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DEVELOPMENT OF AN INNOVATIVE RESIDUAL-CHARGE MEASUREMENT TECHNIQUE FOR WATER-TREE DETERIORATED XLPE CABLE

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ABSTRACT

Several diagnostic techniques for water-tree deteriorated XLPE power cable of 22-77kV class have been applied in JAPAN. Residual-charge measurement technique is one of them, and has been applied to 22/33kV-class XLPE power cables. In the conventional residual-charge technique, DC voltage application of -30kV for 22kV-class XLPE power cable is necessary for charge accumulation in water trees before following AC voltage application, however DC voltage is often restricted to be reduced to -10kV in some case. Therefore, we developed new residual-charge technique with cut-off AC voltage at phase angle 0 degree, which is the substitution for DC voltage application as pre-applied voltage. Electric charge accumulates in water tree during last AC half cycle, which is cut off at phase angle 0. In this paper effectiveness of this new technique in residual-charge measurement is presented, which has enabled to eliminate the some restriction in applying DC voltage. Some results of on-site tests are also presented.

KEYWORDS

residual charge, water tree, DC voltage, cut-off AC voltage

INTRODUCTION

It is well known that water-tree deterioration of XLPE power cable is one of the factors that decrease breakdown voltage. Therefore, several diagnostic techniques have been investigated in JAPAN. Residual-charge measurement technique, which was firstly developed in Central Research Institute of Electric Power Industry [1] and has been improved [2], is one of them.

In the conventional residual-charge measurement technique [1], total residual charge or residual charge per unit length (C/m etc.) is used as an index for determining the degree of water-tree deterioration.

Water tree degradation degree in not generally uniform in the whole length of each cable since surrounding condition of cable varies depending on the circumstances.

On the other hand, dielectric performance such as breakdown voltage strongly correlates to the longest (weakest) water tree. Therefore, accurate diagnosis is not possible by the conventional residual charge measurement technique, in which the total amount of residual-charge or residual charge per unit length are the index of diagnosis since they depend on the total amount of water trees.

Considering the above difficulty in diagnosis by using indexes which depend on the amount of residual charge, new residual-charge measurement technique has been developed [2]. In this technique, maximum electric field strength, at which residual charge is detected (Er), is used as the index of water-tree diagnosis. This index, released electric field strength, is measured as follows. (1) Step-like increased AC voltage is applied to the cable, (2) Residual charge is measured at each voltage step and (3) The maximum electric field at which residual charge is detected shall be Er. This is named as “step-like AC voltage application method”. It is reported that Er corresponds to the longest water tree and not to correspond to the number of water trees. Hence, diagnosis result is independent of the length of cable. The effectiveness of this technique has been also confirmed by on-site tests.

“Step-like AC voltage application method” is effective, but this technique also requires DC voltage application to accumulate charge in water trees before following AC voltage application as conventional ones. DC -30kV is usually applied to 22kV-class cables, but this DC voltage application is restricted to be reduced to -10kV in some case due to the GIS termination structure and so on. From this point of view, we have investigated the possibility of diagnosis with DC -10kV voltage application and have confirmed that it is possible in this case. However, detected charge signal becomes smaller than the case of DC -30kV. It may lead to a less reliability of diagnosis.

To eliminate this inconvenience due to DC -10kV application, we have developed the residual-charge technique without DC voltage application combined with “step-like AC voltage application method”. The remarkable feature of the new technique is that no DC voltage application is required throughout the whole measurement procedure including charge accumulation in water trees. In this technique, AC voltage cut off at phase angle of 0 degree is used for charge accumulation in water tree instead of DC voltage. This AC voltage is named as “cut-off AC voltage” in this paper. Cut-off AC voltage gives many advantages, not only the elimination of DC voltage application but also the reduction of total measurement time due to the substitution of 10 minutes DC voltage pre-application to 10 seconds cut-off AC voltage pre-application.

We have confirmed that residual charge can be detected as a larger signal than in case of DC -10kV application and that there is a strong correlation between maximum released electric field strength and breakdown electric field strength with cut-off AC voltage application.

EXPERIMENTAL

Tested samples

The details of tested samples are listed in table 1. All samples were 22kV-class field aged XLPE power cables for 24 to 37 years. Totally, 59 samples were tested.

Table 1: Tested samples

Voltage	Conductor size	Aged duration	Length
22kV	150 to 250mm^2	24 to 37 years	100 to 273 m

Testing conditions

Residual-charge measurement

Residual-charge measurement was carried out by using cut-off AC voltage application for all samples at ambient temperature. Measurement conditions are shown in table 2 and the procedure is schematically shown in figure 1

Cut-off AC voltage is 12.5kV, which is the same voltage level as the line-to-ground voltage in service. Cut-off AC voltage as a pre-voltage is raised up to 12.5kV in about 5 seconds, its 12.5kV is maintained for about 10 seconds, and is cut off at the phase angle of 0 degree. Cut-off operation is follows after finishing the negative half cycle AC waveform.

