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

Transformer

Short-circuit withstand capability of power transformers – Part I

Introduction

The power transformer is the most vital substation component since its unavailability creates a major problem, given the high costs and the long time involved in repair or replacement.

Power transformers are especially sensitive to short-circuit events, as will be made clear in the following. The effects of short-circuit currents in transmission and distribution networks for electric energy are tremendous, both for the equipment and for the stability of the networks. Since short circuits are not

René SMEETS

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

lifecycle

rare events (as a rule of thumb, one short circuit per 100 km overhead line per year [1]), short-circuit withstand capability is regarded as one of the main characteristics of the equipment installed. The capability to withstand a short circuit is recognized as a major and an essential requirement of power transformers. Failure to withstand it results in damage to the internal (and even external) parts, and can lead, in short or longer term, to loss of service.

Short-circuit current leads to electro-dynamic forces on the windings that cause mechanical stresses in the radial as well as axial direction. They result from the interaction of the current with the leakage magnetic field between the windings, in radial and axial direction.

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

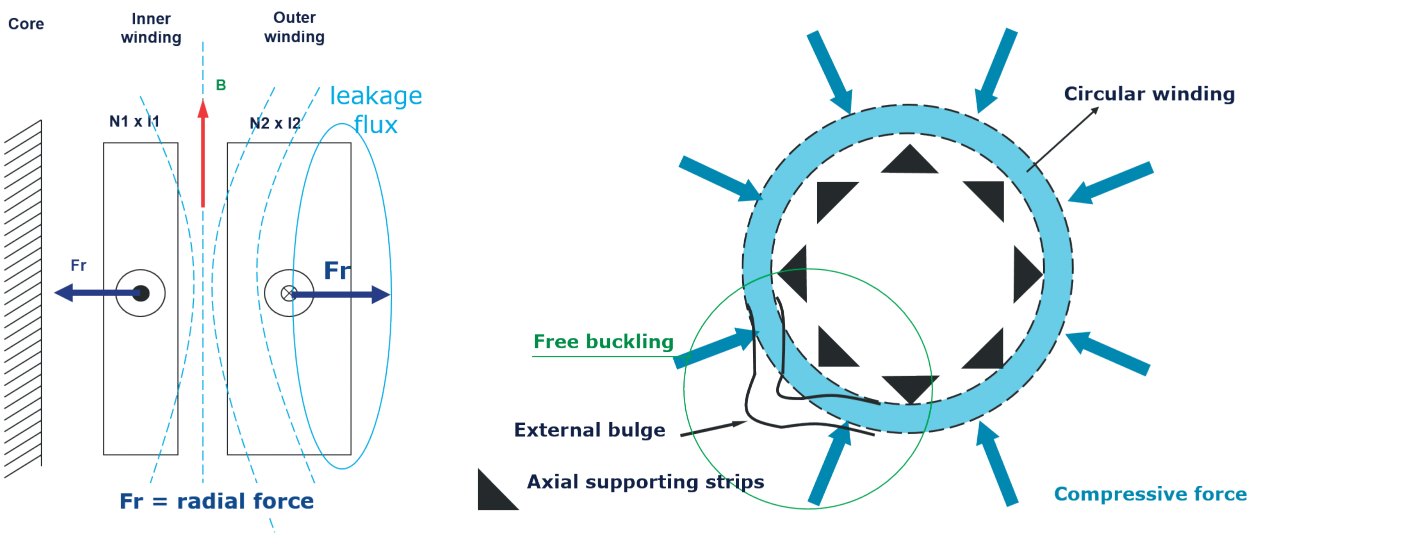

Figure 1. Diagram showing the origin of radial forces (left), and the possible result: buckling of the inner winding (right)

Fault current leads to large electro-dynamic forces on windings and other parts, which have to be managed by proper structural design

Radial and axial forces may have the following effect on the winding:

- The radial forces (see Fig.1) tend to compress the turns in the inner (normally the lower voltage) winding and to expand the turns in the outer winding (higher voltage). When the mechanical design of the supports is not adequate, radial stresses may lead to forced buckling of the inner winding, which is frequently observed.
- The axial forces (see Fig. 2) act in the axial direction with a pulsating compression force. Axial and radial forces have been observed to result in spiralling and/or tilting of turns. Through the deformation of turns, the oil flow may become obstructed, leading to the formation of hot spots.

Apart from winding deformation, a variety of deformation of internal, but also of external parts has been observed in testing [2]. Permanent deformation of windings may lead to immediate damage or long-term issues because of insulation damage, obstruction of oil flow, material weakness or loose parts. Damage and even break of bushings due to the mechanical shock has been observed as well.

The control of the forces and stresses exerted by the short-circuit currents inside the transformer must be an integral part of the design process and quality verification [3].

