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Breakdown Voltage Estimation in Transformer Oils with Low-Cost Humidity Sensor

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Abstract

The relative humidity and temperature of the oil used for insulation purposes in transformers directly affect the breakdown voltage of the oil and accordingly the life of the transformer. Continuous monitoring of the moisture content and breakdown voltage of the transformer oil provides the basis for predictive maintenance practices. This study aims to develop a sensor to continuously monitor the moisture content of the insulating oil and to calculate the breakdown voltage approximately. In this context, firstly, measurements were taken with an industrial oil monitoring sensor which calculates the breakdown voltage in transformer oils with high accuracy and was verified with laboratory measurements. At the same time, EE364 by E+E™ and SHT10 by Sensirion™ also used for temperature and humidity measurements. By comparing the measured data with each other, a relationship was formulated between the humidity and temperature values and the breakdown voltage. As a result, an approximate breakdown voltage calculation method that can be used considering the characteristic parameters of transformer oil has been introduced. Thus, a cost-effective function has been developed that can be widely used for transformer monitoring systems.

1. Introduction

Transformers are one of the most critical elements of the grid. It has become a necessity today to carry out predictive maintenance practices and health index studies on transformers in order to have high network reliability and low SAIDI and SAIFI indices[1]. According to the results of the Cigré 642 document, approximately 36% of the faults that occur in transformers are due to dielectric faults. [2]. When the root causes of the faults are examined, it is seen that 12% of them are due to aging. It can be said that one of the most important factors that accelerate aging in transformers is humidity. In transformers, approximately 98% of the moisture is in the cellulosic insulation paper and 2% is in the transformer oil, and this ratio varies depending on the loading[3]. The amount of moisture in the transformer and the location of the humidity change depending on parameters such as the ambient temperature of the transformer, the load curve, and the amount of load. With the increase in humidity in the transformer, the depolymerization rate of the cellulosic paper increases and the aging rate of the transformer also increases[4]. In addition, with the increase of moisture content in the oil, the breakdown voltage of the oil decreases and fault risk increases. [5].

The breakdown voltage in transformer oils varies according to the relative humidity or water content (wc) in the oil. These parameters differ depending on the temperature. On the other hand, due to the hysteresis feature of the balance between cellulosic paper and transformer oil, different relative humidity values can be seen at the same temperature values. Therefore, it is important to understand the dynamics of moisture content in transformer oil. Once the related concepts are understood, it is possible to switch from relative humidity to breakdown voltage data. In this context, to calculate the breakdown voltage in oils, the relationship between the

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relative humidity parameter and the breakdown voltage should be considered.

In the literature, there are many studies carried out to characterize dielectric liquids and express their different properties with equations. Although breakdown events are likened to gases and solids in different aspects of liquids, in general, the approaches and equations created for gases or solids are not valid for liquids. At present, the breakdown voltage of dielectric fluids (insulating oils) used in transformers to provide insulation and help cooling is determined based on the values measured as a result of the tests performed in the laboratory. However, it is of great importance to prevent possible failures for transformers, which are constantly in operation and are one of the key equipment of a reliable network structure.

In the literature, there are projects in which the concepts of water content, relative humidity, and breakdown voltage in transformer oils are examined and various studies are carried out. In [6], the elements used as the insulation material of the transformer and the necessary terms are explained and the balance between the water content in the cellulosic paper and insulating oil is explained according to the curves and different references. In [7], the effect of the water content in the transformer oil on the breakdown voltage is examined. [8] explains the relationship between the water content in transformer oil and the relative humidity. In this context, the types of water content that can be found in transformer oil, concepts such as solubility and relative humidity, the relationship between relative humidity and water content and breakdown voltage are explained. In [9], the movement of the water content in the insulation system of the transformer between the cellulosic insulation material and the insulation oil was investigated. The relative humidity and water content values that change depending on the temperature are explained through graphics and the hysteresis movement of the water content depending on the temperature is explained.

In [10], the relationship between water content, humidity and temperature in transformer oils is examined with online sensors. Accordingly, measurements were taken with different parameters in different oils and the results were compared. In [11], the structure of a sensor developed to monitor the breakdown voltage of insulating oil in transformers online and continuously is examined. In [12], the variation of relative humidity and water content in transformer oil is examined according to temperature. As a result of the tests carried out, it is said that the flow rate of the oil affects the relative humidity value. In [13], the breakdown voltage of different oil types and their water content at this voltage are compared. In addition, the viscosity values at different temperatures and the relative electrical conductivity values at different water contents are compared. In [14], hysteresis curves for temperature-water content of different humidity sensors are compared. In addition, water content curves are shown according to the temperature of different types of transformer oils.

In [15], the water contents of four different transformer oils, which contain both used and new oils of the same brand, are examined according to the relative humidity values of thirty-five degrees. In [16], mineral and natural ester oils used in transformers are compared. While making this comparison, events such as the water content value formed according to the temperature, the water balance between the cellulosic insulation paper and the oil, the water content in the oil and the change of the water content in the cellulosic insulation paper with time were examined. In order to make these examinations, dynamic models were created and simulations were carried out.

