Technical Review on Parallel Ground Continuity Conductor of Underground Cable systems

Jong-Beom Lee† and Chae-Kyun Jung*

Abstract – The Induced sheath voltage is significantly increased at single point bonding section when the ground fault occurs on power cable system because there is no return path of fault current. For solving this problem, therefore, many researchers recommend the PGCC (Parallel Ground Continuity Conductor). In this paper, the characteristics of PGCC are extensively analyzed for reducing the level of induced sheath voltage at the single point bonded section for Korea underground power cable system.

Keywords: Parallel ground continuity conductor, Overvoltage, Underground cable

1. Introduction

Generally, single point bonding section consists in arranging for the sheaths of the three cables to be connected together and earthed at one point only. In Korea, in each single point bonded section, the SVL (sheath voltage limiter) units should be connected between the unbounded ends of the cable sheaths. In this section, during a ground fault, the zero sequence fault current carried by the cable conductor cannot return by any path because single point bonded cable sheath is ground at one position only or the sheaths are separated by SVLs. Specially, the induced sheath voltage is significantly increased at this point when the ground fault occurs on power cable system because there is no return path of fault current. For solving this problem, therefore, many researchers recommend the PGCC (Parallel Ground Continuity Conductor) in single point bonded section.

The PGCC is very effective for suppressing an induced sheath overvoltage because of providing an external fault current path. Accordingly, a single point bonded cable installation with PGCC which is earthed at both ends of the route is recommended. The spacing between PGCC and phase conductor should be closed to limit the voltage level during a single phase ground fault. The size of PGCC should be also adequate to carry the full expected fault current for the cable system. However, in Korea, the PGCCs are not applied for single point bonded section till now. The sheaths are just separated by SVLs. Recently, the installed SVLs in single point bonded section were exploded by single line to ground fault, which caused heavy damage to joint box.

Therefore, in this paper, the characteristics of PGCC are extensively analyzed for reducing the level of induced sheath voltage at the single point bonded section for Korea underground power cable system. Firstly, the optimal installation section is estimated by evaluating of economical and technical efficiency. Next, the adequate conductor size of PGCC will be decided by maximum fault current considering an expected maximum circuit breaker capacity. The additional various cases are also considered including the dimension and the position of PGCC, spacing between PGCC and phase conductors, faulty phase, cable construction types and two PGCCs usage. Korea electric power company, KEPCO, has now plan for adopting PGCC which is suitable on Korea underground power cable system based on the results of this paper. Accordingly, the PGCC will expect to be applied on real power cable system in Korea, and it also contributes to safety service.

2. Induced sheath overvoltage by PGCC installation

PGCC is installed for reducing a sheath overvoltage occurred at single point bonded section through providing a return path of fault current. The overvoltage \( E_c \) induced on PGCC lying in parallel with set of three conductors cab be expressed by Equation (1).

\[
E_c = 10 \times 10^{-7} \log \left( \frac{S_{1c}}{S_{2c}} \right) + j \sqrt{5} \log \left( \frac{S_{1c}}{S_{2c}} \right) \quad (1)
\]
where, $I_b$ is conductor current of phase B and $S_{1C}$, $S_{2C}$ and $S_{SC}$ are axial spacings between PGCC and conductor of phase A, Phase B and C, respectively.

If $I_o$ or $I_c$ is considered in Equation (1), $I_b$ can be alternated by $a \cdot I_o$ or $a^2 \cdot I_c$, respectively. Where, $a$ is $\frac{-1}{2} + j \frac{\sqrt{3}}{2}$. Also, the maximum overvoltage between sheath and earth can be expressed by Equations (2) to (5) when the single line to ground fault occurs on underground power cable system. For a trefoil arrangement ($S_{1C}$=$S_{2C}$=$S_{SC}$=S) which is considered for PGCC installation in this paper, the sheath voltages are equal and are expressed by Equation (6).

$$E_{ab} = j\omega I_b (2 \times 10^{-7}) [\frac{-1}{2} \ln \left(\frac{2S_{1C}}{d\cdot S_{1C}}\right) + j\frac{\sqrt{3}}{2} \ln \left(\frac{2S_{1C}}{d}\right)]$$ (2)

$$E_{ac} = j\omega I_b (2 \times 10^{-7}) [\frac{1}{2} \ln \left(\frac{4S_{1C}^2}{d^2}\right) + j\frac{\sqrt{3}}{2} \ln \left(\frac{2S_{1C}}{d}\right)]$$ (3)

$$E_{bc} = j\omega I_b (2 \times 10^{-7}) [\frac{-1}{2} \ln \left(\frac{2S_{1C}}{d\cdot S_{1C}}\right) - j\frac{\sqrt{3}}{2} \ln \left(\frac{2S_{1C}}{d}\right)]$$ (4)

where, $S_{1C}$ is axial spacing between phase A and phase B, $S_{2C}$ is axial spacing between phase B and phase C, $S_{SC}$ is axial spacing between phase A and phase C and $d$ is geometric mean sheath diameter.

