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Analysis of Partial Discharge Inception Voltages for the Wrong Positioning Defects in the Joint of Distribution Power Cables

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Abstract – In order to find out partial discharge (PD) phenomena in the cable joint due to the poor workmanship during the installation, the relationship between PD inception voltages and joint defects was investigated. For the purpose, in the joint of 22.9kV CNCV cables, electric fields were calculated for various semiconductive layer wrong positioning (WP) defects. And, PDIV were investigated through the experiments and compared with the results of electric field analysis. In all WP defect cases, the PD inception field calculated using measured PDIVs was similarly shown to be the average value of 1.84kV/mm. In addition, the calculated PDIV and the measured PDIV were almost equal, from the PDIV calculation using maximum electric fields and the measured PDIV for the normal case. Throughout this study, it is possible to analyze WP defects due to the poor workmanship and to establish better joint design for the distribution grade extruded cable system.

Keywords: Partial discharge inception voltages, CNCV cable, Joint, Wrong positioning defect, Electric field calculation

1. Introduction

Besides water trees, especially in the joints, the main insulation degradation mechanism in the distribution grade XLPE power cable system is partial discharge(PD) degradation phenomena [1]. In the joint, partial discharges can be occurred from defects due to the poor construction work such as impurities and voids in the interface between XLPE insulation and EPDM in the splice, wrong positioning(WP) defects between the cable and the splice, knife cuts in the insulation, etc. [2] In case of knife cut defects, electrical trees are generated in the insulation layer from the knife cut and lead to the breakdown through the XLPE insulation. The defects related to the interface such as impurities and wrong positioning can generate interfacial electrical trees that propagate along the interface and the breakdown occurs.

The study for the PD in the joint interface has been mainly focused on the impurities and voids existing in the interface of HV extruded cable joints; PDIV (partial discharge inception voltage) related to interfacial pressure/ lubricants [3] and impurities/voids [4], PD at the interface of XLPE/EPR and EPR/Epoxy [5-8], etc. For the distribution power cable joints, PD inception and degradation would be occurred similar to those in transmission cable joint, even though detailed study related to distribution cables has been rarely reported.

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However, it is not easy to survey literatures related to the partial discharge inception and degradation for the semiconductive layer wrong positioning in the joint interface. The semiconductive layer wrong positioning is the position mismatch between the outer-semiconductive layer of the joint and the outer-semiconductive layer of the cable due to the poor workmanship, which causes higher electric stress. The joint for distribution cables show poorer quality related to the semiconductive layer than that for transmission cables which have been thoroughly tested at the factory production. Moreover, more apprehension about poor construction work would also exist, which causes the wrong positioning defect of the semiconductive layer. The possibility of degradation due to semiconductive layer wrong positioning would be high in the distribution cable joint. Therefore, the analysis is needed for the PD inception related to the defect size, which gives basic information for the reliability of joint design, production and construction work.

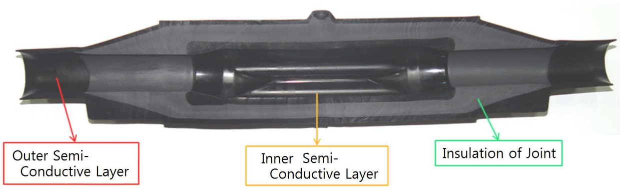
Also, PD detection as a on-site diagnostic tool has been increasingly applied as well as the quality control in the factory, which means that basic data of main defects are more required for the assessment of the cable system [9]. In case of semiconductive layer wrong positioning defects, less study have been reported compared with other types of defects.

In this study, in the joint of 22.9kV CNCV cables, electric fields were calculated for various semiconductive layer wrong positioning (WP) defects. Also, PDIV were investigated through the experiments and compared with the results of electric field analysis. Throughout this work, partial discharge inception electric field was deduced in the joint.

