NEW AND INNOVATIVE SMART AND GREEN TRANSFORMER TECHNOLOGIES

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ABSTRACT

Power transformers with a long lifetime and a high reliability are an essential link in the energy supply chain. The increase of electric power demand and the high pressure to apply environment friendly solutions for transmission and distribution require new and innovative systems, products and technologies. Alstom's future oriented Green power transformer concept contains new technologies and materials in respect of sealing, cooling and insulating, switching (tap changer) as well as control and predictive monitoring linked to Smart Grid technologies.

INTRODUCTION

All the constituent parts of the new, innovative and environment friendly power transformer concept linked to "Smart" grid technologies lead to limited aging and higher lifetime as well a drastically reduced maintenance and lower life cycle costs. The combination of integrated functionalities, environment friendly materials, well-known vacuum based switching technologies and of intelligent monitoring systems ensures to act responsibly towards future generations [1].

NEW SEALING TECHNOLOGY

The insulation system of transformers is subjected to the load-dependent aging. The most effective way to avoid and minimise aging is to design the transformer hermetically sealed and prevent contact with atmosphere (oxygen and moisture). This transformer has neither an oil conservator nor dehydrating breathers, but radiators with integrated functionalities of cooling and oil expansion at rising temperature. More than 100 units with this design are now worldwide in operation [2] (Fig.1).

The aging is further aggravated by oxygen and moisture from the atmosphere. This insulating system is composed of insulating oil and solid insulation such as paper for the windings and pressboards for the coil cylinders, insulating gaps, spacers etc. Both - paper and pressboards - are made of cellulose. It has chain molecules, consisting of glucose rings, linked by OH-bridges. The number of glucose rings in a cellulose molecule is also known as the degree of polymerisation (DP), which is about 1000 for new cellulose (Fig.2).

During the conventional transformer operation, three mechanisms influence the cellulose aging (depolymerisation) [3]:

Fig.1 Off Shore Platform with Green Power Transformer

a) Thermal aging

At temperatures of about 105°C the glucose rings will start splitting (depolymerisation). Typical aging products are free glucose, water, carbon monoxide and carbon dioxide.

b) Oxidative aging

Oxygen leads to a further depolymerisation already at normal operation temperatures lower than 105°C. Investigations have shown that the aging rate is tripled when oxygen is present.

c) Hydrolytic aging

Water is the cause as well as the product of cellulose aging and splits the oxygen bridges between the glucose rings.

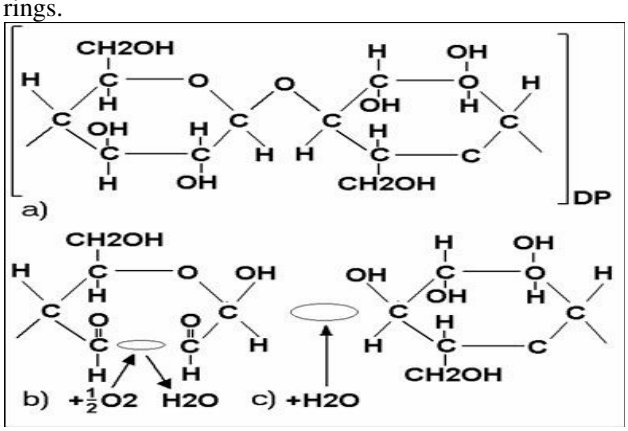

Fig.2 Depolymerisation of glucose [3]

Tests have shown that in presence of oxygen and a moisture content of 2% in the paper insulation the aging rate is

increased by the factor of 20 [4].
The end of the insulation paper lifetime is reached with a DP of 200 and below. The paper loses its mechanical stability (resistance to tearing). Therefore the next mechanical stress, e.g. during a short circuit, would lead to a transformer failure.
The combination of a high water content within the paper and a increasing of the temperature is particularly critical because the water diffuses from the paper into the oil and the dielectric strength of the oil will be reduced (oil aging by moisture) [5]. The Hermetic Design with expanding radiators results in a significantly reduced aging and this process is then largely limited to thermal aging.

