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Impedance Calculation of an Underground Transmission Cable System Installed with a Sheath Current Reduction Device

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Abstract - Previous research results indicated that the designed current reduction device could effectively reduce the sheath circulating current and that its RDP protection device could shield it against both fault and lightning strokes. In this paper, cable impedance is analyzed using wavelet analysis and distance relay algorithm following the installation of these devices so that the operation of distance relay can be estimated. The test results confirm that in these devices, the fault inception angle and SVL bonding types have no impact on the change of cable impedance. In other words, the conventional distance relay can be used without a new relay setting. Thus we can finally assert that the designed current reduction device and its protection device are effective and can be safely installed on the cable transmission system without disturbance.

Keywords: cable impedance, distance relay, reduction device, sheath current, underground transmission system

1. Introduction

In the underground transmission cable system, the increase of sheath current can cause the loss of power and reduce the permissible current. So, in the previous papers [1-3], the characteristics of sheath current and the causes of current increase were extensively analyzed. In addition, in order to reduce the sheath current, the reduction device was developed and installed at the joints. The field test results showed a high level of performance in both normal and transient states.

In South Korea, the current differential relay or the distance relay is often used for primary protection and back up protection. Because of the installation of reduction devices, the impedance of the cable system may undergo change, which in turn may cause a change of impedance to occur at the relay point as well. If the cable impedance at the relay point is altered by the installation of reduction devices, the relay setting must be adjusted in case of any actions resulting from the installing of the current reduction device. Therefore, in this paper, we are going to calculate the cable impedance of an underground transmission cable system installed with a sheath current reduction device using wavelet transform and the typical distance relay algorithm when the single line to ground fault occurs at different positions [4-8]. The calculated impedances are compared with those of a cable system without a sheath current reduction device. From these results, we proved that this reduction device could be safely used on an underground power cable system without changing the relay setting.

2. Sheath Current Reduction Device

2.1 System Model

The system's diagram studied in this paper is shown in Fig. 1. It's a double-circuit, single-core cable transmission system with a voltage of 154kV and load current of 300A. The total length of the cable is 6.245km. It consists of 5 major sections with 3 minor sections for each major section As usual, the sheaths are jointed and crossbonded between two sections. Between the minor sections, each joint is named as insulation joint (IJ) in this paper and the sheaths are connected to the SVL (Sheath Voltage Limiter) to protect against the transients overvoltage. At each joint between two major sections, named as a normal joint (NJ), the sheaths are connected directly to the earth.

As shown in Fig. 1, 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 causes a huge

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increase of the sheath current on the two major sections between junctions 6 and 12.

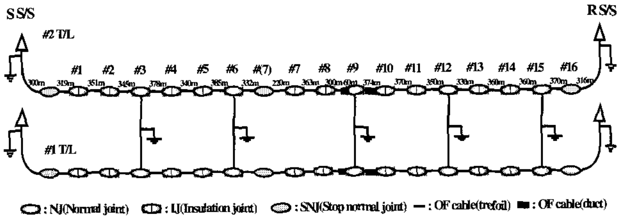


Fig. 1 Double circuit diagram of 154kV underground power cable system

2.2 Sheath Current Reduction Device

The reactors manufactured for reducing the sheath current are shown in Fig. 2. In the previous papers [1-3], the practical field test indicated that the reduction effect was superior. It could decrease the sheath current by as much as 90%.

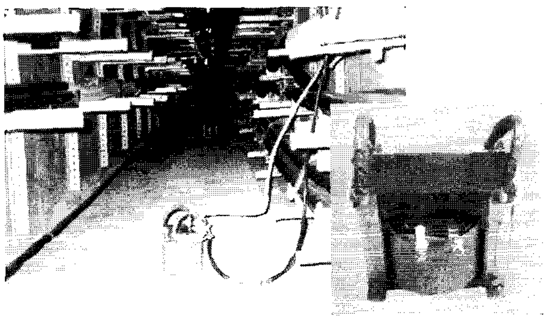


Fig. 2 Sheath current reduction device (reactor)

The reactor is installed at the insulation joint, and has special characteristics. That is, if the overcurrent is generated within a reactor, the voltage and flux density have the fixed value as shown in Fig. 3 and Fig. 4., which show the characteristic of voltage and flux density versus current. The reason for this is that the core of the reactor is saturated by the overcurrent. The saturation characteristic of the developed reactor is tested by the experiment, and the obtained results are applied in transient analysis.

