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New Concepts for Prevention of Ageing by means of On-line Degassing and Drying and Hermetically Sealing of Power Transformers

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Abstract – The moisture and oxygen content of the insulation system has a decisive influence on the ageing rate of power transformers. Description, results and uncertainties of different on- and off-line methods, e.g. Karl Fischer titration, FDS, PDC, capacitive probe, to determine these values are presented in this paper. Where a high level of oil humidity is diagnosed drying can, firstly, be an appropriate measure to ensure reliable operation in the short term by raising the breakdown strength of the oil, which had been lessened by the humidity. Secondly drying can extend the service life of the transformer by reducing the ageing process. The concept of hermetically sealing on large power transformers in order to prevent contact between the insulating oil and oxygen is depicted here for the first time. Besides the advantage of reducing maintenance expenditures this method can also decrease ageing or offer the opportunity of higher loading without accelerating the ageing process.

Keywords: Power Transformer, Dielectric Response Analysis, Karl Fischer Titration, Ageing, Moisture, On-line Drying, Hermetically Sealing

1 INTRODUCTION

The operating life of power transformers is generally specified by the lifetime of the oil paper insulation system, as there will be a risk of dielectric failure and thus a total outage, if the mechanical stability of the insulation paper is lost. Observation of the age structure of the transformer population within German utilities shows that a large proportion is nearing the end of the lifespan as originally projected. Thus knowledge of the ageing status and the factors influencing the ageing are of particular importance for the asset management. Besides temperature as an influencing factor, as discovered by Montsinger, there has also been an increase in recent years in the investigation and discussion of humidity and oxygen level as important catalysts for the ageing process [1, 2, 3]. The significance of these factors also explains the diagnostic efforts to determine the humidity level in the insulation system.

The cellulose from which the insulation paper is manufactured is a polymer, whose recurrent structural units, the glucose rings, are connected by an oxygen bridge. The number of connected glucose rings is termed the level of polymerisation (DP level) of the paper. Non-aged paper generally has a chain length of approximately 1200. Glucose connections already split at temperatures over 105°C and thus open the glucose rings (thermal de-polymerisation). The products of this reaction are: free glucose (HO, O, OH), water (H_2O), and carbon (CO, CO_2). Oxygen already splits the glucose rings at normal operating temperatures (oxidative de-polymerisation). During the oxidation process acids, ketones, phenols and other oxidative molecules are formed. Studies show that the rate of ageing multiplies by three where oxygen

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is present [1]. Water is a particularly decomposing oxidation product. In its turn it splits the oxygen bridges between the individual glucose rings and thus further accelerates the ageing process (hydrolytic de-polymerisation). Thus water is both the cause and the result of the decomposition of the paper. Oxygen together with a water content of 2% in the paper insulation can raise the rate of ageing by a factor of 20 [2]. Under a DP level of 250 the paper has lost its flexibility and resistance to tearing and thus has reached the end of its lifespan. In the event of a short circuit current load on the winding the paper would tear and dielectric failure could occur. Thus for ensuring a long operating life it is necessary to control both oxygen and humidity content of the insulation system.

2 DETERMINATION OF AGEING FACTORS

2.1 Off-line Measurement of Moisture Content

2.1.1 The Influence of Ageing Products on Karl Fischer (KF) Method

The use of volumetric controlled drying processes as described in chapter 3 unveiled a systematic failure of water content measurement using the KF method. Even with water contents up to 50 ppm determined by KF method high breakdown voltages up to 80 kV and more could be measured. Furthermore the volumetric controlled dryers could never extract the amount of water deduced by KF results, but compared with the water content deduced by the breakdown voltage (BDV) the efficiency of water extraction was correct.

In order to confirm these findings the following investigation was made under laboratory conditions [4]. Under defined ambient conditions the water transition between cellulose and oil with dependence of temperature was measured with new (**N**eutralisation **N**umber NN<0.005mg KOH/g) and aged oil (NN=0.18mg KOH/g) by means of KF aquameter (BAUR RFM 1000) and a capacitive probe (VAISALA HMP228 [5]). The water in oil content measured by both methods dependent on neutralisation number is compared in Fig. 1. For aged oil the KF reading is always higher than the real content of the diluted water in the oil, and this deviation increases with the NN-value. On the other hand the measurement by means of Vaisala Probe does not depend on NN, and therefore represents an efficient and universal measuring method.

