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Identification of Partial Discharge Defect Detection in Cast-Resin Power Transformers Using Back-Propagation Algorithm

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Abstract

This paper presents a method used to identify partial discharge defects in cast-resin power transformers using a back-propagation algorithm. The Rogowski-type partial discharge (PD) sensor was designed with a planar and thin structure based on a printed circuit board to detect PD signals. PD electrode systems, such as metal protrusions, particle-on-insulators, delamination, and void defects, were fabricated to simulate the PD defects that occur in service. PD characteristics, such as rising time, falling time, pulse width, skewness, and kurtosis without phase-resolved partial discharge patterns, were extracted to intuitively analyze each PD pulse according to the type of PD defect. A backpropagation algorithm was designed to identify PD defects using a virtual instrument (VI) based on the LabVIEW program. The results show that the accuracy rate of back-propagation (BP) algorithm reaches over 92.75% in identifying four types of PD defects.

Index Terms: Defect identification, Back-propagation algorithm, Partial discharge, Cast-resin power transformers

I. INTRODUCTION

Cast resin power transformers are the most important equipment used in power facilities to improve the stability of electrical power systems. The epoxy resin used in power transformers has numerous advantages such as self-extinguishing characteristics, low-cost installation, and low maintenance. Therefore, cast-resin power transformers are widely used in distribution systems. However, partial discharge (PD) occurs when the insulation deteriorates. Although the magnitude of such a discharge is typically small in its early stage, it can progressively deteriorate insulating materials, resulting in insulation breakdown [1-4]. Most insulation deterioration in cast-resin power transformers is initiated by the PD. Therefore, the detection of PD signals is crucial in preventing insulation failure accidents.

Various PD detection methods, such as coupling capacitors, ultra-high frequency (UHF) sensors, and acoustic emission (AE) sensors, have been used to detect PD signals. A coupling capacitor is connected directly to a power transformer and can detect relatively low-level PD pulses, which can be calibrated in picocoulombs, as specified in IEC 60270 [5]. However, it is necessary to have a high insulation strength at high voltage levels, and it is not possible to locate a PD source. A UHF sensor offers high sensitivity in the high-frequency range, and enables the precise location of the PD source. However, a UHF sensor is relatively expensive compared with other sensors and cannot be calibrated in picocoulombs. Although an AE sensor is sensitive to external noise, it is easy to carry and install [6-9].

Identification of PD defects is crucial for maintaining the lifespan of power transformers. PD diagnosis techniques for defect identification are divided into single-pulse analysis in the time and frequency domains and phase-resolved partial discharge (PRPD) analysis. The diagnostic method for a single pulse intuitively interprets a single PD signal using the rising time, falling time, pulse width, skewness, kurtosis, and

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frequency components. The method offers easy, quick and cost-effective measurement and analysis, without requiring expert decisions. However, it is difficult to analyze complex PD signals that are vulnerable to noise effects. The PRPD diagnosis method is widely used to identify the types of PD defects using pulse magnitude, pulse count, and phase angle. The PRPD method offers high accuracy and reliability. However, the PRPD method is considerably expensive for measuring devices and software and requires expert decision-making to identify PD defects [10-11]. Artificial neural networks (ANNs) have been used to overcome these challenges and improve the accuracy of PD detection and analysis.

This paper presents a method used to identify PD defects in cast-resin power transformers using a backpropagation algorithm. To overcome the limitations of conventional PD sensors, a Rogowski-type sensor [12-13] was designed with a planar and thin structure based on a printed circuit board (PCB) to detect PD signals. PD electrode systems with metal protrusions, particles on insulators, delamination, and void defects were fabricated to simulate the PD defects that occur in service. PD characteristics, such as rising time, falling time, pulse width, skewness, kurtosis, and frequency components without PRPD patterns, were extracted to intuitively analyze each PD pulse according to the type of PD defect. A backpropagation algorithm was designed to identify PD defects using a virtual instrument (VI) based on the LabVIEW program.

II. EXPERIMENTAL METHOD

A PD activity occurs at an early stage and is an indicator of insulation breakdown because it is produced by various insulation defects inside the power transformer in service before the insulation breakdown occurs. Therefore, it is important to detect PD signals before a transformer fails. Fig. 1 shows the PD electrode systems used to simulate defects such as metal protrusions, particle-on-insulator, delamination, and void defects occurring inside the cast-resin power transformer. A metal protrusion consists of needle electrode with a curvature radius of 10 μm and a plane electrode of tungsten-copper alloy with a diameter of 80 mm and thickness of 20 mm. The particle-on-insulator was composed of a particle with a diameter of 2 mm, an insulator with a diameter of 80 mm, and a thickness of 10 mm. A delamination specimen was fabricated by a stack of thin dielectric film with a thickness of 200 μm inserted between high-voltage plane electrode and epoxy plate. A void specimen with a diameter of 4 mm was fabricated by injecting air into a cylindrical aluminum frame using a syringe during the epoxy curing process. The edges of the electrodes were rounded to prevent concentration of the electric field.

