White paper

Designing a transformer that is built to last

Of all the possible scenarios that can befall a utility, a short circuit in the transmission system may be one of the worst. Power transformers are a critical piece of equipment in any substation. When a transformer fails due to a short circuit it almost certainly means extensive repairs if not complete replacement, either of which can mean millions of dollars of unplanned expense for the utility. Compounding that are the additional costs: environmental clean up, collateral equipment damage, fines for excessive unplanned downtime and even litigation costs.

Avoiding these costs requires a transformer that is designed to withstand a short circuit. However, simply stating requirements on design specifications may not be enough. To ensure that the transformer they purchase can handle the rigors of daily use as well as anything today's complex and sometimes unpredictable transmission system can throw at it, buyers need to ask the right questions.

The high cost of failure

When buying a transformer, utilities often compare first cost, or the complete cost of acquiring a transformer, including equipment, transportation and commissioning, with the cost of losses, which measure the efficiency of the transformer over its lifetime. While these are important considerations, they don't take into account the cost of repairing or replacing a transformer should it be unable to withstand a short-circuit event.

In a Hartford Steam Boiler Inspection and Insurance Company study of transformer losses 25MVA and above between 1997 and 2001, the average cost for property damage alone was approximately $9000 USD per MVA. The largest loss occurred in 2000 at a power plant with the cost of business interruption estimated at $80 million Euros or $86 million USD .

Number and amount of losses by year

Year	Total # of Losses	Total Loss	Total Property Damage	Total Business Interruption
1997	19	$40,779,507	$25,036,673	$15,742,834
1998	25	$24,932,235	$24,897,114	$35,121
1999	15	$37,391,591	$36,994,202	$397,389
2000	20	$150,181,779	$56,858,084	$93,323,695
2001	15	$33,343,700	$19,453,016	$13,890,684
Grand total	94	$286,628,811	$163,239,089	$123,389,722

Source: Analysis of Transformer Failures, Hartford Steam Boiler Inspection and Insurance Company, 2003 study.

ABB transformer Research & Development Manager, Giorgio Bertagnolli, wrote a book, *Short-Circuit Duty of Power Transformers*, to help design engineers and specialists involved in designing, purchasing and using power transformers, understand short-circuits and the diagnosis of possible faults. The following is an excerpt from the book, which can be purchased from ABB's website.

"For calculating the stresses caused by axial forces in some components, it has to be accepted that the behaviour of the transformer structure is quite different as regards axial forces, as opposed to radial forces. Both are of a pulsating nature, but the transformer structure is far less rigid, i.e. more "elastic", in the axial as compared to the radial extension.

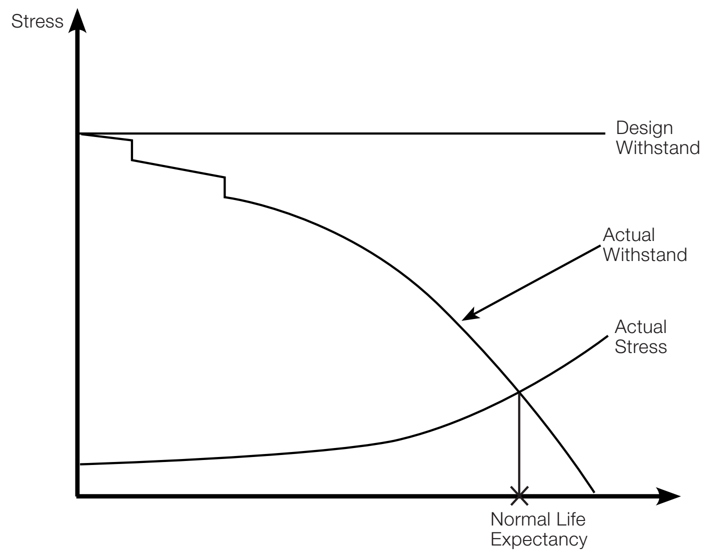
The result is that the winding structure behaves to some extent like a spring, which always contracts with peak force, and then "bounces back" as the current, and therefore the force, cyclically drops to zero.

