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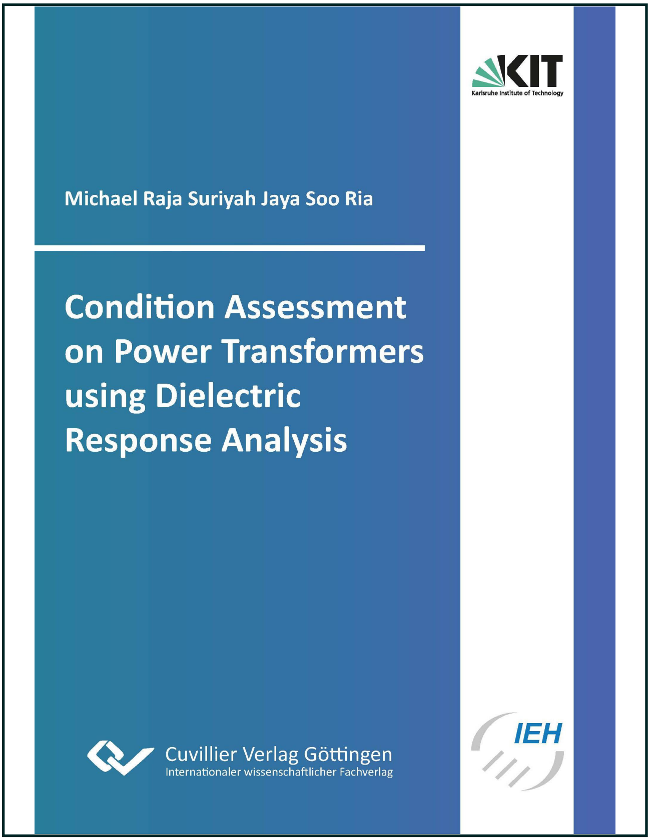
Condition Assessment on Power Transformers using Dielectric Response Analysis



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Chapter 1

Introduction

A reliable, economically viable and yet environmental friendly electrical power supply is the backbone of any modern developed country. It is practically impossible to achieve and sustain a high level of economic growth, employment and prosperity without a functioning power supply infrastructure. The power supply industry has come a long way since the first days of electrification towards the end of the 19th century driven by pioneers such as Thomas Edison, Nikola Tesla, George Westinghouse and Werner v. Siemens, just to name a few. This accelerated the oncoming industrialization and led the way towards the comprehensive power supply industry we still have today.

As the relatively new concept of energy market deregulation continues to be implemented in most developed countries around the world, the impact is set to completely transform the energy market today and eventually in the near future. In most European countries where this concept has been implemented, the electricity supply industry is confronted with new economic challenges and growing competition. The free energy market is supposed to be self-regulated by supply and demand, causing all parties involved to strive towards cost-efficiency in order to remain competitive.

Rising environmental awareness has also played its part in the emerging paradigm shift observed all around the world. In Germany for example, the so called Renewable-Energy-Law (EEG) guarantees uptake of electricity from renewable energy sources at a significantly higher price than the standard market price.

This law was passed as an incentive to boost the research and development of renewable energy sources. Recent events such as the earthquake in Japan which led to catastrophic events at the Fukushima nuclear power plant have caused a rethink towards the existing infrastructure away from conventional centralized large scale power generation more towards many small decentralized units coupled with smart grids to control power flow. This naturally increases the omnipresent cost pressure on power utilities.

An obvious way to increase cost-effectiveness is to maximize the operating life and to utilize the maximal capacity of any given electrical device. All of these factors have ultimately forced the power utilities and network operators to replace the hitherto time-based asset management with risk-based asset management concepts without significantly comprising the supply reliability. Calculated risk can only be taken with adequate information and knowledge, hence paving the way towards the development of diagnostic methods to ascertain at any given time the current state of large electrical equipment.

Power transformers are among the most expensive components of the the power generation and distribution system. Substation transformers connect the transmission and distribution grid with each other whereas generator step-up transformers elevate the voltages coming from power generation plants to feed the transmission grid. Power transformers are hence strategically one of the key components of the entire power supply infrastructure [3]. Their reliability plays a key role in the reliability of the entire supply system. Taking into account that a significant portion of power transformers in most European countries were installed between the 1960 and 1980 and are still in service, the need for accurate and reliable diagnostic methods to determine the aging of power transformers to minimize the risk of failures and unexpected power outages becomes clear.

