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DEVELOPMENT AND EFFICACY OF SHEATH CURRENT REDUCTION DEVICES ON UNDERGROUND POWER CABLE SYSTEMS

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ABSTRACT

In underground power cable systems, high sheath current is usually caused by mixed cable burying formation and different lengths between sections. It can cause sheath loss and reduce the permissible current of cables. Previous research results indicated that the designed current reduction device could effectively reduce the sheath circulating current.

This paper presents a new device to reduce the sheath circulating current by installing a reactor possessing transient protection functions to the cross-bonding lead where the current has increased and describes its efficacy. The newly designed device is applied in an actual underground transmission system for more than 1 year in South Korea.

KEYWORDS

Sheath circuiting current, Sheath current reduction, Underground power cable

INTRODUCTION

Nowadays underground power cables are expanding throughout cities due to large electric energy demand. For high voltage power transmission systems, three separate single-core cables are usually used instead of three-core cables. This leads to high induced voltages in the sheaths owing to unequal spacing between the sheaths relative to any one conductor [1].

In practice, the sheaths are cross-bonded at each end of the cable to suppress the induced voltages. The details of cross-bonding can be referred to IEEE guide [2]. The cross-bonding of the sheaths provides a returning path for the induced current from other phase cables. This current is known as "sheath circulating current" which results in "sheath circulating loss". According to IEC std. 287[3], the high sheath circulating loss has an influence on the permissible current of AC cable. It causes sheath temperature increase and the total thermal resistance of the cable. Thus it reduces the permissible current and must be reduced to a reasonable level.

To prevent the flow of sheath circulating currents, one obvious way is to eliminate cross-bonding and earthing. Such a practice would allow, however, large standing voltages to be present on the sheath which forms a considerable hazard to life as well as the possibility of arcing and consequent deterioration of the cable.

According to the studies of induced voltage in sheaths [1, 4], another possible practice to reduce the sheath circulating current is to increase the spacing of the cables and keep them balanced. However, the increase of cable spacing will increase the size of cable channels, which is not cost effective.

A practical measure, which is widely used in the UK, is to transpose the cable once per section length as well as sheath cross-bonding. Further practice is to bond the sheaths at some intermediate points rather than at joints [4], but this increases the cost and is difficult to maintain.

In practice, because of geometric limitations and planning problems, some transmission cable systems are buried in different formations and at different lengths in each section. An example of such a system is described in the next chapter. This kind of unbalanced arrangement leads to a huge circulating current in the sheaths, and general sheath reduction methods are not enough to reduce the current to a reasonable level [5].

So, in the previous papers [6, 7], the characteristics of sheath current and the causes of current increase were extensively analyzed. Further, in order to reduce the sheath current, the reduction devices of resistors and reactors were developed and installed at the joints. The results indicated that the designed current reduction device could effectively reduce the sheath circulating current.

This paper presented a new device to reduce the sheath circulating current by installing a reactor possessing transient protection functions to the cross-bonding lead where the current has increased. The newly designed device has been in operation for more than 1 year in a South Korean underground transmission system.

CORRELATION OF THE SHEATH CURRENT AND PERMISSIBLE CURRENT

While the underground power transmission cable is in operation, the sheaths are cross-bonded at each end of the cable to suppress the induced voltages in the sheath. The cross-bonding of the sheaths produces a returning path of the induced current from other phase cables. This current is known as "sheath circulating current" which results in "sheath circulating loss". According to IEC std. 287[3], the permissible current of an AC cable is written as Equation [1] in buried cables where drying out of the soil does not occur or cables installed in air.