2.3 Protection Method of Reduction Device

As we discussed in the previous papers [1-3], the reduction device could reduce the sheath current quite effectively. However it wasn't properly protected and as such was under threat whenever it was hit by cable system overvoltage.

The overvoltage (usually transient overvoltage) caused by a cable fault or lightning stroke will damage the reactor and disconnect the crossbonding lead. The disconnection of the crossbonding lead will stop the fault current from flowing through the sheath. That in turn will create an overvoltage produced in the sheath and the joint. The entire cable system may be placed in danger.

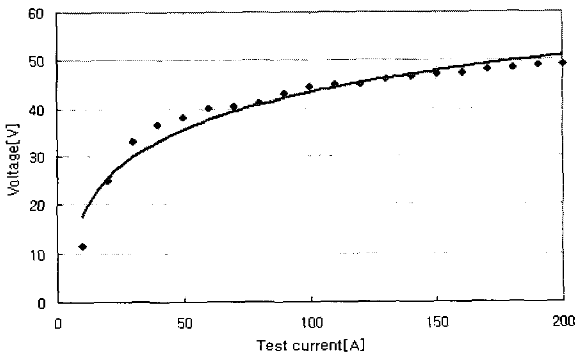


Fig. 3 Characteristic curve of current and voltage of reactor

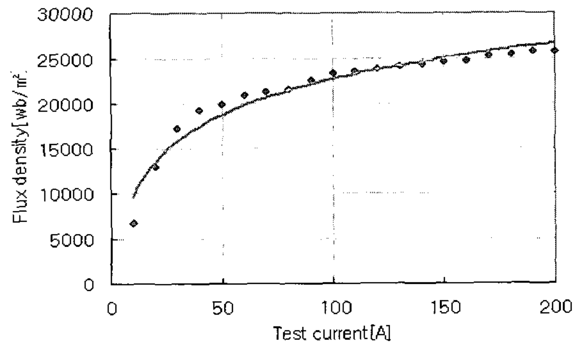


Fig. 4 Characteristic curve of current and flux density of reactor

Therefore, we designed a device similar as SVL, called the Reduction Device Protector (RDP), to protect the reactor against the transient overvoltage as shown in Fig. 5 and Fig. 6.

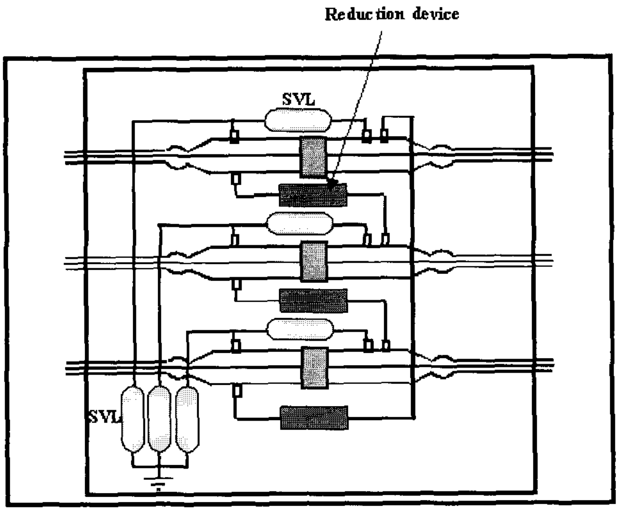


Fig. 5 Installation diagram of reduction device

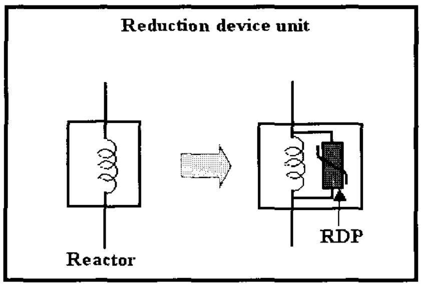


Fig. 6 Reduction device unit

The authors proposed several protection methods for the reduction device using RDP, and proved the superior protection effect of DKC and KDC for both cable faults and lightning strokes [3].