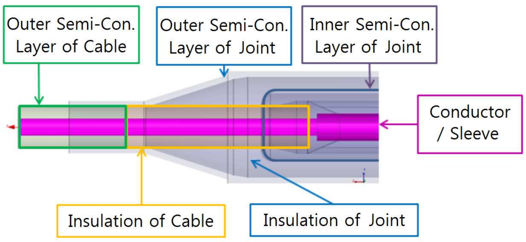
2. Methods of the Electric Field Calculation and the PD Experiment

2.1 Structure of the joint and the condition of electric field calculation

Fig. 1 shows the structure of the joint for the underground distribution power cable system, which consists of 3 main parts of outer-semiconductive layer, insulation layer and inner-semiconductive layer. The stress relief cone structure of the joint can relieve the high electric field due to the edge effect which appears at the edge of the outer-semiconductive layer of the cable.



(a) Photo of the distribution voltage grade straight joint



(b) Structure of the straight joint

Fig. 1. Cross-sectional view of the distribution voltage grade straight joint

During the installation of joints, the outer-semiconductive layer of the joint should overlap the outer-semiconductive layer of the cable, which makes it possible to relieve the electric stress. If the joint is not installed on the right position of the cable, the WP defect of the outer-semiconductive layer would be appeared. Fig. 2 shows higher electric field location due to the WP defect that can lead to the partial discharge initiation and breakdown.

60mm^2 22.9kV CNCV cable and the straight joint were used for this study, and their dimensions were adopted for the calculation of electric fields. The electric field of WP defects was calculated according to their sizes of 1cm, 2cm and 3cm, and their results were compared with the normal case (0cm). Especially, partial discharges initiating at the WP defect propagate through the interface between cable insulation (XLPE) and joint insulation (EPDM), and lead to interfacial electrical trees. Therefore, total electric field and the component of the interface direction were calculated. Table 1 shows various values for the electric field calculation.

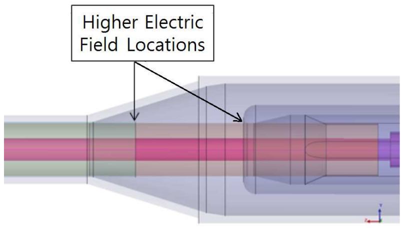


Fig. 2. Higher electric field strength location due to the WP defect

Table 1. Values for the electric field calculation(ε_r : dielectric constant, σ: conductivity [S/m])

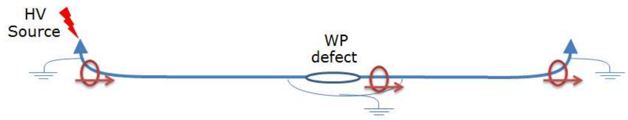
Component		Materials	Values	Applied Voltage
Joint	Inner-Semicon. Layer	EPDM + Carbon Black	ε_r: 3.5 σ: 10 S/m	13.2 kV
	Insulation	EPDM	ε_r: 3.5	
	Outer-Semicon. Layer	EPDM + Carbon Black	ε_r: 3.5 σ: 10 S/m	0 kV
Cable	Conductor	Cu	σ: 5.8×10^7 S/m	13.2 kV
	Inner-Semicon. Layer	EPDM + Carbon Black	ε_r: 3.5 σ: 10 S/m	13.2 kV
	Insulation	XLPE	ε_r: 2.25	
	Outer-Semicon. Layer	EPDM + Carbon Black	ε_r: 3.5 σ: 10 S/m	0 kV
	Sheath	Cu	σ: 5.8×10^7 S/m	0 kV

As mentioned above, the WP defect causes interfacial electrical trees along the interface and the breakdown occurs. Therefore, the tangential component of the electric field at the interface is the key factor to initiate partial discharge and the electrical tree. In this study, the total electric field, the tangential component, and the normal component at the interface were calculated respectively.

2.2 Partial discharge experimental method

For measuring PD inception voltage for the WP defect, the cable system was composed as shown in Fig. 3. The mid-joint having the WP defect was installed at 5m position in the 10m length 22.9kV CNCV cable. The PD free high voltage was applied to the termination at 0m position and PD sensors were installed at 0m, 5m and 10m position.

In this study, the standard partial discharge testing method according to the IEC 60270 was not adopted, but RFCT (Radio Frequency Current Transformer) with the frequency band of 1~200MHz as a PD sensor and 500MHz digital oscilloscope were just used for measuring partial discharges and the applied voltage.



