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EVALUATION OF THE INSULATION CONDITION OF HIGH-VOLTAGE TRANSFORMERS BY DETECTING PARTIAL DISCHARGES USING THE ELECTROMAGNETIC WAVE RADIATION METHOD

OCENA STANJA IZOLACIJE VISOKONAPETOSTNIH TRANSFORMATORJEV Z DETEKCIJO DELNE RAZELEKTRITVE IN UPORABO METODE SEVANJA ELEKTROMAGNETNEGA VALOVANJA

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High-voltage transformers are among the most important elements in an electric-power system. Each one of them is affected by various external factors: overvoltage, partial discharge (PD), overheating, vibrations, etc., which are created by a strong electric field, thermal effect, humidity, impurities, factory defects, dissolved water and gas in oil-type-transformer insulation. These and other factors, caused by the environment, reduce the life of a device. Thus, the evaluation of the device condition is one of the most important factors for a system-safety evaluation, which ensures a reliable and economical electrical-network operation. This work reviews different contact and non-contact methods, used to evaluate the conditions of transformers by measuring the level of PD. The selected method, i.e., the non-contact measurement of electromagnetic-wave radiation was used to evaluate the voltage-transformer status. The experiment was performed at a 110 kV substation. The authors discuss the efficiency of the selected method to evaluate the voltage-transformer insulation condition.

Keywords: insulation, partial discharge (PD), detection, transformers

Visoko-napetostni transformatorji so med najpomembnejšimi elementi sistemov za distribucijo električne energije. Vsak iz med njih je pod vplivom različnih zunanjih faktorjev: napetostne preobremenitve, delnega razelektrenja, pregretja, vibracij, itd., ki so posledica nastanka močnih električnih polj, ogrevanja, vlage, nečistoč, tovarniških napak, raztopljene vode in plinov v oljnih transformatorjih. Ti vplivi in še vrsta drugih okoljskih faktorjev skrajša življenjsko dobo transformatorjev. Zato je ovrednotenje stanja določene naprave ena od najpomembnejših nalog sistema njenega varovanja, ki zagotavlja ekonomično in zanesljivo obratovanje električnega omrežja. V članku so avtorji obravnavali različne kontaktne in brezkontaktne metode, s katerimi je možno ovrednotiti stanje transformatorjev z merjenjem nivoja delne razelektritve. Za oceno stanja napetostnega transformatorja so uporabili brezkontaktno meritev sevanja elektromagnetnega valovanja. Preizkus so izvajali na 110 kV pomožni postaji. V članku so študirali tudi učinkovitost izbrane metode za ocenitev stanja izolacije napetostnih transformatorjev.

Ključne besede: izolacija, delna razelektritev (PD), detekcija, transformatorji

1 INTRODUCTION

According to the data analysis presented in the CIGRE transformer reliability review,[1] in 36.62 % of the examined high-voltage transformers the failure was of dielectric origin – partial discharges, corona, or electric arc.[1,2] The listed phenomena are caused by insulation defects, degradation of insulation, overvoltage, overheating and other factors occurring during the service life.

The insulation of transformers is continuously affected by partial discharges and the transformer lifetime depends on the activity of PDs. Partial discharge (PD) is an electric discharge that does not completely cover the insulation between the conductors.[3] This phenomenon occurs at the weakest points of solid and liquid insulation. This is due to the defects in the insulation, which are affected by the connected voltage. Regarding their properties, partial discharges are of a different nature than electric discharges – the process that happens during a partial discharge is unipolar and no free charges are created.

While other phenomena of dielectric nature can be observed with the naked eye (electric arc) or identified even by smell (the nitrogen smell during the corona effect), PD is impossible to be detected without additional equipment. During this phenomenon, acoustic and electromagnetic waves are emitted into the surroundings, the temperature increases where a PD occurs and, in addition, methane and hydrogen gases are formed in the insulation oil.[3] Due to the high variation speed of the param-

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eters that define the PD, various detection methods are available such as the vibroacoustic, electromagnetic, temperature-observation methods, chromatographic-gas analysis and some other methods.[4–8] Each of these methods has its advantages and disadvantages, and their accuracies are also different. Therefore, it is necessary to determine the general PD level and location mathematical model, with which the advantages and utilization of the above-mentioned methods can be completely used while operating diagnostic devices based on different physical principles. After determining certain correlations between different methods, the remaining operation life of a transformer can be identified better and can allow planning the maintenance or repair of electric-system elements. At the same time, financial losses and a possible risk to human life can be avoided, both of which might arise due to a device's malfunction.

