Sheath Circulating Current Analysis of a Crossbonded Power Cable Systems

Chae-Kyun Jung*, Jong-Beom Lee† and Ji-Won Kang**

Abstract – The sheath in underground power cables serves as a layer to prevent moisture ingress into the insulation layer and provide a path for earth return current. Nowadays, owing to the maturity of manufacturing technologies, there are normally no problems for the quality of the sheath itself. However, after the cable is laid in the cable tunnel and is operating as part of the transmission network, due to network construction and some unexpected factors, some problems may be caused to the sheath. One of them is the high sheath circulating current. In a power cable system, the uniform configuration of the cables between sections is sometimes difficult to achieve because of the geometrical limitation. This will cause the increase of sheath circulating current, which results in the increase of sheath loss and the decrease of permissible current. This paper will study the various characteristics and effects of sheath circulating current, and then will prove why the sheath current rises on the underground power cable system. A newly designed device known as the Power Cable Current Analyser, as well as ATP simulation and calculation equation are used for this analysis.

Keywords: Crossbonding, Power Cable Current Analyser, Sheath circulating current, Underground power cable system.

1. Introduction

In the case of underground power cable systems, the sheaths are crossbonded together at each end of the cable to suppress the induced voltage in the sheaths. The details of the various sheath bonding methods can be referred to in the IEEE guide [1] and technical report of the CIGRE Working group 07 [2]. Specially, the crossbonding of the sheaths produces a returning path of the fault current and also suppresses the overvoltage in a transient state. These phenomena have been investigated by many researchers [3-5]. The current induced from other phase cables is also produced at the sheath of a crossbonded power cable system in a steady state. This current is known as "sheath circulating current". According to IEC Std. 287 [6], the high sheath circulating current has an influence on sheath circulating loss, which increases the thermal resistance of cable and then reduces the permissible current. It will also cause danger to the cable maintenance engineer. Therefore, it's very important to analyse the reason why the sheath current rises obviously.

In this paper, the characteristic of the sheath circulating current is first analysed at the actual underground power cable system that has some problems pertaining to the high sheath circulating current.

For this analysis, a special device named the "Power Cable Current Analyser" is used to measure and examine the sheath circulating current.

Normally, the burying formations as well as the different lengths between joint sections have an influence on the sheath current. They will cause the impedance imbalance between cables, and then further cause the increase of the sheath current. This paper will review the various rise causes of sheath circulating current and their effects using measurement, ATP simulation, and calculating equation. In Section 2, the Power Cable Current Analyser designed for the measurement of the sheath circulating current is introduced. Section 3 discusses how to calculate the sheath current. Section 4 studies the phenomena and characteristics of sheath circulating current according to the various cable conditions. Section 5 concludes the paper.

2. Development of the power cable current analyser

2.1 Basic theory of power cable current analyser

In order to study the sheath circulating currents, a special device was designed to measure this kind of current on the sheath. It is named the "Power Cable Current Analyser". This analyser has 9 channels to measure the current of 9 places at the same time and each channel simultaneously samples the signal. It can also display the basic power

† Corresponding Author: Dept. of Electrical Electronic and Information Engineering, Wonkwang University, Korea (ipower@wonkwang.ac.kr)
* Transmission Technology Group, Korea Electric Power Research Institute, Korea (chekyun@kepri.re.kr)
** Transmission Technology Group, Korea Electric Power Research Institute, Korea (jwkang@kepri.re.kr)
Received 2 September, 2006; Accepted 3 March, 2007

frequency component as well as the 3rd, 5th, 7th and 9th harmonic components using on-line FFT (Fast Fourier Transform) analysis.

When the function of analogue signal is $f(t)$, Fourier transform ($F(jw)$) can be expressed as Equation (1).

$$F(jw) = \int_{-\infty}^{\infty} f(t)e^{jwt} d\omega \quad (1)$$

Inverse Fourier transform ($f(t)$) can also be expressed as Equation (2).

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(jw)e^{jwt} d\omega \quad (2)$$

In the case of digital signal, the frequency spectrum ($X_N(k)$) for the digital signal ($x(n)$, $n = 0, 1, 2, 3, \ldots,$ N-1) can be shown by Equation (3).

$$X_N(k) = \sum_{n=0}^{N-1} x(n)e^{-j(\frac{2\pi}{N})nk} \quad (3)$$

Where, $k = 0, 1, 2, 3, \ldots,$ N-1.

Equation (3) is the digital expression of Fourier transform and this called DFT (Discrete Fourier Transform). IDFT (Inverse Discrete Fourier Transform) is also defined by Equation (4).

$$x(n) = \frac{1}{N} \sum_{n=0}^{N-1} X_N(k)e^{j(\frac{2\pi}{N})nk} \quad (4)$$

Where, $n = 0, 1, 2, 3, \ldots,$ N-1.

