Detection and Localization of Partial Discharges (PD) by Transient Earth Voltage (TEV) Method

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Abstract

Partial Discharge (PD) is a test item for diagnosis of insulation deterioration caused in electric power facilities. We developed a PD detector using the Transient Earth Voltage (TEV) method, which has been attracting increased attention, as it can be retrofitted to the tank wall of a power transformer. Using this device, we conducted a PD test on a basic model of a transformer and detected a PD signal in the oil of several hundred pC. In addition, a single pulse was generated using an Electrostatic Discharge (ESD) gun, and the propagation path of the TEV signal flowing on the wall of the tank was confirmed by experiments. As a result, we established the basic technology for determining the localization of a PD source.

1 Preface

In recent years, as many electric power facilities including power transformers are facing the challenges of aging, there is a rise in momentum among the end-users to properly determine renewal times by considering the balance between maintenance cost and the risk of not being able to provide a stable supply of power.

Condition Based Maintenance (CBM), therefore, becomes important.

The markets demand assistive technology to enable the customers to assess the necessity of life extension or renewal by judging the soundness and the presence or absence of deterioration (trend) from the CBM diagnosis result. From a technical point of view, it has become necessary to explore renewal options together with customers.

Partial Discharge (PD) diagnosis is used for the evaluation of insulation deterioration. It is one of diagnostics used to examine causes in electric power facilities.

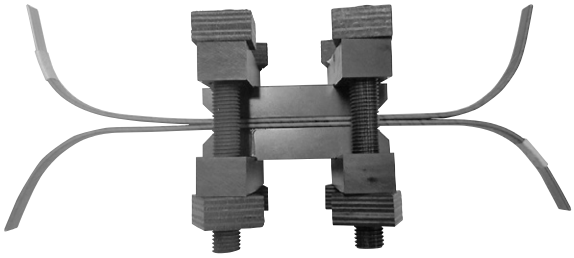
To maintain the reliability of aging equipment, it is a critical issue to continuously monitor and detect the precursor phenomenon (sign) of dielectric breakdown with high sensitivity. One of the precursors of this dielectric breakdown is PD.

Various detection methods are, therefore, used to measure UV rays, ultrasonic waves, electromagnetic waves, high-frequency current of the ground wire, and Transient Earth Voltage (TEV) of the tank wall surface associated with PD. Each method has its own strengths and weaknesses, and the optimum method is selected or used in combination according to the equipment observed and its installation status. In the actual field, however, it is difficult to pick up a feeble PD signal under a noisy environment. There are many cases where it is necessary to stop equipment to install a sensor, or a measuring device is too expensive or too large. PD measurement is currently performed only at limited periodic inspection times.

In recent years, the TEV method, which can be retrofitted to the tank wall of an aging transformer (it is not necessary to stop the equipment to install the sensor and is more resistant to mechanical vibration noise than the AE (Acoustic Emission) method), has attracted attention[(1)-(6)].

This paper introduces the features of the newly developed PD detector equipped with the TEV sensor together with the result of in-oil PD detection at a level of hundreds of pC obtained from an element model of a power transformer. In addition, we will introduce the results of experimental confirmation of the propagation path of the TEV signal by generating a single pulse using an Electrostatic Discharge

(a) Model of foreign substance on wire surface



(b) Turn-to-turn model

Fig. 1 Experimental Models

Two models of (a) model of foreign substance on wire surface and (b) turn-to-turn model are shown.

(ESD) gun, and introduce the basic technology established for the determination of the localization of the PD source.

2 Experiments for In-Oil PD Detection with Transformer Element Model

Using the developed PD detector and a TEV sensor, we implemented a series of experiments on a transformer element model to detect an in-oil PD. Fig. 1 shows the experimental models. We used two types of models: (a) a model of foreign substance on a wire surface where a copper wire is wound around a paper-insulated flat type rectangular conductor and (b) a turn-to-turn model where two paper-insulated flat type rectangular conductors are opposed to each other. An AC voltage was applied to these models to generate a PD within a tank filled with an insulation oil. At that time, a coupling capacitor was connected to the voltage-applied terminal and the amount of electric charges caused by a discharge was measured. Fig. 2 shows the experimental equipment.

As a result of the measurement, we confirmed that about 200pC of electric charges due to the PD was measured in both cases of a model of foreign substance on wire surface and a turn-to-turn model. Fig. 3 shows a result of experiments.

