Estimating the Remaining Life of Water-Treed XLPE Cable by VLF Voltage Withstand Tests

*by Katsumi Uchida *, Yoichi Kato *, Masahiko Nakade *2, Daisuke Inoue *2,*
*Hiroyuki Sakakibara *3 and Hideo Tanaka *3*

ABSTRACT The authors have developed a method that uses very low frequency (VLF) voltages to estimate the remaining life of lines using 22- to 77-kV XLPE cables that have undergone water-tree degradation. VLF testing has been considered the most effective form of voltage withstand testing from the standpoints of the size of the test equipment, water-tree detection capability, and test soundness. Breakdown tests were carried out on field-aged cables and model cables, and the relationship between water-tree degradation and breakdown level was investigated. A database of the results was subjected to statistical analysis, and a novel method is proposed for determining a test voltage that makes it possible to estimate the remaining life of 22- to 77-kV XLPE cables; a suitable test voltage was determined. Based on these results, prototype field test equipment was built, on-site tests were carried out, and satisfactory results were obtained.

1. INTRODUCTION

Water-treeing is typical of the processes involved in the aging of XLPE cables, and it is known that it causes degradation of insulation performance. The occurrence and proliferation of these water trees interfere with the proper operation of the lines, and this has resulted in a strong need for techniques to diagnose water-tree degradation. Information on how many years of service remain in the cable is particularly essential to the stable management of power line operation.

In XLPE cables for 22- to 77-kV service, on the other hand, there is a particular need to detect non-bridging water trees--that is to say water trees that do not bridge the insulation 1). In such cases the degradation signal from the water tree is extremely small, and such methods of diagnosing degradation have not been implemented on practical lines. The authors' attention was therefore drawn to voltage withstand testing as a method that enables both the detection of non-bridging water trees and the estimating of the remaining life of a line.

First of all we considered the waveform of the voltage to be used in the test from the standpoint of applicability to field testing, and it was determined that the most effective for water-treed cable was very low frequency (VLF) high-voltage. We then made a detailed investigation of the breakdown characteristics of water-treed cable, and based on a statistical analysis of the results proposed a method of finding the most suitable test voltage. We also confirmed that these voltages did not have an adverse effect on aged XLPE cables.

Based on these research results prototype on-site testing equipment was built, and field tests were carried out.

2. SELECTING VOLTAGE WITHSTAND TEST WAVEFORM

Normally voltage withstand testing is carried out using either commercial-frequency alternating current (AC) or direct current (DC). These waveforms are unsuitable to on-site testing, however, for the reasons set forth below. First of all for AC, extremely bulky equipment is required to apply voltages greater than the operating voltage, making on-site testing impracticable. For DC, on the other hand, the equipment for providing the voltage is simple enough but grounding trees are easily started, raising problems of soundness 1). We thus realized that in on-site voltage withstand testing it is desirable that the test equipment should:

1) be lightweight and compact;
2) have defect detection capability; and
3) cause no damage to the lines.

The test waveform that most fully satisfies these criteria may be said to be the most suited to withstand voltage testing. The authors conducted experiments regarding items 2 and 3 above using AC and DC, which have traditionally been used for voltage withstand testing, plus VLF

---

* Chubu Electric Power Company
*2 Tokyo Electric Power Company
*3 Energy Transmission Dept., Ecology and Energy Laboratory

and oscillating wave (OSW), which raise the promise of reduced equipment size[2), 3)].

First of all, to determine detection capability using the various waveforms, breakdown tests were carried out using cables[6), 7)] which were provided with water-tree models. Figure 1 shows the breakdown values for the waveforms as multiples of AC. As can be seen the water-tree breakdown voltage was lowest for AC, followed by VLF and OSW, with DC being the highest.

Next we investigated damaging effects. Cables affected by water-treeing have water trees of varying degrees of degradation, and we have assumed the presence both of those that will not cause damage to operation in the immediate future and those that are damaging to operation. In voltage withstand tests, when operationally damaging water trees break down, it is not permissible for the characteristics of water trees that are not immediately damaging to be changed. Specifically if, as exemplified by grounding trees, electrical trees are generated from non-damaging water trees, there will be a significant drop in cable insulation performance. From the above considerations, the breakdown tests were carried out under various voltages using cables provided with a plurality of water-tree models. Depending on the breakdown test, breakdown might occur in one water-tree model, but not in another using the same cable. The tip of the model that did not suffer breakdown was then examined and a check was made as to whether electrical trees had been generated or not.

It was found that AC and VLF presented a very low possibility of electrical trees being generated, but that with DC and OSW they were generated readily.