To replace expensive commercial PD sensors used in cast-resin power transformers, a Rogowski-type PD sensor was fabricated to detect PD signals in PD electrode systems, as shown in Table 1. The Rogowski-type PD sensor was designed with planar and thin structures on a PCB owing to excellent qualities such its high sensitivity, low manufacturing cost,

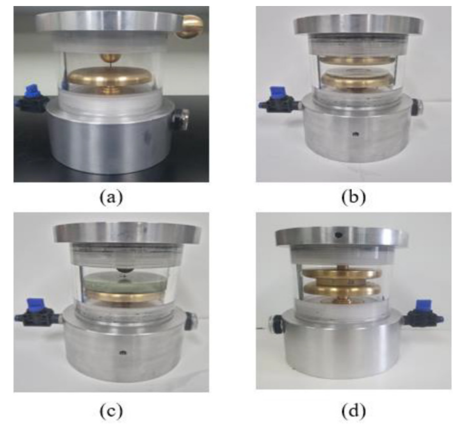

Fig. 1. PD electrode systems

Table 1. Geometrical parameters

Geometrical parameters	Values
Number of turns	20 turns
Width of conductor line	2 mm
Distance between conductors	1 mm
Size of PCB (W×H)	120 mm×80 mm
Thickness of PCB	1.6 mm

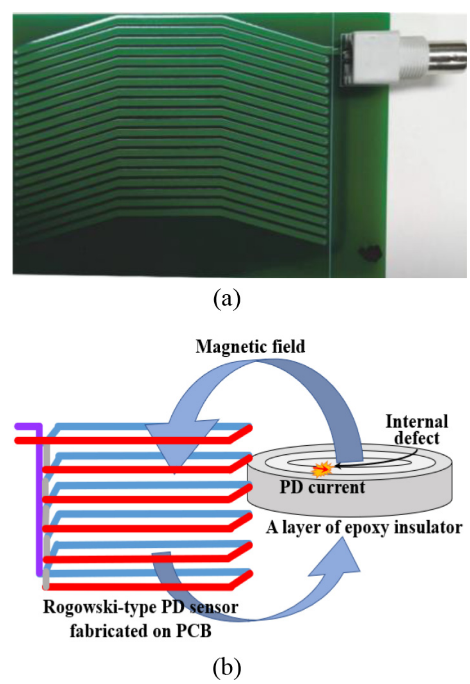

Fig. 2. Rogowski-type PD sensor

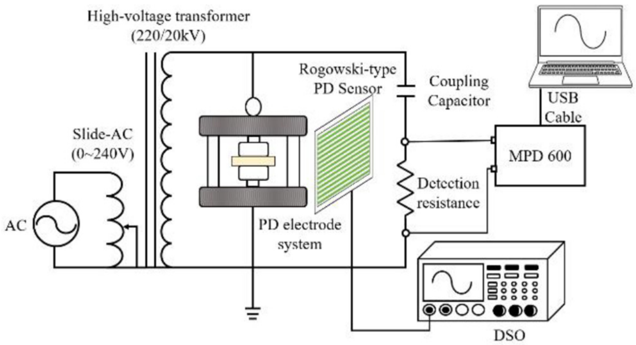

Fig. 3. Experimental configuration

and good linearity, as shown in Fig. 2. It consists of an air core and a coil. According to Ampere's law, a magnetic field is formed around a PD current flowing inside a defect when a PD occurs. According to Faraday's law [14], an induced voltage is generated in the coils of a Rogowski-type PD sensor owing to the magnetic flux linkage. Moreover, the Rogowski-type PD sensor could detect a magnetic field with a high-frequency PD current [15-16].

Fig. 3 shows the experimental setup used in this study. An oil-immersed transformer was used to apply high voltage with a maximum output of 20 kV and a current of 100 mA. To prevent external noise, the PD electrode systems were filled with insulation gas of up to 0.5 MPa. The PD signals were measured using a coupling capacitor and measuring device (Omicron, MPD 600) to confirm the PRPD patterns for PD occurrence according to the types of PD defects specified in the IEC 60270 standard. Subsequently, a single PD signal was measured using a Rogowski-type PD sensor and recorded using an OSC with a sampling rate of 10 GS/s.

