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Research Article

Dielectric Analysis of High Voltage Equipment via 3D Partial Discharge Signal Graphics

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Abstract

Partial discharge (PD) is a very critical phenomenon for high voltage engineering. Accurate measurements and detailed analysis of PD's are necessary to have a reliable electrical system. Therefore, the aim of obtaining graphics of PD signals is to visualize PD's to solve and analyze trend points. Unfiltered and scattered partial discharge signals cause false observations even though these are rigorously measured and calculated. Conventional graphic obtaining methods have some drawbacks, such as ignoring intensity areas that are significant to identify trend areas, misrepresenting the sequential partial discharge signals following each other, and causing high costs. In this sense, this paper proposes an improved and practical method using a multi-paradigm numerical computing programming language without needing expensive methods and tools. High voltage power cables are tested in the laboratory to record digital time-based PD signals. The experimentally measured PD data are converted into 2D and 3D graphics with the proposed technique. In this context, 2D and 3D graphics are compared, and the process of creating 3D graphics is explained. Consequently, the data becomes easy to understand and define with 3D graphics obtained using the method.

Keywords: Partial discharge, 3D analysis, High voltage, Power cable, Graphical modeling.

3D Kısmi Deşarj Sinyal Grafikleri ile Yüksek Gerilim Ekipmanlarının Dielektrik Analizi

Öz

Kısmi deşarj (PD), yüksek voltaj mühendisliği için çok kritik bir olgudur. Güvenilir bir elektrik sistemine sahip olmak için doğru ölçümler ve PD'lerin ayrıntılı analizi gereklidir. Bu nedenle, PD sinyallerinin grafiklerini elde etmenin amacı, trend noktalarını çözmek ve analiz etmek için PD'leri görselleştirmektir. Filtrelenmemiş ve saçılmış kısmi deşarj sinyalleri, titizlikle ölçülüp hesaplansa bile yanlış gözlemlere neden olur. Konvansiyonel grafik elde etme yöntemlerinin, trend alanlarını belirlemede önemli olan yoğunluk alanlarının göz ardı edilmesi, birbirini takip eden ardışık kısmi deşarj sinyallerini yanlış temsil etmesi ve yüksek maliyetlere neden olması gibi bazı dezavantajları vardır. Bu bağlamda, bu makale, pahalı yöntem ve araçlara ihtiyaç duymadan çok paradigmalı sayısal hesaplama programlama dilini kullanan gelişmiş ve pratik bir yöntem önermektedir. Yüksek voltajlı güç kabloları, dijital zamana dayalı PD sinyallerini kaydetmek için laboratuvarda test edilir. Önerilen teknikle deneysel olarak ölçülen PD verileri 2B ve 3B grafiklere dönüştürülür. Bu kapsamda 2D ve 3D grafikler karşılaştırılmakta ve 3D grafik oluşturma süreci anlatılmaktadır. Sonuç olarak, yöntem kullanılarak elde edilen 3 boyutlu grafiklerle verilerin anlaşılması ve tanımlanması kolay hale gelmektedir.

Anahtar Kelimeler: Kısmi deşarj, 3D analiz, Yüksek gerilim, Güç kablosu, Grafik modelleme.

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1. Introduction

Partial discharges in high voltage equipment are crucial methods to detect and identify defects and deterioration that can make equipment operational. Gas-filled cavities in dielectrics contribute to their defects. Stress causes a non-uniform electric field that causes condensation, micro-channels, afforestation, and thus complete deterioration. Cavities cannot always be avoided due to manufacturing processes or during service, so their harmful effects must be investigated to protect the insulation of high voltage equipment (Negm et al., 2016). These crucial methods have become a necessity with increasing voltage levels and energy demand today (Yiğit et al., 2021).