Using the developed PD detector and TEV sensor, we were able to detect in-oil PD several hundred pC in the transformer element model and confirm its usefulness. In this way, this method can be applied to PD detection (sign monitoring) of oil-immersed transformers.

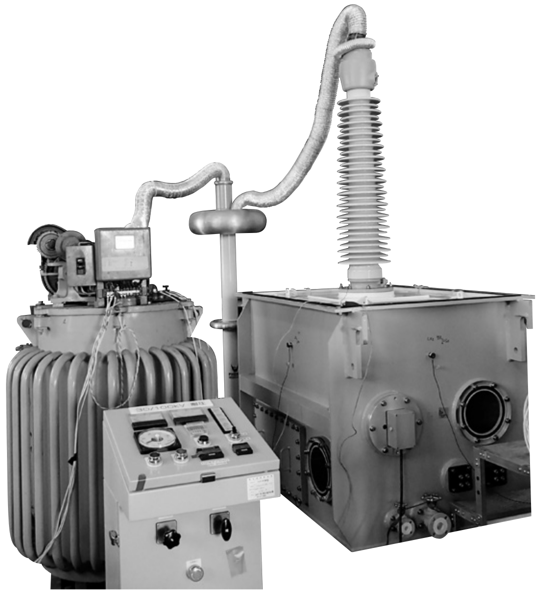
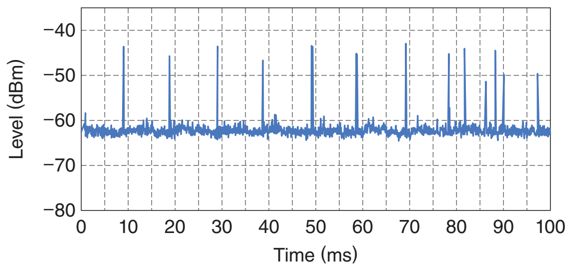
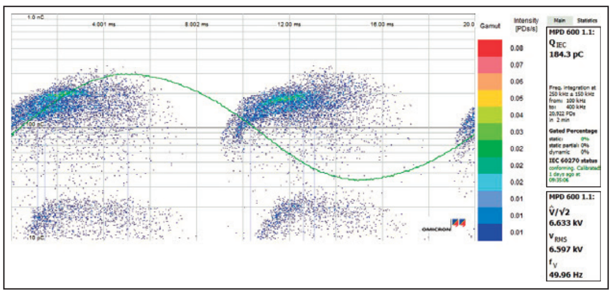


Fig. 2 Experimental Equipment

Experimental equipment for in-oil partial discharge detection on a transformer element model is shown.



(a) Result of measurement by PD detector



(b) Amount of electric charge caused by discharge

Fig. 3 Result of Experiments

Partial discharges were detected at the charge amount of approximately 200 pC. Two cases of measuring results are shown for (a) a result of measurement by PD detector and (b) an amount of electric charge caused by discharge measured with a coupling capacitor.

3 Experiments to Determine Localization of PD with ESD Gun

An ESD gun was employed to examine a TEV signal propagation path in an empty tank where no insulation oil is contained. Fig. 4 shows the experimental equipment. When a single pulse was generated with an ESD gun, an in-air PD was generated at the ignition checker (needle-to-needle electrode) in the tank. When electric waves were radiated from this device, they propagated in the air within the tank and arrive at the tank wall, thus inducing a transient voltage, which was then propagated on the tank surface. This signal was detected by multiple TEV sensors distributed over the tank wall. The detected signal was recorded by an oscilloscope (MSO70404C).

Table 1 shows the test conditions. We confirmed the propagation paths against six conditions. For Condition 2, the ESD gun was directly aimed at the tank's inner wall surface to pick up a TEV signal. For Condition 5, a cover was mounted on the tank to confirm the effect of presence of a tank hole. The sensor positions under the respective conditions are indicated in Fig. 7 to be related later.

Fig. 5 and Fig. 6 show examples of TEV signal waveforms under Condition 1 and Condition 3. Diagram (a) shows entire waveforms and Diagram (b) shows enlarged diagrams where a part of the second wave in-air discharge for (a) is enlarged. In (a), it is considered that the first wave was attributable to a signal from the ESD gun or the main body of the electrostatic tester and that the second wave was caused by in-air discharges. In (b) of Fig. 5 and Fig. 6, the intensity of signals propagating to tank's external wall surface was reduced to approximately 1/10 compared with inner signals. Table 2 shows signal propagation paths from the discharge source and the TEV sensor under the respective conditions, plus expected values and measured values of time. The propagation path for each expected value was determined as the shortest distance for the signal required to get to the sensor along the tank wall after the arrival at the tank wall. The expected value of time was calculated on the assumption that the

