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A PARAMETRIC ANALYSIS OF FAULT CURRENT DIVISION BETWEEN OVERHEAD WIRES AND SUBSTATION GROUNDING SYSTEMS

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ABSTRACT
This paper presents a parametric analysis of the fault current distribution between a substation grounding system and its overhead ground wires and their effects on the grounding systems performance. The influence of the following variables are studied: the resistance of the substation grounding system, the characteristics of the shield wires, the number and the length of the transmission lines connected to the substation, the terminal types (i.e., power source and non-power source terminals), soil resistivity, and power line configurations. It is concluded that the fault current division factor is dramatically affected by the substation grounding resistance, the shield wires conductor characteristics, and the number of transmission lines while it is less influenced by the soil resistivity along the transmission lines and tower resistances. It is difficult to estimate the current division factor for a practical case. The only way to compute accurately the current division factor is to analyze individual cases based on the existing conditions with proper software tools.

KEY WORDS
Grounding System, Fault Current Division Factor, Grounding System Resistance, Overhead Ground Wires, Tower Resistance

1. Introduction

A fault in a high voltage substation may result in large fault currents at the fault location. Consequently, it will cause a ground potential rise (GPR) of the grounding system, ground potential differences (GPD) between different points of the grounding system and touch and step voltages inside and within the vicinity of the substation. Normal operation of low voltage facilities and relay systems may be affected by the GPR and the GPD and equipments may be upset or damaged under serious conditions. Excessive touch and step voltages may appear at exposed locations. These risks must be reduced by designing adequately the substation grounding system. Therefore, the grid current, which flows back to remote terminals through earth and contribute to the GPR of the grid, must be calculated accurately in order to avoid unsafe conditions or unnecessary costly designs.

A common practice in grounding analysis and design is to use the total fault current provided by the planning department as the current discharged by the grounding system. This generally leads to uneconomical overdesigned grounding systems. This is because under most of the conditions, the total fault current doesn't discharge entirely in the substation grounding system. Part of the fault current, which does not contribute to the GPR of the grid, will return to the remote source terminals and to the transformer neutrals through overhead ground or shield wires, neutral wires and other metallic paths connected to the grounding system. The ratio between the current flowing back to remote sources through the overheads wires and neutral wires of the transmission lines and distribution lines connected to the substation and the total fault current is often described as the fault current division factor. Figure 1 shows a simple scenario that illustrates how current is distributed when a fault occurs. It is clear that only the current I_{ba} and I_{bc} contribute to the grid GPR, touch and step voltages at substation B. Currents I_{os1} and $I_{os2,}$ flow to Subtations A and C respectively through the overhead shield wires of the transmission lines, the current I_n that returns to the transformer neutrals will not contribute to the average GPR of substation B. However, the current I_n is a circulating current that contributes to the GPD and distorts the GPR distribution in the grounding system resulting in larger touch and step voltages. Computing these currents accurately is very important for the design of a new substation grounding system or the evaluation of an existing substation grounding system. A simplified model of L.M. Popovic [2] for a one source line is shown in Figure 2. It is shown that the main factors which affect the magnitude of the return currents are the substation ground resistance, self impedance of shield wires and mutual impedance between the faulted phase conductor and shield wires. The other factors include soil resistivity, the structure and number of transmission lines connected to the substation and the number of power source and non-power source terminals [3-4]. Furthermore, the current division factor will be different when the total fault current is the same but the contributions to the fault current from the terminals are different. The approach used in this paper to compute the current division factor is based on a circuit model approach. The circuit model representing the transmission line conductors is built, taking into account the inductive and capacitive mutual impedances between the conductors [1]. Results presented in this paper can be used as a guideline for estimating the fault current division factor for a realistic case before a detailed study is conducted.

