



Transformers and substations

Surviving a short-circuit

Short-circuit withstand capability of power transformers

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The power transformer is a vital component in the transmission of electric power. Thanks to the many years of accumulated knowledge, experience and sophisticated development in production and testing processes, the transformer is now a highly efficient piece of apparatus with an outstanding reliability. Transformers, however, are not the only components to have experienced changes. The rapidly evolving electricity market is causing networks to operate closer to their limits. At the same time, the booming demand for new transformers combined with high material prices is putting pressure on manufacturers and their suppliers. All these aspects combine to make assurance of the robustness of transformers more important than ever before. ABB draws on its vast experience in power transformer manufacturing to deliver equipment that displays a truly outstanding short-circuit performance.

As power ratings and transmission voltages have increased, the thermal and mechanical aspects of transformers have become more pronounced, both in terms of local over-heating control and in the need for withstanding electrodynamic forces originated by fault events occurring in electrical systems. ABB's transformers are today handling 1200 kV, the highest commercial transmission voltages presently in use. They are also handling three-phase ratings of 1500 to 2000 MVA in system intertie applications and up to 1200 MVA in generator step-up applications.

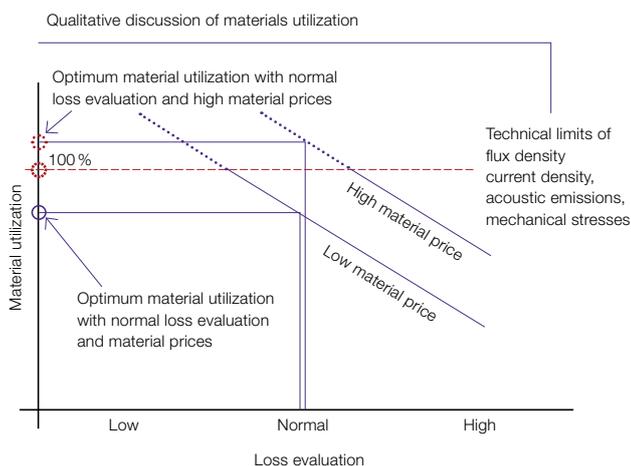
Background

The demand for transformers is now booming in a way similar to the situation after the Second World War. At that time, European and American markets were served by domestic suppliers who invested to full capacity to meet the needs of state-controlled utilities and power companies. Installations of 400 kV to 800 kV AC were implemented. It was also a time when numerous IEC and ANSI international standards were laid down.

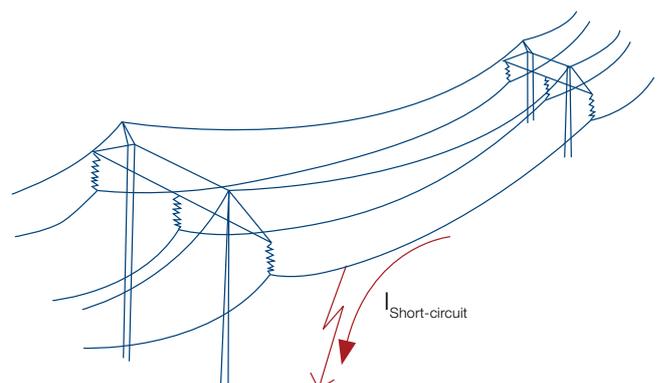
The first signals of a shift in demand were visible in the early 1980s. By the end of this decade, the electrical system industry had gone through its biggest change since the inventions of Edison and Westinghouse.

The last 25 years have been characterized by a huge global consolidation on both the supply and user side of electrical equipment. The entirely domestic business has been transformed into a global one, with consequences for both commercial and procurement matters.

1 The choice of materials involves a trade-off between material losses and a price



2 Failures caused by short-circuits are still a major cause of transformer outages



The procurement side had additionally had to deal with the markets for raw materials, many of which are no longer in their traditional balance.

