. Fault current leads to large axial and radial forces on windings, which have to be managed by proper structural design. Test experience, showing a failure rate of 20-25 % of well-prepared transformers, suggests that the highest degree of reliability with respect to short-circuit withstand verification is ensured through full-scale testing in accordance with the international standards. The prime failure mode is winding deformation, but many other deficiencies, which would not be discovered in a design review, have also been observed.

KEYWORDS

transformer, short circuit, testing, certification, reliability

1. Verification by full-power testing

In short-circuit testing, the transformer is subjected to the actual short-circuit current. Tests are performed in every phase, each one to be subjected to the full asymmetrical current – one time at minimum tap position, one at nominal and one at maximum, during 0.25 s of current. In total, this is nine tests in a three-phase transformer. After every test, the short-circuit reactance is measured. Increase of short-circuit reactance beyond a certain value (1 % for transformers above 100 MVA), laid down in IEC 60076-5, is an indication of unacceptable winding deformation and leads to a negative test result.

As part of the certification procedure, a detailed out-of-tank active part inspection must be carried out after the test is performed, followed by a repetition of the dielectric tests at 100 % of the specified voltage level. After passing all the requirements, a type-test certificate on short-circuit performance is issued.

Short-circuit testing is considered a better means of ascertaining the real performance of equipment at short circuit, since this test

Aerial view of KEMA Laboratories of DNV GL in the Netherlands, with a short-circuit tested transformer (on the barge in the foreground)

lifecycle

verifies that both construction and design are adequate [1].

Test experience shows that, in spite of the ubiquitous use of simulation programs in the design of transformers, still around 25 % of the transformers do not pass the standardized short-circuit test. The large costs and a possible delay of projects, which result from a failure to pass, makes it clear that manufacturers do everything they can to avoid the risk of such a negative result. The fact that nevertheless 25 % fails to pass illustrates that the result of the test cannot be predicted beforehand by calculation.

Short-circuit tests do not reduce the life-time of a well-designed transformer. Reputable manufactures agree on the fact that for a properly designed transformer with enough margin to handle the electro-dynamic stresses, the effect of the short-circuit stress will be that the windings undergo a certain settling [2]. The effect of the settling is that the stiffness of the windings increases and this is visible in a small variation (if any) in the reactance values measured between the first tests, but becoming smaller or nihil at the last tests. Such a transformer is even stronger after the short-circuit tests than before, and can be put safely in operation again. Large utilities in Italy, Canada and Turkey have not seen any service problems on the units which have been short-circuit tested [1]. Chinese experience [3] shows that 40 transformers (110-220 kV) put into service after passing short-circuit tests function without problem during the monitoring period from a few months to more than five years.

Full-scale testing of over 300 transformers of 25 MVA and above, with rated voltages up to 765 kV, shows that around a quarter fails to pass the standardized short-circuit withstand tests

Figure 1. Preparation of a 765 kV transformer prior to short-circuit test in a barge at KEMA Laboratories at DNV GL

Short-circuit tests do not reduce the life-time of a well-designed transformer

2. Utility considerations

In the past, utilities mainly relied on the selection of trusted manufacturers to secure short-circuit capability of their transformers [4]. However, in recent times the situation has changed, with more and more users asking for tests on critical units or prototypes of series of identical units. This might be because a long-term confidence between purchaser and manufacturer is less and less achievable due to increasing deregulation [1].

The high failure rate in service due to poor short-circuit performance before the year 2000 (0.4 % in France [5]; 0.35 % in Italy [6]; 1.2 % in Turkey [6]; in China 84 % of all internal failures was due to short circuit [3]; in India over 80 % of the failures were caused by winding displacement [7]) led to the adoption of short-circuit testing as a method for quality improvement.

There have been reports of a significant and positive influence of short-circuit testing on the reduction of the rate of winding faults in a large overall system during many decades [2, 8, 9].

In the 1960s, it was reported that in the US between 50 % and 85 % of the transformer failures were due to short-circuit withstand deficiency, whereas in 1979 this percentage was estimated to have dropped to 20 % - and remains at this rather high level.

A major utility's experience indicates that premature operational failures occur due to accelerated ageing and/or weakening of short-circuit withstand capability of transformer [10]. This utility introduces a short-circuit withstand test for at least one transformer for each manufacturer, which will be type-tested and benchmarked for future projects.

Other major utilities [3, 6, 11, 12] require suppliers to pass a learning path towards a successful design through full-power short-circuit testing, thereby using it as an essential and successful tool for quality improvement.