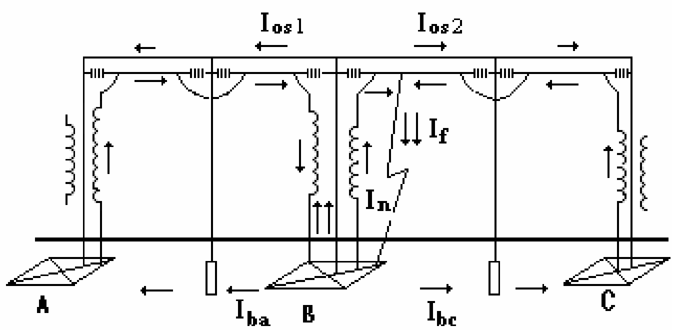

Fig. 1 Distribution of fault current at a station

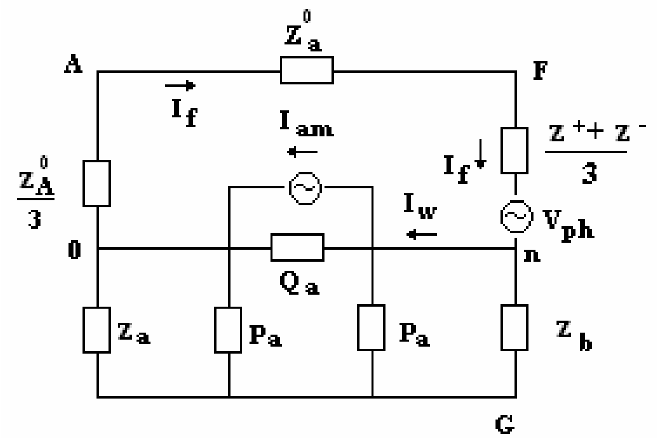

Fig. 2 A Simple Equivalent Circuit
I_f: Fault current in Phase A
I_{am}: Current induced in the ground wires by the phase fault current. It is equal to the induced voltage divided by the self impedance of ground wires
I_w: Portion of fault current in the ground wires
Z_a, Z_b: ground impedance of substation A and B, respectively
Z_a^0: Zero sequence impedance of phase wire
Q_a,P_a: The impedance for the π equivalent circuit of the line. Qa is roughly the total self impedance of the ground wire and Pa the shunt conductance of the ground wire

2. Transformer Neutral Circulating Return Current

The transformer neutral circulating current can easily be calculated as part of the total fault current computation. It exists only in a substation that has many source terminals at different voltage levels. For instance, 500 kV, 220 kV and 35 kV (three voltage levels) in a 500 kV substation fed by several source terminals at 500 kV and 220 kV. When a single-phase-to-ground fault occurs on a 220 kV bus, the 500 kV side will supply fault currents through the 500 kV transformer and this part of the fault current will return to the transformer neutral through the grid conductors (circulating current). Obviously the circulating current does not contribute to the average grid GPR. It contributes to the ground potential differences (GPD) between various locations of the grid and results in higher touch and step voltages.

3. Current Division Factor of Shield Wires

3.1 Transmission Line Shield Wires Connected to Power Source Terminals

Transmission line shield wires emanating from terminals that are not power sources act as a part of the substation grounding grid [4]. Current returns to the sources through the shield wires and discharges into earth at the transmission line tower structures. Since no significant fault current flows in the phase conductors, there are no induced currents in the shield wires of these transmission lines. Therefore the current in the shield wires is smaller than the current in lines connected to power source lines. The current division factor (i.e., ratio of the current in shield wires to the total fault current) for different number of transmission lines has been computed. The results are shown in Figure 3.

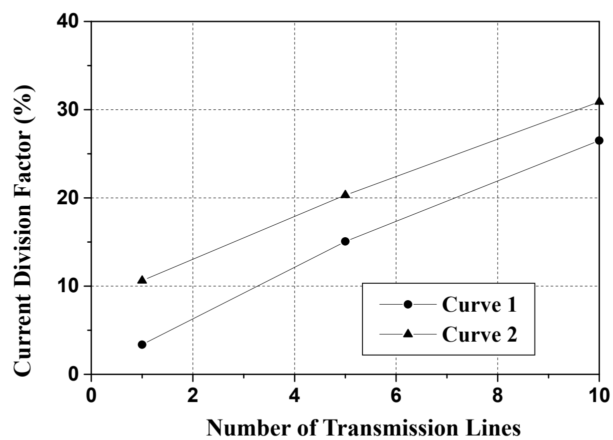

Fig. 3 Current Division Factor with Various Number of Transmission Lines (Substation grounding grid resistance is 0.1 Ω)
Curve 1: transmission line emanating from a non-power source terminal
Curve 2: transmission line with one power source terminal
See Appendix A for detailed transmission line data

Obviously, when the substation grid resistance is low, the current in the shield wires of a non-power source terminal can be small even if there are many transmission lines connected to the substation (in our case, the current division factors for a non-power source terminal and a ten non-power source terminals are 3.37% and 26.5%, respectively.). However, when the ground resistance is high enough, the current division factor for a non-power source terminal can be large. For example, the current division factor for a non-power source (assuming a 10 Ω ground resistance) is 79.64% (Figure 4). The relation between the current division factor and the substation grounding grid resistance is shown in Figure 4. It clearly indicates that when the substation grounding resistance is large, the current division factor of the shield wires is also large.