The objective of this study is to assess the transformer status at 110 kV substations, using non-contact measurements of electromagnetic-wave radiation.

2 REVIEW OF MEASUREMENT METHODS FOR THE DETECTION OF PARTIAL DISCHARGES

During the presence of partial discharges, the following secondary phenomena of the insulation material are observed:[9]

- Generation of electrical impulses;
- Emission of electromagnetic waves;
- Emission of ultrasonic waves;
- Generation of acoustic waves;
- Release of heat;
- Decay of the insulating material.

Each of the above phenomena can be evaluated with appropriate methods such as the recording of electrical parameters (analysis of the emission level of high-frequency (HF) waves or the partial discharge detection approach), recording of mechanical waves (the vibroacoustic method), an analysis of the chemical composition and thermo-vision analysis.

The measurement methods listed above have certain advantages and disadvantages and can be applied differently. This information is further analyzed in the article.

2.1 Electrical methods

The electromagnetic energy measurement method is based on the measurement of the current, induced during the partial discharge, and flows through the grounding conductor, using a current transformer.[6] Two key devices are used with this approach: a PD-signal recording device and a device for data analysis. This approach enables us to record the PD signal by connecting measurement devices (a voltage transformer and a current transformer) directly to the object under investigation (a power transformer, cable, etc.).[4] A typical diagram of the equipment connection for an electrical partial discharge measurement is shown in **Figure 1**.

With this approach, the recording of partial discharge can be performed without stopping the operation of the power transformer. Therefore, it allows an online evaluation of the present condition of the power transformer. Afterwards, the acquired information is analyzed and the time-dependent deviations of the PD parameters are observed to evaluate the condition of the device insulation.[4]

Even though the electrical method of partial-discharge measurement is very accurate, it has several disadvantages. The main disadvantage is the sensitivity of

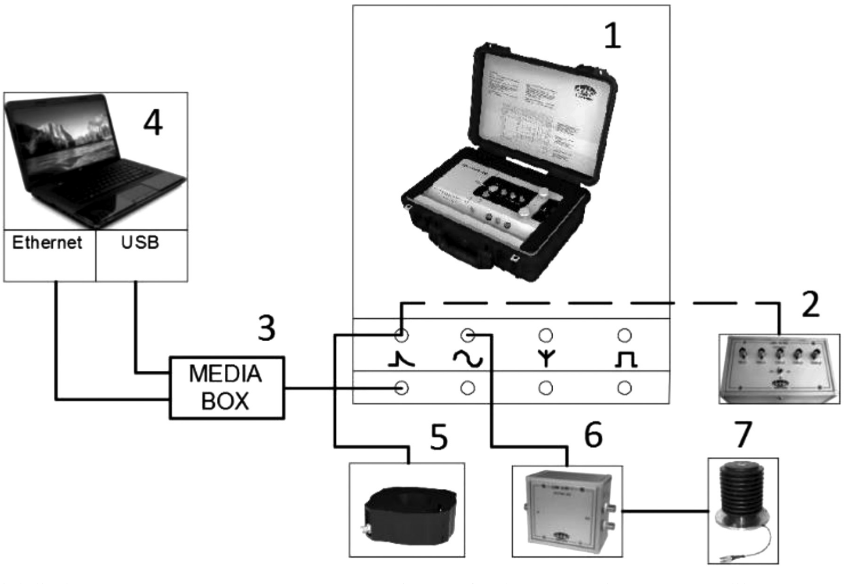

Figure 1: Electrical partial discharge measurement set-up: 1 – PD equipment for data processing, 2 – PD calibrator, 3 – device for connecting the PD measuring equipment to personal computer systems, 4 – PC with data processing software, 5 – sensor for coupling HF PD signals, 6 – measurement data splitting box, 7 – PD decoupler[10]

the measuring device to ambient electromagnetic noises.[6] High-voltage and power equipment (power transformers, cables, insulators, etc.) emit electromagnetic noises in narrow and wide spectral bands, which can affect the recorded data. In some cases, it is difficult to distinguish between the presence of PD and ambient electromagnetic noise due to the very short signal duration of a PD pulse. In such a case, the recorded data should not be used for the evaluation of the equipment-insulation condition.[4]

To solve this issue, manufacturers recommend using additional filters for electromagnetic noises. Another possible way to solve this problem is to disconnect the equipment from the power grid, using an external power supply. However, the latter case is not practical because the disconnection of the device from the power grid can be very costly due to the resulting reduced reliability of the grid.

