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Self-Organizing Map Performance for Partial Discharge Classification

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Abstract

This research work presents a statistical partial discharge (PD) classification model employing Self Organizing Map (SOM) technique. The developed model classified PD patterns into 5 categories which were corona at high voltage side in air, corona at low voltage side in air, corona at high voltage side in mineral oil, corona at low voltage side in mineral oil and surface discharge in mineral oil. PD signals were simulated and measured by the conventional PD measurement technique. Statistical parameters of the PD patterns were analyzed. SOM model was constructed. Then, 60% of the experimented data were used as a training data and the rest of 40% of the data were used as a testing data to evaluate the performance of SOM PD classification model. It was found that the developed SOM model has clearly clustered the test data correctly into five groups of PD patterns.

Keywords: statistical classification, statistical parameter, partial discharge pattern, self-organizing map

1. Introduction

Partial discharge (PD) is an important problem existing normally in high voltage equipment. PD may develop and lead to the failure of high voltage apparatus eventually. Therefore, performing the PD testing is important to detect problems before the failure of such equipment occurring [1-2].

The measured PD patterns from the experiment can be used to classify the problems of the high voltage equipment; however, it is quite difficult to analyze the patterns especially by a nonexperienced staff. This research work simulated five PD types generally occurring in high voltage equipment which comprised of corona discharge at high voltage side in air (HV-A), corona discharge at low voltage side in air (LV-A), corona discharge at high voltage side in mineral oil (HV-O), corona discharge at low voltage side in mineral oil (LV-O) and surface discharge in mineral oil (SF-O). These simulated PD models were experimented and the Self Organizing Map (SOM) technique was applied to categorize the PD types.

2. Theory

2.1 PD measurement

Partial discharge test circuit is shown in Fig.1 according to IEC 60270 [3]. The discharge activity can be measured in pC or μV. The PD level in pC or μV and PD patterns are very important information to evaluate the insulation characteristic of a high voltage component. Then, some measures may be employed when the defective insulation is found.

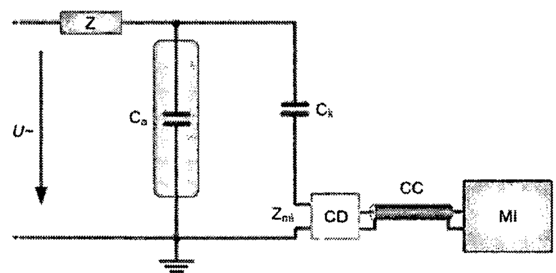


Fig.1. PD Measurement [3]

Where: U~ : high-voltage supply, Z : filter, C_a : test object, C_k : coupling capacitor, Z_{mi}: input impedance of measuring system, CD : coupling device, CC : connecting cable, and MI : measuring instrument

2.2 Partial Discharge Quantity

Partial discharge quantity obtained from PD signals can be divided into three main groups, basic quantities, derived PD quantities, and phase amplitude-related derived quantities [4]. The original statistic variables used in this classification model are skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor following the $\Phi - q - n$ PD patterns. Those independent variables are listed as follow. $H_{qn}(\Phi)$ is the mean pulse height distribution. $H_n(\Phi)$ is pulse count distribution, $Q = (Q^-_s/N^-)/(Q^+_s/N^+)$ is the discharge asymmetry of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$ where Q^+_s and Q^-_s are the sums of pulse height distributions of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$, CC is the cross correlation factor of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$, $mcc = \Phi Q.CC$ which is the modified cross-correlation factor. In this work, Φ is determined as 1.

Each of the factors of $Hqn(\Phi)$ and $Hn(\Phi)$ is also separated into four variables in Sk^+ for the skewness for the positive voltage side, Sk^- for the skewness for the negative voltage side, Ku^+ for the kurtosis for the positive voltage side, and Ku^- for the kurtosis for the negative voltage side.

2.3 Architecture of self-organizing map

SOM is a typical unsupervised neural network, which maps the multidimensional space onto a two dimensional space, preserving the original order [5]. Architecture of SOM is illustrated in Fig.2. For input and the SOM layer, the distance between the input vector p and the weight vector w of all neurons in the grid is computed with the *dict* function which can be calculated as below [6]:

$$\sum_{k=1}^{n}(p_{i,k} - w_{j,k}(t))^2 \qquad (1)$$

A wining neuron is determined by the competitive transfer function. The weight vector of the winner including the weight vectors of its neighboring neurons is adjusted in accordance with some learning rate as:

$$w_j(t+1) = w_j(t) + \eta(t)(p_i - w_j(t)) \qquad (2)$$

Where p is the input vector, w is the weight vector, and η is the learning rate. Then, the final output can be interpreted. After enough number of iterations, each input vector is mapped onto a certain neuron in the Kohonen network in the way that the weight vector of the neuron is closer to the input vector.

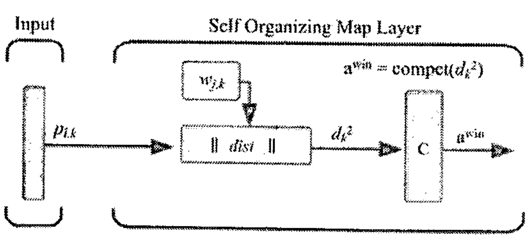


Fig.2. Architecture of self-organizing map

3. Experimentation

3.1 PD Models

The PD models for simulating five different PD patterns which are HV-A, LV-A, HV-O, LV-O and SF-O are illustrated in Fig.3 (a) – (e) respectively. Fig.3 (a), (b), (c) and (d) show a needle with tip radius of 10μm and plane electrode with diameter of 50mm in air and mineral oil to create corona at high voltage and low voltage side respectively. Fig.4 (e) illustrates the needle positioned on the impregnated pressboard employing to simulate the surface discharge.

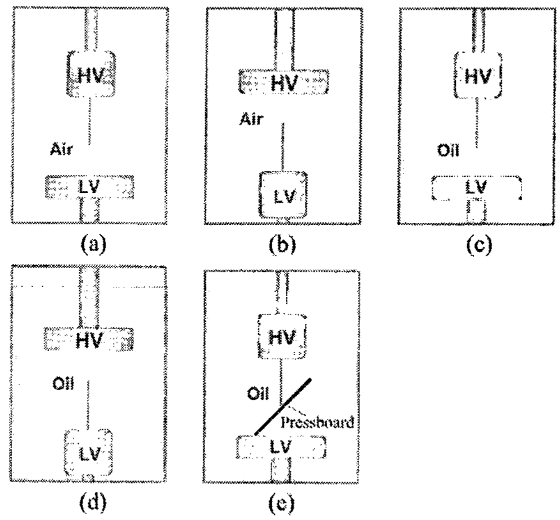


Fig.3. Artificial partial discharge model

3.2 PD Measurement System

The experiments were performed in High Voltage Laboratory, faculty of engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand. A test circuit diagram and the test circuit arrangement for PD activity investigation was set up according to IEC 60270 as shown in Fig.4 – 5 respectively. The measurement system comprises high-Voltage supply, coupling capacitor, coupling device, test object, fiber optical cable and PC with mtronix software.

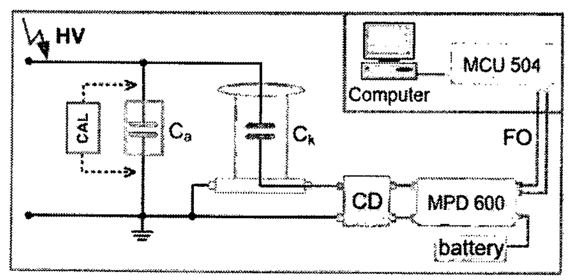


Fig.4. Test circuit diagram for the experiment

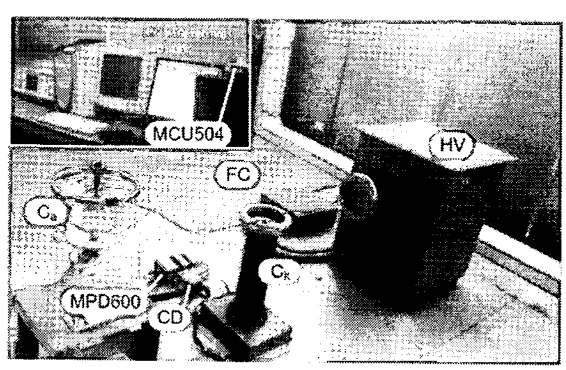


Fig.5. Test circuit set-up

Where HV: High-Voltage supply 75 kV, C_a: Test vessel, C_k: Coupling capacitor 1 nF, CD: Coupling device, FO: Fiber optics cable, MPD600: Acquisition unit, MCU504: Fiber optic controller

At first, the PD model was set up in the test circuit. Then, the background noise was measured. After that, the ac voltage was applied to the PD model until the inception voltage could be detected and then the test voltage was increased at the 120% of the PD inception voltage in order to obviously observe the PD signals and finally recording the PD pattern. The experiment was performed with all PD models which generated 100 experiments in total.