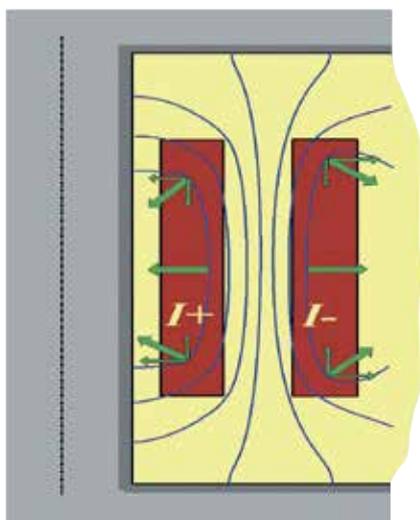
Changes to the grids were motivated by rational reasons for opening up markets to enable trading and regional interconnections. Political stakeholders wished to enable to increase competition. As a result, many former governmental bodies were transformed to profit-making companies. Production, transmission and distribution were broken up into separate entities, with the role of transmission becoming weaker and less clear as a result. It especially became more difficult to obtain a collective responsibility. Fluctuations in prices are considered the concern of end-customers and long-term commitment in infrastructure has shifted to a shorter-term horizon.

For the transformer market in particular, the most significant changes of recent years are caused by the huge demand for electrical energy in regions such as Asia, the Middle East and South America. Additionally, the so-called “old world” has a need for re-investment, as the age of their transformer fleet is close to 40 to 50 years. These developments are additionally boosted by environmental concerns.

Furthermore, the increasing demand for transformers is pushing manufacturing facilities and their material suppliers to the limits of their capacity, resulting in leading to extended delivery times.

Meanwhile, growth in grid utilization is outstripping new investment, leading to individual components being operated closer to their limits.

3 Electromagnetic forces tend to minimize the density of magnetic energy



Testing

Testing of new transformers is the utmost demonstration of their quality. Today’s designs, marked by high material prices and often low loss evaluations, are pushing materials closer to their limits and exosizing them ever before.

The acceptance testing concerning dielectric aspects is well covered by the international standards that have been developed over the years. The proving of thermal and mechanical integrity of new large GSU (generator step-up) and intertie transformers is still, however, a field where design and production weaknesses can pass can escape detection.

This article mainly concerns the manner, in which ABB’s philosophy on design, production, supply chain and testing philosophy verifies mechanical aspects of reliable large power transformers, in other words, their ability to pass a short-circuit test.

Reliability

Modern power systems are complex arrangements systems with a high number of individual pieces of apparatus. To ensure reliable operation, it is of utmost importance that key elements such as large power transformer have a high degree of availability, thus minimizing the outages of individual components or whole power generation units.

The ability to withstand a short-circuit is recognized as an essential characteristic of power transformers. IEC and IEEE Standards, as well as other national standards hence specify that power transformers have to be short-circuit proof and lay out how this should be verified. Unfortunately, however, there is extensive evidence that the matter is not as simple as the standards would suggest. The failures caused by short-circuits are still a major cause of transformer outages – though failure rates vary widely in different countries and systems, depending on various circumstances, network characteristics and the equipment installed.

Nowadays fast developing regions, with steeply rising demand for electric power, are adding more and more generating capacity and interconnections to their systems. In addition to this the western world is characterized by:

- Expanding cross-border electricity trade (bringing network operations close to their physical limits)
- Development of wind generation (which is often integrated into the grid without taking the available network capacities into account)
- Changing load flows
- Ageing network components
- Changing network operating conditions

These factors lead to old and new transformers being exposed to severe short-circuit requirements.

ABB has succeeded in building transformers with an outstanding reliability record. This is a result of dedicated development work, long time experience in building transformers for the most demanding service conditions and meticulous follow-up of incidents occurring during tests and operation.

17th years ago, ABB launched a business concept called TrafoStar™. It integrates engineering tools and manufacturing accuracy of major suppliers with common material specifications, testing and quality management system. This concept is now used for large power transformers in 12 plants in all global regions. Since the inception of TrafoStar™, over 17,000 power transformers have been produced according to this concept, of which 2,000 units are very large GSUs and intertie transformers. Every year, more than 1,800 power transformers with rating above 60 MVA are produced.

Design considerations

How will all those changes affect today's design and future reliability and availability? In view of rising demand, many new suppliers will be entering the market, with distribution-side manufacturers also moving into the power transformer sector. At the same time, the large increase in material prices, com-

pared with traditional low loss evaluations, will drive stresses upwards as margins are reduced.