Of course, it is impractical and even impossible to verify short-circuit withstand of all transformers by testing. In the following cases, purchasers have good reasons to specify short-circuit withstand tests [1]:

- In case of utilities, whose transformer fleet mainly consists of standard units: if several identical units are going to be purchased at one time, or if it deals with units to be manufactured based on new or revised designs, it may be instructive to submit the first unit of that series to a short-circuit test, and then, only after the successful completion of that test, release the following units for production: the "learning path" approach;
- In case of transformers performing a key function in the network, for which the reliability issue is of prime importance: this applies, for example, to key GSU transformers (already having a relatively high failure rate) and unit auxiliary power supply transformers installed in nuclear power stations;
- Strategic interconnection (auto)transformers located in strategic stations or huge consumption centres (server parks);
- Transformers requiring a special design, for example entailing a primary winding and two equally-sized secondary windings, each with half power rating com-

- pared to the primary (axially split winding type [1]);
- Transformers to be installed in networks with high fault incidence (e.g. track feeding transformers), expected to face a heavy-duty operation consisting, for example, of tens of short circuits per year;
- Transformers having a low short-circuit impedance and/or installed in solidly earthed systems: this is often the case in USA, where transformers frequently have a lower short-circuit impedance than in Europe.

3. Laboratory features

After a recent extension at KEMA Laboratories, the laboratory has six generators at its disposal as a power source coupled with ten step-up transformers. The laboratory has direct test-power of up to 15,000 MVA at a voltage of up to 550 kV. A unique feature is a very fast master breaker, which can de-energize the test-circuit within a single power frequency loop and thus significantly limits the consequences of a fault.

A number of test-circuit topologies have been proposed by the industry for optimum conformity with the service situation:

- Three-phase tests: three-phase transformers should preferably be tested three-phase. Each phase is subjected to the specified (peak) current value in three tap positions.
- 1.5-phase tests: with the single-phase method, known as the 1.5-phase method, the phase under test is connected in series with the other two phases paralleled. The RMS currents in the two parallel-connected phases are 50 % of the specified three-phase value. The evolving stresses in the two parallel-connected phases are in this case lower than in the case of three-phase tests, but at the most critical moment, at the asymmetrical current peak in the fully stressed phase, all currents are identical to the situation of a three-phase test.
- Single-phase tests: in case the test station's power is not enough for using the 1.5-phase method, a real single-phase method could be applied, like the method used for single-phase transformers. In this case, the terminals of the other phases are open.

The laboratory can now realize a direct testing voltage of 550 kV. This implies that now, single-phase transformers in the 500-600 MVA class can be short-circuit tested (up to 1000 MVA three-phase). Voltage-wise, transformers with rated (single-phase) voltages up to 800 kV can be tested as well. The first 765 kV transformers were short-circuit tested in 2016 [13], which was world's first test at this level (see Fig. 1).

> **Short-circuit testing is now possible up to the rated voltage of 800 kV and 1000 MVA**

4. Test result statistics of power transformers

An evaluation has been made of short-circuit tests performed in the 21-year period of 1996-2016. The tests were performed in accordance with IEC standard [14] or IEEE standards on transformers with rated power up to 440 MVA and primary voltage up to 765 kV.

The population includes single-phase and three-phase transformers, autotransformers, step-up-, converter-, railway-, auxiliary- and three-winding transformers; 16.7 Hz, 50 Hz and 60 Hz transformers; YD- and DY transformers and YY autotransformers.

The largest transformers tested are 334 MVA single-phase and 440 MVA three-phase transformers.

In detail, the test experience is as follows:

During the past 21 years, a test access for a transformer larger than 25 MVA (278 transformers from which 42 are re-tested) has been counted 320 times in total:

- In 230 cases, the transformer showed no problem at the test-site. These transformers initially passed the short-circuit test.
- In 70 cases, a transformer showed a problem due to short-circuit stresses that became immediately apparent at the test site. Mostly, this problem was an unacceptable increase of short-circuit reactance due to the short-circuit stress, but a range of other, immediately evident problems also occurred.
- 42 transformers from the latter group were re-tested after modification in the factory and most did not show a problem at the test site during the re-test.
- In seven cases, after not having experienced any problem at the test site, transformers did not pass the routine tests and/or visual inspection after the tests.

Based on these results, an initial failure rate is defined as the ratio of tests that resulted in failure to pass the test at first access (70 times) and the total tests (320). Thus, the initial failure rate is 22 %.

When a differentiation is made in power- and/or voltage class, the results suggest a tendency of the failure rate to increase towards the highest ratings: out of the 99 tested transformers rated 200 MVA or higher, 33 % failed, and from the 115 ones with primary voltage 400 kV and up, 29 % failed, see Fig. 2.