3.3 Test Results

The examples of the PD patterns of type of PD obtained from the conventional PD measuring system are illustrated in Fig. 6 – 10 respectively.

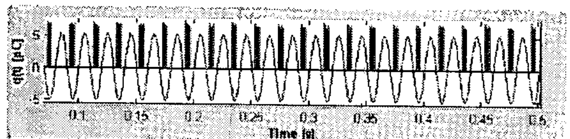


Fig.6. PD pattern for corona at HV side in air

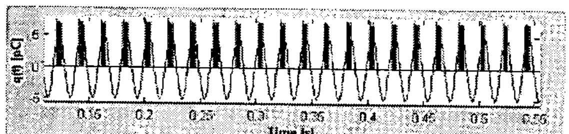


Fig.7. PD pattern for corona at LV side in air

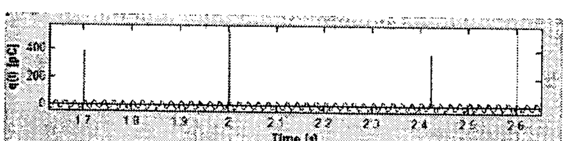


Fig.8. PD pattern for corona at HV side in mineral oil

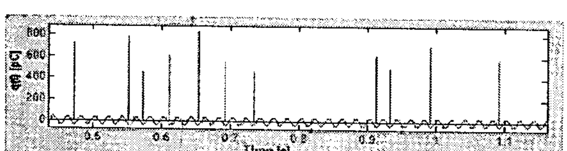


Fig.9. PD pattern for corona at LV side in mineral oil

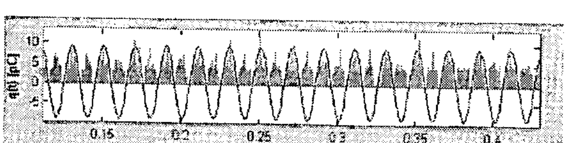


Fig.10. PD pattern for surface in mineral oil

3.4 Feature extraction

To extract the characteristic of the PD signals, the statistical parameters of the PD signals, skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor were calculated from the developed program. Diagram of calculated PD parameter of SF-O is depicted in Fig.11. Examples of a data set of the statistic parameters of each PD type are shown in Table I.

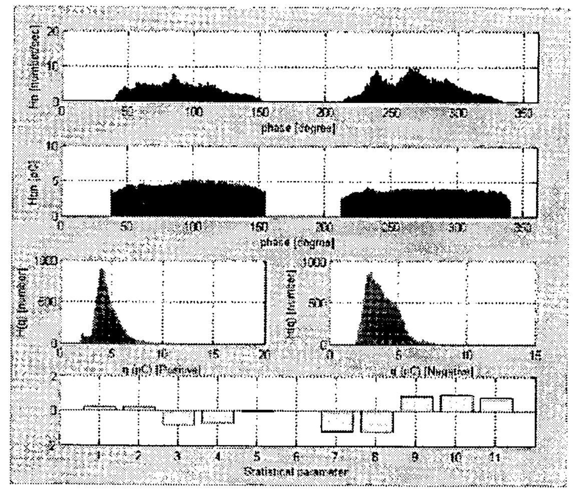


Fig.11. Example of $H_n(\Phi)$, $H_{qn}(\Phi)$, H(q) and statistical parameters of surface discharge in mineral oil

TABLE I

Examples of statistic parameters of PD experiment

PD type	Hn(phase)				Hqn(phase)				Q	cc	mcc
	Sk+	Sk-	Ku+	Ku-	Sk+	Sk-	Ku+	Ku-			
HV-A	0	0.05	0	-0.86	0	0.01	0	-1.22	0	0	0
LV-A	0.13	0	-0.89	0	0	0	-1.22	0	0	0	0
HV-O	0.3	0.11	-0.83	0.45	0.06	0.07	-0.57	-0.86	0.02	0.65	0.01
LV-O	0.02	0.27	-0.74	-0.21	0.01	0.01	-1.15	-0.61	82.57	0.68	55.8
SF-O	0.22	0.21	-0.81	-0.71	-0.05	-0.01	-1.14	-1.16	0.84	0.92	0.78

4. Self-Organizing Map

4.1 Data Preparation

The self-organizing map was used in this research. The original data from 11 variables were normalized to set their average values and variance to be 0 and 1 respectively and then plotted the 11 variables against on another to select the variables that distinguish the PD pattern. 3 independent statistical variables, kurtosis of $H_n(\Phi)$ at positive cycle, kurtosis of $H_n(\Phi)$ at negative cycle, kurtosis of $H_{qn}(\Phi)$ at negative cycle, were selected to be the input data of the designed SOM model. The 3D plot of the selected independent statistical variables for distinguishing the PD patterns as shown in Fig. 12.

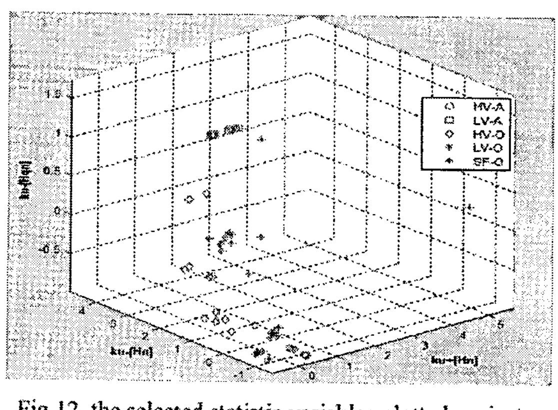


Fig.12. the selected statistic variables plotted against on another

4.2 Self-organizing map design

The SOM PD classification model was investigated with 3 input nodes as selected before. According to Yu Han and Y.H. Song, the size of Kohonen network tended to saturation of mapping error when the grid size was more than seven times of the number of the input vector *p* [7]. In this research work, the network size was determined by $4p$ with $100x4p$ iterations. The number of nodes on the mapped 2D grid was 16 output nodes. The *dist* function was applied to compute the distance between input vector and weight vector of all neurons in the grid before they were input to competitive transfer function node to find the wining neuron, the PD classification model architectures investigated in this research are shown in Fig.13. For training process, 60% from experimented data was used as a training data for SOM model, the rest data of 40% was employed for testing the model. The venetian blinds technique was used for setting the data for training and testing the models. The training and testing flowchart of SOM is depicted in Fig. 14 with 1600 iterations. After the completion of the training process, the SOM can divide PD patterns into 5 groups as shown in Fig. 15. Then, the weight values were saved in the designed PD classification models.