(a) Scheme of the cable system and sensors

(b) Photo of the joint with WP defect and installed sensor

Fig. 3. Concept of the cable system for experiments and PD measurement

3. Results and Discussion

3.1 Electric field calculation result for WP defects

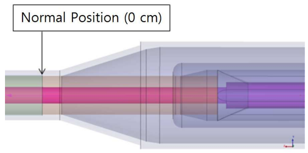
(1) Electric field calculation for the normal position

Before analyzing electric fields for WP defects, the calculation for the normal condition was done. Fig. 4 shows the electric field distribution of the interface between XLPE insulation of the cable and the joint insulation. Fig. 4(a) was the voltage distribution at the interface between XLPE insulation of the cable and the joint insulation. Fig. 4(b) was its total electric field at the interface, which shows the highest field point was the outer-semiconductive layer side.

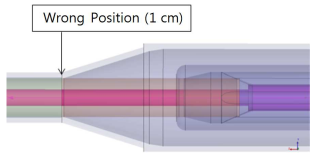
Fig. 4(c) and (d) were the tangential and normal component of the calculated electric field, respectively. The tangential component of the inner-semiconductive layer side was appeared higher than that of the outer-side. Tangential component of the electric field gives an effect to initiate the interfacial electrical tree, so that in the normal case PD would initiate first at the inner-side.

(2) Electric field calculation for wrong positioning (WP) defects

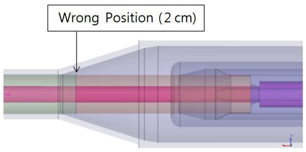
Fig. 5 shows the WP defect models with 0cm, 1cm, 2cm and 3cm for the electric field calculation. It can be easily seen that the outer-semiconductive layer of the cable was located more and more inside of the joint insulation with larger deviation and the length of the interface would be getting shorter.



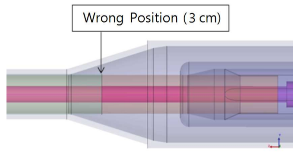
(a) 0cm normal position



(b) 1cm WP defect



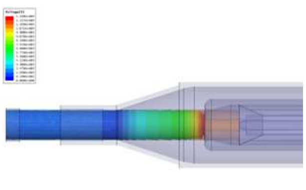
(c) 2cm WP defect



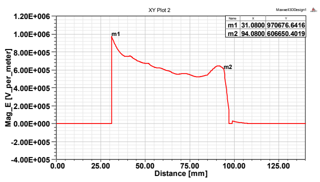
(d) 3cm WP defect

Fig. 5. Structure of wrong positioning(WP) defects

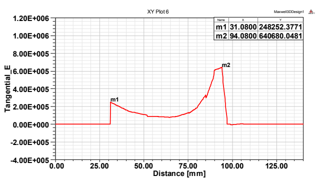
Simulation results for tangential component of the electrical field in various WP defects were shown in Fig. 6. In case of 1cm WP defect, electric field distribution as shown in Fig. 6(b) was similar to that of the normal position in Fig. 6(a), because the outer-semiconductive layer of the cable did not come out to the insulation layer of the joint in spite of 1cm deviation. On the contrary, in case of 2cm WP defect as shown in Fig. 5(c), the outer-semiconductive layer of the cable came out to the joint insulation, which results in higher electric field formation in the outer-semiconductive layer side as shown in Fig.



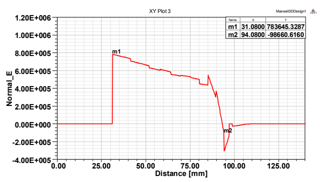
(a) Voltage distribution at the interface



(b) Total electric field at the interface

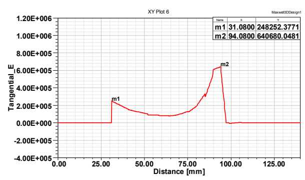


(c) Tangential electric field

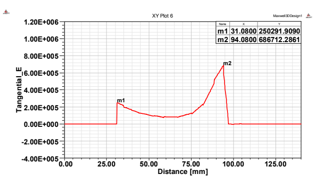


(d) Normal electric field

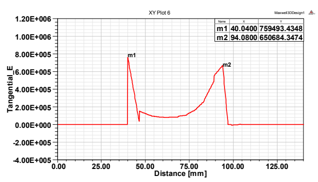
Fig. 4. Electric field analysis for the normal position