Following AC voltage application procedure for residual charge measurement is carried out as follows; initial voltage 2.5kV is applied and voltage increment is 2.5kV step up to final voltage of 12.5kV (see figure 1).

Table 2: Residual-charge measurement conditions

	Procedure
Pre-voltage	[Cut-off AC voltage application] Voltage:up to 12.5kV by 5 seconds, Maintain time: ca. 10 seconds Cut-off phase degree: 0 degree
Residual-charge measurement	[Step-like voltage application] Initial voltage 2.5kV Voltage increment 2.5kV Final voltage 12.5kV

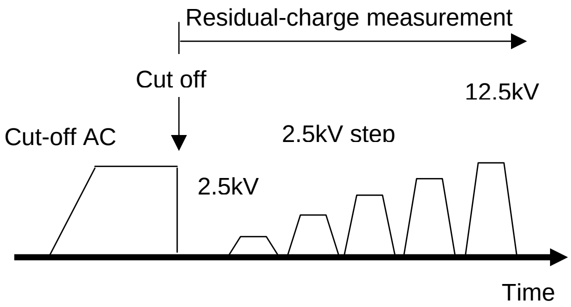

Figure 1: Procedure in case of cut-off AC voltage application

AC breakdown tests

AC breakdown tests were carried out to all samples under the conditions as shown in table 3. Tests were carried out at ambient temperature.

Table 3: AC testing conditions

	Conditions
First voltage	12.7kV/10minutes
Second voltage	20kV/10minutes
Voltage increment after second voltage	5kV/10minutes

RESULTS AND DISCUSSIONS

Residual-charge signal by cut-off AC voltage application

In this section, basic test results by cut-off AC voltage application method are described.

Applied cut-off AC voltage is shown in figure 2 as an example. Figure 2 shows the case of cut-off phase angle of 0 degree. In this case, final half cycle of negative polarity contributes to the charge accumulation in water tree.

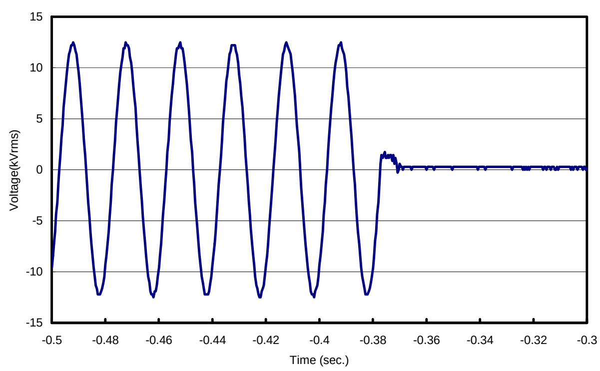

Figure 2: Example of cut-off AC voltage waveform

For example, Residual-charge current signal by cut-off AC voltage application method is shown in figure 3. Figure 3 shows residual-charge current signal after application of cut-off AC voltage at 12.5kV and cut off phase angle of 0 degree as pre-applied voltage. This residual-charge is measured at AC 12.5kV. Residual-charge current signal is indicated as positive polarity in case of negative pre-applied voltage. It is confirmed that this measured residual-charge current is the same as when negative DC voltage was applied.

To confirm whether final half cycle of cut-off AC pre-applied voltage is effective for charge accumulation in water trees, residual-charge measurements were carried out at various cut-off phase angle of AC pre-applied voltage.

Figure 4 and 5 show residual-charge current signals of the same sample. Figure 4 is the result when 12.5kV AC pre-applied voltage was cut-off at phase angle 0 degree and figure 5 at phase angle 180 degree, respectively. The absolute amount of two residual-charge currents (figure 4 and 5) is almost the same but just the polarity is opposite. This indicates that only the final half cycle just before AC voltage cut-off is effective for charge accumulation in water trees.