3.2 Transmission Line Shield Wires Connected to Power Source Terminals

Transmission line shield wires emanating from power source terminals behave differently than those emanating from non-power source terminals because there is an induced emf in the shield wires. The magnitude of the induced current in the shield wires depends on the circuit impedance, the transmission line configuration, the fault current level and soil resistivity. In order to demonstrate the effects of these parameters on the fault current division factor, a one and multi-terminal 500 kV line network model were built to carry out the study using the CDEGS software package [1].

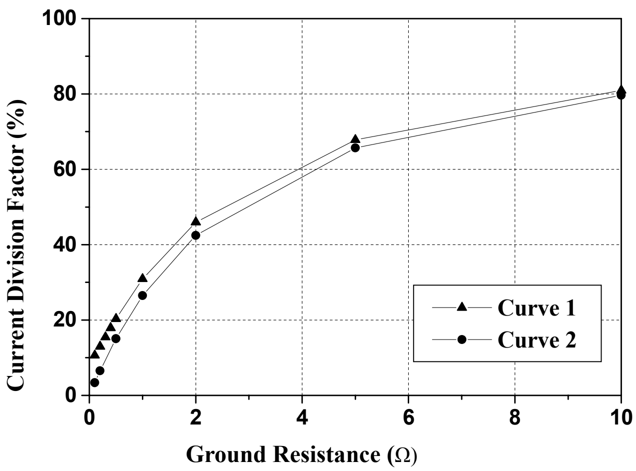

Fig. 4 Current Division Factor with Different Substation Ground Resistances
Curve 1: transmission line emanating from a power source terminal
Curve 2: transmission line emanating from a non- power source terminal
See Appendix A for detailed transmission line data

The following observations can be made from the analysis:

- The current division factor in the transmission line shield wires connected to a power source terminal is higher than that for transmission line shield wires connected to a non-power source terminal (Figures 3 and 4).
- When the resistance of a substation grounding system is small, the number of the transmission lines has a big influence on the current division factor. For example, with a 0.1 Ω ground resistance, the current division factors are 4% (non-power source terminal) versus 10% (power source terminal) and 27% versus 31% for one transmission line and ten transmission lines, respectively as shown in Figure 3.
- When the resistance of a substation grounding grid is large, the number of transmission lines has less influence on the current division factor. For example, with a 10 Ω ground resistance, the current division factors are 81% and 98%, respectively (see Figure 5).

3.2.1 Effects of Substation Grounding Resistance

Figure 5 shows the current division factor as a function of the substation grounding resistance for a network with one and ten transmission lines. Obviously, any increase of the grid resistance dramatically reduces the substation grounding current especially when the ground resistance is small (from 0.1 Ω to 2 Ω in Figure 5). In this case, the soil resistivity and the transmission line configuration remained unchanged. This means that the induced emf per unit length shield wire does not change. Therefore, when the grid resistance increases, more current flow in the shield wires since the substation ground is less attractive as a return current path.

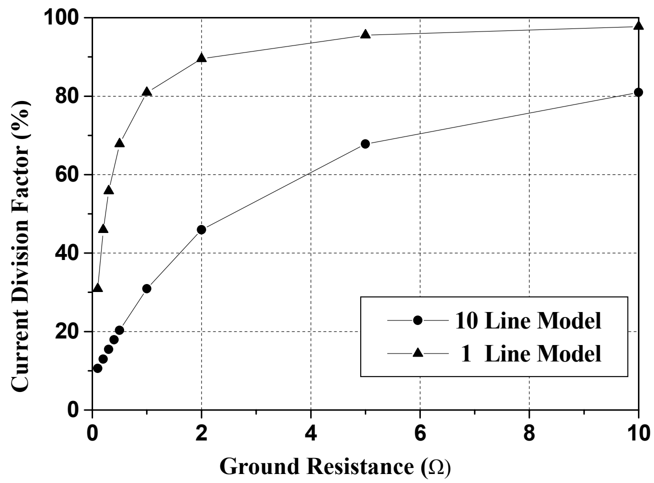

Fig. 5 Current Division Factor for Different Substation Ground Resistances: one line model and ten line model
See Appendix A for detailed transmission line data

For a ten-terminal system model, the reduction of grid current is less significant than for a one-terminal system model. However, the current division factor is still significantly larger (98% compared to 81%).