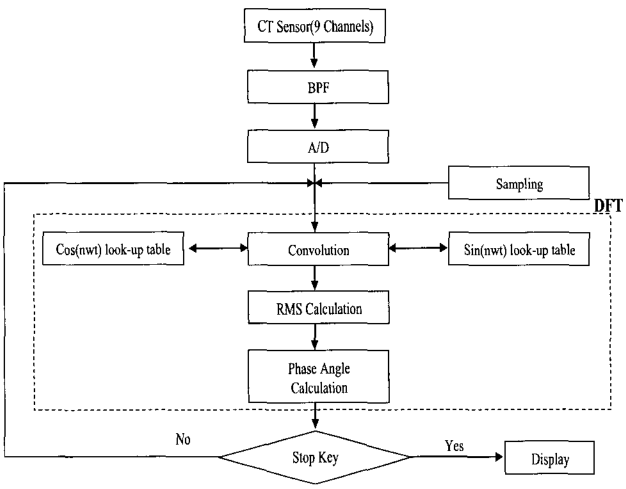


Fig. 1. Flow chart of the developed algorithm for power cable analyzer.

It takes a long time to analyse the signal using DFT because of many repeat calculations. Therefore, the algorithm for the Power Cable Current Analyser omitted the repeat calculation procedure of DFT to calculate the signal faster. Fig. 1 shows the flow chart of the developed algorithm for the Power Cable Current Analyser.

2.2 Structure of power cable current analyser and its application

Fig. 2 presents the picture of the developed Power Cable Current Analyser. It consists of 3 parts: sensor, processing unit, and ancillary devices. The sensor is the current transformer (CT), which measures the sheath circulating current. The processing unit can display the current in magnitude and phase angle, analyse the current in frequency domain by Fast Fourier Transform, and display the 3rd, 5th, 7th and 9th harmonic components. It has a connecting port to the digital oscilloscope to display the current waveforms, and a port to a printer to print the result. The other ancillary is the battery for the operation of the equipment. The Power Cable Analyser has the capability to measure up to 9 currents at a single time. The other specifications are:

1) Maximum current measurement: 500A (± 1%) at power frequency
2) Minimum current measurement: 0.1A (± 3%) at power frequency
3) Operation voltage: DC 24V (Battery)
4) Saving function: amplitude and phase angle of current, including the harmonic component

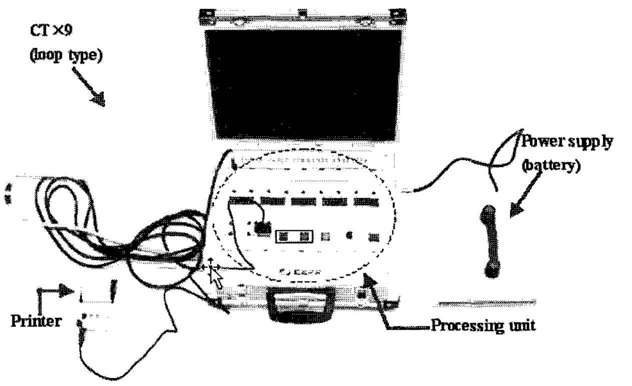


Fig. 2. Picture of power cable current analyzer.

The developed Power Cable Current Analyser can apply to the insulation joint (IJ) and normal joint (NJ) of underground power cable systems for measuring a sheath current. When measuring the sheath currents, CTs are mounted in different connection methods based on the joint type.

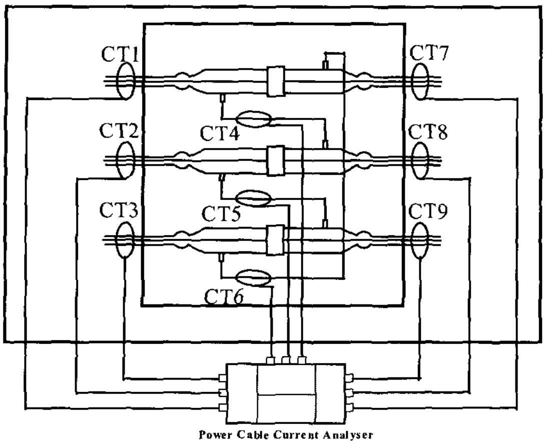


Fig. 3. Application of power cable current analyzer at the insulation joint. (IJ)

Fig. 3 indicates the connection structure of the Power Cable Current Analyser at the insulation joint (IJ). Fig. 4 is the connection structure in the case of normal joint (NJ).

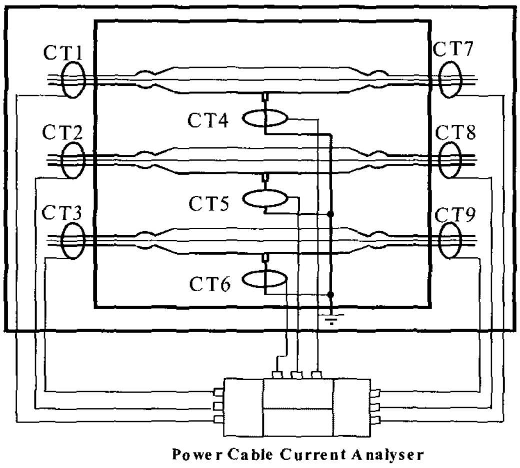


Fig. 4. Application of power cable current analyser at the normal joint. (NJ)

2.3 Measurements and its comparison

The Power Cable Analyser is applied to measure the sheath circulating current in a practical system in South Korea. The system's schematic diagram is indicated in Fig. 5. The cable is single core, oil-filled and paper insulated. The configuration of the cable is shown in Fig. 6. It is a transmission system with 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 at joints between two sections. Between the minor sections, joints are referred to as insulation joints (IJ) in this paper, and the sheaths are connected to the SVL (Sheath Voltage Limiter) to protect against the transients overvoltage. At joints between two major sections, known as normal joints (NJ), the sheaths are connected to earth directly. As revealed in Fig. 5, 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 different from the others. Normally, the cable is buried in trefoil formation. However, minor sections between joints 9 and 10 are buried in duct formation, and the minor section between joints 8 and 9 are buried in mixed trefoil and duct formation. The details of these two formations will be described in the next section.