Based on the test results described above we classified the four withstand voltage test waveforms according to how they satisfied the three criteria. Table 1 shows the results.

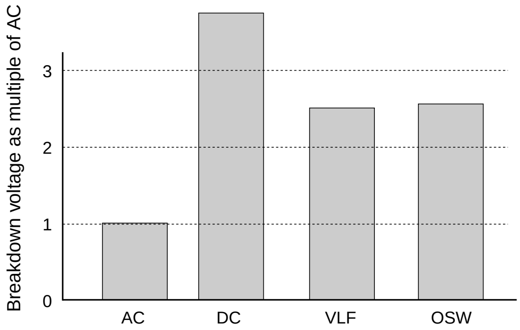

Figure 1 **Comparison of AC, DC, VLF and OSW breakdown voltages during water-tree detection**

Table 1 **Suitability of selected waveforms in voltage withstand tests**

Waveform	Scale of equipment	Water-tree detection capability	Soundness
AC	×	◎	○
DC	◎	×	×
VLF	○	○	◎
OSW	○	○	×

◎: Suitable; ○: OK; ×: Unsuitable

AC provides high water-tree detection capability but bulky test equipment is required to apply voltages in excess of the operating voltage, and can thus not be regarded a suitable as the waveform for use in voltage withstand tests.

DC test equipment is the most lightweight and compact, but its water-tree detection capability is inferior, and it fails in suitability with respect to causing damage.

In the case of VLF, the test equipment can be made lighter and more compact than for AC, and it is second only to AC in terms of water-tree detection capability. It is also superior in terms of cable soundness, and may be considered suitable as the voltage withstand test waveform.

Finally, OSW is the equal of VLF in terms of the size of the test equipment and water-tree detection capability, but with respect to causing damage, cannot be considered suitable.

It was therefore concluded that VLF was the most suitable waveform for use in voltage withstand testing of water-treed cables.

3. AC AND VLF BREAKDOWN VOLTAGES OF WATER-TREED XLPE CABLES

The results obtained as described in Section 2 above demonstrated that the VLF voltage provided the best means for voltage withstand testing of cables with water-tree degradation. To study the conditions for VLF voltage withstand testing we conducted a detailed investigation of AC and VLF breakdown voltage using field-aged cables and model cables. The AC breakdown voltage was obtained by carrying out AC breakdown tests on model cables and by surveying the literature[1)] relating to AC pre-interruption tests on 22- to 77-kV field-aged cables. The VLF breakdown voltage, on the other hand, was obtained by carrying out VLF breakdown tests and pre-interruption tests on model cables and field-aged cables.

Figure 2 shows the relationship between the AC breakdown value and the residual insulation thickness. Here, residual insulation thickness is an index of water-tree degradation, being the length of the sound portion of insulation--the cable insulation thickness minus water-tree length. Thus a smaller value of residual insulation thickness means that water-treeing is more advanced.

The data shown in Figure 2 is for different insulation classes ranging from 22 to 77 kV and the dotted lines show the cable insulation thickness for each of the classes. From the same figure it may be taken that AC breakdown voltage (nominal values shown) shows dependence on residual insulation thickness (though with some deviation) for both model cables and field-aged cables, but may be considered to be as shown by the curves in the figure. That is to say in the region in which water-treeing is not particularly advanced and the residual insulation thickness

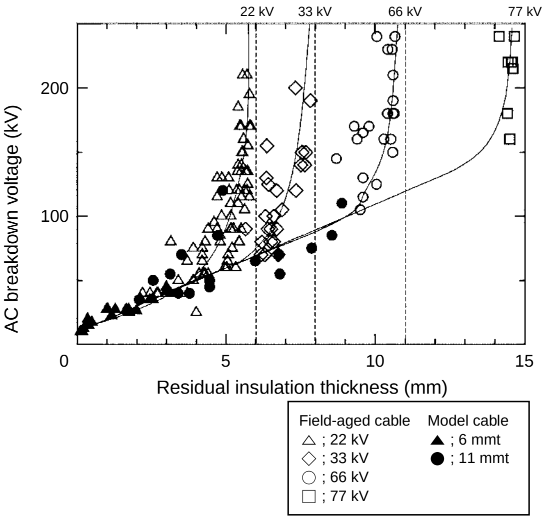

Figure 2 **AC breakdown (pre-interruption) voltage as a function of residual insulation thickness**