3.2.2 Effects of Soil Rresistivity

Let us examine the effects of soil resistivity along the transmission lines on the current division factor. Assuming a soil resisitivity varying from 20 Ω-m to 1000 Ω-m, the computed mutual impedance between the phase conductor and shield wires increases from 0.1959 Ω to 0.3119 Ω per km. Figure 6 shows that the current division factor increases with increasing soil resistivity. This is because the mutual inductive coupling between the phase conductor and the shield wires increases, forcing more current to flow in the shield wires. It is important to note here that Figure 6 assumes that the resistance of the substation and tower structures remains constant as soil resistivity changes. If this was not the case, then more fault currents will return through the overhead ground wires as soil resistivity increases, resulting in an increase of ground resistance that makes the soil path less attractive for fault current to return to the power sources.

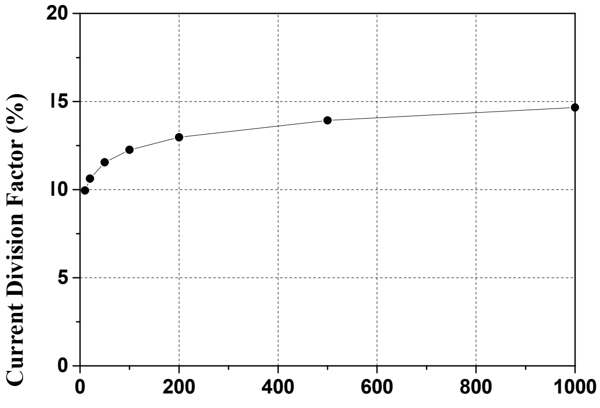

Fig. 6 **Current Division Factor for Different Soil Resistivity**
See Appendix A detailed transmission line data

3.2.3 Effect of Tower Ground Resistance

Figure 7 shows what happens when the average transmission line tower resistance changes. As can be seen from the figure, less fault current flows in the shield wires when the tower resistance increases. However, as the resistance increases beyond 10 ohms, the current division factor reaches a lower level corresponding to the current trapped in the shield wires by mutual coupling.

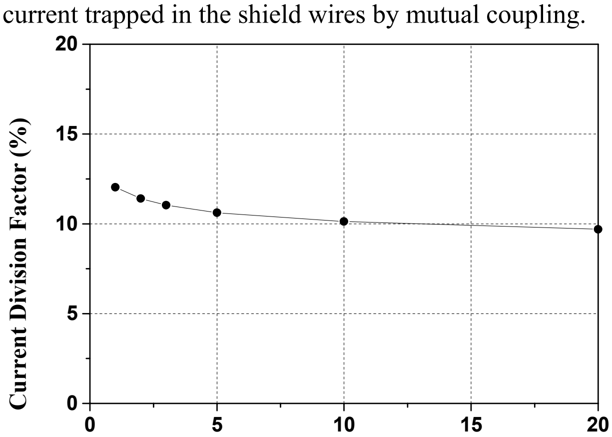

Fig. 7 **Current division factor for different tower ground resistances**
See Appendix A detailed transmission line data

3.2.4 Effect of Shield Wire Characteristics

Finally, the effects of the shield wire characteristics on the current division factor is studied. In Figure 8, Curves 1 and 2 represent the current division factor for a steel and an aluminum conductor, respectively. It can be seen that the current division factor is higher for conductors exhibiting low self-impedances as expected.

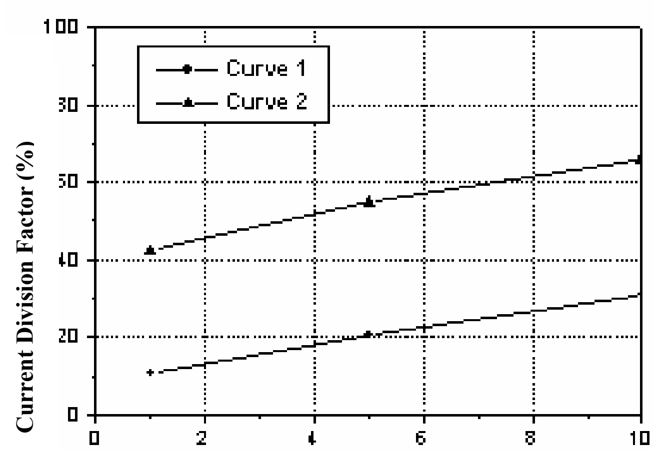

Fig. 8 **Current Division Factor for Different Type of Shield Wires**
Curve 1: transmission line with steel shield wires
Curve 2: transmission line with aluminum shield wires
See Appendix A detailed transmission line data

