Surviving a short-circuit

Short-circuit withstand capability of power transformers

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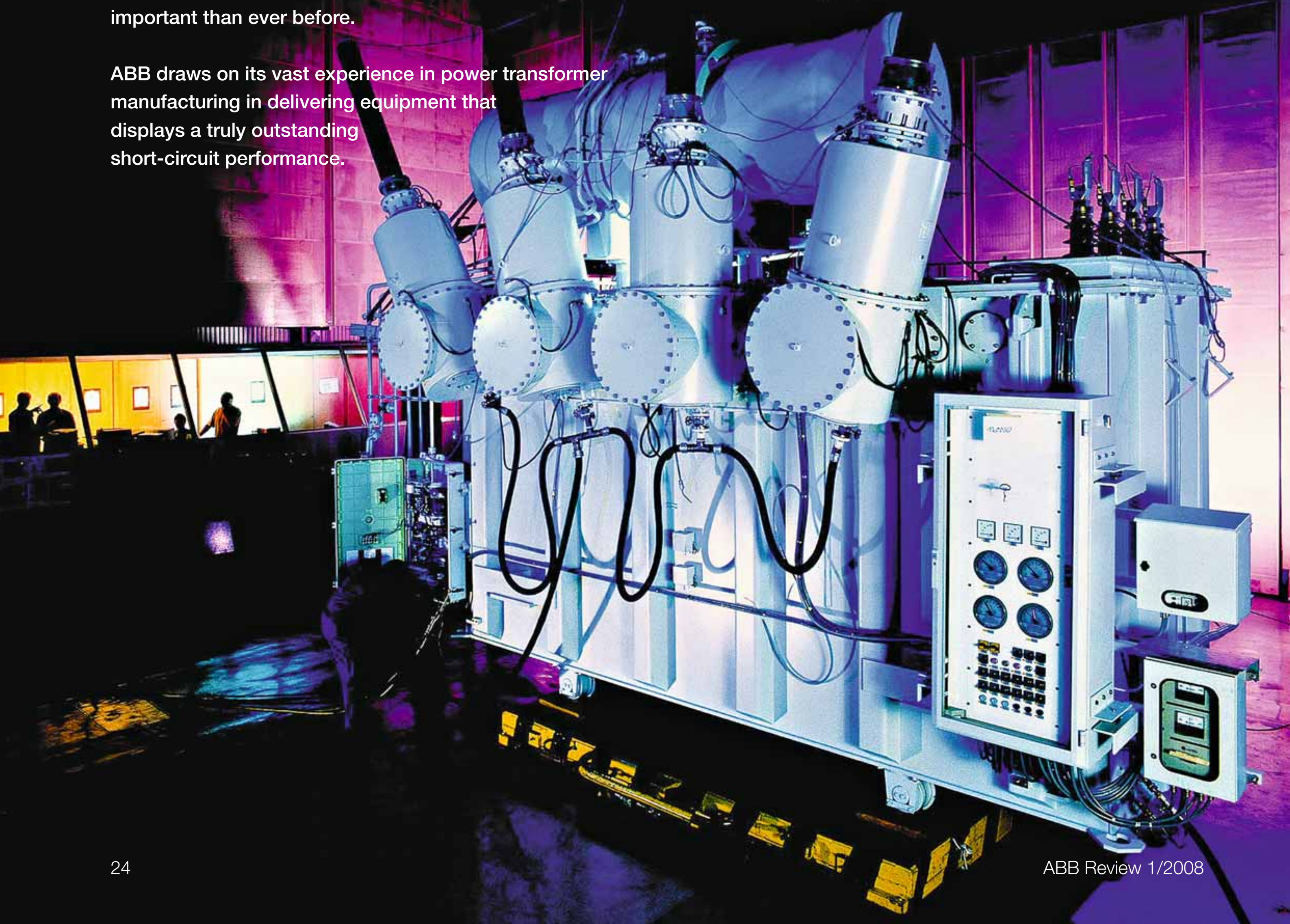
The power transformer is a vital component in the transmission of electric power. Thanks to the many years of accumulated knowledge, experience and sophisticated development in production and testing processes, the transformer is now a highly efficient piece of apparatus with an outstanding reliability.

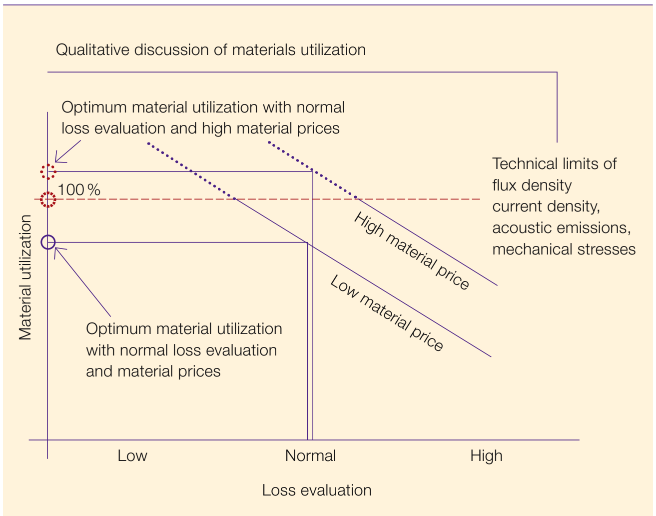
Transformers, however, are not the only components to have experienced changes. The rapidly evolving electricity market is causing networks to be operated closer to their limits. At the same time, the booming demand for new transformers combined with high material prices is putting pressure on manufacturers and their suppliers. All these aspects combine to make assuring the robustness of transformers more important than ever before.

