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Editorial

The Need for Experimental and Numerical Analyses of Thermal Ageing in Power Transformers

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Abstract: Most power transformers are oil-immersed transformers for which its insulation system consists of oil and cellulosic solid. The insulation liquid impregnates the solid-covering air spaces, which improves the efficiency of the insulation system. Not only does the oil ensure electrical insulation but it also works as coolants transferring the heat generated during transformer operation to the exterior of the transformer. Throughout normal operation conditions, transformers experience multiple stresses that degrade their insulation. Since the lifetime of oil-immersed transformers is defined mainly by the state of the insulation paper, it is critical to understand the behavior and degradation mechanisms of new insulation systems that try to overcome the drawbacks of mineral oil as well as to improve power transformer performances. The current increased prevalence of the nonlinear loads additionally stresses power transformers, which generates their premature ageing or even failure. Consequently, new materials and assessment methods are required to guarantee the suitable management of power transformer populations. In this Special Issue "Experimental and Numerical Analysis of Thermal Ageing in Power Transformers", four papers have been published. The guest editor also describes briefly some challenges involved beyond the coverage of this Special Issue.

Keywords: power transformer; oil; paper; ageing; health index; criticality; compatibility; silicone rubber; nanoparticles; dielectric nanofluid

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1. Introduction

Power transformers used in electrical power transmission and distribution systems are one of the most critical elements in electric networks [1,2]. This type of machine can be categorized in different ways, and one of them involves oil-immersed power transformers [3]. The insulation system broadly applied in this type of transformers has been the mixture of both insulation liquid (mineral oil) and paper (cellulose fiber insulation) because it possesses suitable mechanical, insulation, and thermal characteristics [4].

During the normal operation of power transformers, the insulation system suffers degradation due to multiple stresses (mechanical, chemical, thermal, electrical, and environmental) [5]. It has been observed that the main reason for transformers' failure is a breakdown of the insulation system [4]. Consequently, knowing the state of the insulation system of power transformers is critical to ensure a large lifespan of these machines [6]. A proposal of verification measurements and new diagnostic procedures will support a higher reliability of power transformers [7]. The deterioration of the insulation system during transformer operations modifies the chemical structure of the insulation's liquid, which makes some of its properties crucial markers of transformer's health.

Although mineral oil has been widely used in oil-immersed power transformers, it possesses some drawbacks such as low flash and fire points and very low biodegradability. These issues have favored the introduction of eco-friendly liquids (natural and synthetic esters) [8]. Natural esters are organic composites from agricultural products (soybean, flax, rapeseed, olive, poppy, sunflower, etc.) and synthetic esters are chemically manufactured from a direct reaction of an alcohol molecule and a carboxylic acid molecule [2,9].

On the other hand, the growing demand for power, as well as reduced dimensions and higher reliability of power transformers being mandatory, has enhanced the development of nanofluids. They are defined as fluids with nano-sized particles that are homogeneously suspended in the transformer oil at a few weight percentages. Although several authors concluded that nanofluids possess better performance in comparison with base oils, very few studies analysed the impact of thermal ageing on insulation systems based on nanofluids [10].

The introduction of these alternative fluids and new insulation solids into power transformers needs more laboratory and field studies to quantify the deterioration of insulation systems. Knowing how insulation components in power transformers work during ideal operation conditions, considering their compatibility, is required to ensure the mechanical integrity of power transformers [3,7]. Additionally, analyzing the wide range of parameters that impact the insulation system of power transformers through the utilization of mathematical formulation as a health index is vital in managing power transformers [1].

This Special Issue describes some recent developments of thermal ageing in power transformers. This Editorial summarizes the articles published in this Special Issue and discusses some challenges related to these research studies.

2. Special Issue Articles

This section summarizes each of the published articles in this Special Issue which aims at showing interesting developments of thermal ageing in power transformers.

T. Münster, P. Werle, K. Hämel, and J. Preusel in their article "Thermally Accelerated Aging of Insulation Paper for Transformers with Different Insulating Liquids" [11] carried out various physico-chemical, electrical, and dielectric tests of different insulation systems used in power transformers. The focus was on the finding of various aging markers in the insulating liquid as alternatives for the furan content to estimate the condition of the insulating paper in power transformers. Commercial Kraft paper and six insulating fluids (non-inhibited Oil A and the inhibited Oil B with a mineral oil base, oil from natural gas, a synthetic Ester A, and the natural esters Ester B and Ester C based on rapeseed oil and soybean oil) were investigated. Thermally accelerated ageing was performed at 130 °C to simulate the ageing of the transformer insulation. The results showed that different ageing markers in oil can be used to improve the assessment of insulation systems in power transformers depending on the type of insulating fluid.