The reduction effect of the reactor and its protection methods have been thoroughly studied till now. However, prior to applying these devices on actual power cable systems, an estimation of the protective relay system will also be needed. Thus, in this paper, the cable impedance at the relay point is first calculated by the distance relay algorithm on a power cable system without the reduction device and RDP. Then the impedance of the systems with a reduction device or with both respective devices is also calculated. Based on these results, the actions of distance relay will be analyzed.

3. Calculation of Cable Impedance

3.1 Symmetrical Component Impedance

The symmetrical component impedances of a power cable system used to compensate zero-sequence components were obtained by the equivalent circuit of a power cable [5-6]. Fig. 7 shows the equivalent circuit to calculate the cable impedance as the single line to ground fault occurs between conductor and sheath.

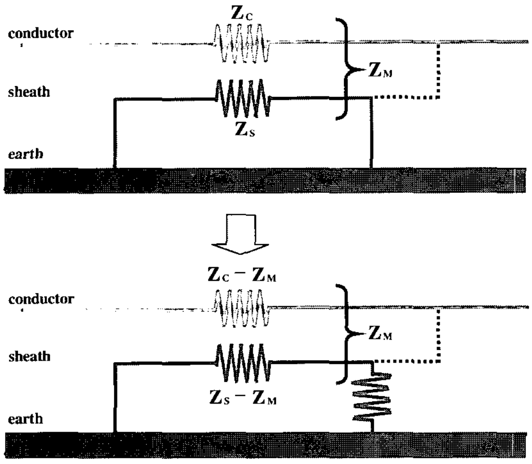


Fig. 7 Equivalent circuit of a three-phase power cable

If the single line to ground fault occurs on a power cable system, fault current flows through the sheath to the ground with the breakdown of the insulation. Therefore, the impedance of power cables can be divided into the following three kinds of impedance according to the flow of current. Zero- sequence impedance of the power cable is obtained from (3).

- In the event that fault current flows directly to ground without passing through the sheath

$$Z_0 = Z_{C0} \tag{1}$$

- In the event that fault current flows solely to the sheath

$$Z_0 = Z_{C0} + Z_{S0} - 2Z_{M0} \tag{2}$$

- In the event that fault current flows to ground passing through the sheath

$$Z_0 = Z_{C0} - \frac{Z_{M0}^{\ 2}}{Z_{S0}} \tag{3}$$

On the other hand, the symmetrical component impedance can be expressed, respectively, as (4) – (8).

- Positive and negative-sequence impedance of cable:

$$Z_1 = Z_2 = R_C + j[4 \cdot \pi \cdot f \cdot \ln(\frac{GMD_{3C}}{GMR_{1C}}) \cdot 10^{-4}] \tag{4}$$

- Zero-sequence impedance of cable conductor:

$$Z_{C0} = R_C + R_E + j[3 \cdot 4 \cdot \pi \cdot f \cdot \ln(\frac{D_E}{GMR_{3C}}) \cdot 10^{-4}] \tag{5}$$

- Zero-sequence impedance of sheath:

$$Z_{S0} = R_S + R_E + j[3 \cdot 4 \cdot \pi \cdot f \cdot \ln(\frac{D_E}{GMR_{3S}}) \cdot 10^{-4}] \tag{6}$$