Now it is obvious that a successful transformer "drying" just by change of oil filling or its regeneration cannot be checked by KF measurements. After change / regeneration of the oil filling the amount of diluted water deposited in the cellulose remains basically the same, only the KF reading before and after is different. Before a high KF-value is measured, because KF evaluates acids and other ageing by-products as diluted water and "adds" this value to the real content of water in the oil**.** Afterwards the KF method evaluates only the diluted water in the new oil which results in a considerably lower reading. Only the dissolved water to be measured by the Vaisala probe or the control of extracted water shows the reduction of moisture in the insulation material correctly.

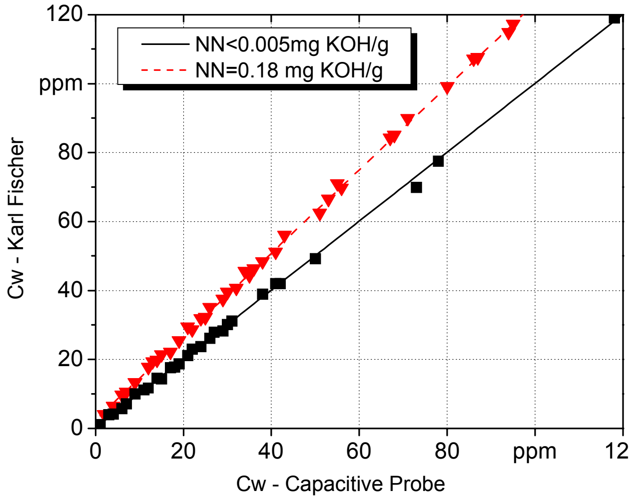

Fig.1: Comparison of KF and capacitive probe measurement of water in oil Cw dependent on neutralisation number NN of oil [4]

2.1.2 Dielectric Response Analysis

In off-line procedures like PDC (Polarisation and Depolarisation Current) and FDS (Frequency Domain Spectroscopy) the dependence of dielectric properties on the water content is used to determine the moisture content of the paper. In FDS procedure a sinusoidal voltage is applied between high voltage (HV) and low voltage winding (LV) [6]. The frequency of the applied voltage is varied in a range from 1 kHz down to 0.1 mHz in order to minimise memory effects. The result is the capacitance and tanδ of the insulation between both windings. These dielectric values are compared with reference data in order to determine moisture in cellulose and oil conductivity. It is not absolutely necessary to know the geometrical data as mass of paper and oil of the insulation to find reproducible results, but it is helpful to achieve a higher accuracy.

The measurement of polarisation and depolarisation currents are performed in the time domain. For measuring the polarisation current a constant DC voltage (e.g. 0.5 kV or more) is applied between the short-circuit HV and LV terminals [7]. The depolarisation current is measured by short circuiting through an electrometer after the DC voltage has been removed. The moisture content of the paper is calculated by comparison with reference data.

Fig. 2 shows the measured power loss factor and the polarisation current for three different transformers. From these measurements the values for moisture content of paper and oil conductivity are derived and given in table 1. The PDC evaluation on unit T1 is not performed, because the mass of insulation material is unknown. The KF investigations as described in chapter 2.1.1. were also used for a validity check of different popular equilibrium curves [9]. These results reveal the good validity of the Oommen diagram [8 (Fig. 5)]. Other diagrams and relations, e.g. [3], often overestimate the water content in cellulose. So for the calculation of the water content from the moisture in oil the Oommen diagram was used.