In [17], the breakdown voltage of transformer oil is compared according to relative humidity and temperature values. In [18], the water content values corresponding to the relative humidity values of mineral, natural ester and synthetic ester oils used in transformers were investigated. In addition, the analyzed oils were dried online and their water content removal performances were evaluated. In [19,20], health index studies were carried out in which the breakdown voltage and the water content in the oil were also evaluated.

In this study, we aimed to realize the approaches for calculating the breakdown voltage for oils over the measured values of temperature and humidity parameters and to create the product design. In this context, measurements were carried out using a datalogger and web interface structure with a commercial brand of breakdown voltage sensor (Trafostick™), which is sold for high accuracy calculation of the breakdown voltage in transformers, and after the breakdown voltage and relative humidity content were taken as data, it was verified with laboratory measurements. Then, the breakdown voltage calculated according to the moisture content output by the Trafostick™ equipment was graphically plotted and a curve suitable for the graph was created. E+E™ 364 model sensor, which is also another trademark, only gives the relative humidity and temperature value to the user. Measurements were also taken with this sensor, and the relative humidity content taken from the Trafostick™ sensor and the relative humidity content, which is the output of the E+E™ sensor, were compared and verified each other. According to the relative humidity-breakdown voltage graph found from the output of the transformer sensor, the breakdown voltage was obtained from the relative humidity data of the E+E™ sensor. Then, measurements were taken with a single sensor named Sensirion that only gives relative humidity, the results were verified with the E+E™ sensor and the breakdown voltage was calculated. In this context, it is seen that the breakdown voltage value calculated with the help of a single humidity sensor is close to the rupture voltage value given by a commercial brand. Although there are no definitely true results in applications such as transformer stick or oil test, a suitable single sensor application has been carried out for the application of trend analysis approach in small power transformers.

2. Relationship Between Humidity and Breakdown Voltage

For the reliability and sustainability of transformers, the relationship between transformer oil and moisture should be well understood. The humidity in the transformer oil affects the breakdown voltage of the oil depending on various parameters. Moisture content in transformer oil can be in different phases. These can be listed as the bonding of dissolved water to the hydrocarbon molecules that make up the oil with hydrogen, the emulsified water being supersaturated in solution but not yet completely separated from the oil, being supersaturated in the free water solution and having a high concentration to form water droplets and separate from the oil.[8].

The moisture that can be dissolved in the transformer oil changes depending on the temperature, and accordingly, the breakdown voltage also changes depending on the temperature. While calculating the breakdown voltage in transformer oil, both the relative humidity value and the water content value can be used.

To calculate the relative humidity value, the maximum solubility values of the environment where the sensor is located must be known. This value changes depending on the temperature.

For liquids, the relative humidity is shown in terms of water activity (aw). When calculating the relative humidity, the calculated value (P) is written in the numerator and the maximum value (P_0) that the environment can solve at the current temperature value in the denominator Eq. (1).

$$a_w = 100x\frac{P}{P_0} \tag{1}$$

In order to calculate the water content, the maximum solubility (S_0) at the relevant temperature must be calculated first. In the literature, the following formula is used to calculate the solubility [8] Eq.(2).

$$logS_0 = \frac{A}{C+273} + B \tag{2}$$

The coefficients A and B in the equation are the characteristic information of the oil. A and B parameters for transformer oils were accepted as -1663.30 and 7.37, respectively. 'C' is the temperature value in Celsius. When the values are substituted in the equation, the solubility value for the relevant temperature can be calculated. The relative saturation (RS) value is the amount of water measured in the oil according to the solubility level at the relevant temperature. That is, the value given as a percentage is the ratio of water content to solubility (S_0) [8] Eq.(4).

$$RS = \frac{w_c}{S_0} \tag{3}$$

When the formulas are simplified.

$$w_c = RSx10^{\left(\frac{A}{Temperature+273}+B\right)} \tag{4}$$

It appears that the relationship between the breakdown voltage of the oil and the relative humidity is more linear than that of the water content. Due to the time constants between the transformer oil and the cellulosic insulation paper, the moisture content of the oil may differ at the same temperatures. This is related to the hysteresis behavior of the isolation system. This phenomenon is shown in the following sections of the article together with the measurement results.

3. Material and Methods

3.1. Introduction of Sensors

Capacitive humidity sensors are generally used in industrial temperature and humidity measurement products. Figure 1 shows the geometric structure of the capacitive sensor.

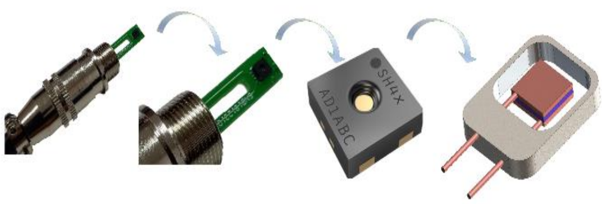

Figure 1. Geometric structure of industrial capacitive humidity sensor

In this study, three different sensors were used to measure the humidity in transformer oil. The first of these is an industirial sensor called Trafostick™, which has been produced as a transformer oil monitoring sensor. Trafostick™ measures and calculates the breakdown voltage, relative humidity, water content and temperature of the transformer oil. While calculating these values, it shows the results as the average of certain sampling intervals as well as the instantaneous calculations. While the Trafostick™ product was being designed, the breakdown voltages obtained from the laboratory results were evaluated in order to calculate the breakdown voltage according to the measured relative humidity value. Accordingly, tests were carried out by taking 3800 oil samples from more than 900 transformers.[21]. In this context, it can be said that the Trafostick™ sensor calculates the breakdown voltage with high accuracy. The other sensor used is the sensor named E+E364. This sensor is a compact temperature and humidity sensor used for measuring the relative humidity and temperature in oils. The sensor provides the relative humidity and temperature information of the oil to the user [22].