Although there are many methods of obtaining partial discharge measurements, the common aim of these methods is to show partial discharge signals without noises in a particular or general region. Detectability of these instant signals, which usually appears at 50-60 Hz as a general standard, is subject of the measurement tools and methods, but we currently need extra software and probes to make it clear for people interested in partiality discharges (Schwarz et al., 2005).

Detection of PD is the first step of data acquisition, analysis, and imaging processes. Appropriately, this first step contains much information about the faults. With these traces, academics and engineers can more precisely analyze the faults and identify the problem (Kania et al., 2007).

PRPD displays the PD movements of the object in the test system over a specified period for each pulse, using the phase of PD occurrences and the load magnitude (Farahani et al., 2005). The phase axis consists of one complete cycle of the applied voltage, while the PD charge magnitude axis forms the detected magnitude range. PD data within a certain number of applied voltage cycles are plotted on the x-axis of a voltage cycle. Thus, a PRPD model shows PD occurrences in a given phase of the applied voltage with a given load magnitude within a given number of applied voltage cycles (Forssén, 2008; Fruth & Niemeyer, 1992).

This paper proposes an improved and practical method using a multi-paradigm numerical computing programming language, with no need for expensive methods and tools. High voltage power cables are tested in the laboratory to record digital time-based PD signals. The experimentally measured PD data are converted into 2D and 3D graphics with the proposed technique. A band-pass filter and Wavelet de-noising technique are applied to the raw PD data. After the filtering and de-noising process, PD signals are scaled due to the raw PD's amplitudes. Novel 3D graphics are obtained in Matlab software according to the processed PD signals. Comparisons and results are presented in the last sections.

2. Material and Method

2.1. Partial Discharge Data

The power cables used in this study are cross-linked polyethylene cables (XLPE). Their specifications are 50 mm² in cross-section and 36 kV medium voltage. They are illustrated in Figure 1, have been tested at various intervals due to defects occurring in the insulation. Different tests have been carried out at various voltage levels and various points to observe the data easily. The data obtained in this study were carried out at the level of approximately 8 kV, and the peak values obtained are indeed partial discharge signals.

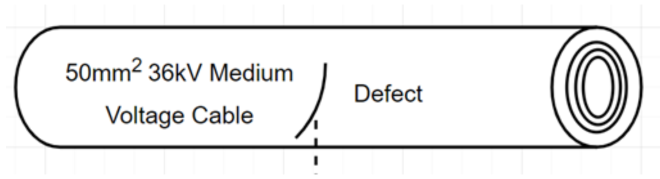

Figure 1. Model of insulation defect and XLPE cable

In this study, partial discharge measurement is practiced on the artificially damaged XLPE cables in the high voltage laboratory of Afyon Kocatepe University, Electrical Engineering Department. High voltage equipment is isolated from the oscilloscope and humans using the faraday cage. Also, other equipment is not close to high voltages during all experiments to ignore noises and keep safe. The PD data are recorded via PicoScope 5204 8-bit 2-ch 250MHz oscilloscope 128MS.

AC high voltages at 50 Hz frequency, the test voltage, are filtered with the coupling capacitor. In this way, only partial discharge signals of higher frequency and much lower voltages can be observed. Transformer and coupling capacitor are connected with XLPE cable prepared as an example (Quizhpi-Cuesta et al., 2017). Defects are formed into these cables. There is a partial discharge measuring device and a digital oscilloscope and data logger connected to the computer.

Measurements are performed according to IEC 60270 standard. In Figure 2, the partial discharge testing circuit of the laboratory is illustrated.