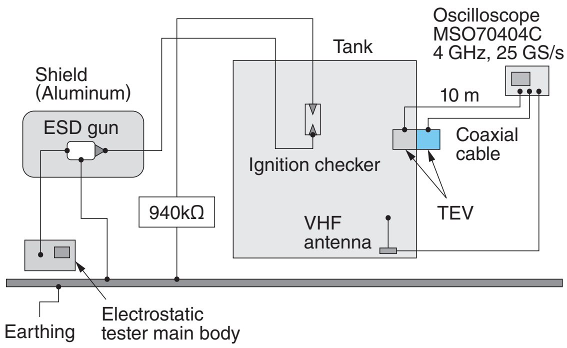


Fig. 4 Experimental Equipment

Experimental equipment for partial discharge localization by using an ESD gun is shown.

Table 1 Test Conditions

The six conditions for propagation path localization are shown.

Condition	Detailed facts
Condition 1	Confirmation of the TEV signal propagation path on the inside of the tank
Condition 2	Confirmation of the propagation velocity of the wall surface current
Condition 3	Confirmation of the TEV signal propagation path on the tank outside
Condition 4	Confirmation of the TEV signal propagation path on the tank inside and outside
Condition 5	Confirmation of the TEV signal propagation path in consideration of presence of a tank hole
Condition 6	Confirmation of the determination of the localization

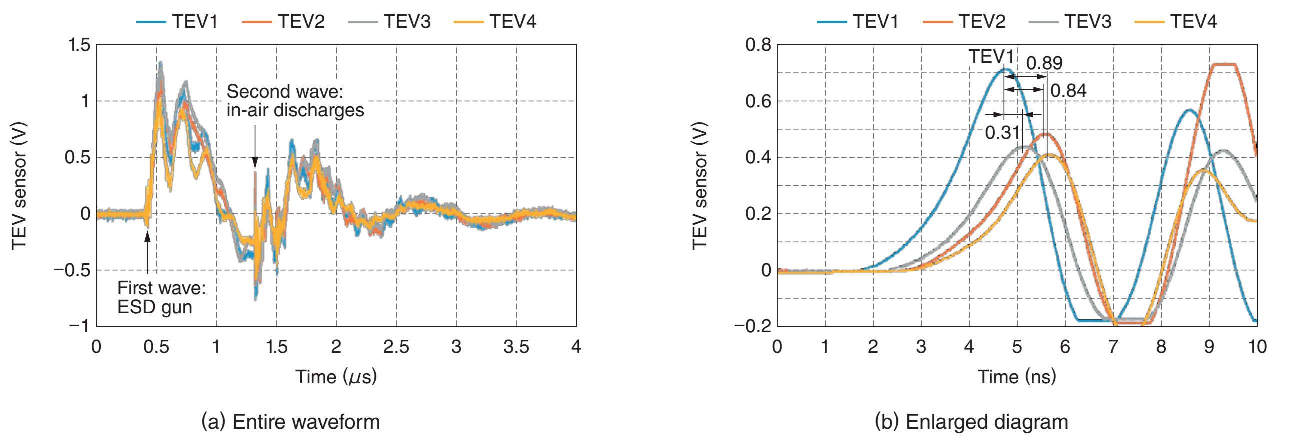
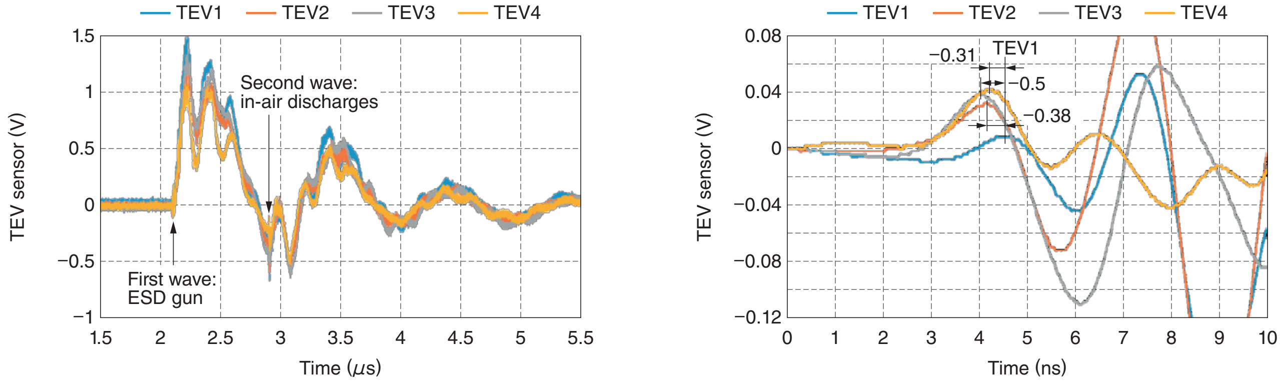