Generalized information about the electrical method for the PD measurement is given in **Table 1**.

Table 1: Advantages, disadvantages and application areas of the electrical partial-discharge measurement method[4,6,7]

Advantages:	• Wide range of applications, • High sensitivity, • Suitable for on-line recording of PD, • Possible to record multiple parameters of PD (charge, voltage, discharge current, etc.).
Disadvantages:	• Measurement results are very sensitive to the electromagnetic interference generated in the environment, • Complicated application at the substation, • Costly measuring equipment as compared with the other methods.
Applications	• Power transformers, • Cables, • Insulators, • etc.

2.2 Ultra-high frequency method

The ultra-high frequency (UHF) partial-discharge detection method is based on electric resonance and electromagnetic-wave radiation, caused by PD in a frequency range of 50 MHz to 1.5 GHz.[6] Electromagnetic waves of the highest amplitude are registered near their source. In this case, it is in the defective region that the PD occurs. This is the reason why the partial-discharge location can be determined according to the intensity of the electromagnetic wave.[12]

The UHF method has been mostly used to detect PD in gas-insulated substations (GISs).[4,13,14] Therefore, this method is relatively new in determining the insulation condition for other devices. Despite that, for GISs, the UHF method is one of the main ones for determining faults. Due to each substation's specific parameters, even a sufficiently weak PD can be critical. Due to the advantages associated with the UHF method, PD can be registered even from 5 PC or lower.[13,14]

Since the introduction of the ultra-high frequency method for determining the insulation condition of power transformers and other high-voltage electric devices, this method has greatly improved. Various tools have emerged, which help determine a PD more accurately. Measurement devices based on this method became essential in order to protect high-voltage components and maintain their reliable operation mode.[13]

Using a UHF registering device, it is possible to determine the PD activity. Another possible use of UHF registering devices is the determination of a partial-discharge location, as presented in **Figure 2**. This principle is used to analyze particular time moments needed to detect electromagnetic waves generated by a PD at different spatial points of UHF receiver antennas. Based on the time difference between signal registering and the wave propagation speed in a medium, the location of PD can be determined.[15]

Due to the complicated structure of the transformer and its unconventional shape, calibration of the measurement equipment for electromagnetic wave radiation is mandatory. Neglecting the influence of different media, internal structures and the shape of high-voltage components, the obtained measurements would have a high error.

Generalized information of PD registration using the UHF electromagnetic wave method is presented in **Table 2**.

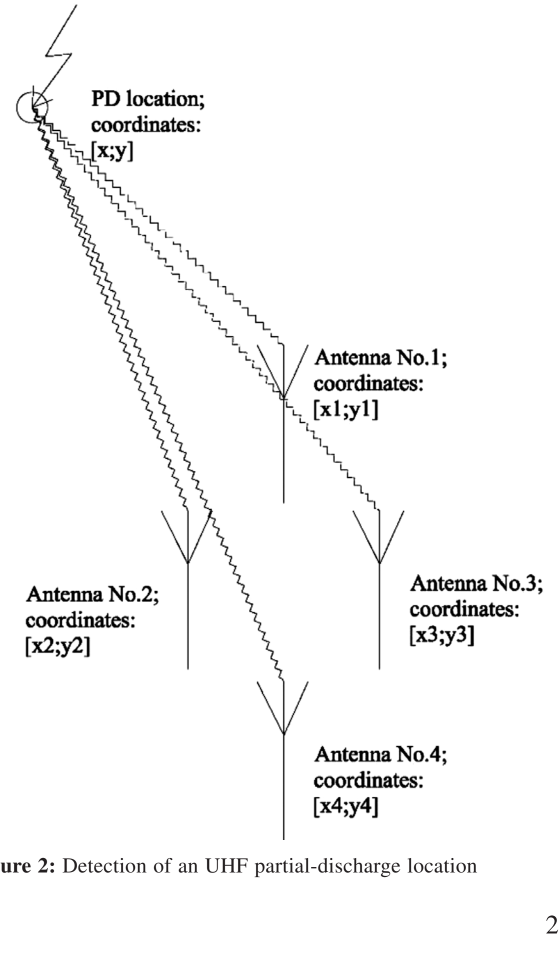

Figure 2: Detection of an UHF partial-discharge location

Table 2: Advantages, disadvantages and applications of the UHF electromagnetic wave radiation method for the registration of partial discharges[4,6,7]