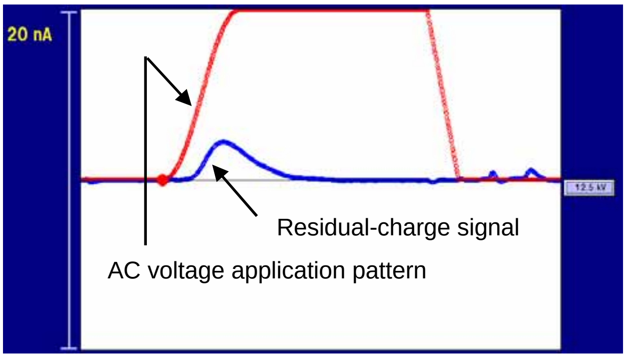

Figure 3 Residual-charge signal measured by cut-off AC voltage application

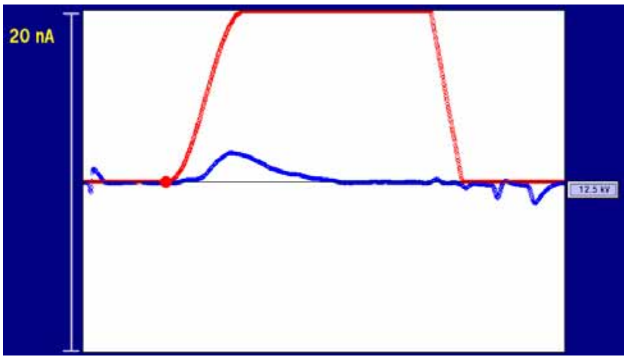

Figure 4: Residual-charge signal measured by cut-off AC voltage application method (cut-off phase angle : 0 degree)

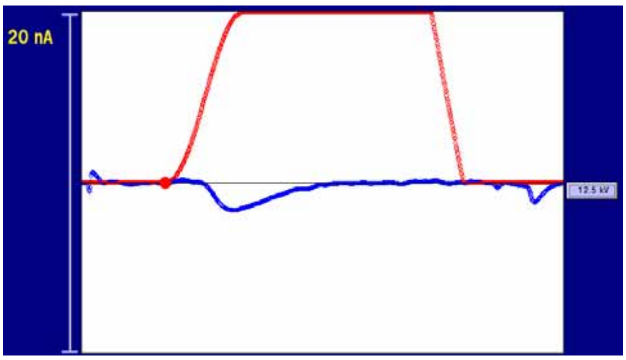

Figure 5: Residual-charge signal measured by cut-off AC voltage application method (cut-off phase angle : 180 degree)

Figure 6 shows residual-charge current signal obtained by DC -10kV application as preas pre-applied voltage. The same sample is used as in the figure 3. By the comparison of the residual charges in figure 3 and figure 6, which can be calculated by integration of the signal, residual charge by cut-off AC voltage application method is about 1.4 times lager than that of DC -10kV DC voltage application. This result indicates that cut-off AC application method can get lager signal than in case of DC -10kV application.

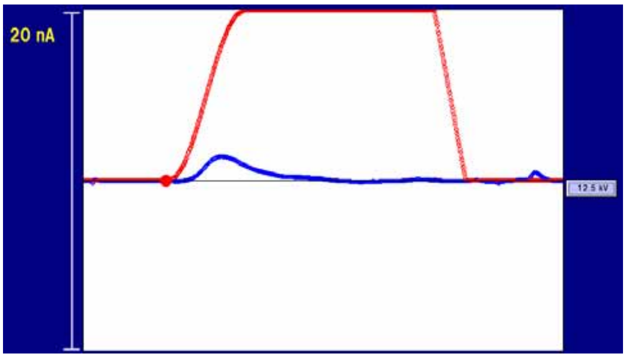

Figure 6: Residual-charge signal measured by DC -10 kV application

Relationship between E_r and E_{BD}

Figure 7 shows the relationship between maximum released electric field strength (E_r) and breakdown electric field strength (E_{BD}).

As shown in figure 7, there is a strong correlation between E_r and E_{BD}, that is, E_{BD} clearly decreases with Increase of E_r. Correlation coefficient between them is -0.887. This is basically the same tendency as that has been reported in DC pre-applied voltage [2].

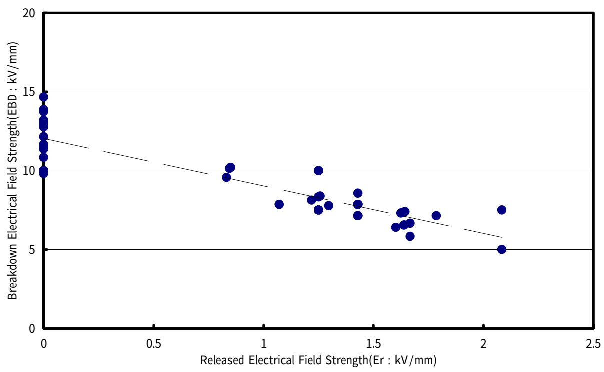

Figure 7: Relationship between E_r and E_{BD}

Table 3: Estimated breakdown voltage

V_r	Estimated breakdown voltage
0kV	60.0 kV<
2.5kV	~56.3 kV
5.0kV	~48.8 kV
7.5kV	~41.2 kV
10kV	~33.7 kV
12.5kV	~26.2 kV

This result clearly shows that cut-off AC voltage application method is capable for diagnosing water-tree deterioration of XLPE power cable. Moreover, considering the larger residual-charge amount at cut-off AC pre-applied case than that of DC -10kV pre-applied case, its reliability in diagnosis shall be higher than that of DC -10 kV pre-application.