The overall behaviour of the structure is very complicated, since the forces to which the various structural components of the transformer are subjected, accounting for inner friction, hysteresis, internal solid and viscous damping, hydrodynamic effects of oil motion etc., are often quite different, both in the magnitude, shape and phase, compared with the internally generated forces of electromagnetic origin. The figure below shows the dynamic response vs. time recorded on an experimental transformer.

Any approach based on the consideration of purely static forces is misleading if applied to power transformers at short circuit. Instead, consideration should be given to the real dynamic situation created by the fault event."

At an average age of forty years, a time in the transformer's life when its ability to withstand a short circuit is declining, these aging assets are expected to do more than ever. While energy usage is anticipated to rise at only a modest rate worldwide, additional stress comes from new sources of energy and new distribution models. For example, renewables like wind and solar add a variability to the power loads transformers are expected to handle. Distributed energy resources, whether renewables or more traditional sources, increase the number of network operations such as switching on and off or reversing power flow. This, too, adds to the mechanical stresses on a transformer, potentially weakening the asset and its ability to withstand a short circuit.

Transformer normal life expectancy



Source: Life-Cycle Considerations of Loading Transformers Above Nameplate Rating, Michael A, Franchek and David J. Woodcock, Weidmann Technical Services, Inc. March, 2009.

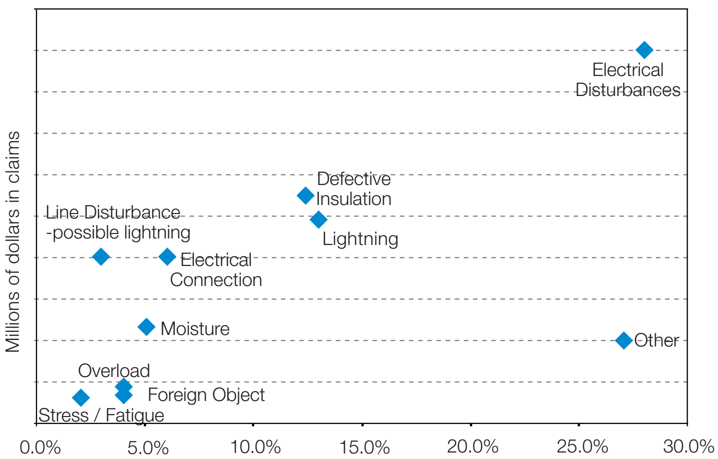
While utilities are under increasing pressure to cut costs in order to keep rates low and maintain a viable business model, cutting corners by choosing the transformer with the lowest first cost can come with a hefty price tag. The power to avoid these catastrophic events is in the hands of the transformer buyer, if they ask the right questions.

Identifying the questions to ask first requires a deeper look into what happens when a transformer succumbs to a short circuit event and how transformer manufacturers play a part in avoiding catastrophic failure through design, testing and manufacturing.

Why transformers fail

Transformers fail for a number of reasons: lighting strikes, overloading, moisture, etc. The figure below shows the frequency of events vs. the cost in claims processed by Hartford Steam Boiler. Electrical disturbances, which include short circuits, occur at both the highest frequency and severity according to Hartford's research.

Why transformers fail
Frequency vs Severity



Source: Analysis of Transformer Failures, William H. Bartley P.E., Hartford Steam Boiler Inspection and Insurance Company, 2012

According to the NERC State of Reliability 2013 report, 15 percent of disturbance events with transmission outages that included substation equipment failure involved a failed power transformer.