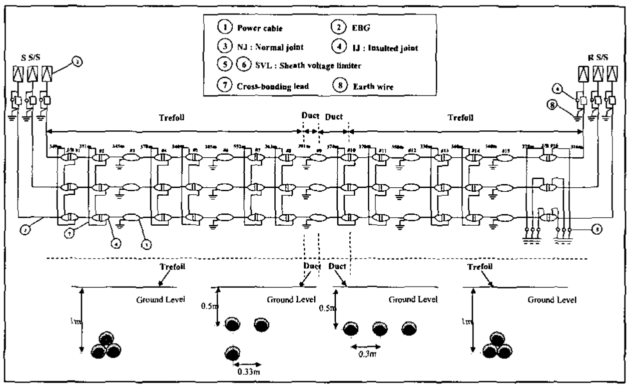


Fig. 5. System diagram of 154kV underground power cable system.

The sheath circulating currents are also simulated by widely used software ATP (Alternative Transient Programs). The measured and simulated currents at each joint are depicted in Fig. 7.

Fig. 7 indicates the sheath circulating current in three phases. The line marked with squares is the measured current. The line marked with diamonds is the simulated current. The trend of the current between simulation and measurement is very similar. First the currents between joints 1 and 5 stay low while the cables are buried uniformly in trefoil formation. Then there is an increase of currents up to 30A between joints 6 and 8. Finally, the currents soar to 80A between joints 9 and 12. They are so high on the sheath that it's out of the tolerance of the power cable. High sheath currents will produce a large amount of heat, which will cause damage to the cable and also the maintenance personnel, result in sheath loss and reduce the permissible current. As such, sheath currents should be reduced to a safe level.

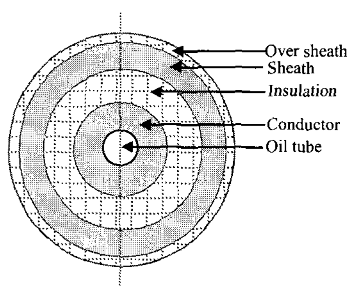
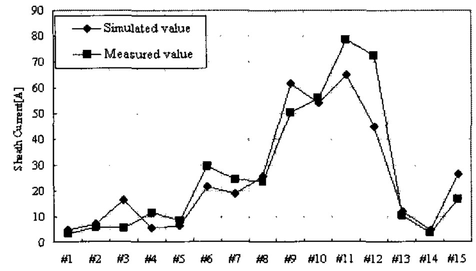
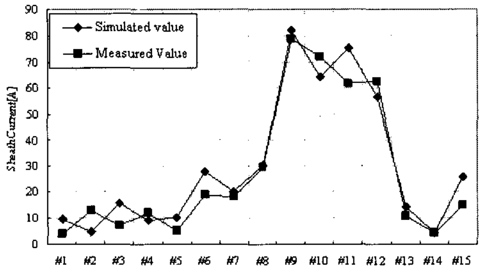


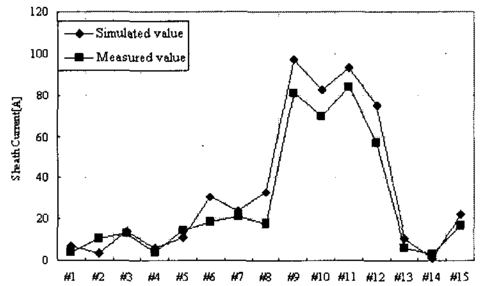
Fig. 6. Structure of single-core oil-filled cable.



(a) In phase A



(b) In phase B



(c) In phase C

Fig. 7. Simulated and measured sheath current.

The increase of the sheath currents is supposedly caused by the mixed burying formation of the cable and the different length of the section. In Section 4, we are going to study the characteristics of the sheath circulating currents to find out which affect them the most. Also from the comparison between test and simulation, it is validated that both test and simulation methods are effective and reliable in current sheath study.

3. Calculation of the sheath circulating current

Fig. 8 is the diagram of a typical single circuit, one major section cable system with sheaths crossbonded between each minor section and connected to earth at both ends of the major section via a resistance. In this system, the sheath circulating circuit is given by Equation (5).

$$l\cdot[z_1][i_{si}]+m\cdot[z_2][i_{si}]+n\cdot[z_3][i_{si}]+[V_s]+(R_1+R_2)\sum_{i=1}^{n} i_{si}=0 \quad (5)$$

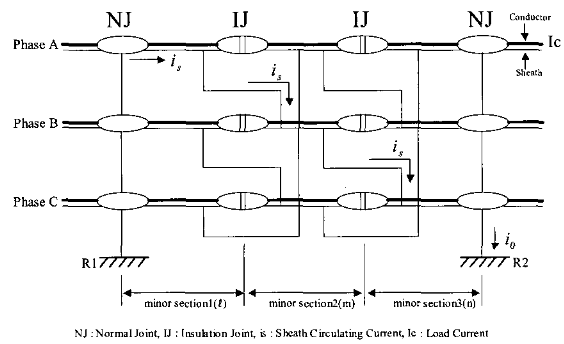


Fig. 8. One major section of single circuit crossbonded underground cable system

Where l, m, and n are lengths of each minor section in km, $[z_1]$, $[z_2]$, and $[z_3]$ are matrices of impedance between sheath and earth in each minor section, $[i_{si}]$ is the matrix of the sheath circulating currents in A, $[V_s]$ is the matrix of induced sheath voltages in V, and R_1 and R_2 are the ground resistance in Ω .

