CIGRE Reference Paper : Insulation condition during transformer manufacturing

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The main objective of this reference paper is to identify gaps in knowledge and issues in relation to verification of cellulosic insulation material properties during and after manufacturing of oil/cellulose insulated power transformers and shunt reactors. It provides input for future work in this field. In addition, it also provides the reader with an overview of this area. Along with the identified gaps, some aspects are discussed in more detail, e.g. physical material parameter(s) that are relevant for a transformer to withstand stresses in service, end-of-life definitions and measurement techniques.

The paper is focused on oil-cellulose insulated, medium- or large power transformers, reactors and similar equipment. It is also confined to cover cellulose properties and their characterization during production of new transformers. The conditions during manufacturing differ significantly from the operation of old transformers in service and the challenges in the characterization of properties differ as well. Hence, the discussion does not cover long term properties of the insulation. It neither includes design dependent issues, nor questions related to short circuit performance.

Background

Transformer insulation

The solid insulation system of power transformers is predominantly made from cellulose and only in rare cases from high temperature resistant polymeric materials. On the conductors, paper insulation is frequently used and in the mechanical structures that are electrically stressed, thick solid cellulose materials, “pressboard”, are used. Cellulose has proven to be a very reliable and cost efficient material for the application as transformer insulation. However, cellulose is hygroscopic, i.e. it easily absorbs moisture when exposed to air, in particular before oil impregnation. The dielectric strength decreases with increasing moisture content and therefore cellulose insulation must be dried before exposed to electric stress. During drying, the transformer is exposed to elevated temperatures which may have a negative influence on the insulation since the aging rate of some material properties increases with temperature [1]. However, the dielectric strength of cellulose deteriorates only to minor extent with thermal aging and is essentially unaffected during the drying process. [2].

Transformer manufacturing

The manufacturing process of power transformers includes mechanical clamping of windings and core and drying- and impregnation of the cellulose insulation. Vapor phase (VP) drying is the most commonly used method, especially for large transformers but a variety of other techniques are also used, for small- and medium size power transformers. All these steps are vital for the long-term function of the transformers. These processes will influence the condition of the cellulose materials (e.g. moisture content), and their functional properties (e.g. paper tensile strength). In general, cellulose insulation materials age with time and temperature under the influence of oxygen and moisture. It is therefore important to ensure that the manufacturing processes are designed in such way that transformers delivered are fit for service and that no unacceptable loss of insulation life has occurred in addition to what can be expected from normal transformer manufacturing. It may be considered that focus is mainly on the mechanical condition and not sufficiently on the remaining water after drying and at the beginning of transformer operation, respectively. As an example taken from ref. [3], it may be preferable to dry down to 0.3 % remaining water content with DP 1050 remaining (lifetime approx. 47 years), rather than DP 1110 with 0.5 % water (lifetime approx. 40 years) or even DP 1160 with 1.0 % water (lifetime approx. 23 years). (These values are based on constant moisture levels in Kraft paper and the example is based on the end-of-life criteria set to DP>200).

Transformer operation and end-of-life criteria

Transformers in operation are subjected to different types of stresses which can be grouped into thermal-, mechanical- and electrical stresses. Examples of these stresses are load or overload (thermal), short circuits (mechanical) and transient over-voltages (electrical). Insulation aging weakens the cellulose fibers, thus mainly affects the transformer's ability to withstand mechanical stresses occurring during short circuit events and transportation. If the force is high and the insulation paper is brittle (e.g. due to severe aging), the insulation function may be impaired with a resulting internal short circuit inside the winding as a final consequence. This normally leads to failure of the transformer. On a more detailed level, the paper insulation of the winding conductors are subjected to compressive and shear stresses of which the shear stresses are the most dangerous. Aging has little effect on the insulation properties of cellulose [2] and thermal stress itself normally do not cause failures of the transformer but can increases the aging of the cellulose insulation.

End-of-life (EOL) of a piece of equipment, such as a transformer, is in general terms defined as the condition when the equipment no longer can perform its intended duty. The transformer EOL can be separated into technical-, economical- and strategic end-of-life [4]. The most discussed aspect is technical EOL but it is most common to take transformers out of operation for economical- or strategic reasons. Examples of economic reasons are high losses and high maintenance- or insurance costs and smoothing of annual reinvestment budgets. Among strategic reasons are changes in voltage levels or load patterns and obsolescence of some major components, e.g. on-load tap changers. Insulation aging is one aspect influencing the technical EOL by lowering the transformers ability to withstand mainly mechanical stresses. Other important technical factors can be design related (strengths/weaknesses of a particular make), e.g. short circuit strength, dielectric strength and margins, electric resonances in windings, depositions on winding insulation etc. Also historic events like repairs, number of experienced short circuits, transports will influence the technical EOL. It is therefore important to understand that insulation aging alone is not determining the EOL of a transformer [5].