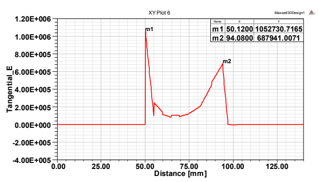
(a) 0cm normal position



(b) 1cm WP defect



(c) 2cm WP defect



(d) 3cm WP defect

Fig. 6. Calculation results of tangential electric field for WP defects

6(c). This result was different from the case of 2cm WP defect. Furthermore, in case of 3cm WP defect as shown in Fig. 5(d) and Fig. 6(d), the result was similar to that of 2cm case, and the higher electric field was appeared.

Table 2 shows calculated tangential electric fields of various WP defects with the applied voltage of 13.2kV. In the normal case and 1cm deviation case, tangential electric fields of the inner-semiconductive layer side of the joint were higher than those of the outer side. On the contrary, in the 2cm and 3cm deviation case, the result was reversed, that is, the field of the outer side was higher than that of the inner side, which means that partial discharges could initiate from the outer side first.

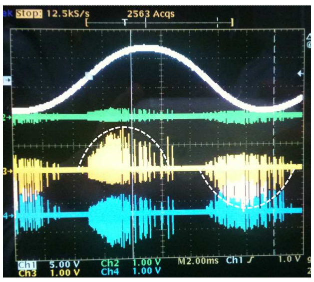
Table 2. Calculated tangential electric field of various WP defects (Applied voltage : 13.2kV)

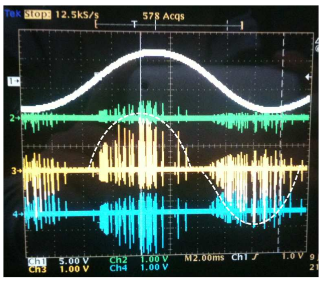
Deviation of wrong positioning	Calculated electric field [kV/mm]	
	Outer-semiconductive layer side of joint/cable	Inner-semiconductive layer side of joint
0cm	0.248	0.640
1cm	0.250	0.686
2cm	0.759	0.650
3cm	1.052	0.687

3.2 Experimental results of partial discharge inception voltage for wrong positioning (WP) defects

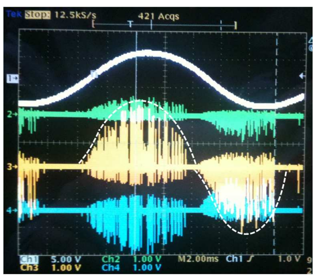
Fig. 7 shows PD inception voltages and PD patterns for WP defects. Here, CH1 was the applied voltage wave shape, and CH3 was the PD pattern measured at the joint (5m position) having the WP defect. (Dotted lines in CH3 were the reference lines of the PD patterns.) CH2 and CH4 were the PD patterns at the voltage applied termination (0m) and the opposite termination (10m) respectively as references. PD patterns of the normal case and 1cm deviation case in Fig. 7(a) and (b) showed similarly the void discharge-like pattern, and PD magnitudes were increased due to the deviation.

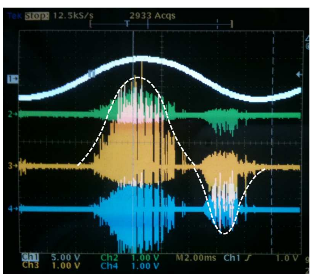
The PD patterns were changed with the defect size. In case of 2cm and 3cm deviation case as shown in Fig. 7(c) and (d), the shapes of PD pattern were different from those of other cases. Especially, in 3cm deviation case, the positive PD pattern showed larger magnitude than the negative one, which seems to be originated from different PD mechanism such as interfacial electrical trees.





(a) normal case (37.2kV) (b) 1cm WP defect (34.3kV)





(c) 2cm WP defect (32.1kV) (d) 3cm WP defect (24.4kV)

Fig. 7. PD patterns and inception voltages for WP defects

As shown in Fig. 8, the PD inception voltage of 3cm deviation case was abruptly decreased campared with those of other defects, which also implies that there must be some changes in the mechanism.