The last sensor used in the study is a single sensor named Sensirion SHT10. This sensor is designed for use in the air environment and only gives the temperature and relative humidity information to the user.[23]. In this study, the sensor named Sensirion SHT10 was used to measure the relative humidity of transformer oil, and the results were compared in detail with the results of other sensors. Three-dimensional CAD models of Trafostick™, E+E™364 and Sensirion SH10 products are shown in Figure 2 (a), (b) and (c), respectively. In addition, the capacitive sensor shown in Figure 1 is the Sensirion product. The sensor visible when the brass coating on the front of the structure shown in Figure-2 (c) is removed is shown in Figure 1.

Figure 2. 3D CAD models of humidity-temperature sensors used in the project (a) Trafostick™ (b) E+E™364 (c) Sensirion SHT10.

3.2. Installation of Sensors on the Transformer

When the devices are mounted on the transformer, the oil must be in contact with the sensors. In this context, a suitable place should be determined in the transformer tank. Due to the radiator positions of the transformer, the upper part of the tank is usually more suitable. For the mounting process of the sensors, a suitable hole is drilled in the relevant location and a rod adapter is welded there. Then the sensors are mounted on the rod adapter. In Figure 3, the position of the Transformer and E+E364 sensors on the transformer tank is shown in the three-dimensional CAD model.

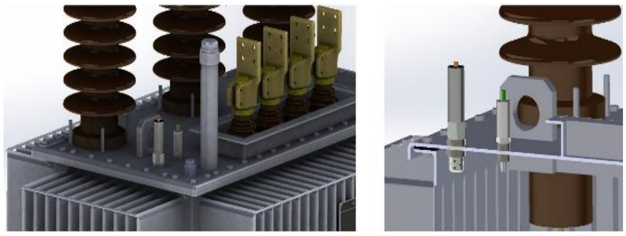

Figure 3. 3D CAD model of Transfostick and E+E364 sensor mounted on transformer tank.

3.3. Introduction of the Web Interface

The sensors used give raw data output with MODBUS. A parameter is defined for each address used in the sensors. To retrieve data, there must be a datalogger communicating over the MODBUS protocol. Within the scope of the project, a data logger was designed and manufactured to communicate with the sensors. The designed datalogger (named PDA Gateway) has one Ethernet port, one USB port for network operators to connect wireless internet providers, an RS485 connection port, and sensor connection inputs.

Sensors can be used on transformers located in areas where continuous site visits and data acquisition are not possible. In this context, the product called PDA Gateway can upload raw sensor data to a server via cellular or serial internet connection. USB-type cellular modem of mobile network service providers is used for internet connection. On the developed web-based user interface, measurement data can be plotted instantly and historical data can be downloaded in ".csv" format. In this way, it is possible to make trend analysis according to daily, monthly and even annual measurement data. [24].

4. Results and Discussion

4.1. Heating Analysis Tests

First, the heating analysis tests were carried out in the distribution company on the 400 kVA transformer where the Trafostick™ and E+E364 sensors were mounted. While performing these tests, both the data obtained from the sensors were examined and the breakdown voltage tests were carried out simultaneously. The field view of the sensors mounted on the transformer is shown in Figure 4.

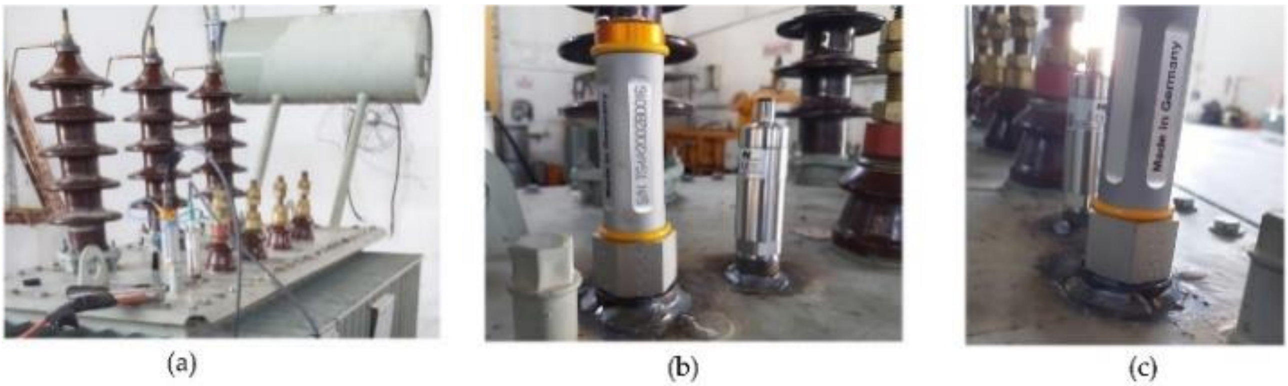

Figure 4. Views of the Trafostick™ and E+E™ sensors mounted on the transformer in the distribution company for heating tests.