NEW COOLING AND INSULATION FLUIDS

In liquid-filled transformers, the insulating liquid plays two important functions by providing the electrical insulation (in combination with a solid such as cellulose) and transferring the heat generated by the windings and magnetic circuit. Liquid-immersed transformers have been mainly filled with mineral oil for more than one hundred years. The use of this petroleum-based product has been justified until now by its wide availability, its good properties, its good combination with cellulose and its low cost. However, with environmental issues now becoming extremely important, the use of a product with high biodegradability is becoming extremely attractive. Thus, the recent availability of natural ester fluids based on "renewably sourced" vegetable oils has provided a new insulating liquid for use in transformers.
The growing interest in the vegetable oil-based dielectric fluids is also motivated by two fundamental points: (1) their excellent fire safety characteristics. Indeed, the high values of both flash and fire points compared with mineral oils ensure better safety in operation, handling, storage and transportation of vegetable oils and thus the operation safety of transformers using such liquids; and (2) the alarming predictions concerning the shortage of petroleum oils by the mid of this century; one can expect serious crisis of petroleum oils and rapid increase in their price.
Electrical insulation: previous studies [6] have shown that processed natural and synthetic esters present AC breakdown voltage (IEC 60156) relatively close to that of mineral oil and above the limits of IEC 60296 for mineral oil (namely breakdown voltage > 70kV on the mean of 6 measurements). It is well known that ester oils are able to contain more humidity than mineral oil and thus can extract more humidity from cellulosic insulation. This higher water content can be seen in term of absolute water content (Fig. 3) but in term of relative water content, dielectric strength properties remain the same as for mineral oil (Fig. 4). As a reminder, a new processed mineral oil (after treatment) has generally relative water content below 10% at ambient temperature.
Heat transfer: This function is realized thanks to both

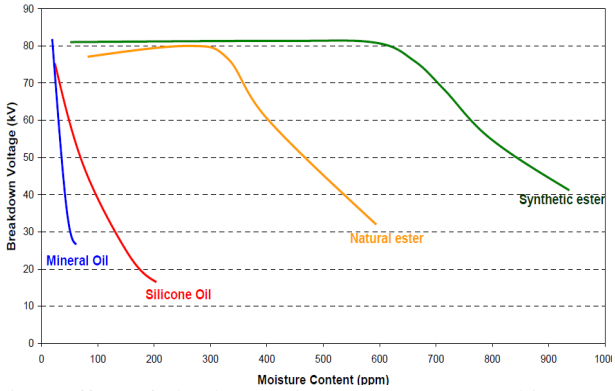

Fig.3 Effect of absolute moisture content (at ambient) on AC breakdown voltage (IEC 60156/2.5mm) [7]

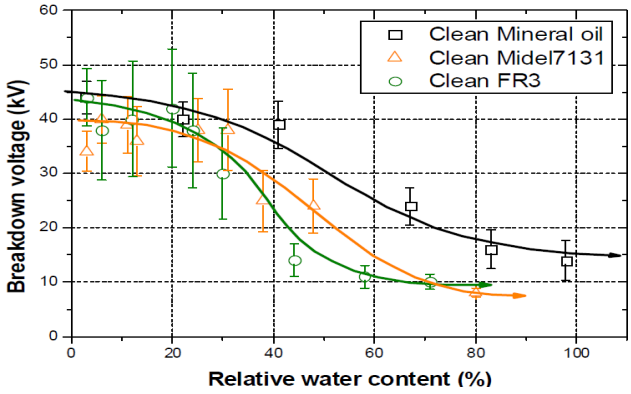

Fig.4 Effect of relative moisture content (at ambient) on AC breakdown voltage (ASTM D1816/1mm) [7]

thermal conductivity and convection. The convection represents all the properties which lead to the heat transfer by fluid displacement (viscosity, specific heat, thermal expansion coefficient) whereas the conduction depends on the conductivity of the fluid. The most influential parameter for convection and even for the heat transfer in general is the kinematic viscosity [8]. It defines the ability of a fluid to move at a specific temperature. The lower the kinematic viscosity, the higher the heat transfer by convection is. Fig. 5 shows that transfer of heat will be more efficient with mineral oil (MO..) than with ester oils (VO.. and SE).