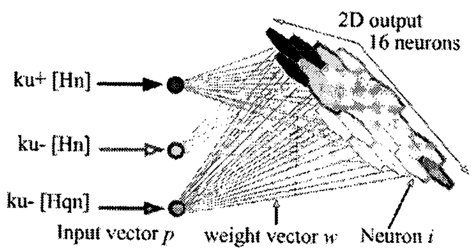


Fig.13. System structure of SOM

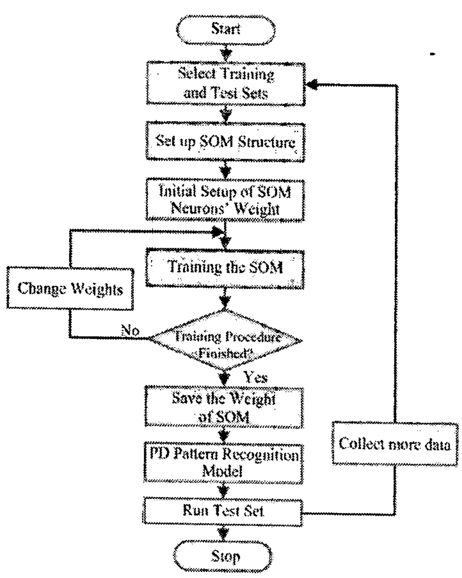
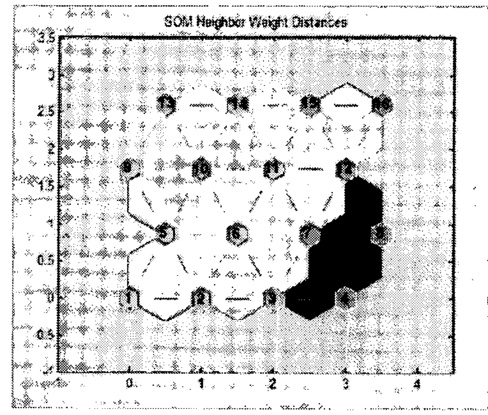
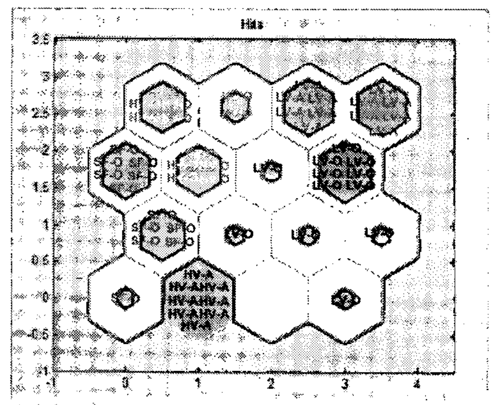


Fig.14. Self-organizing map training flow chart



(a) SOM neighbor weight distances



(b) SOM sample hits

Fig.15. Results from SOM training process

4.3 Test results

The performance of the SOM for PD classification is illustrated in Fig.16.

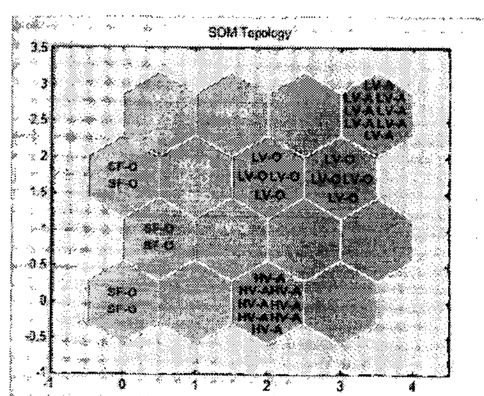


Fig.16. Classification results of test data

5. Conclusion

In this document, the statistic parameters were extracted the characteristic of the original PD signals from the developed program. 3 independent statistical variables, kurtosis of $H_n(\Phi)$ at positive cycle, kurtosis of $H_n(\Phi)$ at negative cycle, kurtosis of $H_{qn}(\Phi)$ at negative cycle, were selected to be the input data of the designed SOM model. The designed SOM model was used to classify PD patterns into five categories listed as corona at high voltage side in air, corona at low voltage side in air, corona at high voltage side in mineral oil, corona at low voltage side in mineral oil and surface discharge in mineral oil. It was found that the developed SOM model has clearly clustered the test data correctly into five groups of PD patterns.

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Generalized Regression Networks for Partial Discharge Classification

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Abstract — This document represents a partial discharge (PD) classification by using Generalized Regression Networks (GRNN) model. Two PD classification models, GRNN1 with 11 input variables and GRNN2 with 3 selected derived statistic parameters, were investigated for classification of PD signals into 5 patterns, corona at high voltage side in air, corona at low voltage side in air, corona at high voltage side in mineral oil, corona at low voltage side in mineral oil and surface discharge in mineral oil. The conventional PD measurement was performed for measuring PD signals of the artificial PD models. The statistical parameters of the PD signals such as skewness, kurtosis, asymmetry, cross correlation and so on were calculated from the developed computer program. Then, 60% of the experimented data was used as a training data for the developed PD classification models. Another 40% experimented data was used to evaluate the performance of the designed PD classification models. It was found that the GRNN1 model can classify PD patterns better than GRNN2 model. The accuracy for PD classification of GRNN1 model was 100% while the accuracy of GRNN2 model was 97.5% of 40 testing data.

Keywords: partial discharge measurement, statistical classification, statistical parameter, partial discharge pattern, generalized regression neural network

I. Introduction

Partial discharge (PD) is one of a crucial problem of high voltage equipment. PD occurring in the equipment can propagate and may cause the failure of high voltage apparatus eventually. Therefore, to detect PD especially at the partial discharge inception voltage level can schedule an appropriate maintenance program of such equipment to lengthen the life time of the equipment and also reduce the maintenance cost. According to the mentioned reasons, PD testing is commonly performed with a new and in serviced high voltage equipment. Various techniques that can be applied to determine the presence of PD activity are as follows [1]:

Electrical technique: PD charges from PD pulse currents can be measured according to IEC60270,
Antenna technique: The electromagnetic wave generated by PD can be detected with an antenna,
Acoustic technique: The pressure wave emitted from the PD phenomena can be detected with an acoustic sensor,
Thermograph technique: The emitted light from the PD phenomena can be detected with a streak camera,
Chemical technique: By products from PD activity can be detected by DGA method.

II. Theory

A. PD measurement

The basic equivalent circuit for PD measurements based on the detection of PD pulse current $i(t)$ circulating in the parallel-connected capacitors, C_k (coupling capacitor) and C_t (test object capacitance), via measuring impedence Z_m is shown in Fig.1 [2]. The discharge activity can be measured in pC or μV. The PD level in pC or μV and PD patterns are very important information to evaluate the insulation characteristic of a high voltage component. Then, some measures may be employed when the defective insulation is found.

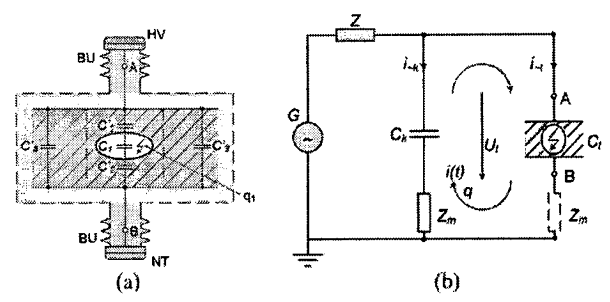

Fig.1. Equivalent circuit for PD measurement

Where: C_t: test object capacitance, C_k: coupling capacitor, G: voltage source, $i(t)$: PD pulse current, $i_{-k,-t}$: displacement currents, Z : voltage source connectors, q : transferred charge, U_t : voltage at parallel-connected capacitors, Z_m : measuring impedance

B. Partial Discharge Quantity

Partial discharge quantity obtained from PD signals can be divided into three main groups, basic quantities, derived PD quantities, and phase amplitude-related derived quantities [3]. The original statistic variables used in a designed classification model are skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor following the $\Phi - q - n$

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PD patterns. Those independent variables are listed as follow. $H_{qn}(\Phi)$ is the mean pulse height distribution. $H_n(\Phi)$ is pulse count distribution, $Q = (Q^-_s/N^-)/(Q^+_s/N^+)$ which is the discharge asymmetry of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$ where Q^+_s and Q^-_s are the sums of discharges of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$ distributions, CC is the cross correlation factor of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$, $mcc = \Phi Q.CC$ which is the modified cross-correlation factor. In this work, Φ is determined as 1. Each of the factors of $Hqn(\Phi)$ and $Hn(\Phi)$ is also divided into four variables as Sk^+, Sk^-, Ku^+, and Ku^-. Sk^+ and Sk^- are designated the skewness of the positive voltage side and the negative voltage side respectively. Ku^+ and Ku^- indicate the kurtosis of positive voltage side and negative voltage side respectively.

