Regular Paper
J. Korean Inst. Electr. Electron. Mater. Eng.
Vol. 32, No. 4, pp. 307-312 July 2019
DOI: https://doi.org/10.4313/JKEM.2019.32.4.307
ISSN 1226-7945(Print), 2288-3258(Online)

TEV 검출에 의한 가스 절연 개폐기의 절연 진단

공정배[1], 길경석[1], 김성욱[2]
[1] 한국해양대학교 전기전자공학과
[2] ㈜효성 Power Asset Management팀

Insulation Diagnosis of Gas-Insulated Switchgears by TEV Detection

Jeong-Bae Kong[1], Gyung-Suk Kil[1], and Sung-Wook Kim[2]
[1] Department of Electrical and Electronics Engineering, Korea Maritime and Ocean University, Busan 49112, Korea
[2] Power Asset Management Team, Hyosung Corporation, Changwon 51529, Korea

(Received March 4, 2019; Revised March 30, 2019; Accepted April 1, 2019)

Abstract: Transient earth voltage (TEV) signals propagate on metal surfaces when partial discharge (PD) occurs due to the deterioration of insulation performance in the operation of gas-insulated switchgears (GIS). A TEV sensor has advantages of high sensitivity and convenient installation for detecting PD defects. However, the TEV sensor depends on imports in domestic and detailed studies have not been conducted. In this study, a sensor was designed and fabricated by the TEV principle and its response characteristics were evaluated for detecting PD defects, which were simulated as protrusion on conductor (POC), protrusion on enclosure (POE), and free moving particle (FMP) defects. Finally, the PD-induced TEV signals were measured and phase-resolved partial discharge (PRPD) patterns were analyzed to identify the type of defect.

Keywords: Transient earth voltage, Partial discharge, Gas-insulated switchgears, Insulation defect

1. INTRODUCTION

Partial discharge (PD) is one of the important indicators of insulation deterioration for high- and medium-voltage power equipment. In IEC 60270, PD is defined as a localized electrical discharge that only partially bridges the insulation between conductors and which can or cannot occur adjacent to a conductor [1]. PD can occur at any point in the insulating system, where the electric field strength exceeds the breakdown strength of that portion of the insulating material. Although the magnitude of such discharge is usually small in the early stage, it causes progressive deterioration and finally results in the failure of power facilities such as high-voltage power transformers, gas-insulated switchgears (GIS), and medium-voltage switchgears. Therefore, it is essential to detect PD in the early deterioration process of insulating system to prevent their failure [2-4].

The on- and off-line PD measurement methods have been developed to improve their performances over several decades. PD measurement methods can be divided into a conventional method based on IEC 60270 and non- conventional methods including ultra high frequency, acoustic emission, and transient earth voltage (TEV). One of them, the non-contact TEV method has advantages to install sensors conveniently without any intrusion in service and it does not affect the insulation since the sensor detects the TEV signals induced by

✉ **Gyung-Suk Kil; kilgs@kmou.ac.kr**
Sung-Wook Kim; number1@hyosung.com

PD. In the past, TEV sensor was used to measure time-varying electric field but recently it has been widely used as a high-sensitive sensor to detect high-frequency signals such as PD and electrical arc for condition monitoring and power asset management [5]. The research and development of the TEV sensor, however, were mainly performed in foreign countries and detail studies have not been conducted in Korea [6].

In this paper, the high-sensitive TEV sensor was designed and fabricated to detect PDs and phase- resolved partial discharge (PRPD) patterns were analyzed to identify types of PD causes for GIS. The performance of TEV sensor proposed in this paper was confirmed to be appropriate for PD diagnosis of GIS and would be utilized for asset management through optimal maintenance of power equipment in the future.

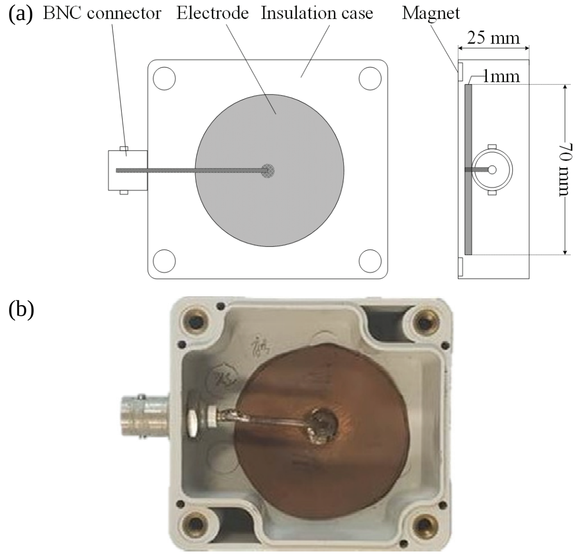

Fig. 1. TEV sensor. (a) Structure and (b) prototype.