Advantages:	• Easy application when measuring in a substation, • Instantaneous data analysis available, • Defect localization, • Measurements are performed while a high-voltage component is connected to the power grid.
Disadvantages:	• Measurements are very sensitive to the ambient electromagnetic noises, • Difficult to determine the remaining operation life of a high-voltage component based on instantaneous measurements.
Applications	• Transformers, • Gas-insulated substations (GIS), • Cables, • Insulators, • etc.

2.3 Vibrodiagnostic method

During a partial discharge, the resulting energy heats the adjacent insulating material to a possible explosion of its fraction. This tiny explosion emits electromagnetic, optic and acoustic waves.[11] The vibrodiagnostic method for detecting PDs is based on on-line registration of acoustic waves.

During the application of the vibroacoustic method, information-processing equipment (a computer with corresponding software), a data-acquisition system and sensors (piezo element, accelerometer, etc.) operating within a frequency range of 10–300 kHz are used to record mechanical vibrations generated during a PD.[4,6,8] This measurement set-up can be used to determine the spatial location of a partial discharge in the high-voltage component being inspected.

Defects of the internal insulation of cables, anomalies in insulators, circuit breakers, oil-immersed power transformers and gas-insulated electrical-system components can be identified by recording mechanic waves propagating through the elements of a power system, using the vibrodiagnostic method.[9] By recording mechanic waves, not only a PD can be identified but also conditions of the insulation material such as changes in it, fractures or impurities.[16]

When the vibrodiagnostic method is used for detecting a partial discharge, we can determine the location of the defect by examining the decrease in the amplitude of the acoustic waves emitted from the defective location or the time difference between the propagated waves. One of the possible vibroacoustic sensors is the piezoelectric transducer (PZT). When mounting the PZT to an outdoor power-transformer tank, it captures the interference in the environment, which can cause additional measurement uncertainties. Moreover, because of different designs of the power-transformer tank, measurements may vary so that additional measurements are required to adjust the results to a particular design of the power-transformer tank. To reduce the influence of ambient factors on the measurement results, a PZT transducer can be mounted inside a power transformer. Detection of a PD location with this method is based on the measurement of the difference in the mechanical-wave propagation time recorded by a transducer pair to estimate the exact location of the PD. This method is more resistant to the influence of ambient factors than other on-line measurements (electric or high-frequency ones).[6]

The data recorded with the vibrodiagnostic method are unaffected by electromagnetic noise and, therefore, contrary to the situation involving electric PD-detection methods, the high-voltage component under investigation does not need to be disconnected from the power system to obtain more accurate data. However, this method also has drawbacks. Since power transformers or other equipment under investigation are not homogeneous – they consist of layers of different materials – the propagation of acoustic waves is difficult to predict in advance. This makes it extremely difficult to precisely locate the spatial position of the PD. Another problem is caused by partial discharges themselves and the parameters of detection devices – PDs emit acoustic waves of very low amplitudes while measuring devices require an extremely high sensitivity to register such signals.

As a result, the vibroacoustic method detects the PDs that already strongly affect the insulation and the component under investigation may already be in a critical condition. In this case, the component must be disconnected from the power system before a critical failure occurs.[4]

A summary of the vibrodiagnostic method used for detecting PDs is given in **Table 3**.

Table 3: Advantages, disadvantages and application areas of the vibrodiagnostic method[4,6,7]

Advantages:	• Resistant to electromagnetic interference, • Defect localization.
Disadvantages:	• Measurement results are very sensitive to external vibrations, • Not suitable for early detection of PD, • Not suitable for evaluation of equipment condition, • Not suitable for continuous device diagnostics.
Applications	• Transformers, • Gas-insulated substations (GIS).

2.4 Chromatographic analysis

The chromatographic method used for detecting partial discharge in a high-voltage transformer is based on an analysis of the insulating oil and gas of the transformer for the detection of particular changes during the PD process.[6]

There are two important chromatographic-analysis methods: high-performance liquid chromatography (HPLC) and dissolved gas analysis (DGA).[6] HPLC analyses the resulting products of PD, such as decomposed glucose, released during the breakdown of solid insulation. DGA analyses the amount of gas produced during PD in a test substance.