The purpose of the heating tests is to compare the breakdown voltage data given by the Trafostick™ sensor with the test results and evaluate its accuracy. In addition, it has been determined to constantly monitor the breakdown voltage and relative humidity, establish a relationship between them and use this relationship in E+E364 and Sensirion sensors. In this context, five different heating tests were carried out. The start and end dates of the heating tests performed are shown in Table 1.

At the beginning and end of the heating tests, oil samples were taken from the transformer tank and tests were carried out in accordance with the IEC 60156:2018 standard. [25]. Tests were carried out with a Multi-Tech MTH-OBDV-80 device.

Table 1. Start and end dates of heating tests.

Test adı	Start date	End date
First oil test	23.11.2020 17:32	24.11.2020 08:06
Second oil test	26.11.2020 09:46	27.11.2020 10:09
Third oil test	01.12.2020 19:38	02.12.2020 10:32
Forth oil test	03.12.2020 19:51	04.12.2020 10:21
Fifth oil test	07.12.2020 23:56	08.12.2020 10:58

As a result of five different heating tests, the data of the Trafostick™ sensor was examined and compared with the data of the test device. In Figure 5 the temperature, relative humidity and breakdown voltage values given by the Trafostick™ sensor as a result of the third heating test are shown.

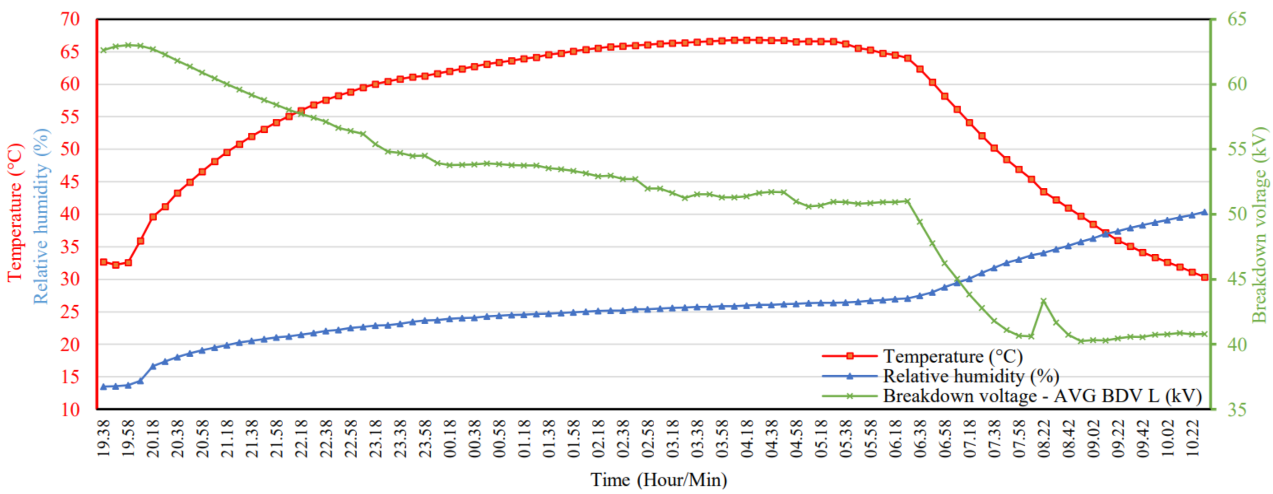

Figure 5. Temperature, humidity and breakdown voltage values measured by the Trafostick™ sensor during the heating tests (for the 3rd heating test)

As can be seen from the third test result, the oil temperature rises from about 32 ºC degrees to 67 ºC degrees in the heating test. It can be said that the relative humidity increased from approximately 13% to 27% during this period. As the transformer heats up, the moisture contained in the cellulosic paper passes into the oil. As the temperature increases, the maximum amount of water that can be dissolved by the oil increases, so the increased rate of relative humidity in this range is less compared to the cooling period. As the transformer cools, the maximum amount of moisture that the oil can dissolve decreases. On the other hand, the rate of return of the water content in the oil back to the cellulose paper is less than the cooling rate of the oil. For this reason, it can be seen from the graph that the relative humidity value increases while the transformer cools down. As a result, it can be said that there is a dynamic hysteresis loop between the transformer oil and the water content in the cellulosic insulation paper. Heating tests are insufficient to clearly see the hysteresis curve, however, the hysteresis curve formed according to the results obtained from long-term measurements is shown in Figure 6.

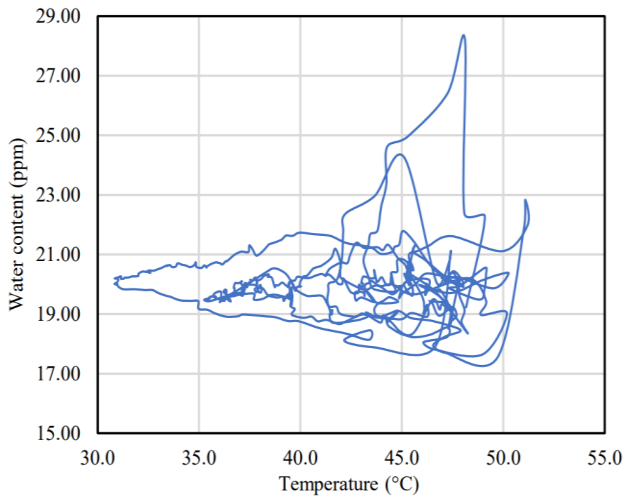

Figure 6. Hysteresis curve created according to the measurement results

The superimposed version of the temperature and humidity values measured during each test is shared in Figure 7.