[Vs] is given by:

$$[V_s]=l\cdot[Z_1][I_i]+m\cdot[Z_2][I_i]+n\cdot[Z_3][I_i]=0 \quad (6)$$

Where $[Z_1]$, $[Z_2]$ and $[Z_3]$ are matrices of impedance between conductor and sheath in each minor section, and $[I_i]$ is the matrix of load currents.

In the event of considering a single circuit underground cable system, Equation (5) can be expressed as Equation (7).

$$l\cdot[z_1][i_{si}]+m\cdot[z_2][i_{si}]+n\cdot[z_3][i_{si}]$$
$$=l\cdot\begin{bmatrix} z_{11} & z_{12} & z_{13}\\ z_{21} & z_{22} & z_{23}\\ z_{31} & z_{32} & z_{33}\end{bmatrix}\begin{bmatrix} i_{s1}\\ i_{s2}\\ i_{s3}\end{bmatrix}+m\cdot\begin{bmatrix} z_{22} & z_{23} & z_{21}\\ z_{32} & z_{33} & z_{31}\\ z_{12} & z_{13} & z_{11}\end{bmatrix}\begin{bmatrix} i_{s1}\\ i_{s2}\\ i_{s3}\end{bmatrix}+n\cdot\begin{bmatrix} z_{33} & z_{31} & z_{32}\\ z_{13} & z_{11} & z_{12}\\ z_{23} & z_{21} & z_{22}\end{bmatrix}\begin{bmatrix} i_{s1}\\ i_{s2}\\ i_{s3}\end{bmatrix} \quad (7)$$

The matrix of induced sheath voltages can also be expressed as Equation (8).

$$[V_s]=l\cdot\begin{bmatrix} Z_{11} & Z_{12} & Z_{13}\\ Z_{21} & Z_{22} & Z_{23}\\ Z_{31} & Z_{32} & Z_{33}\end{bmatrix}\begin{bmatrix} I_1\\ I_2\\ I_3\end{bmatrix}+m\cdot\begin{bmatrix} Z_{21} & Z_{12} & Z_{23}\\ Z_{31} & Z_{32} & Z_{33}\\ Z_{11} & Z_{12} & Z_{13}\end{bmatrix}\begin{bmatrix} I_1\\ I_2\\ I_3\end{bmatrix}+n\cdot\begin{bmatrix} Z_{31} & Z_{32} & Z_{33}\\ Z_{11} & Z_{12} & Z_{13}\\ Z_{21} & Z_{22} & Z_{23}\end{bmatrix}\begin{bmatrix} I_1\\ I_2\\ I_3\end{bmatrix} \quad (8)$$

Therefore, in a single circuit, the sheath circulating current can be calculated by Equations (7) and (8), and the induced sheath voltage can be also calculated by Equation (8). But, both equations can be relevant for multiple circuit underground power cable systems.

Specific impedance calculations can also be given by [7-8]

○ mutual impedance between conductor and sheath

$$Z_{ii}=0.000989f+j0.0029f\cdot\ln\frac{D_e}{r}\ [\Omega/\text{km}] \quad (9)$$

○ mutual impedance between conductor and another phase sheath

$$Z_{ij} = 0.000989\,f + j0.0029\,f \cdot \ln\frac{De}{S} \quad [\Omega/\text{km}] \qquad (10)$$

○ sheath self impedance

$$z_{ii} = R_s + 0.000989\,f + j0.0029\,f \cdot \ln\frac{De}{r} \quad [\Omega/\text{km}] \qquad (11)$$

○ sheath mutual impedance

$$z_{ij} = 0.000989\,f + j0.0029\,f \cdot \ln\frac{De}{S} \quad [\Omega/\text{km}] \qquad (12)$$

Where f is the power frequency, D_e is the equivalent depth of earth return path, r is the radius of sheath in mm, S is the spacing between center points of the conductor in mm, and R_s is the AC sheath resistance in Ω /km.

The above equations indicate that the sheath circulating currents are affected by the impedance of the sheath, while the impedance of the sheath is determined by the sheath itself and its conducting path to the other conductor. Therefore, by changing the conducting path, the sheath circulating current will be increased or decreased.

4. Analysis of sheath circulating current

4.1 Correlation of the sheath current and permissible current

While the underground power transmission cable is in operation, the sheaths are crossbonded at each end of the cable to suppress the induced voltages in the sheath. The crossbonding of the sheaths produces a returning path of the induced current from other phase cables. This current is known as "sheath circulating current", which produces "sheath circulating loss".