2. METHOD FOR EXPERIMENT

2.1 TEV Sensor

2.1.1 Detection principle

TEV is induced on the grounded metal surface when PD occurs owing to insulation deterioration in power equipment. When PD occurs on the discontinuous shielding point between an insulator and a flange joint, electromagnetic waves with high frequencies are produced and induced on the metal surface. The TEV sensor is used to detect voltage of stray capacitance between a grounded metal enclosure and a metal plate with a gap of a few millimeters. The magnitude of TEV signal V is obtained by

$$V = \frac{\sigma\delta}{C(1+j)} \int \left(\iint_S E_0 dS \right) dt \tag{1}$$

here E_0 is electric field parallel to the surface of metal plate, C is capacitance between the grounded metal enclosure and the metal plate, S is the cross-sectional area of the electrode, δ is the skin depth, σ is the conductivity, and j is the current density induced on metal enclosures. The magnitude of signal detected by the TEV sensor is proportional to the cross-sectional area and is non-proportional to the capacitance and impedance of metal surface.

The TEV sensor was designed considering above detection principle. The structure and prototype are shown in Fig. 1. For high-sensitive PD detection, a copper plate with a diameter of 70 mm and a thickness of 1 mm was used. The shape of the TEV sensor was circular in order to avoid concentration of non-linear electric field at the edges, and a BNC connector and PVC insulation paper were directly attached on its contact surface. The thickness of insulation layer for fabricating sensor enclosure was 1 mm.

2.1.2 Response characteristics

In order to verify the response characteristics of the fabricated TEV sensor, experimental system consisted of a signal generator (SG, 1710), a pulse generator (PG, CAL1A), a metal-clad enclosure, and digital storage oscilloscope (DSO, DL 9140) was configured. The experimental setup is shown in Fig. 2. The signal generator with frequency range up to 1 GHz was used to identify the characteristic of frequency response and the pulse generator with apparent charge up to 100 pC was used to identify the characteristics of sensitivity and response time. The metal- cylindrical enclosure with size of 180 mm × 50 mm was used for simulating metallic surface of the GIS. The pulse produced from the signal generator propagated on the metal-cylindrical enclosure by skin effect and the TEV sensor installed on the enclosure detected the TEV signal. The DSO was used for signal acquisition.

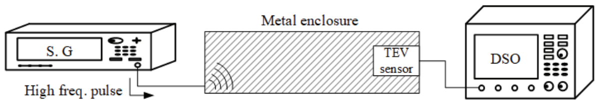

Fig. 2. Configuration of experimental setup for verifying the response characteristics.

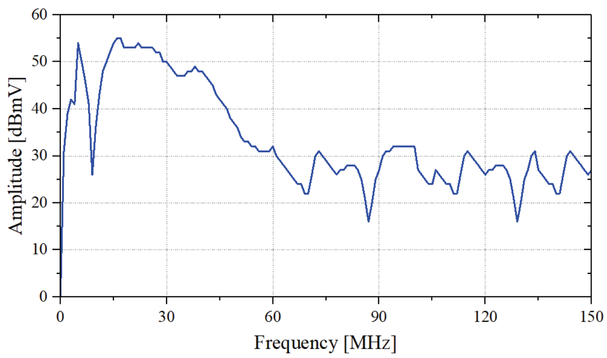

Fig. 3. Frequency spectrum of TEV sensor.

The characteristic of frequency response was analyzed using the signal generator. The sinusoidal wave with a magnitude of 1,000 mVrms was changed from 1 Hz to 150 MHz considering the frequency ranges of TEV signal. Figure 3 shows the result of frequency response of the fabricated TEV sensor. The sensitivity was relatively higher in the vicinity of 15 MHz to 30 MHz and was relatively lower in the vicinity of 60 MHz and 90 MHz but the magnitude at a specific frequency may be amplified due to the inherent capacitance by the resonance phenomenon.

The characteristics of sensitivity and time response were analyzed using the pulse generator. The pulse generator is usually used to calibrate the experimental system by generating a signal similar to the PD magnitude up to 100 pC. In this experiment, it was used to identify the sensitivity and time response. Figure 4(a) shows the example of response time between the direct detection waveform of the current signal applied by the pulse generator and the signal detected by the TEV sensor. It can be seen that the time difference was 8ns. Since average repetition time of PD pulse is a few hundred microseconds to a few milliseconds when PD occurs, there is no problem in sampling all the PD pulses detected from TEV sensor which has response time of several nanoseconds. Figure 4(b) shows sensitivity of TEV sensor depending on magnitude of apparent charge produced by the pulse generator. The results showed that sensor output was linear and proportional to magnitude of apparent charge. Its sensitivity was 1.2 mV/pC.