III. RESULT AND ANALYSIS

A Rogowski-type sensor was used to measure typical single pulses depending on the four types of PD defects. Parameters in the time domain, such as rising time, falling time, pulse width, skewness, and kurtosis, were extracted. The rising time is the time interval from 10 to 90% of the peak value, falling time is the time interval from 90 to 10% of the peak value, and falling time is the time interval between 50% of the peak value [16]. Skewness measures the asymmetry of a probability distribution. Positive skewness values indicated that the distribution was skewed to the right, whereas negative skewness values indicated that the distribution was skewed to the left. A symmetrical distribution indicates a skewness of zero. The kurtosis measures the steepness of a probability distribution. A normal distribution indicates a kurtosis of 3. A kurtosis value higher than 3 indicates a steep distribution, whereas kurtosis values lower than 3 indicate an even distribution [17]. Parameters in the frequency domain, such as the first and second maximum frequencies, were extracted.

Table 2. Parameters in time domain

Parameters in time domain	Metal Protrusion	Particle	Delamination	Void
Rising time [ns]	1.49	6.63	32.85	6.70
Falling time [ns]	0.89	15.00	15.88	13.83
Pulse width [ns]	1.19	10.82	24.37	10.27
Kurtosis	-0.8971	0.3702	-0.9597	-1.2219
Skewness	-0.7423	-0.6969	0.2657	-0.1532

Table 3. Parameters in frequency domain

Parameters in frequency domain	Metal Protrusion	Particle	Delamination	Void
1^{st} peak [MHz]	40	30	30	30
2^{nd} peak [MHz]	580	890	240	220

Each single PD pulse was recorded at discharge inception voltage of 120%, considering voltage regulation ratio in service. Summaries of the measured parameters in the time and frequency domains, which are the average values extracted from 20 pulses for each case, are listed in Tables 2 and 3, respectively. For metal protrusion defects, the PD pulses were shorter than those of other defects. The results showed that the PD pulses of the particles on the insulator defects had the longest rising time, falling time, and pulse width. Each PD pulse has a different shape. For skewness and kurtosis, the PD pulse distributions of all defects were skewed to the right side, and the pulses of the particles on the insulator had a steeper distribution than those of other defects. Examples of the single pulses and frequency spectra are shown in Figs. 4 and 5, respectively.

The ANN is composed of connected nodes, called artificial neurons, organized into seven layers, two hidden layers with each 10 nodes, and four output layers, as shown in Fig. 6. The input layer receives the data and passes them to the output layer through the hidden layers. The hidden layers are the intermediary stages responsible for learning the intricate structures in the data and creating neural networks between the input and output layers. During data processing, the features were extracted using nonlinear transforms in the hidden layer. In the output layer, a linear combination of output weights was based on the output of the problem [18].

In the ANN, PD defects were identified by the back propagation (BP) based on the LabVIEW program in Fig. 7. The BP algorithm enables the adjustment of weights and biases through data training as a supervised learning method. It includes the forward propagation of the input data and back-propagation of errors between the actual and desired outputs. The seven parameters extracted from single PD pulses in the