C. *Architecture of Generalized regression neural networks*

A generalized regression neural network (GRNN) is mostly used for function approximation and for recognizing different types of patterns. It has a radial basis layer and a special linear layer. The architecture of the GRNN is shown in Fig.2. [4]

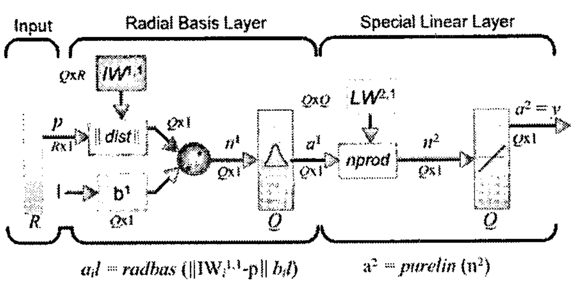


Fig. 2. Architecture of GRNN network

Where: R: no. of elements of input vector, Q: no. of input/target pairs

The radial basis layer has as many neurons as input/target vectors in $IW^{1,1}$ which is set as the weighted matrix. Each neuron's weighted input is the distance between the input vector (p) and training weight vectors, computed with the *dist* function which can be calculated as (1).

$$D = \sqrt{\sum_{i=1}^{Q} (IW_i^{1,1} - p_i)^2} \tag{1}$$

The bias b^1 is set to a column vector of 0.8326/*spread*. The different *spread* parameters were used in this research to compare the performance of the designed models. Each neuron's net input is the product of its weighted input with its bias, calculated with *netprod* function. Each neuron's output is its net input passed through *radbas* function which can be calculated as (2).

$$a^1 = radbas(n^1) = e^{(-n^1)^2} \tag{2}$$

The special linear layer having neurons as input/target vectors, $LW^{2,1}$ is set to create a target vector. The *nprod* box (code function of normprod) generates Q elements in vector n^2. Each element is the dot product of a row of $LW^{2,1}$ and the input vector a^1 which are normalized by the sum of the elements of a^1, then passed through *purelin* function to produce the output y of GRNN model.

III. EXPERIMENTATION

A. *PD Models*

The PD models were simulated as follows: (a) corona at high voltage side in air (HV-A) (b) corona at low voltage side in air (LV-A) (c) corona at high voltage side in mineral oil (HV-O) (d) corona at low voltage side in mineral oil (LV-O) and (e) surface discharge in mineral oil (SF-O) as illustrated in Fig.3 (a) – (e) respectively. The needle with tip radius of 10 µm and the plane electrode with diameter of 70 mm were used as the electrode of the PD models. The gap distance between high voltage and grounded electrode was set up for 25 mm. Furthermore, the impregnated pressboard with dimension of 100x100 mm and of 3.2 mm thick was utilized in case of surface discharge investigation.

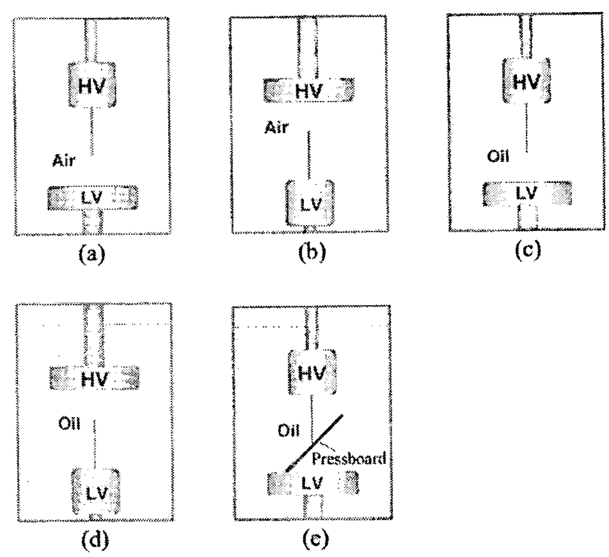


Fig. 3. Artificial partial discharge models

B. *PD Test circuit*

The experiments were performed in accordance with IEC 60270[5] in the high voltage laboratory, faculty of engineering, King Mongkut's Institute of Technology Ladkrabang, Thailand. A test circuit diagram and the test circuit arrangement for PD activity investigation are shown in Fig.4 – 5 respectively. The test circuit for PD investigation comprised high-voltage supply, coupling capacitor, coupling device, test object, fiber optical cable and PC with mtronix software.

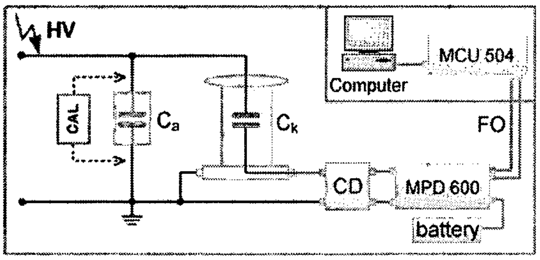


Fig. 4. Test circuit diagram for the experiment

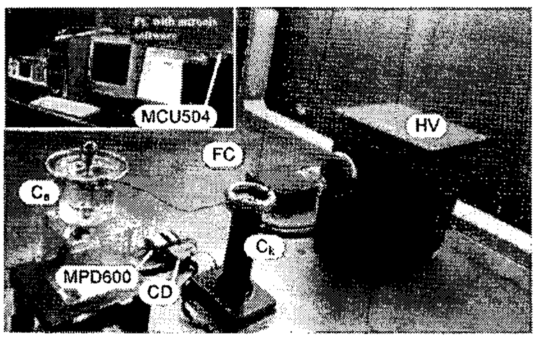


Fig. 5. Test circuit set-up

Where: HV: High-Voltage supply 75kV, C_a: Test vessel, C_k: Coupling capacitor 1nF, CD: Coupling device, FO: Fiber optics cable, MPD600: Acquisition unit, MCU504: Fiber optic controller

C. Test Procedure

At first, the test circuit was set up. Then, the background noise was measured. After that, the ac voltage was applied to the PD model until the inception voltage could be detected. The test voltage was increased at the 120% of the PD inception voltage in order to obviously observe the PD signals. These signals were recorded finally. 20 experiments of each PD were performed for each PD model.

D. Test Results

The examples of the PD patterns of each PD type are illustrated in Fig. 6 – 10 respectively.

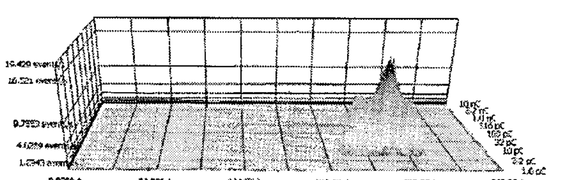


Fig. 6. PD pattern for corona discharge at HV side in air at 3.7 kV test voltage

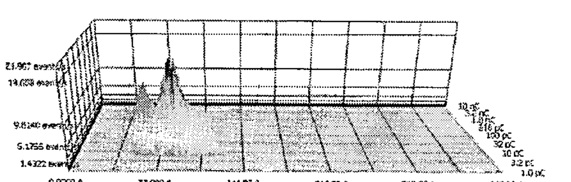


Fig. 7. PD pattern for corona discharge at LV side in air at 3.85 kV test voltage

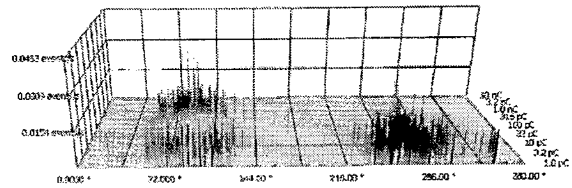


Fig. 8. PD pattern for corona discharge at HV side in mineral oil at 21.4 kV test voltage

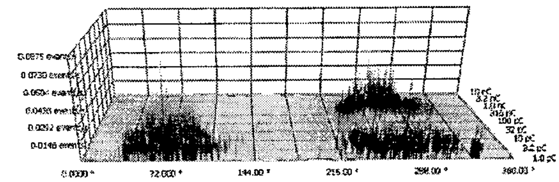


Fig. 9. PD pattern for corona discharge at LV side in mineral oil at 26.1 kV test voltage

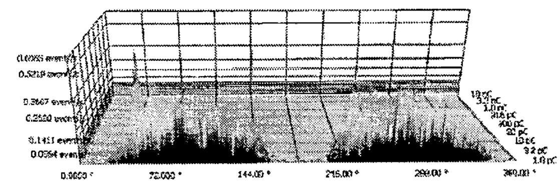


Fig. 10. PD pattern for surface discharge in mineral oil at 5.4 kV test voltage

E. Feature extraction

To extract the characteristics of the PD signals, the statistical parameters of the PD signals, skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor were calculated from the developed computer program. Diagram of calculated PD parameter of surface discharge in mineral oil is depicted in Fig.12. Examples of the data set of the statistic parameters of each PD type are shown in table I.