According to IEC Std. 287 [6], the permissible current of an AC cable is written as Equation (13) in buried cables where drying out of the soil does not occur on cables installed in the air.

$$I = \sqrt{\frac{\Delta\theta - W_d[0.5T1 + n(T2+T3+T4)}{RT1 + nR(1+\lambda_1)T2 + nR(1+\lambda_1+\lambda_2)(T3+T4)}} \qquad (13)$$

Where, T_1 to T_4 mean the internal and external thermal resistances of cable. λ_1 is the ratio of losses in the sheath to total losses in all conductors in that cable, λ_2 is the ratio of losses in the armouring to total losses in all conductors in that cable. Power loss in the sheath λ_1, is expressed as Equation (14).

$$\lambda_1 = \lambda'_1 + \lambda''_1 \qquad (14)$$

Where,

λ'_1 : loss caused by sheath circulating current

λ''_1 : loss caused by eddy current

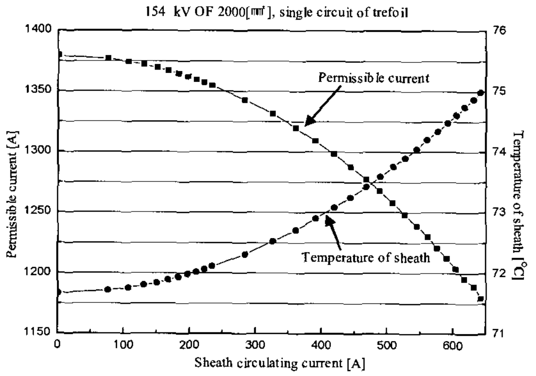


Fig. 9. Correlation of the sheath circulating current and permissible current.

The correlation between sheath circulating current and permissible current is shown in Fig. 9. If the sheath circulating current rises, the loss caused by sheath circulating current will increase, and then the ratio of loss dissipated in sheath per unit length to loss in conductor per unit length will increase, too. By such effect, the temperature and total thermal resistance of the cable is on the rise, and the permissible current is reduced. Therefore, the sheath circulating current must be reduced for the increment of transmission capacity. In addition, the high sheath current has an effect on individuals and may cause the fault by the breakdown of insulation.

4.2 Correlation of the sheath current and length imbalance

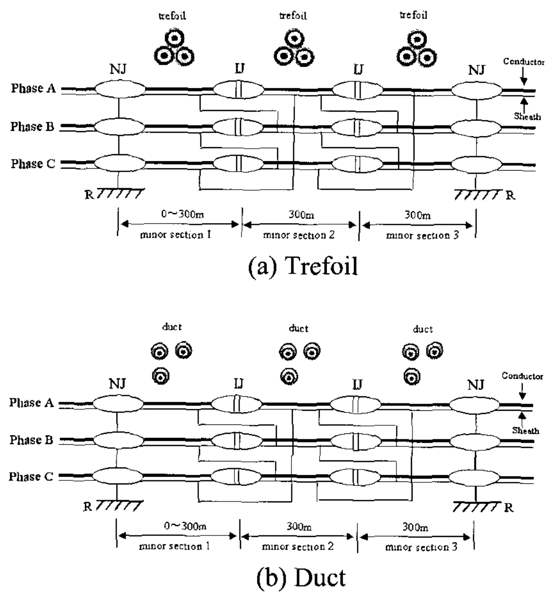


Fig. 10. Trefoil and duct in unified burying formation.

The correlation of the sheath circulating current and section length is discussed in this section. First, we consider unified burying formation, which is constructed by the same formation as trefoil or duct, then the mixed burying formation will be applied. When the cables in each minor section have the same length, the cables are referred to balance and the length imbalance rate is zero. In trefoil and duct formation like Fig. 10, supposing the normal length of the cable is 300 meters, and the lengths of the cables in the first minor section are changing, then the imbalance rate of the system and the sheath circulating currents are indicated in Fig. 11.

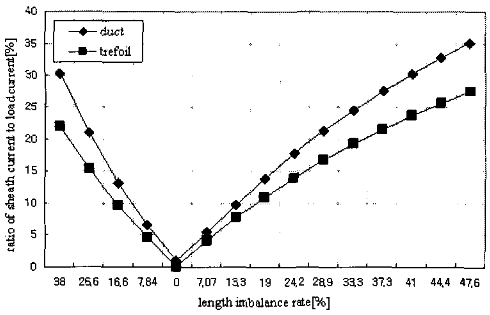


Fig. 11. Sheath circulating current with length imbalance rate.

In Fig. 11, the current marked with squares is the cable in trefoil formation while the other is in duct formation. The results are similar for these two types of formations. When the cables have the same length, the sheath circulating currents reach the lowest. For the trefoil type arrangement, it is zero because the arrangement is symmetrical. Also, because of the asymmetrical arrangement of the duct formation, it always has a higher sheath circulating current than the trefoil arrangement. For both types, the sheath circulating currents rise with the increase of the length imbalance rate. Such analysis results remind us that the sheath current can be reduced by keeping the cables balanced. This balance can be the same length of the cable or the same impedance of the cable.

The mixed burying formation, as well as different lengths between sections, has an influence on the sheath current. Fig. 12 shows the examples of mixed burying formation in different lengths between sections.

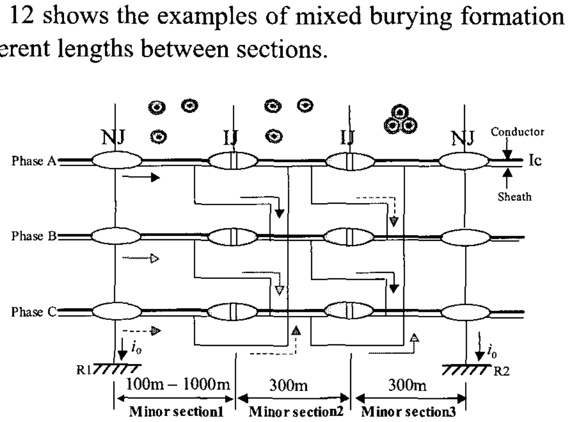


Fig. 12. Example of mixed burying formation.