- Mutual impedance between conductor and sheath:

$$Z_{M0} = R_E + j[3 \cdot 4 \cdot \pi \cdot f \cdot \ln(\frac{D_E}{GMR_{3S}}) \cdot 10^{-4}] \tag{7}$$

- Zero-sequence impedance of cable:

$$Z_0 = Z_{C0} - \frac{Z_{M0}^{\ 2}}{Z_{S0}} \tag{8}$$

Where,

f : frequency[Hz]

R_C : AC conductor resistance[Ω/km]

R_S : sheath resistance[Ω/km]

R_E : equivalent grounding resistance[Ω/km]

D_E : equivalent depth of earth return path[mm]

GMD_{3C} : geometric mean distance between conductors[mm]

GMD_{3S} : mean radius of sheath[mm]

GMR_{1C} : geometric mean radius between conductors[mm]

GMR_{3C} : geometric mean radius assuming that a three-conductor is modified as a single-conductor [mm]

As the single line to ground fault occurs on a power cable system, the cable impedance at the relay point is calculated by (9)

$$Z_{Cable} = \frac{V_A}{I_A + I_0 \cdot (\frac{Z_0 - Z_1}{Z_1})} \tag{9}$$

Where,

V_A : voltage at the relaying point [kV]

I_A : current at the relaying point [kA]

I_0 : zero-sequence current at the relaying point[kA]

Z_0 : zero-sequence impedance of cable[Ω/km]

Z_1 : positive-sequence impedance of cable[Ω/km]

3.2 Algorithm for Calculating the Cable Impedance

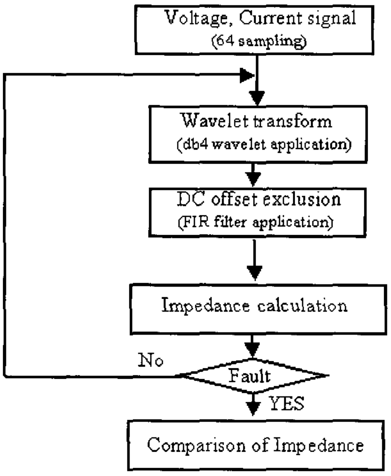


Fig. 8 Calculation of cable impedance flow chart

In this section, we are going to explain how the cable impedance is calculated. The voltage and current measured at the relay point include the harmonic and DC offset. First, the fundamental components of both signals are extracted by wavelet transform. The wavelet function used in this paper is db4. DC offset is removed by the FIR filter. Then the cable impedance is calculated by (9) on the power cable system without a reduction device and its protecting device when the ground fault occurs. Finally, the impedance of the system with a reduction device as well as RDP is calculated and the results are compared with the original system. Fig. 8 shows the flow chart of impedance calculation and comparison.

4. Results and Analysis

In this paper, the reactor and its protection device RDP are intended to be installed at 4km from the left side. The fault is supposed to be occurred at 2km, 4km and 5km, respectively. The fault inception angle will be 0 degrees and 90 degrees. Then three cases of the system will be analyzed, namely

- Case A: D or K
- Case B: RD or RK
- Case C: PRD or PRK

Case A is the power cable system with neither reduction device nor RDP. Case B is the system with current reduction device only and Case C is the system installed with both reduction device and RDP.

The cable impedance is calculated under these three different cases when the fault occurs at various positions. The SVL bonding type and saturation of the reactor are also considered while calculating the impedance. The detailed explanations of these settings are as follows.