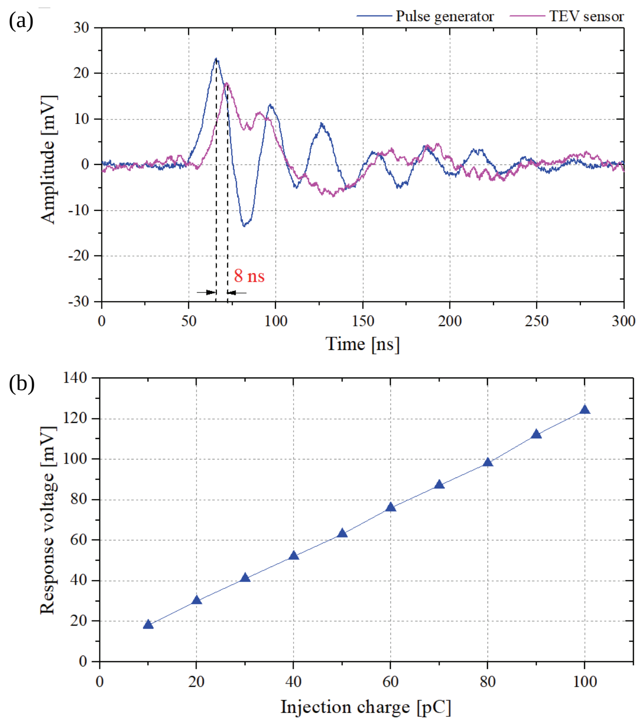

Fig. 4. Result of response characteristics. (a) Response time and (b) sensitivity.

3. RESULTS AND CONSIDERATION

3.1 Partial discharge measurement

3.1.1 Experimental setup

In order to simulate PD generated by the insulation deterioration in GIS, the experimental system was set up as shown in Fig. 5. The high voltage was applied by a dry-type transformer with a maximum output of 50 kV and was measured by a voltage divider with a ratio of 10,000:1. PD-induced voltage pulse and TEV signal were simultaneously detected by a 50 Ω non-inductive resistor and a TEV sensor mounted on the shielding box, respectively. A DSO with and a data acquisition (DAQ) were used for recording the signals. The PRPD patterns depending defect types were acquired based on the developed LabVIEW program [7].

Figure 6 shows PD electrode systems including protrusion on conductor (POC), protrusion on enclosure (POE), and free moving particle (FMP) to simulate the defects inside the GIS. Each of them was placed in a shielding room to minimize the influence of external interference. The POC and POE, which were respectively used for simulating defect on GIS conductor and enclosure, consisted of a needle electrode and a plane electrode. The curvature radius of needle electrode was 10 um and the plate electrode with a diameter of 50 mm was made of tungsten- copper alloy. The edge of plate electrode was rounded to prevent the concentration of the electric field. The distance between the needle and the plate electrode was 3 mm. In the FMP, the diameter of free particle was 2 mm.

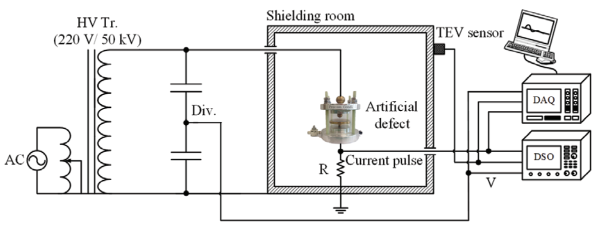

Fig. 5. Configuration of experimental setup.

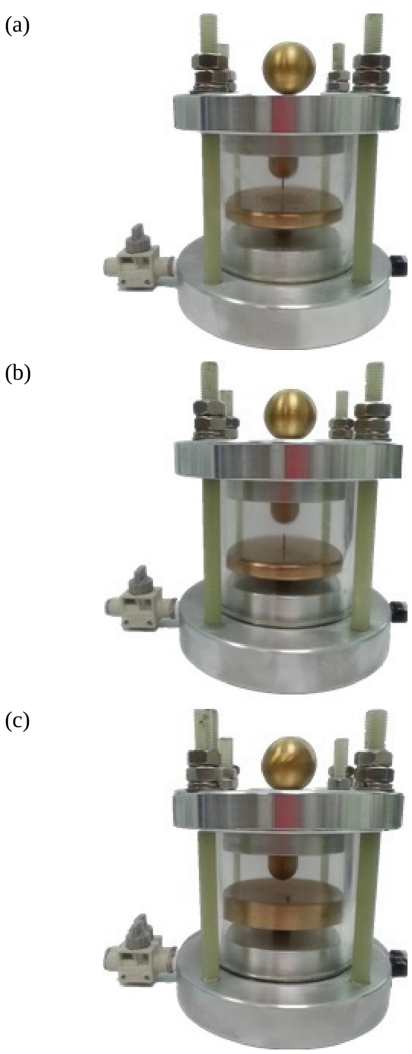

Fig. 6. Electrode systems. (a) Protrusion on conductor, (b) protrusion on enclosure, and (c) free moving particle.