Regardless of the type of external event that causes a short circuit, it is the stresses within the transformer that cause a failure. These stresses can be divided into three categories:

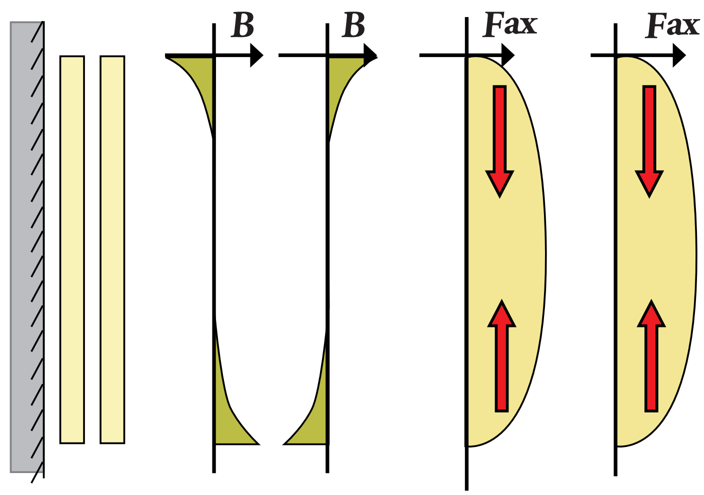
Mechanical – the forces between conductors, leads, and windings due to overcurrent or fault currents caused by short circuits and inrush currents
Thermal – stress due to local overheating, overload currents, and leakage fluxes when loading above nameplate ratings or due to the malfunction of cooling equipment
Dielectric – stress due to system overvoltages, transient impulse conditions, or internal resonance of the windings

A transformer's windings are exposed to stresses even during normal operation. During a short-circuit event, the current that runs through the transformer generates a magnetic field much greater than under normal load conditions. Since this field increases proportionally to the current, the forces will increase to the square of the current. This magnified current subjects the windings to tremendous mechanical forces.

There are two types of forces at work: radial and axial. Axial forces are a consequence of leakage flux caused by inclined flux or winding height offsets. During a short circuit event, the magnetic centers of the windings shift, resulting in axial forces between concentric windings.

Radial forces are dominant due to the axial direction of the main flux and cause a number of problems:
- Forced buckling – inward bending
- Free buckling – outward bending
- Increased diameter for outer windings
- Spiraling of ends in helical and layer winding

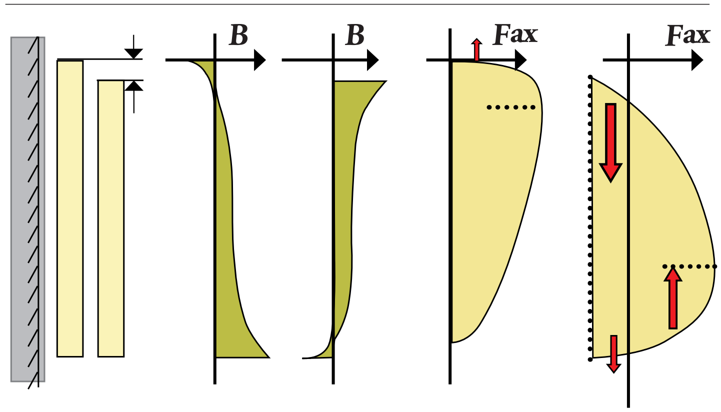
Figure 1:
Axial short circuit forces accumulate towards winding mid-height



The radial component of the leakage flux creates forces in axial direction

As shown in Figure 1, between windings with magnetic centers of the same height, the forces are equal and balanced in both windings. However, if they are offset (displaced) then the forces change significantly. Therefore, it is imperative to use the correct offset when designing for short circuit.