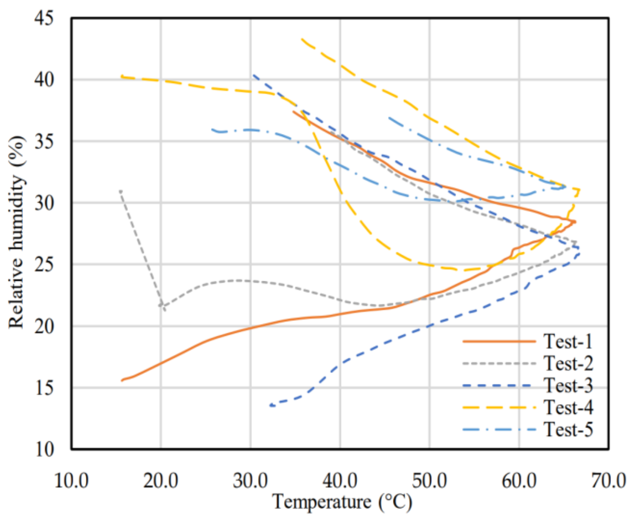

Figure 7. Temperature-humidity curve for each test

As a result of the five tests performed, the results of the test for breakdown voltage and the Trafostick™ sensor are shown in Table 2. According to the IEC 60422:2013 standard, a breakdown voltage between 30 kV and 40 kV is defined as normal, above 40 kV as good, and below 30 kV as bad.[26].

Table 2. Comparison of the breakdown voltages found by the Trafostick™ and breakdown voltage tester as a result of the heating tests carried out

Oil sample	**Samples Taken**	**Oil temperature**	**Breakdown voltage (kV) (Test device)**	**Breakdown voltage (kV) (Trafostick™)**
First oil	Before test	15 °C	72	68
	After test	35 °C	40	40
Second oil	Before test	15 °C	58	52
	After test	40 °C	29	31
Third oil	Before test	33 °C	53	62
	After test	30 °C	45	41
Fourth oil	Before test	16 °C	53	48
	After test	35 °C	41	40
Fifth oil	Before test	25 °C	43	44
	After test	45 °C	18	29

As seen in Table 2, it can be said that the breakdown voltage calculations of the Trafostick™ sensor and the test results are consistent. There are some differences, but various parameters such as the time the oil is exposed to air during sampling can affect the results. While evaluating the breakdown voltage of the transformer oil, it is more useful to examine the change in a certain period instead of examining it momentarily. According to the value of the breakdown voltage or humidity level, appropriate actions can be taken on the transformer and unplanned interruptions can be prevented[27]. For this reason, constantly monitoring the breakdown voltage online is a more reliable application than having a test at certain periods. In addition, when oil samples are taken from a transformer in operation and tests are carried out, the results may be affected by environmental conditions and the equipment used in the laboratory. In this context, the applicability of the trend analysis approach of online breakdown voltage monitoring systems is important because of the shortening of the response time in case of risk occurrence and predictive maintenance applications thanks to continuous monitoring.

By evaluating the data of the five heating analyses carried out, the relationship between the breakdown voltage of the Trafostick™ sensor and the relative humidity was examined. In this context, the moisture values in all the data and the breakdown voltages were matched and plotted on a graph. The breakdown voltage given by the Trafostick™ sensor according to the relative humidity is shown in Figure-8. According to the results shown in Figure 8, a curve was created to calculate the breakdown voltage from the relative humidity. This curve is shown as the black line shown in Figure 8 and its equation was obtained. After the relative humidity values of the E+E™364 and Sensirion SHT10 sensors are verified with the Trafostick™ sensor, the equation obtained will be used in the breakdown voltage estimation.

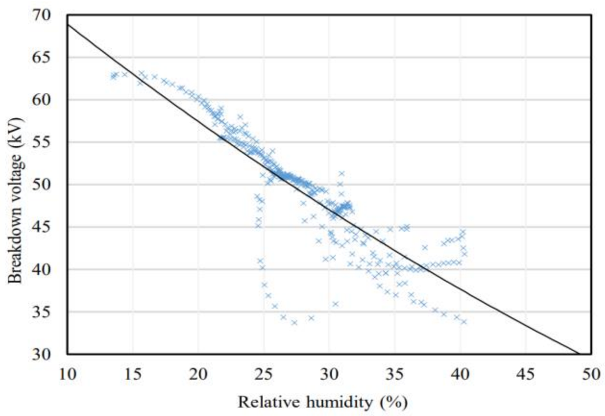

Figure 8. The graphical status of the relative humidity values corresponding to the breakdown voltages according to the Trafostick™ data obtained as a result of the heating tests

4.2. Long Term Field Measurement

After the accuracy of the Trafostick™ sensor was confirmed by the test results, the transformer where the Trafostick™ and E+E™364 sensors were mounted was taken to the place where it was planned to be installed and commissioned. At this stage, the relative humidity measurement values of the Trafostick™ and E+E™364 sensors have been compared. The E+E™ sensor only outputs relative humidity and temperature. In this context, by using the temperature and humidity values measured by the E+E™ sensor, we will try to approximate the breakdown voltage calculated by the Transformer sensor. In the next step after the verification, the relative humidity value of the E+E™364 sensor and the Sensirion sensor will be compared and the breakdown voltage will be tried to be estimated by calculations. In this context, after the installation of the transformer, the data of both sensors were compared and examined. Accordingly, the temperature and humidity values are shown in Figure 9.

