Chapter 1

Introduction

Power transformers are a critical and essential part of each power transmission system. They are used as generator step-up transformers inside power generation plants, as substation transformers to interconnect power grids with different voltage levels, or as distribution transformers to connect households to the power grid, just to name a few essential applications. Even modern developments like HVDC links or the connection of offshore wind farms to the onshore grid depend on the voltage transformation capability of power transformers.

Nowadays, utilities and network operators are interested in maximizing cost-effectiveness of each piece of equipment installed in the grid. This focus is a result of advancing deregulation of energy markets and the related increase in competition. Especially power transformers, which rank among the most expensive components of power transmission and distribution systems are in focus. In conclusion, the early detection of transformer faults plays an important role in cutting potential transformer damages and in lowering the risk of unexpected power outages. Aggravating this situation, during the last decade, a large percentage of the world's transformers population has reached or exceeded its expected lifetime. Utilities and network operators working under growing cost-effecting pressure, therefore, show an increased interest in transformer life evaluation and monitoring. The aim is to decide whether an aged transformer is still fit to operate, or needs to be retrofitted or even replaced. For this purpose, modern diagnostic measurements like frequency response analysis, dielectric spectroscopy, winding resistance test or gas-in-oil analysis are used. In [66] the authors provide more details on condition monitoring and diagnosis methods.

Apart from aging processes, various faults arising during normal operation can impact transformer reliability and lifetime. Some examples are high mechanical stress caused by magnetic forces due to high short-circuit currents, dielectric stress resulting from high impulse voltages or partial discharge as effect of deteriorated transformer insulation.

The steadily increasing demand for electrical power results in growing generating capacities and increasing interconnections in power grids. These developments contribute to an increase in short-circuit capacity of power grids with negative consequences, especially for power transformers. Rising short-circuit currents in such strongly connected grids make the short-circuit withstand capability of power transformers more severe.

Under normal operation conditions transformer windings are exposed to low magnetic forces. In a short-circuit event winding currents can increase up to $10 \ldots 30$ times based on rated current [17]. As magnetic forces depend on the square of the current, they rise by a factor of $100 \ldots 900$. Although protection devices usually quickly interrupt fault currents after a few supply voltage cycles this time is long enough to cause serious damage to the transformer. A further downside is that the peak short-circuit current occurs within the first cycle [36, p. 239] and can take values up to twice of the steady-state short-circuit current. The occurrence of short-circuit events in power grids is quite rare but the probability of such events increases during the transformer lifetime which is typically up to 50 years.

The result of a transformer failure survey based on the investigation of 750 massive transformer failures from 1996 to 2010 confirms the importance of short-circuit strength [59]: Almost half of the failures have been correlated to windings and the insulating system, as shown in Figure 1.1 a).

A low short-circuit strength can result in mechanical deformation of windings, breakdown or failure of clamping structures which may end up with winding-winding or winding-ground fault connections. Figure 1.1 b) shows the effect of excessive short-circuit forces on a transformer winding which failed by radial buckling. Such internal faults can end up in bursting of the tank, blow-out of bushings or even fire. In short, insufficient short-circuit strength can lead to a total loss of the transformer, and additional severe environmental impact.

Windings and supporting structure are designed to withstand short-circuit forces without permanent deformation or failure. However, aging processes such as cellulose degradation can favor the initiation of these faults. Insulating system materials, which often serve as winding support structure experience a reduction in stiffness and mechanical strength due to aging.