4. A Practical Example

This section presents the computed results corresponding to a large 500 kV substation connected to 500 kV and 220 kV transmission lines and 35 kV distribution lines [5]. The fault currents were calculated for a single-line-to-ground (S-L-G) fault on a 220 kV bus and a 500 kV bus at the substation. Tables 1 & 2 summarize the fault currents based on the existing system capacities. Figure 9 shows typical cross-sections used to represent the 200 kV and 500 kV lines connected to the substation. The shield wires are made of steel for the 220 kV lines and are of the optical type for the 500 kV lines. A resistance of 5 ohms is used for all tower structures. Figure 10 presents the results for the 220 kV circuit model. When a fault occurs on a 220 kV bus, six remote 220 kV sources contribute to the fault current; two of the 220 kV lines don't contribute any fault current, but since their overhead ground wires are connected to the substation ground, they help reduce the current injected into the ground grid, i.e., increase the current division factor. Furthermore, two 500 kV contribute to the fault current through 220 kV transformers in the form of a circulating current confined almost entirely in the grounding system conductors (i.e., circulating current).

The fault current distribution has been calculated for a fault on a 220 kV bus, using the Right-Of-Way software [1]. Table 3 shows the currents injected into the substation grounding system (earth currents) as well as the ground potential rise (GPR) of the grid without considering the circulating current in the ground conductors, while Figure 11 shows the distribution of the fault current along the transmission line overhead ground wires.