$$E_{ab} = j\omega I_b (2 \times 10^{-7}) \ln \left(\frac{2S_{1C}}{d}\right)$$ (5)

Fig. 1 and Fig. 2 illustrate the overvoltage induced on SVL at single point bonded section according to installation of PGCC or not. As shown in Fig. 1, in the absence of a PGCC, if the ground fault occurs on a cable, in the case of trefoil arrangement, the overvoltage induced on SVL is the vectorial sum of voltage gradient on sheath($E_e$) expressed in Equation (5) and the earth potential rise($V_E$). Accordingly, in this case, it is possible to damage SVL according to the amplitude of added overvoltage.

However, as shown in Fig. 2, if PGCC is installed in same system, the fault current is distributed to sheath and PGCC because PGCC provides a return path of fault current. Consequently, the overvoltage induced on SVL is significantly reduced to $E_e E_{mg}$. Equation (6) shows the voltage gradient on sheath when the PGCC is installed on underground power cable system. Where, $S$ is the distance between PGCC and phase conductor, $r_e$ is GMR(geometric mean radius) of PGCC.

$$E = j\omega I_{mg} (2 \times 10^{-7}) \ln \left(\frac{S}{r_e}\right)$$ (6)

As shown in Equation (6), the sheath voltage can be influenced by the distance between PGCC and phase conductor. GMR of PGCC($r_e$) can be also influenced when the PGCC is installed on the system. The sheath voltage is reduced by closer distance of $S$ and thicker GMR of $r_e$.

3. Model System

The diagram of a real power cable system discussed in this paper is shown in Fig. 3. It is a single core cable transmission system with the voltage of 154 kV. The total length of the cable is 3.392 km. It consists of three crossbonded major sections with three minor sections for each major section. Joint No. 9 is the single point bonded section. As usual, the sheaths are jointed and cross bonded between two sections.
4. Selection of PGCC conductor size

The conductor size of PGCC has been determined by IEC 60364-5-54 in this paper. Equation (7) expresses the calculation method. As shown in Equation (7), the conductor size of PGCC is determined by fault current of PGC, duration time and material characteristics.

\[
A = \frac{I \cdot t_c}{k} 
\]

where,

\[
k = \sqrt{\frac{Q_c (B+20)}{\rho_{20}}} \ln \left(1 + \frac{\theta_f - \theta_i}{B+0}\right) 
\]

\[
A : \text{conductor size of PGCC [㎟]}, \ I : \text{conductor current in PGCC [A]}, \ t_c : \text{duration time [sec]}, \ B : \text{reciprocal of temperature coefficient of resistance at 0°C [K]}, \ \rho_{20} : \text{electrical resistivity at 20°C [Ω.m]}, \ \theta_i : \text{initial temperature [°C]}, \ \theta_f : \text{final temperature [°C]}
\]

**Table 1.** Factors and result for calculation of conductor size

<table>
<thead>
<tr>
<th>Factor</th>
<th>Value</th>
<th>I</th>
<th>t_c</th>
<th>B</th>
<th>(\rho_{20})</th>
<th>(\theta_i)</th>
<th>(\theta_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>50,000</td>
<td>0.5</td>
<td>234.5</td>
<td>1.7241\times10^{-4}</td>
<td>30</td>
<td>250</td>
<td></td>
</tr>
</tbody>
</table>

Calculated conductor size : 201.3[㎟]

In this paper, fault current of 50 kA and duration time of 0.5 sec are assumed for calculation of PGCC conductor size as a Korean standard. The detailed data are listed in Table 1. Finally, the calculated conductor size is 201.3 ㎟. Accordingly, the conductor size of TFR-CV 240 ㎟ is selected for PGCC. However, for more detailed analysis according to the change of conductor size, TFR-CV 500 ㎟ of PGCC is also considered. In Table 2, the dimension and permittivity are listed according to the kinds of conductor size.