The selection of the oil sample, gas separation and, finally, chromatographic analysis give rise to a number of uncertainties and errors that affect the accuracy of the results. This method is not appropriate for detecting sudden changes in transformer insulation as it is applied over scheduled periods.[5]

Summarized information on the chromatographic analysis is given in **Table 4**.

Table 4: Advantages, disadvantages and applications of chromatographic analysis for a detection of partial discharge[5,6]

Advantages:	• Suitable for identifying events that occur in a device,
Disadvantages:	• The set amount of gas does not correlate with the functionality reserve of the component being inspected, • Not suitable for instantaneous evaluation of the high-voltage component condition, • Large uncertainties due to the measurement principle.
Applications:	• Transformers.

2.5 Thermovision analysis

Every body with a temperature greater than absolute zero emits infrared radiation.[11] These rays and their intensity can be recorded using a thermal imager.

This method is described as mobile, non-invasive, contactless, wide-ranging and it provides fast measurement results.[5] However, the results of thermographic analysis using a thermal imager are easily influenced by environmental factors and, in the case of polished surfaces of the transformer housing, the results are also affected by errors. The thermal imager can only provide the temperature of the external surface of the transformer housing, which rarely reflects the actual condition of the transformer. Also, heat dissipation is only one of many parameters that are measured to detect the existing defects, making it difficult to determine particular defects (except couplings or joints) and having a high degree of uncertainty.[5]

Figure 3: Object under investigation: a current and voltage transformer

A summary of the thermovision analysis is given in **Table 5**.

Table 5: Advantages, disadvantages and applications of the thermovision analysis[5,11]

Advantages:	• Mobile, • Instantaneous data.
Disadvantages:	• Inappropriate for setting up a device operation resource, • Only the condition of the outer layer can be assessed, • Does not represent the actual condition of a transformer.
Applications:	• Transformers; • Cables.

3 APPLICATION OF THE UHF METHOD FOR REGISTRATION OF THE ELECTROMAGNETIC WAVE RADIATION OF HIGH-VOLTAGE TRANSFORMERS

In order to investigate the applicability of the UHF method on site (at real substations), a DFA300 Doble Lemke device is used for measuring electromagnetic wave radiation. This device is intended for the detection of insulation or mechanical defects in gas-insulated substations or in open-source substations. DFA300 registers the radio frequency interference (RFI) of radiated electromagnetic waves due to PD from 50 to 1000 MHz and acoustic emissions (AEs) from 10 to 300 kHz.[17]

3.1 Experimental diagram and measurement principle

Using the DFA300 measuring device, 110-kV substations equipped with high-voltage Pfiffner current (EJOF 123) and voltage (EOF 123) transformers were subjected to a condition analysis. The object under investigation is presented in **Figure 3**.

More than two hundred different high-voltage transformers at over sixty different substations were tested in the study.

Measurement principles:

- A plan for the installation of the substation's measuring equipment is drawn up;

- A baseline background spectrum analysis near the substation is conducted, more than 20 meters away from the high-power components;
- A baseline background spectrum is captured with the DFA300 to allow an instant evaluation of the component condition;
- A spectrum analysis of the received electromagnetic-wave signals of each investigated component is performed and compared to the baseline background;
- Doble Lemke recommends an analysis of a spectrum range of 600–900 MHz to detect partial discharge;
- If spectral mismatches are detected within the specified frequency range, an additional analysis of the component under investigation is performed by recording radiation intensities during the wave period, level values with the alternating phase and level measurements;
- Device failures are identified.

During the measurements, the background spectrum within the range from 50–1000 MHz, more than 20 m away from the nearest interfering component, was scanned. At the points shown in **Figure 4**, the measurement was repeated in order to compare the results with the background spectrum. The measurements close to the component under investigation were made at a distance of 1–1.5 m, depending on the height of the component installation. The measuring results at these measuring points were considered to be scarcely affected by the other transformers. The spectral analysis of each component was performed twice.

The results of the stored spectrum were further analyzed using the MATLAB software. The spectral-analysis values recorded for each component were compared with the baseline background. The results were plotted, showing all the spectral analyses (background and component) and providing a differential graph that subtracts the spectral-analysis values of the background from the spectral values of the component. The differential graphs of each phase transformer were compared to determine which phase transformer was most affected by the insulation degradation. Examples of graphs are provided in Section 4 of this article.

