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SURGE PROPAGATION AND PROTECTION OF UNDERGROUND DISTRIBUTION CABLES

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ABSTRACT

The lightning surge and switching surge could be injected to the underground distribution line through the riser pole in the mixed distribution line of overhead and underground. These surges travel along the cable and are reflected at the end of cable. It can be doubled and affecting underground distribution facilities.

We made a underground distribution model representing KEPCO's distribution system. We measured propagation characteristics by applying lightning surges to this underground distribution model. Meanwhile, we simulated this system with ATP-EMTP and compared these results.

There were differences between real test measurements and EMTP simulated results. Those differences come from cable parameters and surge wave shapes. To minimize those differences, relative permittivity of the cable insulation material must be measured from the real cable and surge source type should be used.

To protect underground distribution system from surge, arrester should be installed at the open terminal in which doubled voltage are reflected.

KEYWORDS

URD, Surge, Protection, EMTP, Cable

INTRODUCTION

Underground distribution of Korean distribution system became 12% in 2006, and in Seoul 50%. The more economy grows, the more underground distribution system increases.

Overhead distribution lines are protected from lightning by installing arresters, while underground distribution lines have the only riser pole arrester. In the underground distribution line, during lightning surge discharge through arrester residual voltage is applied to the cable and travel along the cable line. This traveling surge is reflected at the terminal with doubled voltage and travels again. This traveling surge could make a fault at the weakened insulation point.

To analyze traveling surge mechanism and solve the problem, we constructed a field test model of underground distribution line and applied impulses and measured voltages. We also simulated our test model with ATP-EMTP(Electro-Magnetic Transient Program) and compared the results of field test and EMTP simulation. To accord EMTP results with field test results, we tuned parameters of EMTP. Until now it has been rare to verify EMTP simulation results by field test results. Therefore the result of EMTP not accepted easily.

If EMTP parameters fixed precisely we can simulate various cases which are difficult to test in the real underground distribution system. Through this process we can make a solution for the surge protection of underground distribution system.

CONSTRUCTION OF UNDERGROUND DISTRIBUTION LINE FOR TEST

We constructed a underground distribution line for test with cables, pad-mounted switchgears and pad-mounted transformers used in Korea. Four switchgears, three transformers, two type of cables and joints are installed onto the 4 circuits of 250 m long. This test line connected to the impulse generator through about 100 m long cable.

Line length and branching can be varied by switchgear operation.

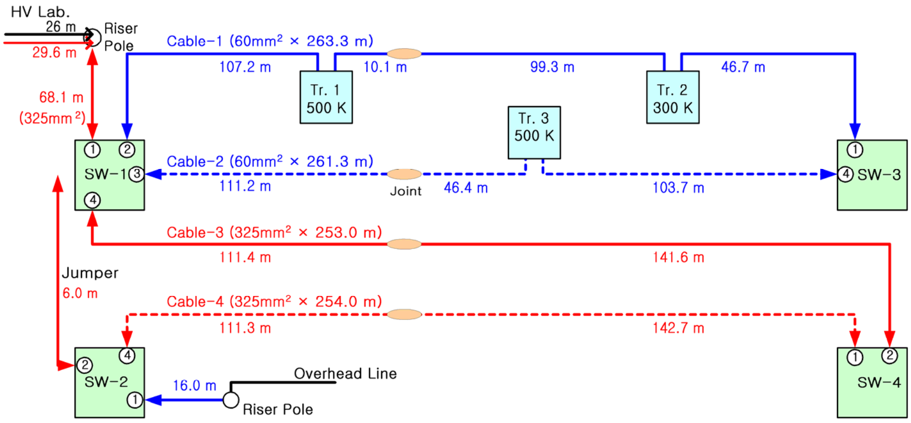

Figure 1: Field test model of underground distribution system

IMPULSE GENERATOR

Impulse generator was installed in the high voltage laboratory and connected to the test line with cable and overhead line. Standard impulse voltage (1.2x50 ㎲) is 50 kV to protect cable. In case of the impulse current test we applied 8x20 ㎲, 50 kA.