End-of-life of a material such as cellulose insulation is not necessarily the same as end-of-life of the transformer itself and is defined in another way. The function of the material is maintained as long as it withstands various service stresses. EOL of the material is related to the capability to endure these stresses and is normally defined based on a sufficiently high retained strength/value of some important and relevant material property. The properties used in to define technical EOL for cellulose insulation have essentially been tensile strength in the machine direction and the DP value (average viscosimetric degree of polymerization) [6, 7].

It is often convenient to be able to calculate and follow the change of the EOL parameter with time. For tensile strength and DP this is difficult. For tensile strength there is no commonly accepted simple functional form for the time dependence. Also for DP the time dependence function is complex having a fast initial decrease followed by a slower decrease – almost like exponential time dependence. It must be mentioned that the aging conditions such as paper temperature, moisture, and acidity continuously vary with time and are not precisely known, making the mathematical approach even more difficult. An alternative way to characterize the degradation by the number cellulose chain scissions with the advantage of a more linear time dependence (after an initial non-linear increase). In addition the initial DP-value should be indicated.

Cellulosic insulation material properties

General summary

The base material for cellulosic insulation used today is derived from soft wood pulp. The sulfate or the so called kraft wood pulp is most widely used. It is derived from coniferous wood chips which have been chemically and mechanically treated to significantly reduce the amount of non-cellulosic constituents. These removed parts would promote dielectric and chemical instability. The structure within the paper, the fiber length, the bonding between chains and the orientation of these chains form the basis for the mechanical properties of the paper. The aging process in the paper (causing a reduction of the mechanical properties) consists mainly of changes in cellulose chains and bonding between chains [8, 9]. The rate at which the paper is degraded in this aging process is strongly dependent on the structure and the portion of amorphous substance of the paper. Also the presence of nitrogen compounds, added by so called thermal upgrading, will influence the rate of degradation under certain conditions [10, 11]. During VP drying, which can be seen as a thermal conditioning of the paper, a cross linking of the cellulose chains will take place especially for papers made of high grade refined pulp. At the same time, some of the chains will be shortened. The cross linking of the chains will cause an initial increase in tensile strength, especially CMD (cross machine direction) and E-modulus [12].

It is well known that during the initial phase of paper thermal conditioning, such as during drying, there is an increase in bonding between fiber chains causing the mechanical strength to stay constant or even increase [13] while later during the transformer life the degradation of the paper is dominated by the decrease in fiber length, seen as a decrease in DP.

Measurement techniques for unused papers

The specification for new, unused cellulose papers [14] gives definitions and general requirements with agreed parameter values for different properties to qualify different paper types to be used as transformer insulation. However, there are no requirements given for degree of polymerization (DP) for new paper.

The mechanical strength of paper can be measured in different ways such as tensile strength, elongation to break, bursting strength and folding strength [15]. The tensile strength and elongation to break are tested according to [16] and requires a minimum of 9 strips of paper in machine direction (MD) and/or cross machine direction (CMD). Each strip should be straight and perfectly cut with no initiation points for rupture and the strips need to be conditioned before testing. The bursting strength is a biaxial tensile test [17] and will show not only the strength of the paper but also how homogenous the sample tested is. A number of samples, 20 preconditioned pieces, are required. Folding strength [18] tests the brittleness of the paper. Out of the listed tests tensile strength and bursting strength are direct methods which show the strength of the paper, both for new paper and also for used (aged) paper.

The ratio of the average molecular weight to the mass of the monomeric unit represents the average degree of depolymerization (DP) of the paper. This can be determined by testing the specific viscosity of a solution of the paper sample [19, 20] and therefrom the viscosimetric degree of polymerization DPv is calculated. It is thus an indirect method. The sample size needed is very small compared to samples required for mechanical testing. This method will give an average DPv only if the sample is completely dissolved. Cross linked cellulose substance will give a colloidal form of liquid when subjected to copper ethylene diamine solution (CED), which is used during DP-testing. This CED-solution will only be able to partly affect the cross linked parts of the material and the test result will not reflect the true value of degree of polymerization in the sample [15].

A few general remarks – a new paper with very high initial DP could sometimes age at a higher aging rate than a paper with less high initial DP. When comparing different papers, a high DP does not necessarily correspond to high mechanical strength. As already mentioned, the DP number is not a standardized material parameter. It can also be noted that a specification of the level of nitrogen compounds in cellulose is not sufficient to specify the thermal upgrading properties.

Measurement techniques for paper in the transformer manufacturing process

There are no specific requirements agreed on, or specified, for the properties of a paper which has undergone the transformer manufacturing process including drying. To ensure that the paper is dry would be appropriate as well as to ensure that the mechanical strength of the paper is sufficient. The problem is to take samples to be tested that are representing the paper in the transformer windings. Most often the thermal and chemical history during the drying of the winding insulation and paper insulation available for sampling are different. Normally, the paper available for sampling is subjected to a different degradation stress. In addition, the conductor insulation consists of several layers also subjected to different stress – the outer layers normally more stressed during the drying process. For tensile strength or for bursting strength, a large number of samples need to be tested and preferably from a sheet of plain paper and this will not be found on the conductors. Possibly a number of plain sheets of paper could be assembled and put along with the active part through all drying processes for testing after completion of the manufacturing process.