However, also factory new power transformers are not immune to winding faults. Especially, the short-circuit behavior of large power transformers, which today cannot be tested, is highly topical.
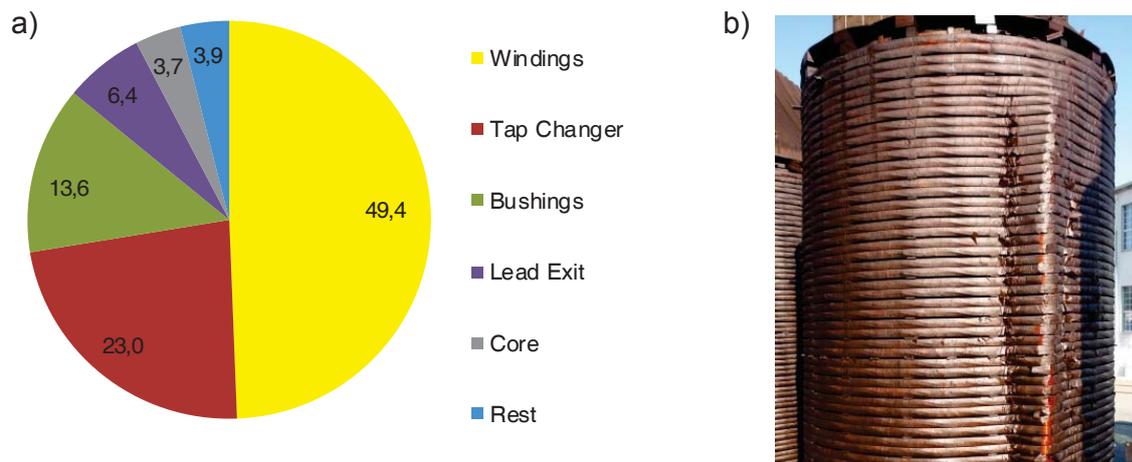
Figure 1.1: a) Fault location distribution from transformer failure survey [59]
b) Deformed power transformer winding resulting from high
short-circuit currents

1.1 Standardization of Short-Circuit Withstand Capability

The short-circuit strength is among the most challenging aspects of transformer design. This section gives a brief insight into the underlying standard IEC 60076-5 [68] with focus on 3-phase core-type transformers with separate windings. A power transformer has to resist both thermal and mechanical effects of short-circuit events. Thermal withstand capability has to be demonstrated by calculation as testing would lead to degradation of the transformer. The standard provides equations for calculating the average temperature of each winding during a symmetric short-circuit with a duration of 2 s as a worst-case. For oil-immersed transformers with insulation system of thermal class A (105 °C) the greatest permissible temperature of a copper winding is 250 °C.

The ability to withstand mechanical effects of short-circuits can be demonstrated either by tests or by calculation and design considerations. For this purpose the standard defines three transformer categories:

- Category I is up to 2.5 MVA and covers small distribution transformers. The short-circuit performance validation is usually done by testing of one or two units. This is the cheapest and fastest way to verify conformity. If a transformer does not pass testing, it is easy to do the disassembly and failure analysis. Improvements and modifications are often cheap compared to order costs. The short-circuit test is passed if a visual inspection of the active part does not show changes in comparison to its original condition before the test. Measurement of short-circuit impedance after the test is another important criterion. Its value may not differ by more than 2 % from the original value. Furthermore, routine tests including dielectric tests have to be successfully repeated after short-circuit testing.

- Category II is above 2.5 MVA and up to 100 MVA. This group covers medium-size power transformers. Short-circuit testing costs start to have impact on the total order expenditure. Also, inspection and modification of failed designs require much more resources. This indicates that a deeper understanding of design parameters that influence short-circuit performance and the ability to forecast short-circuit behavior become more important. The criteria to pass short-circuit test are of category I.
- Category III covers large power transformers above 100 MVA. Units rated above several 100 MVA often cannot be tested due to either the lack of test facilities or large distances between factory and testing laboratory. If a short-circuit test can be conducted, the transformer has to fulfill the same conditions as for category I, except the limit of change in impedance which is tightened to 1 %. Otherwise, if testing is not practical, a critical design review of manufacturer's calculations has to be carried out.

Particularly concerning large power transformers with ratings above 100 MVA it is essential that manufacturers can calculate and predict their short-circuit performance precisely. This demand is associated with the need for precise design and simulation tools, a reliable material characterization and experienced engineers to calculate the short-circuit behavior of power transformers.

1.2 Thesis Objectives

1.2.1 Current State of Science

In the past, there has been a variety of experimental, analytic and simulation-based work about the short-circuit strength of power transformers: In [54] the authors presented a short-circuit test apparatus to measure the strength of inner transformer windings against radial forces. [38] proposed a study about short-circuit strength of large transformer windings. The authors derived a simple equation for the radial buckling strength of windings based on a circular ring. The authors of [34] published further investigations including the effect of supporting spacers and material plasticity. Another experimental study of [57] conducted radial buckling tests on small transformer winding models. With these tests, the effects of various types of radial support structures on the radial buckling phenomena have been investigated and analyzed by the means of analytic calculations including nonlinear material behavior. In [65] dynamic simulations regarding the axial and radial deformation behavior of multilayer disk-type transformer coils are presented. The authors of [7] calculate spiraling effects of conductors in a helical transformer winding based on a 3D simulation model. In [5] the effects of winding process-induced strain on the mechanical strength of transformer windings exposed to radial short-circuit forces are investigated.