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T_1 + n(T_2 + T_3 + T_4)}{RT_1 + nR(1+\lambda_1)T_2 + nR(1+\lambda_1+\lambda_2)(T_3+T_4)}} \quad [1]$$

T_1 to T_4 means the internal and external thermal resistances of cables. λ_1 is the ratio of losses in the sheath to total losses in all conductors is that cable. λ_2 is the ratio of losses in the armouring to total losses in all conductors in the cable. Power loss in the sheath λ_1 is expressed as Equation [2].

$$\lambda_1 = \lambda_1' + \lambda_1'' \qquad [2]$$

Where:

λ_1' : loss caused by sheath circulating current

λ_1'' : loss caused by eddy current

If the sheath circulating current rises, the loss caused by sheath circulating currents will increase, and then the ratio of loss dissipated in sheath per unit length to loss in conductor per unit length will increase too. Therefore, the temperature and total thermal resistance of the cable increases, and the permissible current is reduced. The sheath circulating current must be reduced for the increment of transmission capacity. In addition, the high sheath current has an effect on people and may cause faults by due to insulation breakdown.

MEASUREMENT OF SHEATH CIRCULATING CURRENT

Development of Power Cable Current Analyzer

In order to study the sheath circulating currents, a new equipment, names as "Power Cable Current Analyzer (PCCA)", was designed to measure the sheath current. The new equipment has several advantages over conventional equipment. Firstly, it has a CT (current transformer) to measure the current rather than hook meter. Thus its capacity is high. Secondly, even if some equipment uses CT, only currents on small wires can be measured. One current would have to be measured at one point which is inappropriate for measuring the current in power cable systems. The new designed device has nine channels which can measure and sample nine signals simultaneously, including conductor currents and sheath currents.

The device can also display the currents in magnitude and phase angle, analyse the currents in frequency domain by Fast Fourier Transform (FFT) and display the basic and 3rd, 5th, 7th and 9th harmonic components. Finally, it has a port which connects to a digital oscilloscope and can display the current waveforms. Another port connects to a printer to print the result. Figure 1 shows the picture of PCCA.

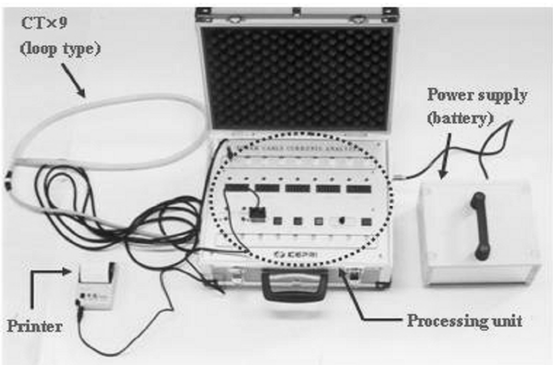


Figure 1: Picture of Power Cable Current Analyzer

When measuring the sheath currents, CTs are mounted in different connection methods based on the Joint type. Figure 2 shows the circuit of measuring currents at the insulation joint.

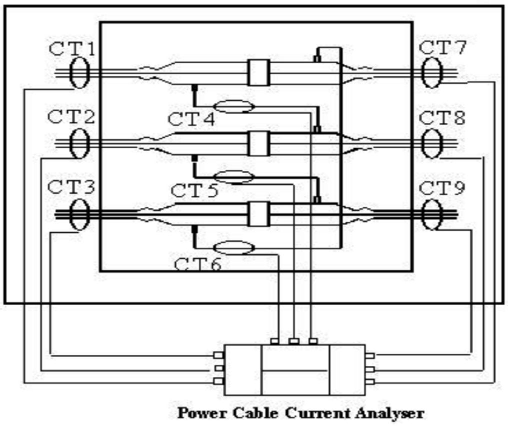


Figure 2: Application of Power Cable Current Analyzer

Transmission System 1

The first underground transmission system studied in this paper is a South Korean 154kV transmission system with load current of 300A. The system's schematic diagram is shown in figure 3. The cable is single core, oil-filled and paper insulated. The total length is 6.245km. It consists of 17 minor sections with lengths which are different from each other. As usual, the sheaths are jointed and cross-bonded at the end of each section. The sheaths are earthed at joint 3, 6, 9, 12 and 15, which are labelled as normal joints (NJ) in this paper. Other joints are referred to as insulation joints (IJ). The sheaths are connected to a SVL (Sheath Voltage Limiter) to protect against the transients overvoltage. As shown in figure 3, the system is very complicated. Not only the length of each minor section is different, but also the burying formation between joints 8 and 10 is unlike the others. A duct formatted circuit is mixed with the trefoil circuit between sections 8 and 10. This kind of arrangement causes a huge increase in the sheath current on the two major sections between junctions 6 and 12.