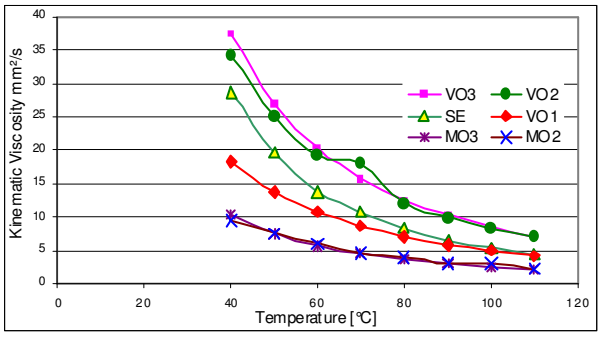

Fig.5 Kinematic Viscosity (ISO 3104) evolution versus average transformer temperatures [9]

Nevertheless, the higher viscosity of ester oils can be slightly compensated by their thermal conductivity. It defines the ability of a material to conduct the heat from a point to another point of its bulk. The higher the thermal conductivity, the more uniform the temperature of the oil will be in the transformer. It means that heat will be conducted away from the coils easier and thus would help to prevent hot spot. Fig. 6 shows that thermal conductivity of ester liquids (SE and VO) is higher than for mineral oil (MO).

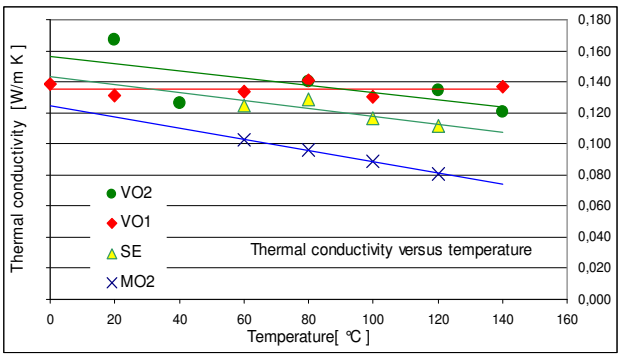

Fig. 6 Evolution of thermal conductivity versus temperature (diffusivity measurement) [9]

NEW SWITCHING TECHNOLOGY

The arc extinction of conventional tap changers takes place in the tap changer oil. This results in oil contamination and shorter service intervals. Therefore a new switching technology has to be adopted to combine the lifetime advantages of the hermetic transformer design with the switching performance. This new technology uses vacuum interrupters (Fig. 7), which fully encapsulate the switching arc [10].

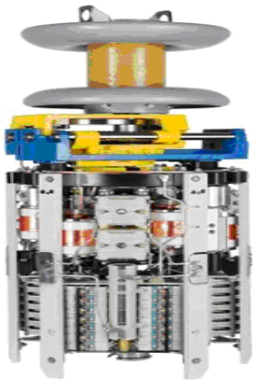

Fig.7 On load tap changer with vacuum interrupters (Supplier: Maschinenfabrik Rheinhausen)

Because of the extremely low internal pressure in vacuum interrupters, only a small gap of few millimetres is required to achieve a high dielectric strength. The short arcing time generates less energy, which together with the high rate of metal vapour recombination minimizes the contact wear. Therefore, vacuum interrupters improve significantly the switching capability in respect of numbers of operations and values of currents, which have to be interrupted [11].

The tap changer is used to change the turn ratio between windings in a transformer. This ratio determines the voltage ratio between the windings and is essential for the stabilisation of network voltage under variable load conditions. An "On load tap changer" normally has a regulation range of +/- 20% of the rated line voltage, regulation is performed in roughly 9…35 steps and operates 10 to 20 times a day in normal grid applications.

There is also a large demand for tap changers adopted in industrial transformers in rectifier and furnace applications, in phase shifting transformers (for management of power flow in AC networks) and in HVDC converter transformers (for long distance transmission and coupling of unsynchronized networks).

Due to the fact, that during the switching operations no oil contamination occurs and constant service condition are maintained over the whole lifetime, the service interval could be extended from 50000… 100.000 up to 300.000 operations independent on the kind of ambient fluid.

When calculating and comparing the cost of maintenance in the overall life –cycle costs for conventional and new transformers, it becomes evident that hermetically sealed transformers -always combined with vacuum based OLTC - offer considerable savings in addition to reduced paper and oil aging.