Figure 2: Axial forces with imbalanced windings



Axial imbalance will create extra axial forces

Figure 3: Axial forces vs. winding displacement

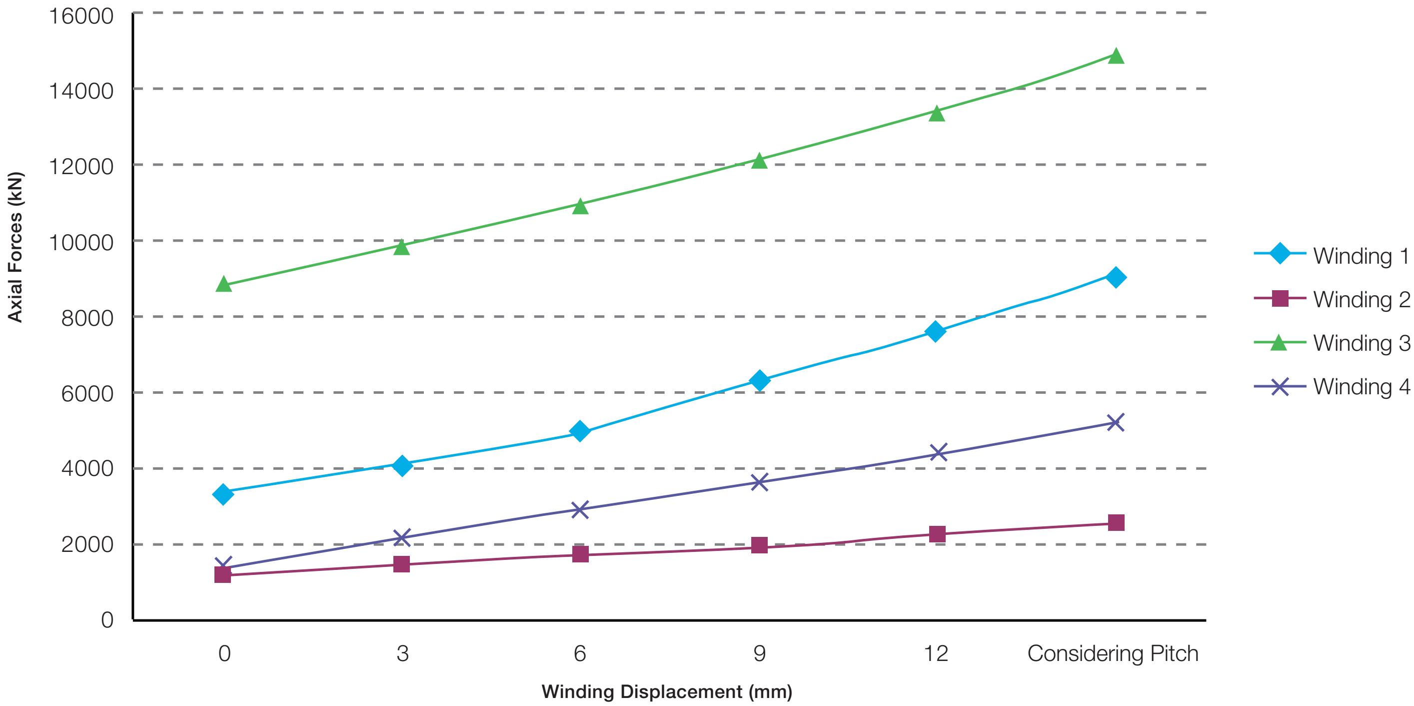
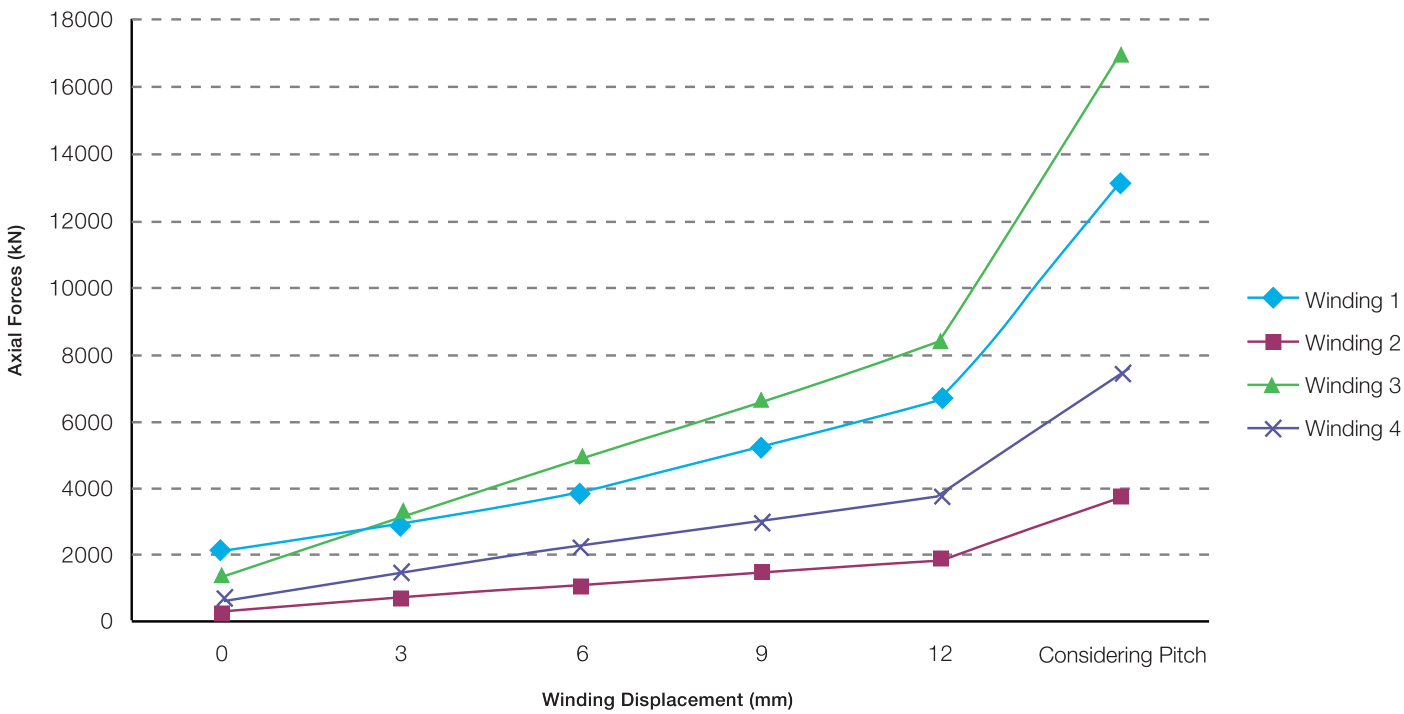


