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State of the art in short-circuit for transformers

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SUMMARY

Short-circuit strength of transformers is a fundamental piece of the network reliability, due to the fact than when a short-circuit failure takes place, the repair of a failed unit is costly and not immediate.

The main ambition of this paper is to address the above topic by a review of the state of the art and best practices for the design, manufacturing, and quality verification of core-type power transformers in terms of short-circuit. The paper will start with some guidelines about the considerations to design a transformer capable to withstand short-circuits. It will consider all the elements of the transformer involved during a short-circuit event: windings with supporting structures and active part in general, cleats and leads etc. Moving through the entire procurement phases, the paper will continue with the manufacturing processes, routine testing, and the short-circuit test in dedicated laboratories.

Another important topic is the design review, and the comparison between the unit under evaluation and other short-circuit tested units. When the short-circuit testing is out of the scope, other short-circuit tested units with similar design features are reviewed and compared to unit under evaluation. For that purpose, some examples of how reference tests can be used to evaluate the short-circuit strength will be included in the paper, referring to applicable IEEE and IEC standard. It will also be discussed which forces and stresses are the most relevant to check for different kinds of failures and how finite element and dynamic calculations may help to evaluate the risk of the different failures. Also, included in the paper is one of the recent cases of large transformers short-circuit tested in the last year. The most relevant aspects and rated values of the unit are included.

Furthermore, considering that the more related IEC Standard (IEC Standard 60076-5, with current edition since 2006) is under revision and that many authors of this paper are members of the maintenance team that is revising the document, the paper will highlight the main challenges during the revision of the standard and its implications on the procurement process. The new revision of the standard is already distributed among the IEC National Committees as committee draft for voting.

KEYWORDS

Short-Circuit, Design Criteria, Manufacturing Processes, Lorentz Force.

1. INTRODUCTION

Numerous changes have recently occurred in the electrical network in due to an increased focus on renewable energy sources and related trends in the distribution of energy. The resilience of transformers, in terms of short-circuit strength, is a critical component to network stability as related failures are expensive and the duration of downtime, due to supply chain issues, is significant.

Transformers together with all equipment and accessories shall be designed and constructed to withstand without damage the thermal and dynamic effects of external short-circuits according to IEC 60076-5 [1] and IEEE C57.12.00 [2]. However, short-circuit test of a Large Power Transformer (LPT from now on) is for many reasons a special test. It is very expensive and time-consuming test to perform and there are only a few labs in the world having the capability to test LPT. The limited availability of these test laboratories determines that only a relatively few transformers can be tested each year, orders of magnitude less that the units purchased. For the largest units, not even those labs have the capability. For this reason, there is a need of a reliable method to demonstrate the transformers capability to withstand short-circuit events by calculation.

The capability of a transformer to withstand short-circuit should be demonstrated in the design review by checking the most critical mechanical force and stress values appearing in the transformer because of specified fault conditions. The values of the forces and stresses should either be compared with the corresponding ones relating to a reference transformer that has been successfully short-circuit tested, on the condition that the reference transformer is similar, or be checked against the manufacturer's design rules for short-circuit strength according to IEC 60076-5, Annex A.

LPT are designed for specific projects and for this reason, it is usually very difficult to find a similar transformer fulfilling all the specified requirements of a similar transformer according to IEC 60076-5. For this reason, a check against the manufacturer's design rules for short-circuit strength has traditionally been used for LPT. However, a short-circuit event is complex and dynamic, and manufacturer's design rules for short-circuit strength must be based on both theoretical and experimental knowledge. According to IEC 60076-5, the rules should stem from the analysis of either of the results of several short-circuit withstand tests performed on actual transformers or the outcome of tests performed on representative/similar transformer models. Upon, request the manufacturer should present the result of such reference tests.

There is an ongoing revision of IEC 60076-5. In the revision, it is proposed to make the comparison of forces and stresses with those in a reference transformer mandatory. Since for LPT it is usually not possible to find a similar transformer fulfilling all the present requirements according to IEC 60076-5, it is proposed to rather compare forces and stresses in similar windings. This means that multiple reference transformers can be used, but the comparison is only valid within the same technology, design rules, material and manufacturing procedures and process.