In [12], P. Bohatyrewicz and A. Mrozik presented the article "The Analysis of Power Transformer Population Working in Different Operating Conditions with the Use of Health Index". The authors presented a health index algorithm that is divided into three parts (the diagnostics of the physicochemical properties of the insulating oil, the assessment of dissolved gases in the oil (DGA), and the evaluation of the transformer's solid insulation). The calculation equations of these parts were defined as linear functions to ensure that even the smallest changes in the input values would result in a change in the overall value. Additionally, the criterion of transformer criticality was implemented because this impacts the level of maintenance and the frequency of transformers' inspections. Finally, these authors tested their algorithm on a population of 220 transformers working in the Polish power system and characterized by various ages and a wide range of operation conditions. The results showed that a large reference database will allow the detection of anomalies, improving the efficiency of transformer maintenance.

The article "Compatibility Study of Silicone Rubber and Mineral Oil" [13] written by S. Karambar and S. Tenbohlen considers the compatibility of three types of room temperature-vulcanized silicone rubbers (insulative silicone rubber and conductive silicone rubber and silicone rubber samples containing insulative and conductive layers) with mineral oil. Furthermore, pressboard samples in mineral oil and mineral oil without any solid insulation materials were also studied under the same ageing conditions and established as reference samples. All these samples were thermally aged at 130 °C for 360 h, 720 h, and 1080 h. On the other hand, these types of samples were aged at 23 °C, 98 °C, and 130 °C for

360 h to study the impact of temperatures on the performance of solid samples. The effect of thermal ageing was studied through the measurement of moisture content, breakdown voltage, colour number, dissolved gas analysis, and the total acid number of mineral oil and moisture content in insulation solids. The results concluded that insulative silicone rubbers possess a suitable potential as insulation materials in power transformers.

Finally, D. Pérez-Rosa, B. García, and J. C. Burgos contributed an article titled "Influence of Nanoparticles on the Degradation Processes of Ester-Based Transformer Insulation Systems" [14]. The study concentrates on the ageing process of Kraft paper immersed in an ester-based nanofluid, which was obtained by mixing the commercial natural ester Bioelectra with small quantities of Fe_3O_4 dispersion. Moreover, this behaviour is compared with the performance of Kraft paper when the insulation liquid is the natural ester. Ageing tests were carried out at 110 °C for 60 days. The influence of nanoparticles on both insulation systems was analysed using the tensile strength of Kraft paper and the moisture of Kraft paper and insulation liquid. In addition to these measurements, FTIR and XPS analyses were implemented to observe chemical changes suffered by insulation materials during the ageing tests. The results exhibited that nanoparticles affect the ageing process of natural ester and Kraft paper.

3. Future Challenges

The guest editor would like to describe challenges related to the topics explained in this Special Issue that should be considered in future papers.

Although nanofluids have shown improved thermal conductivity and insulating behavior, providing a solution to create the next-generation of insulation systems in power transformers, there are still issues that have to be solved. For instance, the size and type of nanoparticles as well as their concentration in the base fluid need more research. Moreover, the use of surfactants and the process of nanofluids preparation require standardisation and optimisation to improve nanofluids' performance. Moreover, dealing with nanoparticlesagglomeration, environmental and health issues, as well as their real application in transformers is needed. Consequently, more research is required to solve these current drawbacks involved in the implementation of real nanofluids [4,8].

The quick development of data processing and computer science and their application to power transformers has resulted in the implementation of different Artificial Intelligence techniques (fuzzy logic, artificial neural networks, expert systems, and support vector machines) relative to fault diagnosis in power transformers. The high accuracy and reliability of fault diagnosis will guarantee the extension and optimisation of a transformer's life, minimizing down times due to predictive and corrective maintenance. This will help improve the electrical network's performance. The selection and combination of the most critical data analysis from power transformers that are the input to these techniques of Artificial Intelligence is an intricate challenge. Real samples of dissolved gases, moisture, acidity, furan compounds, partial discharges, and also data about operation and the transformers' age play a fundamental role in real-time assessments of transformers' health. Therefore, an optimized set of parameters of different insulation systems used in the assessment of their ageing and compatibility in power transformers represents an aim that will provide valuable results with respect to the deterioration of these electric machines, leading to effective cost strategies in power system management.

4. Conclusions

This Special Issue comprises four papers with different concerns involved in the thermal ageing of power transformers. In this editorial, the main ideas of each work have been described. The *Energies* journal would like to thank all individuals who have collaborated in this Special Issue. We hope that all these papers can contribute to the improved management of power transformers.

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