Study Committee A2

Transformers and Reactors

Paper 10506

State of the art in short-circuit for transformers

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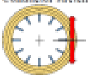
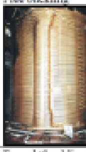
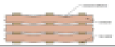
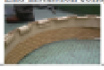
Introduction

- Continuous developments in the electrical network put pressure on the reliability of transformers.
- Standards require the demonstration of the transformers ability to withstand short-circuits either by test or theoretical evaluation.
- Highest reliability method to prove the SC withstand is the SC test. However, it is a special test, which only a few laboratories can perform. For this reason, there is a need of an alternative method to prove the ability to withstand short-circuits by calculation.
- According to IEC 60076-5, a comparison of relevant SC forces/stresses either with manufacturer's design rule or with equivalent values in reference transformers should be made.
- A check against the manufacturer's design rules has often been used for large transformers, since a similar reference unit fulfilling all the requirements is often not available.
- Design rules should be based on both theoretical & experimental knowledge, analyzing the results of either SC tests on transformers or on representative models.
- There's an ongoing revision of IEC with proposed changes that have a high impact on the demonstration by calculation.
- Main objective of this paper is to review the state of the art and best practices for design, manufacturing and quality verification related to short circuit withstand in transformers.

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.
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.

Ongoing revision of IEC60076-5 Std

- Committee draft released in 2021.
- Most significant changes introduced are:
  - Transformer parts definitions
  - Standard short-circuit current calculation formulae
  - Updated network short circuit power based on circuit breaker capacity
  - Clarified SC test procedure and pass-fail criteria
  - Transformer categories revised
  - Thermal withstand formula corrected
  - Revised proof of withstand by calculation.
- Mandatory to compare forces / stresses with those in reference transformers. Multiple reference transformers can be used since it is often not possible to find a similar large transformer fulfilling all the present requirements
- Comparison tables introduces the concept of safety margin for each stress. Comparison is valid if the safety margin of the unit under evaluation is at least as high as the margin for the reference.
- Model tests are applicable in cases where a full-scale test is not required/possible:
  - If the manufacturer has experience of SC tests but no reference for a particular stress.
  - If there is no laboratory with enough capacity to perform SC on a particular transformer.

Force/stress	Failure mode	Type	Description
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) and ring.

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Considerations from design to testing

- SC strength of power transformers depend both on design and manufacturing processes.
- Analytical methods form the incipience for design criteria. Results from full-scale testing and evaluation of field-units submitted to short-circuit events enable design criteria to be empirically tuned and maintained.
- Dynamic effects should be considered when calculating axial forces. Due to the high elasticity of copper, there is less dynamic effect for radial forces.
- Axial forces are also influenced by any misalignment of magnetic centra due to manufacturing tolerances, winding pitches etc.
- For the windings there are various failure modes to check. According to IEC 60076-5 Annex A, the most relevant forces/ stresses should be compared with manufacturer's design rules.
- Most important manufacturing requirements to ensure the short-circuit withstand capability of a power transformer are:
    - keeping the windings and insulation parts as dry as possible and ensure maximum moisture content requirements are met.
    - ensuring that the intended design is manufactured as designed (tolerances, accuracy of conductor winding on the winding machine, tightness of conductors in turns/ disc sections, and thorough stabilization process performed on windings and winding blocks,..).
- Prior to short-circuit testing multiple checks are carried out. Care should be taken with installation of bushings to avoid stressing the leads. Standard procedures should be followed for oil filling and oil status should be checked etc.