This little insight into the state of science points out that the short-circuit performance of power transformers is a long-standing traditional topic. The availability of new simulation tools and a steadily increasing computation power open up

new and more precise calculation approaches. A variety of simulation work has already been done in the field of short-circuit current and forces analysis [26, 37, 21, 1]. However, there hardly exist publications about the mechanical effects of these forces and specially how to handle stranded conductors like the Continuously Transposed Conductor (CTC). Especially this kind of conductor has become increasingly popular for the use in large power transformers over the last couple of years, as it significantly reduces losses.

In [49] tilting failures of CTCs due to axial short-circuit forces have been investigated. Concerning the strength against radial forces, the author of [17, p. 275] proposes to use a model with an equivalent thickness of twice the strand thickness without further proofs. In the case of bonded CTCs the same book assumes a thickness equal to 80 % of the outer CTC dimension in the radial direction. However, the following quotation intensifies the need for more investigation, in particular on the topic of CTCs:

> "An area of some uncertainty is how to treat transposed cable, with or without bonding, in the stress calculations. It is not exactly a solid homogeneous material, yet it is not simply a loose collection of individual strands. We believe that we have taken a conservative approach in our calculations. However, further experimental work in this area will be useful." [17, p. 313]

1.2.2 Buckling Analysis on Transformer Windings

This work presents analytic equations for radial buckling phenomena adapted to CTC-based, inner transformer windings. Furthermore, simulation models are proposed based on Finite Element Analysis (FEA). A comparison between analytic and simulation-based approaches points out the limitations and influencing factors of the analytic equations.

Experimental work has been conducted in the field of dynamic short-circuit testing by the means of a test stand. The aim was to expose test windings to similar magnetic force conditions as in the short-circuit case of a real transformer. The development of acceleration sensor and camera based deformation measurement systems for the use within this test stand are explained. The winding's buckling strength gathered from the experiments is compared to the analytic and simulation-based approaches with good correlation.

1.2.3 Characterization of Conductors

Precise calculations and simulations demand for reliable material characterization. Therefore, the necessary parameters for copper as a main material have been estimated from tensile tests. The insulating paper properties were characterized by the means of zero- and wide-span tensile tests. A precise FEA simulation of bonded CTCs is possible based on adhesive parameters deduced from shear- and

peel-tests. Bending tests verify the results from the analytic and simulation based CTC models.

1.2.4   Impact of Insulating Paper Aging

Static bending tests on bare and paper insulated conductors enable preliminary investigations of the impact of the paper covering on the overall conductor stiffness. Dynamic tests on the developed test stand confirm this stiffness contribution of the paper insulation. The contribution of the insulating paper to the total conductor stiffness is expected to be largest for unbonded CTCs: Due to thin strands, the stiffness of the copper core is relatively small while the stiffness of the paper covering significantly increases with the outer CTC dimensions.

The investigation of aged conductors from old transformers is not practical as it is very difficult to obtain aged test samples from real transformers. To get around this, aged conductor samples have been produced by the means of an artificial aging procedure. Due to the length limitation for the aged samples, a testing on the test stand has not been possible. However, the bending tests conducted with aged, paper covered CTC samples demonstrate how the cellulose deterioration affects the buckling strength of such conductors. With the help of simplified simulation models, a more detailed analysis is possible based on the measured stress-strain characteristic for the aged insulating paper.