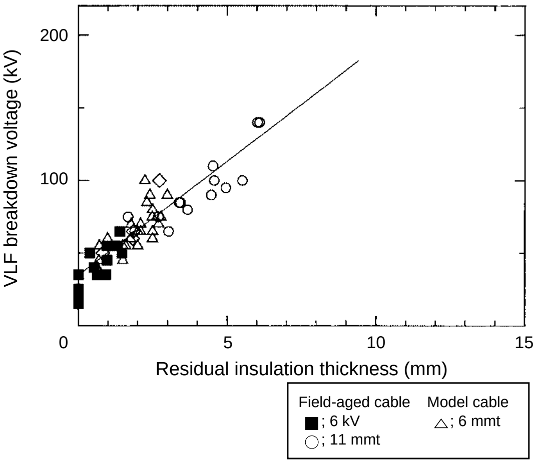

Figure 3 **VLF breakdown (pre-interruption) voltage as a function of residual insulation thickness**

in the water-treed portion is substantially the same as the insulation thickness, the breakdown voltage drops precipitously with a reduction in residual insulation thickness. When water-treeing becomes further advanced and the residual voltage thickness is about 2 mm less than the insulation thickness, the breakdown voltage continues to drop gradually.

The breakdown values in this region where the residual insulation thickness is small followed the same characteristics curve irrespective of differences in cable insulation thickness. This means that the breakdown voltage is determined by the electrical field at the tip of the defect, and is an acceptable result. When the residual insulation thickness becomes larger, the breakdown voltage is affected by insulation thickness due to the effect of the background electrical field. Since life diagnosis is targeted at cables in which the breakdown voltage has dropped within the operating voltage region, it is thought that even for cables of differing insulation class, breakdown value characteristics can be evaluated using the same curve.

Figure 3 shows the relationship between the VLF breakdown value (shown as peak value) and residual insulation thickness. It can be seen that for VLF too, the breakdown value is dependent on residual insulation thickness. It can also be seen that since the data are for regions in which the residual insulation thickness is less than half the insulation thickness, that breakdown voltage follows the same curve as it does for AC.

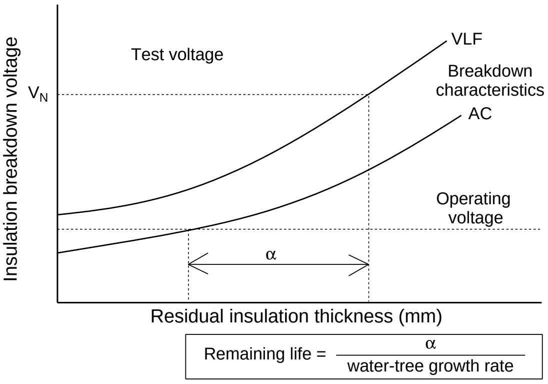

Figure 4 **Basic method of estimating remaining life**

The test voltage is found on the basis of this type of data on the rate of water-tree growth, plus the residual insulation thickness dependence of AC and VLF breakdown values shown in Figures 2 and 3.

4. CONCEPT OF ESTIMATING CABLE LIFE BY VOLTAGE WITHSTAND TESTS

We then considered methods of estimating the remaining life of water-treed cables by means of VLF voltage withstand tests.

Figures 2 and 3 demonstrated the characteristic that the smaller the residual insulation thickness (i.e., the longer the water trees), the lower the insulation breakdown voltage will be. Figure 4 shows the relationship between insulation breakdown voltage and residual insulation thickness, illustrating the behavior whereby, as water trees grow and residual insulation thickness is reduced, the insulation breakdown voltage drops until breakdown occurs at the operating voltage.

Defining α in Figure 4 as the difference between that value of residual insulation thickness at which breakdown occurs at the test voltage and that value at which breakdown occurs at the operating voltage, we may estimate that those cases passing at the test voltage have a remaining life greater than the product of α and the rate of water-tree growth. Conversely the required test voltage can be set by deciding the years of remaining life that it is desired to find.

As can be seen from Figures 2 and 3, however, there is a deviation or dispersion in breakdown voltage. Thus the voltage withstand characteristics shown in Figure 3 have a certain breadth, depending on the deviation. Accordingly when aged cable is subjected to voltage withstand tests we can expect to produce four types of test results, as shown in Table 2, depending on whether it passes the

VLF voltage withstand test or not, and whether breakdown occurs at AC operating voltage within the evaluation period or not (whether it is safe or not in the immediate future).

Under an ideal voltage withstand test, cables that can continue in service will pass the voltage withstand test and only those cables incapable of further service will suffer breakdown in the voltage withstand test. In actual practice, however, cables capable of further use may suffer breakdown in the voltage withstand tests and cables that pass the voltage withstand tests may break down in operation. This is because of false results from the voltage withstand tests.