3.1.2 Detection and analysis

Figures 7 and 8 show typical detected voltage pulse and TEV signal in time and frequency domain, respectively. It can be seen that the voltage pulse had a pulse width of 0.34 μ s and a frequency up to 60 MHz. On the other hand, the PD-induced TEV signal had a pulse width of 2 μs. The frequency of TEV signal was distributed at a few MHz and nearby 100 MHz. In addition, it was hard to distinguish the type of insulation defect by comparing the waveform and the frequency spectrum.

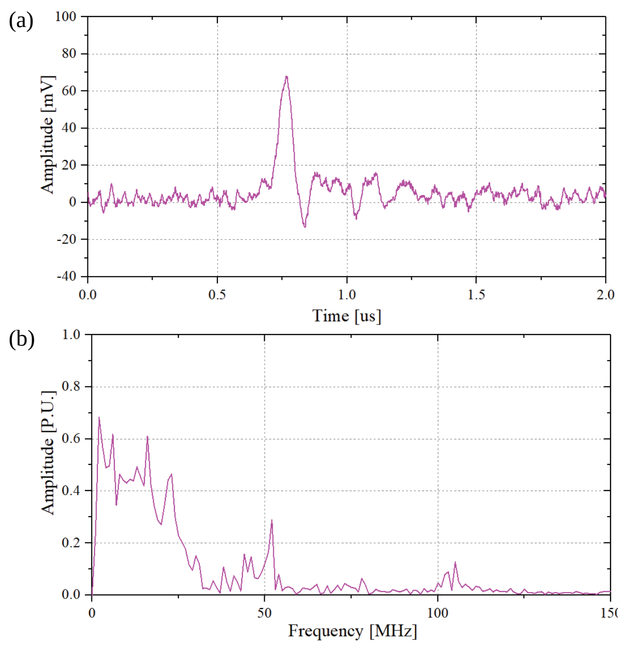

Fig. 7. PD voltage pulse. (a) In time domain and (b) in frequency domain.

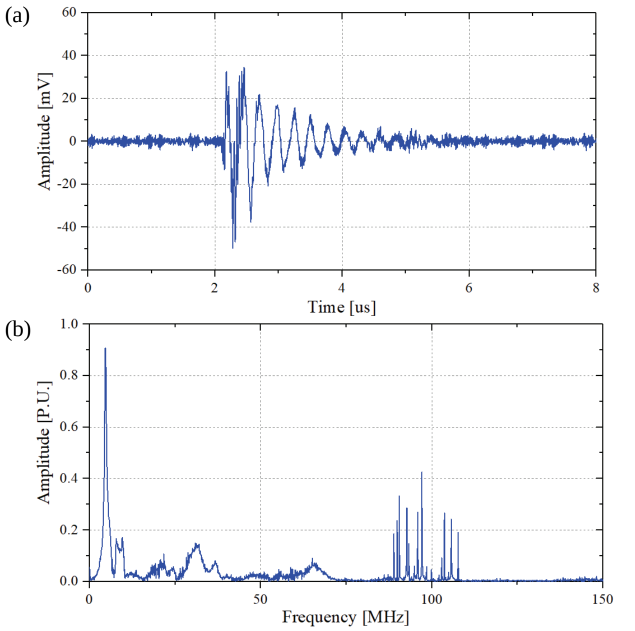

Fig. 8. PD-induced TEV signal. (a) In time domain and (b) in frequency domain.

3.1.3 PRPD patterns

PRPD analysis of signal measured by the TEV sensor was performed to identify type of insulation defects. PRPD pattern was found to be very useful for identifying the type of PD defect using phase angle, discharge magnitude, and count of discharge occurrence by accumulating discharge pulses within one cycle of the applied voltage. Figure 9 shows the PRPD patterns depending on the electrode systems. The applied voltage was about 8 kV. In the POC, most of the PD pulses were distributed in the positive half of the applied voltage with phase ranges from 30° to 130°. In the POE, on the other hand, most of the PD pulses were distributed in the negative half of the applied voltage with phase ranges from 215° to 320°. This was because discharge initiated at the needle tip in the positive and negative of the applied voltage in the POC and POE, respectively. Both of them, pulse counts were almost same. PD pulses in the FMP were distributed over whole phases and pulse counts were much less then other two defects. Since the PRPD patterns presented distinguishable features, they can be used to identify the defect type for on-line condition monitoring of GIS.

