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Considering the technical difficulties to apply short-circuit testing, but also manufacturing tolerances and unknown parameters of the transformer design and materials, is it possible to rely only on numerical simulation to assess the short-circuit withstand ability?

To answer this question, we need to consider the current situation in proof of short-circuit ability of power transformers. Full-scale testing is applied only in very rare cases of new transformer designs due to lead time limitations, costs and for very large units due to lack of high-power test facilities. Although this method is seen in the industry as the one with the highest reliability also other methods of proof have been established.
Therefore, according to the existing IEC standard, which is currently under revision, manufacturer can perform a theoretical check of stresses in an actual designed unit to either manufacturers design rules or against similar successful short-circuit tested reference transformers.
With the existing standard, in practice many difficulties occurred with this comparison checks. Especially for large power transformers designed for specific projects it is difficult to find similar short-circuit tested units. Therefore, for the revised IEC standard, it will be allowed to use multiple reference transformers or even (partial) models, which have been tested, to proof the ability of an actual design to withstand short-circuits.
Beside this, high power test facilities report a quite high failure rate at full scale short-circuit testing, which is in the range of 25%! From this current state, somebody may conclude, that there is still some knowledge deficit in the transformer industry, which must be eliminated in future by proper methods and processes to reduce this high testing failure rate. One of the risk mitigations can be the use of modern simulation tools in the design phase, which becomes more and more common during the last decade.

But in which cases can simulation tools improve the situation and reduce failure risks?
Looking at the most severe and frequent failure types occurred in the last decades during short-circuit testing, there is spiraling of open turns in layer windings as well as axial winding collapse coming from bounce-back forces towards the yoke and winding end-support collars, one of the most frequent failures. Both failure types are associated with the dynamic axial oscillation of clamped winding disks. It turned out in practice that a pure static analysis of electromagnetic axial forces is not sufficient in many design cases to evaluate the withstand adequately. This is due to the dynamic transient response of the winding disks and turns in axial direction during short-circuit forces. Friction between spacers and turns to prevent spiraling effects of open-turns as well as back-bounce forces are influenced by resonance effects and clamping forces of the winding. Transient nonlinear spring-mass models[1)] can improve the evaluation of axial and friction forces in windings in a proper way without increasing the design and computation time in daily design work. Failure risks related to spiraling effects in layer windings, especially for those located between main windings can be reduced efficiently by proper mechanical design measures.
Some other examples for numerical simulation with some benefit for reliable short-circuit design are modeling and computation of mechanical stresses in the common press ring and lower winding table. Dynamically calculated axial forces and bounce-back forces from winding response shall be taken to design and evaluate the withstand capability of structural clamping components. 3D-FEM computation may be in some cases preferable because of winding lead-exit cut outs in press rings, which can lead to high delamination stresses in those parts made of transformer-board or laminated wood. Commonly used simplified analytical beam models may not be the adequate approach to proof the short-circuit capability. 3D-FEM simulation models shall be simplified to shorten computation and design time and to make it useable in daily design practice.

How can we now rely on those numerical simulation models and which actions must be taken beside?
Reliability of simulation model is as good as it reflects the main physical parameters of the real components to be evaluated. Such models are reliable if the main physical parameters have been determined by representative methods. This must be done by manufacturers in three different fundamental steps.
- one is the material testing at hot and aged condition of simple winding and support parts like transformer-board components, graded support rings, paper covered CTC´s, bolts and nuts for leads and cleats etc.
- the other is to perform mechanical tests on (partial) models or mock-ups representing a smaller cut out of real winding assembly or structural component
- and finally, and most important is to empirically tune the parameters in such simulation tools from successfully performed short-circuit tests on full scale units. In-service failure experience, if available, may also be helpful for model validation. Consequently, such “tuned” simulation models can also consider some manufacturing and shrinkage tolerances.

Numerical simulation is reliable if some experimental validations and empirical tuning is made in parallel!

[1)] Koczka, G.; Leber, G.; "Empirical Damping of Non-Linear Spring-Mass Systems," in IGTE Symposium, Graz, 2020.