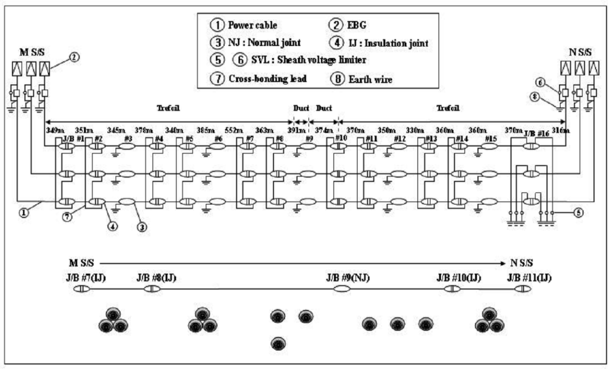
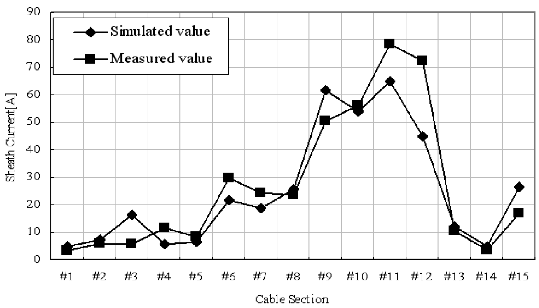


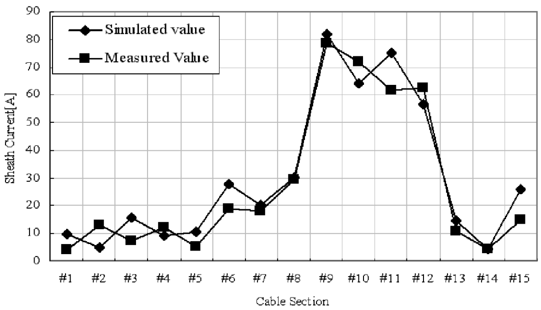
Figure 3: Schematic Diagram of 154kV underground transmission System 1

Measurements and Comparison

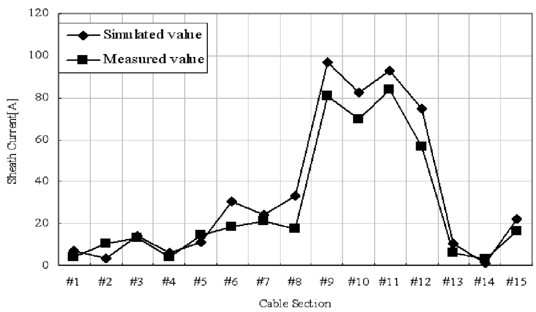
In order to evaluate the accuracy of current measurements, the measured current using the PCCA and simulated current using the ATP (Alternative Transient Programs) at each joint are compared. The measured and simulated currents in three phases at each joint are showed in figure 4. The square markers are the measured currents, while the diamond markers are very simulated currents. The simulation and measurement current trends are similar. First the currents between joints 1 and 5 stay low while the cables are buried uniformly in trefoil formation. Then the currents increase to 30A between joints 6 and 8. Finally the currents soar to 100A between joints 9 and 12 on phase C. They are so high on the sheath that it's beyond the tolerance of the power cable. The increased of the sheath current is supposed to be because of the mixed burying formation and different length of the section. High sheath current will produce a large amount of heat which will cause damage to the cable. Further, it will cause sheath loss and reduce the permissible current so that it should be reduced to a safety level.