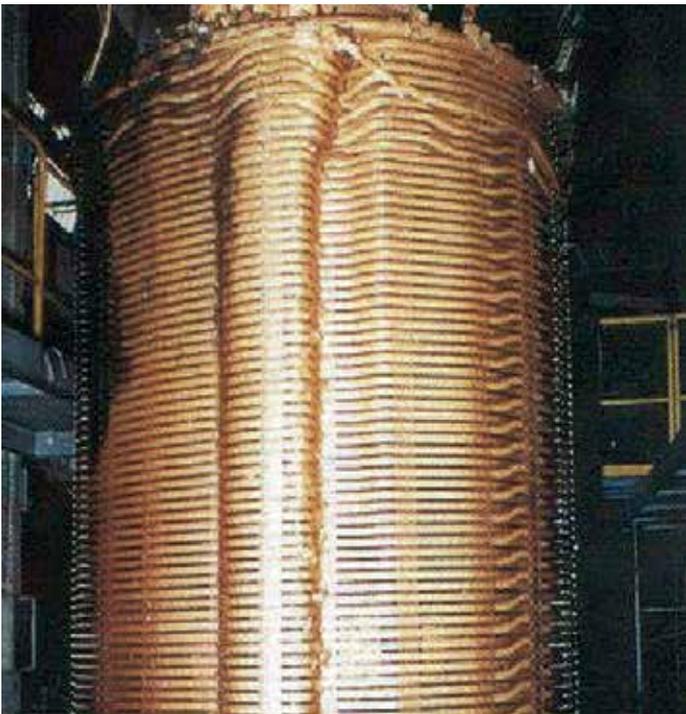
The mechanical rigidity of the transformer will become the most vital performance factor for the future. There are three reasons for this:

- A requirement to withstand short-circuit stresses
- Seismic requirements
- Transport handling

The short-circuit force gives rise to mechanical forces that can reach hundred of tons in milliseconds. The current peaks and the corresponding forces depend on many factors. In high-voltage systems, the most probable type of a short-circuit is a single-line-to-earth flashover, normally due to environmental conditions such as a lightning strike on the line, equipment failure at the station, pollution of insulation strings, and similar causes. Sometimes, short-circuit faults will develop into other more extensive faults, such as single-phase-to-earth faults developing into a double-phase-to-earth and eventually three-phase faults. The relative severity of the different types of fault depends on the characteristics of the system. On the other hand there are factors such as arc resistances and earth network impedances that have some compensatory effects. The severity of a short-circuit and the peak current and forces depends to a considerable extent on the condition of the

4 Examples of windings deformations caused by extreme forces:

a) Buckling: Collapse of the cylindrical winding shell,



b) Spiraling: Tangential shift of the end turns in helical-type windings



installation, and in particular on the short-circuit impedance value of the transformer and the short-circuit apparent power of the system(s).

Configuration of the fault that normally yields the highest through-currents in any winding of the transformer is the symmetrical three-phase fault. Hence, it is meaningful to use this fault mode as a basic design criterion for the transformer.

In dealing with short-circuit events in power transformers, the first step is to evaluate any very high fault currents that will affect the windings in connection with the various types of faults the unit is likely to experience in service.

When determining the magnitude of the currents, circuit analysis and theory of symmetrical components are used. The calculations are performed by automated programs, where characteristics of the system and the transformer serve as input data.

Force calculations per failure mode

Electromagnetic forces tend to deform the windings so as to minimize the magnetic energy density stored in their volume. In the case of a two-winding transformer, this would mean that the inner winding tends to reduce its radius, while the outer winding tends to increase its radius. In axial directions, the windings undergo compression in order to have their height reduced – see figure 3.

Forces and relating withstand criteria can be split between the two components:

- Radial forces
- Axial forces

The failure modes for radial forces include:

- Buckling of inner windings figure 4a
- Stretching of outer windings
- Spiraling of end turns in helical windings figure 4b

The failure modes for axial forces include:

- Mechanical collapse of yoke insulation, press rings and press plates, and core clamps
- Conductor tilting
- Conductor axial bending between spacers
- Possible initial dielectric failures inside windings, followed by mechanical collapse

The axial forces are calculated with programs based on finite element method (FEM) that fully take into account axial displacements caused by workshop tolerances and pitch of helical type windings. Windings are dimensioned for maximum compression forces, where dynamic effects are embedded.