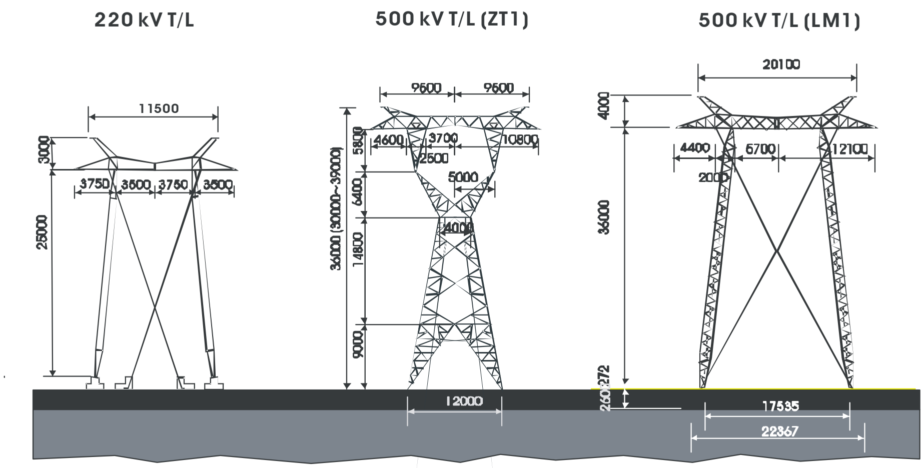

Fig. 9 Cross-Sections of the 500 kV and 220 kV transmission lines

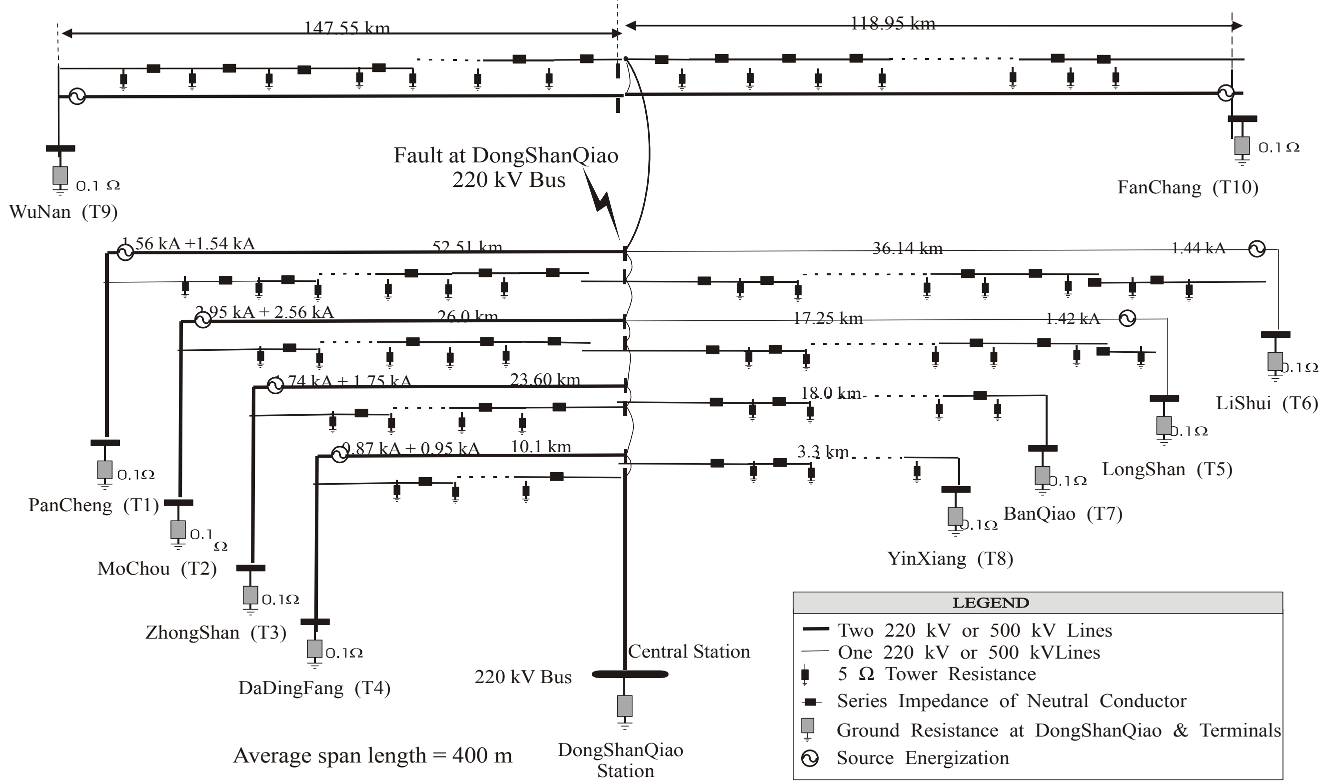

Fig. 10 Circuit Model of the 220 kV Network Used to Determine the Fault Current Distribution

Table 3 and Figure 11 show quite clearly that a lot of the fault current returns to the sources through the overhead ground wires (close to 50%). This is due to the mutual coupling between the faulted phase and overhead ground wires on one hand and because of the low transmission line ground resistances (about 5 ohms) on the other hand as shown in Figure 11. Indeed, the horizontal portions of the curves correspond to the inductive coupling that maintains the current flowing in the ground wire despite the fact that the fault current has already dissipated entirely in the tower grounds located within 2-3 km from the substation.

Table 1 Fault Currents Contributions for a 220 kV Fault

Transmission Line (transformer) Name	Line Fault Current (kA)
Zhongshan to Dongshanqiao 1#	1.74
Zhongshan to Dongshanqiao 2#	1.75
Dadingfang to Dongshanqiao 1#	0.87
Dadingfang to Dongshanqiao 2#	0.95
Longshan to Dongshanqiao	1.42
Mochouhu to Dongshanqiao 1#	2.95
Mochouhu to Dongshanqiao 2#	2.56
Lishui to Dongshanqiao	1.44
Pancheng to Dongshanqiao1#	1.56
Pancheng to Dongshanqiao 2#	1.54
Transformer 1#	14.69
Transformer 2#	15.56
Total current	46.8

Table 2 Fault Currents Contributions for a 500 kV Fault

Transmission Lines Name	Line Fault Current (kA)
Wunan to Dongshanqiao 1#	2.886
Wunan to Dongshanqiao 2#	4.92
Fanchang to Dongshanqiao 1#	3.807
Fanchang to Dongshanqiao 2#	3.225

Table 3 Fault Current and Ground Potential Rise at the Substation

Total Fault Current	Ground Wires Current	Substation Ground Current	Ground Potential Rise
$16810.7<84.2^0$	$8658.0<-93.7^0$	$8388.6<-74.6^0$	$884.99<-74.6^0$