With an increase of the short-circuit power during the years, the most severe short-circuit currents will appear when the transformer is aged. Also these short-circuit currents have to be withstood without impairing the

Short circuits are not rare events - as a rule of thumb one short circuit happens per 100 km overhead line per year

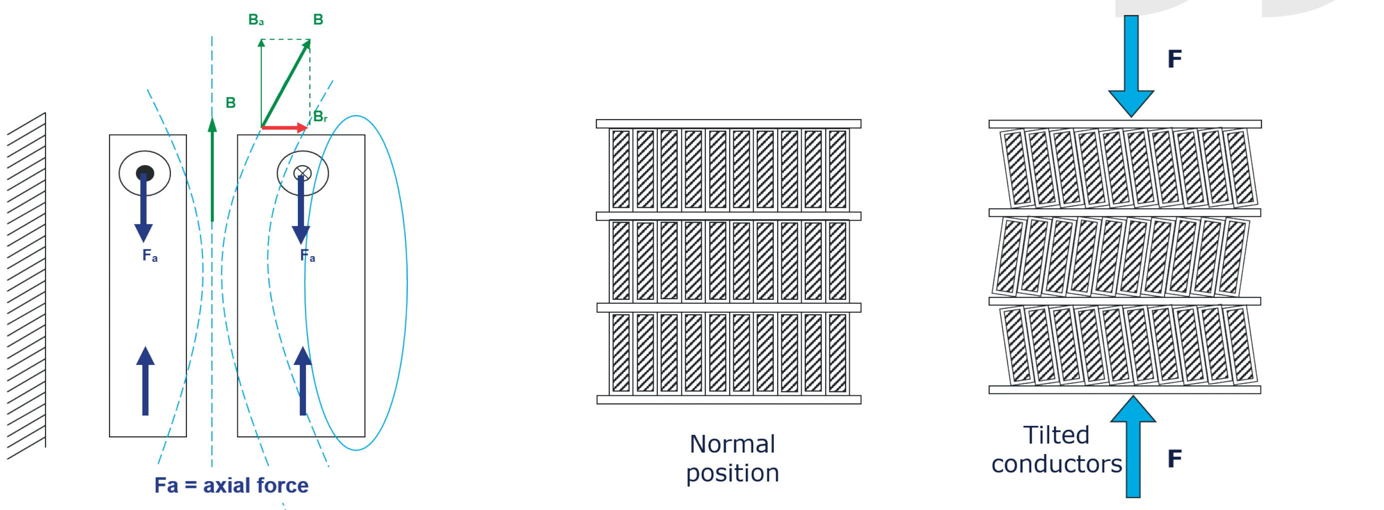

Figure 2. Diagram showing the origin of axial forces (left), and the possible result: tilting of the conductors (right)

Table 1. Failure rates of transformers in the CIGRE 2015 study

69 ≤ kV < 100	100 ≤ kV < 200	200 ≤ kV < 300	300 ≤ kV < 500	500 ≤ kV < 700	kV ≥ 700	**all**
0.93 %	0.44 %	0.55 %	0.75 %	0.54 %	0.37 %	**0.57 %**

transformer. A large-scale study showed that aged transformers are more prone to short-circuit winding deformation because of diminishing winding fastening strength, which is caused by insulation shrinkage and pieces of insulating material disappearing or becoming displaced [4].

Power transformer in-service failure

A number of international studies, all conducted between1974 and 2005, report a failure rate in the range of 0.4-3 %.

In 2015, a new extensive survey, covering the period of 1996-2010, of 964 major transformer failures during 167.459 transformer years from 56 utilities in 21 countries was reported by CIGRE WG A2.37 [5]. This study reports an overall failure rate of 0.57 % ("one major failure per 200 transformers in a year"). In Table 1 a breakdown is given in terms of voltage class.

More detailed analyses on failed subcomponent, failure mode and failure cause reveals the following:

- Ageing and external short-circuit are the largest known failure causes (12.3 % and 11.6 %, respectively).
- Windings are the most common failure location (40 %), followed by tap-changer (27 %) and HV bushing (14 %).
- Mechanical failures account for over 20 % of all failures, the second largest after dielectric failures (36 %).
- The failure rate of GSU units is in all voltage classes higher than that of substation transformers.

EPRI (USA) maintains the IDB database [6] that began to be populated in 2006. By now it has collected data on more than 20.000 U.S. power transformers. One result that clearly stands out is that "inadequate short circuit strength" is by far the largest cause of failure, with 20 % of the total of 654 clearly identified failures.

Converter transformers supplying DC links are of a special design. Their reliability (in LCC based DC projects) has been addressed in several publications [7, 8, 9]. It is striking to observe that their failure rate is significantly higher than that of conventional station transformers, between 1.6-5.4 % depending on their size, compared to the rate of 0.6 % of AC transformers.