Chapter 2

Fundamentals

2.1 Power Transformer Windings

2.1.1 Winding Types

In the most typical case of a three phase core-type power transformer, each limb of the core contains at least two windings named Low Voltage (LV) winding and High Voltage (HV) winding. In the case of a variable transformation ratio the tappings usually are connected to the HV winding. The corresponding turns are separated in the so-called tapping winding. Some high rating transformers often have a third tertiary winding, apart from the LV and HV winding. The tertiary winding is connected in delta formation, and limits fault currents in the event of a short-circuit between line to neutral. During normal operation, it reduces the unbalancing in the LV winding in the case of an unbalanced load. Sometimes the tertiary winding supplies auxiliary loads at a different voltage level than the HV load. Figure 2.1 visualizes a typical winding arrangement by the means of cut-through views of a 5 limb 3 phase core.

Power transformer windings are wound as concentric cylinders. As the core provides the flux return path, it encloses the windings. One principal aim in transformer design is to reach a low leakage flux in the core windows to reduce winding eddy current losses. Generally, tall and slim windings have less leakage flux compared to a short, squat design [24, p. 123]. In a tall and slim design, the leakage flux will be mostly axially directed. Therefore, it is essential to divide the conductors in the direction perpendicular to the leakage flux (the radial direction) to reduce eddy current losses. The subdividing strands have to be individually insulated against each other.

The two most important winding types for power transformers are layered and disk winding, as shown in Figure 2.2.
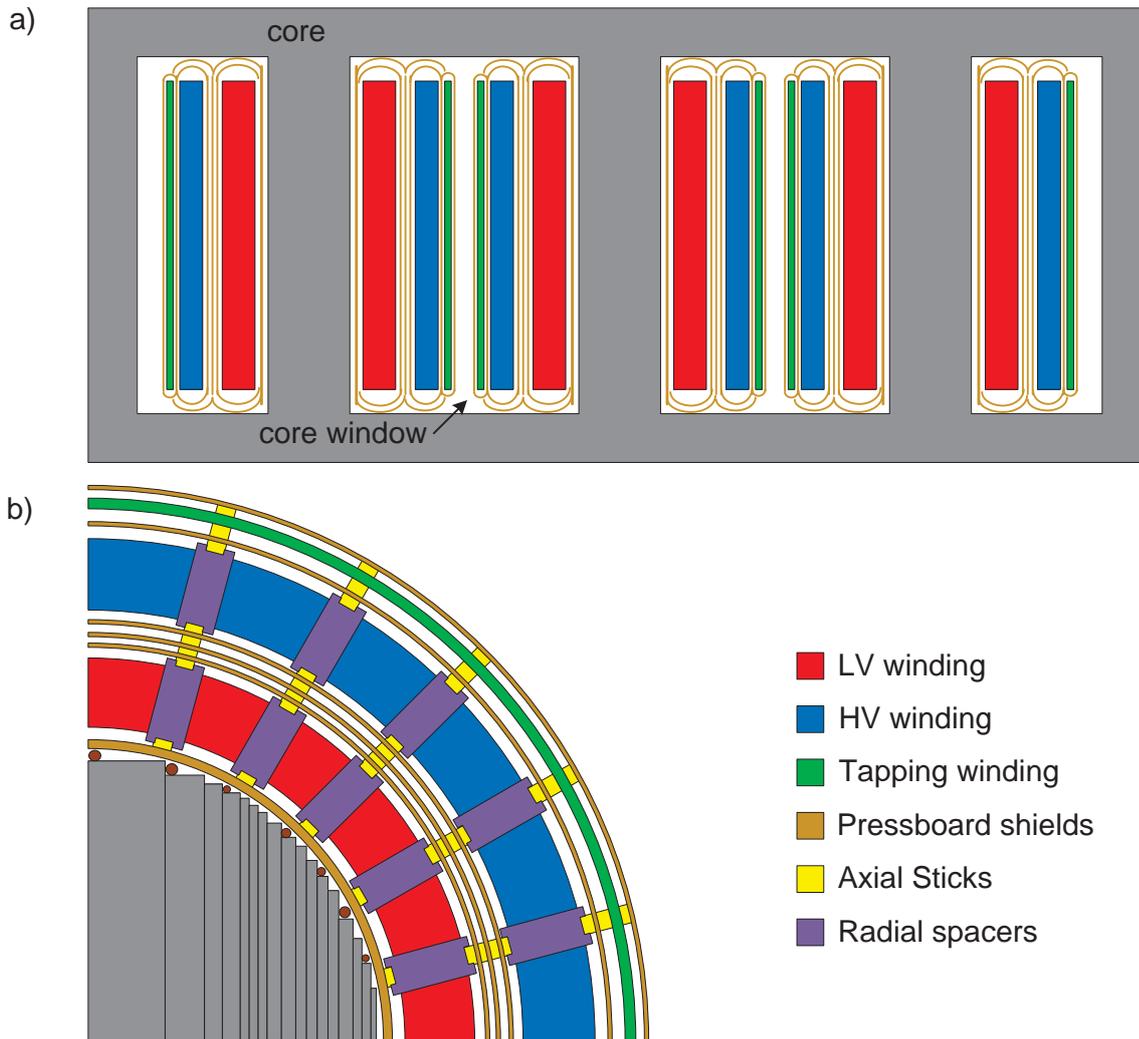
Figure 2.1: a) Cut-through a 5 limb 3 phase core
b) Cut-through view of one phase

