

# Design and Optimization of Power Transformer Diagnostics

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## 1. Introduction

From year to year, humanity's dependence on electricity supplies is growing, which affects virtually all areas that improve the comfort of people's lives. Electricity is beginning to play a key role in areas that until recently were not associated with it, such as cars, planes, and self-propelled vehicles. It is difficult to imagine the functioning of humanity without electricity supply, and we only realize its importance in the event of a lack of it. A reliable supply of electricity is possible due to the operation of the power system. Power transformers are the most important element of this system.

Currently, most power transformers working in the world are approaching or exceeding their technical lifetime, predicted by manufacturers as being 25–30 years. Replacing these transformers with new units is very expensive, because the cost of a new transformer is an expense of up to several million euros. On the other hand, a large number of transformers in operation today were designed at a time when energy companies were a state monopoly in most countries. This means that economic factors did not play such a significant role. As a consequence, transformers were not as optimized in terms of construction and materials as those used today. In other words, a large number of transformers working today are oversized, which naturally extends their safe lifetime. Both of these facts speak in favor of not replacing working transformers with new units too hastily. For these reasons, the intensive development of power transformer diagnostics, whose task it is to extend the life of transformers, is observed.

Transformer diagnostics is a field that has been developing for decades. Despite this, scientific centers around the world continue to investigate this topic. Currently, diagnostics do not only subtract the basic measurements of various transformer parameters as part of periodic inspections, as was the case until recently. Many diagnostic methods focus on online measurements. Diagnostics are already thought about during the design stage of transformers. An example of such an approach is the so-called “dielectric windows” mounted in the transformer tank, which are used to measure partial discharges using the UHF (ultra high frequency) method.

Diagnostic methods are becoming more and more sophisticated. These methods draw upon the latest knowledge from various fields, such as acoustics, telecommunications, vibro-acoustics, chemistry, and computer science. With high probability, it can be concluded that the diagnostic methods of transformers will always be developed, as is the case with diagnostic methods in medicine. These methods must also take into account the latest requirements for transformers, such as environmental and fire protection requirements, as well as the new operating conditions of the transformer, related to green energy sources in the power system. Some of the above-mentioned aspects are discussed in detail in the articles of this Special Issue.

## 2. The Prospect of a Special Issue

The Special Issue of *Energies* entitled “Design and Optimization of Power Transformer Diagnostics” was a great success, and was composed of work from many institutions. The Guest Editor would like to firstly thank all of the authors and teams of scientists who



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decided to publish the results of their valuable research in this Issue. Thanks should also be addressed to all of the reviewers who reliably reviewed the articles, which contributed to the high level of the final published articles. The success of this Special Issue was also made possible by the tremendous commitment and work of the MDPI Editorial and Publishing teams, especially the Section Managing Editor Stephen Wang.

The response to our call for papers was very good, with the following statistics: submissions: 20 papers; publications: 17 papers; rejections: 2 papers; withdrawn: 1 paper. Of the submitted and published articles, 3 articles were reviews and 14 articles were of a scientific nature. The articles were the result of research usually conducted by international scientific teams from countries such as Poland, China, Germany, Turkey, Morocco, Spain, Brazil, Switzerland, the UK, the US, India, Slovakia, and Denmark. However, considering the corresponding author as the lead author, the articles came from the following countries: Poland: 11; China: 2; Germany: 2; Turkey: 1; Morocco: 1. A summary of the articles published in this Issue is described in the following chapters of this Editorial.

### 3. Review of the Special Issue

#### 3.1. Introduction

Most articles in this Special Issue, as many as eight, are devoted to issues related to alternative liquids [1–8], such as natural esters and synthetic esters. However, there are also five papers devoted to the methods of measuring partial discharges [9–13], and one article each is devoted to the following subjects: the determination of dielectric losses in transformers [14], the design of the dry suppressor core [15], the estimation of the transformer health index [16], and the working conditions of fitters carrying out diagnostic measurements [17].

#### 3.2. Alternative Liquids

Alternative liquids, which include natural and synthetic esters, are a response to the growing role of environmental and fire protection factors. These liquids are an alternative to mineral oil, which is a traditionally used electrical insulating liquid in power transformers. Esters are characterized by a higher flash point and are more easily biodegradable compared to mineral oil. The use of alternative liquids in transformers is not without problems. This is due to their different structure and therefore other properties, for example, dielectric properties or the ability to exchange heat in a transformer. Below, we discuss issues related to fire protection [1], electrical [2], thermal [3], and gassing properties [4], the streaming electrification phenomenon [5], moisture [6,7], and the degradation of cellulose fibers [8] working with alternative liquids and their mixtures with mineral oil.