In general, the request of reference values gives a more reliable theoretical evaluation of a short-circuit strength of the transformer, and therefore also more reliable networks. However, the number of tested LPTs within one year is very limited and still with possibility to use multiple reference transformers, it may be difficult to find suitable references for every project. In addition, full-scale short-circuit tests are not performed with increasing severity until failure. This means, that reference values for some stresses may be significantly lower than the critical values. This may cause unnecessary increase in cost for some transformer designs. It may also trigger a trend of unnecessarily decreasing critical stress limits as the benchmark designs stress levels become the new critical levels.

Some examples of how reference tests can be used to evaluate the short-circuit strength are presented in this paper. It is discussed which forces and stresses are the most relevant to check for different types of windings and failures, and how finite element and dynamic calculations may also help to evaluate the risk of the different failures. Also, one of the recent cases of LPTs subjected to short-circuit tests in the last years is presented.

2. ONGOING REVISION OF IEC 60076-5 STANDARD

Short circuit withstand capability has been always a significant concern for transformers. Historically major problems started since the early 1950s, after the end of second world war, when following a strong request of electric energy coming from intensive re-construction of infrastructure, there was a huge increase of both power generation capacities and extension of interconnection of electric system with consequent increase of the short-circuit apparent power of the system.

Subsequently, failure due to poor short circuit withstand performance started to increase in Europe, particularly in Italy and France, due to extended use of autotransformers for line interconnection with relative low impedance (7% - 8%). On the contrary in Germany a different approach was used:

- Conventional transformers instead of autotransformers
- Relatively high short circuit impedance (15% - 24 %)

The result was that Germany remained practically immune from failure caused by short circuit events. Consequently, National Utilities like Enel in Italy and EDF in France reconsidered the technical parameter in their specifications in order have better short circuit performance of their transformers and introduced the short circuit test as a method to prove the strength of the transformers from short circuit point of view.

In those years the short circuit performance of power transformers was selected as preferential subject at many CIGRE sessions, and a lot of publications were presented as a confirmation of the importance of the issue in electrical power transmission systems. In the same period, IEC technical committee 14, created in 1939 with the aim to cover the technical requirements for the specification, manufacture and testing of power transformers started to write international standards. The first edition of IEC 60076 was issued in 1955 as a recommendation for power transformers while the IEC 60076-5, with the target to identify the requirements for power transformers to sustain without damage the effects of overcurrents originated by external short circuits was published first time in 1997.

Over the years some revisions of the standard have been required, keeping in line with the technological growth of both transformers and networks. Similar revision and improvements process have been developed in other standardization bodies such as IEEE and other regions.

Current applicable edition of IEC 60076-5 is the third one that was published in 2006. The Convener of experts was Mr. Giorgio Bertagnolli [3] who introduced a much more detailed version of the Annex A that gives guidelines for theorical evaluation of the ability of a transformer to withstand the dynamic effects of short circuit based on calculation and consideration of the design characteristics and manufacturing practices. This Annex is a valid alternative to the short circuit test for transformer manufacturers and customers to assess, during design reviews, the capability of a transformer to survive during network short circuit event.

In 2016 IEC subcommittee MT60076-5 met in Paris with the aim to start to write down the fourth revision of the 60076-5. Since then, there have been many meetings between the representative of transformer manufacturers, customers, and test laboratories with the target to find an agreement on different proposed amendments coming from the parties involved. The main significant changes introduced, with respect to the previous edition, are:

- Inclusion of definitions of transformer parts to provide a common understanding during design review as well as during pre- and post-test inspections.
- Inclusion of standard short circuit current calculation formulae (new Annex A) to calculate the short circuit current of the most common transformers with information of the network and transformer reactance as well as positive and zero sequence reactances to be used unless otherwise agreed between user and manufacturer.

- Updated network short circuit power based on the breaking capacity of the circuit breakers in the network to be used for the design and tests for all cases where the customer doesn't specify.
- Clarified mechanical withstand test procedure and pass-fail criteria have been revised for clarity and boundaries of transformer categories have been revised to reflect the technology.
- Includes a new thermal withstand formula to correct the old one that is mathematically incorrect.
- Revised proof of withstand by calculation procedure. The new concept relies on the idea that no transformer should be more severely stressed than a tested object. The tested object can be within certain limits either a set of actual transformers or relevant models.