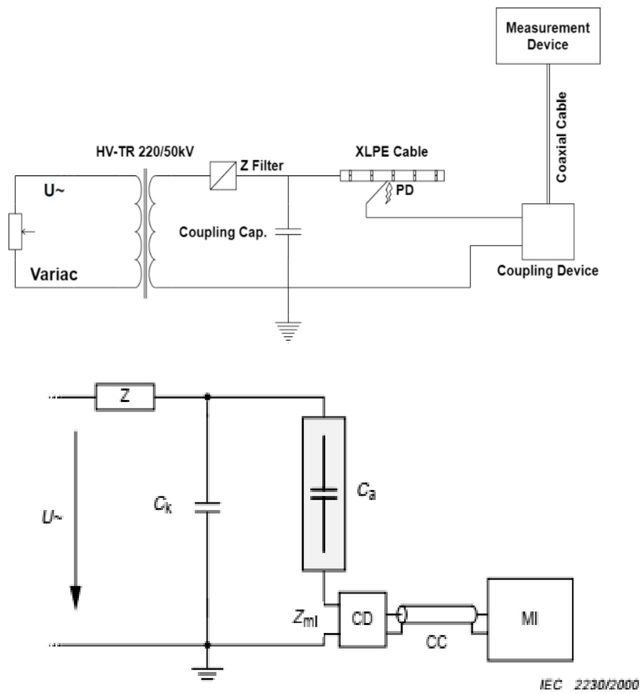

Figure 2. Circuit diagrams of the PD test system

2.2. Proposed Method

Although conventional and standard PD monitoring systems provide sufficient data, the end-user is challenging to understand because they represent a single graph and two-axis planes. Although the whole of the processes suggested in this study seems to be challenging, today's computer systems can process this big data to the desired extent thanks to the developing processing and graphics power.

Transferring PD data from one source to another and displaying it is both a tedious and slow process. This process, which is more suitable for instant viewing, cannot show the data wholly or partially. Moreover, these monitoring methods are separate and independent processes; also, an observer needs to follow them.

The main difference and advantage of the suggested method are that it shows all processes with a single process and creates the graphs in the same process. In addition, it can process data obtained from different sources without additional processing because filters and other operations are suitable for each data. This compatibility has been tested with other data sets.

2.2.1. Converting Data

The text file containing the partial discharge signals obtained from the oscilloscope appears columns and rows as format tab-delimited in Table 1. In this study, each sinus wave cycle contains 9964 pieces of discharge magnitude data and 9964 pieces of sinus voltage data. In addition, various data sets and methods measured at different voltage levels are available on the internet.

Table 1. Measured PD signals from two channels

Time (ms)	Channel A (V)	Channel B (V)
-0.00523531	-0.06299213	-0.01574803
-0.00322731	-0.07874016	-0.01574803
-0.00121931	-0.07874016	0.00000000
0.00078869	-0.06299213	0.00000000
0.00279669	-0.06299213	0.00000000
0.00480469	-0.06299213	0.00000000
…	…	…

The recorded original PD data is illustrated in 3. The maximum points of the signal show PD pulses are seen.

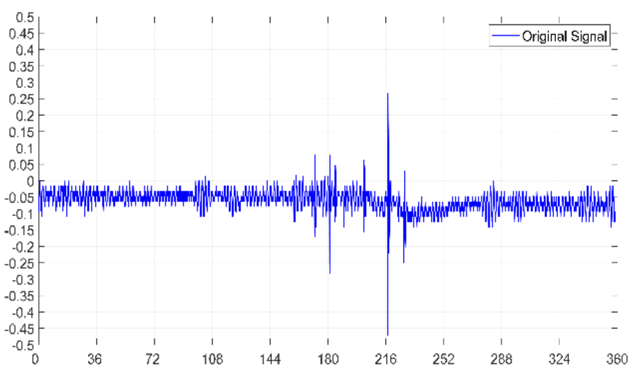

Figure 3. Original PD signal.

2.2.2. Filtering and Scaling PD Data

The basic concept behind analyzing partial discharge is to filter the signals. In this sense, it is essential to distinguish essential information from the phenomenon of partial discharge (Fruth & Niemeyer, 1992; Macedo et al., 2012). Following each step, partial discharge signals that represent the essential signals solely became evident. In addition, losses from filters have been re-gained by using simple basic mathematical equations to scale the data. The general approach, the way, and formulas can be seen in the Flowchart given in Figure 4.