D: SVL bonding type – direct ground type connected to SVL (without the reduction device and RDP)

K: SVL bonding type – non-grounding type with cross connection to SVL (without the reduction device and RDP)

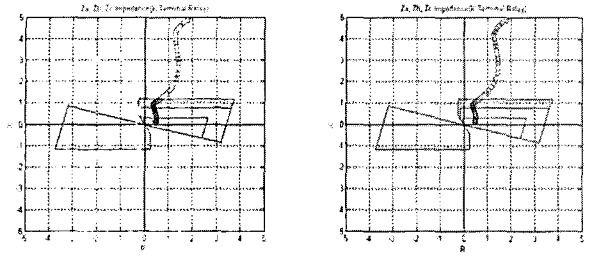
RD: SVL bonding type is D type, and the reduction device is also applied, but the RDP isn't considered

RK: SVL bonding type is K type, and the reduction device is also applied, but the RDP isn't considered

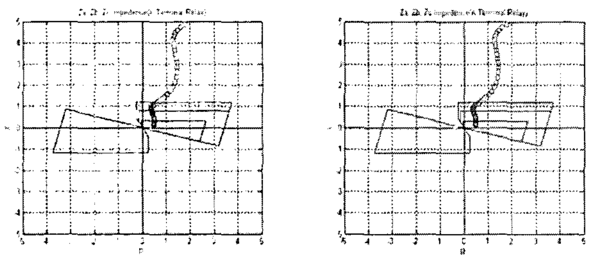
PRD: SVL bonding type is D type, and both reduction device and RDP are applied.

PRK: SVL bonding type is K type, and both reduction device and RDP are applied.

Fig. 9 depicts the R-X diagram when the fault occurs at the 2km point with the SVL bonded as D type and the reactor is 2.65mH and 1.325mH. As shown in Fig. 9, the relay certainly operates in all cases. Tables 1 and 2 show the difference in impedance between Case A and others. For both tables, in case that the saturation characteristic of the reactor is not considered, the error impedance for the reactor of 1.325mH is lower than that of 2.65mH. However it's certainly reduced following the application of the saturation characteristic.



(a) Case A (b) Case B (Reactor-2.65mH)



(c) Case C (Reactor-2.65mH) (d) Case D (Reactor-1.325mH)

Fig. 9 Characteristic of relay operation (SVL – D type)

Table 1 Impedance comparison at relay point in the case of the reactor of 2.65mH and the fault point at 2km

Fault inception angle			0 deg.				90 deg.			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault point	**Saturation of the reactor**	**SVL bonding types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
2km	**Without**	**D**	0.012	0.012	0.007	0.004	0.008	0.009	0.01	0.001
		K	*0.017*	*0.011*	*0.014*	*0.018*	*0.021*	*0.012*	*0.015*	*0.016*
	With	**D**	0	0.001	0	0.001	0.009	0.003	0.009	0.006
		K	0.002	0.009	0.002	0.009	0.003	0.005	0.001	0.008

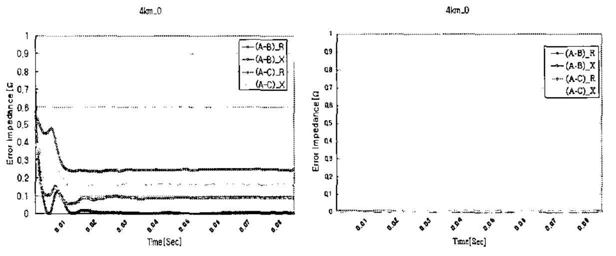
* A : Case A, B : Case B, C : Case C

Table 2 Impedance comparison at relay point in the case of the reactor of 1.325mH and the fault point of 2km

Fault inception angle			0 deg.				90 deg.			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault point	**Saturation of the reactor**	**SVL bonding types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
2km	**Without**	**D**	0.006	0.006	0.004	0.004	0.002	0.001	0.004	0.004
		K	0.009	0	0.008	0.013	0.013	0.004	0.0093	0.015
	With	**D**	0	0	0	0.001	0.005	0.002	0.004	0
		K	0.001	0	0.008	0.009	0.004	0.001	0.003	0.007