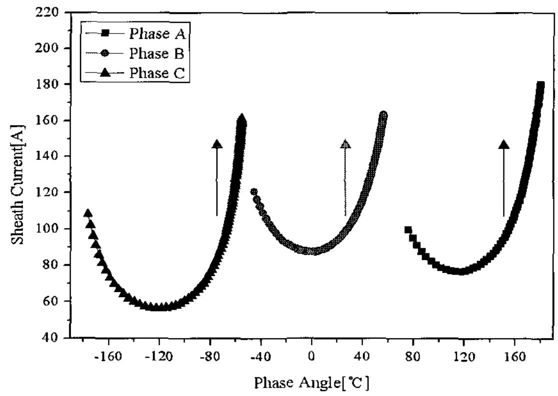


Fig. 13. Sheath circulating current with length imbalance in mixed burying formation.

Fig. 13 reveals the sheath currents in mixed burying formation. As shown in Fig. 13, the magnitude of sheath current is higher than unified burying formation, and the phase angle is also irregularly changed.

4.3 Correlation of the sheath current and burying formation

In this section, we mainly investigate how duct formation affects the sheath circulating current. For a duct formation, the three cables are placed on the corners of an isosceles right-angled triangle. Normally, the length of the two equal edges, C12 and C23, is 330 mm, as indicated in Fig. 14.

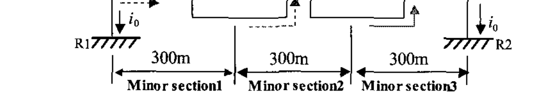
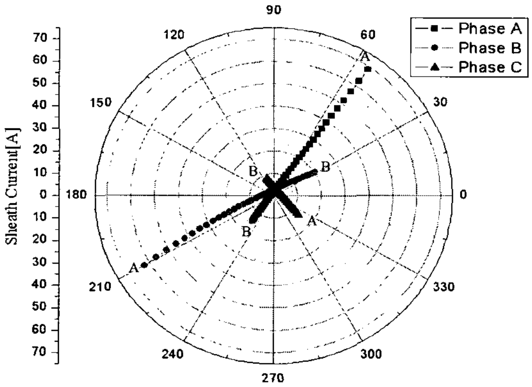
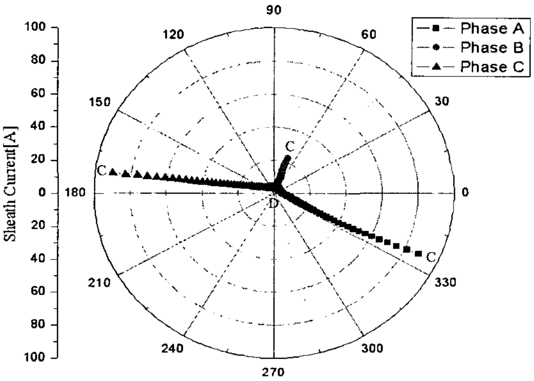


Fig. 14. Duct burying formation within a major section.

Supposing the cables are rearranged and one edge of the triangle is increasing from 100mm to 500mm, then the induced circulating currents with the variation of the spacing are presented in Fig. 15. The figure shows the combined magnitude and the phase angle. Fig. 15(a) is the magnitude and phase angle of the circulating current with relation of spacing C12. Here the sheath current is changing from A to B. Fig. 15(b) indicates the spacing of C13, and the sheath current is also changing from C to D. The results are similar at both conditions. The magnitude of the current will decrease to a minimum when the spacing is increased to a certain value, then it will increase slowly with the increase of the spacing. In Fig. 15(a), that value is 330mm and in Fig. 15(b), it is 470mm. Thus, the present structure is the most optimal one for the sheath circulating current.



(a) Sheath current and phase angle with spacing C12



(b) Sheath current and phase angle with spacing C13

Fig. 15. Sheath current and phase angle with variation of spacing C12 and C13.

Fig. 16 presents the major section similar with the practical system shown in Fig. 5. The cables are buried with mixed duct formation on the first minor section and trefoil formation on the second and third minor sections. The corresponding sheath circulating currents are presented in Fig. 17.