The layered type is usually used for the LV winding. Due to its low voltage rating, the LV winding is located close to the grounded core. It is wound in vertical layers (top–bottom, bottom–top, ...) on a robust tube of high strength insulating material like synthetic resin bonded paper. Between the tube and the innermost winding layer axial sticks made from Pressboard are placed, to provide axial cooling ducts for the transformer oil. If necessary, radial spacers between the turns in axial direction provide radial cooling ducts.

LV and HV winding are insulated from each other by several Pressboard cylinders separated by oil gaps. This method provides a high dielectric strength barrier. Axial sticks support the cylinders against each other, providing a rigid support for the HV winding, which is usually built in disk type construction.

Disk type windings are arranged in horizontal layers called disks. The winding sequence is alternately out–in, in–out, and so on. The turns within a disk either touch each other, or are separated by Pressboard spacers. This method provides axial ducts to improve cooling performance. Furthermore, structural separators in

the form of radial spacers form radial cooling ducts and support the whole winding in the axial direction. As the voltage drop between two adjacent disks is quite moderate, compared to the layers of a layered winding, the disk type winding is preferred for HV windings. Another advantage concerning high voltage surges is the possibility to interleave disks near the HV lead exit. This method influences stray capacitances between disks. Based on this method, it is possible to shape the surge voltage distribution along the winding height.
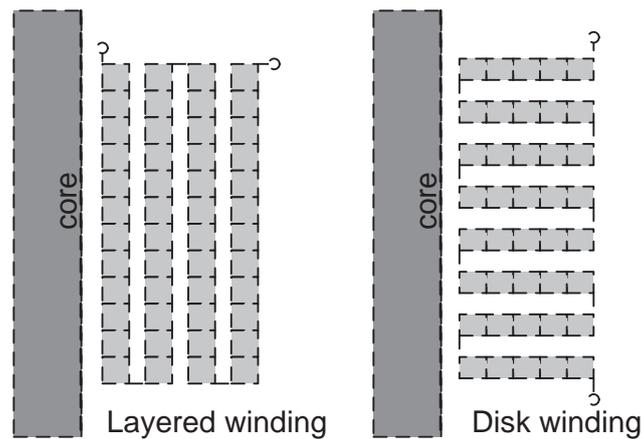
Figure 2.2: Two major types of windings for core-form power transformers

2.1.2 Conductor Types

Medium and large power transformer windings are usually made from high-conductivity copper. The most commonly used conductor is the rectangular shaped conductor, as it offers the best space factor for a winding. The latter defines the ratio between copper cross-section and total winding cross-section. Circular cross-section wires decrease the space factor, as there are many gaps between the turns. Furthermore, the mechanical stability of a winding made from round wires is lower, compared to rectangular wires. Therefore, circular cross-section wires are restricted to distribution transformer sizes [24, p. 60]. Wires with a rectangular cross-section can be single stranded flat conductors, bunched conductors or Continuously Transposed Conductors (CTC). Some schematic examples are drawn in Figure 2.3. Special conductor types, usually used in low voltage coils of distribution transformers, are copper or aluminum foils.