The current industrial practice so far has been to use DP after completed manufacturing although some customers request DP values also before final dryout. Only considering DP will neglect taking the dominating parameter for the insulation EOL into account: the remaining moisture inside the transformer after drying [3, 21]. As cellulose aging is strongly dependent on the moisture content, a higher DP of a delivered transformer may with time be overridden by accelerated aging due to a high moisture content. In addition, DP determination is connected with practical difficulties and problems such as not getting completely dissolved samples giving erroneous results as well as to have truly representative samples [9]. In this respect, the type of drying process, VP drying or Hot Air Vacuum (HAV) combined with impregnation, thermally upgraded paper or standard Kraft paper, all will have different issues in the DP-testing and may have an effect on the results. However, these issues and effects are barely investigated and scarcely reported in literature yet. Although the normalized test methods for DPv [19, 20] are most of the time acceptable [22], there is a lack of definitions and criteria for determining whether the sample has been dissolved completely or not, and there are no numbers given for reproducibility, repeatability or uncertainty. The results are also affected by the experience of the laboratory and its staff. All of this causes uncertainty and could or will lead to discussions among testing laboratories with different test results.

Identified knowledge gaps and issues

The above mentioned methods are associated with advantages and disadvantages in terms of procedure, accuracy and how well they represent the actual stress on the solid insulation in transformers in service. As of today, it is questionable whether a test via an indirect parameter (e.g. DPv) or a mechanical test of a paper sample located somewhere in the VP oven can be suitable for evaluating the aging status of the solid insulation of the transformer. In general, it can be discussed whether any paper mechanical strength test is suitable, – even if taken directly from a conductor. More work needs to address the relevant parameters to be measured that are representative for and have impact on the long term function of a transformer. In addition, practical methods of test which are useful for all types of papers after transformer manufacturing processes, including paper sampling procedure, need to be defined.

Commercial aspects

Any acceptance criteria may have large financial impact both for users and for transformer manufacturers. In particular, as insulation materials in transformers cannot be replaced without rebuilding the active part and replacing the windings, the consequence of a rejection based on excessive paper aging in the factory is huge both in terms of delays to the user and costs to the transformer manufacturer. However, there is no established view on what is reasonable to expect in terms of insulation aging during normal transformer manufacturing and there are no existing guidelines of acceptance criteria nor for compensation if these criteria are not met. Conditions vary considerably from case to case, from very stringent to none at all. This in combination with a very high financial impact makes it an urgent subject to address, preferably within the framework of CIGRE.

Degree of polymerization is the dominating parameter today used for specifying insulation properties after factory drying. As previously discussed in previous sections, loss of insulation life is not linear in DP and loss of insulation life is not necessarily related to the end of life of the transformer itself. As an example calculated from (1) in ref. [3]: if we assume DP=1200 as new paper, and DP 200 as end-of-life, it is often by mistake understood that DP 1000 represents 20 %, or DP 800 represents 40 % lifetime consumed. However, correct values are 3 % resp. 10 % consumed lifetime: DP loss is hence not linear over time. It should also be considered that the relation between the effect of the operating temperature and of the initial DP is such that a change of DP from 1000 to 900 can be compensated by a 0,2 °C reduction of the average lifetime operating temperature of the transformer. This recalculation of time into temperature can be derived using the Montsinger equation for the temperature dependence of the aging rate [6].
It is therefore important that this is considered in the sanctions for exceeding stipulated limits in contracts. It is today common that the consequence of not fulfilling the conditions are not stipulated in the specifications which implies the possibility of rejection based on a small deviation from contractual values. Considering the small impact of a deviation from guarantee values, this is not reasonable, at least not from a manufacturer's perspective. It is therefore desirable to have guidelines within the industry on reasonable limits where compensation applies, how compensation should be determined and when rejection may be applicable. Similar conventions apply e.g. for losses.

Conclusions and recommendations

This paper gives a general review of the present situation regarding insulation aging during transformer manufacturing. It is of vital interest to ensure that the buyer gets a transformer that is fit for service and that no significant loss of insulation life has occurred in addition to what can be expected from normal transformer manufacturing. It is of equal importance that there are commonly accepted guidelines within the industry how to specify, guarantee, verify and to compensate or correct potential deviations from specified properties.
The paper points at existing uncertainties in the areas of measurement techniques, insulation material properties and commercial aspects as well as on the relevance of the commonly used measurements of degree of polymerization (DP). Based on these observation, it is recommended that the international community addresses these issues in order to fill the discussed gaps.
In summary, the main gaps to fill are the following:

- What is (are) the recommended technique(s) to determine the status of the paper after the transformer drying?
- If physical cellulosic insulation samples are required: how to get representative samples before and after the drying process?
- What are the guidelines for acceptance criteria to evaluate the aging caused by the drying process?
- What are the guidelines for measures and compensation in case the criteria are not met?

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