INTEGRATED CONTROL AND LIFE-TIME EVALUATION

Continuous monitoring is essential to evaluate the transformer performance as well as its components and the safe operating conditions. Therefore intelligent Monitoring Systems (e.g. MS 3000) [12] are requested, which integrate control and predictive lifetime evaluation as well as expert systems (Fig.8).

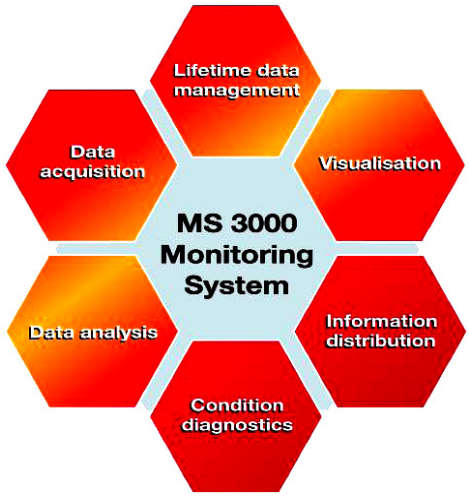

Fig. 8 Main functions of MS 3000

The Monitoring System MS 3000 contains the integration of control and supervision functions: the data acquisition, data analysis and condition diagnostics – reflecting a high level of expert knowledge, the lifetime data management, the distribution of information and evaluated data to upper level systems.
MS 3000 provides the most effective solution for communications with power automation systems using the new IEC 61850 standard. This is the key factor, reducing overall configuration costs and achieving improved inter-operability, flexibility and reliability in data exchange.
The user-friendly visualisation shows the actual and/or the historical information, e.g. measurement data, alarms or warnings, and recommendations for preventive maintenance. That means that the system supports the right operation and maintenance decisions at the right time to avoid failures.
All data, analytical algorithms and diagnostic modules, like thermal, aging, tap changer, moisture, bushing, overload and cooling module, are stored in the Intelligent Electronic Device (IED). The IED may act as Web server to create and communicate all information and recommendations - based on expert systems - by Ethernet, modem or defined software protocols. In addition, a direct access with laptop over TCP/IP or RS 232 is also available (Fig.9).

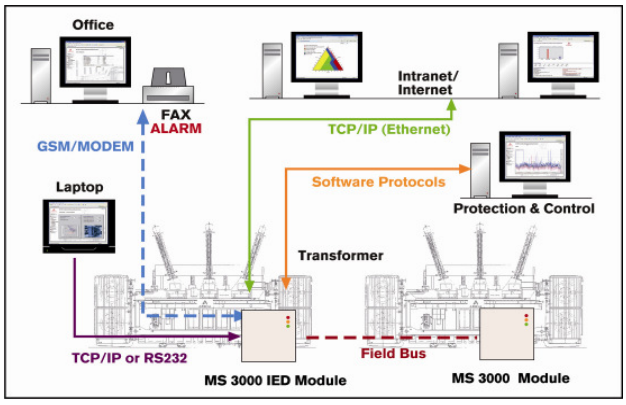

Fig.9 Basic architecture of MS 3000

The system implicates the new substation automation protocol IEC 61850. MS 3000 integrates a simulation module for prediction of different system operation scenarios including the dynamic overloading limits based on the integrated thermal and aging models, which take into account effects of moisture and oxygen.
One system can be used for monitoring of one or more power transformers and their key components, independent on the transformer manufacturer.
Furthermore, this system - implemented in a "Smart" grid - generates an increased flexibility in consequence of energy system stability and quality of supply and an increase in short circuit power due to connection of distributed generation as well as energy storage, which will include a significant proportion of renewable sources [13].

CONCLUSION

There is a worldwide trend to apply environmentally friendly and intelligent systems, products and technologies. The combination of hermetic tank design with integrated functionality of expanding radiators [14], biodegradable ester oils, well-known vacuum based switching technology and intelligent monitoring systems fulfils these requirements and ensures customer advantages, like higher lifetime and lower life-cycle costs at reduced maintenance. Over 100 of these Green eco-efficient power transformers were sold worldwide. During the last years, the transformer design and the applied technologies as well as materials were continuously refined. Furthermore, this Green Design Concept has been extended to higher rated voltage (225 kV and above) and rated power (up to 250 MVA).

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