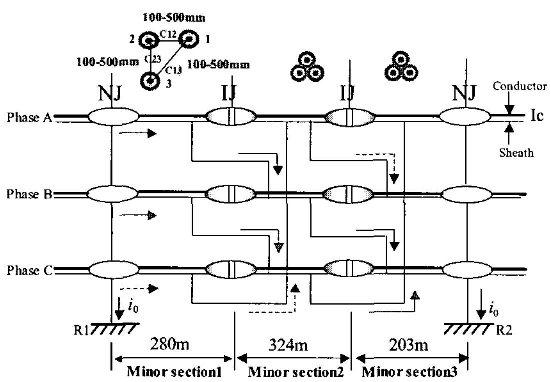
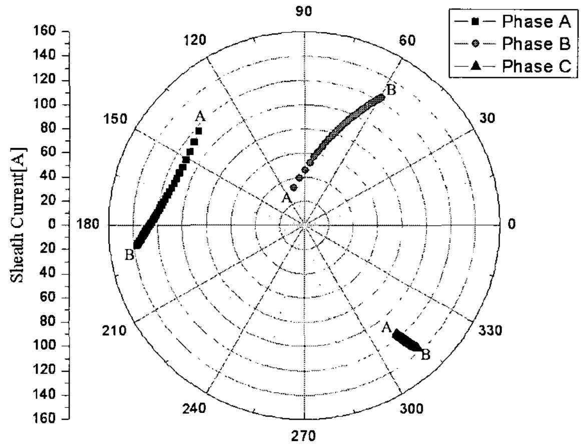
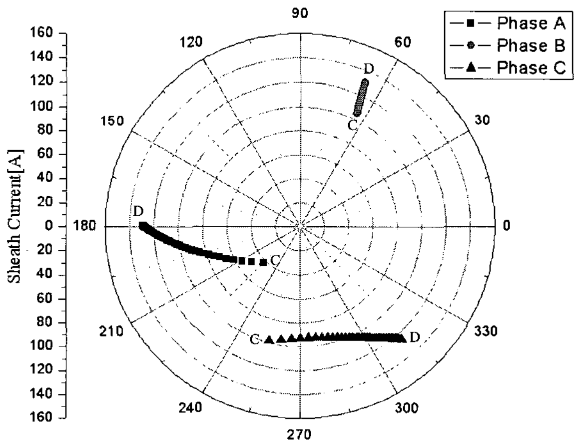


Fig. 16. Mixed burying formation within a major section.

Fig. 17(a) shows the magnitude and phase angle of the circulating currents with spacing C12. Fig. 17(b) indicates the spacing of C13 and the sheath current is also changing from C to D. In Fig. 17(a), the sheath current is changing from A to B. The results are quite different with the currents under uniformed formation as shown in Fig. 15. Not only the magnitude, but also the phase angle changes with the spacing. In Fig. 17(a), the amplitude of sheath current in phase A decreases slowly to 120A, and then increases up to a maximum of 140A while the spacing C12 is changing from 100mm to 500mm. The current always keeps a high level no matter if the spacing is increasing or decreasing. The phase angle is also steeply increasing. However, the amplitude of phase B increases more steeply than the phase angle. The results in Fig. 17(b) are similar to those in Fig. 17(a). They look like the same if the sheath circulating currents turn around with a certain angle. We can also see that the phase angles of the three phases are not separately uniform. That will cause a huge zero-phase current that is very dangerous to the maintenance engineer and to the cable life itself.



(a) Sheath current and phase angle with spacing C12



(b) Sheath current and phase angle with spacing C13

Fig. 17. Sheath current and phase angle with variation of spacing C12 and C13.

4.4 Correlation of the sheath current and distribution cable system

Both transmission cable systems and distribution cable systems are normally installed in the same duct or tunnel. Their sheaths are also connected on the same earth terminal because the space for grounding is very small and narrow. Especially, in the distribution cable system, the imbalanced load current is often measured because of the imbalanced load. The imbalanced current is also induced on a sheath of distribution cable, then that current travels to the sheath of the transmission cable system through the common grounding point. Therefore, the sheath circulating current of the transmission cable system is also increasing because of that. In this section, we study the characteristic of sheath circulating current by the imbalanced load of the distribution cable system.

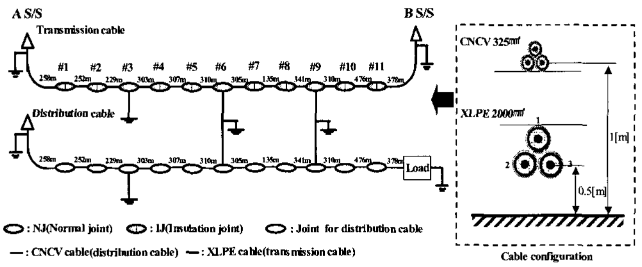


Fig. 18. Model system for effect analysis by the distribution cable system.

Fig. 18 presents the model system for effect analysis by the distribution cable system. As shown in Fig. 18, the XLPE transmission system with a voltage of 154kV and the CNCV distribution system with a voltage of 22.9kV are installed at the same cable tunnel, and the common grounding points are joint 6 and 9. For the various analyses, 4 types are set up according to the imbalanced load rate of the distribution cable system as expressed in Table 1. In the case of Type 1, there is no imbalanced load. However, type 2 to type 4 have the imbalanced load rate of 17.5% and 37.5%, respectively.

Table 1. Imbalanced load rate of the distribution cable system.

	Imbalanced load rate [%]		
Types	Resistance (R)	Reactance (X)	Average
Type 1	0 %	0 %	0 %
Type 2	20 %	15 %	17.5 %
Type 3	27 %	30 %	28.5 %
Type 4	42 %	33 %	37.5 %

Fig. 19 indicates the change of sheath circulating current of the transmission cable systems according to the various types expressed in Table 1. In Type 1, the maximum sheath current is the 130A at joint 9. However, the maximum sheath currents from Type 2 to Type 4 are 157A, 188A and 226A, respectively. These results demonstrated, in the case of connection at the same earth terminal, that the imbalanced load rate of the distribution cable system had an effect on the increase of the sheath circulating current of the transmission cable system.