With conventional voltage withstand tests, there was an emphasis on being sure to produce breakdown in damaged cables, and where there was a dispersion in breakdown voltages, it was more common to try to be on the safe side, by, for example, taking the minimum value. This made sure that damaged cables were indeed withdrawn from service but there was a strong possibility that cables capable of further service were also withdrawn. From the standpoint of the efficient operation of the equipment, however, what is necessary is to reduce false results and thereby raise evaluation accuracy, rather that working on the safe side.

Accordingly we developed a technique 7) for determining the appropriate withstand test voltage by carrying out a statistical analysis of breakdown voltages and calculating the probabilities that the four possible types of result described above would be obtained at various VLF voltages.

By using this statistical analysis to find test voltages for evaluating a remaining life of three and five years for water-treed cables of 22- to 77-kV, the voltages shown in Table 3 were deemed suitable, with the exception that for 66- and 77-kV cables there are still aspects to be studied, so the conditions are provisional.

When the voltage withstand tests at the above test voltage were passed by quantitative evaluation using statistical analysis, there was a 97% probability that breakdown would not occur within the estimated remaining life, suggesting that estimating the remaining life can be achieved with sufficient accuracy.

Table 2 Four examples of VLF test results

		Test result	
		Fail	Pass
AC operating voltage	Unsafe	Accurate	False
	Safe	False	Accurate

Table 3 VLF test voltages for XLPE cables rated 22~77 kV

Insulation class	Years of life estimated	
	3	5
22 kV	50 kV_p	53 kV_p
33 kV	60 kV_p	65 kV_p
66 kV	95 kV_p	100 kV_p
77 kV	110 kV_p	115 kV_p

Note: Values for 66 and 77 kV are under provisional conditions

5. FIELD TEST EQUIPMENT AND ON-SITE VOLTAGE WITHSTAND TESTS

To apply the results of the above studies on site, prototype field testing equipment was built and voltage withstand tests were carried out on an practical line.

Figure 5 is a photograph of the field testing equipment, and Table 4 gives its specifications. The equipment is owned by the Chubu Electric Power Co. The VLF generator is of a 2-stage cascade design. VLF voltage withstand tests for 22/23-kV class cables are performed by Stage 1, and for 66/77-kV class cables by Stage 2.

On-site voltage withstand tests were performed in May 1999 on 33-kV XLPE cable for Chubu Electric Power and in February 2000 on 66-kV XLPE cable for Tokyo Electric Power. The specifications of the lines on which the voltage withstand tests were performed were as shown in Table 5.

In all cases, voltage was applied to the line 3 phases simultaneously, as shown in Figure 6, by an energizing from an air sealing end on the substation side.

Figure 7 is a photo of the voltage withstand test setup.

All tests ended without breakdown, and it was estimated that the line had a life expectancy of three years more.

Table 6 shows the time required for the testing of 66-kV XLPE cable. The Table separates the work done with the

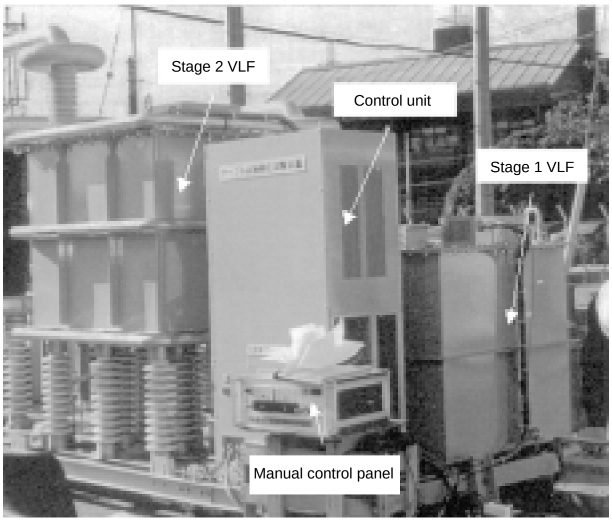

Figure 5 VLF high-voltage generator

Table 4 Specifications of VLF high-voltage generator

Specification	Stage 1	Stage 2 cascade
Voltage generated	VLF 85 kV_p	VLF 170 kV_p
Load capacitance	2 μF	1 μF
Frequency	0.01~0.19 Hz	
Weight of equipment	Approx. 2 t	Approx. 4 t