(a) In phase A



(b) In phase B



(c) In phase C

Figure 4: Simulation and measured sheath current

SHEATH CURRENT REDUCTION DEVICES

We first proposed a new method to reduce sheath currents by installing a 1Ω resistor on the cross-bonding lead. The resistors are serially connected to the cross-bonding lead on insulating joint that sheath circulating current increases. The connection circuit and the connection in the actual system are shown in figure 5 and 6.

After resistors were installed in joint 11 (figure 3), the sheath current obtained practical measurements shown in table 1. Also in Table 1, the sheath current reduction device(resistor) reduce the sheath current by an average of 91%.

Figure 5: Sheath current reduction device (resistor)

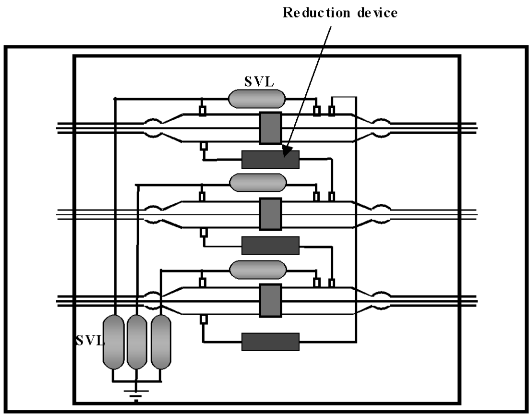


Figure 6: Connect diagram of reduction device

Table 1: Reduction effect of resistor

J/B	Phase	Sheath circulating current [A]		
		Measurement		Reduction Rate [%]
		With	Without	
#9 (NJ)	A	10	50.6	82.3
	B	6.1	78.9	92.2
	C	7.4	80.95	90.8
#10 (IJ)	A-C	4.7	56.1	91.6
	B-A	2.5	72	96.5
	C-B	3.8	69.9	94.5
#11 (IJ)	A-C	2.5	61.6	95.9
	B-A	3.4	83.8	95.9
	C-B	2.7	78.35	96.5
#12 (NJ)	A	9.2	56.8	83.8
	B	7.8	72.4	89.2
	C	7.7	62.55	87.6
Average [%]				91

Figure 7: Sheath current reduction device (Reactor)

The 2.65mH reactor was also proposed for the reduction of sheath currents. The reactor are connected in series to the crossbonding lead as shown in figure 6. The connection in the actual system is shown in figure 7. The reactor's specifications are listed in table 2 and the characteristic curve of current and flux density are also expressed in figure 8 and 9, respectively.
After the reactors were installed joint 11 (figure 3), the sheath current obtained practical measurements shown in table 3. Also shown in table 3, the reduction device (reactor) could reduce the sheath current by an average of 89.6%.
At both resistors and reactors, the average sheath current reduced was 91% and 89.6%. From these results, we prove that that's quite effective.

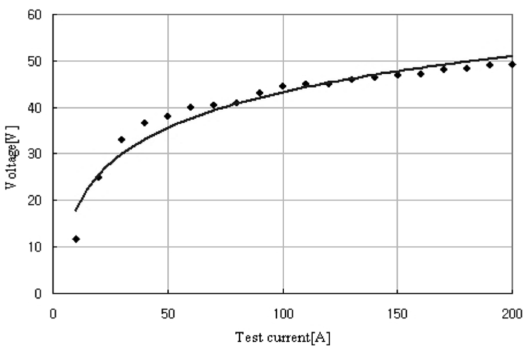


Figure 8: Curve of Current and Voltage of Reactor

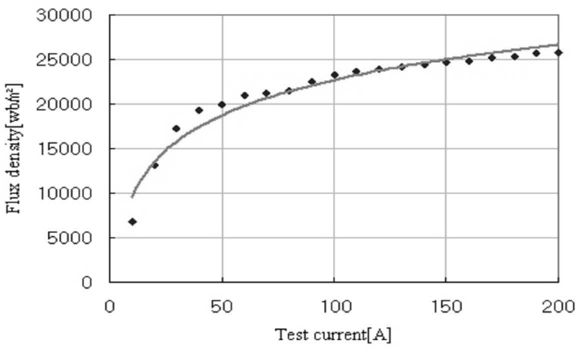


Figure 9: Curve of Current and Flux Density of Reactor

Table 2: Specification of the reactor

Items	Specifications
Characteristic	Waterproof, Indoors
Rating impedance	1Ω (60Hz, 2.65mH)±3% at 20°C
Rating Current	100A, 60Hz
Capacity	10kVA
Insulation resistance	200MΩ