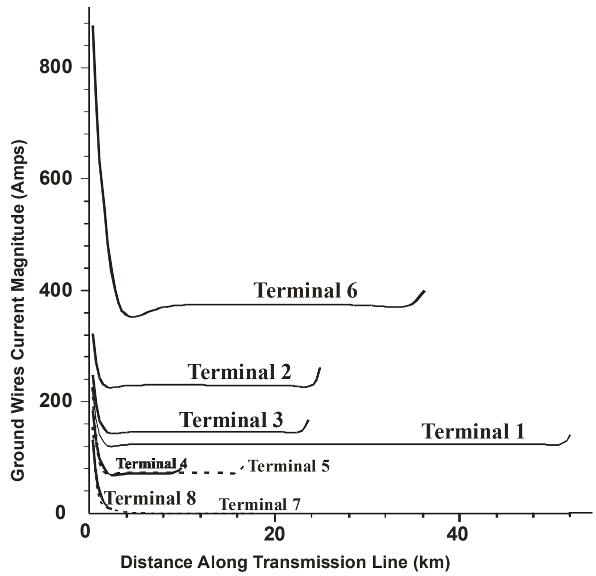

Fig. 11 **Computed Fault Current in the Transmission Line Overhead Ground Wires (only one line for each terminal is represented. The currents in the other lines are about the same).**

5. Conclusion

This paper discusses the distribution of currents between a substation grounding system and its overhead shield wires during a single-phase-to-ground fault at the substation. This analysis has been done while varying a number of key parameters that include the resistance of the substation grounding system and tower structures, the type of shield wires, the number of the transmission lines connected to the substation, the terminal types (i.e., power source and non-power source terminals) and soil resistivity. The following conclusions can be drawn from the study:

● The fault currents emanating from the remote power sources contribute to the overall GPR of the grid, while the current originating from substation transformers have a negligible effect on the average substation GPR, but dramatic effects on the local GPR (i.e., potential rise of ground conductors at a given location).

● The current division factor is mainly affected by the substation grid resistance, the type of shield wires and the number and type (power source or non-power source) of transmission lines. The soil resistivity along the transmission lines has a small effect on the current division factor if this resistivity variation does not affect average tower ground resistances.

● When the ground resistance of the substation is low, the increase of the number of power source lines connected to the substation will lead to a significant increase of the current division factor. However, the current division factor increases slightly with the increase of the number of transmission lines if this ground resistance is high.

A complete circuit model of the overhead transmission line network has been built in order to determine the current distribution during a single-phase-to-ground fault for a practical case. The results clearly show that significant fault current returns to the sources through the overhead ground wires. Therefore, costly over-designed grounding system can be avoided if accurate computations of the current division factor are carried out.

6. Appendix A

The cross-sections of the 220 kV and 500 kV transmission lines are shown in Figure 9. Fro Figures 3-8, the phase conductors and shield wires are LGJQ-400 steel and GJ-95 optical type for the 220 kV and 500 kV transmission lines, respectively. Shield wires are grounded at every tower. The average ground resistance of the towers is 5 Ω. The soil resistivity along the transmission lines is 20 Ω-m. The remote substation ground resistance is 0.1 Ω. Each parameter was varied while the others remained constant.

7. Acknowledgments

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References

[1] CDEGS Software Package, Safe Engineering Services & technologies ltd., Montreal, Quebec, Canada, Version 11, June 2004.

[2] L.M. Popovic “Practical Method For Ground Fault Current Distribution in Station Towers and Grounding Wire,” IEEE Trans. On Power Delivery, Vol.13 No.1. jan.1998, pp. 123-128.

[3] IEEE Guide for Safety in AC Substation Grounding ANSI/IEEE Std 80-2000.

[4] G. Yu, J. Ma and F. P. Dawalibi “Computation of Return Currents Through Neutral Wires in Ground Analysis,” Proceedings of The Third IASTED International Conference on Power and Energy System, Las Vegas, Nevada, Nov. 1999, pp.455-459.

[5] F. P. Dawalibi, J. Ma, Y. Li and Y. Yang, “DongShanQiao Substation Grounding Analysis,” Report 129 (414), Project No. 129 (414), Prepared for Jiangsu EPRI, China (DongShanQiao Grounding Project), October, 2003.