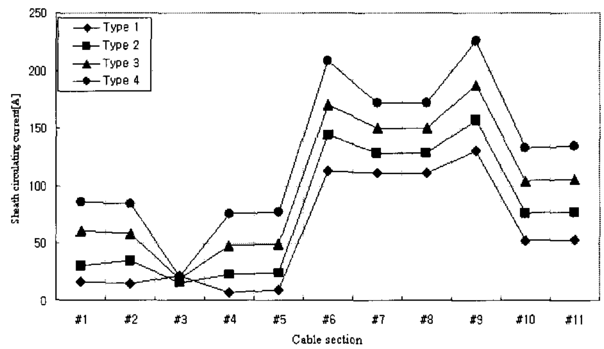


Fig. 19. Sheath circulating current of transmission cable system according to the imbalanced load rate of distribution cable system.

5. Conclusions

This paper analysed the various characteristics and effects of sheath circulating current, then proved the reason of the increase of sheath circulating current on the crossbonded power cable system. The Power Cable Current Analyser was newly designed to measure the sheath circulating current and the structure and application method of that was also introduced.

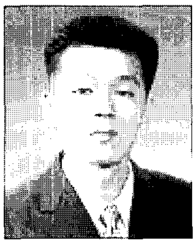
First, in this paper, the correlation between the sheath circulating current and permissible current was analysed. From this analysis, we proved that the sheath circulating loss by high sheath current had an influence on the permissible current of the AC cable. It causes the increase of sheath temperature and total thermal resistance of the cable. Then the various reasons of the increase of sheath circulating current have been analysed. These can be summarized as:

- The duct formation has received a higher sheath circulating current than the trefoil.
- The sheath circulating currents rise with the increase of the length imbalance rate by different lengths between sections.
- The sheath circulating current was also increased by the mixed burying formation.
- The sheath circulating current was the highest at the mixed burying formation in different lengths between sections.

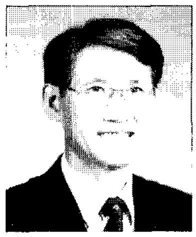
- When the spacing of duct formation was changed at the mixed burying formation, sometimes, the magnitude and phase angle of the sheath current also changed with the spacing. Occasionally, this current keeps a high level no matter if the spacing is increasing or decreasing.
- The imbalanced load rate of the distribution cable system had an effect on the increase of the sheath circulating current in the case of the connection at the same earth terminal.

Reference

[1] IEEE, "IEEE Guide for the Application of Sheath Bonding Methods for Single-conductor Cables and Calculation of induced Voltage and Current in Cable Sheaths", ANSI/IEEE Std. 575-1998.
[2] Working Group 07 of Study Committer 21, "Guide to the Protection of Specially Bonded Cable Systems against Sheath Overvoltage", Electra, No. 128.
[3] B. Gustavsen, J. Sletbak, T. Henrikson, "Simulation of Transient Sheath Overvoltage in the Presence of Proximity Effects", IEEE Trans. On Power Delivery, Vol. 10, No. 2, April 1995.
[4] B. Gustavsen, J. Sletbak, "Transient Sheath Overvoltage in Armoured Power Cables", IEEE Trans. On Power Delivery, Vol. 11, No. 3, July 1996.
[5] Y. Itoh, N. Nagaoka, A. Ametani, "Transient Analysis of a Crossbonded Cable System Underneath a Bridge", IEEE Trans. On Power Delivery, Vol. 5, No. 2, April 1990.
[6] IEC 287-1-1 "Electric Cables – Calculation of the Current Rating, Part 1: Current rating Equations (100% Load Factor) and Calculations of Losses, Section 1: General", 1995.
[7] M. G. Dwek, M. N. Eggleton, "Electrical parameters of 400kV and 275kV cables used in England and Wales".
[8] J. A. Williams, P. L. Ostermann, R. W. Samm, "Underground Transmission System Reference Book", 1992 Edition.



Chae-Kyun Jung
He received his B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering from Wonkwang University, Korea, in 1999, 2002 and 2006, respectively. He was a Postdoctoral Researcher at the University of Siegen, Germany in 2007. He is currently working at the Korea Electric Power Research Institute (KEPRI) since 2007 where is he is a researcher in Transmission Technology Group. His research interests include power systems operation, analysis of power cable systems, fault location, protective relaying.



Jong-Beom Lee
He received his B.Sc., M.Sc. and Ph.D. degrees in Electrical Engineering from Hanyang University, Korea, in 1981, 1983 and 1986, respectively. He worked at the Korea Electrotechnology Research Institute from 1987 to 1990. He was a Visiting Scholar at Texas A&M University and the Swiss Federal Institute of Technology (ETH), Switzerland. He is currently a Professor in the Department of Electrical, Electronic & Information Engineering, Wonkwang University, Korea. His current research interests are power systems operation, analysis of power cable systems, protective relaying, and application of AI to power systems. He is a member of KIEE and IEEE.

Ji-Won Kang
He received his B.Sc., M.Sc. and P.hD. degrees in Electrical Engineering from Hanyang University, Korea, in 1987, 1993 and 2003, respectively. He has been working at the Korea Electric Power Research Institute (KEPRI) since 1993 where he is currently a Senior Technical Staff Member in the Transmission Technology Group. His current research interests are power systems operation and the analysis and diagnosis of power cable systems.