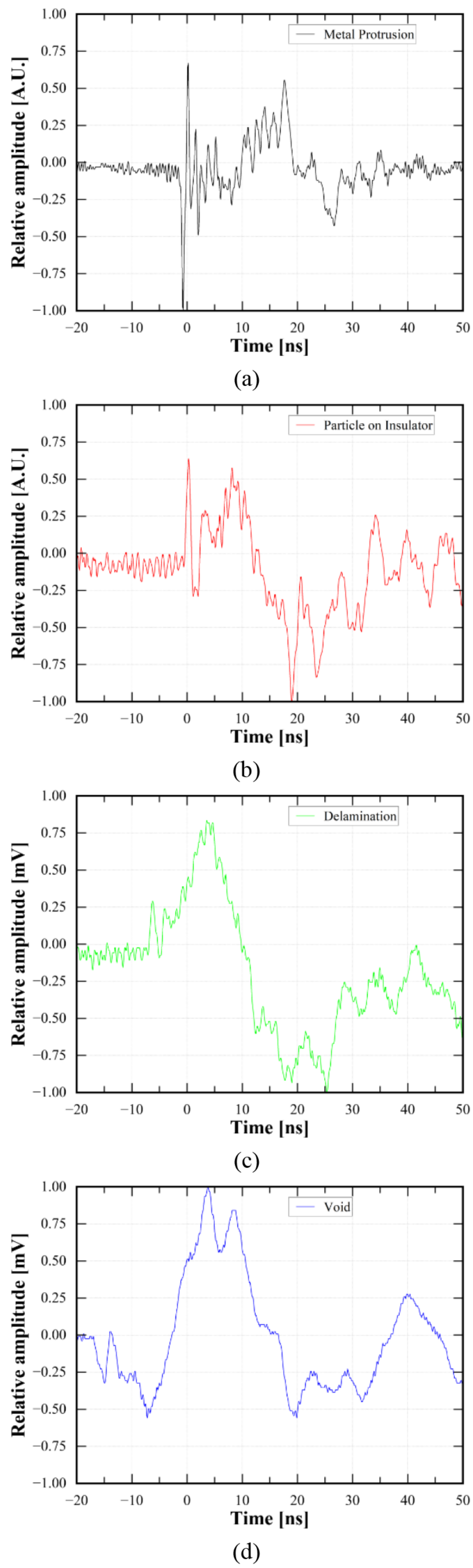

Fig. 4. Typical single PD pulses according to types of defects

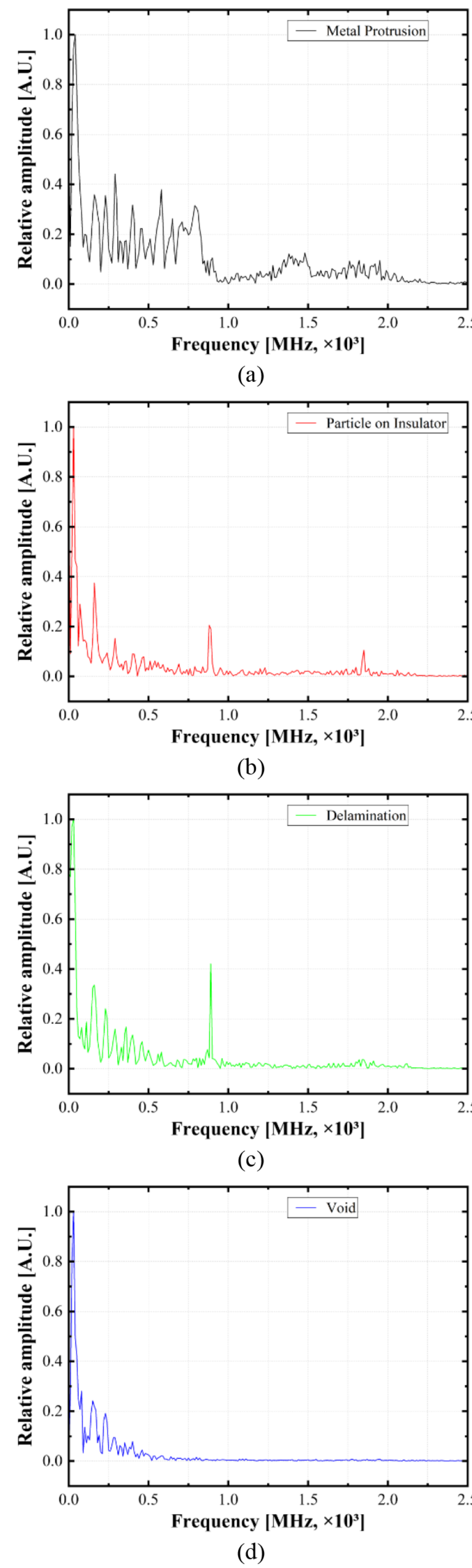

Fig. 5. Frequency spectrum of PD single pulses

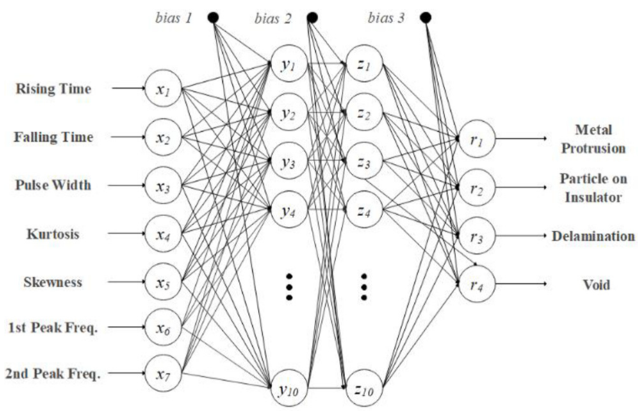

Fig. 6. Structure of the artificial neural network

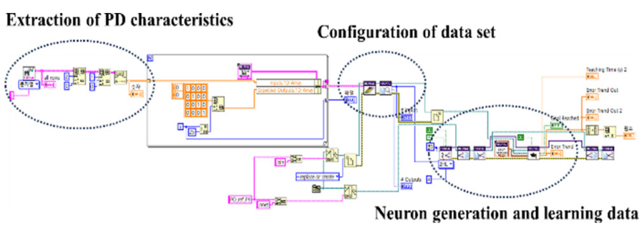

Fig. 7. Back propagation algorithm

Table 4. Accuracy of identification of PD defects

PD defects	Identification [%]			
	Metal protrusion	Particle on insulator	Delamination	Void
Metal protrusion	96	1	0	3
Particle on insulator	1	99	0	0
Delamination	0	1	90	9
Void	0	0	14	86

time and frequency domains were learned 25 times in the input layer. Depending on the learning results, the output value was derived and compared with the target value of one. The differences between the output and target values were calculated and the BP algorithm operated continuously until the output value approached the target value [19-20]. The learning rate was 0.1 for 786 epochs, the learning rate reaches an error mean square of 0.0621. The results show that the BP algorithm has over 92.75% accuracy rate in identifying four types of PD defects in Table 4.

IV. DISCUSSION AND CONCLUSIONS

This paper describes a method used to identify partial discharge defects in cast-resin power transformers using a back-propagation algorithm. The Rogowski-type PD sensor was designed with a planar and thin structure based on a PCB to detect PD signals and replace conventional PD sensors. PD electrode systems, such as metal protrusions, particle-on-insulators, delamination, and void defects, were fabricated to simulate the PD defects that occur in cast-resin power transformers. PD characteristics, such as rising time, falling time, pulse width, skewness, and kurtosis without PRPD patterns, were extracted to intuitively analyze each PD pulse according to the type of PD defect. A BP algorithm based on an ANN was designed to identify PD defects using the LabVIEW program. From the results, it was confirmed that the accuracy rate of the proposed BP algorithm has over 92.75% to identify four types of PD defects. In the future, additional types of PD defects, such as cracks and particles on insulators, should be investigated.