IMPULSE VOLTAGE TEST

When 50 kV 1.2x50 ㎲ impulse applied to 97.7 m cable, the first step voltage shows 2 kV and the reflected second step voltage shows 5.3 kV from 1.2 ㎲.
Propagation velocity of impulse surge is calculated as follows;
(97.7x2) / 1.2 [m/㎲] = 162.8 m/㎲

Figure 2: Impulse voltage test setup

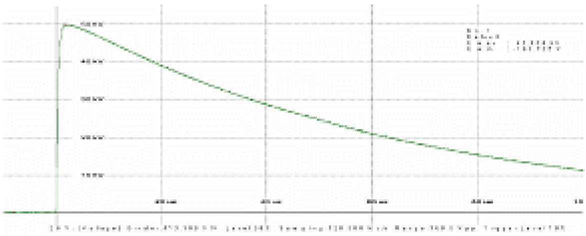

Figure 3: Impulse voltage wave shape

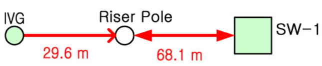

Figure 4: Impulse voltage test for 97.7 m cable line

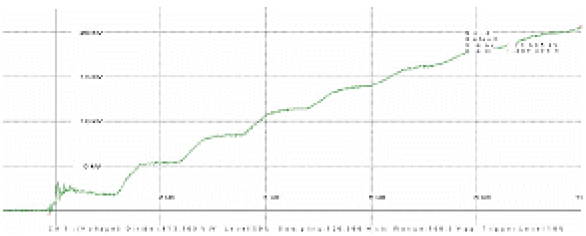

Figure 5: Test result of 97.7m cable line at IVG

With switchgear SW1 operating to extend cable length to 350.7 m and applying same impulse, the first step voltage is about 2 kV and reflected second step voltage was became 5.2 kV.
The impulse propagation velocity is calculated as follows;
(350.7x2) / 4.3 [m/㎲] = 163.1 m/㎲
The simplified impulse propagation process is shown in figure 9. We can see how voltages increase by reflecting.