The first draft of the standard to national committees for comments was released last year. The committee draft includes the new informative Annex F which includes proposed guidelines for determining the withstand capability of the transformer by calculations for all cases where, for specific reasons, a short circuit test is not required/possible.

According to draft demonstration by calculations can be supported on model test results as references for the following situations:

- If the manufacturer has experience of full-scale short circuit tests but no reference covering a particular stress.

- If there is no laboratory with enough capacity to perform the short-circuit test on a particular transformer.

In the new Annex it also stated that it is possible to perform the demonstration by calculations by performing tests on a partial transformer model representative of the transformer under evaluation. In case any relevant stress cannot be verified by the transformer partial model short circuit test, then for this particular stress, either a reference of a test in a similar transformer or a special partial model test can be used to complete the verification of the short-circuit withstand capability of the transformer under evaluation. This approach is valid for both shell and core type transformers.

3. CONSIDERATIONS FROM DESIGN TO TESTING

The short-circuit strength of power transformers is multifaceted, comprising combinations of factors. The design concepts and manufacturing processes of a power transformer must be adequate and are of equal importance for the short-circuit withstand capability of power transformers. These two aspects are covered in this chapter, with a focus on the factors that are clearly defined, reliable, and controlled; additionally, critical aspects of unit testing are included.

Analytical methods, based on electrodynamics and structural dynamics, form the incipience for design criteria. Results from full-scale testing and conclusions from evaluating field-units that have undergone short-circuit events provide invaluable insight into phenomena associated with the electrodynamic forces acting on the windings. Additionally, tests and field cases enable design criteria to be empirically tuned and maintained, and, additionally, establish adequate and safe stress limits. The need for testing lies in the complexity of power transformers, consisting of non-homogenous and non-linear materials of different physical properties, and the manufacturing process, which involves a significant amount of manual craftmanship.

When a short-circuit event occurs, the currents in the windings reach magnitudes that are one order higher than rated, increasing Lorentz forces by two orders of magnitude. As the affected structures are excited in a complex harmonic manner, time-variant forces are to be utilized. The dynamically excited components include conductors, end supports, press rings, clamps, cleats and leads. Mechanical forces, for the respective components, may vary in magnitude and waveshape from the electromagnetic forces.

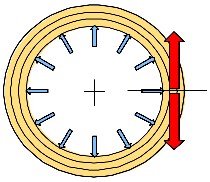
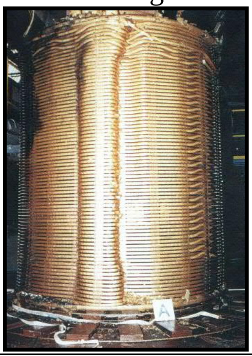
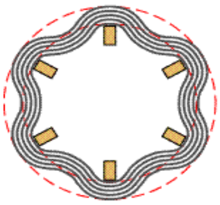
Accounting only for the electromagnetic forces would mean that the short-circuit analysis is static in nature, disparate from the proven structural response. A more stringent analysis requires accounting for dynamic mechanical forces induced in the various structural components, i.e., impacts, resonance, and friction in the entire mechanical system, akin to the validated structural response. Dynamic effects should be considered when calculating axial forces due to the large axial stack of insulation material. Due to the high elasticity of copper, there is less dynamic effect for radial forces. It should also be considered that axial forces are influenced by any occurring misalignment of magnetic centra due to manufacturing tolerances, winding pitches etc.

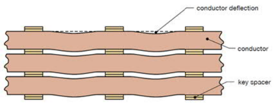
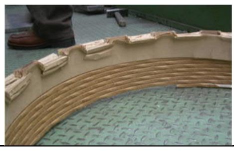
During the design stage, concerning short-circuit withstand capability, the windings, core, active part, and connection leads are to be checked. The windings are usually the most the critical components to be considered.

For the windings there are various failure modes to consider. Some failure modes are limited to a specific winding type, while others must be checked for all winding types. For dimensioning, radial forces are converted to mechanical hoop stresses in the conductor.