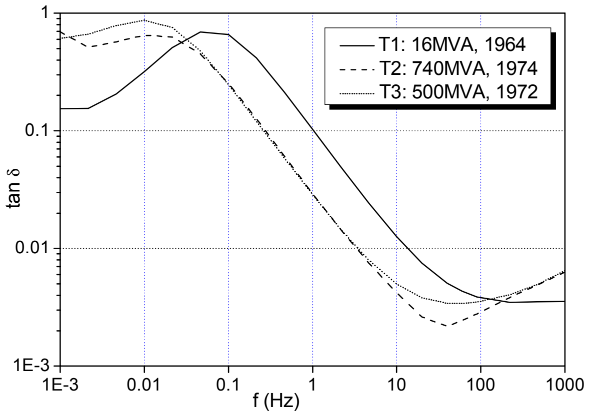

Fig. 2a: Power loss factor (FDS)

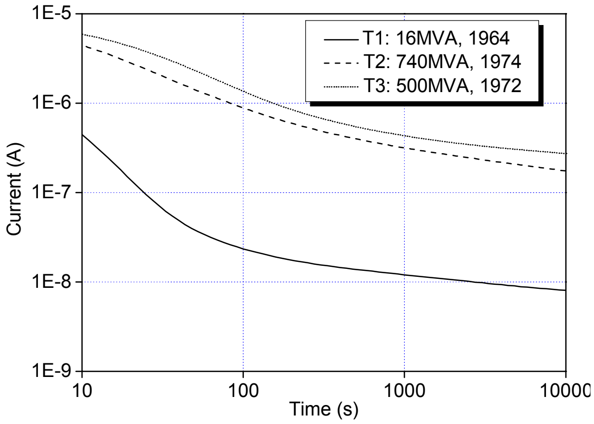

Fig. 2b: Polarisation current (PDC)

Table 1: Transformer data and results from the FDS, PDC measurement and oil laboratory analysis. (The oil data are from samples taken up to a year before the dielectric measurements.)

Transformer			**FDS**		**PDC**	**Oil Laboratory Analysis**		
Unit	Rating kV/kV (MVA)	Year	Moisture Content [%]	σ_{oil} [S/m]	Moisture Content [%]	Tanδ [%] IEC	Moisture Oil [ppm] (T [°C])	Moisture Content [8] [%]
T1	21/6.6 (16)	1964	1.2	$2\ 10^{-11}$	not evaluated	1.08	6 (25)	2.1
T2	420 / 27 (740)	1974	1.6	$5\ 10^{-12}$	3	0.3	12 (44)	1.9
T3	245 / 21 (500)	1972	1.8	$5\ 10^{-12}$	3.2 to3.5	0.33	13 (48)	1.8

The comparison of both dielectric response methods reveals higher values detected by the PDC analysis. Despite the different analytic methods a reason for this deviation can be found in the way the dielectric parameters are converted into material characteristics. This conversion is done by means of using previous laboratory measured characteristics of pressboard material samples as reference data, which is mainly based on new pressboard material; so both methods have a lack of reference data for aged material, which has different dielectric characteristics. Therefore it would be helpful for further investigations to know the dielectric characteristics of aged material for implementation in the evaluation models.

The moisture in paper content derived from the oil samples are in good consistency with the results achieved by the FDS method. However, the values have to be taken with care, because there is no additional information available, if the insulation system was in equilibrium during sampling. Therefore deviation from dielectric measurements are possible. Furthermore the accuracy of equilibrium curves in the low moisture and temperature region is uncertain.

2.2 On-line Monitoring of Moisture Content

Moisture in paper can be determined on-line by measuring the moisture in oil with a humidity sensor Vaisala HMP228 [5] and calculations by means of moisture equilibrium curves which are backed up as a formula in the Monitoring System MS 2000 [10]. The equilibrium of the insulation system can be achieved firstly through intelligent control of the cooling system to keep the oil temperature constant. Secondly the discrepancies from the equilibrium can be compensated for by incorporation of the absorption time constants into the process of calculating the moisture of the paper [9]. Figure 3 shows the oil temperature and oil moisture level displayed together with the humidity level in the paper of a 600 MVA grid-coupling transformer (date of construction: 1973). The data was measured and calculated by the Monitoring System MS 2000. During the displayed time interval the transformer was equipped with an on-line drying system based on an absorption process by dried cellulose (see chapter 3.2). The dependency of oil humidity on oil temperature can be seen clearly. Absorption of water by the paper insulation increases as temperature falls and so oil humidity decreases at lower oil temperatures. During one year of drying approx. 6 litres of water were separated from the insulation. This value is quite low, because of the relative low value of moisture in the insulation. The determined level of moisture in paper is consistent with the value derived from the amount of separated water by the on-line drying equipment. Because of the low value of separated water no significant decrease of the moisture in paper value can be seen. Before drying, a KF measurement revealed a moisture in paper content of approx. 2.5% (water in oil: 19ppm @ 50°C) which was basically the reason for the application of the drying, but this value was determined incorrectly because of high acidity of the oil (0.17mg KOH/g). So on-line measurement by a capacitive probe gives more precise results.