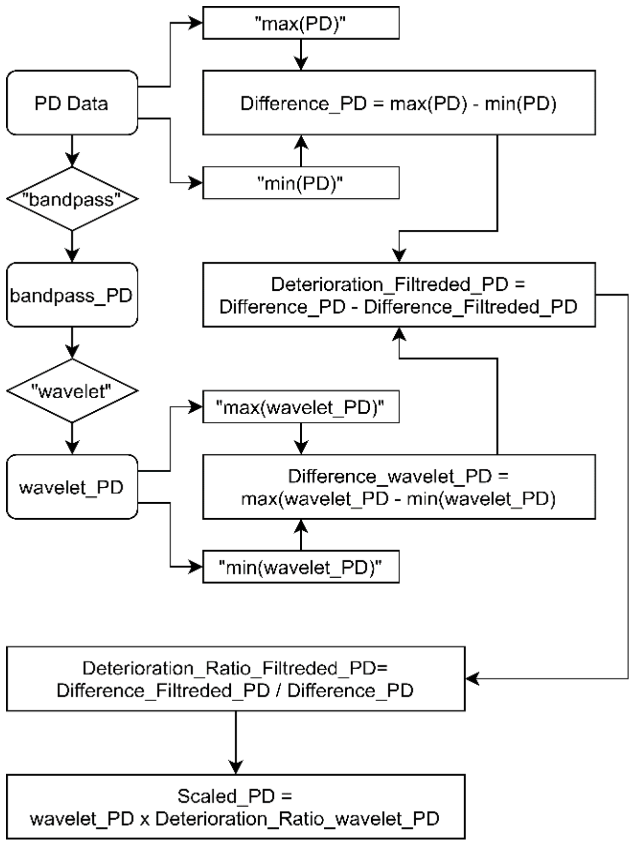

Figure 4. Flowchart of the proposed algorithm

The band-pass filter is recommended to filter low-frequency data to eliminate noise that has its own frequency. After this process, the filtered signal can be seen in Figure 5.

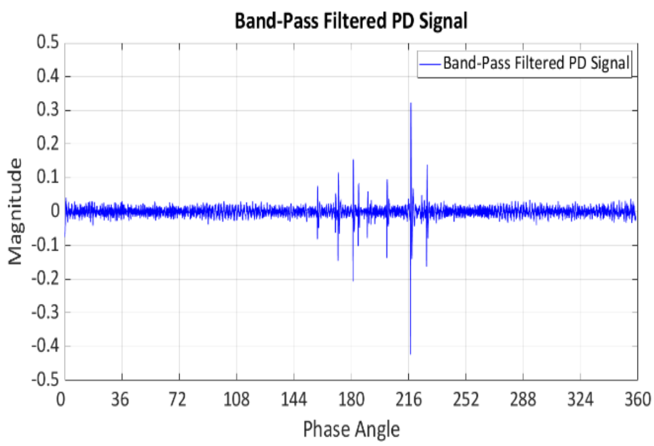

Figure 5. Bandpass filtered PD signal

2.2.3. Wavelet De-noising Technique

Wavelet is a small wave whose energy focus over time and is a tool for analyzing transient and unstable signals or signals that change over time. Fourier analyses are splitting a signal into sine waves of different frequencies, and wavelet analysis divides a signal into a shifted and scaled type of the main wavelets (Satish & Nazneen, 2003).

Many noise sources can directly affect the partial discharge forecast. Among many mathematical techniques applied to noise reduction partial discharge signals, the wavelet transform, considered an alternative to the Fourier transform, is one of the most powerful.