1.1 Failure Mechanisms in Power Transformers

Being a complex device consisting of many different materials and components, power transformers have to withstand various different stresses of distinct origin. Basically the stresses can be divided into four main categories [23] by origin as shown in Table 1.1.

Table 1.1: Stresses on power transformers according to origin

Dielectric	Thermal	Mechanical	Chemical
service voltage switching surges lightning surges resonances traveling waves	ohmic losses eddy currents hysteresis losses	short circuit	moisture acids oxidation

Table 1.2: Typical faults and defects in a power transformer

Fault	Dielectric	Magnetic	Mechanical	Other
Location	coil insulation main insulation	iron core	winding	bushing tap-changer
Defects	breakdown partial discharge	increased losses increased noise	deformation buckling	hot-spots arcing

Figure 1.1: Effects of flashover due to a dielectric fault in a transformer coil

The stresses depicted in Table 1.1 cause various different faults to occur within a power transformer. These faults can be placed into four categories according to the type and location of faults [23] (see Table 1.2). A good overview of the various testing methods available to assess and maintain the power transformer “healthy” and reliable is given in [22] and [43]. Effects of dielectric fault inside a power transformer for example are shown in Figure 1.1.

1.2 Objectives of the Thesis

There has been quite understandably huge interest in the estimation of the moisture content especially with the intent of extending the service life of a power transformer. The general objective of this thesis was therefore to improve the **D**ielectric **R**esponse **A**nalysis (DRA) applied to power transformers. More specifically, this work’s contributions to the field are listed below.

1.2.1 Investigations on the Relationships between Dielectric Response of Cellulose Materials, Moisture and Temperature

Testing the dielectric response of an insulation system is as simple as measuring the insulation resistance. The difficulty arises when trying to interpret the results. Similar to other diagnostic tests, historical data are important. However, the required historical data go beyond that needed for simple trend analysis. Literature suggests that each insulation type and even insulation structure may have its own signature and proper interpretation of the dielectric response may require a complete knowledge of the details of the insulation system including construction, temperature, type of insulation, age, and history of measurements [43]. Any transformer insulation system comprises several different grades and various thicknesses of cellulose insulation and types, grades, and physical condition of oil vary considerable from one unit to another. Even without this complication, it has been shown that moisture migration between the cellulose and oil is a very complicated process. It is very temperature dependent, time constants for moisture moving between the cellulose and oil are different for each direction, moisture in the cellulose is not evenly distributed, and not all of the moisture in the cellulose is available for transfer to the oil. In addition, dissolved moisture in oil can precipitate out during rapid cool down periods and become free water, which may or may not re-dissolve. Therefore any method of moisture determination that gives a single value for the moisture content of the cellulose is by definition global in nature and cannot give any indication of the non-linearity of the distribution of moisture and may give a false impression of the integrity of the insulation. In order to properly interpret the measurement data from DRA, the behavior of the **O**il **I**mpregnated **P**aper (OIP) insulation must be known, for which reason extensive laboratory tests were performed on a variety of paper samples.

1.2.2 Accurate and Reliable Moisture Analysis

It is well accepted that water is bad for power transformers. The specific effects of moisture are however not so simple or widely known. In addition to accelerated paper aging over the long term, evolution of vapor bubbles or free water from paper insulation can cause a transformer to fail within the short term [22]. The dangerous effects of high moisture content in the cellulose insulation of power transformer are explained in detail in [9], and will only be briefly mentioned here. Moisture acts as a catalyst for the scission of cellulose glucose chains (Hydrolysis), causing brittle paper and decreasing the tensile strength which is important to withstand the mechanical forces during a short circuit. Decrease in dielectric withstand strength could cause dielectric breakdown, while increased dielectric losses causes thermal runaway and ultimately thermal breakdown. Increasingly stringent dryness criteria have evolved over the years with improved factory and field drying processes, particularly for higher voltage levels and ratings. Moisture equilibrium characteristics between oil and paper insulation are well established and often used. However, the dynamics of moisture movement between the paper and the oil during temperature cycling is significant. This is particularly true in transformers which have load profiles that are cyclical and have periods of rapid change. It is recommended to keep the transformers at a constant temperature for several days during the application of global diagnosis methods such as **F**requency **D**omain **S**pectroscopy (FDS) or **P**olarization and **D**epolarization **C**urrent Measurement (PDC) [43]. Thus, accurate modeling of the insulating materials is needed to enable a reliable moisture evaluation. It will be shown that alternative modeling methods apart from the conventional ones , e.g. by simple RC circuits, used together with the FDS allow a thorough evaluation.