**Table 2.** Dimension of PGCC according to kinds of conductor size

<table>
<thead>
<tr>
<th>Type</th>
<th>Radius of conductor [㎟]</th>
<th>Radius of insulation [㎟]</th>
<th>Permittivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFR-CV</td>
<td>0.00915</td>
<td>0.01085</td>
<td>2.4</td>
</tr>
<tr>
<td>TFR-CV</td>
<td>0.0132</td>
<td>0.0174</td>
<td>2.4</td>
</tr>
</tbody>
</table>

5. Selection of PGCC installation section

5.1 Classification of installation section

For analyzing the effects of PGCC, the installation conditions are variously considered including installation section, conductor dimension, the use of two PGCCs and the distance between PGCC and phase conductor. Firstly, for more detailed analysis, 3 kinds of installation methods are proposed as shown in Fig. 4. In Type 1, the PGCC is installed between last NJ 2 to B S/S. Type 2 and Type 3 are installed between NJ 1 and B S/S, single point bonded section and B S/S, respectively.

**Fig. 4.** Installation types of PGCC.
5.2 Selection result of installation section

For the selection of optimal installation section, the proposed 3 kinds of installation types are simulated and compared in duct as well as trefoil arrangements when the single line to ground fault is assumed to occur on phase A. Table 3 classifies the analysis cases according to the construction formation and kinds of types expressed in Fig. 4. The PGCC is installed at vacant duct in duct formation, and it is supposed to be installed closely to Phase C in trefoil arrangement. The induced sheath voltages measured at center SVLs of 3 set SVLs in single point bonded section are compared because the voltage induced at center SVLs is higher than one of left hand or right hand SVLs. Fig. 5 shows the reduction rate of induced sheath voltage in duct arrangement. As shown in Fig. 5, Type 1 and Type 2 are similarly reduced, but Type 3 has no effect on induced sheath voltage by installation of PGCC. Averagely, Type 1 and Type 2 in duct formation show 36.1 % and 34.8 % of sheath voltage reduction, respectively. But, Type 3 is just 5.07 %. Fig. 6 is in case of trefoil arrangement. As shown in Fig. 6, the induced sheath voltage of Type 1 and Type 2 are also similarly reduced, Type 3 is very slightly reduced. The average reduction rate of each type is 62.1 %, 62.3 % and 4.19 %. In addition, the reduction rate of phase C is better than one of other phase. From these results, it can be proved that the distance between phase conductor and PGCC is closer, the sheath voltage reduction rate is better.

Table 3. Cases according to construction formation and kinds of installation types

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Types</th>
<th>Conductor size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct</td>
<td>Type 1</td>
<td>TFR-CV 240 mm²</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>TFR-CV 240 mm²</td>
</tr>
<tr>
<td></td>
<td>Type 3</td>
<td>TFR-CV 240 mm²</td>
</tr>
<tr>
<td>Trefoil</td>
<td>Type 1</td>
<td>TFR-CV 240 mm²</td>
</tr>
<tr>
<td></td>
<td>Type 2</td>
<td>TFR-CV 240 mm²</td>
</tr>
</tbody>
</table>

Fig. 5. Sheath voltage reduction rate of Type 1 to Type 3 in duct formation.

Fig. 6. Sheath voltage reduction rate of Type 1 to Type 3 in trefoil arrangement.

Consequently, although the reduction rates of Type 1 and Type 2 are almost same, Type 1 is more economical than Type 2 considering installation length of PGCC. On the other hand, there is no reduction effect in Type 3. Therefore, in this paper, Type 1 is selected for optimal installation section of PGCC. In addition, the reduction effect of trefoil arrangement is better than duct because of closer distance between phase conductor and PGCC. As shown in Table 4, the average reduction rates in duct and trefoil are 36.1 % and 62.1 %, respectively.

Table 4. Average reduction rate according to installation types and arrangement

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Average reduction rate [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Duct</td>
<td>Type 1</td>
</tr>
<tr>
<td></td>
<td>36.1</td>
</tr>
<tr>
<td>Trefoil</td>
<td>62.1</td>
</tr>
</tbody>
</table>

6. SIMULATION RESULTS

6.1 Change of conductor size

As discussed in Sections 4 and 5 for optimal installation of PGCC, TFR CV 240 mm² of conductor size and Type 1 of installation section are selected. However, in this section, the reduction effect of TFR CV 500 mm² is also analyzed for comparison according to the change of conductor size in Type 1 of installation section. In Fig. 7, the induced voltages of TFR CV 240 mm² and TFR CV 500 mm² are compared in duct formation. As shown in Fig. 7, the reduction effect of TFR CV 500 mm² is averagely a little better than that of TFR CV 240 mm². The average reduction rates of both conductor sizes are 36.1 % and 42.6 %, the difference is just 6.5%. In trefoil arrangement, the reduction effect of TFR CV 500 mm² is also slightly better than TFR CV 240 mm² as shown in Fig. 8. The average reduction rates
for both conductor sizes are 62.1 % and 66.3 %. The difference is very small. Accordingly, although TFR CV 500 ㎟ is a little better, TFR CV 240 ㎟ is more economical for optimal conductor size of PGCC because the reduction difference is not big.