According to the measured data examined, it is seen that the relative humidity values of the E+E™364 and Trafostick™ sensors are consistent. To ensure this consistency, the raw data of the E+E™364 sensor has been multiplied by a constant value. Since the sensors are different, it is considered natural to have differences between them. In the literature, it is seen that there are similar differences due to the different reference values of sensors belonging to different brands. Since the data of the Trafostick™ sensor is considered as a reference, the data of the E+E™364 sensor has been manipulated to be close to the data of the Trafostick™ sensor.

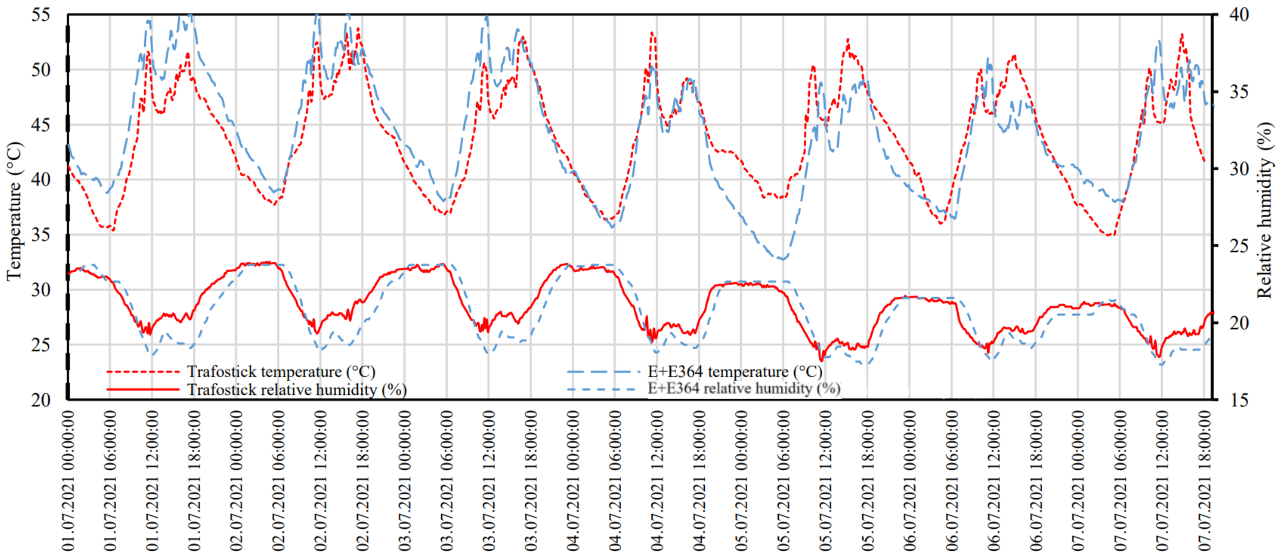

Figure 9. As a result of long-term field measurement, the relative humidity and temperature graph, taken from the Trafostick™ and E+E364 sensor in a one-week time interval.

The breakdown voltage was calculated with the measured data of the E+E™364 sensor, using the relationship between the breakdown voltage and the relative humidity obtained from the heating test. For this purpose, the relative humidity value of the manipulated E+E™364 sensor was multiplied by the formula obtained from the heating test to estimate the breakdown voltage. When the estimated breakdown voltage is compared with the Trafostick™ sensor, it is seen that the results are close to each other. The graph in which these data are compared is shown in Figure 10.