Fig. 5 Example of TEV Signal Waveform (Condition 1)

The diagrams show (a) the entire waveform and (b) the enlarged diagram. It is considered that the first wave is caused by the ESD gun or the electrostatic tester main body, and that the second wave is attributable to in-air discharges.



(a) Entire waveform (b) Enlarged diagram

Fig. 6 Example of TEV Signal Waveform (Condition 3)

The diagrams show (a) the entire waveform and (b) the enlarged diagram. Compared with inner signals, the intensity of a signal propagating on tank's outside is approximately 1/10.

Table 2 Result of Experiments

The table shows both expected and measured values of propagation path and time from the discharge source to the TEV sensor under each condition.

Condition	Sensor type	Propagation path	Propagation velocity	Expected values				Measured values	
				Arrival of electromagnetic waves		Difference from criterion		Difference from criterion	
			(m/ns)	Distance (mm)	Time (ns)	Distance (mm)	Time (ns)	Time (ns)	Error (mm)
Condition 1	TEV1 (Criterion)	①	0.3	474	1.42	–	–	–	–
	TEV2	②	0.3	726	2.18	252	0.76	0.84	28
	TEV3	③	0.3	570	1.71	96	0.29	0.31	8
	TEV4	④	0.3	726	2.18	252	0.76	0.89	45
Condition 2	TEV1	①	0.3	731	2.19	701	2.1	2.19	30
	TEV2	②	0.3	720	2.16	690	2.07	1.92	−50
	TEV3	③	0.3	731	2.19	701	2.1	2.19	30
	TEV4 (Criterion)	④	0.3	30	0.09	–	–	–	–
Condition 3	TEV1 (Criterion)	①	0.3	1311	3.93	–	–	–	–
	TEV2	②	0.3	1202	3.6	−109	−0.33	−0.38	−18
	TEV3	③	0.3	1111	3.33	−200	−0.6	−0.5	33
	TEV4	④	0.3	1202	3.6	−109	−0.33	−0.31	5
Condition 4	TEV1 (Criterion)	①	0.3	474	1.42	–	–	–	–
	TEV2	②	0.3	654	1.96	179	0.54	0.52	−6
	TEV3	③	0.3	736	2.21	915	2.74	2.88	46
Condition 5	TEV1 (Criterion)	①	0.3	1337	4.01	–	–	–	–
	TEV2	②	0.3	1851	5.55	514	1.54	1.51	−10
	TEV3	③	0.3	1475	4.42	138	0.41	0.19	−75
	TEV4	④	0.3	1365	4.09	28	0.08	−0.2	−95
Condition 6	TEV1	①	0.3	503	1.51	−374	−1.12	−1.61	−163
	TEV2	②	0.3	727	2.18	−151	−0.45	−0.2	84
	TEV3	③	0.3	619	1.86	−259	−0.78	−1.05	−92
	TEV4 (Criterion)	④	0.3	878	2.63	–	–	–	–

propagation velocity, both in air and on the tank wall, was identical with the light velocity under the vacuum. Regarding the time difference in the TEV signal, we noted the peak value of the second wave so that calculation is based on the time difference between the TEV sensor defined as the criterion and other TEV sensors. According to Table 2, errors seemed to be small, so we considered that the premise for the aforementioned calculation is adequate. The six test conditions are as described below.

(1) Condition 1: Confirmation of the TEV signal propagation path on the inside of the tank

The TEV sensor installed inside the tank was assumed to define the shortest distance of a path to directly receive electromagnetic waves.

(2) Condition 2: Confirmation of the propagation velocity of the wall surface current

Propagation took place along the shortest path from the surface of the inside of the tank to the TEV sensor located on the outside. It was assumed that the propagation velocity of the wall surface current was identical with the light velocity under the vacuum.

(3) Condition 3: Confirmation of the TEV signal propagation path on the outside of the tank

Regarding the propagation path, the radiated electromagnetic waves generated by discharges were assumed to arrive at the tank's corner part and then flow along the wall surface to get to the TEV sensor located on the outside of the tank.