Higher rating presents a challenge of keeping the dimensions as small as possible for

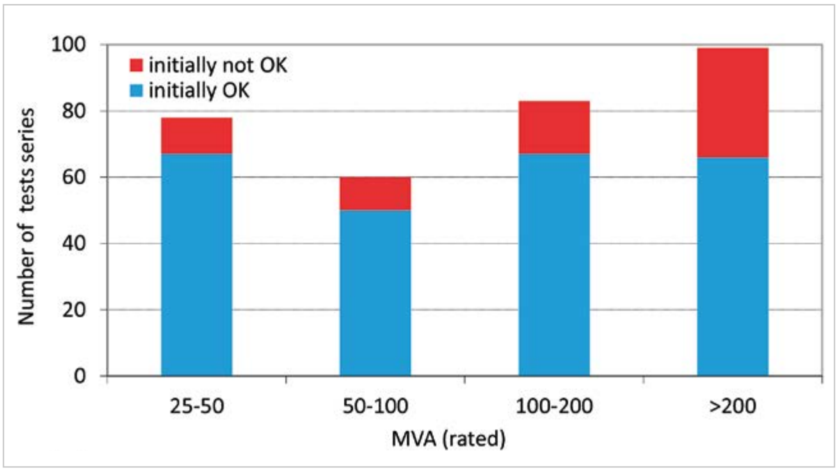

Figure 2. Power transformer test-statistics (OK/not OK) in four MVA ranges covering 320 test series

Preparation of a power transformer at the test site

> **A gradual increase of reactance during the short-circuit tests, although below 0.5 % to 1.0 %, indicates a progressive movement of winding conductors**

transportation reasons and at the same time shall meet all the electrical clearances and provide sufficient cooling of all the parts.

The failure rate at testing observed by KEMA Laboratories is in the same order as the experience reported by another major test laboratory, which reports a failure rate of 20-25 % out of 20 units >100 MVA [15]. Other sources state an overall failure rate of 23 % for a total of 3,934 tests [4], 21.4 % failure rate for units of 2.5-100 MVA, and 41.9 % failure rate for units >100 MVA [6].

5. Failure modes

Commonly, the reason for not passing short-circuit tests is that the winding reactance change (usually an increase) is larger than specified in the standards.

Evidence of damage, as suggested by measured reactance variation, is usually confirmed by visual inspection. In addition, other most clearly recognizable defects are evident directly at the test site or upon inspection of the internal parts.

A wide variety of defects are revealed, including:

- Axial clamping system: looseness of force in axial clamping, of axial compression force, of axial supporting spacers and of top and bottom insulating blocks;
- Windings: axial shift of windings, buckling, spiraling of windings (helical or layer winding);
- Cable leads: mechanical movement, for instance from tap-changer to regulating windings; deformed or broken leads, outward displacement and deformation of exit leads from inner windings; broken exit leads;
- Insulation: crushed and damaged conductor insulation; displacement of vertical oil-duct spacers; dielectric flashover across HV-winding or to the tank; displacement of pressboard insulation; tank current due to damaged conductor insulation;
- Bushings: broken or cracked bushings, leading to oil spraying;
- Enclosure: spraying of oil; exhaust of hot gases; evaporated oil; measurement of current to enclosure.

On the other hand, in the cases (which are the vast majority) when the reactance change is within the tolerances set by the standards, it is our observation that (visual) inspection sometimes still leads to rejection of a certificate. Visual inspection is necessary because deformations and displacements in supporting structures, clamping systems, insulating materials, winding exit leads, external connections from the coils to the tap-changer and within the on-load tap-changer cannot be detected by the reactance measurements only.

In addition, defects to the voltage regulation winding, often not detectable by impedance change, can only be confirmed by visual inspection [16].

Our experience with the short-circuit reactance measurements is that for power transformers a variation of more than 1.0 % indicates a large deformation in one or more coils. Also, a gradual increase of reactance during the short-circuit tests, although below 0.5 % to 1.0 %, indicates a progressive movement of winding conductors. Variations of the reactance values between the short-circuit tests in an unusual way are an indication of large flexibility of the windings.

In the case that a continuous increase of winding reactance is observed during all tests, it is reasonable to assume (by extrapolation) that the transformer undergoes accelerated ageing due to the short-circuit tests. In most cases, at the first tests the reactance increases slightly to stabilize at subsequent test.

Conclusions

- Short-circuit current leads to extreme mechanical forces in transformers which need to be managed in the design by adequate clamping and support of all relevant subcomponents, not only the windings.
- Short-circuits are a major contributor to damage to power transformers in service (forming up to 20 % of the major failures).
- Short-circuit testing is the only complete verification method of short-circuit withstand capability of power transformers. KEMA Laboratories are now ready to short-circuit test power transformers with rated voltage up to 800 kV and power up to 1000 MVA (based on three-phase transformer banks). The actual limit depends on many variables.
- Design review is based on calculation results of idealized, homogeneous structures; it does not cover transient phenomena; it excludes a number of key subcomponents; and it is not embedded in a strict quality surveillance system. It is not a good representation of the reality and it cannot serve as a complete and reliable verification tool.
- Failure to pass a short-circuit test is in the 20-30 % range, as confirmed by major test laboratories worldwide.

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