Short – Circuit withstand capability
Short - Circuit withstand capability

Agenda

- Fault currents in network and their interaction with transformers
- ABB Technology (TrafoStar™) and design consideration to build SC safe transformers
- Advanced manufacturing and SC tests experience
- Customer considerations to mitigate future risk by using new SC IEC recommendations
- ABB recommendations
Short - Circuit withstand capability

- Why talking about Fault Currents in network today?
- Are Fault Currents affecting Transformers more today?
- Who cares about Mechanical Forces in transformers?
Short - Circuit withstand capability

- History – Why SC tests?
  - SC tests have been used in different countries
    - Customers didn’t get SC safe transformers
  - SC tests introduced 1950 -1960
  - SC tests have been debated during the years
    - Many opinions in different countries about the needs and what one test show
  - IEC has edited Standards the first about 1976
  - This discussion about SC test or not SC test seems relevant also today!
What is the overall driver?

- Two infrastructure S-curves
  - 1950-1980 Western infrastructure build out
  - 2000-2020 South & East Asian infrastructure build out and EU replacements/interconnections
- Energy & material prices related to these megatrends
Short - Circuit withstand capability

- Networks are today more loaded, new in-feeds as wind power are added
- Load flows are changing
- Network components are ageing

- The network operation conditions have changed, increasing of short circuit power in growing environment such as Asia.
- New transformers will see more severe SC duty than before
Short - Circuit withstand capability

How will this affect today's transformer designs?

- There is now a trend to save active material and/or design closer to mechanical/electrical limitations.

Does the Industry have defined efficient measures/test Standards to check the mechanical integrity of products like Power Transformers?

- New IEC SC standard proposes
  - Full scale SC Tests
  - Design review evaluation/verification
    - IEC edition 2006 proposes typical allowable, critical stresses
Short circuit integrity

- Short Circuit Integrity
- A key for reliable operation

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Network disturbances must not give rise to consequential damages in transformers
Short circuit integrity

- Short circuit current gives rise to:
  - Mechanical force (msec) with hundred of tons
  - Temperature rise (sec)
Short circuit integrity

- Flux and current interact and give rise to mechanical forces

\[ dF = I_{ds} \times B \]

- And Losses and Temp

\[ \text{Losses} = I^2 \times R \]
\[ \text{Temp} = f(\text{Losses}) \]
Short circuit integrity

- Critical temperature rise
  - Loss development proportional to the square of the current
  - A tenfold increase means a hundredfold increase in loss development
  - Only a limited time can be permitted with such high current
  - Normally this is not important.
Short circuit integrity

- **Fault current** is governed by:
  - Open-circuit voltage
  - Source impedance
  - Instant of fault onset
Short circuit integrity

Forces are proportional to the square of the current (instantaneous values)

\[ F \propto I^2 \]

\[ B \propto I \]

\[ F \propto I \times B \]

\[ = F \propto I^2 \]
Short circuit integrity

- Risk for Short Circuit Failure depends mainly on:
  - Source impedance
  - Instant of the fault onset
    - Those factors give the current peak and the final force
- Therefore fault currents in service operations often do not load the transformer with the maximum force. The likelihood is that forces of 20-40% of the max theoretical forces will be seen.
Short circuit integrity

- Electromagnetic forces tend to increase the volume of high flux or minimize the magnetic energy density in the volume
  - Inner winding towards reduced radius
  - Outer winding towards increased radius
  - Winding height reduction subjected to axial forces.
The axial component of the leakage flux creates forces in radial direction.
Short circuit integrity

- Radial forces failure modes:
  - Buckling of inner winding
  - Diameter increase of outer winding
  - Spiralling of end turns in helical winding
Short circuit integrity

**Inner winding:**
Radial forces inwards
⇒ compressive stress

**Outer winding:**
Radial forces outwards
⇒ tensile stress
Short circuit integrity

- Force distribution across the inner and outer windings
- Conclusion
  - For withstand analysis the mean value across a winding can be used
Short circuit integrity

- Buckling
- Characteristic failure mode
- for inner winding
Short circuit integrity

- Collapse of a cylinder shaped winding from evenly distributed external force

a) Typical deformation in when winding strength is achieved via the insulation supports

b) Typical deformation of Self supporting winding
Short circuit integrity

- Buckling of inner windings
- Unit removed after 15 years of service due to increased impedance.
- Note: No electrical damages
- 250 MVA, 400 kV auto
Short circuit integrity

- The radial component of the leakage flux creates forces in axial direction.
Axial short circuit forces accumulate towards winding mid-height

Short circuit integrity
Axial imbalance will create large axial forces.