(4) Condition 4: Confirmation of the TEV signal propagation path on the inside and outside of the tank

It was assumed that the TEV sensor on the inside directly received electromagnetic waves along the shortest distance. The current arrived at the tank's corner part on the outside and then flows on the wall surface to get to the sensor.

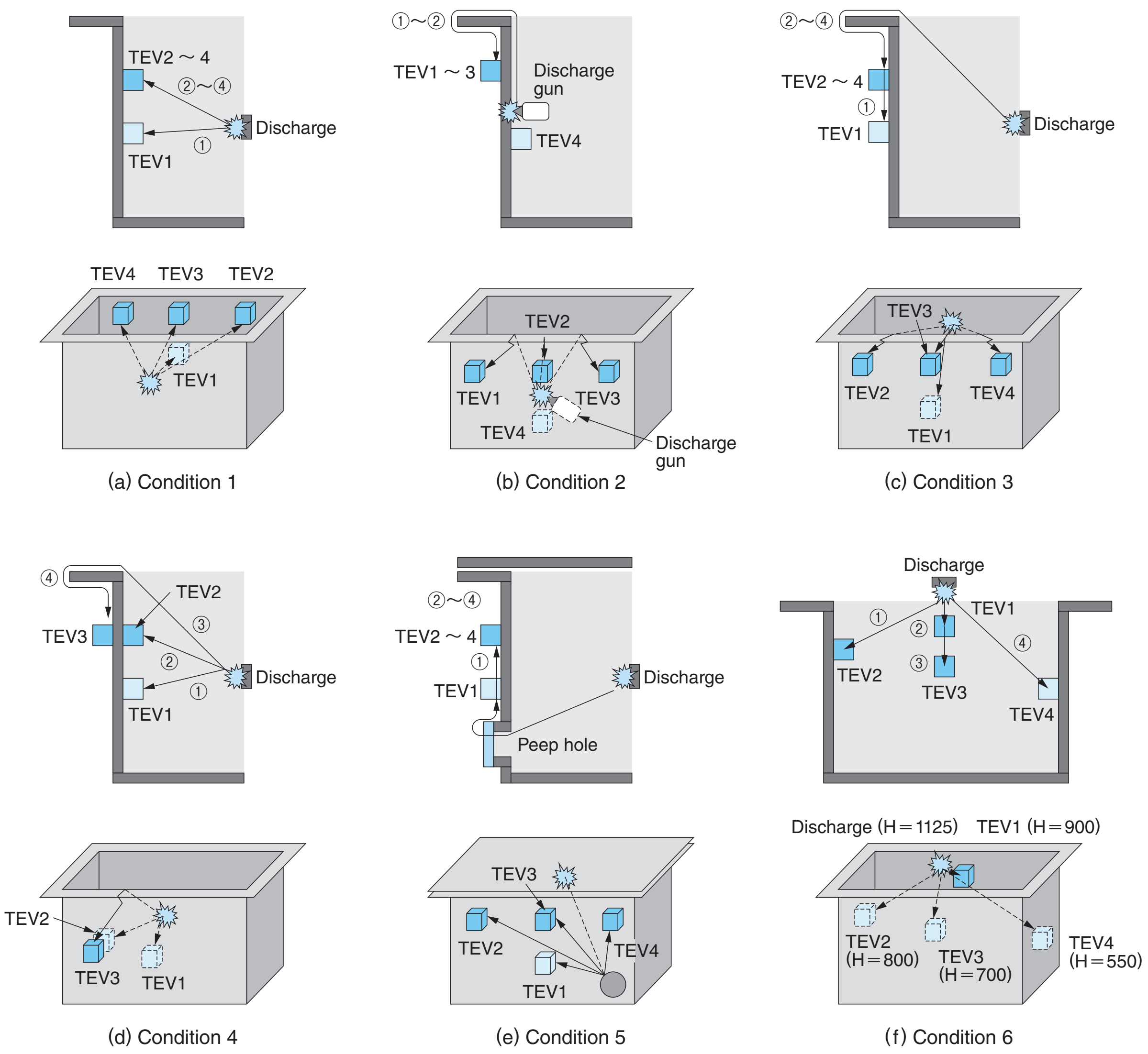


Fig. 7 TEV Signal Propagation Paths

Diagrams (a) to (f) show the respective TEV signal propagation paths under Conditions 1 to 6. It is presumed that the signal runs along the shortest distance to the TEV sensor located on the inside of the tank while the signal on the outside of the tank runs along the wall surface to the sensor after arriving at the tank's corner part or the tank hole.