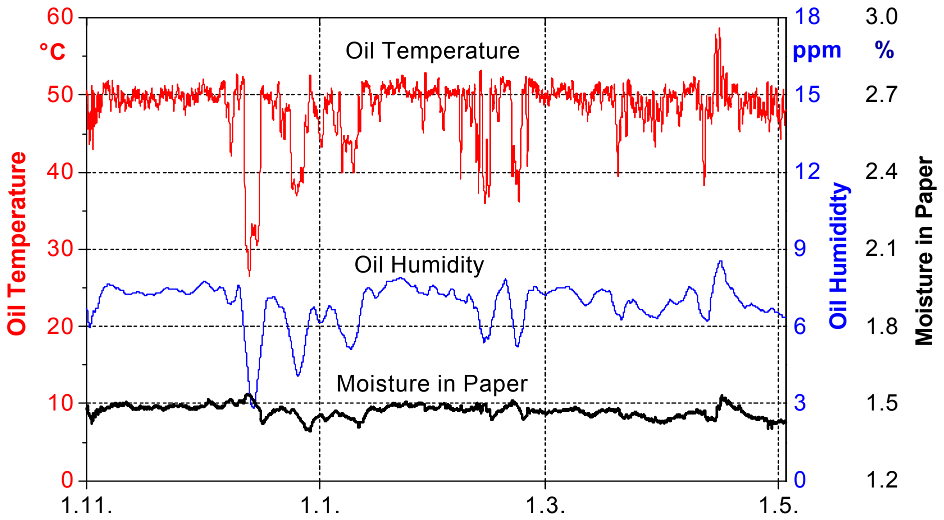

Fig. 3: On-line determination of moisture in paper for a 600MVA / 400kV grid-coupling transformer

2.3 On-line Monitoring of Gas Content

In order to assess the application and efficiency of measures for the prevention of ageing it is important to monitor its influencing factors. The **T**ransformer **G**as **M**onitor (TGM) developed by GATRON is installed at the transformer and monitors continuously all influences on ageing on-line: degree of gas saturation, oil temperature, moisture and oxygen content [11]. A gas provisioning column represents the heart of the device. It is connected to a level controlled oil pump, thus creating an isochorous equilibrium gas space. The sensor unit works without consuming any measuring or reference gas.

By definition, the degree of gas saturation is the quotient of the equilibrium gas pressure and the atmospheric pressure. The equilibrium gas pressure is the direct physical reflection of the total gas household of the oil on the basis of Henry-Dalton’s law. As this is independent of variation in the atmospheric pressure, the equilibrium gas pressure is best suited to monitor influences on the gas household of the transformer. Figure 4a shows the comparison of the equilibrium gas pressure measured directly with the TGM and the equilibrium gas pressure calculated in laboratory analyses for an air-breathing generator transformer. The on-line values of the equilibrium gas pressure are very consistent, whereas the values deduced from oil sampling are scattering. It becomes obvious that this main value of the gas household cannot be monitored exactly by off-line laboratory analyses. The reason for the big deviations may be variations during sampling and vacuum extraction which will be bigger the lower the equilibrium gas pressure is. The equilibrium gas pressure would be significantly decreased by on-line degassing or hermetically sealing. Using the TGM, this remains continuously controllable which makes it possible to detect abnormal conditions in an early stage. The reduced equilibrium gas pressure increases the operational safety of the transformer because it decreases the risk of a Buchholz warning significantly. On the one hand, air release is prevented because over-saturation cannot be reached when the air pressure falls, on the other hand fault gas bubbles most probably dissolve completely in case of incipient faults, e.g. partial discharges.