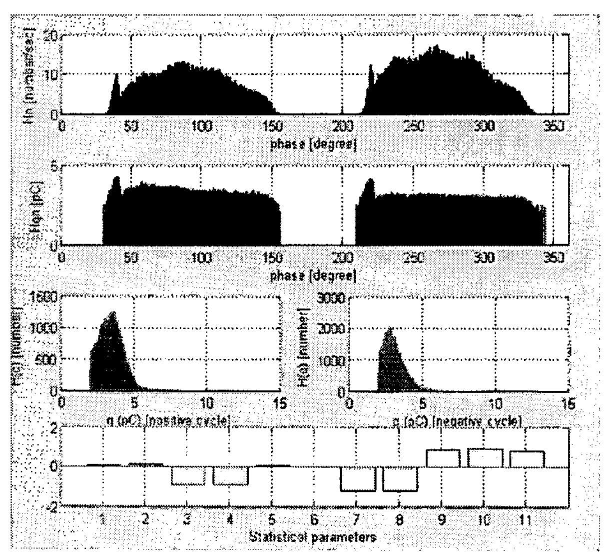


Fig. 11. Example of $H_n(\Phi)$, $H_{qn}(\Phi)$, $H(q)$ and statistical parameters of surface discharge in mineral oil

TABLE I
Examples of the statistical parameters of PD signal

PD type	Hn(phase)				Hqn(phase)				Q	cc	mcc
	$Sk+$	$Sk-$	$Ku+$	$Ku-$	$Sk+$	$Sk-$	$Ku+$	$Ku-$			
HV-A	0	0.05	0	-0.86	0	0.01	0	-1.22	0	0	0
LV-A	0.13	0	-0.6	0	0	0	-1.22	0	0	0	0
HV-O	0.3	0.11	-0.8	0.45	0.06	0.07	-0.57	-0.86	0.02	0.65	0.01
LV-O	0.02	0.27	-0.7	-0.21	0.01	0.01	-1.15	-0.61	82.5	0.68	55.8
SF-O	0.22	0.21	-0.1	-0.71	-0.05	-0.01	-1.14	-1.16	0.84	0.92	0.78

IV. GENERALIZED REGRESSION NEURAL NETWORK

A. *Input/Out Data preparation*

The original variables and selected variables were used to design the neuron models (NN) in this research. The 11 original variables extracted from feature extraction were normalized to set their average values and variance to be 0 and 1 respectively. Then these variables were used as input of the designed GRNN1 model. Furthermore, the aforementioned 11 variables were plotted against on another to select the variables that clearly distinguished between each type of the simulated PD patterns. Three variables, kurtosis of $H_n(\Phi)$ at positive cycle, kurtosis of $H_n(\Phi)$ at negative cycle, and kurtosis of $H_{qn}(\Phi)$ at negative cycle were selected to be used as the input of the designed GRNN2 model for PD classification. The 3D plot of the selected independent statistical variables for distinguishing the PD patterns as shown in Fig. 12.

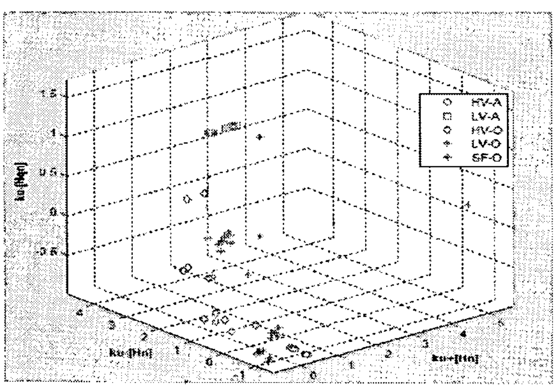


Fig. 12. the selected statistic variables plotted against on another

The set of original input data, both all variable data and selected variable data, was composed of five types of PD patterns, HV-A, LV-A, HV-O, LV-O and SF-O, each type of PD pattern contained 20 observations. The original data matrix for classification models were created as shown in (3). The output target was coded for the target vector as shown in (4).

$$X1 = \begin{bmatrix} [HV\text{-}A]_{20\times 11} \\ [LV\text{-}A]_{20\times 11} \\ [HV\text{-}O]_{20\times 11} \\ [LV\text{-}O]_{20\times 11} \\ [SF\text{-}O]_{20\times 11} \end{bmatrix}_{100\times 11} \quad X2 = \begin{bmatrix} [\text{selected } HV\text{-}A]_{20\times 3} \\ [\text{selected } LV\text{-}A]_{20\times 3} \\ [\text{selected } HV\text{-}O]_{20\times 3} \\ [\text{selected } LV\text{-}O]_{20\times 3} \\ [\text{selected } SF\text{-}O]_{20\times 3} \end{bmatrix}_{100\times 3} \tag{3}$$

$$Y = [1\ 2\ 3\ 4\ 5]^T \tag{4}$$

Where:
X1 is the entire variable data matrix.
X2 is the selected variable data matrix.
Y is the target vector 1 for HV-A, 2 for LV-A, 3 for HV-O, 4 for LV-O, and 5 for SF-O.

B. *Generalized regression neural network design*

The Generalized regression neural network, or GRNN, was utilized in this research. Two GRNN models, GRNN1 and GRNN2, were investigated. The first proposed GRNN architecture (GRNN1) used 11 derived statistical parameters as the input nodes. The second proposed GRNN architecture (GRNN2) utilized three selected statistical parameters as the input node as explained before. Both models had two layers, the radial basis layer with 60 neuron's weight vector and the special linear layer with 60 neuron's weight vector with the output node. Moreover, the *round ( )* function was used to make the integral number code outputs for the test sets.

C. *Training and Testing Data Set Selection*

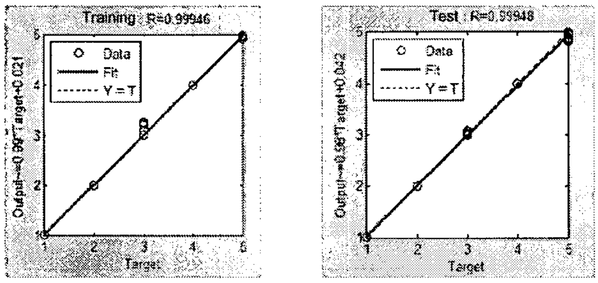
To train and test the designed PD classification models, the variable data matrix (X1, X2) was divided into two subsets. The first subset was the training set, which was used for computing the distance in radial basis layer and normalized dot product in special linear layer. The second subset was the test set. The test set was not used during training, but it was used to verify the performance of the designed models. The block method was used to divide all the data with 60% into training set and the rest of 40% for testing set. The designed model was trained with different spread parameter, 0.2, 0.4, 0.6, 0.8, 1.0 and 1.2 in the radial basis layer.

V. PD CLASSIFICATION RESULTS

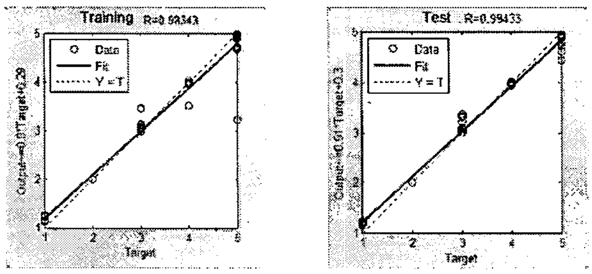
The training and testing result is illustrated in Table II. It was found that the optimal spread parameter of GRNN1 and GRNN2 model were 0.8 and 0.4 respectively. The linear regression between the network outputs and the corresponding targets is represents in Fig.13 - 14 respectively. It is clearly observed that the designed GRNN1 model provides better the PD classification property than the designed GRNN2 model especially when the spread parameter value are higher than their optimal values.

TABLE II
The training and testing results of GRNN1 and GRNN2

spread parameter	GRNN1		GRNN2	
	% Classification	R-value	% Classification	R-value
Training results				
0.2	100	1.0	100	0.999
0.4	100	1.0	100	0.983
0.6	100	1.0	67	0.956
0.8	100	0.999	33	0.911
1.0	96	0.996	28	0.861
1.2	95	0.991	14	0.813
Testing results				
0.2	92.5	0.873	97.5	0.949
0.4	97.5	0.949	97.5	0.994
0.6	100	0.999	60	0.956
0.8	100	0.999	50	0.898
1.0	100	0.997	52.5	0.854
1.2	100	0.993	22.5	0.827



(a) (b)
Fig.13. Linear regression between the GRNN1 network outputs and the corresponding targets at the spread parameter of 0.8



(a) (b)
Fig.14. Linear regression between the GRNN2 network outputs and the corresponding targets at the spread value of 0.4

The performance of the proposed PD classification models is illustrated in Table III.