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REFERENCES

[1] S. J. Park, S. C. Hwang, G. Wang, and G. S. Kil, “Partial discharge characteristics and localization of void defects in XLPE cable,” *Journal of the Koran Society for Railway*, vol. 20, no. 2, pp. 203-209, Apr. 2017. DOI: 10.7782/JKSR.2017.20.2.203.

[2] M. K. Chen, J. M. Chen, and C. Y. Cheng, “Partial discharge detection in 11.4 kV cast resin power transformer,” *IEEE Transaction on Dielectrics and Electrical Insulation*, vol. 23, no. 4, pp. 2223-2231, Aug. 2016. DOI: 10.1109/TDEI.2016.7556498.

[3] M. Erdogan and M. K. Eker, “A comparative analysis of partial discharge in 13 combined insulation structures of 11 materials used in cast-resin dry-type transformers,” *IEEE Transaction on Dielectrics and Electrical Insulation*, vol. 29, no. 6, pp. 2330-2339, Sep. 2022. DOI: 10.1109/TDEI.2022.3205285.

[4] B. A. de Castro, V. V. dos Santos, G. B. Lucas, J. A. Ardila-Rey, R. R. Riehl and A. L. Andreoli, “A comparative analysis applied to the partial discharges identification in dry-type transformers by hall and acoustic emission sensor,” *Sensors*, vol. 22, no. 5, pp. 1716, Feb. 2022. DOI: 10.3390/s22051716.

[5] International Electrotechnical Commission 60270, “High-voltage test techniques-partial discharge measurements,” Geneva, Switzerland, 2015.

[6] H. D. Ilkhechi, and M. H. Samimi, “Applications of the acoustic method in partial discharge measurement: A review,” *IEEE Transaction on Dielectrics and Electrical Insulation*, vol. 28, no. 1, pp. 42-51, Feb. 2021. DOI: 10.1109/TDEI.2020.008985.

[7] P. Wenger, M. Beltle, S. Tenbohlen, U. Riechert, and G. Behrmann, “Combined characterization of free-moving particles in HVDC-GIS using UHF PD, high speed imaging and pulse-sequence analysis,” *IEEE Transactions on Power Delivery*, Vol. 34, no. 4, pp. 1540-1548, Aug. 2019. DOI: 10.1109/TPWRD.2019.2909830.