3.2 Advantages of the selected measurement method

Using DFA300, the measurements are performed under real operating conditions. The components under investigation are connected to the power grid. The power grid does not suffer from the extra line loads as the component does not need to be disconnected.

The measuring device provides various tools for monitoring and assessing the condition of the facility being measured, such as:

- "Spectrum analyzer": during this measuring mode, the device registers radiation of electromagnetic waves at different frequencies in a range of 50 MHz to 1000 MHz;
- "Time resolved": during this measuring mode, the device synchronizes with the frequency of the power grid via a wireless synchronization adapter. In this way, the distribution of the electromagnetic-wave intensity over the corresponding period is recorded at the selected fixed frequency. This type of measurement can accurately represent the type of fault existing in the component under investigation;
- "Level versus Phase": these measurements detect the periodic distribution of peak-wave magnitudes at a given fixed frequency. When the measuring device is synchronized with the main frequency of the power grid, the selection of the number of different peaks per measurement (1000, 2000, 5000) shows the pattern of peak distribution. According to this regularity, it is possible to characterize the defect;
- "Level meter": it records the intensity level of the electromagnetic wave at a certain fixed frequency. This measurement can be used to estimate which high-voltage component emits electromagnetic waves

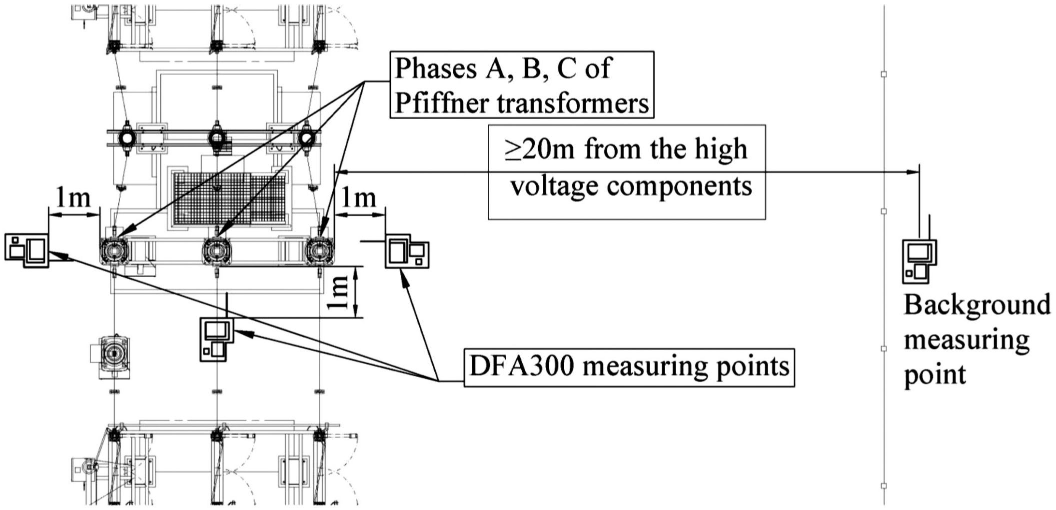

Figure 4: Partial-discharge measurement plan

of a higher intensity than the nearby ones (thus determining which particular component requires an additional analysis) or which component is already defected.

The measuring device is mobile, user friendly and convenient for daily measurements when visiting a number of different substations.

3.3 Disadvantages of the selected measurement method

During the measurements, an environmental impact on the measuring-device operating characteristics was encountered. Depending on the humidity of the air, the accuracy of the measurements changes. In the morning, when the humidity level in the environment was relatively high, the device was not able to register the distribution of the peak values of emitted electromagnetic-wave intensity versus phase at a fixed frequency value ("Level versus Phase" mode). By the middle of the day, when the air humidity dispersed, the measurements were again performed smoothly.

The registered spectrum values of the emitted electromagnetic waves (background or particular high-voltage component) during the spectrum analysis had a significant error of about 4–9 %. This error was calculated by comparing the results of two consecutive measurements of the same component.

The intensity values of the emitted electromagnetic waves registered during a period at the selected frequency cannot be stored in a time interval for a later analysis. The only way to save data is to stop the measurement and capture the current image. The disadvantage of this is that during the recording period, the anomaly that could identify a malfunction of the component is not always recorded. This causes additional difficulty during the analysis of the measurement results.