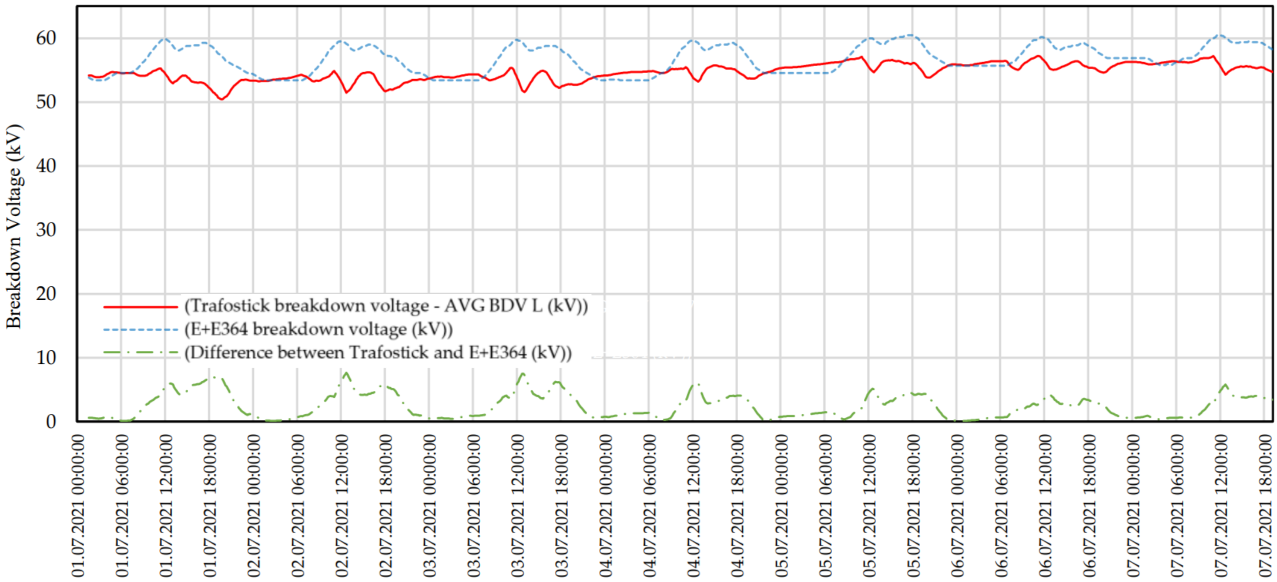

Figure 10. As a result of long-term field measurement, the breakdown voltage graph, taken from the Trafostick™ and E+E364 sensor in a one-week time interval.

When the breakdown voltage graph is examined, it is seen that the results are consistent. In some areas, even if the difference gets higher, the values are still close. In this context, it has been confirmed that the curve created according to the results of the heating test for the estimation of the breakdown voltage from the relative humidity is approximately consistent.

4.3. Measurement Studies with Sensirion

In the heating tests and long-term field measurement studies, the breakdown voltage data of the Trafostick™ sensor was confirmed by laboratory tests, and the relative humidity data was compared with the data of the E+E™364 sensor. Approximate breakdown voltage was calculated according to the relative humidity data from the formula created with the help of the obtained breakdown voltage and humidity graph. In this context, it is aimed to calculate the approximate breakdown voltage with the Sensirion™ SHT10 sensor, which is a low-cost single sensor. The relative humidity value obtained from this sensor has shifted with a constant to equalize with the relative humidity value given by the Trafostick™ sensor and the breakdown voltage is calculated. In the previous section, the relative humidity value of the E+E™364 sensor and the breakdown voltage were calculated. Measurement studies carried out in this section were made with Sensirion SHT10 and E+E™364 sensors. These two sensors were immersed in transformer oil in a jar and measurements were taken. Since the data belongs to E+E™364 sensor and Trafostick™ compared, E+E™364 accepted as a reference in this step. In this context, firstly, the manipulated relative humidity values of the E+E™364 sensor according to the Trafostick™ sensor were compared with the Sensirion™ SHT10. The difference between the response times due to the membrane structure of the sensors used in the study is reflected in the graphics.

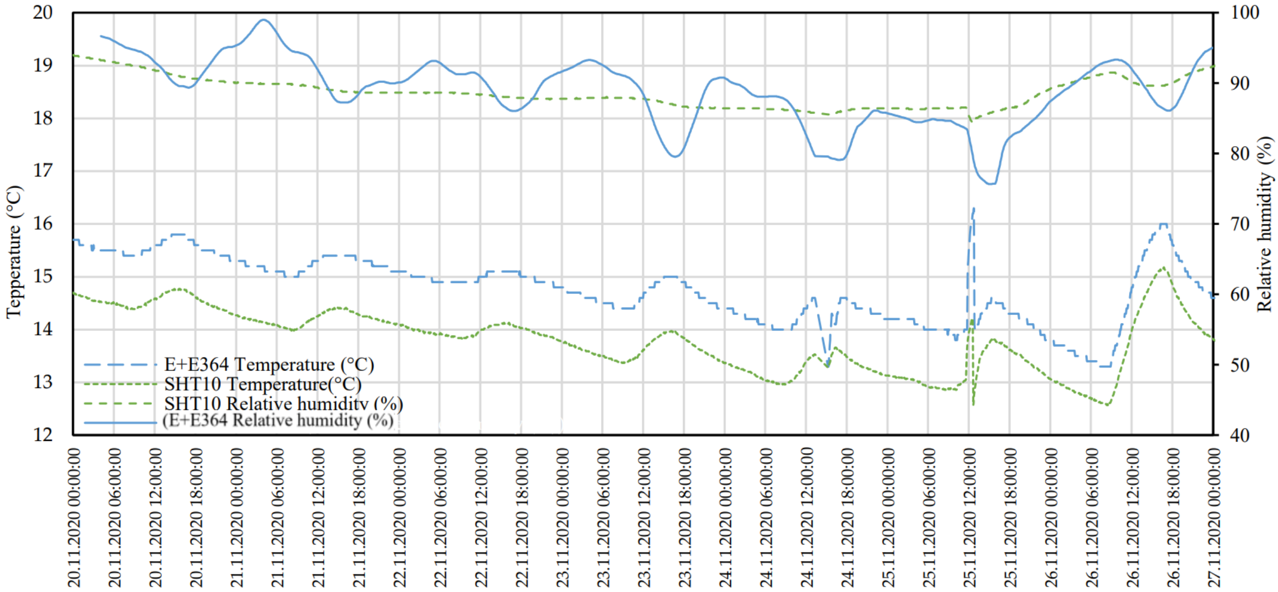

Figure 11. As a result of the measurement studies carried out with the SHT10 and E+E364 sensors, the temperature and relative humidity graphs of both sensors were taken in a one-week period.