[8] A. Darwish, G. coapes, S. S. Refaat, H. Abu-Rub, and H. A. Toliyat, “PD Signal Attenuation in 550-kV GIS: Impact of different barriers on the propagation of electromagnetic waves,” *IEEE Transactions on Instrumentation and Measurement*, Vol. 70, Nov. 2021. DOI:

10.1109/TIM.2021.3126400.
[9] M. Ariannik, M. A. Azirani, P. Werle, and A. A. Azirani, "UHF measurement in power transformers: an algorithm to optimize accuracy of arrival time detection and PD localization," *IEEE Transactions on Power Delivery*, Vol. 34, no. 6, pp. 1530-1539, Aug. 2019. DOI: 10.1109/TPWRD.2019.2909706.
[10] S. J. Kim, H. E. Jo, G. W, Jeong, G. S. Kil, and S. W. Kim, "Analysis on PD Pulse Distribution by Defects Depending on SF6 Pressure," *Journal of the Korea Institute of Electrical and electronic Material Engineering,* Vol. 28, no. 1, pp. 40-45, Jan. 2015. DOI: 10.4313/JKEM.2015.28.1.40.
[11] M. S. Kim, S. J. Kim, G. W. Jeong, H. E. Jo, and G. S. Kil, "Characteristics of partial discharge under HVDC in SF6 gas," *Journal of the Korea Institute of Electrical and electronic Material Engineering*, Vol. 27, no. 4, pp. 238-243, Apr. 2014. DOI: 10.4313/JKEM.2014.27.4.238.
[12] S. Sharifinia, M. Allahbakhshi, T. Ghanbari, A. Akbari, and H. R. Mirzaei, "A new application of rogowski coil sensor for partial discharge localization in power transformers," *IEEE Sensors Journal*, Vol. 21, no. 9, pp. 10743-10751, May 2021. DOI: 10.1109/JSEN.2021.3062770.
[13] M. H. Samimi, A. Mahari, M. A. Farahnakian, H. Mohseni, "The Rogowski coil principles and applications: A review," *IEEE Sensors Journal*, vol. 15, no. 2, pp. 651-658, Feb. 2015. DOI: 10.1109/JSEN.2014.2362940.
[14] U. J. Kim, M. S. Song, and R. Y. Kim, "PCB-based current sensor design for sensing switch current of a nonmodular GaN power semiconductor," *Energies*, vol. 13, no. 19, pp. 5161, Oct. 2020. DOI: 10.3390/ en13195161.
[15] M. Shafiq, K. Kauhaniemi, G. Robles, M. Isa, and L. Kumpulainen, "Online condition monitoring of MV cable feeders using Rogowski coil sensors for PD measurements," *Electric Power Systems Research*, Vol. 167, pp. 150-162, Feb. 2019. DOI: 10.1016/j.epsr.2018.10.038.
[16] G. Wang, W. H. Kim, G. S. Kil, S. W. Kim, and J. R. Jung, "Green gas for grid as an eco-friendly alternative insulation gas to SF6: From the Perspective of Partial Discharge under AC," *Applied Sciences*, vol. 9, no. 4, pp.651, Feb. 2019. DOI: 10.3390/app9040651.
[17] H. H. Sinaga, B. T. Phung, and T.R. Blackburn, "Recognition of single and multiple partial discharge sources in transformers based on ultra-high frequency signals," *IET Generation, Transmission & Distribution*, Vol. 8, no. 1, pp. 160–169, Jan. 2014. DOI: 10.1049/iet-gtd.2013.0131.
[18] W. Y. Chang, "Partial discharge pattern recognition of cast resin current transformers using radial basis function neural network," *Journal of Electrical Engineering and Technology*, vol. 9, no. 1, pp. 293-300, Jan. 2014. DOI: 10.5370/JEET.2014.9.1.293.
[19] M. N. Danikas, N. Gao, and M. Aro, "Partial discharge recognition using neural network: A review," *Electrical Engineering*, vol. 85, pp. 87-93, May 2003. DOI: 10.1007/s00202-002-0151-5.
[20] N. Hozumi, T. Okamoto, and T. Imajo, "Discrimination of partial discharge patterns using neural network," *IEEE Transaction on Dielectrics and Electrical Insulation*, vol. 27, no. 3, pp. 550-556, Jun. 1992. DOI: 10.1109/14.142718.

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