Different measurement times were estimated when measuring the level of electromagnetic wave in the "Level versus Phase" measuring mode. As a result, during the investigation of high-voltage components, for some components, 1000 peak values were accumulated in a few seconds and for others, in a few minutes. Therefore, it is not possible to determine the total duration during a measurement.

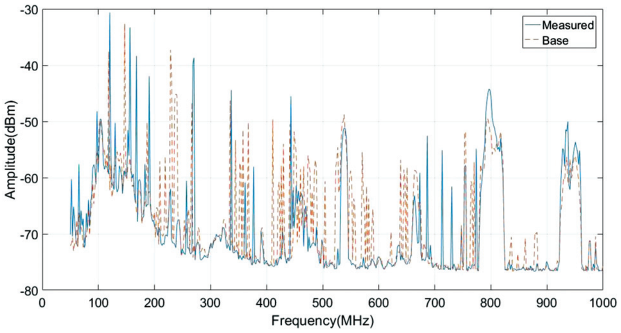

Figure 5: Baseline background and Phase B spectra of transformer "ĮT-T101"

The device cannot compare the results of certain measurements. For this reason, additional measurements are required when analyzing the recorded data using a mathematical model and in case of doubt concerning the obtained results.

4 RESULTS

During the analysis of the data of each phase of the transformer, the baseline background spectrum and the particular phase transformer spectrum (**Figure 5**), the difference between these spectra (**Figure 6**) and a comparative graph of the differences between all the phases of the transformer (**Figure 7**) were provided. The data below is from one of the 110-kV substations' voltage transformers "ĮT-T101" (grade EOF-123).

According to the recommendations of Doble Lemke, the manufacturer of the DFA300 instrument, partial-discharge signals are analyzed in the 600–900 MHz range where the maximum spectral divergence is determined.[17] Based on this assumption, an anomaly is detected in a frequency range of 780–820 MHz – the intensity of the electromagnetic wave is higher than the background in the whole spectrum. This effect, although small, is attributed to PD. Based on the information provided in **Figure 7** for the comparison of the difference of all three phase spectra with the baseline background spectrum, it can be stated that the Phase-B voltage transformer shows

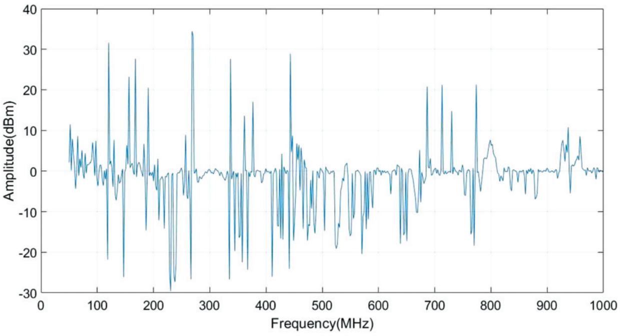

Figure 6: Difference between "ĮT-T101" Phase B spectrum and baseline background spectrum

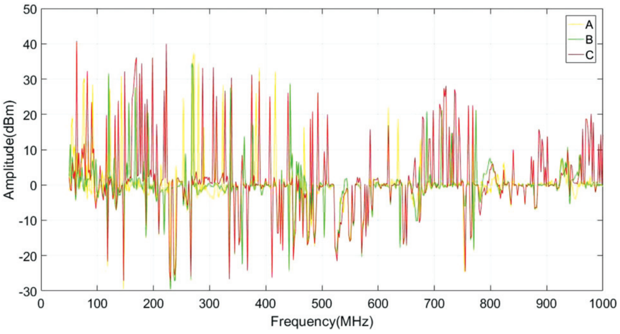

Figure 7: Comparison of the differences of all three phase spectra of "ĮT-T101" with the baseline background spectrum

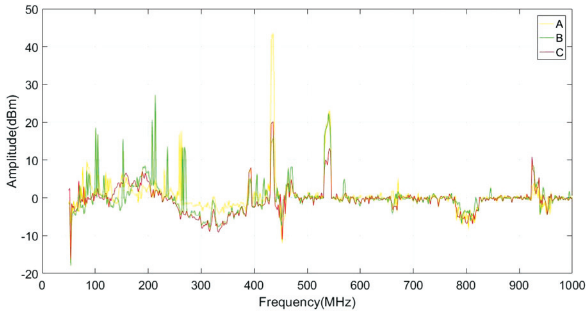

Figure 8: Comparison of the differences of all three phase spectra of the replaced "ĮT-T101" with the baseline background spectrum after the Phase-B accident

the highest PD level and Phase A shows the lowest PD level.