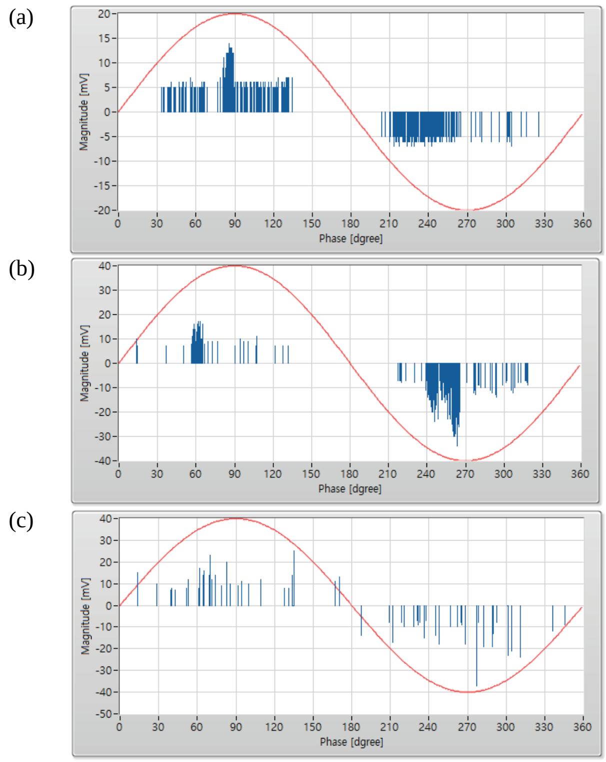

Fig. 9. PRPD patterns. (a) POC, (b) POE, and (c) FMP.

4. CONCLUSIONS

The research and development of TEV sensor were not conducted in detail in domestic even though it has significant advantages in PD detection for condition assessment of GIS. In this paper, the TEV sensor was fabricated with theoretical analysis and its response characteristics were analyzed to check the performance for detecting PD signals. From this paper, the following conclusions can be obtained.

1) It is well known that PD-induced TEV signal has frequency range up to 150 MHz and the fabricated sensor can detect the signal in the whole frequency range.
2) Discharge pulse has average repetition time from a few hundred microseconds to a few milliseconds when PD occurs. The time differences between the directly detected voltage signal and the TEV signal was 8ns, the proposed sensor therefore can acquire all the PD pulses.
3) PRPD patterns were analyzed to distinguish types of PD defects. The results showed that most of PD pulses were distributed in the positive and negative half of the

applied voltage in the POC and POE, respectively. PD pulses in the FMP were distributed over the whole phases and PD counts were much less than other two defects.

ORCID

Gyung-Suk Kil https://orcid.org/0000-0002-1672-2812
Sung-Wook Kim https://orcid.org/0000-0001-9705-3544

REFERENCES

[1] IEC Publication 60270, *High-Voltage Test Techniques: Partial Discharge Measurements*, 2010.

[2] CIGRE JWG 33/23/12, *Insulation Co-Ordination of GIS: Return of Experience, on Site Tests and Diagnostic Techniques*, Electra No. 176, 1998.

[3] S. M. Markalous, S. Tenbohlen, and K. Feser, *IEEE Trans. Dielectr. Electr. Insul.*, **15**, 1576 (2008). [DOI: https://doi.org/10.1109/TDEI.2008.4712660]

[4] G. Wang, H. E. Jo, S. J. Kim, S. W. Kim, and G. S. Kil, *Measurement*, **91**, 351 (2016). [DOI: https://doi.org/10.1016/j.measurement.2016.05.033]

[5] B. H. Lee, S. H. Lee, and G. S. Kil, *Proc. Conference of The Korean Institute of Electrical Engineers* (KIEE, Seoul, Korea, 1994) p. 287.

[6] N. Davies, J.C.Y. Tang, and P. Shiel, *Proc. 19th International Conference on Electricity Distribution* (Elec. Dist., Vienna, Austria, 2007) p. 1.

[7] G. Wang, W. H. Kim, J. B. Kong, G. S. Kil, and H. K. Ji, *Trans. Electr. Electron. Mater.*, **19**, 195 (2018). [DOI: https://doi.org/10.1007/s42341-018-0037-5]