Dombek and Gielniak, in [1], investigated the influence of the proportion of mixing mineral oil with natural ester with reduced viscosity on selected dielectric and fire properties. It was shown that mixing the two liquids can contribute to an increase in the flash point and burning of the resulting mixture, relative to the mineral oil. In addition, it was found that the permittivity and activation energy change linearly, and the dissipation coefficient and conductivity increase exponentially as the ester content in the mixture increases.

Rozga et al. [2] analyzed the electrical strength of alternative liquids and mineral oil at AC, DC, and pulse voltages. Studies have shown that synthetic esters, followed by natural esters, are characterized by greater electrical strength than oil for DC and AC voltages. However, in the case of impulse voltage, mineral oil turned out to be the liquid with the highest electrical strength. The obtained conclusions prove that the selection of insulating liquid should be guided by various criteria. Although AC voltage is the natural operating environment of a transformer, one should not forget about the impact exposures that affect the transformer.

Nadolny et al. [3] described the influence of various parameters of electrical insulating liquids used in power transformers affecting the heat transfer coefficient  $\alpha$ , which is the key thermal property of the liquid. The influence of the type of liquid, the thermal load of the cooled surface, and the length of the heating element on the value of the  $\alpha$  coefficient

was analyzed. The analyzed liquids were mineral oil, natural ester with reduced viscosity, natural ester, and synthetic ester. It was proven that the greatest influence on the value of the heat transfer coefficient is both the type of liquid and the heat load of the cooled surface. In turn, the length of the heating element did not have a significant impact on the value of the  $\alpha$  coefficient. Among the analyzed liquids, mineral oil had the highest value of the heat transfer coefficient, which was 10–20% higher than that of the other liquids. This is a very important conclusion in the context of growing interest in alternative liquids, mainly esters, in transformers, which for environmental and fire protection reasons are increasingly replacing mineral oil. It was also proven that the higher the heat load of the cooled surface, the higher the heat transfer coefficient  $\alpha$  liquid, regardless of its type. This is a beneficial feature of the liquid, which makes the ability of the liquid to cool the transformer increase as the temperature increases.

Amalanathan et al. [4] discussed the study of the effects of temperature and electric field on the gassing tendency of a wide group of insulating liquids used in power transformers. The article describes research techniques for the identification of gases in liquids. The gassing tendency of mineral oils, synthetic oils, and ester liquids was compared. Precautions are indicated that must be taken into account when diagnosing damage in the insulation of the transformer. The dependence of the regeneration of insulating fluids using various adsorbents on the number of cycles was also demonstrated. This white paper may be useful for engineers involved in the diagnosis of power transformers.

Amalanathan et al. [5] presented a literature review on the phenomenon of streaming electrification of insulating liquids used in power transformers. The physical background of the discussed phenomenon is presented and the most important techniques for measuring the electrification current are compared. The influence of hydrodynamic conditions, temperature, and electric field, as well as the type of liquid and solid material, on the generation of streaming electrification is discussed. This work suggests the development of standardized rules for the measurement of electrostatic charges in liquid dielectrics. The need for further research on the electrostatic properties of electrostatic insulating liquids is also indicated, especially in the context of the use of nano-additives to improve their properties.

Regardless of the insulating liquid used in the power transformer, there is a need to periodically check its humidity. Solubility in water in ester liquids and mineral oil fundamentally differs. Przybyłek [6] proved that it is possible to use near-infrared spectroscopy to reliably assess the water content of both types of esters. It was shown that using the Karl Fischer method can be an alternative method to measuring water content, and also has the potential to be used to measure moisture in ester liquids online.

Kierczynski et al., in [7], compare the current parameters of a new factory mineral oil with moistened oil which is identical to oil humidification in transformers. They highlighted that humidification caused changes in the electrical parameters of the oil, such as admittance temperature dependence, dielectric relaxation time, permittivity, and conductivity. An increase in  $\tan(\delta)$  values at low frequencies, a decrease in the minimum value with an increase in frequency, and an increase in conductivity activation energy were observed. These changes are caused by the diffusion of water from the pressboard into the oil as the temperature increases. The results of this research are important for the analysis of the insulation of power transformers.

Wolny et al. [8] analyzed the effect of the degree of thermal degradation of cellulose fibers in semi-synthetic cellulose-aramid insulation-type NOMEX<sup>®</sup>910 saturated with biodegradable synthetic ester MIDEL<sup>®</sup>7131, using the polarizing diagnostic method PDC (polarization and depolarization current). The results of their research, which were performed under controlled conditions using appropriately prepared insulation samples, showed a fairly good correlation between the activation energy and the degree of thermal degradation of cellulose. Similar conclusions were obtained for the second dominant time constant determined via Debye's equations, using the depolarization current regression

method. The research took into account the impact of the measurement temperature in the range encountered in the operation of this type of insulation in power transformers.