Wavelet transform is a relatively new concept, but it is one of the most popular time-frequency transformations (Todorova & Parvanova, 2017). While the Fourier transform expands the signals in terms of infinitely expanded sinuses and cosines, wavelet transform methods use distinct ripples that concentrate their energy over time or in space, generally an excessively enlarged point (Fan et al., 2012; Macedo et al., 2012). In addition, the wavelet method was applied after the band-pass filter, and as clearly seen, essential partial discharge signals were separated from the noises. However, before applying this filter, the wavelet function in MATLAB should be used with appropriate settings. These settings should be evaluated according to the signal output state and should be reviewed at each application. The settings applied in this study are given in Table 2 and are specific to this study only.

Table 2.Wavelet De-noiser settings

Wavelet De-noising Rule	Rule Value
Wavelet	coif1
Level	10
Denoising Method	FDR
Q-value	0.1
Threshold Rule	Hard
Noise	Level Dependent

2.2.4. Scaling Process

After all the filters, the scaling process is necessary to minimize gains and losses due to filters' nature. Also, these losses and gains are not caused by electrical components for the process studied in this paper. It is more about solver and iteration method using MATLAB. Scaled PD signals are shown in Figure 6. After this scaling, the amplitudes of the partial discharge signals remain the same, preventing possible data loss. The amplitude changes can be interpreted and corrected using various simple methods, and they can be interpreted and corrected using a variety of simple methods, including simple mathematical equations. The minimum and maximum values of the partial discharge data obtained from the transformations are given in Table 3, and the resulting deterioration values are given in Table 4.

Table 3. Maximum and minimum values

	Max. Value	Min. Value	Difference
Sample PD	0.2677	-0.4724	0.7401
Band-Pass	0.3223	-0.4235	0.7459
Wavelet	0.3396	-0.4265	0.7661

Table 4. Deterioration values

	Sample PD	Band-Pass	Wavelet
Sample PD	-	-	0.006
Band-Pass	0.01	%0.78	-
Wavelet	0.03	%3.51	0.02

In order to obtain scaled PD signals, the wavelet signal multiplied with percentage ratio should be added to the wavelet signal, as seen in (1).

$$\text{Scaled}_{\text{PD}} = \text{Wavelet}_{\text{PD}} + (\text{Wavelet}_{\text{PD}} * \%3.5047) \quad (1)$$

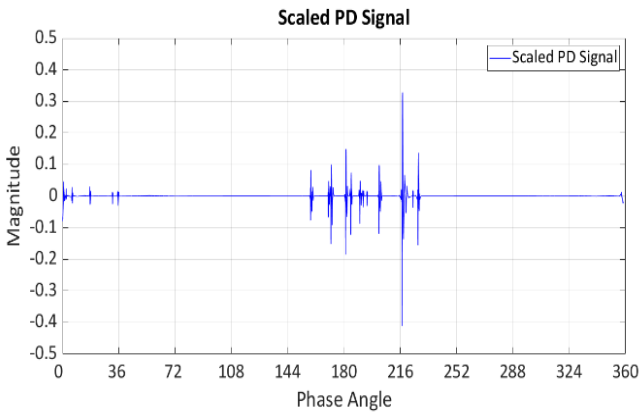

Figure 6. Scaled partial discharge signal.

2.3. Analysis of Potential Errors

This study uses a variety of evaluation criteria and deviation methods to analyze the final signal and raw data. Deliberately extracted PD signal can be seen in Figure 8. The primary approach is that if partial discharge data is deliberately extracted in Figure 7, the final scaled data can show accurate partial discharge signals. Visual representation of the errors is expected to be as in Figure 8. The firstly raw partial discharge signal and the final partial discharge signal are compared in each deviation method to apply this approach. Typically used evaluation criteria are based on errors as the following.

The Root Mean Square Error (RMSE) is given by (2).