According to IEC 60076-5 Annex A, the most relevant forces and stresses should be compared with manufacturer's design rules (and/ or references) in a comparison table. In principle, each force/ stress represents a risk evaluation of a specific failure mode. In Table I, some examples are given.

Table I. IEC 60076-5, Annex A Description of some of the common failure modes that are checked

Force/stress	**Failure mode**	**Type**	**Description**
Mean hoop tensile stress on disc-, helical- and layer-type windings (MPa)	Conductor stretching 	All	Outwards acting radial force may cause the conductor to stretch to increase its diameter. Radial force is converted into a conductor tensile hoop stress to dimension for this. Failure may occur if copper yield strength is exceeded.
Mean hoop compressive stress on disc-, helical- and layer-type windings (MPa)	Free buckling 	All	Inwards acting radial force may cause the winding to buckle from the pressure. To dimension for this, radial force is converted into a conductor compressive hoop stress. It is a complex dynamic elastic instability problem and the withstand depends on conductor width etc. and is significantly lower than the yield strength of copper
Stress due to radial bending of conductors between axial sticks and spacers (MPa)	Forced "buckling"/ Radial bending between sticks 	All	Inwards acting radial force may cause the conductor to bend between sticks if it is designed with very stiff support and with a weak conductor. This type of failure mode in principle disappeared with the increased yield strength of copper and the invention of epoxy-bonding of strands.

Force/stress	Failure mode	Type	Description
Stress due to axial bending of conductors between radial spacers (MPa)	Axial bending between spacer columns 	Disc and Helical	Axial force may cause the conductor to bend axially between spacer columns. Bending stress must not exceed the yield strength of copper.
Thrust force acting on the low-voltage winding lead exits (kN)	Spiralling 	Helical and Layer	Thrust force acting on low-voltage lead exits may cause the winding to deform tangentially in a spiralling pattern. Thrust force on exit leads is calculated by multiplying mean hoop stress by the conductor area. Winding clamping force and friction in the structure are important to avoid this failure.
Maximum axial compression force on winding compared to crit. force for tilting (kN)	Tilting of conductors 	All, except epoxy-bonded CTC	Axial compressive force on winding may cause conductor tilting. It is an elastic instability problem and the withstand depends on strand width and height, diameter etc. It can often be avoided by epoxy-bonding.
Compressive stress on conductor paper insulation and radial spacers (MPa)	Paper damage and loss of clamping pressure	All	Compressive stress on paper and spacers may cause paper damage and loss of clamping pressure and friction in the structure if irreversible compression of the insulation material occurs.
Compressive stress on end stack insulation structures and end ring (MPa)	End insulation collapse 	All	Compressive stress on end ring may cause ruptures in the pressboard, especially in case of wound type (vertically laminated pressboard) end ring.

There are many manufacturing aspects to consider and monitor, but two basic manufacturing requirements to ensure the short-circuit withstand capability of a power transformer: (1) keeping the windings and insulation parts as dry as possible and (2) being systematic.

Preventing moisture absorption in insulation materials composed of cellulose ensures dimensional compatibility, straightness of ribs, barriers, and cylinders. Additionally, it mitigates irreversible drying issues from arising, and the loss of stability and altering the design stiffness of the windings.

Being systematic ensures that the intended design is manufactured as specified by design; with a few of the most critical being tolerances, accuracy of conductor winding on the winding machine, tightness of conductors in turns or disc sections, and thorough stabilization process performs on windings and winding blocks.

Prior to short-circuit testing there are multiple checks and verifications to be carried out to ensure the test conditions mirror what a tested unit would experience in the field. A visual check of all parts is to be carried out, essential safety equipment should be in place, care should be taken with installation of bushings to avoid stressing the leads, follow standard procedures for oil filling, circulate and heat oil prior to testing, and check oil status.

4. COMPARISON FOR VALIDATION WITH REFERENCE UNIT

It's widely acknowledged in the industry that the highest reliability method to prove the short circuit withstand ability is the short circuit withstand test. For different reasons, as for example laboratory limitations worldwide or even the customer preferences, it might be necessary to consider an alternative method based on the theoretical calculation of forces and stresses together with the comparison of those with the equivalent values on tested objects.