### 3.3. Partial Discharges

Partial discharge measurement methods in power transformers have been used for decades. This statement applies primarily to the traditional method (electrical method), but this does not mean that these methods are not developed qualitatively and quantitatively. Qualitative development should be understood as new methods of measuring incomplete discharges, especially based on online technology. However, the term quantitative development should be understood as an increase in the accuracy of these methods. Below, the methods of partial discharge measurement via the radio method [9], the FRA (frequency response analysis) method [10], the UHF method [11], the capacitive method [12], and methods of measuring discharges on the surface of multiphase oil–gas insulation [13] will be discussed.

Kozioł and Boczar, in [9], carried out an analysis of signals in the radio frequency (RF) range and optical radiation emitted via incomplete surface discharges. Both of these techniques have advantages over traditional methods because they are non-contact methods, enabling online diagnostics of transformers. Some characteristic features of signal spectra in the VHF (very-high-frequency) and UHF bands that could be used to develop and improve existing diagnostic methods, based on RF signal analysis, for high-voltage power equipment were identified. The identification of faults in transformers, accompanied by partial discharges, can be more effective and easier to carry out.

Tenbohlen et al. [10] classified transformer winding faults using random forest and the FRA method. As is well known, the interpretation of FRA measurement results still poses a serious barrier against the widespread use of this method in transformer diagnostics. This is due to the fact that virtually every transformer has a slightly different structure and geometric dimensions, which directly affects the FRA measurement result. Thus, a technique learning machine (TLM) to support the assessment of the transformer condition was proposed. The research took into account the most common transformer states, such as mechanically damaged winding, short-circuit winding, and open-circuit winding. In doing so, the method of the automatic interpretation of FRA results was created, which is characterized by more than 90% recognition of winding defects.

Tenbohlen et al. [11] analyzed the frequency range of electromagnetic waves generated via partial discharges in power transformers. The technique of measuring the wave generated via partial discharge (UHF) has been known for several decades. Its advantage is that PD measurements can be performed online. For the first time, this method was used to measure PD in a GIS (gas-insulated system) and then in transformers. Although the method has been used for a long time, there are still discussions about which wave frequency range gives the most information about the developing defecation. A review of the literature indicates that the current frequency range was in a range from 200 MHz to 1 GHz. Now, the latest publications indicate the range as being from 3 GHz to 6 GHz. Extensive research, both in the laboratory and on real units, has been conducted. Transformers with a wide power range, with different defects and different positions, and during different stages of operation were analyzed. On the basis of the conducted research, it was found that the basic frequency range, which was mostly common to all of the analyzed cases, is in a range from 400 MHz to 900 MHz. In turn, the extended frequency range, covering all of the analyzed cases, is in a wider range, i.e., from 50 MHz to 1800 MHz.

Walczak, in [12], proposed a new method of locating partial discharge sources in small-sized objects, e.g., high-voltage insulators, such as bushing insulators. This method uses the system of capacitive-associated probes and the interdependence of their indications. The procedure uses the influence of distance from the source of partial discharge on the amplitude of the signal recorded by the capacitive sensor. Depending on the number of pairs of probes used, it is possible to locate them in one, two, or three dimensions. The achieved accuracy of localization, confirmed experimentally, was 0.5 cm.

Zhou et al. [13] analyzed electrical discharges on the surface of multiphase oil–gas insulation. This phenomenon is very rarely described in the scientific literature. This phenomenon often occurs in transformers, and especially in insulating bushings, when oil leakage occurs. Analyses of this phenomenon using physical and computer simulation were conducted. It was proven that the described phenomenon is a typical streamer process. As the distance between the electrodes increases, the streamer’s development speed and discharge voltage increase. A deeper understanding of this phenomenon can help to predict the negative effects of oil leakage from transformers and other power equipment.

### 3.4. Other Topics

Other topics, described in this Special Issue, include estimating dielectric losses in a transformer [14], designing a dry suppressor core [15], determining the transformer health index [16], and analyzing the working conditions of fitters performing diagnostic measurements [17].