Figure 4: End support forces vs. winding dsplacement



To calculate short circuit forces properly, the correct geometry has to be used. Designers cannot just use any value of winding displacement (offset) because offset values depend on the type of winding. Windings with pitch, both helical and layer, have to be considered as these will influence the short circuit forces calculated. The height of the pitch and the lead exit position low-voltage or high-voltage side has to be considered, as the force will vary around the circumference due to the effect of the winding pitch.

Figures 3 and 4 show how the forces vary with winding displacement. In Figure 3, the forces on winding 3 with a 6mm displacement (not considering the pitch) increase by 37 percent when the winding pitch is considered. The same can be seen on the end support forces. The increase is 342 percent. From this, it can be concluded that when determining short circuit forces, it is vital to consider the windings with pitch.

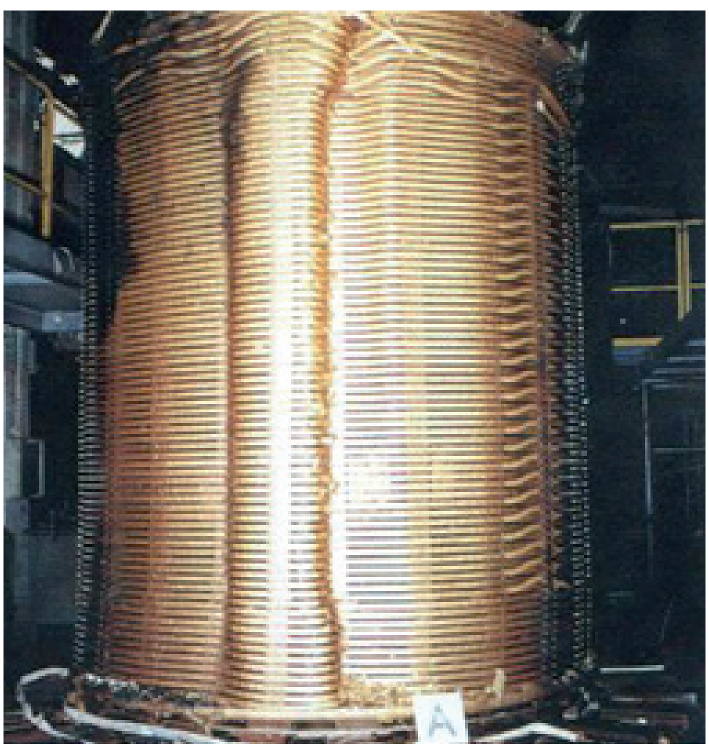
But it's not just the windings that are at risk. Gary McLeish is an engineer at ABB with more than 17 years of experience in transformer design. According to McLeish, "The windings may be strong enough to stand up to the increase in dynamic forces during a short circuit, but these dynamic forces then get transferred to the structure. Therefore, the structure also must be designed to be strong enough to withstand the generated forces." In the image below, it can be clearly seen that end support was too weak to withstand the short circuit.

Failure mode: collapse of end support.

The challenge according to McLeish is that designers must look at transformers as a system. A weakness in one area, such as the materials used for the clamping structure, can offset design strengths in other areas. Transformers really are only as strong as their weakest link.

Knowing how to determine where that weakest link lies requires a thorough understanding of design principles and material limits, but experience plays a vital role, too.

An example showing buckling of inner windings.



Experience matters

Transformer standards created by the IEEE and IEC specify the forces that a transformer must be able to withstand. By definition, a model makes certain assumptions and can't possibly account for all the possible variables a transformer will be exposed to once it's put into service. As any utility manager knows, the real world is full of variables.

To produce a transformer that can stand up to a short circuit, the manufacturer must closely couple manufacturing elements with design and control using proven, standardized best practices based on practical experience. For manufacturers who are new to the market, short circuit testing is one way to gain experience quickly. However, testing can be expensive. KEMA, one of the most well-known and trusted labs available is located in The Netherlands, and the shipping alone can make it cost prohibitive for many buyers. It is ABB's understanding that only about 1 percent of transformer designs are ever short-circuit tested.

Without testing to validate designs, manufacturers have to rely on field experience, something that puts newer manufacturers at a disadvantage.

In addition to lack of field experience, another challenge many transformer manufacturers face is a lack of consistency of manufacturing and design processes among various factories. A transformer built to the same specifications in one factory may not stand up to the same forces as a transformer built in another.

"Any number of minute differences in design or manufacturing can have an impact on a transformer's reliability," says Krzysztof H Kulasek, Vice President of Engineering for ABB's transformer group. "It might be in the materials chosen for the design. It could be part of the manufacturing process such as how the insulation is dried or the windings sized. Or when the active parts are assembled and put into the tank, does the manufacturer do it in a way that controls the exposure time? It could be something as simple as an inattention to the cleanliness of the factory that allows dust or other foreign material to be introduced into the insulation."

ABB built its first three-phase transformer for the very first commercial power transmission with alternating current (AC) in 1893. Since then, ABB has been a leader in designs including the world's first self-cooling transformer in 1932, the first single-phase transformer for 400 kV transmission in 1952, and the world's first high voltage direct current (HVDC) transmission in 1954. Today, ABB transformers handle 1200 kV, the highest commercial transmission voltages in use, as well as three-phase ratings of 1500 – 2000 MVA in system intertie applications and up to 1200 MVA in generator step-up applications.

Over the years, ABB has also acquired the transformer business of a number of leading manufacturers: Westinghouse, ASEA, Brown Boveri, GE (greater than 40 MVA), Molony Electric, National Industries, PowerTran, Kuhlman Electric, Stromberg, just to name a few.