These measurements were made on April 4, 2019. In May, an accident occurred at one of the 110-kV substations – a Phase B voltage transformer "ĮT-T101" exploded. Prior to the accident, the parameters of the power grid did not exceed the normal-mode limits.

On July 26, 2019, additional measurements were carried out with the replacement of the Phase B voltage transformer "ĮT-T101" (grade EOF-123). The comparison of the differences between the three phase (A, B and C) spectra of the replaced "ĮT-T101" with the baseline background spectrum is shown in **Figure 8**. The comparative spectra of the first and second measurement in absolute values for Phase-B voltage transformer "ĮT-T101" are shown in **Figure 9**.

According to the information from **Figure 8**, an anomaly of spectral differences for Phase B similar to that before the accident with the transformer is observed in the frequency range of 780–820 MHz. Therefore, such a difference could be used as a reliable parameter for identifying the condition, in which the level of PD is increased and the transformer is under risk of being affected by failure.

Comparing the spectra in **Figures 7** and **8**, it can be concluded that during the second measurement the substation was much less loaded. For this reason, it is possible to see the difference in **Figure 9** within the range of 780–820 MHz. When analyzing the comparative graph (**Figure 8**), it can be stated that Phase B of the replaced transformer "ĮT-T101" is no longer different from other phases (A and C).

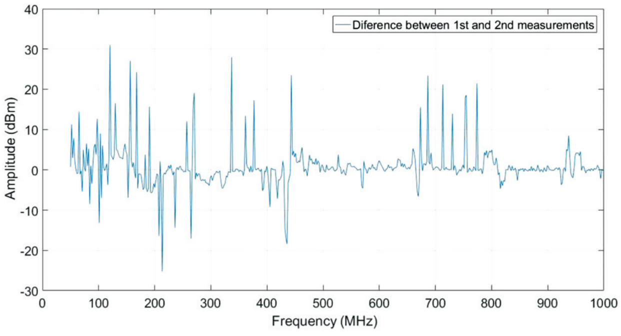

Figure 9: Comparative analysis of the absolute values of spectra of the first measurements (defected "ĮT-T101", before the replacement) and second measurements (after the replacement of "ĮT-T101") of the Phase-B voltage transformer

This method comparing the background and high-voltage component spectra differences is based on the accuracy of the results recorded. If the results are false, frequencies of a possible PD may not be determined, which may result in an incorrect estimation of the insulation condition of the component under investigation.

5 CONCLUSIONS

This study reviews different contact and non-contact methods, used to evaluate the condition of operating transformers that are not disconnected from the electrical grid, by measuring the levels of PDs. The selected non-contact UHF measurement method using electromagnetic-wave radiation was used to evaluate the voltage transformers' status. The experimental investigations were performed at a 110-kV substation.

The spectrum of the electromagnetic waves emitted was registered by a DFA300 device with a 4–9 % error tolerance; therefore, during unfavorable conditions the frequency needed for the detection of partial discharges could be undetermined.

It makes the most sense to perform a condition evaluation of a component when the substation has the highest power load.

Measurements performed at one of the 110-kV substations could have helped to evade the failure; however, the registered differences between the phase spectra within the frequency range of 780–820 MHz were quite small, making it difficult to identify the presence of a high-level failure of "ĮT-T101" Phase B. However, the difference we detected shows that the level of PD increased and the transformer was under risk of being affected by failure.

We need to capture a broader parameter, combining electromagnetic and vibrodiagnostic partial-discharge measurement methods (if allowed by the measuring-device type), additionally considering the system's voltage, frequency, current and other surrounding factors such as temperature and humidity.

6 FUTURE WORK

As routine inspections are performed at certain time intervals, they are not completely accurate due to the undefined status of the device between predefined intervals – the set examination intervals may be too long to prevent the device's failure or too short and inaccurate. Therefore, future research should concentrate on optimizing the inspection procedure for the insulation condition of the transformer and its variations due to operating factors. We need to propose a method that would allow us to schedule the device's repair time and perform the examination according to the condition of the insulation, using the obtained data.

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