1.2.3 Improvement of Measuring Methods for Dielectric Response Analysis on Power Transformers

Dielectric response analysis on power transformers have come a long way since the first days of the **R**ecovery **V**oltage **M**easurement method (RVM). After a brief period, where the Polarization and Depolarization Current method was widespread, Frequency Domain Spectroscopy is currently the method of choice when performing DRA on power transformers. Due to the physical nature of the insulation materials involved and their geometrical setup inside a power transformer, interfacial polarization occurs with very large time constants which inadvertently leads to long measuring durations. One of the objectives of this work was to investigate possibilities to reduce the measuring durations without compromising frequency resolution or robustness towards noise.

Chapter 2

Fundamentals

In this chapter, the fundamentals for understanding this work will be presented. Firstly the assembly of a power transformer is treated with a special focus on the insulation system. Then the relevant models and properties of dielectric materials are presented before rounding up with the measurement methods used for power transformer diagnostics with an emphasis on frequency domain spectroscopy.

2.1 Composition of Power Transformers

Power transformers are used in the electrical power grid for coupling systems and grids with different voltage levels and for transmitting the electrical power between these levels. Depending on its position along the supply chain from power plants to the consumer, one can distinguish between different classes of power transformers:

- **G**enerator **S**tep-**U**p transformers (GSU)
- Network coupling transformers
- Distribution transformers

Other types of power transformers are for example regulating transformers or converter transformers. From a design point of view, a power transformer is divided into several components. Figure 2.1 shows a cross-section of a three-phase GSU and illustrates the essential components. These include the active part inside the tank, the bushings, the compensator (oil overflow tank) and the cooling system. The active part includes the iron core with compressed frame, the windings, the insulation system and the on-load tap-changer.