Factbox

Features of power transformers manufactured by ABB

- A short-circuit safe transformer is characterized by
- Mechanically sound design and technology based on fundamental mechanics and verified by many short-circuit tests
 - Rigid core clamping structure for short-circuit strength and easier transportation
 - Accurate manufacturing process guided by strict tolerances and quality systems
 - Rigid winding mandrels
 - Verified drying and pressing procedures
 - Rigid low-voltage winding design and clamping

Recommendations

Which units are worth being considered for short-circuit testing?

- Important generator step-up transformers and auxiliary units in power plants
- Key feeding transformers at power plant sub-stations or huge load centers
- Strategic intertie transformers three-winding system transformers (tertiary), auto-transformers
- Transformers with axial split winding connections
- Series of transformers, one to be taken out
- Always track feeding transformers
- Transformers connected to networks known for many faults and high fault currents

All power transformers designs/contracts to be checked by design reviews to IEC 60076 – Part 5 (2006-02)

An important feature of ABB's short-circuit technology is that inner windings subject to radial compression are designed to be completely "self-supporting" as regards any collapse by "free buckling". For this reason, any – often questionable – contribution to stability granted by radial supports from the core to the windings or from one winding to another is deliberately ignored in any ABB transformer designs.¹ This means that the mechanical stability of the winding is determined by the hardness of the copper (yield point) and conductor geometry. Spiraling in helical type windings is avoided by strictly limiting the forces that can occur, or by changing the type of winding. Also the dynamic response from the winding is considered.

Designing power transformers is an iterative and interactive process seeking the optimal solution from the point of view of:

- Masses and losses
- Sound level
- Short-circuit strength
- Winding temperatures, hot spots and cooling equipment
- Dielectric strength between windings and inside windings

¹ – The reliance on radial supports can compromise the mechanical stability of the windings due to relaxation of the supports under load and over time

5 Manufacturing of transformers requires a high degree of accuracy



ABB's designers are supported by the world's most advanced design and verification software dedicated to power transformers. Today, those interactive applications are used today in 12 power transformer plants.

Manufacturing and accuracy

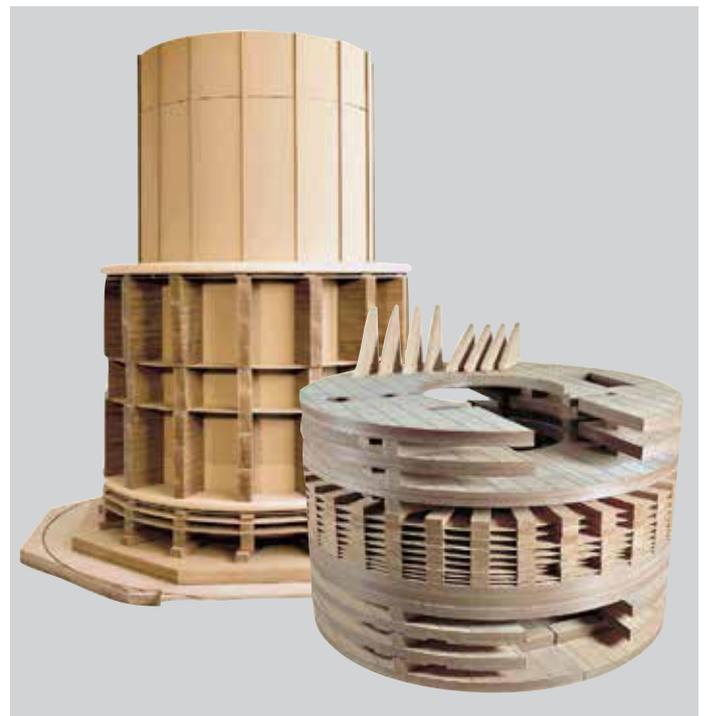
Ampere-turn balancing between the windings is a prerequisite to avoid excessive axial forces on the windings.

This is achieved through strict manufacturing tolerances for windings – see figure 5.