(5) Condition 5: Confirmation of the TEV signal propagation path in consideration of presence of a tank hole

The radiated electromagnetic waves generated by discharges were assumed to arrive at the tank hole and the current then flowed on the wall surface until it got to the TEV sensor located on the outside of the tank. Such a propagation path suggests that it is important to install an externally attachable TEV sensor in the vicinity of the tank hole where electromagnetic waves may easily leak out.

(6) Condition 6: Confirmation of the determination of the localization

Like Condition 1, the TEV sensor installed inside the tank wall was assumed to provide for a path through which electromagnetic waves could be received directly along the shortest distance.

Fig. 7 shows the TEV signal propagation paths under the respective conditions all together. The TEV sensors installed inside the tank were presumed to provide for the respective paths through which waves propagated along the shortest distance and arrive at the tank's corner part or the tank hole. The current then flowed along the wall surface and arrived at the sensor.

Based on the TEV signal arrival time difference in 4 cases of Condition 6 in **Table 1**, we carried out the determination of the localization of the discharge source. Regarding this localization, the result of localization was (x: 700 mm, y: 541 mm, z: 1036 mm) against the expected values (x: 650 mm, y: 450 mm, z: 1125 mm). The results indicate that the localization accuracy was favorable.

In addition, we performed the determination of the localization on a model that is similar to an actual transformer, in consideration of allocation of the core and coils and in reference to literatures by Judd, et al., (2011 & 2017)[(3)(4)]. **Fig. 8** shows the results on determination of localization of PD on a transformer. The result indicates that the localization determination was made at the upper section of the windings. Specifically, multiple optional points were plotted and a path from a typical point to the target sensor was displayed. This result closely matches that of the localization stated in literatures by Judd, et al., (2011 & 2017)[(3)(4)].

We were, therefore, able to confirm the propagation paths of the TEV signal by experiment and establish the basic technology for the determination of the localization the PD source. TEV signals include high-frequency components that are detected directly through space and low-frequency components that are detected via the ground wire[(2)]. The target of the PD detector is mainly the latter, but it is necessary to target the former to determine the localization of the discharge source from the difference in arrival time of multiple TEV signals. Also, we need to consider the propagation path outside the tank.

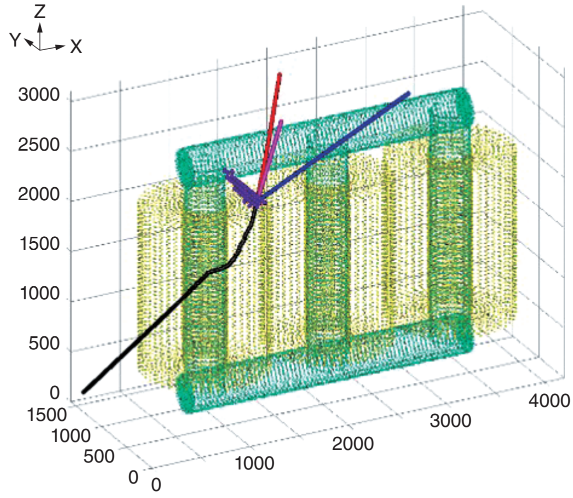


Fig. 8 Results on Determination of Localization of PD on Transformer

A result of the determination of the localization of PD at the upper part of windings was obtained. (Multiple optional points were plotted and a path from a typical point to the target sensor was displayed.) This result closely matches that of localization stated in literatures by Judd, et al. (2011 & 2017)[(3)(4)].

4 Postscript

We developed a PD detector by using the TEV sensors. Based on experiments of in-oil PD detection on a transformer element model and those of PD localization with a help of an ESD gun, the following results were derived:

(1) Using a newly developed PD detector, hundreds of pC of in-oil PD were detected in a transformer element model.

(2) A single pulse was generated by using an ESD gun and the propagation path for TEV signals was confirmed by experiments. As a result, the basic technology for the determination of the localization of PD generation source was established.

(3) Based on the difference in TEV signal arrival time, the determination of the localization of signal sources was carried out. The localization accuracy was found favorable.

In the future, we intend to utilize the TEV method for equipment maintenance, especially as one of the sophistications of live-line PD diagnostic technology and the enhancement of the service menu line-ups among the various diagnostic menus in the CBM.

・All product and company names mentioned in this paper are the trademarks and/or service marks of their respective owners.

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