Figure 6: Impulse voltage wave shape

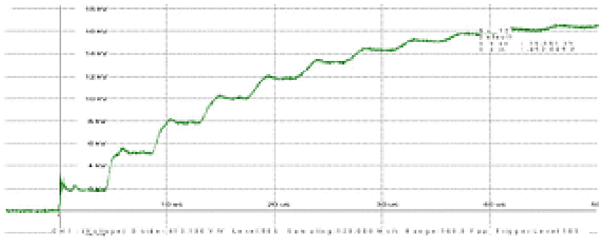

Figure 7: Test result of 350.7m cable line at IVG

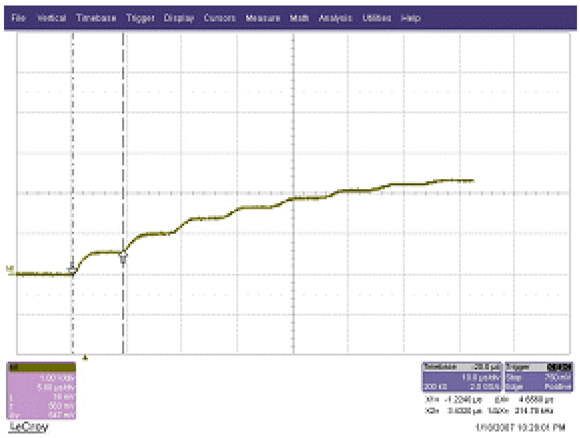

Figure 8: Test result of 350.7m cable line at SW4

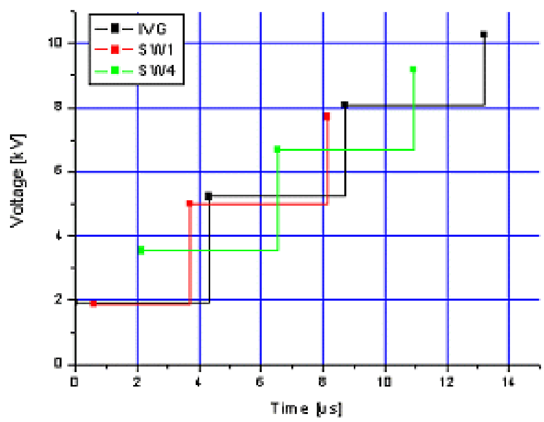

Figure 8: Simplified impulse propagation process

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With switchgear SW1 and SW4 operation to extend cable length to 604.7 m and applying same impulse, the first step voltage is become about 1.8 kV and the reflected second step voltage is become 5.0 kV increased from 7.5 ㎲.
The impulse propagation velocity is calculated as follows;
(604.7x2) / 7.5 [m/㎲] = 161.3 m/㎲

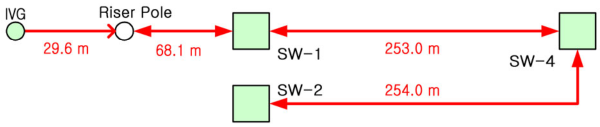

Figure 9: Impulse voltage wave shape

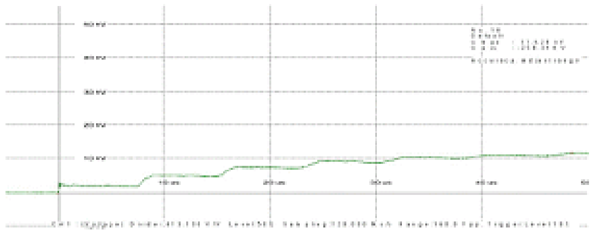

Figure 10: Voltage variation measured at IVG

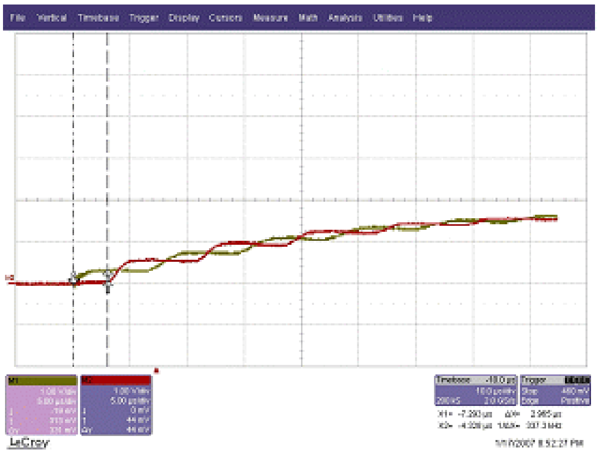

Figure 11: Voltage variations measured at SW1, SW2

EMTP SIMULATION OF IMPULSE VOLTAGE TEST

We make EMTP simulations for our field test model of underground distribution system. In this EMTP simulation we used ramp type source for impulse surge.(See figure 12) This source was typical for simulation of surge propagation these days. As we change the frequency at which the line parameters will be calculated, the resulting surge propagation changes like figure 13. The results from 500 kHz were more similar to real test results. The surge propagation results calculated at power frequency of 60 Hz were different from the results of real test.
These results will be come from the surge shape of 1.2x50 ㎲. The duration of rise is 1.2 ㎲ and the most variations of wave shape is occurred within 2 ㎲, so it can be translated to frequency domain as follows;

f = 1/T = 1/(2 ㎲) = 500 kHz.