Table 3: Reduction effect of reactor

J/B	Phase	Sheath circulating current [A]		
		Measurement		Reduction Rate [%]
		With	Without	
#9 (NJ)	A	10.1	50.6	80
	B	7.3	78.9	90.7
	C	9.4	80.95	88.4
#10 (IJ)	A-C	7.2	56.1	87.1
	B-A	5.7	72	92.1
	C-B	7.2	69.9	86.7
#11 (IJ)	A-C	1.7	61.6	97.2
	B-A	1.6	83.8	98.1
	C-B	1.4	78.35	98.2
#12 (NJ)	A	9.5	56.8	83.3
	B	8.6	72.4	88.1
	C	8.8	62.55	86
Average [%]				89.6

NEW SHEATH CURRENT REDUCTION DEVICE

Early research studies show that when the cable is under switching, lightning and fault conditions, voltage of up to tens of thousands of volts will be produced on the sheath [8-11]. The reactor introduced in the system would be damaged under these situations, which leads to the disconnection of cross-bonding leads. The disconnection will stop the current flowing, which results in the overvoltage in the sheath and at the joint. The whole cable system may be in danger. Therefore it's very important to protect the reactor against various transient conditions.
In this paper a new sheath current reduction device possessing transient protection function was designed.
Figure 10 shows the new sheath current reduction device, which is developed by KEPRI (Korea Electric Power Research Institute) and LS cable corporation. The principal characteristic of new sheath current reduction device listed in table 4.

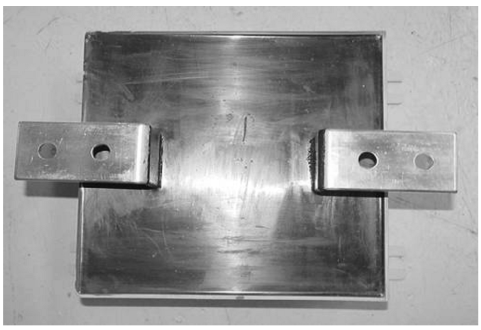


Figure 10: New sheath current reduction device

Table 4: The principal characteristic of new sheath current reduction device

Item	Details
Voltage-Current Characteristic	- Non saturation characteristic (30[A] and less) V/I = 0.5±50[%] - Saturation characteristic (200[A] and over) Δ V/Δ I = 0.15[Ω] and less
Short-time current Characteristic	- For 25[kA] : effective value 25[kA] (the first peak value of first wave : 25[kA] × 2.5) × 0.1 [sec] × 3 times - For 40[kA] : effective value 40[kA] (the first peak value of first wave : 40[kA] × 2.5) × 0.1 [sec] × 3 times
Insulation Efficiency	- Withstand power-frequency voltage : 4[kV] × 1[min] (to ground) - Withstand standard impulse voltage : ±21[kV] × 10 times (to ground), ±42[kV] × 10 times (to terminal) - Insulation resistance: 10[MΩ] and over
Waterproof Characteristic	- Based on JIS C 0920 (the waterproof test of electrical equipment and protection grade for and invasion of a solid), It immerses device 150[mm] and over, then, after 300 seconds, insulation efficiency of 5[MΩ] and over must be maintained.

In addition, after the new sheath circulating current reduction device was installed into the system, which has been running for over one year, all of its results were recorded.