TABLE III
Confusion table for proposed models

GRNN1 model with 0.8 spread parameter							
		%Predicted Group					Total
		HV-A	LV-A	HV-O	LV-O	SF	
PD Type	HV-A	8					100
	LV-A		8				100
	HV-O			8			100
	LV-O				8		100
	SF-O					8	100
Total		100	100	100	100	100	100
GRNN2 model with 0.4 spread parameter							
		%Predicted Group					Total
		HV-A	LV-A	HV-O	LV-O	SF	
PD Type	HV-A	8					100
	LV-A		8				100
	HV-O			8			100
	LV-O				8		100
	SF-O				1	7	87.5
Total		100	100	100	100	87.5	97.5

VI. CONCLUSION

In this document, the statistic parameters of the PD signals were extracted by using the developed program. Two PD classification models, GRNN1 and GRNN2, were constructed and investigated. All the original variables were used to be the input data of the GRNN1 while the three selected variables were used as the input data of the GRNN2 model. Both designed GRNN models were applied to classify PD patterns into five categories listed as corona at high voltage side in air, corona at low voltage side in air, corona at high voltage side in mineral oil, corona at low voltage side in mineral oil and surface discharge in mineral oil. It was found that the designed GRNN1 model have a better PD classification compared with the designed GRNN2 model. The accuracy for PD classification of GRNN1 model was 100% while the accuracy of GRNN2 model was 97.5% of the 40 testing data.

VII. ACKNOWLEDGMENT

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Partial Discharge Classification using Probabilistic Neural Network Model

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Abstract— The aim of this paper is to propose the probabilistic neural network (PNN) model for classification partial discharge (PD) patterns, which comprised of corona discharge at high voltage side and at low voltage side in air, corona discharge at high voltage side and at low voltage side in mineral oil and surface discharge in mineral oil. Partial discharge signals were investigated by conventional method according to IEC60270. Independent parameters such as skewness, kurtosis, asymmetry, and cross correlation of the Φ-q-n PD patterns were analyzed. The PNN PD classification model was constructed. Moreover, the principal component analysis (PCA) was utilized to reduce the input dimension of the developed PD classification model. After that, 60% of the experimented data was used as a training data for the PD classification models. Another 40% experimented data was used for evaluation the performance of the designed PD classification models. Effects of spread parameters and input neuron numbers on the PD classification performance were examined. It was found that the first four score variable was appropriate to be used to construct the designed PNN model with the optimal spread value of 1.2. The proposed PD classification model can classify PD types with the accuracy of 100% of 40 tested data.

Keywords: partial discharge measurement, statistical classification, statistical parameter, partial discharge pattern, probabilistic neural network

I. Introduction

Partial discharge (PD) is a localized electrical discharge occuring in the insulation system without completely bridging the electrodes. PD occurring in high voltage apparatus gradually deteriorates the integrity of the insulation system which may lead to the failure of high voltage equipment at the end. The consequence may cause the injury of people, damaging of eqipment, power shortage and so on. Hence, PD testing is very important to indicate the incipient fault in high voltage equipment before they fail [1]. Classification of PD patterns is a highly-skill task needed to perform by an expertise. Simple PD patterns generally could be classified by an experienced staff. However, the combination or PD patterns may occur in pratice. This paper proposes the PD patterns classification model employing probabilistic neural network (PNN) technique. The PD signals were created from the PD models experimented by employing the conventional PD measurement according to IEC60270 [2]. Five types of PD models, corona discharge at high voltage side in air (HV-A), corona discharge at low voltage side in air (LV-A), corona discharge at high voltage side in mineral oil (HV-O), corona discharge at low voltage side in mineral oil (LV-O) and surface discharge in mineral oil (SF-O), were simulated and investigated.

II. Theory

A. PD measurement

A basic partial discharge measuring circuit is shown in Fig.1. An apparent charge (q) and other PD quantities, such as the PD inception (PDIV) and extinction voltage (PDEV), the pulse repetition rate (n), the pulse repetition frequency (N), the phase angle (Φ), the average discharge current (i) were measured to evaluate the quality of insulation of a high voltage component.

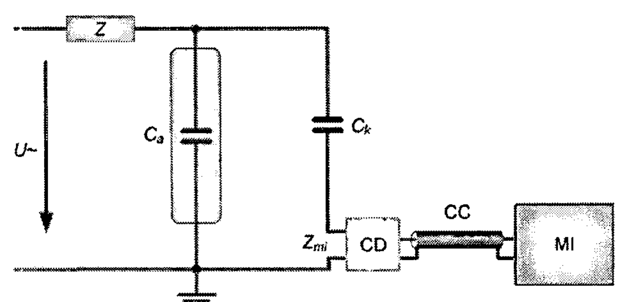

Fig. 1. PD measurement

Where: $U\sim$: high-voltage source, Z: low pass filter, C_a: test object, C_k: coupling capacitor, Z_{mi}: input impedance of measuring system, CD: coupling device, CC: connecting cable, and MI: measuring instrument

B. Partial Discharge Quantity

The PD quantity comprising of Φ, q, n and voltage V is obtained from PD measurement. The PD statistic variables composing of skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor were calculated from mean pulse height distribution, or $H_{qn}(\Phi)$ and

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pulse count distribution, or $H_n(\Phi)$ as equations in table 1 [3]. Each of the $H_{qn}(\Phi)$ and $H_n(\Phi)$ is divided into four variables which are Sk^+, Sk^-, Ku^+, and Ku^-. Sk^+ and Sk^- represent the skewness for the positive voltage side and the negative voltage side respectively, whereas Ku^+ and Ku^- stand for the kurtosis of the positive voltage side and negative voltage side respectively.

TABLE I
Statistical operators

Skewness	$Sk = \frac{E(q-\mu)^3}{\sigma^3}$
Kurtosis	$Ku = \frac{E(q-\mu)^4}{\sigma^4}$
Discharge asymmetry	$Q=(Q^-_s/N^-)/(Q^+_s/N^+)$
Cross correlation factor	$cc = \frac{\sum x_i y_i - \sum x_i \sum y_i / n}{\sqrt{[\sum x_i^2 - (\sum x_i)^2/n][\sum y_i^2 - (\sum y_i)^2/n]}}$
Modified cross-correlation factor	$mcc = Q \times cc$

Where:
q represents the mean discharge magnitude in a phase window.
μ represents the mean of q.
σ represents the standard deviation of q.
E represents the expectation operator.
Q^+_s and Q^-_s stand for the sums of discharges of $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$ distributions.
N^- and N^+ stand for the number of discharges of the $H_{qn}(\Phi^+)$ and $H_{qn}(\Phi^-)$ distributions.
x is designated for the mean discharge magnitude in a phase window in the positive half of the voltage cycle.
y is designated for the mean discharge magnitude in the congruent phase window in the negative half of the voltage cycle.
n represents the number of phase positions per half cycle.

C. Principal Component Analysis (PCA)

PCA is a statistical technique which is used for transformation a correlated variable set to a new variable set, called principal components. Each principal component is a linear combination of the original variables which are uncorrelated or orthogonal with each otheras illustrated in (1).

$$\boldsymbol{T}_{q\times s} = \boldsymbol{X}_{q\times r} \boldsymbol{P}_{r\times s} \tag{1}$$

Where: $\boldsymbol{T}$ is a new set of variables (score matrix), $\boldsymbol{X}$ is the original data matrix, $\boldsymbol{P}$ is the principal component matrix (PC coordinates), q is the number of observations, s is dimensionality of the PC space, r is dimensionality of original space

The full set of principal components is as large as the original set of variables. However, the sum of the variances of the first few principal components (s components) commonly exceeds 80% of the total variance of the original data [4].