State of the art finite element calculation

- Magnetic FEM has been since long time used to calculate electromagnetic forces in the windings.
- Mechanical FEM has less often been used to calculate the mechanical stresses in the windings. These calculations may be time-consuming and are usually only done in specific cases. Mechanical modelling requires a deep understanding of the dynamic behavior, different failure modes, material properties etc.
- Dynamic FEM can for example be used to improve accuracy of calculated:
    - axial forces and stresses in the windings
    - elastic instability failure modes such as tilting or buckling

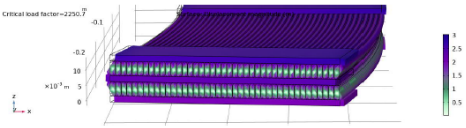
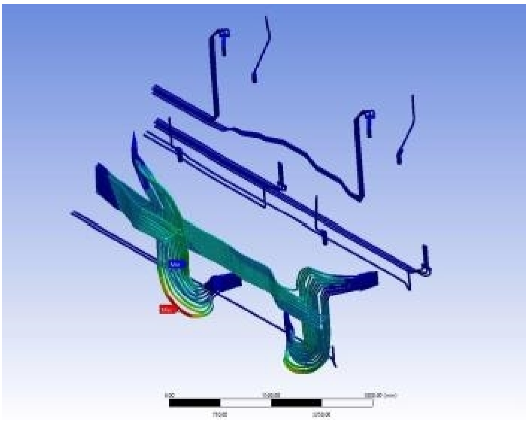


Figure 2 : 3-D FEM calculation of critical conductor tilting force

    - forces and stresses in cleats and leads

- Draft revision of IEC 60076-5 proposes to make mandatory to present calculated stresses in the cleats and leads. Such calculation requires a 3D FEM of the stray flux and 3D mechanical FEM to check the stresses and deformations.



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Recent Short circuit tested large transformers

- Comparison of calculated mechanical stresses with SC tested transformers was used to theoretically verify the short-circuit withstand ability of a 334 MVA single-phase auto transformer 515/230/36 kV before sending it to short-circuit test.
- In 2021, the 334 MVA transformer was successfully SC tested according to IEC 60076-5.
- This is one of the largest single-phase units tested.

- Due to limitations in test lab capacity etc., the largest transformers cannot always be short-circuit tested according to IEC 60076-5.
- An alternative is to build and test a transformer partial model (mock-up).
- Design and test of mock-up transformer of a 570 MVA single-phase GSU transformer is described in Cigré A2-206.

Discussion and conclusions

- Draft revision of IEC60076-5 introduce the idea that no transformer should be more severely stressed than a tested object. Theoretical verification of SC withstand should be performed by comparison with values in SC tested units valid as references.
- Transformer SC is a complex dynamic event. Latest technics such as dynamic and mechanical FEM calculations improves the knowledge of behavior during SC as well as the accuracy in the calculated stresses.

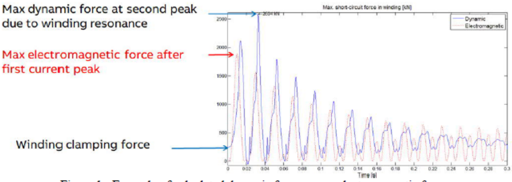
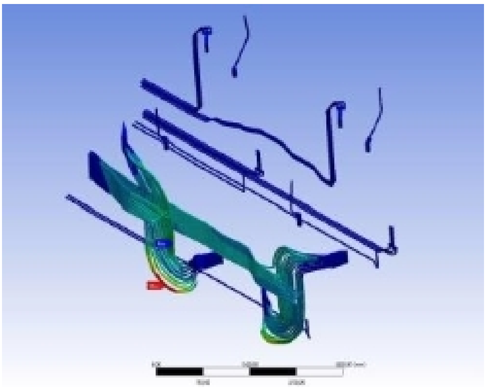


Figure 1 : Example of calculated dynamic force versus electromagnetic force



- Transformer short-circuit strength also depends on manufacturing procedures and process. Comparison with reference transformers should consider aspects impacting the SC withstands (technology, design rules, manufacturing procedures and process,…)
- Request of reference values as per the new requirement in 60076-5 proposed draft gives a more reliable theoretical evaluation of the SC strength of the transformer. However, only few large transformers are SC tested and it may be difficult to find suitable references for every project.
- Full-scale SC tests are not performed with increasing severity until failure. Therefore, reference values for some stresses may be significantly lower than critical values. This may cause unnecessary increase in cost.

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