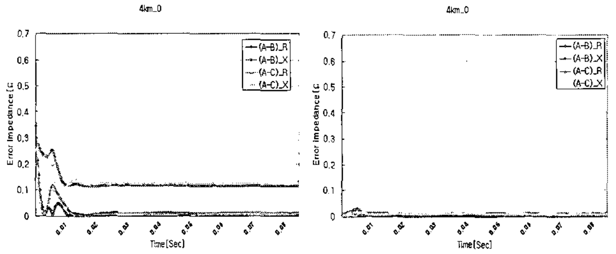
* A : Case A, B : Case B, C : Case C

Fig. 10, Fig. 11, Table 3 and Table 4 show the error impedance after the installation of the reduction device and RDP when ground fault occurs at the 4km point as being the same position in which the reactor and RDP are installed. Fig 10 and Table 3 are for the reactor of 2.65mH, and Fig. 11 and Table 4 are for the reactor of 1.325mH. In case that the saturation characteristic of the reactor is not considered, some errors appear in all cases. However, they are reduced to approximately zero when the saturation characteristic is considered, and there are no differences for different fault inception angles and SVL bonding types. From these results, we can say the distance relay operates normally after the installation of current reduction device and its protection device RDP.



(a) Without saturation (b) With saturation

Fig. 10 Error impedance in the case of D type SVL bonding, the reactor of 2.65mH, fault inception angle of 0 deg and fault point at 4km



(a) Without saturation (b) With saturation

Fig. 11 Error impedance in the case of K type SVL bonding, the reactor of 1.325mH, fault inception angle of 0 deg and fault point at 4km

Table 3 Impedance comparison at relay point in the case of the reactor of 2.65mH and the fault point at 4km

Fault inception angle			*0 deg.*				*90 deg.*			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault *point*	**Saturation *of the* reactor**	**SVL bonding types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
4km	**Without**	**D**	0.004	0.086	0.245	0.156	0.015	0.1	0.242	0.168
		K	0.025	0.067	0.196	0.164	0.025	*0.065*	*0.196*	*0.172*
	With	**D**	0.003	0.003	0.002	0.002	0.001	0.005	0.001	0.002
		K	0.003	0.01	0	0.006	0.003	0.001	0.004	0.007

* A : Case A, B : Case B, C : Case C

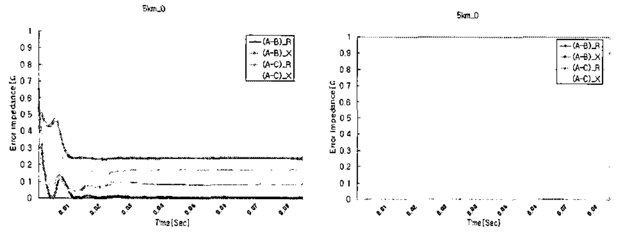
Table 4 Impedance comparison at relay point in the case of the reactor of 1.325mH and the fault point at 4km

Fault inception angle			0 deg.				*90* deg.			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault *point*	**Saturation *of the* reactor**	**SVL *bonding* types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
4km	**Without**	**D**	0.009	0.002	0.133	0.129	0.015	0.018	0.128	0.131
		K	0.011	0.012	0.116	0.126	0.009	0.01	0.116	0.126
	With	**D**	0.006	0.002	0.004	0.003	0.001	0.009	0.001	0.002
		K	0.003	0.009	0.002	0.007	0.001	0.008	0.002	0.007

* A : Case A, B : Case B, C : Case C

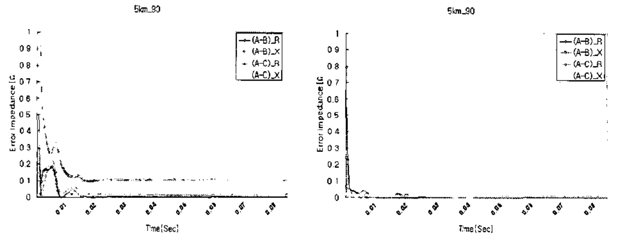
Fig. 12, Fig. 13, Table 5 and Table 6 display the error impedance between two different cases at D type and K type, respectively, while the fault occurs at 5 km. The results are quite similar as the case in which the fault is at 4km. The current reduction device and RDP have no impact on the operation of the relay while the saturation characteristic of the reactor is considered.