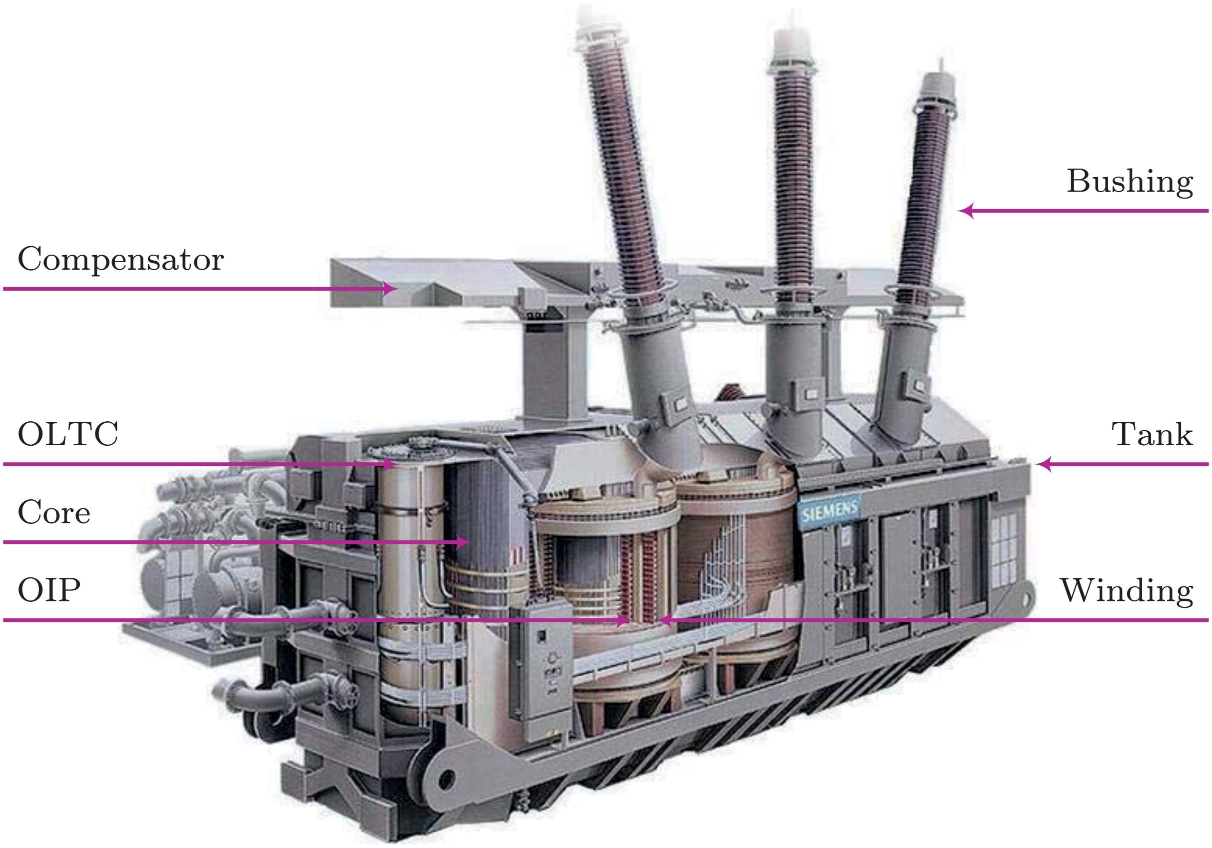

Figure 2.1: Cross-section of a GSU transformer, 850 MVA (Siemens)
OIP: Oil impregnated paper insulation
OLTC: On-load tap changer

For the modeling of the insulation system, both the active part as well as the tank play a significant role. Therefore the following sections take a closer look at these components, and their elements. Since the compensator and the cooling system are not the subject of modeling in this work, they will not be described in detail.

2.1.1 Tank and Iron Core

A transformers tank houses the active part in its interior and is filled with electrical grade insulating oil for cooling and insulation purposes. The electrical connection from the outside to the active part is done using bushings, which are screwed unto the tank. In the area around the coils, shielding plates are attached to the inside of the tank to reduce its heating due to stray magnetic fluxes. The formation of eddy currents are somewhat attenuated due to the shielding plates, which are often multi-layered (Figure 2.5).

The iron core of a transformer acts as a channel for the magnetic flux generated by current flow in the coils. In order to keep the losses due to eddy currents as low as possible, the core is laminated parallel to the direction of the magnetic flux. In order to reduce the overall height of a power transformer, often two additional outer limbs are present, reducing the width of the upper and lower yokes. In order to maximally utilize the space between the limbs and the cylindrical coils i.e. to maximize the channeling of the magnetic flux into the iron core, the cross-section of the limbs are approximated as a circle. The resulting steps and edges are then shielded electrically to avoid high electrical fields using a semi-conductive layer called the core screen cylinder. The individual sheets are held together by the core bandage made of reinforced fiber glass. Pressing frames together with yoke bandages provide the necessary mechanical stability for the yokes.

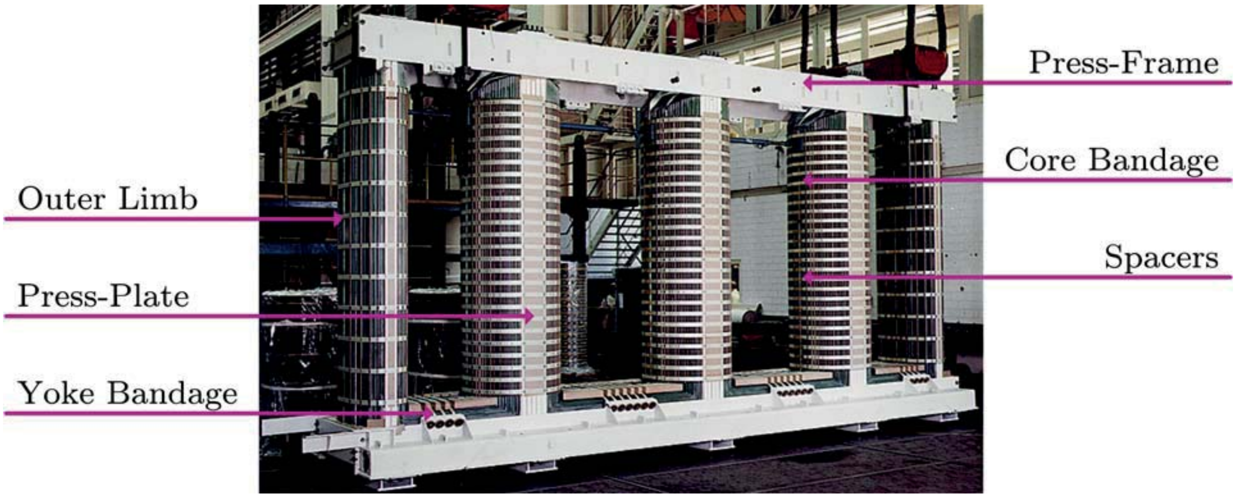

Figure 2.2: Bandaged 5-limbed iron core. Top yoke not yet assembled.(Siemens)