The relative humidity-time graph formed according to the measurement results is shown in Figure 11. Here, the relative humidity value of the E+E™364 is 1.1 times higher than the measured value. This manipulation was applied since the Trafostick™ has been considered as a reference. The data of the SHT10 sensor is multiplied by 1.24, at this rate the data of the two sensors were very close to each other. This difference occurred due to the different calibration settings of the sensors, this problem almost disappears with manipulated values. According to the breakdown voltage-relative humidity graph obtained from the heating tests, the output of the SHT10 and E+E™364 sensors and the estimated breakdown voltage graph are shown in Figure-12.

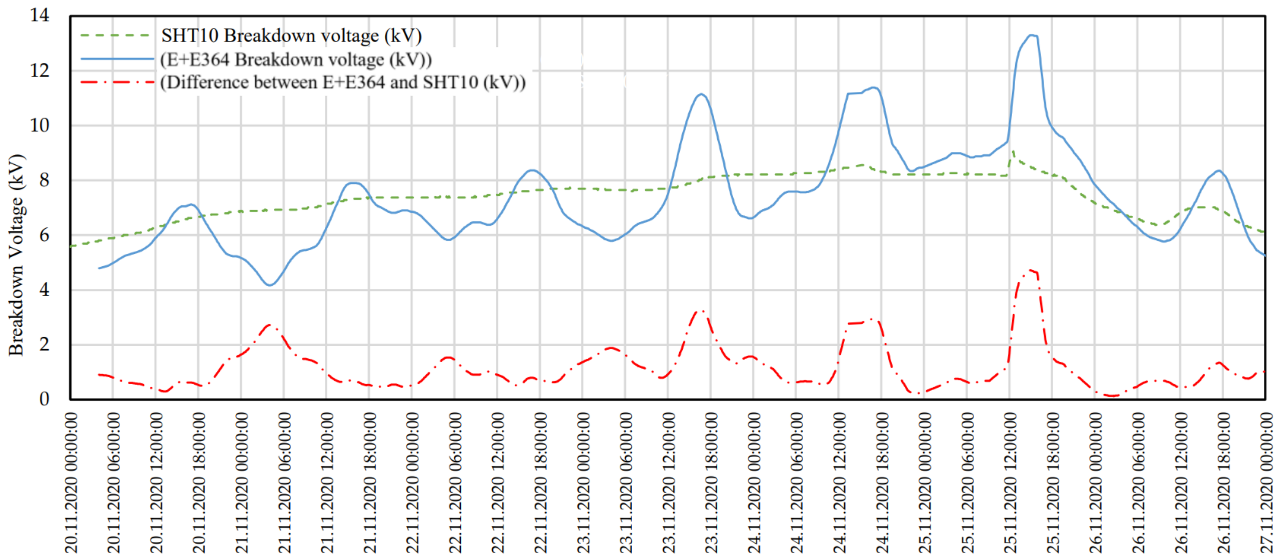

Figure 12. As a result of the measurement studies carried out with the SHT10 and E+E364 sensors, the breakdown voltage graph of both sensors was taken in a one-week period.

5. Conclusions

Dielectric oils are used in transformers to provide insulation inside the tank. The breakdown voltage of these oils is directly dependent on the humidity and temperature values. As the relative humidity of the oil increases, the breakdown voltage decreases. In addition, the moisture content directly affects the life of the transformer. In this context, continuous monitoring of the humidity, temperature and breakdown voltage of the transformers and trend analysis applications are important in terms of operational reliability. With online monitoring systems, different analysis results can be combined, and predictive maintenance applications can be carried out together with health index studies.

This study aims to develop an approach that measures humidity, temperature and estimates approximate breakdown voltage using a low-cost single sensor. In line with this goal, first of all, laboratory tests were carried out together with the heating tests by using the Trafostick™ by Passerro, which is an industrial oil monitoring sensor that calculates the breakdown voltage in transformer oils with high accuracy, and it has been confirmed that the product calculates the breakdown voltage reliably. At this stage, an equation was created between the relative humidity and breakdown voltage values to be used in other sensors. Then, the relative humidity values measured by the E+E™364 by E+E™ sensor were verified with reference to the Trafostick™, and the breakdown voltage was calculated. Finally, measurements were taken with the low-cost single sensor. The measurements were verified, and the breakdown voltage was calculated with the obtained formula. The features related to sensors and measurements are mentioned in detail in the article.

In this context, the relative humidity in the transformer oil was measured with the Sensirion used to measure the humidity in the air in a single sensor structure, and the breakdown voltage was calculated approximately. Although the calculated breakdown voltage is not as consistent and reliable as an industrial product e.g. Trafostick™ and conventional oil testers, it provides an advantage in terms of the feasibility of the trend analysis approach by enabling continuous monitoring. It is seen that the low-cost single sensors are suitable for use in trend analysis and health index applications in distribution transformers that are not at very high power levels and have a low risk ratio. In addition, it is recommended that products with high reliability of calculations such as Trafostick™ should be used in transformers with high power or in critical position.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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