As discussed in Section 2.2, the developed current reduction device and the reactor contain saturation characteristics. The saturation characteristics of the relay reduce the error impedance to nearly zero while the fault is at different positions. That means it has no impact on the relay operation. The results also demonstrated that the fault inception angles and SVL bonding types have no influence on the change of cable impedance and therefore no impact on the operation of the relay as well.



(a) Without saturation (b) With saturation

Fig. 12 Error impedance in the case of the D type SVL bonding, the reactor of 2.65mH, fault inception angle of 0 deg and fault point at 5km



(a) Without saturation (b) With saturation

Fig. 13 Error impedance in the case of K type SVL bonding, the reactor of 1.325mH, fault inception angle of 90 deg and fault point at 5km

Table 5 Impedance comparison at relay point in the case of the reactor of 2.65mH and the fault point at 5km

Fault inception angle			0 deg.				90 deg.			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault point	**Saturation of the reactor**	**SVL bonding types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
5km	**Without**	**D**	0.002	0.085	0.238	0.165	0.001	0.072	0.232	0.16
		K	0.016	0.06	0.195	0.163	0.016	0.064	0.193	0.16
	With	**D**	0	0	0.002	0.001	0	0.008	0.001	0.003
		K	0.002	0.01	0.001	0.006	0.006	0.003	0.002	0.01

* A : Case A, B : Case B, C : Case C

Table 6 Impedance comparison at relay point in the case of the reactor of 1.325mH and the fault point at 5km

Fault inception angle			0 deg.				90 deg.			
Cable impedance			R[Ω]		X[Ω]		R[Ω]		X[Ω]	
Fault point	**Saturation of the reactor**	**SVL bonding types**	**Error impedance**				**Error impedance**			
			A-B	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**	**A-B**	**A-C**
5km	**Without**	**D**	0.001	0.006	0.122	0.123	0.003	0.006	0.118	0.117
		K	0.011	0.013	0.109	0.117	0.011	0.015	0.108	0.118
	With	**D**	0	0.002	0.001	0.001	0.001	0.005	0.005	0.001
		K	0.002	0.008	0.003	0.004	0.002	0.008	0.003	0.006

* A : Case A, B : Case B, C : Case C

5. Conclusions

In the previous paper, the authors designed the current reduction device to reduce the sheath circulating current, and also designed its protection device named as RDP (Reduction Device Protector). The test and simulation results indicated that the current reduction device could effectively reduce the sheath circulating current and the protection device could protect it from any damage by lightning. In this paper, in order to evaluate their impacts to the operation of distance relay while the single line to ground fault occurred, the impedances of the underground power cable system with current reduction device and RDP were calculated and then these impedances were compared with impedances without current reduction device and RDP. Because of the saturation characteristics of the designed RDP, the current reduction device and RDP just slightly changed the cable impedance at the relay point. The results also proved that the fault inception angle and SVL bonding types had no effects on the cable impedance. From these results, we expect that the distance relay can safely operate after the installation of the sheath current reduction device and RDP on an underground power cable system without new relay setting.

Acknowledgements

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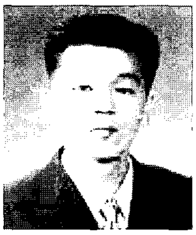

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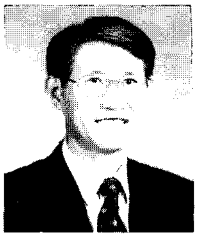

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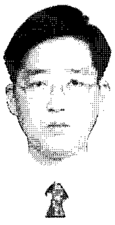

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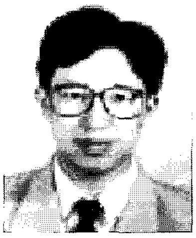

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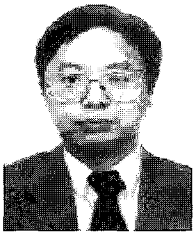

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