The failure rate of converter transformers supplying DC links is significantly higher than that of conventional station transformers

Short-circuit withstand assessment

Basically, two methods are applied to assess short-circuit withstand capability of power transformers: design review and testing.

Assessment by design review

One of the methods for purchasers to assess the short-circuit current withstand capability of transformers is to conduct a design review. CIGRE has issued guidelines on this method [10] that are implemented in the international standard IEC 60076-5, annex A [11]. This annex is an informative document giving guidelines only, and it is not a standard by itself.

In the design evaluation of a transformer, two alternative approaches can be adopted:

a. Comparison with a short-circuit tested reference transformer

This method describes a comparison with a reference transformer that passed short-circuit tests successfully, on the condition that:
- the design under review can be considered similar to the reference transformer;
- it is designed using the same calculation methods and withstand criteria;
- it is manufactured according to the same QA/QC practices;
- the margins for short-circuit strength of both designs overlap.

b. Checking against manufacturer's design rules for short-circuit strength

In this method, evaluation is conducted by checking the force and stress parameters against the manufacturer's design rules for short-circuit strength.

These rules shall be based on a "solid experimental basis", a number of short-circuit withstand tests of actual transformers or the outcome of tests performed on representative transformer models combined with any indirect supportive evidence based on long duration and trouble-free operation of a number of transformers in the field.

Limitations of the design review approach

CIGRE studies show that calculation methods are an indispensable tool in the design phase of electrical equipment and that modern, multi-physics finite-element 3D simulation tools can predict internal stresses. However, they cannot be applied for equipment performance verification [12]. This also applies to power transformers.

For a number of reasons listed below, the value of design review is limited, and generally insufficient to be used as a replacement for short-circuit withstand verification by laboratory testing. The main limitations are as follows:

- Simulation tools are a simplification of the reality [13]. The most obvious simplifications are disregard of the influence of the other phases; and consideration of the windings as rigid and circular symmetrical.
- The list of reviewed sub-components is not complete. It should ensure that all necessary aspects are considered. Calculations related to lead supports and connections to bushings are not requested.
- The design review approach is static whereas the phenomena are dynamic. As the dynamic behaviour of the windings during a short circuit is not mentioned in design review, no aspects of inter-

Installation work carried out on one of the ten laboratory's step-up transformers

Multi-physics simulation tools can predict internal stresses, but they cannot be applied for the verification of equipment performance

winding (dynamic) oil flow or tank stress calculations are considered.

- Design review does not cover material and production deficiencies. Natural variations in properties of material, quality assurance, workmen's skills etc., cannot be taken into account fully, nor can any design review reveal deficiencies resulting from this.
- Many failures occur in other than the "design reviewed" sub-components. Complicated 'secondary' physical phenomena like shock waves in oil, shocks and vibrations (leading to untimely falling-off of Buchholz relays or damage to ancillary equipment – bushings, tap-changers, etc.) are normally not considered at all in calculation methods.
- There is no quality control on the performance of a design review. No uniform and generally accepted validation procedure for the design calculations is established. Statement letters provided are in general unique to the inspecting body. On the other hand, a short-circuit tested transformer is certified by an accredited test laboratory which covers everything. The certificates (see an example in Fig. 3) provided by accredited test laboratories operating under the umbrella of the "Short-circuit Testing Liaison" (STL) are uniform in style and acknowledged everywhere without any restriction.

Design evaluation was partly introduced as an alternative to short-circuit testing because of testing limitations in the past. In due time, test laboratories have increased their short-circuit power and can cover the vast majority of power transformer ratings.

There is very limited information on direct evidence of failures in service after short-circuit withstand evaluation. From a survey conducted by CIGRE SC12 (covering 121,460 transformer years in the period of 1993-1997), 15 failures attributed to short circuit were identified. In 5 cases (33 %) design reviews were performed, whereas none of the failed units (or similar designs) was short-circuit tested [5].

References

[1] CIGRE WG 13.08, *Life Management of Circuit Breakers*, CIGRE Technical Brochure 165, August 2000

[2] G. Bertagnolli, *Power Transformers & Short Circuits. Evaluation of short-circuit performance of power transformers*, Book printed on behalf of ABB Ltd. Transformers, Switzerland, 2014