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{N}(y_i-\bar{y})^2}{N}} = \sqrt{\frac{\sigma^2}{N}} \quad (2)$$

The Pearson Correlation Coefficient (PCC) is given by (3).

$$r_{xy} = \frac{\sum_{i=1}^{N}(x_i-\bar{x})(y_i-\bar{y})}{\sqrt{\sum_{i=1}^{N}(x_i-\bar{x})^2 \sum_{i=1}^{N}(y_i-\bar{y})^2}} \quad (3)$$

The Mean Absolute Error (MAE) is given by (4).

$$\text{MAE} = \frac{\sum_{i=1}^{N}|y_i-\bar{y}|}{N} \quad (4)$$

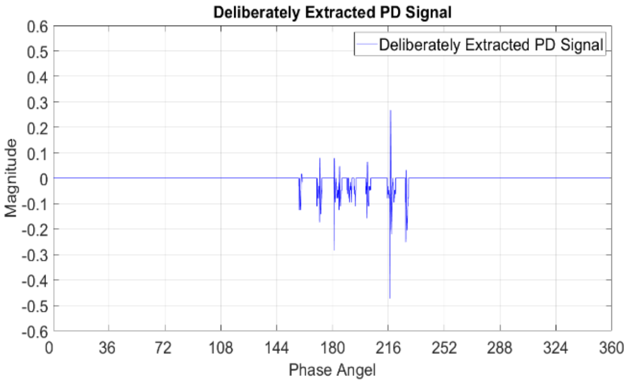

Figure 7. Deliberately extracted PD signal

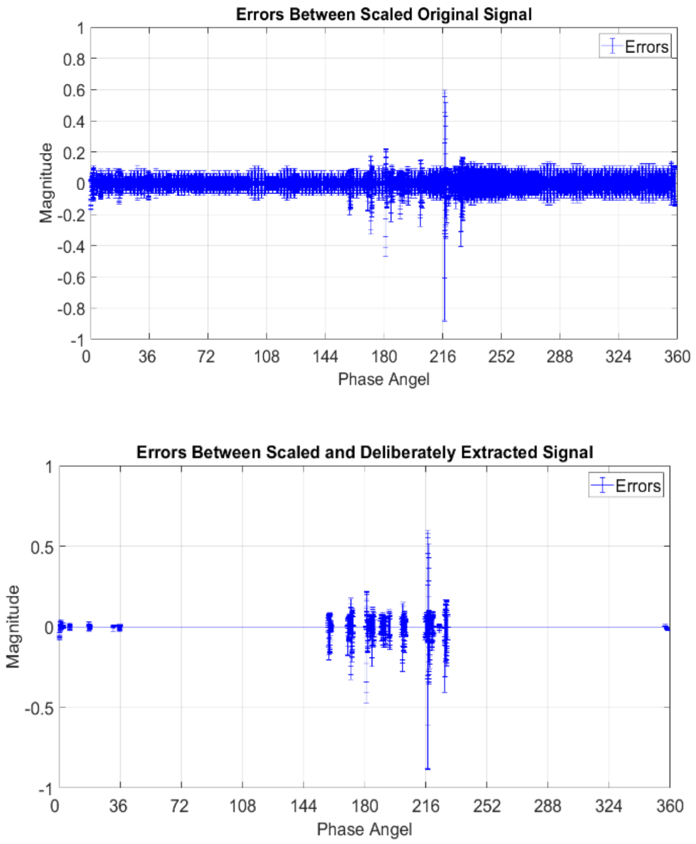

Figure 8.Comparison between "Errors Between Scaled Original Signal" and "Errors Between Scaled and Deliberately Extracted Signal".

3. Results and Discussion

The results obtained after the error analysis are shown in Table 3, Table 4 and Table 5.. The irrelevant reference signal is a different signal with the same data length. All error analysis gives the expected result and proves the accuracy of the final output. Instead of performing these analyzes one by one in each phase, they can be analyzed automatically with the help of MATLAB codes. Other methods and approaches can be increased to improve the analysis, and various analyses used in forecasting can also be preferred for control purposes(Franses, 2016; Qian et al., 2006).