Those tested objects might be either transformers submitted to short circuit test whose stresses are comparable with the ones in the transformer under evaluation or a test object built specifically to prove a certain stress or the majority of the stresses for a specific transformer.

Although the criteria to consider the test object to be valid for the comparison purpose are defined in the relevant IEC/IEEE standards and it has been in many cases interpretated in different ways by suppliers or end users. The parties involved in the design reviews have need to discuss and agree on the validity of the proposed references.

In addition to that, motivated by the concern of the customers that the manufacturer design rules were based on a reliable knowledge and a wide experience on short circuit testing, it has been proposed on the ongoing IEC 60076-5 revision the requirement to use references for the theoretical evaluation. In this case, only the comparison with the manufacturer's allowable values shall not be a valid method for the theoretical evaluation to prove the short circuit withstand ability anymore. Therefore, the clarity and consensus on the criteria to consider a test object as a valid reference is very important.

The first requirement is that both the transformer under evaluation and the reference test object should be built using the same technology, processes, and design criteria. Also, the quality system, environmental conditions, work-force skills and, in general, all aspects that may impact the short circuit withstand ability should be reviewed, compared and evaluated.

For transformers of categories II and III according to IEC 60076-5, the comparison tables shall be made winding per winding, evaluating for each one the stresses and the withstand ability. In this way, multiple references can be used provided that each of them complies with the following requirements:

- Same category and type of transformers, for example core vs shell, dry vs liquid, etc.
- Same type of winding, for example helical-, disc-, layer-type, pancake coils, etc.
- Same type of winding conductor, for example aluminium vs copper, metal foil, round wire, rectangular conductor, CTC, epoxy bonding, etc.
- For core type, same direction of radial forces.

The comparison tables include also other elements different to the windings such as the cleats & leads and the winding support structure, core frame and clamping structure. For those, the requirements are that both the transformer under evaluation and the test object should have the same general design principles and design rules.

The use of test object different from a transformer submitted to short-circuit test can be considered either in case of laboratory limitations for a particular transformer or to prove a particular stress for which the supplier has not a reference.

The new revision of IEC 60076-5 includes in one of its Annexes a guide for the application of test objects for the theoretical evaluation of short-circuit withstand capability. It provides guidelines which requirement those test objects must comply with, and also the degree of confidence of the test on the test object depending on the stress to be evaluated.

The comparison according this new proposal introduces the concept of safety margin for each stress. The new tables consider the margin between the manufacturer allowable value and the calculated stress for both the transformer under evaluation and the test object. The comparison is valid if the safety margin of the unit under evaluation is at least as high as the margin for the reference.

5. STATE OF THE ART FINITE ELEMENT CALCULATIONS

Since long time magnetic field finite element calculations have been used to calculate electromagnetic forces in the windings. However, traditionally mechanical finite element models have less often been used to calculate the mechanical stresses occurring in the windings due to the electromagnetic forces. These calculations require time and are not usually done in all the transformers but in those that it can be really relevant.

Mechanical modelling requires a deep understanding of the dynamic behaviour, different failure modes, material properties etc. Insulation materials such as paper and pressboard exhibit a complex nonlinear behaviour and considering the magnitudes of forces occurring in the windings during a short-circuit, this nonlinear behaviour cannot be neglected.

Some examples of finite element models that can be used to improve accuracy of calculations are:

- Dynamic finite element model to calculate axial forces and stresses during short-circuit
- Finite element models to calculate elastic instability failure modes such as tilting or buckling
- Finite element model to calculate forces and stresses in cleats and leads
- Etc.

Traditionally, the normal approach to short circuit withstand of power transformers is based on static force analysis with escalation factors to account for the dynamic effects. This may overestimate or worse underestimate the individual transformer short circuit behaviour. When one considers the winding as a spring with time varying applied short-circuit force, it becomes clear that the winding response depend on the system's resonance frequencies and that there will for example be a considerable "bounce back" force acting towards the clamping system structural parts. In a dynamic finite element model, the clamping pressure and its important effects on the dynamic behaviour, winding displacements and stresses can be studied. In Figure 1, an example of calculated dynamic forces and electromagnetic forces plotted versus time is shown.