The desired effect of the reduced gas content is the decrease of oxygen content in the oil. There has been no confirmed on-line data for oxygen content as the measuring equipment was not available so far. Laboratory values are often doubted because of missing reproducibility. First practical experience with the TGM confirms this and shows at the same time that the TGM yields reliable oxygen values [12]. Figure 4b provides an overview of the oxygen contents of different air-breathing transformers. The following results can be deduced from these on-line measurements:

1. The oxygen value varies at different times of the year: It increases in winter and decrease in summer time. A possible reason could be found in the different intensity of convection between the main tank and the conservator.
2. In case of similar construction and identical operation mode, the oxygen content falls with increasing age of the transformer (case 1, 2). So once the oil is saturated with oxygen ageing processes start and lead to a consumption of oxygen.
3. In case of comparable age, the oxygen content is lower, the higher the total load was (case 2, 3)
4. The oxygen content decreases with increasing oil temperature (case 3). Air cooling was not able to prevent an increase in the vessel oil temperature by 11° in summer. The common influence on the solid insulation accelerates the oxygen decrease.

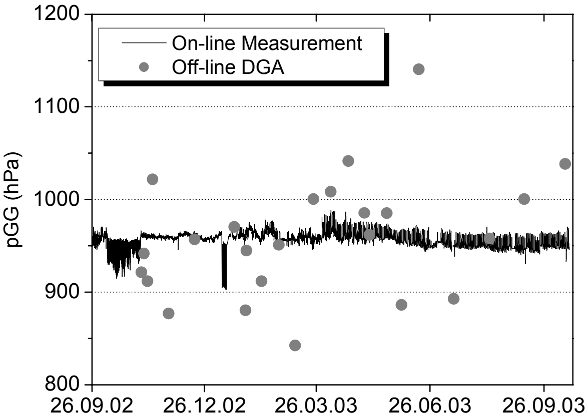

Fig. 4a: Yearly slope of the total gas content of a 500MVA generator transformer (as equilibrium gas pressure pGG)

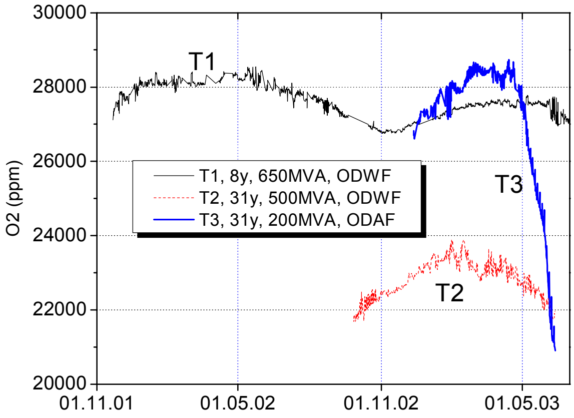

Fig. 4b: Dissolved oxygen content O_2
T1: generator transformer (8 years, 650 MVA, ODWF cooling, medium-load operation)
T2: generator transformer (31 years, 500 MVA, ODWF cooling, medium-load operation)
T3: grid-coupling transformer (31 years, 200 MVA, ODAF cooling, low-load operation)

As the absolute oxygen slopes can be influenced externally by degassing or the application of hermetically sealing, the oxygen-nitrogen relation should be preferred for assessment. The increasing application of the TGM will bring statistically substantiated criteria which will allow the assessment of the solid insulation or the extension of its time of usage. There are excellent chances for this kind of age determination as it can be done without additional costs for the state diagnostics or for alarm prognosis and gas alarm evaluation on the TGM.

3 ON-LINE DRYING AND DEGASSING PROCESS

The degassing and drying bypass process can improve the long-term operational reliability of a transformer with positive impacts on its actual dielectric parameters. The potentially very dangerous overdrying of solid insulation materials can be easily and continuously checked by measuring the volume of the separated water. A vacuum and an absorption based apparatus are described, allowing the continuous degassing and moisture extraction (VS-06) or the continuous moisture extraction (ADT) of power transformers. A remote supervision and control system of both systems with inherent security philosophy allows the use of such systems especially in unmanned substations [13].