D. Architecture of probabilistic neural network

A probabilistic neural network (PNN) was used for PD classification problems in this research. It had a radial basis layer and a competitive layer. The architecture of the PNN is shown in Fig.2. [5]

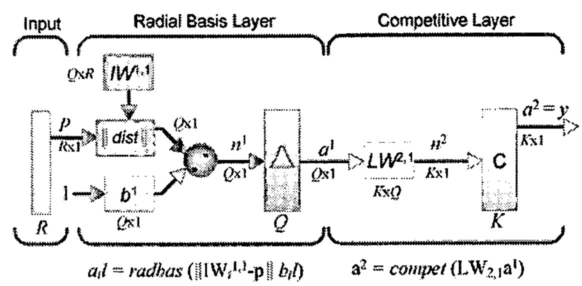


Fig. 2. Architecture of PNN network

Where R: number of elements in input vector, Q: number of neurons in the first layer, K: number of classes of input in the second layer

When an input is presented, the first layer calculates distances, *dist* function as shown in (2), between the input vector (p) and the training input vectors ($IW^{1,1}$) and creates a vector whose element indicates how close the input is to a training set. These elements are multiplied, element by element, by the bias b^1 and sent to the *radbas* transfer function as calculated in (3). The bias b^1 is set to a column vector of 0.8326/*spread*.

$$D = \sqrt{\sum_{i=1}^{Q} (IW_i^{1,1} - p_i)^2} \tag{2}$$

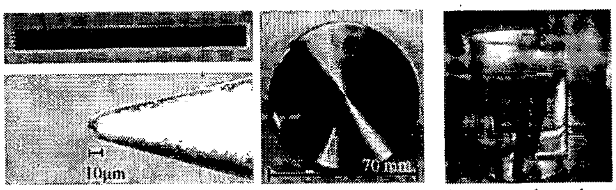
$$a^1 = radbas(n^1) = e^{(-n^1)^2} \tag{3}$$

The sum of these contributions for each class of inputs is done in the second layer to generate its net output as a vector of probabilities. Finally, a *compete* transfer function on the output of the second layer selects the maximum of these probabilities, and creates a 1 for that class and a 0 for the other classes.

III. EXPERIMENTATION

A. PD Models

The PD models were constructed with various electrode types are illustrated in Fig.3 to simulate PD patterns: HV-A, LV-A, HV-O, LV-O, and SF-O, respectively as shown in Fig.4. A tungsten needle with tip radius of 10μm and a plate electrode with 70 mm. diameter were used to simulate corona discharge in air and in mineral oil as well. The gap distance between high voltage and grounded electrode was 25 mm. While the needle positioned on the impregnated pressboard setting on the ground plane electrode was employed to simulate the surface discharge.



(a) Tungsten needle (b) grounded electrode (c) Impregnated pressboard

Fig. 3. Electrodes for PD model

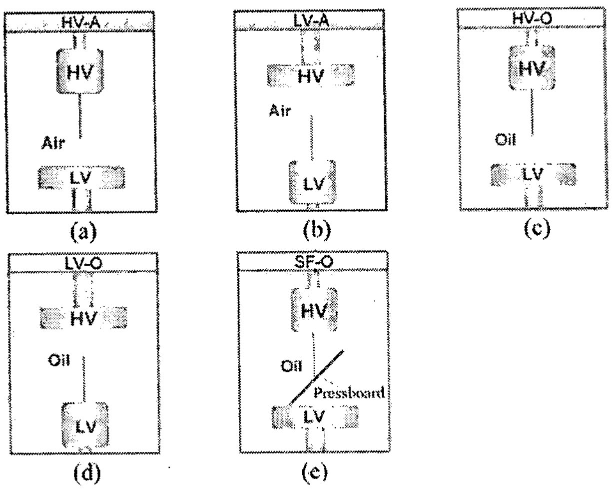


Fig. 4. Artificial partial discharge models

B. PD experiment

To investigate the PD patterns of each PD model, the PD test circuit was set up as shown in Fig.5 according to IEC 60270. The background noise was firstly measured. Then, AC voltage was applied to the PD model at the 120% of the PD inception voltage. The PD signal was measured and recorded. The experiment was done with all PD models for 100 experiments in total.

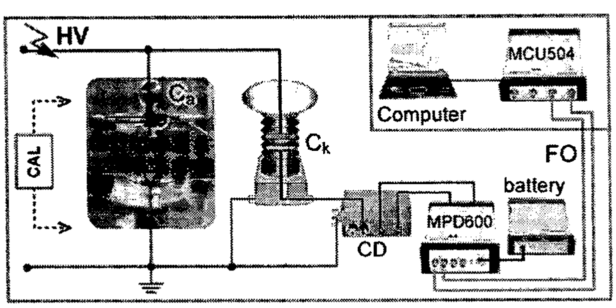


Fig.5. Test circuit diagram for the experiment

Where HV: High-Voltage supply, C_a: PD test model, C_k: Coupling capacitor, CD: Coupling device, FO: Fiber optic cable, MPD 600: Acquisition unit, MCU504: Fiber optic controller

C. Test Results

The examples of the PD patterns of each PD type obtained from the conventional PD measuring system are represented in Fig. 6.

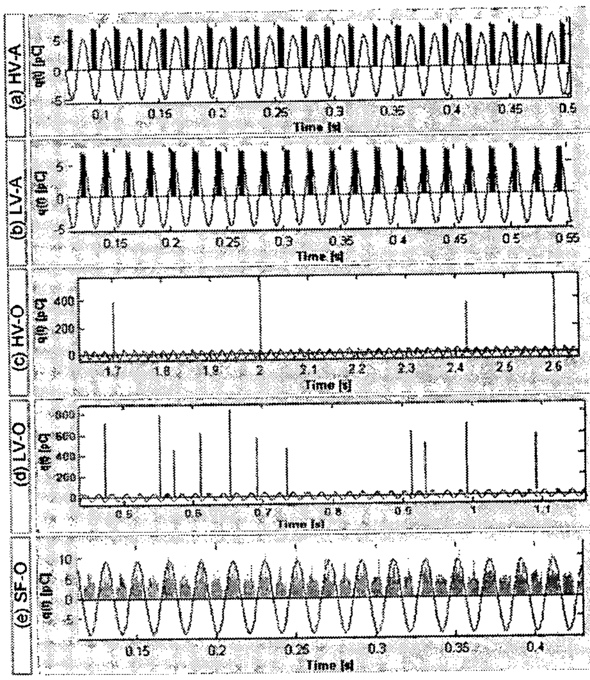


Fig. 6. Experimental results of PD patterns

(a) Corona discharge at HV side in air at 3.58 kV test voltage
(b) Corona discharge at LV side in air at 3.72 kV test voltage
(c) Corona discharge at HV side in mineral oil at 21.2 kV test voltage
(d) Corona discharge at LV side in mineral oil at 25.4 kV test voltage
(e) Surface discharge in mineral oil at 5.6 kV test voltage

D. Feature extraction

The phase-resolved $H_n(\Phi)$ and $H_{qn}(\Phi)$ were analyzed from the collected PD pattern data. Then, the PD characteristic of each PD type such as skewness, kurtosis, asymmetry, cross correlation, and modified cross-correlation factor was computed. The example of $H_n(\Phi)$ and $H_{qn}(\Phi)$ distribution of corona discharge at HV side in mineral is depicted in Fig.7. The example of statistic variables of each PD type is shown in Fig.8.

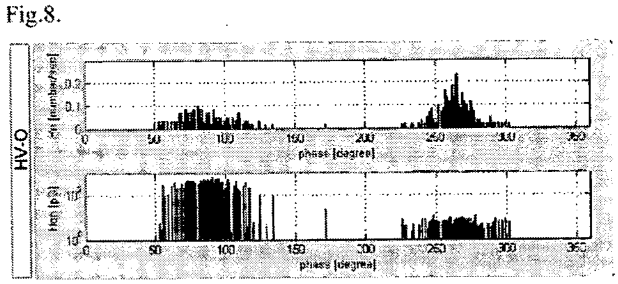


Fig. 7. Example of $H_n(\Phi)$ and $H_{qn}(\Phi)$ distribution of corona discharge at HV side in mineral

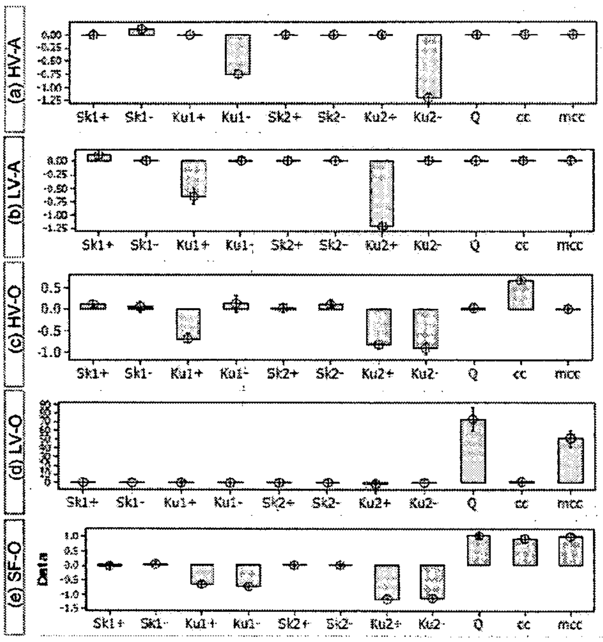


Fig. 8. Statistical variables of PD experiment

Where: $Sk1^+$, $Sk1^-$, $Ku1^+$ and $Ku1^-$ belong to the statistical variables of $H_n(\Phi)$ distribution. $Sk2^+$, $Sk2^-$, $Ku2^+$ and $Ku2^-$ belong to statistical variables of $H_{qn}(\Phi)$ distribution.