The forces tend to increase the imbalance.
Gaps in a winding will create large variations in the radial component of the leakage flux.

Consequently, large axial forces will be developed.

Short circuit integrity
The failure modes for axial forces include:

- Mechanical withstand of yoke insulation, core clamps and spacers
- Conductor tilting
- Axial bending between spacers
- Spiralling
Short circuit integrity

- Excessive axial forces towards yoke
- Damages from a SC test
Short circuit integrity

Tilting of conductors
Short circuit integrity

- Tilting at a local place
- Damages after a SC test
Axial force tend to bend the conductor, may be critical for low conductor heights
Short circuit integrity

- **Spiralling**
- A tangential shift of end turns in helical type windings
Short circuit integrity

- Alternative view of spiralling
Spiralling on the winding of a 370 MVA GSU transformer during the short-circuit withstand test.

- a) entire outer layer of the LV winding
- b) detail of the upper lead exit on the same layer heavily bent and distorted
Designing for short-circuit strength - background

- Each company forming ABB has performed a large number of short circuit tests forming the basis for its design standards
- The “Merger-projects” evaluated the different Power Transformer technologies and standards
  - In each area; Buckling, Tension, Compression, Tilting, etc the various standards were compared against actual test results.
  - The standards and principles that were found most relevant and safe were adopted
- A new ABB Technical Standard was issued containing the agreed “best practices”
- This Standard is adopted worldwide in the TrafoStar™ concept
- The TrafoStar concept has been proven by 49 full scale tests since 97
- The Standard is continuously improved as a result of new findings
Designing for short-circuit strength

- ABB is designing and manufacturing all transformers as if they would be SC tested

- Design features of the ABB windings:
  - All windings are radial self supporting
  - Spiralling of windings is prevented
  - Dynamic response of the winding is considered
Designing for short-circuit strength

- To verify the strength of a winding ABB considers all failure modes with the currents and forces as at a real SC test:
  - Radial buckling
  - Radial tension
  - Axial tilting
  - Axial bending
  - Axial forces against core yokes
    - +
  - All forces on Cleats and Lead structures from Winding exits to Bushings
Designing for short-circuit strength

- Design with respect to radial forces:
  - All windings are radially self supporting
  - Inner windings are subject to “free buckling”
    - No radial support
    - A dynamic phenomenon
    - Strength is determined by Cu hardness (yield point) and conductor geometry
  - Outside windings are subject to tension
    - Strength is determined by Cu hardness
Designing for short-circuit strength

- Design with respect to axial forces:
  - Axial forces are calculated by FEM
    - Considering axial displacement due to workshop tolerance
    - Considering axial displacement due to winding pitch when applicable
  - Windings are dimensioned for maximum compression forces
    - Dynamic effects are considered by dynamic factors on the forces
  - Winding ends are dimensioned for
    - Maximum unbalance forces
    - A part of the maximum compression force (“Bounce Back”)

Designing for short-circuit strength

- Designing Power Transformers is an iteration and interaction process to find an optimal solution from:
  - Weights and Losses
  - Short Circuit Strength (see all earlier SC cases)
  - Temperatures and winding hot spots and cooling equipment
  - Dielectric strength between windings and inside windings

- As a support the ABB designer has the world’s most advanced set of design and verification programs for Power Transformers, totally interactive and used today in 13 transformer plants. “TrAce” for SC design.

- The TrafoStar™ concept is developed and maintained by a dedicated team of about 50 engineers.
Manufacturing aspects and accuracy

- Work hardening and epoxy coating of conductors when needed
- Ampere-turn balancing
  - Max axial displacement < 0.3 % of winding height
- Strict manufacturing tolerances for windings
  - Winding height + 0 – 2 mm
  - Inner diameter controlled by ABB mandrels +2 – 0 mm
  - Outer diameter -1 – 0 mm
- Rigid clamping of windings
  - Twice at the winding work with above tolerances
  - Once at the final pressing after VP drying with temperature control to match the real spring constant for each winding
  - Six Sigma measurements for feedback into the TrafoStar™ system
Manufacturing aspects and accuracy

- Strict Manufacturing
- Procedures and Tolerances
Short circuit strength verification