3.1 Degassing and Moisture Extraction by means of the VS-Process

The basic rule for any treatment of the oil inventory is to remove only the undesired substances from the oil. So a high vacuum and high temperature, which potentially deteriorate the oil, should be prevented. This is achieved by the VS-process which freezes up the water vapour under low vacuum and thus limits the necessary oil temperature level at about 60°C only. The applied "vacuum", better said under pressure is modest and far away from the absolute zero pressure, which is normally used in oil treatment plants. A liquid piston principle enables a continuous degassing of the oil without the undesired removal of light oil fractions. In the first stage (evacuation), the sinking oil level acts as a piston and creates the vacuum necessary to separate gases and vapours from the oil. In the second stage (compression), the liberated gas mixture is gradually compressed by the rising oil level. The recombination of oil vapours takes place and the lighter fractions get mixed back in the oil. Only non-condensable substances are then brought out from the dryer into ambient.

3.2 Moisture Extraction by means of the ADT-process

The device is based on Water Absorption – Desorption reconstitution principle. In the first cycle the wet oil from the transformer is forced through the ADT cellulose filter insert, the diluted water is absorbed from the oil and the dry oil is forced back into the transformer. In the second cycle, the filter insert itself is dried and the water is separated as a liquid and deposited in a water trap. In contrast to classical absorption dryers, the internal drying process avoids the regular exchange of adsorption cartridges and allows a volumetric control of the dehydration process of a transformer.

3.3 Results of Drying and Degassing

The significant extension of the lifespan of solid insulation materials by a continuous degassing was convincingly demonstrated [1], but a positive long-term impact of a semi-continuous degassing may remain questionable. The following data show that a semi-continuous treatment of the transformer, e.g. for a half year, could be an alternative to the continuous treatment. This can be easily proven by DGA readings of fault gas levels before and 6 or more months after treatment.

Table 2: DGA history of industrial power transformers subjected to on-line oil treatment

Type of transformer	**T1: 150 MVA / 220/33/6kV**			**T2: 20 MVA / 33 kV**			
Date of sample	**14.12.99**	**02.08.01**	**09.11.01**	**16.06.99**	**10.05.00**	**24.01.01**	**02.08.01**
Total gas cont.	92937	20890	64808	72498	26253	24193	81572
N_2 Nitrogen	65247	11843	43913	66493	17831	17036	66434
O_2 Oxygen	17921	8372	18683	1298	7258	6698	9495
CO_2 Carbondioxide	8993	636	1875	3908	949	387	4912
CO Carbonmonoxide	546	13	124	175	53	38	618
H_2 Hydrogen	101	2	60	70	13	12	46
CH_4 Methane	22	2	27	94	4	5	15
C_2H_2 Ethin Acetylene	16	5	10	1	1	1	1
C_2H_4 Ethan Ethylene	11	7	65	29	7	4	14
C_2H_6 Ethan Ethan	14	2	9	216	19	1	7
C_3H_6 Propen Propylene	39	6	36	43	35	6	18
C_3H_8 Propane	27	2	6	171	84	6	12
Solution pressure	861	189	617	763	247	234	826
Oil Data							
Water content (ppm)	18	6	13	36.7	22	13	15
El. Strength (kV/2,5mm)	33	78	80	25	63	81	81

The industrial transformer **T1** presented in table 2 was connected to a VS-system between 14.12.99 and 02.08.01. The first DGA shows the values before the treatment and the readings give the typical picture of an aged transformer, e.g. high level of CO and low breakdown voltage. The O_2 content is high, since the flat conservator for rail transport has an enormous surface to feed the oil inventory. The second DGA reflects that gas levels are sharply reduced. This is not due to the fact, that the fault gases are separated, but it is obvious, that under treatment with a reduced O_2 and N_2 the internal catalysts for ageing are reduced. This is proven by the fact, that after treatment and successive resaturation the internal gas levels stabilise at lower values as before. The third DGA, taken five months after the treatment,