Transmission System 2

The secondary underground transmission system studied in this paper is also a South Korean 154kV transmission system. The system's schematic diagram is shown in figure 11. The system is also very complicated, like the underground transmission system 1. Not only the length of each minor section is different, but also the burying formation is a combination of trefoil circuits and duct formatted circuits throughout the whole section.
The results showed that, the highest sheath circulating current of 188.4[A] was measured in B phase of joint box #6.

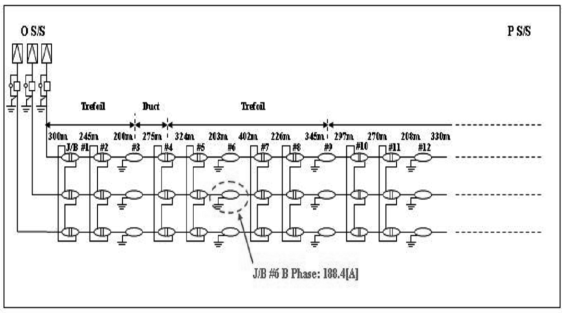
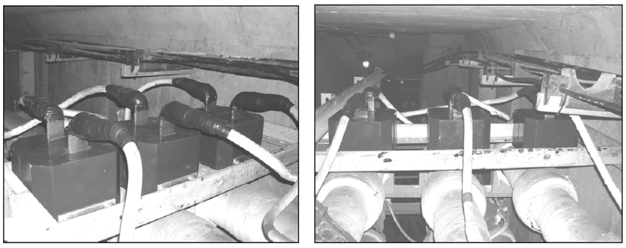


Figure 11: Schematic Diagram of 154kV underground transmission System 2

Installation effects of new reduction device

The new sheath circulating current reduction device was installed on insulation joint box #5 and #7, through a simulation using ATP, which have the greatest sheath circulating current reduction effects. The image of the sheath circulating current reduction device installed onto the actual system is displayed in figure 12 and sheath circulating current values immediately following installation and 1 year after installation are shown in table 5. As can be seen in table 5, the new reduction device showed an average reduction of 80.8% immediately following installation and 80.9% 1 year after installation.
Based on the results, it was possible to verify excellent reduction effects of the new reduction device, and because analysis of sheath circulating current change transition showed no change in the characteristic of reduction effect, its mechanical stability was also verified.



(a) Joint Box #5 (b) Joint Box #7

Figure 12: New sheath current reduction device installed in actual underground transmission system

Table 5: Reduction effect of new reduction device

J/B	Phase	Sheath circulating current [A]			
		Measurement			Reduction Rate [%]
		With (immdiately)	With (1 year)	With out	
#5 (IJ)	A-B	11.1	11	83.1	86.6 (86.8)
	B-C	22.1	21	108.6	79.7 (80.7)
	C-A	10.5	12	58.5	82.1 (79.5)
#6 (NJ)	A	25.7	26	123.1	79.1 (79.1)
	B	41	40	188.4	78.2 (78.8)
	C	22.3	21	124.5	82.1 (83.1)
#7 (IJ)	A-B	11.5	11	72.3	84.1 (84.8)
	B-C	26.4	26	107	75.3 (75.7)
	C-A	10.9	11	55	80.2(80)
Average [%]					80.8(80.9)

CONCLUSION

This paper presents a new device to reduce sheath circulating currents by installing a reactor possessing transient protection functions to the cross-bonding lead where the current increased. During more than one year of practical application of the actual system, reduction effects of the new device were described. The description can be summarized as follows.

- Seeing that results of sheath circulating current measurement through PCCA are almost identical to results of measurements through ATP simulation, it can be assumed that analysis results using ATP

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simulation are reliable.

- The new reduction device showed an excellent average reduction effects by up to 80.8% after installation.2 etc.
- Analysis of sheath circulating current change transition showed no change in the characteristic of reduction effect, and its mechanical stability was also verified.
- Although analysis through ATP simulation is not required for installation of the reduction device, it is recommended that effects of the reduction device on the system are pre-analyzed for effective installation.

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