3.3 Comparison of calculated electric fields and PD inception voltages

In order to analyze the PD phenomena for WP defects, PD inception voltages were compared with calculated electric fields.

At first, PD inception electric fields were recalculated using calculated tangential fields (Table 2; voltage application of 13.2kV) and PD inception voltages (Fig. 8) for various WP defects. That is, the ratio of PD inception voltage and 13.2kV was multiplied to the calculated tangential field for each WP defect. As shown in Table 3, all the result was appeared to be similar with the average value of 1.84kV/mm, which implies that PDs initiated in various WP defects were due to similar mechanism.

And next, because the PD inception field was similar in all cases, that is, in each WP defect PD inception mechanism seems to be the same, the PD inception voltage(PDIV) could be calculated using normal case PDIV(37.2kV) and maximum calculated electric fields in Table 2. If PD would initiate at a certain electric field

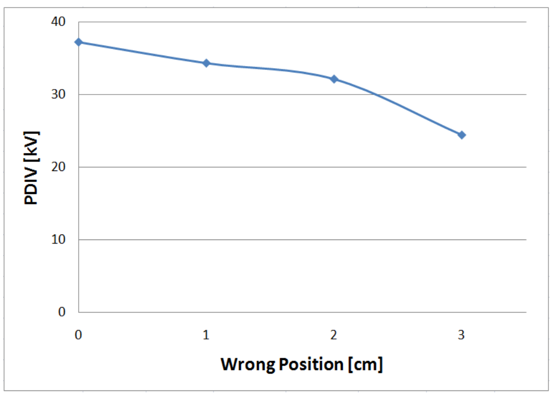


Fig. 8. Measured PD inception voltages according to the size of WP defects

Table 3. PD inception electric fields (tangential component) for WP defects

Deviation of wrong positioning	PD inception electric fields (tangential component) [kV/mm]	Average value [kV/mm]
0cm	1.804	1.844
1cm	1.783	
2cm	1.846	
3cm	1.945	

because of the same PD inception mechanism, PDIV for WP defects, $PDIV_{WP}$ can be calculated by following equation.

$$PDIV_{WP} = PDIV_{normal}\,(37.2\,kV) \times \frac{E_{\max-normal}\,(0.640\,kV/mm)}{E_{\max-WP}} \quad [kV]$$

Here, $PDIV_{normal}$: PDIV for normal case (37.2kV in Fig. 8)

$E_{max\text{-}normal}$: Maximum calculated electric field for normal case (0.640kV/mm in Table 2)

$E_{max\text{-}WP}$: Maximum calculated electric field for various WP defects (see Table 2)

The calculated $PDIV_{WP}$ were shown in Fig. 9, comparing with the measured PDIV as shown in Fig. 8. It is noticeable that the calculated value and measured one were almost equal.

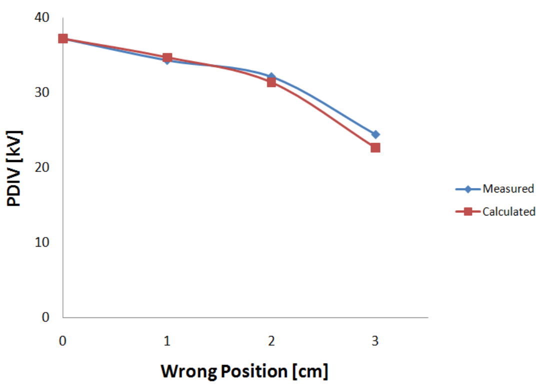


Fig. 9. Calculated and measured PDIV for various WP defects

4. Conclusion

From the electric field calculation and the PD measurement for various WP defects the conclusion could be deduced as follows ;

According to the WP defect size the maximum electric field was formed at the inner-semiconductive layer side or the outer-side, and in the larger defect case the outer-side showed the maximum electric field. However, in all cases the PD inception field calculated using measured PDIVs was similarly shown to be the average value of 1.84kV/mm. In addition, the calculated PDIV and the measured PDIV were almost equal, from the PDIV calculation using maximum electric fields and the measured PDIV for the normal case.

Throughout this study, it is possible to analyze WP defects due to the poor workmanship and to establish better joint design for the distribution grade extruded cable system.

Acknowledgements

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