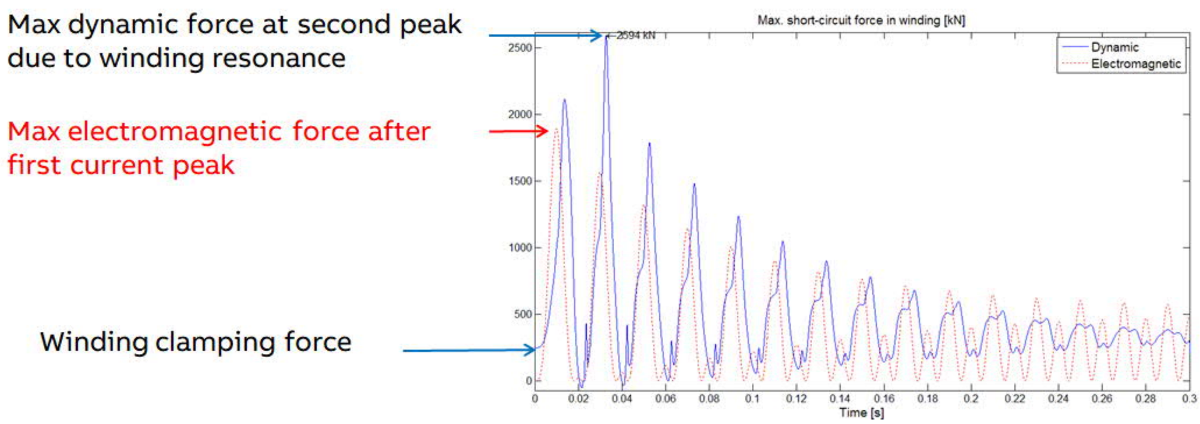


Figure 1 : Example of calculated dynamic force versus electromagnetic force

For estimation of critical conductor tilting force, analytical equation has traditionally been used. Finite element models can be used for more accurate calculation methods for elastic instability failure modes such as tilting. Tilting requires a very detailed geometry. Every individual strand in the conductor, including even the corner radius of the strands must be modelled since it has an important effect on the critical load. To reduce computational time symmetry can be used to reduce the model size. A study of the effect of area covered with spacers on critical tilting force also requires a 3D FE model as shown in Figure 2.

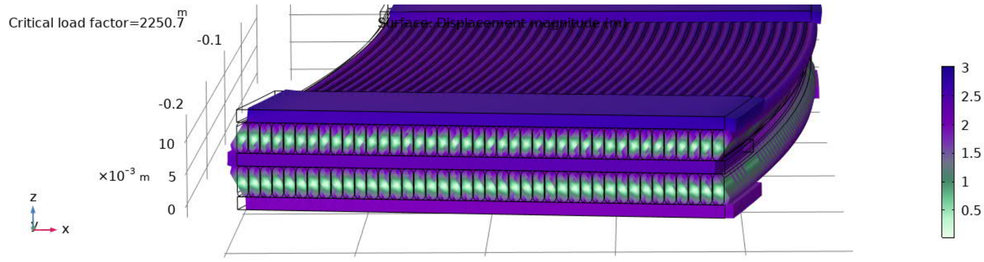


Figure 2 : 3-D FEM calculation of critical conductor tilting force

In the ongoing revision of IEC 60076-5, it has been proposed to make it mandatory for transformer manufacturers to present calculated stresses in the cleats and leads of manufactured units. Analytical methods are available to estimate attractive or repelling forces between leads, but there is a need to develop methods to also estimate the Lorentz forces resulting from stray magnetic flux interaction with the leads. Such calculation requires a 3D finite element model of the stray flux. In addition, mechanical stresses and deformations resulting from the electromagnetic forces must be calculated. Figure 3 depicts an example of electromechanical verification of a production design's leads.