[3] CIGRE WG 12.19, *The Short-Circuit*

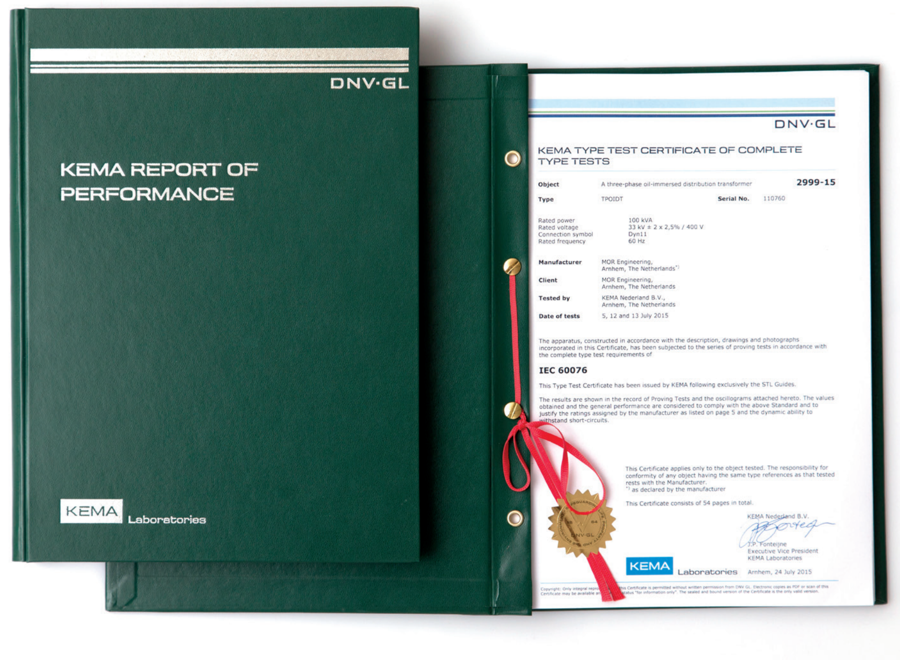

Figure 3. The test certificates provided by STL test laboratories are uniform in style and acknowledged worldwide

Performance of Power Transformers, CIGRE Technical Brochure 209, August 2002

[4] T. Kobayashi, Y. Shirasaka, Y. Ebisawa, H. Murakami, *Expected Life and Maintenance Strategy for Transformers*, CIGRE 6th Southern Africa Regional Conf., paper P102, 2009

[5] CIGRE WGA2.37, *Transformer Reliability Survey*, CIGRE Technical Brochure 642, December 2015

[6] B. Desai and M. Lebow, *Needed: ASAP Approach*, Power and Energy Magazine, IEEE, vol.8, no.6, pp. 53-60, November 2010

[7] CIGRE Joint TaskForce B4.04/A2-1, Technical Brochure 240, *Analysis of HVDC Thyristor Converter Transformer Performance*, 2004

[8] CIGRE WG A2/B4.28, Technical Brochure 406, *HVDC Converter Transformers. Design Review, Test Procedures, Ageing Evaluation and Reliability in Service*, 2010

[9] CIGRE WG B4.04, Technical Brochure 617, *HVDC LCC Converter Transformers Converter Transformer Failure Survey Results From 2003 To 2012*, 2015

[10] CIGRE WG 12.22, *Guidelines for Consulting Design Reviews for Transformers 100 MVA and 123 kV and above*, CIGRE Technical Brochure 204, August 2002

[11] IEC standard 60076-5, *Power Transformers - Part 5, Ability to withstand short-circuit*, 2006

[12] B. Verhoeven, R.P.P. Smeets, *Secure Verification of T&D Equipment needs Laboratory Testing*, Position paper KEMA Laboratories, www.dnvgl.com/energy/publications/download/KEMA_Laboratories_Position_Paper.html, 2015

[13] K. Spoorenberg, *The relevance of insulation supports in large power transformers for short-circuit withstand*, on behalf of Royal SMIT, Transformer User's Meeting, 2016

Author

Dr. René Peter Paul Smeets is Service Area Leader with KEMA Laboratories of DNV GL, Arnhem, the Netherlands. He received his M.Sc. degree in physics (cum laude) from the Eindhoven University of Technology, the Netherlands, and a Ph.D. degree following research work on switchgear. Until 1995, he was an assistant professor at Eindhoven University. During 1991 he worked with Toshiba Corporation in Japan on the development of switchgear. He joined KEMA in 1995. In 2001 he was appointed part-time professor at Eindhoven University in the field of high-power testing. He has received six international awards. In 2013 he became adjunct professor at Xi'an Jiaotong University, China. Dr. Smeets is convener and member of working groups and study/advisory/turorial committees of CIGRE in the field of emerging high-voltage equipment. He is convener of two maintenance teams of IEC on high-voltage switchgear. He has published and edited three books and authored over 250 international papers on testing and switching in power systems. In 2008 he was elected Fellow of IEEE and since 2008 he has been the chairman of the "Current Zero Club", a scientific study committee on current interruption. All over the world, he has conducted many international workshops and trainings on high-voltage equipment, including technology, application, requirements, testing and certification.