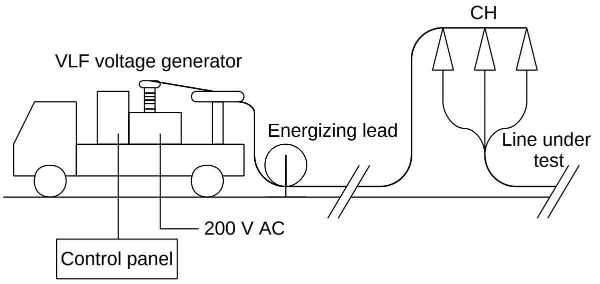

Figure 6 Setup for on-site VLF voltage withstand test

Figure 7 VLF voltage withstand test for 66-kV XLPE cable

Table 5 Cable lines for on-site VLF voltage-withstand tests

Cable tested	33 kV	66 kV
Years elapsed	27	22
Cable type	Triplex type; 3x150 mm^2	Triplex type; 3x80 mm^2
Length of cable	Approx. 150 m	Approx. 260 m
No. of straight-through joints	1	2
Laying configuration	Part in conduit, part direct-laid	
Sealing ends	EB-A at both ends	EB-A at both ends (one end on tower)
Test conditions	VLF 60 kV$_p$ for 10 min	VLF 60 kV$_p$ for 10 min*

* 66-kV cable tested under provisional conditions

Table 6 Time required for VLF voltage withstand test

Power on		Power off	
Procedure	Time (min)	Procedure	Time (min)
Preparation	60		
		Connecting lead to tower	90
		Calibrating voltage (no load test)	20
		Measuring insulation resistance	20
		VLF voltage withstand test	20
Clear-up	60		
Total	120	Total	150
Grand total 270 min			

power turned on from that done with power off. Thus we see that VLF voltage withstand testing allows tests to be carried out extremely easily.

VLF voltage withstand tests require no special measurements, and no special measures against on-site noise or the like need be taken on site. The testing method is a simple one, so that the remaining life of the line can be estimated with a simple pass or fail.

It is also considered from the results obtained that performing VLF voltage withstand tests on-site will present no problems, and that the way has been cleared for practical VLF voltage withstand testing of XLPE cables. As our track record in on-site VLF voltage withstand testing accumulates, we propose to establish techniques for estimating the remaining life of cable lines.

6. CONCLUSION

Voltage withstand tests of XLPE cables with water-tree degradation have been carried out using very-low frequency (VLF) voltage, and we have assessed testing methods for estimating remaining cable life. It is felt that VLF voltage withstand testing is the most effective method of voltage withstand testing from the standpoints of size of the test equipment, water-tree detection capability, and cable soundness.

A survey was made of the AC and VLF breakdown characteristics of both field-aged cables and model cables, and the relationship between water-tree length and breakdown voltage was investigated. These data were subjected to statistical analysis, a new method of estimating the remaining life of 22- to 77-kV water-treed XLPE cables was proposed, and a suitable test voltage was determined.

Based on the results obtained, prototype field testing equipment was built, on-site tests were carried out, and good results were obtained. We intend to continue accumulating field data.

REFERENCES

1) High Voltage XLPE Cable Insulation Diagnosis Technology Research Committee: Degradation Mode of High Voltage XLPE Cable Insulation and Trends in its Diagnosis Technology, IEEJ, Technology Report No.668, 1998 (in Japanese)
2) K. Uchida, S. Kobayashi, T. Kawashima, H. Tanaka, S. Sakuma, K. Hirotsu, and H. Inoue: "STUDY ON DETECTION FOR THE DEFFECTS OF XLPE CABLE LINES", IEEE Trans. on Power Delivery, vol.11, No.2, pp663-668 (1996)
3) P. Gronefeld and R. von Olshausen: "TREE INCEPTION AND PROPAGATION IN POLYETHYLENE AT 0.1 Hz AND 50 Hz AC

VOLTAGE", 5th International Symposium on High Voltage Engineering, 21.10 (1987)

4) R. Bach and W. Kalkner: "Comparison of different voltage types for the evaluation of layed medium voltage cables", 8th International Symposium on High Voltage engineering, 61.04 (1993)

5) J. Y. Koo, J. T. Kim, S. J. Kim, I. K. Song, J. Y. Kim, and Y. O. Cho: "A study on the oscillating wave voltage test as an after-laying test for distribution power cables", Conf. on Electrical Insulation and Dielectric Phenomena, Minneapolis, October 19-22, (1997)

6) Uchida et al.: Remaining Life Estimation of Water Treed XLPE Cables by VLF (Very Low Frequency) Voltage Withstand Test, Report of Wire and Cable Research Group, IEEJ, EC-99-8, (1999) (in Japanese)

7) Uchida et al.: Life Estimation of Water Treed Cables by Very Low Frequency Withstand Test, Trans. IEEJ, Vol.120-B, No.11 (in Japanese)

Manuscript received on November 27, 2000.