IV. Probabilistic Neural Network

PD signals from various PD types, as previously discussed, can be classified by using the statistic variables extracted from $H_n(\Phi)$ and $H_{qn}(\Phi)$ distribution. To recognize the PD patterns, the probabilistic neural network, or PNN model, was used in this research. Besides, the original variables acquired from the feature extraction process were transformed to a new set of variables before input to the proposed PD classification model as depicted in Fig.9.

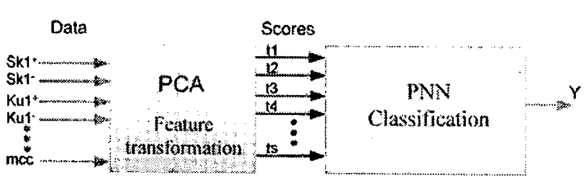


Fig. 9. Principle Component Neural Network

A. Feature transformation

The statistical variables were set to be the original matrix X and transformed to a new score matrix T as depicted in (4).

$$X = \begin{bmatrix} [\text{HV-A}]_{20\times 11} \\ [\text{LV-A}]_{20\times 11} \\ [\text{HV-O}]_{20\times 11} \\ [\text{LV-O}]_{20\times 11} \\ [\text{SF-O}]_{20\times 11} \end{bmatrix}_{100\times 11} \xrightarrow[\text{transformation}]{\text{PCA}} T = \begin{bmatrix} [\text{Score HV-A}]_{20\times 11} \\ [\text{Score LV-A}]_{20\times 11} \\ [\text{Score HV-O}]_{20\times 11} \\ [\text{Score LV-O}]_{20\times 11} \\ [\text{Score SF-O}]_{20\times 11} \end{bmatrix}_{100\times 11} \quad (4)$$

First, the original matrix X was normalized by eq. (5) to set their average values and variance to be 0 and 1 respectively. Then, the original matrix X was transformed to new features, or new score matrix, by using PCA technique which was implemented by using MATLAB statistic toolbox function as eq. (6).

$$Z = (x - \mu) / \sigma \quad (5)$$

Where μ is the mean value and σ is the standard deviation along each column of X.

$$[PC, Latent, Explained] = PCACOV(XC) \quad (6)$$

Where XC is the covariance matrix of the original matrix (X), PC is the principal component matrix, $Latent$ is the eigen values of XC, and $Explained$ is the vector of variance in each PC [5].

The relationship of principal components and their cumulative percentage variance explained are illustrated in Fig. 10. It can be seen that the summation of the first 5 PCs contains about 92% variance explained of the original information. PC6 to PC11 contain only the small percent of variance explained compared to the first 5 PCs. Therefore, the first five PCs should be implemented to create the initial PD classification model. The PC matrix with 5 PCs is illustrated in table II.

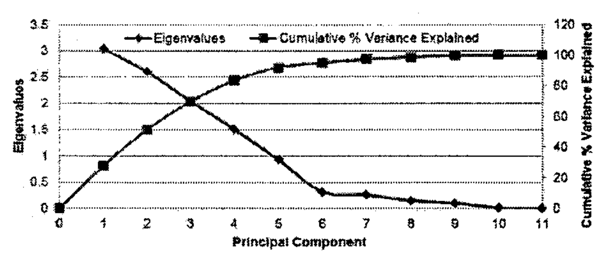


Fig.10. Plot of principal components and cumulative % variance explained versus eigenvalues.

TABLE II
Principal component matrix

		Principal Component (PC)				
		1	2	3	4	5
Hn(phase)	Sk1+	-.496	.025	-.205	.075	.230
	Sk1-	-.229	-.017	-.165	-.499	-.579
	Ku1+	-.495	-.057	.252	.124	.005
	K1u-	-.224	.076	-.570	-.040	-.038
Hqn(phase)	Sk2+	-.505	.032	.032	.018	.389
	Sk2-	-.072	-.382	-.331	-.397	-.040
	Ku2+	-.351	-.255	.386	.066	-.278
	Ku2-	-.001	.171	-.515	.464	-.040
Q		-.109	.581	.090	-.048	-.209
cc		.052	.266	.052	-.588	.537
mcc		-.092	.583	.090	-.052	-.215

B. *Probabilistic Neural Network design*

The PNN classification model was created by using MATLAB neural network toolbox function [5]. The architecture of designed PNN model had the input node, a radial basis layer and a competitive layer. The numbers of input node were designated as 1n, 2n, 3n, 4n and 5n in conformity with the first five PCs respectively. The mentioned PCs were applied to radial basis layer which was composed of 60 neuron's weight vector. The competitive layer had five classes in which each class composed of 12 neurons. Finally, a *compete* transfer function produced a 1 for the class that composed maximum probability.

C. *Training and Testing Data Set Selection*

To train and test the designed model, the score matrix ***T*** was first divided into two subsets. The former subset was the training set, which was used for computing the distance in radial basis layer and probabilities in competitive layer. The latter subset was the test set for testing the performance of the developed PD classification model. The block method was used to divide the data with 60% as the training set and the rest of 40% as the test set. The designed model was trained with various input node numbers and different spread parameters, 0.2, 0.4, 0.6, 0.8, 1.0, 1.2, 1.4, 1.6, 1.8 and 2.0 in radial basis layer.

V. PD Classification Results

The test result is depicted in Table III. The PNN models with different architecture were evaluated their performance with the testing data set. It was found that the accuracy of the PNN model increased with the increasing of the number of PCs. Nevertheless, the accuracy of the model decreased with increasing of the spread parameter. Thus, the first four score variables (4PCs) were suitable more than using 5 PCs for construction of the PD classification model. Besides, the designed PNN model should utilize the optimal spread value of 1.2. The proposed PD classification model with 4 PCs input was proved that it can classify PD types with the accuracy of 100% of 40 tested data as shown in table IV.

TABLE III

Testing results of PNN models

spread parameter	% Classification				
	1PC	2PCs	3PCs	4PCs	5PCs
0.2	62.5	92.5	95	100	100
0.4	60	87.5	95	100	100
0.6	60	80	95	100	100
0.8	60	80	95	100	100
1.0	60	80	90	100	100
1.2	60	80	90	100	97.5
1.4	57.5	77.5	90	95	95
1.6	57.5	75	90	95	95
1.8	55	75	90	95	95
2.0	55	75	90	95	92.5

TABLE IV

Confusion table for the proposed PNN model

		Target Class					% Classification
		HV-A	LV-A	HV-O	LV-O	SF-O	
Output Class	HV-A	8					100
	LV-A		8				100
	HV-O			8			100
	LV-O				8		100
	SF-O					8	100
% Classification		100	100	100	100	100	100

VI. Conclusion

In this document, the statistic parameters of the PD signals were extracted. All the original variables were transformed to the new variables by PCA technique to be the input variables for the PNN model. The designed PNN model were used to classify PD patterns into five categories listed as corona at high voltage side in air, corona at low voltage side in air, corona at high voltage side in mineral oil, corona at low voltage side in mineral oil and surface discharge in mineral oil. It was found that the accuracy of the PNN model depended on the number of PCs. Moreover, the accuracy of the PD classification model is affected from the spread parameter. According to this investigation, the first four score variables (4PCs) were suitable to build up the designed PNN model with optimal spread value of 1.2. The proposed PD classification model can classify PD types with the accuracy of 100% of 40 tested data

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ประวัติส่วนตัว(หัวหน้าโครงการวิจัย)

ชื่อ-สกุลนายนรเศรษฐ พัฒนเดช

เพศ ☑ชาย ☐หญิง วันเดือนปีเกิด 21เมษายน 2518อายุ..... 40 ปี

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