Using this relationship for cut-off AC voltage application method, breakdown voltage can be estimated. Estimated breakdown voltages against V_r are shown in table 3.

Residual-charge measurement for combined samples of different degree of degradation

In the field-installed cable lines, the degree of water-tree deterioration of each cable in the whole length shall be different due to the difference of the circumstances along with the cable route. To confirm the effectiveness of this new method before on-site tests, 4 samples with different degree of water-tree deterioration, that is, cables showing different E_r are selected. Residual-charge measurements by cut-off AC pre-voltage application with step-like AC voltage application were carried out in combined samples composed of 3 or 4 samples out of them. Profiles of selected samples and combined conditions are shown in table 4 and 5, respectively.

Table 4: selected samples

Samples	Voltage and size	Aged duration	Length
A	22kV/150mm^2	34 years	160m
B	22kV/150mm^2	34 years	100m
C	22kV/250mm^2	32 years	125m
D	22kV/250mm^2	32 years	161m

Table 5: Assembling conditions

	Phase	Sample			
		A	B	C	D
Case1	R	Joined	Joined	Joined	-
Case2	B	Joined	Joined	Joined	-
Case3	W	Joined	Joined	Joined	-
Case4	R	Joined	-	Joined	Joined
Case5	B	Joined	-	Joined	Joined
Case6	W	Joined	-	Joined	Joined
Case7	R	Joined	Joined	Joined	Joined
Case8	B	Joined	Joined	Joined	Joined
Case9	W	Joined	Joined	Joined	Joined

Table 6: Results of residual-charge measurement

	Phase	Sample / Each V_{r_each}				Total V_{r_total}
		A	B	C	D	
Case 1	R	7.5kV	7.5kV	5.0kV	-	7.5kV
Case 2	B	7.5kV	7.5kV	7.5kV	-	7.5kV
Case 3	W	7.5kV	10kV	5.0kV	-	10kV
Case 4	R	7.5kV	-	5.0kV	2.5kV	7.5kV
Case 5	B	7.5kV	-	7.5kV	5.0kV	7.5kV
Case 6	W	7.5kV	-	5.0kV	5.0kV	7.5kV
Case 7	R	7.5kV	7.5kV	5.0kV	2.5kV	7.5kV
Case 8	B	7.5kV	7.5kV	7.5kV	5.0kV	7.5kV
Case 9	W	7.5kV	10kV	5.0kV	5.0kV	10kV

Measured Er in each sample of cable phase (A~D) is shown as V_{r_each} in table 6. Measured Er in combined cables is shown as V_{r_total} in the column of 'Total' in table 6.

As shown in Table 6, each V_{r_total} is the same as the maximum V_{r_each} in all cases. It indicates that even in the cables having different degree of water-tree deterioration, the worst degree of water-tree deterioration can be efficiently detected. This indicates that the new technique shall be effective on site.

On-site testing

It is confirmed that the residual-charge measurement by cut-off AC pre-applied voltage method is effective as shown in the above. Therefore, we have investigated the on-site effectiveness in several field lines. We have estimated 8 lines with lengths form 750m to 2200m.

In these estimations, residual-charge measurements by DC -10kV pre-applied voltage are also carried out to compare the results by cut-off AC pre-voltage application method.

Measured Er by each method are the same in all cases at present. These on-site test results clearly show the effectiveness of this new method in on-site application.

CONCLUSIONS

We have developed cut-off AC pre-applied voltage method as a substitution of DC voltage pre-applied voltage method in residual-charge measurement. This method eliminates the difficulty in applying DC voltage in some field-testing cases.

In this paper, residual-charge measurement technique by cut-off AC pre-applied voltage method is described and its effectiveness is also reported with some on-site testing results.

The conclusions are summarized as follows.

1) Residual-charge by cut-off AC pre-applied voltage can be obtained as a larger signal than in case of DC -10kV pre-applied voltage.
2) It is confirmed that final half cycle just before AC voltage cut-off is effective for charge accumulation in water trees.
3) It is confirmed that strong correlation appears between Er obtained by cut-off AC pre-applied voltage method and breakdown electric field strength.

4) The effectiveness of the new technique is confirmed by investigation of combined samples and on-site testes.

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