Since the windings can be regarded as springs made in about 20 percent of cellulose, the correct compacting when exposed to moisture and temperatures is important in obtaining the exact length and spring constant for long-time service. Well defined processes in the winding shop and active part assembly of components are necessary. The final pressure setting after the vapor-phase process is used to bring the windings under pressure for their life time.

The most important criterion is that all windings need a specific pressure to avoid any displacements between the coils. The different cellulose-based components are manufactured and treated from raw material entirely in ABB's own pressboard machines and kit-centers around the world. This secures

6 ABB's common manufacturing method secures a successful production of all key elements. This has a significant impact on the winding dynamic strength



a common method of producing all those key elements that significantly impact the dynamic strength of the winding – see figure 6.

A short-circuit force gives rise to mechanical forces that can reach hundreds of tons in milliseconds.

Verification of the short-circuit strength

The 3rd edition of IEC Standard 60076-5 (2006-2) provides two options for verifying the transformer’s ability to withstand the dynamic effects of a short-circuit.

These are:

- a) A full short-circuit test performed at a certified lab or
- b) A theoretical evaluation of the ability to withstand the dynamic effects of short-circuit events based on the manufacturer’s design rules and construction experience, in line with the IEC guidelines

On account of the high investment costs in test equipment, such tests are possible in only a handful of locations in the world. The test requires power capacities in the range of a large power grid together with sophisticated control and

7 Due to the high investments involved, short-circuit testing of power transformer can only be performed in a few places in the world. The below photo presents KEMA in the Netherlands



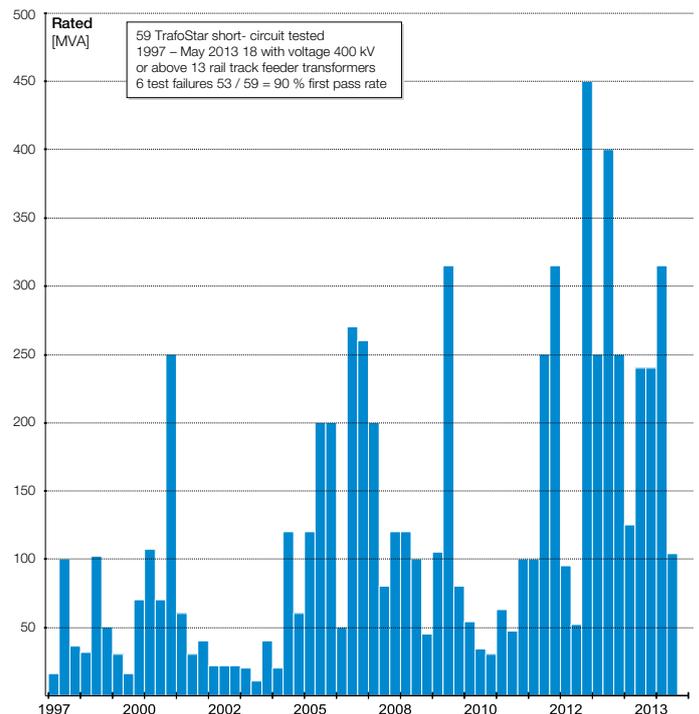
measuring equipment. One such facility is KEMA in the Netherlands, where a number of short-circuit tests were carried out on behalf of ABB – see figure 7.

More than 163 ABB power transformers of different designs have passed short-circuit tests, including around 58 that were built after 1996 according to TrafoStar technology – see figure 8.

In CIGRE and at other technical conferences, KEMA reports are showing test failures in around 30 to 40 percent of the performed SC tests on power transformers. ABB’s own test record from over the last 17 years present 6 failures out of 59 tests. When the ABB tests are removed from the overall statistics, other manufacturers are showing much higher short-circuit test failure rates. This highlights the extreme challenge of building fully short-circuit safe transformers in the world today.

The 3rd edition of IEC Standard also allows for a design-related verification, where the manufacturer may present its calculated stresses and compares them with its own rules manifested by several short-circuit tests. To comply with this Standard, stresses shall not exceed the manufacturer’s maximum allowable stresses or 0.8 of the critical stress value identified by the manufacturer. The stress values must furthermore comply with the corresponding maximum ones specified in the 3rd edition of IEC Standard 60076-5 as guidance.

8 TrafoStar short circuit strength – Verification by testing



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