![Fig. 7](image1.png)

Fig. 7. Sheath voltage reduction rate according to change of conductor size in duct formation.

![Fig. 8](image2.png)

Fig. 8. Sheath voltage reduction rate according to change of conductor size in trefoil arrangement.

6.2 Effects of faulty phase and two PGCCs

![Fig. 9](image3.png)

Fig. 9. Sheath voltage reduction rate according to change of faulty phase.

In this section, firstly, the sheath voltage reduction rate is discussed according to the change of faulty phase in trefoil arrangement of Type 1 listed in Table 3. PGCC is installed closely to Phase C. Fig. 9 shows the simulation results when the single line to ground fault occurs on each phase. As shown in Fig. 9, averagely, the reduction rate of faulty phase C is better than other phase faults because of position of PGCC. The average reduction rates of faulty phase A, B and C are 62.1 %, 68.8 % and 72.4 %, respectively.

Next, the sheath voltage reduction rate is also discussed in case of the use of two PGCCs in trefoil arrangement of Type 1. Its result is compared with result of one PGCC. The detailed arrangement information is listed in Table 5.

![Fig. 10](image4.png)

Fig. 10. Sheath voltage reduction rate comparison of one PGCC with two PGCCs.

6.3 Transposed installation of one PGCC

Finally, in this paper, the sheath voltage reduction rate is analyzed in case of transposed installation of one PGCC recommended by ANSI/IEEE Std. 575. As shown in Table 6, PGCC is transposed between Phase C and Phase A. In other words, firstly, the PGCC which is placed closely to Phase C is installed from No. 8-1 to No. 9 as shown in Fig. 3, than it is transposed closely to Phase A from No. 9 to B S/S.
Table 6. Case of transposed PGCC

<table>
<thead>
<tr>
<th>Arrangement (Transposed PGCC)</th>
<th>Type</th>
<th>Conductor size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefoil</td>
<td>Type 1</td>
<td>TFR-CV 240 mm²</td>
</tr>
</tbody>
</table>

Fig. 11. Sheath voltage reduction rate comparison of no transposed PGCC with transposed PGCCs.

In Fig. 11, the sheath voltage reduction rate of transposed PGCC is compared with no transposed PGCC. As shown in Fig. 11, the effect of transposed PGCC is better than no transposed PGCC. The average reduction rate of transposed PGCC is 70.8 %, about 8.7 % better than no transposed PGCC. Consequently, the difference is not big compared with duct formation or directly buried formation because the spacing between phase conductors is closer than duct or directly buried formation.

7. CONCLUSION

This paper describes the characteristics of PGCC for single point bonded underground power cable systems. The optimal PGCC conductor size and installation section are selected, in addition, the various analysis considering conductor size, two PGCCs and transposed installation are also performed. The detailed results are the following:

The conductor size of PGCC has been determined by IEC 60364-5-54, the calculated conductor size is 201.3 mm². Accordingly, the conductor size of 240 mm² is selected as optimal conductor size for PGCC.

For selection of optimal installation section, 3 kinds of installation types are proposed in duct as well as trefoil arrangement. In duct formation, averagely, each sheath voltage reduction rate of Type 1 and Type 2 is 36.1 % and 34.8 %, respectively, but Type 3 is just 5.07 %. In trefoil arrangement, the sheath voltage reduction rate of Type 1, Type 2 and Type 2 are 62.1 %, 62.3 % and 4.19 %, Type 1 and Type 2 are also similarly reduced, but Type 3 is just slightly reduced. Comparing Type 1 and Type 2, Type 1 is more economical than Type 2 considering installation length of PGCC. Therefore, in this paper, Type 1 is selected for optimal installation section of PGCC. In addition, the reduction effect of trefoil arrangement is better than duct because of closer distance between phase conductor and PGCC.

In trefoil arrangement, the reduction effect of TFR CV 500 mm² is also slightly better than that of TFR CV 240 mm². The average reduction rates for both conductor sizes are 62.1 % and 66.3 %, the difference is very small. Two PGCCs are much more effective than one PGCC with difference rate of 21.8 %. Finally, the average reduction rate of transposed PGCC is 70.8 %, 8.7 % better than no transposed PGCC. Comparing duct formation and directly buried formation, there is little difference in trefoil arrangement because the spacing between phase conductors of trefoil arrangement is closer than duct or directly buried formation.

Korea electric power company is now planning for adopting PGCC based on the results of this paper. Accordingly, in the near future, the results of this paper will contribute to the application of PGCC on real power cable system in Korea.

References

Jong-Beom Lee 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 Engineering, Wonkwang University, Korea. His current research interests are power systems operation, analysis of power cable systems and DC system analysis.

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