2.1.2 Coils and Insulation System

The coils of the active part are arranged concentrically around the limbs. Beside the **H**igh **V**oltage winding (HV) and **L**ow **V**oltage winding (LV) coils, one often encounters an additional **R**egulating **W**inding (RW, refer Figure 2.6), which is used to vary the voltage ratio using the on-load tap changer. Network coupling transformers usually consist of three voltage systems, the high, medium and low voltage system. Figure 2.6 shows a cross section based on a schematic arrangement of the coils and insulation system. The insulation system of a transformer consists not only of the conductor insulation. The main insulating material for a power transformers is electrical grade insulating oil. However, since the dielectric strength of an oil channel does not increase linearly with its length, the oil channels are further divided into sub-columns using pressboard barriers. Such barrier systems are found between the coils in the form of screen cylinders, Figure 2.3 and Figure 2.6. In the area around the coil ends, these elements are curved to follow the equipotential surfaces, Figure 2.4 and Figure 2.6. This curvature corresponding to the equipotential surfaces is necessary to prevent high tangential components of electrical field at the interfaces between oil and pressboard, which could lead to creeping. The barriers made from pressboard cylinders are however unable to withstand the axial mechanical forces produced by the coils, making the use of additional laminated Pressboard between the cylinders necessary.

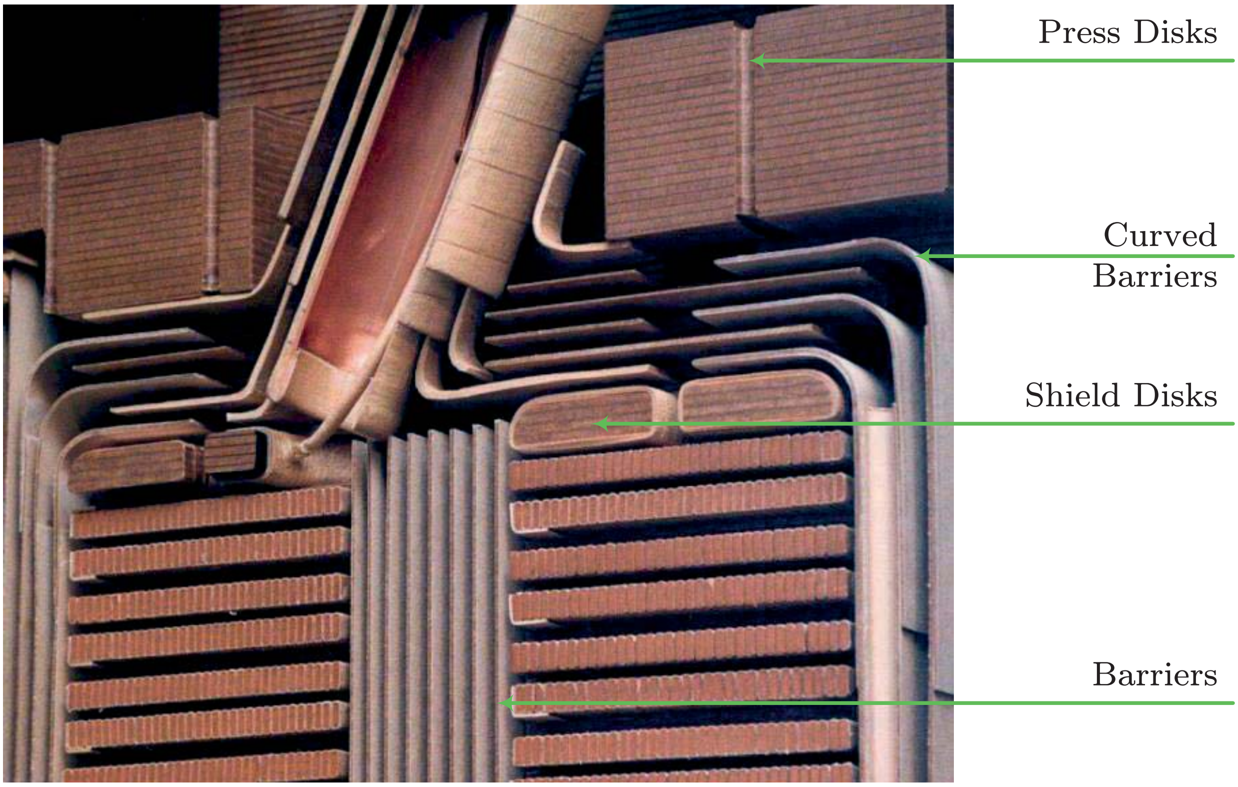

Figure 2.3: Cross section of coils and insulation system at a coil end