Table 5.The Root Mean Square Error (RMSE) results

Parameter	Parameter	Error(%)
Raw PD Signal	Scaled	0.0669
Test PD Signal	Scaled	0.0174
Scaled	Scaled	0
Ref. irrelevant signal	Scaled	0.9452

Table 6. The Pearson Correlation Coefficient (PCC) results

Parameter	Parameter	Coefficient
Raw PD Signal	Scaled	0.5143
Test PD Signal	Scaled	0.0649
Scaled	Scaled	1.0000
Ref. irrelevant signal	Scaled	0.0000

Table 7.The Root Mean Square Error (RMSE) result table

Parameter	Parameter	Error(%)
Raw PD Signal	Scaled	0.0609
Test PD Signal	Scaled	0.0046
Scaled	Scaled	0
Ref. irrelevant signal	Scaled	0.8493

3.1. Obtaining 3D Graphics

MATLAB allows creating charts and making various adjustments to these charts. Thanks to that visual skill, 3-D graphics can be made desired with codes (Ferreira & Fantuzzi, 2020).

In this study, for 3D graphics, color maps and color bars are required to define values or areas showing partial discharge signals. MATLAB enables this with "colormap" and "color bar" codes. "colorbar" displays a vertical color bar to the right of the current axes or chart. Colorbars display the current colormap and indicate the mapping of data values into the colormap.

The most delicate part of adjusting the color bar is choosing the right spot that matches the white area of the white color map and the minimum values of the partial discharge signals. This process can now be applied to the signal whose average was reduced to 0 in the previous stages. For this reason, using "set(gca, 'CLim', [min max]);" and "zlim([min max])" codes are essential after plotting codes also these min and max values' magnitudes have to be the same such as "-0.5 and 0.5". MATLAB has several 3D drawings codes and methods for creating 3D graphics, but "surf" and "mesh" are more suitable for this study. The "all_final_scaled_signals" matrix must be the (examples)x9964 matrix. Finally, the final 3D graphic is visible in Figure 9.

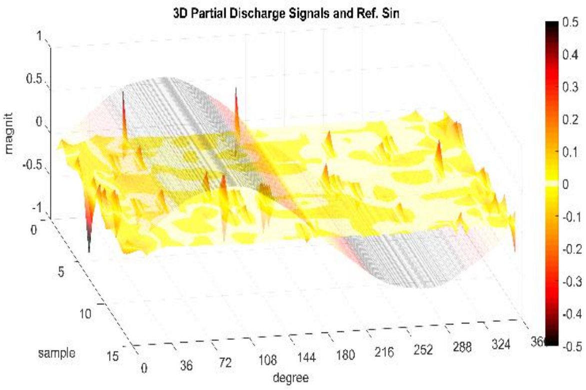

Figure 9. PD 3D graph

Partial discharge analysis is a crucial issue in high voltage electrical systems. Before a complete discharge, a partial discharge level should be determined, and precautions should be taken. In this paper, an experimental PD testing on the power cables is realized, and a basic PD graphic obtainer is developed according to the measured PD signals. Cross-linked polyethylene cables are selected as samples. However, any high voltage equipment may be selected as well. PD signals show similarities, and the analysis methods are analogous.

Due to the processor limits to achieve these results, all de-noising methods may seem like long processes, but filtering and processing partial discharge does not have to be instant measurements. With the correct understanding of these limitations, partial discharges can be measured, filtered, and graphed without the need for expensive measuring tools. In addition, this data can be reprocessed freely, and different results can be obtained without using external programs and methods. This 3D graphic, similar to PRPD, is obvious compared to 2D graphics in legibility and clarity.

4. Conclusions and Recommendations

It can be mentioned that they can benefit from the 3-dimensional evaluation to be reviewed in terms of reviewing the two objects to be made from the partial usage areas. In addition, more efficient results of the datasets were obtained by applying the target for the use of the datasets.

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