"In 1995, ABB introduced a concept they call TrafoStar™ that leverages the combined experience of ABB and its acquired businesses," says Scott Curley, ABB Vice President for Power Transformers, North America. "Due to our tenure in the industry and our acquisitions, we have technical schematics for more than 70 percent of the power transformer designs still in service. That's a tremendous basis upon which to build."

Kulasek adds that, "Some people think it's our design system that contributes to our track record of performance, but TrafoStar is really more of a technology platform. It builds upon our experience and in service knowledge in the industry and employs common design tools across all of our factories, but it also incorporates other aspects like the manufacturing processes, material, supplier selection, and quality assurance processes that go into building a transformer that can withstand a short circuit."

> "Any number of minute differences in design or manufacturing can have an impact on a transformer's reliability"

This deployment of a common process is one of the keys to ABB's success. Since its introduction, more than 17,000 transformers have been built using the TrafoStar concept. "This is a living tool," says McLeish. "We build an average of 1000 units per year using TrafoStar. Of the more than 160 ABB transformers that have been short-circuit tested and passed, 58 were TrafoStar designed. We believe this record has yet to be matched or exceeded by any other manufacturer."

TrafoStar has been a proven success for ABB and its transformer customers. As reported at CIGRE, around 28 percent of all power transformers short-circuit tested at KEMA fail, whereas ABB's failure rate is closer to 11 percent. Over the last 10 years, the success rate has remained consistent.

In addition, with more than 25,000 ABB power transformers installed in the past four decades and a Mean Time Between Failure rate of 715 years, ABB's field performance reliability is unmatched as well. The significance of this track record of proven performance is magnified when you consider that each of the transformers tested is designed using the common platform. The lessons learned from these tests, additional tests performed within ABB's facilities, and experience in the field is incorporated back into the tool for use across ABB's factories worldwide.

"The knowledge gained is critical," adds Kulasek. "TrafoStar allows us to use the same material standards, the same tolerance, the same production processes worldwide. We also incorporate this knowledge into the short-circuit design tool within TrafoStar, making it available to our design teams no matter where they are located. This provides a tremendous advantage for our customers around the world."

Designing transformers to withstand a fault

Verifying the short-circuit strength of a transformer starts with calculating the short circuit currents that the transformer will be exposed to during a short-circuit event. The ABB rules require the design engineer to systematically calculate the fault currents in all failure cases with the tap changer(s) in different positions:

- Three phase faults line to ground
- Single phase to ground faults
- Single phase line to line
- Two phase faults line to ground

The designer must also consider three additional elements: the network impedances in line with the standard or the specification, that impedances are subject of tolerances, that current limiting reactors may show saturation effects.

All TrafoStar transformers are designed with radial and axial forces in mind. The radial strength of inner windings is determined by its copper yield point and conductor geometry, while the radial strength of outside windings is determined by the copper yield point.

With respect to axial forces, the optimum ampere-turn balancing of all windings is calculated. Axial and radial forces are calculated by Finite Element Method (FEM), considering axial displacement due to workshop tolerance, which makes the windings to be positioned axially not exactly as theoretically foreseen. The variation of the force along the winding circumference due to the effect of the winding pitch when it deals with layer and helical windings. Windings are dimensioned for maximum compression forces, dynamic effects are considered by dynamic factors on the forces, and winding ends are dimensioned for maximum unbalance forces and for a part of the maximum compression force or "bounce back."

Experience also matters when selecting the materials used in a transformer. Material choice is a primary factor for both. For a large power transformer, materials can be as much as 50 percent of the cost. As in any design, ABB design engineers work with customers to determine the best balance between first cost, cost of losses, and material withstand value of the transformers. Selecting the materials to be used is a key step in that process.