ABB draws on its vast experience in power transformer manufacturing in delivering equipment that displays a truly outstanding short-circuit performance.

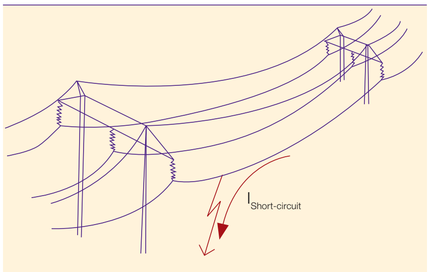


As power ratings and transmission voltages have increased, the thermal and mechanical aspects of transformers have become more pronounced, both in terms of local over-heating control and in the need for withstanding electrodynamic forces originated by fault events occurring in electrical systems. ABB's transformers are today handling 800 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.

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



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



Background

The demand of transformers is now booming in a way similar to 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 appeared in the early 1980s. By the end of this decade, the electrical system industry has 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. A fully domestic business has been transformed to a fully global one, with consequences in both commercial and procurement matters. The procurement side has 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 increased competition. As a result, many former governmental bodies have been 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 has especially become 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 needed to re-invest, as the age of its transformer fleet reaches 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, leading to extended delivery times.

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

Testing

The 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 seeing materials being pushed closer to their limits and exposed to greater stresses than ever before 1.

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 without being detected.

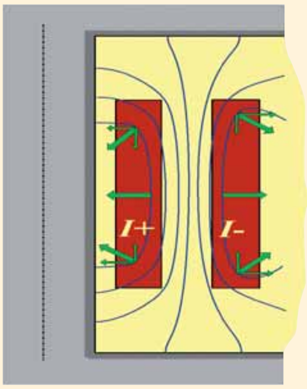
This article mainly addresses how ABB's design, production, supply chain and testing philosophy verifies mechanical aspects of reliable large power transformers – in other words, their ability to pass a short-circuit test.

Reliability

Modern power systems are complex arrangements 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 blocks of power generation.

The ability to withstand a short circuit is recognized as an essential characteristic of power transformers. IEC and IEEE Standards, as well as other

3 Electromagnetic forces tend to minimize the density of magnetic energy



Factbox Attributes of power transformers manufactured by ABB

A short-circuit safe transformer is characterized by
- Mechanical sound design and technology
- Based on fundamental mechanics
- Verified by many short-circuit tests
- Rigid core clamping structure for short-circuit strength and transport
- Accurate manufacturing 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)

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 2 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 into account available network capacities)
- Changing load flows
- Ageing network components
- Changed 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 taking place in tests and operation.

Ten years ago, ABB launched the business concept, TrafoStar™. This integrates engineering tools, manufacturing accuracy, major suppliers with common material specifications, testing and quality management system. This concept is now used for large power transformers in 14 plants in all global regions. Since the inception of TrafoStar™, 10,000 power transformers have been produced according to this concept; of these, 2,000 units are very large GSUs and intertie transformers. More than 1,500 power transformers of more than 60 MVA rating are produced every year.

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

The mechanical rigidity of a transformer will become the most vital performance factor for the future. There are three reasons for this:
- Withstand to 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 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 installation, and in particular on the short-circuit impedance value of the transformer and the short-circuit apparent power of the system(s).

The fault configuration that normally gives 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 means of automated programs, since the system and the transformer characteristics constitute the 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. For a two-winding transformer example, this means that an inner winding will tend to reduce its radius and an outer winding to increase its radius. In axial directions, the windings get compressed to reduce their height 3.

Forces and relating withstand criteria can be split into two components:
- Radial forces
- Axial forces

The failure modes for radial forces include:
- Buckling of inner windings 4a
- Stretching of outer windings
- Spiraling of end turns in helical windings 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.

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 iteration and interaction process that seeks 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

ABB's designers are supported by the world's most advanced set of design and verification programs for power transformers. These interactive appli-

Footnote

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

4 Examples of deformations caused to windings by extreme forces:

a Buckling: Collapse of the cylindrical winding shell

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

5 Transformer manufacturing requires a high degree of accuracy

cations are used today in 14 power transformer plants.

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

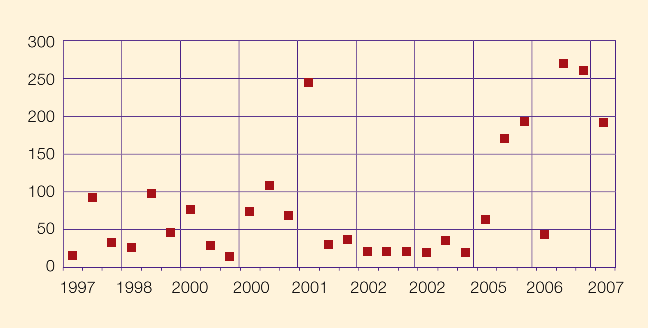
This is achieved through strict manufacturing tolerances for windings 5.

Since the windings can be regarded as springs built of about 20 percent 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 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 criteria are that all windings need a given 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 a common method of producing all these key elements with significant influence on the winding's dynamic strength 6.

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

7 Rated power (MVA) of SC tested TrafoStar™ transformers



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

Short-circuit strength verification
The new 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 new IEC guidelines

8 Due to the high investments involved, power transformer short-circuit testing can only be performed in few places in the world. This is KEMA in the Netherlands.

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

More than 140 ABB power transformers of different designs have passed short-circuit tests, including around 30 that were built after 1996 according to TrafoStar technology 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 over the last 11 years has been three failures out of 28 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 new IEC Standard also allows for a design verification where the manufacturer shows its calculated stresses and compares it 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 given for guidance in the new IEC Standard 60076-5.

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