So the frequency at which cable parameters are calculated should be 500 kHz. Generally in the surge simulation, 500 kHz has been used and showed good results.
To make the propagation velocity from the EMTP calculation accord with that of real test, the relative permittivity of cable insulation has to be changed. In general the relative permittivity of XLPE insulated cables was used 2.3. This value was measured with XLPE material sheet not with cable. But in our EMTP simulation this value gives big errors in propagation velocity of surges.
We calculated relative permittivity from the wave propagation in the perfect dielectric media.

$$v = \frac{1}{\sqrt{\mu\varepsilon}} = \frac{c}{\sqrt{\mu_R \varepsilon_R}}$$

Where, v is propagation velocity, μ is a permeability of media, ε is a permittivity of media, c is velocity of light, μ_R is relative permeability of media, ε_R is relative permittivity of media.
From above equation, we got 3.39 for relative permittivity of our cable. This value is quite different from 2.2, which is a common value of XLPE insulation.
The surge propagation time of simulation results using 3.39 as relative permittivity of cable insulation was in accord with real test.

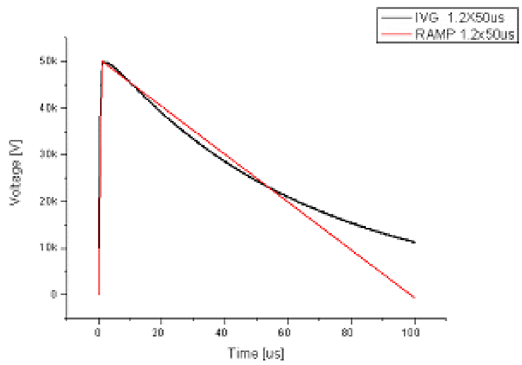

Figure 12: Surge waves for real test and EMTP

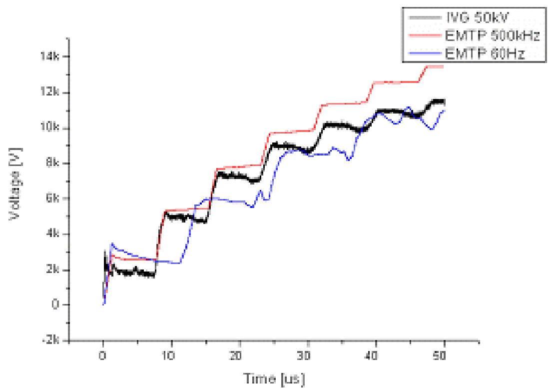

Figure 13: Surge waves for EMTP frequency

The permittivity difference between XLPE material and cable probably will be caused by the effect of semi-conductive layer and water blocking filled conductor. But it is not the subject of this paper.
Meanwhile, as reflection is repeated in the EMTP simulation the amplitude of surge begin to differ from real test result as seen in figure 14.
Surge source type has to be changed from 2-slope ramp (Type 13) to two exponentials (Type 15) to minimize the accumulation effect of errors. This can be seen in the figure 14.
To minimize errors in EMTP simulation some parameters must be carefully inputted. Especially the relative permittivity of cable insulation, frequency at which line parameters will be calculated and surge wave shapes should be inputted with real value.