Nadolny, in [14], analyzed the value of dielectric losses that occur in the electrical insulating liquid and paper insulation in the power transformer, using as an example a 110/220 kV unit. It was proven that the value of dielectric losses is a fraction of a percent of the total losses in a power transformer. Dielectric losses depend on the electric field intensity, pulsation, permittivity, and dielectric loss coefficient. The influence of permittivity and the dielectric loss coefficient of liquids and paper on the value of these losses was examined. The change in the permittivity of one material not only affects the dielectric losses directly, but also the distribution of the electric field intensity in the liquid and paper, which also affects the value of dielectric losses. Research results indicate that an increase in paper permeability causes a decrease in total dielectric losses in the transformer. In contrast, an increase in the permittivity of a liquid causes an increase in the total dielectric losses. The increase in the dielectric loss coefficient of both liquid and paper affects the increase in dielectric losses in the transformer.

Xie et al. [15] proposed a method for the optimal design of the dry core of the suppressor used in the power system, among other things, to regulate the flow of reactive power. The main goal was to reduce both costs and losses. For this purpose, a three-dimensional finite element method model (FEM) of a dry iron core reactor was created. This model assumes that the financial cost and losses of the reactor are treated as two objectives. Then, a set of Pareto solutions was used, which was created on the basis of the NSGA-II algorithm (Non-dominated Sorting Genetic Algorithm II) and Matlab-FEM (Manufacturer: Math-Works, city: Massachusetts, country: USA) simulation. In the later part of this research, the entropy mass method and the TOPSIS (Technique for Order Preference by Similarity to Ideal S) method were used to determine the optimal wire size in the reactor design process. In the final part of the study, a validation experiment was carried out. It was found that both financial costs and losses are reduced by 20% compared to traditional suppressor core design methods.

Laayati et al. [16] proposed a hybrid transformer predictive health management (PHM) architecture combining diagnostic algorithms, a health score, and an estimated loss of life rate. These tests are a response to the changing operating conditions of transformers, which are becoming more and more unstable and which in turn can lead to power failures. These volatile operating conditions are caused by the increasing integration of distributed energy sources (renewable energy and electric cars) into the electricity transmission system. The inclusion of all information describing the condition of transformer elements, such as insulation, core, windings, bushing, tap changer, housing, and cooling system, was proposed. For this purpose, virtually all diagnostic methods used in the case of transformers should be used, such as temperature analysis, vibro-acoustic analysis, analysis of gases dissolved in oil, analysis of winding displacements, and analysis of incomplete discharges. It was proven that among all of the diagnostic methods, the dissolved gas analysis was the best for detecting failures and estimating the loss of life as well as the transformer’s health index.

Nadolny, in [17], analyzed changes in the regulations relating to the limit values of electric and magnetic field intensity in Poland on the working conditions of fitters during the operation and diagnostics of transformers at high-voltage stations. Changes in regulations in Poland were a consequence of the implementation of the European Union Directive, which unifies the limit values of electric and magnetic field intensity in European countries. Results of 110, 220 and 400 kV of electric and magnetic field intensity measurements at high-voltage stations were used. Changes in the law have improved the working conditions of fitters, taking into account the electric field intensity. Unfortunately, from the point of view of the magnetic field, working conditions have deteriorated. However, it should be taken into account that the limit values of magnetic field intensity, which until recently were in force in Poland, were the most stringent in Europe.

#### 4. Conclusions

In this Special Issue, most of the articles are devoted to alternative liquids. The different properties of esters were analyzed and compared with mineral oil. Electrical, fire, and thermal properties were investigated. The phenomena of gassing liquids, their ability to dissolve in water in the context of moisture, and the influence of the degree of thermal degradation of cellulose fibers in semi-synthetic cellulose-aramid insulation were studied. It was proven that many more problems need to be solved before esters can fully replace mineral oil.

Many of the articles are devoted to issues related to the methods of measuring partial discharges in a transformer. Particular attention was paid to the frequency ranges of partial discharge (FRA) and radio wave (UHF) electrical pulses. A new method for measuring discharges using capacitive probes was also proposed. It was proven that there is continuous development of methods for measuring partial discharges and they are being increasingly refined, thus increasing their accuracy in the identification and location of discharges in a transformer.

It is possible to find works devoted to losses. One of the articles describes the dielectric losses in the transformer that occur in its insulation system. Another paper proposes a method for the optimal design of a dry suppressor. This method takes into account both the size of the reactor losses and its financial costs. One interesting work is the analysis of the transformer health indicator. Another work concerns the working conditions of fitters performing diagnostic measurements on a transformer.

To sum up, it can be stated that alternative liquids are the most common research topic in the field of transformer diagnostics. Many works are devoted to improving the methods of measuring partial discharges. Other works concern the analysis of the size of losses, the transformer's health index, and the working conditions of fitters.

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