"You can calculate the ability of any given material to withstand mechanical forces, but transformer design requires something more than a point by point analysis." says McLeish. "Every transformer design will have different winding characteristics: different conductors, spacers, amount of paper, and so on. There are a lot of variables to consider, but they all function together. A weakness in one area can bring the entire system down. TrafoStar looks at materials as part of the overall system. "You can calculate what the forces are, but unless you know how those forces relate to real world line performance and materials capabilities, the data won't be of much use," adds Kulasek. "To compensate, some buyers specify an infinite bus be used in the design. While it adds margin, it also adds to the cost of the product. But, this margin is not equal for high- and low-impedance units. On paper, the margin may look sufficient, but if the geometry of the windings is not considered or maintained during the production process, it won't be enough."

Rigid tolerance and production performance are as important as proper design. ABB transformers are wound within strict tolerances measured within millimeters. When you consider that a winding could be eight feet high or more, that's an exacting specification. During manufacturing, a final pressing is done after vapor phase drying with strict time constraints based on ambient temperature and humidity to minimize loss of pressure once the transformer is put into service. This keeps windings in place despite the increase in mechanical forces during a short-circuit event.

As reported at CIGRE, around 28 percent of all power transformers short-circuit tested at KEMA fail, whereas ABB's failure rate is closer to 11 percent. Over the last 10 years, ABB has only seen 5 failures among the 50 transformers short-circuit tested.

The manufacturing environment is also crucial to avoiding contamination. "When most people think of a shop that produces heavy equipment, they probably imagine a dusty and somewhat disorganized place." says Kulasek. "That's because they've never been to an ABB factory where transformers are produced. ABB has built a culture of continuous improvement into its TrafoStar platform, incorporating quality and process improvement tools like the 4Q methodology, 5S, Six Sigma, TPS, and Kaizen."

Asking the right questions

Ensuring your transformer is robust enough to handle a short circuit requires buyers to ask the right questions. ABB's McLeish suggests a few:

1. What is the peak, full asymmetric current used for short-circuit calculation?
2. Is the pre-fault voltage considered?
3. Were all short-circuit cases considered? i.e. Single phase to ground, single phase line to line, three phase line to ground and two phase line to ground.
4. Are the calculated short-circuit currents accurate? Was a system study performed?
5. How was the accuracy of the calculated short-circuit currents determined? Was a system study performed?
6. What calculation method was used to determine the short-circuit forces?
7. What is the maximum axial displacement (offset) used in the calculation and was the pitch of the windings considered?
8. How do you ensure that the maximum offset used in the calculation will not be exceeded during the manufacturing process?
9. How are the permissible limits for spacers and pressboard determined? Were short-circuit tests performed?
10. How are the forces on clamps, tie-bars, tie-rods, tie-plates, pressure rings, and end supports calculated and what is the basis for the limits on these items? By short-circuit testing?
11. Are the forces calculated static or dynamic?
12. Are all windings subject to buckling self supporting?

In addition to asking the detailed questions, ABB's McLeish recommends looking at the big picture as well. "If the buyer is trying to decide between suppliers with similar costs, short-circuit reference lists can help ensure they make the right choice. For many of our buyers, ABBs extensive reference list provides peace of mind.

McLeish also recommends the 2013 CIGRE report, WG A2.36, Transformer Procurement Process: Guide for Design Review for Power Transformers. "For a buyer who is new to power transformers or even someone who's been around awhile, this guide provides invaluable insights into the considerations that go into designing a transformer that is able to withstand a short circuit," says McLeish.

Given the high cost of failure, selecting a transformer that can withstand a short circuit is too important to leave to chance. Putting the required specifications in a request for proposal simply isn't enough.

"We realize it isn't always possible for a buyer to visit every factory," says Curley. "That's why we encourage buyers to ask questions and demand test results. Doing the due diligence is the only way to be sure you get what you pay for."

References

[i] Analysis of Transformer Failures, William H. Bartley, P.E., Hartford Steam Boiler Inspection and Insurance Co., 2003

[ii] NERC State of Reliability Report 2013, May 2013

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