- IEC gives two options to verify the ability to withstand the dynamic effects of a Short Circuit, IEC 60076 – 5: (2006-2)
  - By full SC test at a certified lab
  - By theoretical evaluation of the ability to withstand a SC event by manufacturer’s experiences supported by IEC guidelines
Outstanding SC strength test record

- More than 140 ABB power transformers of different designs have passed short-circuit tests 49 of which using TrafoStar™ technology.
- The world’s largest short-circuit tested transformer was manufactured by ABB.
- No other manufacturer has such an extensive test record.
Short circuit tests

- The SC Test requires high power laboratories, accredited, only a handful are available

Arial view of KEMA in the Netherlands
Short circuit tests

- ABB GSU transformer 775 MVA – 24/230±2x2.5% kV - 60 Hz,
- The transformer with the highest MVA rating submitted to short-circuit withstand test in the world so far.
Short circuit tests

- ABB 250 MVA – 400/135 ± 10% kV autotransformer in the test bay at CESI High-Power Test Station at Rondissone - Italy
Short-circuit tests ABB transformer in China

- **ABB Zhongshan Transformer Company**
  - 110kV 63MVA power transformer
    - Transformer type: SZ11-63000/110
    - Date of testing: April 2011
    - Laboratory: Shenyang Transformer Institute Co., Ltd. Transformer Laboratory

- **ABB Zhongshan Transformer Company**
  - 220kV 240MVA power transformer
    - Transformer type: SFSZ11-240000/220
    - Planning date of testing: November 2012
    - Laboratory: Shenyang Transformer Institute Co., Ltd Transformer Laboratory

- **ABB Hefei Transformer Company**
  - 220kV 240MVA power transformer
    - Transformer type: SFSZ11-240000/220
    - Planning date of testing: November 2012
    - Laboratory: Shenyang Transformer Institute Co., Ltd. Transformer Laboratory
TrafoStar short circuit strength – Verification by testing

49 TrafoStar short-circuit tested 1997 – May 2012
14 with voltage 400 kV or above
12 rail track feeder transformers
5 test failures 44 / 49 = 90 % first pass rate
Short circuit tests at KEMA
KEMA numbers published at CIGRE 2006

- 25 -30% of large transformers (> 25 MVA) fail to pass initially short-circuit tests.
- The 10% ABB TrafoStar™ fail to pass initially short-circuit tests.
- No common root-cause
The following three criteria are recommended by IEC:

- Variation in Short Circuit impedance
- Successful repetition of routine test
- No visible physical damages to the active part

Additionally:

- Frequency response analysis
- Low voltage impulse
Short - circuit withstand capability

- From the statistics it seems that ABB has less SC test failures the other suppliers
- ABB has done the most number of tests during the years and have got a large amount of feedback and experience
- ABB is using simple physical rules to calculate forces and applies modest critical stresses
- ABB has stringent manufacturing control on winding related dimensions and processes
SC strength evaluation by IEC guidelines

Theoretical evaluation of the ability to withstand the dynamic effects of short circuit by either:

- **Design Review** where forces and stresses are compared with a SC tested Reference Transformer from the Manufacturer.

- **Design Review** by checking against the manufacturer’s design rules for SC stresses
  
  - Stresses shall not exceed manufacturers allowable stresses or 0.8 of the critical stress value identified by the manufacturer
  
  - The stresses shall be compared to the stress guidance in the new IEC norm
A SC safe transformer?

- What characterize a SC safe Transformer?
  - Mechanical sound Design and Technology
    - Based on fundamental mechanics
    - Verified by many SC tests
    - Rigid core clamping structure for SC strength and transport
  - Accurate Manufacturing guided by Tolerances and Quality Systems
    - Rigid winding mandrels
    - Verified Drying and Pressing Procedures
    - Rigid LV clamping and procedures
ABB Short circuit recommendation

- All transformers are high voltage tested
- Some very few are SC tested
- Customers shall consider in tender documentations to include new 60076-5@IEC:2006
  - Always to require manufacturers’ stresses compared with their allowed or critical values, deviations to IEC guidelines to be commented. Design reviews to be required.
  - As alternative require a full scale S.C.
ABB Short circuit recommendation

- What units to be SC tested?
  - High value units like GSUs, key node Network Transformers
    - 3 winding system transformers (Tertiary), Autos
  - Series of transformers, just one to be S.C. tested.
  - 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 acc to IEC 76 Part 5 (2006-02)
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