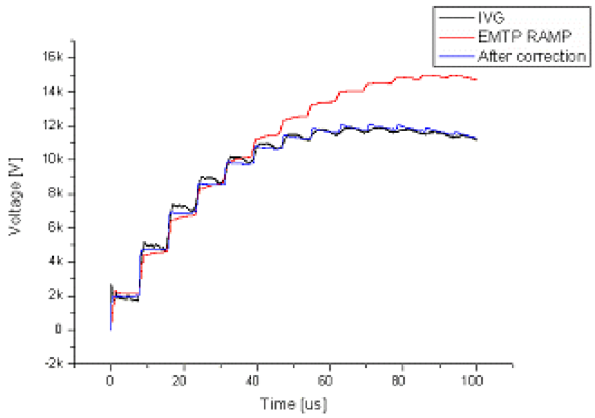

Figure 14: Surge propagations and surge shape

IMPULSE CURRENT TEST

When lightning surge hit the overhead line, arrester of riser pole discharges surge voltage and limits voltage to the residual voltage level of arrester. But this residual voltage is applied to cable and travels underground distribution line and is reflected at the end of cable. We would like to see this surge propagation in the real test line.
From the restriction of test facility, we set the impulse current test configuration of arrester and attached cable line to the arrester terminals. Impulse current shape was 8x20 ㎲ and discharge current was 5 kA. The arrester rating is 18 kV and residual voltage is about 60 kV.
Figure 15 and 16 show the test set for impulse current injection to cable and its propagation characteristics.

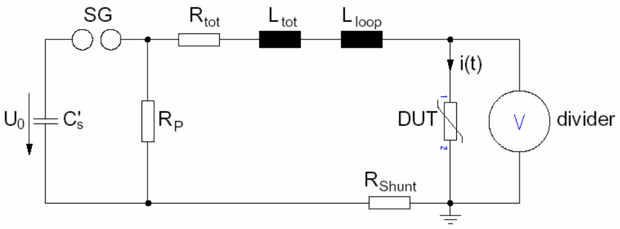

Figure 15: Impulse current test set for arrester

Figure 16: Impulse current test set for arrester

When cable length was 97.7 m, the maximum voltage measured at impulse current generator was within 60 kV. But the peak voltage at switchgear SW1 was 69 kV. It is estimated because the end of cable is not far from the arrester the voltage rise at the end of cable is restricted by arrester.
When cable length was 350.7 m, the maximum voltage measured at the end of cable was 98 kV.(Figure 19, 20)
When cable length was 604.7 m, the maximum voltage measured at the end of cable was 102 kV. (Figure 21, 22)

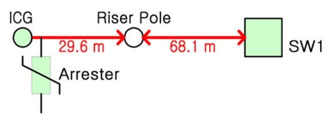

Figure 17: Impulse current test for cable 97.7 m

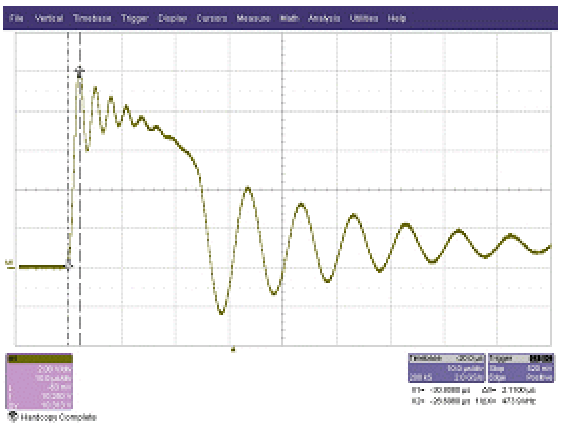

Figure 18: Voltage measured at SW1

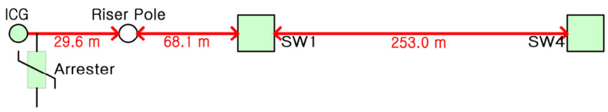

Figure 19: Impulse current test for cable 350.7 m

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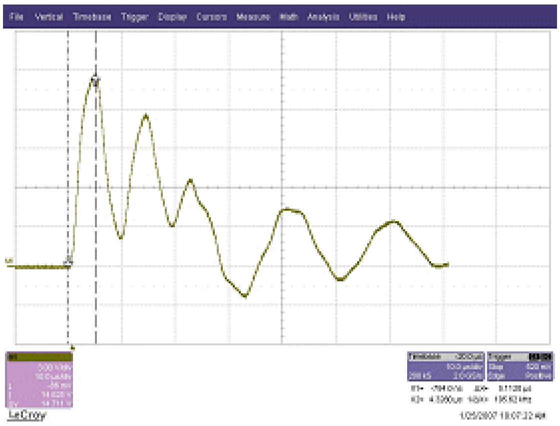