shows that the production of CO and CO_2 remains low and the O_2-level is higher as before the treatment, but most of the other internal gases have restored. For this overaged transformer a continuous treatment should be foreseen, in order to keep the insulation system from final deterioration.
During the VS-drying process between 17.1.00 and 24.1.01 about 15 litres of water were separated from transformer **T2** (table 2) which resulted in a moisture in paper of approx. 2.5%. Also the decrease in the amount of internal fault gases under the influence of a reduced water content can be seen by analyzing the first three DGA. Paradoxically the O_2 content is increased by the treatment, because the O_2 consumed for oxidation processes is decreased under treatment, so ageing is decreased. At the end of the drying process the transformer is in the best operational condition. The water level is reduced from 36.7 to 13 ppm and the dielectric strength has increased from 25 to 81 kV/2.5mm. The DGA taken approx. 7 months after drying shows that the condition of the transformer remains stable. The DGA value of N_2 is the same as before the treatment – it means the gas conditions have recovered to the normal saturated situation. But the levels of internal fault gases are notably lower as before treatment. It means that for this aged transformer the deterioration processes are strongly reduced by the semi-continuous treatment.

4 HERMETICALLY SEALING OF POWER TRANSFORMERS

Transformer oil becomes saturated with oxygen through contact with the air in the conservator. Despite the silica gel filled air breather the oil takes up additional moisture from the surrounding air. Also the use of a rubber bag cannot ensure separation of oil and air because of frequent failures of this system. The transformer can be hermetically sealed from the outside environment in order to prevent these processes and thus to lessen depolymerisation processes with the additional water formation. This has been used successfully with distribution transformers for a long time. The transformer tank itself then takes up the varying oil volume. This kind of design is not possible in power transformers because of the substantially larger changes in oil volume. Furthermore the tank must be vacuum tight. In order to enable an alteration in the oil volume without conventional conservator an expansion radiator was developed and patented. By using a special welding procedure the radiator is capable of taking over both the cooling function and the function of the expansion without an accompanying loss in mechanical stability. The expansion that takes place does not hinder the airflow between the radiator sections, which is necessary for the cooling of the transformer. The long-term stability of this welded structure was proven during extended time tests with full load cycles based on the standard for distribution transformers [14].

Fig. 5: Hermetically sealed power transformer 80 MVA / 110 kV

Because in conventional on-load tap changer design gases are produced during the switching procedure, the diverter switch is normally connected to a separate conservator. In order to use the hermetic concept ideally to its full extent a maintenance-free OLTC equipped with vacuum switches, which do not allow the generation of switching gases, was selected. The OLTC and the transformer tank are each fitted with a gas collecting device for the detection of fault gases and with a pressure relief device for the protection of the transformer in the event of a failure. Figure 5 shows the first hermetically sealed transformer with a nominal power of 80 MVA at a nominal voltage of 110 kV. In order to collect operational experience with this new type of power transformer both hermetic transformer tank and OLTC are monitored by means of the Monitoring System MS 1000. When selecting the sensor set-up to be used particular interest was placed on the pressure and temperature conditions inside transformer tank and OLTC compartment. The experience gathered with several hermetically sealed transformers and the data acquired by the monitoring system prove the advantages of this new concept for power transformers. Maintenance expenditures could be reduced due to no more necessary inspection and exchange of the air breathers.

5 CONCLUSION

The moisture and oxygen content of the insulation system has a decisive impact on the ageing behaviour of power transformers. In order to perform a precise condition assessment these values have to be determined which can be done by means of off-line (KF, FDS, PDC) or on-line moisture measurement with a capacitive probe. The results determined with the KF method are strongly influenced by the acidity of the oil. Also the accuracy of both dielectric methods (FDS, PDC) has to be improved by new reference data especially for aged insulation material. All parameters such as degree of gas saturation, moisture and oxygen content can be determined on-line by a measuring device which is directly connected to the transformer oil. The on-line measurements offer the advantages of continuous supervision and the minimising of errors due to incorrect sampling and analysing.

A high moisture and gas content can be removed from the insulation system by means of a semi-continuous drying process. The described drying systems represent, together with the improved measurement and control methods, suitable tools which not only increase operational reliability but can also be used as safe and long-term attested base elements for the life-extending treatment of aged power transformers. The accumulation of moisture and oxygen can be prevented by hermetically sealing of the active part which was performed for the first time for higher ratings with the depicted power transformer of 80 MVA/110kV for wind farm application. Besides the abandonment of the conventional conservator, this new type of design offers the advantage of a reduced ageing speed of the oil-paper insulation system due to the hermetically sealing and savings of maintenance costs, because there is no longer a need for the inspection or exchange of the silica gel filled air breathers.

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