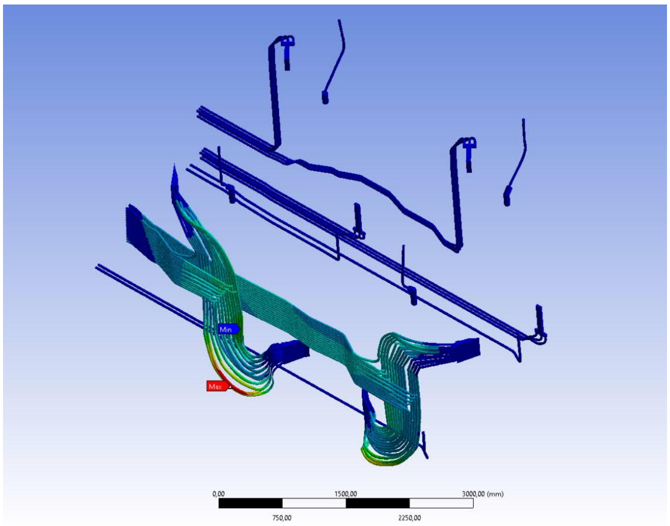


Figure 3, Structural deformation of leads

6. RECENT SHORT-CIRCUIT TESTED LARGE TRANSFORMERS

Comparison of calculated mechanical stresses with short-circuit tested transformers was recently used to theoretically verify the short-circuit withstand capability of a 334 MVA single-phase auto transformer before sending it to short-circuit test. This is one of the largest units ever tested considering the 334 MVA per wound limb, and the size of the core diameter (1.2 m). Rated voltages are 515 kV/230 kV/36 kV.

In 2021, the 334 MVA transformer was successfully short-circuit tested according to IEC 60076-5. Short-circuit withstand tests included testing of the tertiary winding and were performed for high-voltage (HV) to medium-voltage (MV) windings, HV to low-voltage (LV), and MV to LV, single-phase to neutral tests. Maximum measured impedance deviation was 0.43%, which is significantly below the 1% limit according to IEC 60076-5. After completing the short-circuit tests, the transformer was inspected by endoscopic and there was no visible damage to the structural integrity, the windings, or the core. The dielectric and other routine tests were successfully repeated. See Figure 4.

Figure 4 : 334 MVA single-phase auto transformer in the test room

Due to limitations in test lab capacity etc., the largest transformers cannot always be short-circuit tested according to IEC 60076-5. An alternative for such cases is to build and test a transformer partial model (mock-up) transformer. The design and test of mock-up transformer of a 570 MVA single-phase GSU transformer is described in [4]. See figure 5.

Figure 5. Mock-up transformer of 570 MVA single-phase GSU transformer

7. DISCUSSION AND CONCLUSIONS

Developments in the electrical network have put pressure on the reliability of transformers. Given that such high demands are placed on LPTs along with the cost of testing, reliable methods are essential to demonstrate withstand capability.

It's widely acknowledged in the industry that the highest reliability method to prove the short circuit withstand ability is the short circuit withstand test. For different reasons, as for example laboratory limitations worldwide or even the customer preferences, it might be necessary to consider an alternative method based on the theoretical calculation of forces and stresses together with the comparison of those with the equivalent values on tested objects. During design reviews, critical checks are carried out to ensure withstand capability, alternatively production designs are compared to units that are similar, according to IEC 60076-5, Annex A and B.

There are some significant changes introduced in the draft revision of IEC60076-5, with respect to the previous edition. The revised proof of withstand by calculation procedure has an important impact on transformer design. The new concept relies on the idea that no transformer should be more severely stressed than a tested object. In general, the request of reference values gives a more reliable theoretical evaluation of the short-circuit strength of the transformer. However, the number of tested LPTs within one year is very limited and still with possibility to use multiple reference transformers, it may be difficult to find suitable references for every project. In addition, full-scale short-circuit tests are not performed with increasing severity until failure. This means, that reference values for some stresses may be significantly lower than the critical values. This may cause unnecessary increase in cost for some transformer designs. It may also trigger a trend of unnecessarily decreasing critical stress limits as the benchmark designs stress levels become the new critical levels.

Short-circuit of a power transformer is a complex dynamic event and the design of short-circuit proof transformers requires both theoretical knowledge and experimental experience. Finite element and dynamic calculations may help to improve the prediction of forces and stresses occurring during short-circuit. However, transformer short-circuit strength also depends on manufacturing procedures and process. Comparison with reference transformers should therefore only be made within the same technology, design rules, manufacturing procedures and process.

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