Figure 20: Voltage measured at SW4

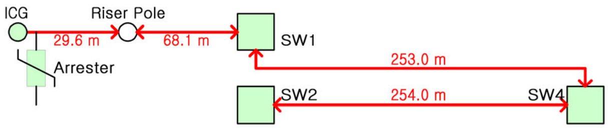

Figure 21: Impulse current test for cable 604.7 m

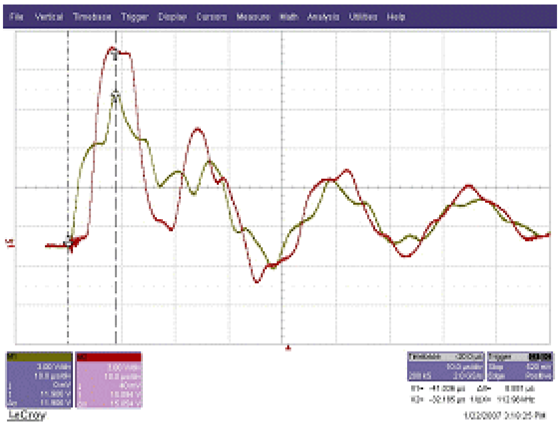

Figure 22: Voltage measured at SW1 and SW2

As cable length is increased, the voltage at the end of cable is also increased, but not exceeded twice of arrester residual voltage. The voltage rise at the end of cable and its travelling in the underground distribution line can make faults or degradation of solid insulation especially in the aged insulations. Really in our tests some of elbow joints are faulted by several ten times of impulse tests.

BIFURCATED CABLE LINE

We tested also for the bifurcated cable lines. Cable line is bifurcated at the switchgear SW1 in figure 23.
The maximum voltage was measured to 114 kV at SW2. This voltage is very near to the Basic Impulse Level of 25kV underground distribution system.

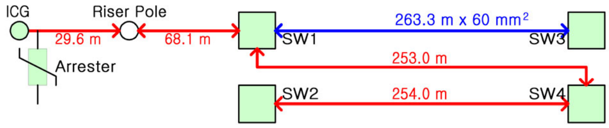

Figure 23: Bifurcated cable line

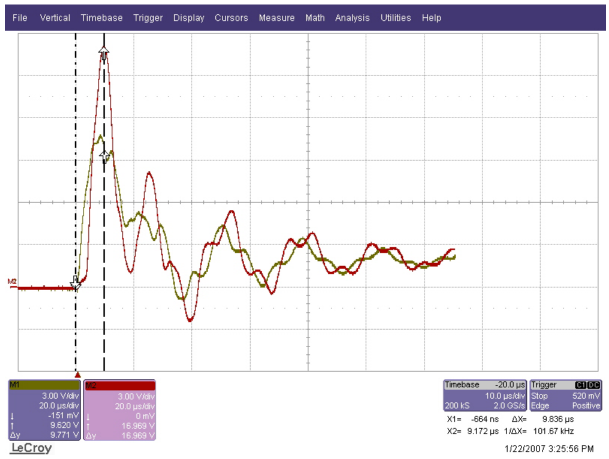

Figure 24: Voltage measured at ifurcated cable line

RESULTS AND DISCUSSIONS

From the real test and EMTP simulation for the surge inje ction to cable line, we get;
1. To simulate the surge behaviour in cable line with EMTP, cable parameters like relative permittivity should be carefully chosen.
2. Surge is reflected double voltage the end of cable.
3. Although surge is discharged through the arrester at riser pole, residual voltage surge is injected to the cable line and reflected with double voltage.
4. As cable length increase, the end of cable is further from the arrester and the reflected surge voltage is increased.
5. In the real underground distribution system, the reflected double voltage surge is propagated various paths of distribution line and reflected double again at the other ends, this surge can threaten the insulations.

Acknowledgments

This study was sponsored by ETEP.

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