Insulating materials directly applied to the conductor provide electric insulation between winding turns. Wide-spread methods are enamel-coating of conductors or a paper insulation. The enamel itself is often used as polyvinyl acetate coating with a thickness ranging from $50 \ldots 70 \, \mu m$. Its principal purpose is to insulate multi-stranded conductors against each other. If a higher dielectric strength for turn-turn insulation is needed, the paper covering is the preferred method. More details concerning paper insulation will be given at the end of this section.

Flat Conductors

Flat Conductor
enamel insulated

Flat Conductor
paper insulated

Bunched Conductors

Twin Conductor
strands and bundle paper insulated

Triple Conductor
strands enamel insulated, bundle paper insulated

Continuously Transposed Conductors

CTC
paper insulated

Giant CTC
paper insulated

Netting tape CTC
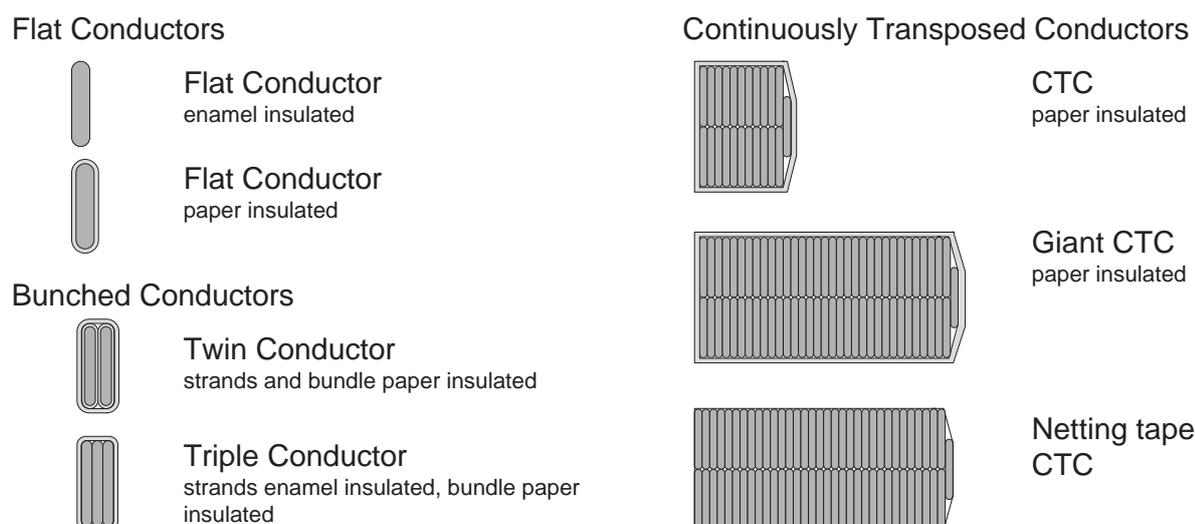
Figure 2.3: Conductors for transformer windings

Single-stranded conductors like the flat conductor are either enamel or paper insulated. The same applies to bunched conductors. The strands are often enamel insulated with an overall paper covering around the whole bundle. There are also conductors with individual paper covering around each strand and a bundle paper covering.

CTCs consist of many enamel insulated strands, which are arranged in two stacks. Usually, there is also a paper covering around the whole bundle (Figure 2.4 a)). The advantage, which arises from the use of CTCs, is a significant reduction in eddy current losses due to the small strand size. The transposition of the strands (Figure 2.4 b)) compensates loop voltages. Such residual voltages are induced between the strands connected in parallel, due to a variation of stray magnetic field with the radial winding position. The distance between two transpositions has to ensure, that each strand has passed through the same average stray magnetic field within one winding turn. Another advantage is the reduction of winding time and the reduced space factor for CTC-based windings. The higher amount of copper inside the core window compared to insulating materials facilitates a reduction of core dimensions and overall transformer dimensions, thus reducing its costs.

For the purpose of a high short-circuit forces withstand capability, thermosetting epoxy bonded CTCs are available. Their strands are covered by a thermosetting epoxy resin. This resin polymerizes during the drying process of the active part, resulting in a significantly increased bending stiffness of the whole CTC.

Depending on the dielectric strength needed between the turns of a coil, different types of electrical insulation are used. The most commonly used material is Kraft paper. It is among the cheapest and best electrical insulation materials known [24, p. 61]. The paper is produced in strips with a width ranging from $20 \dots 30\,\text{mm}$.